Semiconductor Laboratory, Ångström Laboratory, Microtechnology Centre – an evaluation

Three major academic laboratories for microelectronics and micro/nanofabrication in Sweden

Semiconductor Laboratory, Ångström Laboratory,
Microtechnology Centre – an evaluation

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Cover photos
Top: Array of High Electron Mobilty Transitors (MEMT) fabricated from Indium Phosphide material. (MC2)
Left: Opto-electronic integrated circuit with light detector and Heterojunction Bipolar Transistors fabricated from Indium Phosphide material. (The Semiconductor Laboratory)
Right: Nozzle used for micropropulsion in space. (The Ångström Laboratory)

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Preface

The Swedish Research Council is a governmental agency with the mission to support basic research within a broad range of scientific fields ranging from humanities and social sciences to medicine and natural and engineering sciences. The main part of the Swedish Research Council's budget is allocated to fund high-quality research projects but the Swedish Research Council also supports the operation of national laboratory facilities.

The evaluation of the three microelectronics laboratories – the Semiconductor Laboratory (the Royal Institute of Technology), MC2 (Chalmers University of Technology) and the Ångström Laboratory (Uppsala University) – will form the basis of the assessment by the Swedish Research Council of the need for a national co-ordination of resources within the area. The Swedish Agency for Innovation Systems (VINNOVA) has cooperated with the Swedish Research Council in this evaluation.

The members of the evaluation committee were Dr. Klas-Håkan Eklund, Eklund Innovation, Sweden, Prof. Stephen Fonash, Penn State University, USA, Prof. Jørn Hvam, the Technical University of Denmark and Dr. Herman Maes, IMEC, Belgium. Professor Karl-Fredrik Berggren, Linköping University, was appointed chairman of the evaluation committee. During the evaluation, Dr. Leif Eriksson (Swedish Research Council), Dr. Per Karlsson (Swedish Research Council) and Dr. Sven-Ingmar Ragnarsson (VINNOVA) have assisted Prof. Berggren.

The report starts with an executive summary where the findings and recommendations are summarized. This is followed by the directives for the evaluation. The presentation of the evaluation committee precedes a large chapter where the impressions from the site visits are presented and a chapter with concluding remarks from the visits. The last chapter contains the recommendations of the evaluation committee.

The Swedish Research Council would like to express sincere gratitude to the evaluators for devoting their time and expertise to this evaluation and for their invaluable contribution of finding a structure for effective national use of the micro- and nanofabrication facilities in Sweden. I would also like to thank Prof. Berggren for skilful and firm guidance of the work of the evaluation committee in accordance with the directives. Dr. Eriksson, Dr. Karlsson and Dr. Ragnarsson are hereby thanked for assisting the evaluation committee and for providing background material. Thanks also go to Dr. Anders Sjölund (SSF) for supplying useful information. Finally, the Swedish Research Council would like to thank representatives of the three laboratories for delivering reports and for giving informative presentations to the evaluation committee.

Kåre Bremer
Secretary General
The Scientific Council for Natural and Engineering Sciences

Contents

Acronyms:

KAW	–	Knut and Alice Wallenberg Foundation
KTH	–	Royal Institute of Technology
FMV	–	Swedish Defence Material Administration (Försvarets materielverk)
FRN	–	The Swedish Council for Planning and Coordination of Research (Forskningsrådsnämnden)
MFR	–	The Medical Research Council (Medicinska forskningsrådet)
NFR	–	Swedish Natural Science Research Council (Naturvetenskapliga forskningsrådet)
SSF	–	The Swedish Foundation for Strategic Research (Stiftelsen för Strategisk Forskning)
TFR	–	Swedish Research Council for Engineering Sciences (Teknikvetenskapliga forskningsrådet)
UHÄ	–	The National Swedish Board of Universities and Colleges (Universitet och Högskoleämbetet)
VINNOVA	–	The Swedish Agency for Innovation Systems (Verket för Innovationssystem)
ÖCB	–	The Swedish Agency for Civil Emergency Planning (Överstyrelsen för Civil Beredskap)

CR	–	Clean Room
CTH	–	Chalmers University of Technology
KTH	–	The Royal Institute of Technology
UU	–	Uppsala University

Executive summary

This evaluation is of the three major academic microelectronics laboratories: The Semiconductor Laboratory at the Royal Institute of Technology, Kista/ Stockholm; The Ångström Laboratory at Uppsala University, Uppsala; Microtechnology Centre (MC2) at Chalmers University of Technology, Göteborg.

Background

The three laboratories are important for research and education in microelectronics, the field that underlies modern information technology. However, microelectronics is just a part of microtechnology, which is quickly broadening into nanotechnology. The sciences and technologies associated with microtechnology and nanotechnology are already providing exciting scientific discoveries and new innovations for industrial development. *Consequently, because of these rapidly occurring shifts in science and technology, this report will present a broader perspective than merely that of "microelectronics".*

Present status

The present investment in the KTH, Uppsala, and Chalmers facilities puts Sweden in an excellent position for participation in the continued spread of micro-structure technologies and for the coming development of nano-structure technologies. The clean rooms, the equipment sets, and the expertise found at these facilities are a national resource. The costs incurred in setting up these three facilities with their clean rooms and equipment sets are in line with what is seen elsewhere in Europe and in the U.S. and the staffing needs, pressures, and costs are exactly what is seen elsewhere. Taken as a whole, these facilities give Sweden the potential to develop the full spectrum of microtechnology applications and to participate actively in the creation of the new spectrum of nanotechnologies.

High costs

Creating three laboratories of this calibre is a high-cost investment and they are an outstanding national resource. However, the existence of these three broad-based laboratories and their locations are not the result of a coherent national planning process. In general the laboratories have grown incoherently out of the activities of different research groups and the ambitions of departments/universities. They have also been allowed to grow due to the existence of a rather diffuse external funding structure. For example, the KTH Semiconductor Laboratory and the Ångström Laboratory are located within commuter distance.

Recommendations: specialization

There is a place for these three laboratories in a national Swedish strategy for micro- and nanofabrication if they enter into a task-sharing where the laboratories focus on specific roles. A natural specialization of the laboratories emerges from their established research backgrounds and the expertise and facilities that have already been built up in the three locations.

- The Semiconductor Laboratory at KTH is a well-established centre for device research within semiconductor technology. It has created an excellent environment for collaboration with industry and efficient technology transfer which should be further developed, particularly within the fields of microelectronics and photonics.
- The Ångström Laboratory is planned as a multidisciplinary centre for research and education within micro- and nanotechnologies. It should be marketed as a multidisciplinary R&D resource for the development of new applications within nanotechnology, biotechnology and life science. It should also serve as the national centre for teaching graduates and post-graduates in these fields.
- MC2 at Chalmers has the scientific expertise and the technical facilities to become a world-leading research centre for micro- and nanotechnologies. Its facilities are unique in Sweden and should be promoted as such. It is recommended that its specific user mission should be in the focused areas of high-speed electronics and nanoscale lithography.

Recommendations: a national network

It is recommended that the Swedish Research Council creates a Swedish Nanotechnology Network (SNN) as a distributed National Facility to take advantage of the expertise and equipment base already in place at KTH, Uppsala, and

Chalmers. *This network would be mandated to serve as a shared national resource for all of Sweden.*

The specific objectives of SNN will be (1) to avoid unnecessary duplication of expensive, difficult-to-maintain equipment, (2) to ensure co-ordinated resource utilization and future development, (3) to ensure adequate technical support staffing of facilities, (4) to provide facilities and staff support for the R&D activities of qualified users coming from all of Swedish academia and industry, (5) to provide facilities to enable qualified educational activities from all of Swedish academia, and (6) to have each facility of SNN take responsibility for a segment of micro- and nanofabrication. The performance of SNN as a national facility, as well as that of each participating facility, will be judged to determine whether these six objectives are being met.

It is very unusual that large-scale facilities of the present kind are operated without basic support for infrastructure and user support. It is recommended that the funding support for the activities of the proposed Network must at least be at a minimum level of 20 MSEK (+ university surcharges) per year. This support should be allocated for 5 years. Network performance should be evaluated every six months. *A decision to continue or discontinue the Network or a specific facility would be made with an evaluation at the conclusion of the fourth year.* It is recommended that the budget be divided into 5 MSEK per year for each facility. In the first year the remaining 5 MSEK would be evenly distributed among the facilities. In successive years, the remaining 5 MSEK per year would be distributed on the basis of the performance criteria of Appendix 8.

SNN will require a national steering board. The board, which should report to the Swedish Research Council, must be small with, tentatively, representatives from KAW, VINNOVA, SSF and the Swedish Research Council, the centres, users, and industry plus a chairman. To be effective the board will need a part-time co-ordinator/manager employed part-time by the Swedish Research Council. This person should have an established scientific background in relevant fields. SNN offers the possibility of future dynamic and coherent planning of the centres participating in the national network. *There is then a clear mechanism for downsizing of a particular site as well as upgrading it. There is also the possibility to include other smaller centres that may offer unique equipment, special materials, and/or services or to respond dynamically to new developments.*

The main external funding to individual researchers and research groups comes as short-term grants from the Swedish Research Council, SSF, and VINNOVA, with SSF as the dominant contributor. The cost for SNN should therefore be shared among them.

Recommendations: funding

Scientific equipment

Microelectronics and micro/nanofabrication are dependent on large capital investments in scientific equipment. The ongoing rapid miniaturization within these fields requires continued investments, which tend to be on a higher level because of increasing sophistication in instrumentation. There has been ample funding for equipment. There is, however, a problem in that investment and maintenance costs are separated. In many cases one therefore encounters inefficient use of equipment. *It would be a great improvement if investment and maintenance costs (for an adequate scientific lifetime) could be funded as one package.*

Research grants

Level of grants: Too often, external grants do not recognize costs/fees for use of clean room (CR) equipment and facilities. This easily leads to underfunding of projects and ineffective use of CR facilities. This problem must be taken seriously and *it is crucial that additional project funding is directed to cover the cost of CR use.*

Infrastructure

Funding for infrastructure: Funding scientific equipment is normally the outcome of successful grant applications within a competitive system. Within such a system it is hard to find support for investments for general infrastructure. This situation is unfortunate since the high-quality infrastructure is a prerequisite for research projects to be successful.

Introduction

This document presents an evaluation initiated by the Swedish Research Council and the Swedish Agency for Innovation Systems (VINNOVA). This evaluation is of the three major academic microelectronics laboratories:

The Semiconductor Laboratory at the Royal Institute of Technology, Kista/Stockholm, The Ångström Laboratory at Uppsala University, Uppsala, Microtechnology Centre (MC2) at Chalmers University of Technology, Göteborg,

These laboratories are of obvious importance for academic research and education in microelectronics, the field that underlies modern information technology. These laboratories also play key roles in the interactions between academia and R&D in the Swedish electronics industry. In the very immediate future these laboratories are also in a position to play an important role in the rapidly emerging field of nanotechnology.

Microelectronics is just a part of microtechnology, which is quickly broadening into nanotechnology. The sciences and technologies associated with microtechnology and nanotechnology are already providing exciting scientific discoveries and new innovations for industrial development. Consequently, because of these rapidly occurring shifts in science and technology, this report will present a broader perspective than merely that of "microelectronics".

The shift that is occurring from microelectronics to a broader microtechnology and into the vast field of nanotechnology can be gauged by the following meaning of the term "chip". This word originally referred to microelectronics circuit structures fabricated using semiconductor substrates. Today the term "chip" encompasses structures used in a variety of fields. These include electronic chips but they also include applications as diverse as chemical reactor chips for functions such as point-of-use delivery of potentially dangerous chemicals and biochips for functions such as DNA sorting and toxin detection. Today substrate materials vary from semiconductors to plastics. The technology to make all these structures has evolved to the point where the size of the features on these chips is no longer necessarily in what is often referred to as the microstructure range (greater than 100 nanometers (nm)) but has become so small that features can be in the nanoscale range (less than 100 nm). This technology has developed to a level where microscale is the larger size range of feature sizes that have evolved down to the nanoscale. The trend is toward further evolution into the nanoscale. This sub-100 nm size range is receiving increasing attention because it offers possibilities that are not available in larger size ranges. The appearance of these possibilities is not due to any new science but is due to a shift in the dominance of surface over volume effects and to a shift in the dominance of quantum over classical phenomena. Exciting developments will be coming from nanotechnology and will be having a tremendous impact because, for the first time, it is possible to engineer, make systems and exploit phenomena in the nano-range spanning sizes from those of viruses down to small molecules.

In microelectronics, R&D can require many steps involving deposition, etching, and sophisticated lithography. This means that researchers must have convenient access to a variety of sophisticated instruments and processes and these must be provided in clean rooms (CR). This need for all of these processing steps, and for staff who sustain these processes, exists in all aspects of microtechnology, not just microelectronics. It exists in all of nanotechnology as well. In fact, in nanotechnology the need for precision equipment, staff support, and clean room environments is more severe since one is dealing with sizes of the order of virus molecules or smaller. These requirements for a sustaining staff, for a broad spectrum of processing and characterization tools, and running costs for clean room facilities make the required funding level of micro- and nanotechnology research high. The level of these costs can be beyond the reach of a single research group, university department or small start-up company. The KTH Semiconductor Laboratory, the Ångström Laboratory, and MC2 have processing tool bases and clean rooms to support micro- and nanotechnology R&D as well as educational efforts. When taken as a whole, these laboratories do lack sufficient staff support; however, the KTH Semiconductor Laboratory, the Ångström Laboratory, and MC2 are examples of high-level interdisciplinary facilities that have the potential to provide professional service to academic and company users.

The KTH Semiconductor Laboratory, the Ångström Laboratory, and MC2 were singled out for this assessment because of their existing investments in equipment, clean rooms, and staff and for the expertise base they have in place. However, they are not the only academic sites in Sweden that provide microfabrication and CR facilities. Indeed, there are quite a few (see, e.g., "Elektroniktidningen", 13–14 September 2001). The most recent addition to this group is a new semiconductor laboratory, which has been inaugurated as late as 2002 in Sundsvall as part of EU regional support. Investments in this new 200 m^2 CR facility were undertaken using EU funding backed by local resources. All of these other laboratories listed in "Elektroniktidningen" are, in general, smaller and/or more specialized than the KTH Semiconductor Laboratory, the Ångström Laboratory, and MC2. *Therefore, a reason for the Swedish Research Council and VINNOVA for selecting the three laboratories for this evaluation is that they are the major laboratories that offer full processing lines, which can serve* a *wide class of internal and external users from academia as well as industry.* These laboratories have the broadest equipment base and are therefore a very valuable resource. As noted, however, the initial investment, sustaining costs, and running costs of laboratories of this type are very high. The cost of new advanced instrumentation, for example, is reaching such levels that duplications become inconceivable. These three laboratories have realized this dilemma and have noted the need for cooperation, specialization, and co-ordination. Realizing the urgency of these issues, these three laboratories have already proposed an organization for working together. This is discussed in the SPIN document ("Swedish Microtechnology Process Integration Network", Appendix 6).

The three laboratories, taken as a whole, are a national resource. However, the existence of these three broad-based laboratories and their locations are not the result of a coherent national planning process. In general the laboratories have grown incoherently out of the activities of different research groups and the ambitions of departments/universities. They have also been allowed to grow due to the existence of a rather diffuse external funding structure. For example, the KTH Semiconductor Laboratory and the Ångström Laboratory are located within commuter distance.

External funding for academic research at the three centres is obtained from the Swedish Research Council, the Swedish Agency for Innovation Systems (VINNOVA), and the Swedish Foundation for Strategic Research (SSF). The Knut and Alice Wallenberg Foundation (KAW) has also generously funded expensive scientific equipment. Overviews of present and planned funding from the Swedish Research Council, VINNOVA, and SSF plus contributions from KAW for scientific equipment are given in Appendix 7. One notes in particular that funding is given to projects, not to sustainable support for infrastructure. One also notes that the level of funding is dwindling. Given the importance of microelectronics to Swedish industry this should be of great concern. This concern is understood when one considers the probably even greater importance of the forthcoming, more general micro- and nanotechnology R&D to Swedish industry.

With the general background given above, an evaluation of the three la-boratories is indeed timely. The evaluation was organized in the following way. The committee (Section "Expert committee" and Appendix 1) was given the directives presented in the next section. The three laboratories were asked to submit reports covering the points raised in the directives (Appendices 2–5). Visits were made to all the laboratories (Section "Impressions from the site visits" and Appendix 2). Impressions from the visits are summarized in the following section. Summaries and recommendations are given in the last section.

Directives

The following text is a translation from Swedish.

The evaluation of the three microelectronics laboratories: the Semiconductor Laboratory (the Royal Institute of Technology), the Ångström Laboratory (Uppsala University) and MC2[1] (Chalmers University of Technology) will form the basis of the assessment by the Swedish Research Council on the need of a national co-ordination of resources within the area. The evaluation shall contain the aspects that are stated in this document and shall be presented in a written report no later than March 31, 2002. The Swedish Research Council will then consider the need of national resources. The Swedish Research Council will complete this task during 2002.

Description of the present situation

The quality and the future potential of the research and the technical equipment at the three laboratories shall be assessed by the evaluators, from the perspectives of both fundamental and applied research. International comparisons shall be made. The profile and spectrum of each laboratory shall be reported.

The present industrial contacts shall be described. The importance for Swedish industry as well as the potential for future enterprising shall be assessed from local, national and international perspectives. Joint utilization of the laboratories with industrial research institutes shall be studied and the need for industrially compatible process equipment shall be evaluated.

The present use of the laboratories by local research groups, external Swedish groups, foreign research groups and companies shall be evaluated.

The economy of the laboratories: rental costs and other costs shall be accounted for as well as the need for continuous investments.

Description of experienced problems and needs for change

Problems experienced by the management of each laboratory, as well as opinions and wishes from the research groups and industry. The accessibility to different user groups.

[1] Some of the directives will not apply to the newly established MC2.

Suggestions

The evaluators should suggest at least one recommended level of ambition and hence suitable organization and co-ordination of the activity at the three laboratories. The purpose should be to obtain an effective use of the resources. At least one suggestion should include a national co-ordination. A specialization of activities should be considered. Travel support should be considered. The report shall contain an assessment of which of the present activities are complementary or overlapping as well as an assessment of the possibilities and limitations of joint use of resources. The importance of laboratories for graduate and post-graduate education shall be considered. The evaluation group should also assess if all three laboratories are needed from a national perspective, or if one or two laboratories (should be named) would satisfy the needs. The development potential of the different locations should be considered.

Suggestions of organization schemes and co-ordination of the activities should comprise a time span of 5–10 years but must be more detailed during the first three years, for which a budget shall be included. At least one of the budget proposals should be at the same financial level as the present one. The cost of operation, maintenance and support for unaccustomed user groups shall be specified. The budget shall also show the development of the costs of material and salaries during the first three years. Sponsoring from industry (donations) and regional development resources should be considered.

All proposals must account for a phase-out of the proposed organization scheme.

Expert committee

The Swedish Research Council has appointed the following four experts for the evaluation:

Dr. Klas-Håkan Eklund
Eklund Innovation
Sollentuna, Sweden

Professor Jørn Hvam
Research Centre COM
Danish Technical University, Lyngby
Denmark

Professor Stephen J. Fonash
Director of PSU Nanofabrication Facility
The Pennsylvania State University
University Park, USA

Dr. Herman E. Maes
Vice-President IMEC
Director Silicon Technology and Device Integration
Professor at the K.U. Leuven
Leuven, Belgium

Brief presentations of the experts are given in Appendix 1.

Chairman appointed by the Swedish Research Council:
Professor Karl-Fredrik Berggren
Theoretical Physics, Head of Theory and Modeling
Linköping University, Sweden

Support persons:
Dr. Per Karlsson
Co-ordinator, Swedish Research Council
Dr. Leif Eriksson
Scientific equipment, Swedish Research Council

Dr. Sven-Ingmar Ragnarsson
Program Manager, Microelectronics/Photonics
Swedish Agency for Innovation Systems (VINNOVA)

Observer:
Dr. Anders Sjölund
Program Manager, Microelectronics/Materials science
Swedish Foundation for Strategic Research (SSF)

Impressions from the site visits

The committee has visited the three laboratories for presentations of activities, project highlights, and discussions. Thus the Semiconductor Laboratory in Kista was visited on February 4, the Ångström Laboratory in Uppsala on February 5, and MC2 in Göteborg on February 6. Well in advance of the visits, the laboratories were invited (see letter in Appendix 2) to submit reports covering the different aspects raised in the directives above. The reports from the labs are included in Appendices 3–5.

The Semiconductor Laboratory at KTH

Profile

The Semiconductor Laboratory is a research and education facility dedicated to semiconductor processing and device research within a fairly broad range of topics. It is serving academia as well as promoting industrial development and providing support for start-up companies. As such it has been quite successful, even to the point where start-ups and other industrial activities have drained the laboratory's own staff of process specialists.

As a result, the laboratory has been reorganized to distribute the responsibility for the performance and maintenance of the equipment to the various user groups. This also means that the overall profile and strategy of the laboratory are formed by the user groups according to their individual research strategies and their ability to raise funding for their user fees.

The Semiconductor Laboratory basically has five process lines covering Si electronics and MEMS, SiC electronics, GaAs and InP optoelectronics. They serve research efforts within silicon electronics, (bio-)MEMS, and photonics.

Quality

The laboratory has for some years delivered about 10 PhD candidates per year with major expertise in semiconductor process technology, who have been of instrumental importance for existing industries as well as new start-up companies.

The laboratory has supported world-class research in selected areas, particularly within power electronics and photonics. Fast optoelectronic devices like directly modulated lasers (30 GHz, 1.55 μm) and modulators (untersubband at 6.2 μm and travelling wave at 1.55 μm) can be mentioned as standing world records.

Future potential

The SiC work has lost the major industrial player. It is unclear to what extent the laboratory wishes to sustain the SiC research or convert into work on GaN. Within photonics there are strong ambitions to develop and expand the activities within a broad range of modern topics like nanophotonics, quantum information, photonic crystals, bio-photonics, coherent interactions (EIT), and ultrafast phenomena. Some focusing of these aims seems to be in place.

Selected topics within physics and materials science are in the process of moving to Kista in order to strengthen the scientific base of materials research. Still, it appears that the overall focus on semiconductor device research will be kept.

Quality and future potential of the technical equipment

The KTH laboratory has a 1300m^2 CR area, with classes 100, 1000 and 10000.

The lab is subdivided in 5 sections. In each of these sections the emphasis is on the fabrication of microelectronic devices from substrates to chip level, and even some small-scale production (prototyping) is going on. Hence the equipment is certainly not intended for materials research only.

The different units cover Silicon IC, bipolar and MOSFET device fabrication, Silicon MEMS fabrication, GaAs optoelectronics, InP optoelectronics and SiC electronics. In the latter unit, ABB Corporate Research was using until recently about 300m^2 of area in which they had installed their own equipment. Due to the decision of ABB to quit SiC development, this equipment is now either to be taken over by KTH, to serve its own future research and development programmes on SiC or to be taken over by others. A final decision on this has not been made so far. In addition to the process equipment, necessary equipment for die mounting and physical characterization is available. There is no separate exhaust for the different technology units.

On the tour to the laboratory we got a good impression of the equipment and the CR usage.

Most of the equipment is 4" based but some systems can accept 6" wafers and some even allow 8" wafer processing (for instance the ASM Epsilon 2000 system for Si/SiGe epitaxy).

The CR is operated on a 5 days/week, 8-12 hours/day (60 hours/week) basis.

The total usage is estimated at 40,000 hours/year (i.e. about 25 days per user per year) but this could be increased by at least a factor of 2 according to the KTH managers. The daily operation, maintenance and co-ordination involve 10 people (not including the users). The equipment is operated by the users (more than 180!) who need to qualify ("driver's license") before being allowed to run the systems. Exchange of wafers with other laboratories seems to be a common practice and according to the management the existing precautions to avoid contamination are adequate. Moreover, part of the CR can be accessed by undergraduate students for some hands-on experiments (realization of a diode in 1 day or of a MOS transistor in 3 days). ACREO is today the major external client and has about 70 users of the CR facilities.

Generally speaking, the CR is well equipped although many of the basic systems have reached their lifetime expectancy of 10–15 years and need urgent replacement, according to the management. The available equipment has nevertheless allowed the group to fabricate devices with impressive performances.

The optical lithography capabilities are limited to 0.5 μm (i-line). For both Si processing and the photonics research, use is made of the Chalmers JEOL e-beam system for obtaining smaller feature sizes. According to the management this is adequate for processes requiring only a single access (for instance for the 100 nm MOSFET gate definition) but is very impractical in case of the photonics programme which requires multiple access to the e-beam system.

According to the management the available funding for equipment is rather limited. From the Wallenberg Foundation there was a 30 MSEK financial grant in 1996 followed by a second one 2 years ago of 25 MSEK, which however consisted of only 5 MSEK for processing equipment and 20 MSEK for advanced characterization equipment. Only for equipment aiming at very specific research programmes can such financing (by the Wallenberg Foundation) be obtained; for replacement of generic equipment the financing has to be found through the laboratory's own means. The management estimates that for equipment renewal about 20 MSEK/year is an absolute minimum requirement, which represents about 6–8% of the actual present value of the equipment park. The SPIN agreement on co-ordinating the need of new expensive equipment, avoiding duplication of such purchases and increasing the common use of such equipment, is an initiative which deserves to be praised and continued, but we had the impression that this initiative was not considered by the KTH group as providing a real solution to the problem.

As a conclusion, we estimate that the available infrastructure should allow the group to continue to carry out most of the present programmes. It was however not clear from the presentations what the mid-term or long-term objectives are in either of the mentioned fields of expertise, and exactly what corresponding equipment would be needed in the coming years (except for the replacement of some of the basic systems). There was certainly no indication of a specific investment plan or of an equipment wish list.

The present utilization of the Laboratory by local research groups, external Swedish groups, foreign research groups and companies

The lab has a history of 15 years of collaboration with academia and industry and describes itself as an open environment for education, academic research, and industry—including serving as an incubator for start-ups. It is used by 180 users per year. Of these, 60 are graduate students from KTH. Undergraduate students also use the lab in processing course work but are not included in the 180/year user base. There is also work with other universities to provide the undergraduates of these institutions with some clean room exposure. This activity is at the level of about 25 students/year. The overall flavour of the facility is that it is very heavily oriented toward electrical engineering, and very specifically oriented toward sustaining the research interests of its principal electrical engineering research groups. To increase interdisciplinary interaction, four faculty members in solid state physics have been moved to have their operations contiguous with the laboratory.

The laboratory appears to be run by having a collection of equipment sets, each controlled by these electrical engineering research groups or, apparently, in some cases, controlled by a particular company. It gives the impression of being a confederation and, in general, any user must make arrangements with the controllers of the various equipment sets in order to arrange utilization. The majority of the users are local KTH academics, spin-offs from KTH, or local Stockholm industry. The number of users not falling into these groups is very small. The management stated that, overall, only about 1% of their users are from non-Stockholm groups. Clearly they are making no attempt to draw users from outside Stockholm or are very ineffective at doing so. They state that the lab has a general philosophy of wanting many users since this will lead to cost efficiency. They have interactions with foreign groups and these are through about 7 EU projects. The interaction appears to be solely through sample exchange where several EU groups contribute to the process flow.

The lab has only 10 staff members. The various groups controlling the equipment sets provide the manpower for equipment maintenance, and for sustaining and developing processes. All equipment sets are operated by the respective groups controlling the sets. These are responsible for training new users and for scheduling users who want to have time on the equipment sets. They voiced the opinion that having a completely professional staff sustaining processing and equipment could be counterproductive. They feel that having research groups in charge of equipment sets causes a constant infusion of new ideas and new processing into the laboratory.

The total facility use of about 40,000 hours per year corresponds roughly to 25 people working 5 eight-hour days per week. This utilization is said to occur mainly over a 12-hour period, 5 days per week. It was felt that this level of utilization could be doubled or even tripled. With the present management system, each group controlling an equipment set would have to agree. If more users were added, each group would have to do more training and more maintenance, and would lose access hours. The advantage would be a reduction of costs, but there was apparently no consideration given to the issues of increased teaching, maintenance, and wear and tear.

Importance of the Laboratory for Swedish industry as well as for future enterprise (local, national, and international perspectives)

The lab is very much involved in pushing forward the boundaries of current technology and its activities seem to match well with the needs of current Swedish industry. In general, the research thrusts are excellent and would appear to enhance local industry—both major companies and start-ups. One wonders, however, how well these activities position Sweden for future breakthroughs, technology shifts, and future economic competitiveness. The emphasis of the lab is clearly on Si and compound semiconductor technologies, which is fine, but one must be ready for shifts which may occur to areas such as organic transistors, molecular electronics, and the whole broad area of nanotechnology. Grant applications are in this direction.

The lab appears to be run in a fashion that greatly aids KTH researchers and Stockholm companies working in the Si and compound semiconductor areas. This appears to close the door to its excellent facilities for researchers who are not in the Stockholm area or those who want to practice microfabrication but on non-Si or non-compound semiconductor materials systems.

Common utilization of equipment with industry and need for industrially compatible equipment

This lab definitely has equipment designed to help the microelectronics industry. In some cases the group controlling an equipment set is a company. The only drawback to the ability of the lab to assist industry lies in the sizes of the substrates it can handle. In some cases the capability is only 4" or 6".

The financial status of the clean room facilities

The turnover of the clean room facilities was 35 MSEK for 2001. The main income to the laboratory derives from user fees, which amount to 19.4 MSEK. KTH provides general support of 10 MSEK for laboratory usage to KTH groups. An additional 2.6 MSEK comes from sales. The cost for premises is the largest expense, 8.5 MSEK, followed by costs for personnel (4.9 MSEK). A more detailed budget is found in the report in Appendix 3.

As a whole the lab operation is mainly paid by user fees, although research projects are generally underfunded because external grants often do not cover the cost of CR. The laboratory resources are currently not fully used. With the current budget the laboratory can offer support to present users.

Problem: it is difficult to get funding for new investments in standard process equipment. The Swedish Research Council and KAW mainly support equipment enabling novel scientific results. The laboratory has difficulties in financing support for new user groups. New users (physicists, biologists, chemists) are not accustomed to paying high fees for CR etc. As noted above, research grants are underfunded in this respect.

Industrial contacts

The KTH laboratory is used at a 20–30% level and it was stated that this figure could easily be increased by a factor of 2. Half of the cost today is covered by ACREO through industrial cooperation. At the visit it was stated that the proportion could probably be increased, but no plan for this was shown.

The laboratory has a unique position in possessing a marketing arm in ACREO, which covers about half the laboratory cost through cooperation with its industrial partners. Today there around 10 companies which are using the laboratory through ACREO.

Together with ACREO the lab has lately been able to spin off several successful companies, such as ADC-Altitun and Optillion in the photonic area where the basic technology has been developed in the laboratory, and the companies are continuing to use the laboratory as external customers.

A very recent spin-off company is Silex which makes miniaturized pressure sensors. The basic research was done within the Microsystem Technology department, which is continuing the work for smaller sensors together with Radimedical Systems AB.

The department has further cooperation with Datex-Ohmeda and Instrumentarium Corp.on biopotential electrodes, winner of the national "Innovation Cup" in 2000.

The laboratory has a successful history of developing and transferring state-of-the-art IC technology to Ericsson Microelectronics. Presently the lab is involved in a MEDEA project, "High Speed Silicon Bipolar Technology", in which, besides Ericsson Microelectronics, ST Microelectronics and Philips are industrial partners.

Ångström Laboratory, Uppsala

Profile

The Ångström Laboratory is an integrated part (centre) of the Faculty of Science and Technology of the University of Uppsala. It is thus clearly a university facility and it wants to continue as such. It emphasizes materials, energy sciences, biotechnology and physical sciences rather than semiconductor device technology. The Ångström Laboratory operates in a scientific environment that includes materials science, solid-state electronics, space technology, biotechnology and medical sciences. As of yet, there is limited use by external partners from industry with a potential for expansion. The laboratory has been in use for less than five years, so it is only on the way to establishing its profile which, to date, has primarily arisen from the university campus users. A user advisory committee reporting to the Board of the Materials Science Department develops the overall strategy, and there is a Steering Committee which makes decisions about the daily running of the laboratory. There is presently only a small staff (5) of service engineers rendering service to the users. A process manager has been hired (starting in April 2002), and it is the plan over the next two years to build up a larger laboratory staff (10) including process specialists/engineers. This is deemed necessary in order to improve process quality and up-time, which is particularly important for meeting the demands from external (industrial) users.

Quality of research

There is a large number of scientific projects related to the clean room facilities of the Ångström Laboratory. Almost fifty were mentioned, covering a very wide spectrum of research topics from thin film technology, RF-power transistors, and bio-fluidic MEMS for mass spectroscopy to silicon microsystems for space technology. There is participation in about 5–6 EU projects, and in particular the space technology programmes seem rather successful. About 10 PhD candidates with extensive clean-room experience are finishing every year.

Future potential

The clean room facilities are new (state-of-the-art) and well equipped within selected areas, e.g. materials analysis. There is plenty of room for expansion and increased use of the facilities. There seems to be a tendency (wish?) to widen the spectrum of fields and topics rather than focusing on fewer specialized topics. Biotechnology, micro-optics and aerospace technology are mentioned as strategic areas. Particularly the latter is unique to Uppsala and should probably be pursued. A new nanotechnology centre is in the planning (proposal) stage. The focus here is on bio- and medical sciences/technologies. This is well chosen considering the scientific environment at the Uppsala University campus.

Quality and future potential of the technical equipment

The Ångström Laboratory has a 1700m^2 CR area, of which about 200m^2 is of class 100. The facility is very new and was opened in 1997 but has been in more or less full operation only since 1998.

The CR is subdivided in 2 sections, the first part being mainly occupied by characterization equipment, the second part dedicated to processing. The latter includes basic silicon processing (standard process below the level of packaging), RF-CMOS and RF-MEMS, MEMS, CIGS thin film Solar Cells, some MCM processing, starting biotechnology activities. The laboratory is very well equipped with up-to-date characterization systems such as high-resolution TEM, electron microscopes, STM/AFM instruments, ESCA, etc., and plans exist to order a dual-beam FIB system shortly.

The lab does not have a stepper but is equipped with a laser pattern generator for mask fabrication and mask aligners. The minimum feature sizes that can be realized are of the order of 0.8 µm.

Today the users include both university people and external users. The former account for about 94 man-years, the latter for 14 man-years (in terms of individuals this amounts to about 150 people). It was not possible to get an estimate of the number of man-hours of usage of the CR facilities. Basically the CR runs on a 5-day/week and 8-hours/day scheme. This could be extended to a two-shift system, but safety regulations could pose a limiting factor here.

The major external user is Åmic, a local SME with about 26 employees which is active in biochips, RF-MEMS, opto-MEMS and InkJet systems. They occupy a section of the lab with their own equipment which is not accessible to the other users.

The CR is basically a 4" line but a number of systems can accept 6" wafers. For the daily operation today there are about 4.5 assigned persons: 1 in the characterization area and 3.5 in the processing area. These people were referred to as "maintenance engineers" and certainly not as processing or service engineers. The management, however, has concrete plans to increase this number significantly in the coming years (also dependent on the further funding). First of all, a Fab manager (Process Lab manager) has been hired and will start in mid-April. Next, several process engineers (for lithography, dry etching, furnaces, general services) are on the wish list and about 3 of these are expected/hoped to start within 2002. The plan is to eventually reach a total of about 10 service and process engineers.

All equipment is operated by the users; no dedicated operators are available. The external customers can have separate lab sections with proprietary equipment to which the other users do not have access (cf. Åmic). Part of the CR can be accessed by undergraduate students (either local or from nearby universities) for hands-on laboratory classes (for instance fabrication of NMOS transistors).

The CR is thus very new, spacious and well equipped, mostly with new equipment that was granted by the Wallenberg Foundation (for a total of about 62 MSEK). Some other systems (like an Ion Implanter) were transferred from other laboratories at the start of the lab. There is undoubtedly much room for expansion of the equipment set available to users.

The managers have expressed their strong intention of further developing a Center of Nanotechnology at Uppsala University that would make ample use of the CR facility. The lab should, according to them, indeed not be regarded as a microelectronics facility but rather as a lab for "nano- and microfabrication". The main focal areas would then be on biotechnology, micro-optics and aerospace applications. At present the indication is that these types of activities are just beginning in the CR (see discussion of Åmic and space technology work above).

Today the principal problem, as stated by the managers, is the rising cost of the operation of the facility and the diminishing faculty resources that can be made available to cover these operational costs. The problem does not seem primarily to be getting the funds for new equipment (it is expected that these can be further acquired through the special foundations), but in guaranteeing the access to this equipment and the availability of skilled service people. It was stated that basically this problem could be significantly alleviated by annual funding of about 6 MSEK/year, although in the documents provided by the lab the amounts for required funding are in fact about twice as large.

In conclusion, we consider that the available technical resources should allow the Ångström group to carry out most of the present programmes with sufficient margin for extending the activities towards nanotechnology and nanofabrication. From the presentations there is, however, no indication of sufficient focus of the activities. The authors refer to a list of "projects" but what is rather needed is a list of "strategic programmes". The projects have to be seen as a means for realization of this strategy. The list of projects, either ongoing or planned in the facility, is very broad and the intended direction is not obvious except for the aforementioned biotechnology interests, space interests, and nanotechnology centre interests. There is also no indication of a specific investment plan for the near future.

The present utilization of the Laboratory by local research groups, external Swedish groups, foreign research groups and companies

The lab is thus used by a total of 150 users per year. Of these about 126 are graduate students or research staff from Uppsala. Uppsala undergraduate students also use the lab in processing course work but are not included in the 150/year user base, which counts R&D users. There is also work with other universities to provide the undergraduates of these institutions with some clean room exposure and the offering of microtechnology processing courses, which is a very commendable sharing of facilities for education. Twenty-four of the 150 R&D users per year are external users. These 24 external users include 7 from Åmic, a local start-up. The overall flavour of the facility is that it is not heavily oriented toward electrical engineering but more involved in non-electrical engineering applications of microtechnology, which is a very advisable diversification. For example, all the current research activities discussed by Uppsala University and local industry presenters were in non-microelectronics areas. These included presentations on biomedical devices produced by moulding and embossing based on Si masters, X-ray lens development work, space propulsion structures, and piezoelectric sensor structures.

Academically the lab is located within a very interdisciplinary Materials Science Department with groups engaged in activities from mechanics to electrical engineering. The lab spokespersons stressed their vision of moving into nanotechnology and want to add professorships in nanotechnology, nanophysics, and nanobiology. Physically the lab is located within a cluster of medical and biotech activities and a start-up building. The broad academic interest-base and the physical positioning would seem to be very conducive to bringing even more users from medicine and the life sciences into the facility.

The laboratory is not a confederation of research groups but is a genuine user facility where equipment is not owned or controlled by a particular group. In addition, it has an area where equipment is owned by specific groups (e.g. the solar cell group) or companies (e.g. Åmic). The user core facility is broken into a processing function and a materials characterization function. Currently there is some staff to maintain this core facility to some degree with help from the users, but the facility is very staff-limited. They have just hired a full-time PhD engineer with 9 years of industry experience to run the core user facility, as well as to oversee the rest of the lab. At present, new users of the core user facility must be trained by current users and must develop their own processing or acquire processing recipes from current users. Their plan is to hire an engineering staff to maintain the equipment, to develop processing, and to teach processing to new users. This must be done.

The majority of users are local Uppsala academics or from local industry. They have a conveniently located start-up building which is where Åmic is located. The number of users not falling into the Uppsala academic or local industry groups is very small. It was stated that, overall, less than 10% of the users are from non-Uppsala groups. There are interactions with foreign groups and these are through about 6 EU projects.

The lab only has about 5 staff members and they too realize that they are very understaffed. They want a professional staff whose function would be to sustain processing and equipment and to develop new processing. They presented a plan for new hiring over a four-year period to develop this badly needed professional staff. Their first step has already been taken with the hiring of the director for the core user facility, noted above.

It is difficult to judge the lab utilization since the number of man-years is based on the number of paid four-month periods, whose time may or may not be used. They say this utilization mainly occurs over a 9-hour period, 5 days per week. They felt the level of utilization could easily be doubled and there appears to be general managerial agreement on this. The user fee for industry is 340,000 SEK per user per year, regardless of actual use time in that period. The user fee for Uppsala academic users is 80 000 SEK per year.

Basically the Uppsala group appears genuinely interested in offering a wide range of micro-processing (and nano-processing) to a wide range of users. The problem is clearly a severe lack of staff and of maintenance support.

Importance of the Laboratory for Swedish industry as well as for future enterprise (local, national, and international perspectives)

The lab is very much oriented toward non-microelectronics uses of micro- and nanotechnology. It appears to be very anxious to use its location within a ring of medical and bioscience activities to grow in that direction. That vision would appear to be very important for Sweden's future enterprise since the greatest increase in the use of micro- and nanotechnology probably will come in biological, medical, and chemical areas.

Common utilization of equipment with industry and need for industrially compatible equipment

This lab is equipped with a number of tools that would be of considerable interest to industry. One always has the problem of substrate size compatibility but university facilities will never be able to keep up with industry substrate size increases.

The financial status of the clean room facilities

The clean room facilities have not been an independently organized unit within the Ångström Laboratory. With the new organization from January 2002 onward, this will be the case with own director and advisory boards. The annual turnover for 2001 was estimated to be 21 MSEK. The main income is from the University. UU provides 12 MSEK for the rent plus 3 MSEK for service personnel and running costs. Internal user fees amount to 3.6 MSEK and 3.0 MSEK from external users, essentially Åmic. For 2002 the budget is 26 MSEK with an increase of 5 MSEK for a new lab manager, process engineer, safety and environment. By 2004 the expected budget will be 30 MSEK with additional costs due to improved service and maintenance level.

The budget in the Ångström report does not include depreciation/investment costs for equipment or instrumentation. If we estimate this to be 5–10 MSEK it bring us to the same level as KTH.

Industrial contacts

The Ångström Laboratory is well aware that the cost coverage by industrial cooperation has a great potential, and is planning to approach this with a new organization supported by "Teknikbrostiftelsen".

The laboratory was initiated with a multidisciplinary vision and especially to support the strong surroundings of companies in biomedicine and biotech with MEMS solutions, and the lab seems to be well prepared to support these companies in the new growth area. Even though the laboratory is still in its infancy in creating an organization for handling industrial needs, it has received much attention from surrounding biomedical and biotech companies, especially Åmic, which rent space in the laboratory and account for most of the external sales of around 3 MSEK.

Companies which, through Åmic, are using the laboratory include Gyros, Biacore and Gnotis.

Other companies in the field directly using the lab include Amersham Pharmacia Biotech, Radi Medical Technology, and Silex.

With planning of a more professional organization and marketing effort, the revenue from external users in this area could easily increase from today's 3MSEK by at least 30–40% per year. For example, Åmic indicated an increase of around 50% per year. This, together with the increase of fees, which seems to be low by a factor of 2, could easily increase that revenue up to around 10 MSEK in the time frame of 3–4 years.

Companies involved in MEMS in other areas:
Ericsson Microelectronics – RF-MEMS.

ACR Electronics – Micro propulsion unit for space application

Micronics Laser System – Linear micro motors

Microtechnology Center at Chalmers (MC2), Göteborg

Profile

The Microelectronics Center at Chalmers (MC2) is a new clean room facility replacing old laboratories in the Electrical Engineering and Physics Departments of the Chalmers Institute of Technology. The main idea is to serve (and support) the research activities at Chalmers that make extensive use of micro- and nano-processing technologies, as well as competitive industrial activities in existing companies and new start-up companies. The MC2 clean room facility is run as an independent unit in close interaction with the relevant schools (EE, physics, chemistry) within Chalmers as well as with the Chalmers central administration. There is an executive board with representation from the participating schools, as well as an advisory board with representation from industry and from (international) academic research.

The clean room facility itself is state-of-the-art, and among the very best in the world on a university site. There is a well-functioning lab management and the technical staff has about 10 process specialists and 5 service specialists. This staff provides service to the research users as well as service and direct sales to industry. There are 150–200 registered users of the clean room, of which about 80% are from within Chalmers, 10% from industry and 10% from other institutions.

Quality of research

The research strategy is mainly determined by the participating groups and their ability to attract external funding. There are strong, in some cases world-leading, activities within high-frequency microwave devices, liquid crystals, single-electron and superconducting devices. There is also excellent work going on within photonics, e.g. on VCSELs and GCSELs (Grating Coupled Surface Emitting Lasers).

Future potential

From a technical point of view MC2 has the potential to become one of the leading university-based facilities for micro- and nanotechnologies in the world. The human resource environment has high priority and the special (private) status of Chalmers makes it possible to recruit and keep personnel of the highest quality. There is also a strong research base in selected fields that can serve as the driver for new developments in science and technology. The management points towards high-frequency devices (GaN), bio-MEMS (for medical diagnostics?) and quantum-dot based laser structures (and devices?). It is not quite clear from where the biotechnology expertise is coming, and to what extent device packaging and performance testing can be handled. There is a willingness to open the facility to new user groups (for a price) and also to expand on the interaction with industry. An issue that needs to be addressed further is the handling of IPR, particularly when it involves industrial partners.

Quality and future potential of the technical equipment

The MC2 laboratory has a total of 1240m^2 CR area. Of this, 1000m^2 is for the actual processing activities, with class 1–1000. The 240m^2 CR (class 10,000) is devoted to training of undergraduate students, and also contains some special systems for f.i. laser ablation and wire bonding. The main CR has a ballroom concept with service area underneath the CR. The construction is such that the vibration levels are kept very low, as is required for the e-beam lithography activities. The class 1 is maintained only in the advanced e-beam room (which moreover has a temperature control over 0.1°C). There are 3 yellow rooms, one for nanolithography (special e-beam resists), one for III-V litho and one for silicon litho. The CR has 6" processing capability (as is used for the silicon processing), and disposes of an i-line stepper (ASM).

As noted above, the number of users of the CR is about 150–200 at present, 80% of whom are from Chalmers, 10% from other universities and 10% from industry. The CR is operated on a 5-day/week, 8-hours/day scheme. The total CR staff amounts to 15 people today. There are a Lab Manager, 4 people for service and maintenance, and 10 process specialists (silicon, nano, ablation, III-V, LCD). For 2002, there are vacancies for 4 more process specialists.

Each user has to follow an introductory course that lasts $^1/_2$ day before getting access to the CR. This does not include the training on the specific system. The driver's license for a specific system is delivered by the process specialist after appropriate training.

The total investment is 758 MSEK. The equipment investments amount to 120 MSEK of which 90 MSEK was granted by the Wallenberg Foundation (50 MSEK in 1996, 40 MSEK in 2000) and 30 MSEK by the Chalmers Foundation.

The CR is very spacious, with a lot of potential for expansion (partly also because of the chosen ballroom arrangement). All the necessary safety precautions and installations are available. The equipment set is state-of-the-art and undoubtedly makes this facility one of the best-equipped university facilities in Europe. It certainly offers the right environment for carrying out world-class research in the different fields envisaged by the user groups.

In conclusion, although the MC2 facility has been in operation only since June 2001, it is clear that this is a first-class CR, already with an impressive equipment set, with a very high potential for future microelectronics and nanofabrication and with ample expansion capabilities. The facility management structure is in place and looks very capable of coping with the problems. Access for non-Chalmers users is still rather low today but this can certainly be improved in the future.

The present utilization of the Laboratory by local research groups, external Swedish groups, foreign research groups and companies

The Chalmers MC2 laboratory already has developed 200 annual users in its brief period of existence. This use is focused in electronics, optoelectronics, optics, and MEMs. However, these are primarily "in-house" users; i.e., approximately 160 of the 200 annual users are graduate students or research staff from Chalmers. The use is R&D support only. The MC2 laboratory is not used in any microtechnology education function for Chalmers undergraduate students, since there are no funds for meeting the costs for such activities. In addition, MC2 does not share its facilities with other universities in support of undergraduate education in microtechnology processing courses. Approximately 40 of the 200 users per year are external users. These external users include 20 from local companies and about another 20 from other Swedish universities. The laboratory also does service work for companies and this activity is not included in the user base numbers, since it is carried out by lab staff. Among these industries using the lab for service work are companies from all over Europe and from the U.S. Work is done for these companies in areas such as bio-MEMs and SiC transistors.

All users pay user fees to the lab. These vary from a general 15% per year per project charge for Chalmers groups to specific per-hour fees for outside users. Unlimited time is available to Chalmers users for this 15% charge. For all tools except the e-beam lithography tool, the outside user fees are 1700 SEK/hour if the user does all the processing, and 2200 SEK/hour if MC2 does the processing. If the new JEOL JBX 9300 FS e-beam machine is required, the outside user fee is 12,000 SEK/hour and MC2 does the running of the e-beam tool.

The laboratory is not a confederation of research groups, but appears to be a genuine user facility where equipment is not owned or controlled by a particular group. The user facility is broken into a large processing area and a smaller, but adequate, materials and devices characterization area. MC2 also has ancillary laboratories housing facilities such as MBE. Currently the staff of 15 (10 process specialists and 5 service/maintenance) assists users. In addition to training users and maintaining processes and the facility, these staff people also run a half-day safety/lab-use course, which is held about once per month, for all new users. The lab's attention to safety and to user training, and its development of this course, are all commendable. The plan is to hire up to 15 additional engineering staff to enhance these activities of maintaining equipment, developing processing, and teaching processing to new users. This new staff would also support the additional outside service work which, it is felt, must be done for industry in order to sustain the lab.

It is difficult to judge the lab utilization and no information on hours of use per year was available. However, it appears that the staff feel they can triple the utilization. They say this utilization mainly occurs during the day over 5 days per week. However, they describe the lab as a 24-hour/7-day-per-week activity and their safety procedures define a buddy-system protocol for off-hour equipment use.

In summary, the majority of users are local Göteborg academics or from local industry. External use of the lab is mainly through the company service work, which is not counted in the 200-user base. The number of users not falling into the Chalmers academic or local industry R&D groups is very small. There are no users utilizing the facility for undergraduate education.

Importance of the Laboratory for Swedish industry as well as for future enterprise (local, national, and international perspectives)

The MC2 laboratory is certainly a world-class academic facility and is, therefore, very important to Sweden. It has clean rooms, a tool set, and an engineering/technician staff that are each very important resources. Having this engineering/technician staff dedicated to sustaining the facility (as opposed to being dedicated to a specific group) is, in itself, an extremely valuable resource.

The overall flavour of the facility is that it houses a mixture of activities covering electronics, optoelectronics, optics, and MEMs. It is particularly strong in e-beam lithography, which is critical to future technology development in general, and to nanotechnology development in particular.

Common utilization of equipment with industry and need for industrially compatible equipment

This lab has a tool set that is of considerable interest to industry. All silicon processing is at least 6" capable. The service work they do for industry, and the additional service work they believe they can do, attests to the attractiveness of the equipment to industry. The e-beam lithography capability alone is very useful for mask making and direct writing.

The financial status of the clean room facility

The financial status of the brand-new MC2 is greatly coloured by the unfortunate story of the missing 38 MSEK annual support. When planning MC2 in 1994 the Government supported the concept of allocating this amount per year for the running of the facility. This was stated in a bill to the Parliament. This government interest started the project to design the new building. In the fall of 1999, after expressing favourable support since 1994, the Government withdrew the funding for MC2. Of course, an action like this makes long-term planning for such a complex project as MC2 hazardous.

Great efforts have been taken to compensate for the missing 38 MSEK and to bring the budget into balance. As stated by the President of Chalmers at the visit to MC2, the Chalmers Foundation takes an overall financial responsibility in this process. The report from Chalmers (Appendix 5) discusses a number of different scenarios (Increased Income Model, Action Plan, MC2 "free-standing", Fig. 5 in the MC2 report). The MC2 "free-standing model" is an extreme model that forces MC2 too much into sales and the laboratory would lose its academic missions. The Action Plan Model assumes that the 38 MSEK are recovered. Efforts should be made in this direction but the outcome is uncertain. The Increased Income Model is the most realistic one if MC2 is to remain an academic facility. However, it still contains elements of uncertainty, e.g. the expected income from MC2 Partners. It also requires substantial sales, although much less than in the stand-alone model.

MC2 is an independent unit within Chalmers. The annual turnover for 2001 was close to 60 MSEK. The main income is from the Chalmers Foundation, which provided 27 MSEK for premises according to the report from MC2. Income from internal research amounts to 3.5 MSEK. There is a "season card" principle that charges 15% of the total value of a project and allows for unlimited access during a season. External sales amounted to about 1 MSEK in 2001. Two items, depreciation contribution and rentals and cleaning, will balance as income and costs, and in a way mask basic activities. Costs for personnel were about 9 MSEK. Running cost for process lab was 11 MSEK.

For 2002 the budget is 91.5 MSEK. The support from the Chalmers Foundation is increased to 36 MSEK. External and internal sales are increased to 5 and 6 MSEK, respectively. Running costs are increased to 20 MSEK and personnel to 12.6 MSEK.

The budget for the five-year period is ambitious and foresees a gradual expansion with increasing contributions from internal groups, industrial service, MC2 partners, products and spin-offs (Fig. 7 in MC2 report). The contribution from Chalmers (and the Swedish Research Council) will decrease at the same time.

Industrial contacts

The MC2 Laboratory has strong industry contacts particularly in the microelectronics area. In discussing the financial situation, the MC2 management showed a scenario in which running costs could be, at least partially, covered by selling components. Through IMEGO, which is similar to ACREO, MC2 could have a marketing arm, but this was hardly mentioned at the presentation.

There is a history of close connection and cooperation with EMW in the very-high-frequency area. Presently MC2 has several projects which are related to EMW using the lab. Other projects with industry include: SIC projects with Philips, diffraction optics projects, work with Micronic, Sintet, Nanocomp, ADC, Optillion, sensor and superconductor work, efforts with Lake Shore INC US and Selectron, and work just starting in bio-MEMS.

Concluding remarks from site visits

The three laboratories are ranked in condensed form in the following matrix (5 = very good, 1 = poor). Obviously the exact numbers should be considered with caution.

Criterion	KTH	Ångström	MC2
Present CR status	3	4	5
Future potential for CR	2	4	5
Present Processing Equipment status	3	4	5
Present Characterization/Metrology status	3	5	3
Management/Organization	2[1]	3[2]	4
Present CR Staff	3	2	4
Capability for micro-structure fabrication in multi-materials	4	4	4
Preparedness for nano-structure fabrication in multi-materials	2	4	5
Preparedness for multidisciplinary activities	3	4	4

Investment in equipment and running costs

The numbers are not out of line with corresponding investments and costs at international laboratories. The equipment at KTH is overdue (from the old IM, "Institutet för Mikrovågsteknik", in 1986), requiring refurbishing of premises. The vibrational standard of the CR at KTH is not at the same high level as at the two new laboratories.

Organization status

All laboratories have high priority within the respective university. The Semiconductor Laboratory at KTH is an independent unit that reports to the president. KTH gives direct support, 10 MSEK per year to supplement user fees.

[1] Equipment in different areas of the lab are owned by different groups.

[2] Under reorganization.

The Ångström Laboratory is an integrated unit within materials science and technology. However, it is under reorganization in order to become an independent unit. The university covers rent, approximately 15 MSEK, taken from grants (normal overhead). MC2 is an independent unit and reports to the president. The Chalmers Foundation gives support of 36 MSEK for 2002. It is uncertain how durable these various forms of supports are.

Scientific strategies

The competence of the laboratories is set by the local user groups. Naturally the strategy builds on, and is thus determined by, local user groups.

Strengths

KTH: Photonics, high-frequency Si and SiC devices, marketing arm via ACREO.
Ångström: Microfabrication for microtechnology, microoptics, aerospace, biotechnology.
MC2: High-speed electronics, optoelectronics (VCSEL, GCSEL), single electron devices, lithography.

Environment

The KTH Laboratory is strongly integrated with the microelectronics industry. At the same time, it is not well integrated academically with the main campus in the city. The Ångström Laboratory is physically and academically well integrated with surrounding campus and developing biotech interests. The new MC2 is potentially strong in this respect.

Education/sales conflict

The following table illustrates the conflict between education and sales. In this table an X denotes a possible combination, whereas 0 denotes incompatibility. The present activities in the three laboratories are indicated in the table. Shaded boxes represent areas where the laboratories could play a national role.
Sales = products and services by the laboratory staff.

IF YOU → PROVIDE	Education	Academic user support	Industry user support	Sales
YOU CAN DO ↓				
Undergrad teaching	**X**, KTH, Å	**X**, KTH, Å	**0**	**0**
Grad teaching	**X**, KTH, Å, MC2	**X**, KTH, Å, MC2	**X**, KTH, Å, MC2	**0**
R&D	**X**, KTH, Å	**X**, KTH, Å, MC2	**X**, KTH, Å, MC2	**X**, KTH, MC2
Prototyping	**0**	**X**, KTH, Å, MC2	**X**, KTH, Å, MC2	**X**, MC2

Recommendations

Organization among centres

The following recommendations are in the order of increasing integration of, and commitment from, the centres. The first level, which is in the spirit of SPIN, should be implemented irrespective of level two. The first level will not require additional funding. Level two assumes that the first one is in place. The national network proposed for the second level will require funding for national user support and organization of the network. Comparison should be made with the national metacentre SNIC (Swedish National Infrastructure for Computing) for high-performance computing.

Level one:

- We see a place for the three laboratories in a national Swedish strategy for micro- and nanofabrication if they enter into a task-sharing where the laboratories focus on specific roles. A natural specialization of the labs emerges from their established research backgrounds and the expertise and facilities that have already been built up in the three locations.
  - The Semiconductor Laboratory at KTH is a well-established centre for device research within semiconductor technology. It has created an excellent environment for collaboration with industry and efficient technology transfer to be further developed, particularly within the fields of microelectronics and photonics.
  - The Ångström Laboratory is planned as a multidisciplinary centre for research and education within micro- and nanotechnologies. It could be marketed as a multidisciplinary playground for the development of new research fields within nanotechnology, biotechnology and life science. It could also serve as the national centre for teaching graduates and postgraduates in these fields.
  - MC2 at Chalmers has the scientific expertise and the technical facilities to become a world-leading research centre for micro- and nanotechnologies. Its facilities are unique in Sweden and should be promoted as such. It is recommended that its specific user mission should be in the focused areas of high-speed electronics and nanoscale lithography.

This level requires no additional funding.

Level two:

- It is recommended that the Swedish Research Council creates a Swedish Nanotechnology Network (SNN) as a National Facility to take advantage of the expertise and equipment base already in place at KTH, Uppsala, and Chalmers. This network would be mandated to serve as a shared resource for all of Sweden in two areas: (1) for the micro- and nanofabrication research and development needs of academia and industry, and (2) for micro- and nanofabrication education activities. It is also recommended that this proposed Swedish Nanotechnology Network become active within the European Union in fostering the network approach of co-ordinated facilities and resource-sharing across the EU. The National Nanofabrication Users Network (NNUN) in the U.S.A. serves as a good model for SNN, which should consider contacts with NNUN and NSF.

- The specific objectives of SNN will be (1) to avoid unnecessary duplication of expensive, difficult-to-maintain equipment, (2) to ensure co-ordinated resource utilization and future development, (3) to ensure adequate technical support staffing of facilities, (4) to provide facilities and staff support for the R&D activities of qualified users coming from all of Swedish academia and industry, (4) to provide facilities to enable qualified educational activities for all of Swedish academia, and (5) to have each facility of SNN take responsibility for a segment of micro- and nanofabrication. The performance of SNN as a national facility, as well as that of each participating facility, will be judged to determine whether these five objectives are being met. This assessment will be undertaken using the criteria found in Appendix 8.

- It is very unusual that large-scale facilities of the present kind are operated without a basic support infrastructure and without user support. It is recommended that the funding support for the activities of the proposed Network must at least be at a minimum level of 20 MSEK (+ university surcharges) per year. This support should be allocated for 5 years. Network performance should be evaluated every six months using the criteria of Appendix 8. *A decision to continue or discontinue the Network or a specific facility would be made with an evaluation at the conclusion of the fourth year.* It is recommended that the budget be divided into 5 MSEK per year for each facility. In the first year the remaining 5 MSEK would be evenly distributed among the facilities. In successive years, the remaining 5 MSEK per year would be distributed on the basis of the performance criteria of Appendix 8.

- To make previous points operative and to make long-term strategic decisions, SNN must have a national steering board. The board, which should report to the Swedish Research Council, must be small with, tentatively, representatives from KAW, VINNOVA, SSF and the Swedish Research Council, the centres, users, and industry plus a chairman. To be effective the board will need a part-time co-ordinator/manager employed part-time by the Swedish Research Council. This person should have an established scientific background in relevant fields. The co-ordinator will need administrative support (part-time employment, 25%). The cost for the first start-up year is estimated to be 1 MSEK. The organization of the national metacentre SNIC is a good model also for SNN. A brief outline of the organization is given in Appendix 9. SNN offers the possibility of future dynamic and coherent planning of the centres participating in the national network. *There is then a clear mechanism for downsizing of a particular site as well as upgrading it.* There is also the possibility to include other smaller centres that may offer unique equipment, special materials, and/or services or to respond dynamically to new developments (cf. "grid concept" in SNIC).

- The main external funding to individual researchers and research groups comes as short-term grants from the Swedish Research Council, SSF, and VINNOVA, with SSF as the dominant contributor (see Appendix 7). The cost for SNN should therefore be shared among them.

Specific issues

- User fees among the centres should be harmonized. The fees for external academic users from Sweden (and Europe?) should be calculated on the basis of a true cost analysis including rent, salaries and consumables. If the host university contributes to these costs, the fees for local users may be reduced accordingly. Users from industry pay full costs including depreciation of equipment, installations and buildings. There may be different levels of industrial use: from rent of clean-room space only (price per m^2) to limited/unlimited use of all facilities (price per user month). Pure sales should cover full costs (including depreciation and full salary of staff used) and also include profit if current market prices allow for it.

- Expensive equipment: As described above, microelectronics and micro/nanofabrication are dependent on large capital investments in scientific equipment. The ongoing rapid miniaturization within these fields requires continued investments, which tend to be on a higher level because of increasing sophistication in instrumentation. The KAW has played a major role in funding the expensive equipment at the laboratories and should be given all credit for the high standards of the Ångström and MC2 laboratories in particular. Also FRN, one of the predecessors of the Swedish Research Council, has contributed but on a lower level. Although this is most beneficial, one problem is that investment and maintenance costs are separated. In many cases one therefore encounters inefficient use of equipment. It would be a great improvement if investment and maintenance costs (for an adequate scientific lifetime) could be funded as one package.

- Level of grants: Too often, external grants do not recognize costs/fees for use of CR. This easily leads to underfunding of projects and ineffective use of CR facilities. This problem must be taken seriously and it is crucial that additional project funding is directed to cover the cost of CR use. This additional funding of research grants could be paid directly to the laboratories by the funding agency.

- Funding for infrastructure: Funding scientific equipment is normally the outcome of successful grant applications within a competitive system. Within such a system it is hard to find support for investments for general infrastructure. This situation is unfortunate since the high-quality infrastructure is a prerequisite for research projects to be successful. This problem requires further attention.

APPENDICES

Appendix 1

CV for external experts

External reviewers appointed by the Swedish Research Council:

Dr. Klas-Håkan Eklund
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Dr. Eklund received his PhD in 1974 at Chalmers University of Technology in Göteborg in the field of Solid State Electronics. In 1993 he started Eklund Innovation. Pursues innovations and entrepreneurship in microelectronics. He is presently involved in starting a company making RF amplifiers. Dr. Eklund has more than 30 years of experience of most aspects of semiconductors, with a recent main focus on the start-up of new business activities. Different management positions within Ericsson Microelectronics (1974-86). In the latest he was in charge of getting the company started in the MOS field. Project manager at Data General, U.S. (1986-88). Key founder and director of Power Integrations (1988-92), Dr. Eklund was elected "Innovator of the Year" 1990 by the EDN Magazine for the device and product concept behind this company.

Professor Jørn M. Hvam
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Professor Jørn M. Hvam received his M.Sc. degree in electrical engineering in 1969 and his PhD degree in physics in 1971, both from the Technical University of Denmark. From 1971 to 1993 he held various positions at universities and research laboratories in Denmark, France and the United States. Since 1993 he has been a full professor at the Technical University of Denmark, where he is now heading Optoelectronics at Research Center COM and also III-V Nanolab run jointly by COM and the Niels Bohr Institute, Copenhagen University.

The scientific work of Prof. Hvam falls within the optical and optoelectronic properties of semiconductors. In the last decade he has been engaged mainly in the fabrication and optical (including near-field optical) characterization of low-dimensional semiconductors, with special emphasis on ultrafast spectroscopy and dynamics of semiconductor nanostructures and devices.

Prof. Hvam has authored and co-authored more than 240 scientific articles in international journals and books, and he has given numerous invited talks and lectures at international conferences, meetings and summer schools.

Professor Stephen J. Fonash

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Professor Stephen Fonash holds the Bayard D. Kunkle Chair in Engineering at Penn State. He is the director of the Penn State Nanofabrication Facility, a national NSF user facility, and is also director of the Nanofabrication Manufacturing Technology (NMT) Partnership and its NSF Advanced Technology Education Center.

The research activities of Prof. Fonash focus on the processing, chemistry, and physics of micro- and nanostructures. Current research programmes include studies of the effect of surface chemistry and nanostructure on cell confinement, growth, and differentiation, the development of matrix-less MALDI for small molecule detection, nanoscale fluidic structures, thin film transistors on plastic substrates, and integrated micro-channel and sensor/transistor systems on plastics.

Prof. Fonash has published over 250 refereed papers and one book, and holds 16 patents in his research areas. He is a Fellow of the IEEE.

Dr. Herman E. Maes
Vice-President IMEC
Director Silicon Technology and Device Integration
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Professor Herman E. Maes received the M.Sc. degree in electrical engineering in 1971 and the PhD degree in 1974, both from the Katholieke Universiteit Leuven in Belgium. From 1971 until 1974, he was a Research Assistant (Fellow of the National Fund of Scientific Research of Belgium, NFWO) in the laboratory for Physics and Electronics of the University of Leuven.

In 1974 Prof. Maes spent 14 months at the Electrical Engineering Research Laboratory of the University of Illinois, Urbana, Illinois as a Research Associate and a CRB Fellow. From 1975 until 1985, he was with the ESAT laboratory at the University of Leuven as a Senior Research associate of the Belgian National Fund for Scientific Research and a lecturer at the University. Since 1985, he has been a Professor at the University of Leuven.

In 1985 Prof. Maes joined the newly established R&D Laboratory of the Interuniversity Micro-Electronics Center (IMEC) in Leuven, Belgium, as Head of Analysis and Reliability. In 1990 he became an Associate Vice-President in IMEC and in 1998 Vice-President, heading the Division on "Silicon Technology and Device Integration". He has been elected a Fellow of the IEEE (Institute of Electrical and Electronics Engineers) in 1997 for contributions in the field of non-volatile silicon memory devices and for contributions to MOS Reliability Physics.

Prof. Maes has authored or co-authored more than 320 international technical papers including 9 book chapters and more than 300 conference papers including about 45 invited papers. He has been guiding 25 students to the PhD degree over the past 10 years.

Appendix 2

Letters to the three laboratories (translation from Swedish)

Program for the lab visits

October 26, 2001

Evaluation of microelectronic laboratories

The Swedish Research Council together with VINNOVA will, in reply to the letter from Sören Berg dated January 17, 2001, perform an evaluation of the three microelectronic laboratories the Semiconductor Laboratory (KTH), the Ångstöm Laboratory (UU)and MC2 (CTH). The evaluation shall put forward suggestions how to organise and co-ordinate the activities at the three laboratories in order to achieve an effective use of the resources at a national level. The directives for the evaluation are included. The evaluation shall be completed by March 31, 2002.

The chairman of the group that performs the evaluation is Professor Karl-Fredrik Berggren, IFM, Linköping University. The evaluation group will consist of, in addition to Karl-Fredrik Berggren, 3-4 members who are in the process of being nominated. The group will visit the laboratories during a week in January or February.

The Swedish Research Council asks each laboratory, as a guide for the evaluators, to send the latest Annual Report and a report of at most 20 pages which elucidates the aspects covered in the paragraphs "Description of the present situation" and "Description of experienced problems and needs for change" in the directives. The report shall be written in English. Applications for Expensive Equipment can also be included. The documents must be received by the Swedish Research Council (Att: Per Karlsson) no later than December 14.

Sincerely yours,

Kåre Bremer
Secretary General,
The Scientific Council of Science and Engineering Science

Program for the visits by the evaluation committee to the Semiconductor Laboratory, the Ångström Laboratory and MC2

10.00: Short introduction by Karl Fredrik Berggren and presentation of the committee members.

10.15: The faculty's view on the lab. (Presented by dean or equiv.)

10.30: Short presentation of the lab. What are your highlights in research? What are the most serious problems?

11.00: A guided tour of the lab.

12.00: Lunch.

12.45: The committee members ask questions according to the sections "Description of the present situation" and "Experienced problems and needs for change" in the directives.

14.00: Break.

14.10: The committee members ask questions regarding the future organisation of the labs.

Examples of questions:

How could a national co-ordination of the labs be done?

Is a Metacenter a possible solution? If so, should there be a national board? Who would have the economic responsibility? What would be the distribution of tasks in the Metacenter; niche or overlap? What role would your lab play? Is a GRID-concept possible?

How many labs are needed? Is there a phase out plan for your lab?

What should the level of project funding be to finance the use of the lab?

What are your needs for investments? Is "remote instrumentation" a possibility?

What is the importance of the lab(s) for graduate and postgraduate education?

14.00: Departure.

Appendix 3

Report from the KTH Semiconductor Laboratory

Executive summary

The KTH Semiconductor Laboratory has since its establishment in 1987 been Sweden's leading infrastructure in microelectronics research and development. It has for almost 15 years provided a technically comprehensive and intellectually creative meeting place for academic science and industrial development. This fruitful collaboration between university and industry projects has not only achieved an unprecedented cost effectiveness in expensive resource utilization but has also received international recognition as a means to provide the R&D community with a top quality process microelectronics laboratory with a broad technology profile.

The Lab activities are built around system relevant device research and covers the entire fabrication from crystal growth to flip chip mounting and delivery to in-house or external groups for device characterization. The technical areas are matched to the project portfolio of the main user groups and is geared towards enabling rather than mainstream technologies in the fields of photonics, high performance silicon electronics, power devices and micromechanics.

The Lab serves scientists and students at KTH Departments and engineers at the national research institute Acreo as well as industrial staff working in joint projects with KTH or Acreo. There are over 160 registered users with an average Lab user time of 6 hours per week. Out of these approximately 60 are graduate students, meaning that 10–15 Ph.D. students annually get their degrees based on significant personal use of the Lab. A similar number of Ph.D. students indirectly rely on the Lab for state-of-the-art samples. In this process the scientific issues are naturally and continuously renewed and the quality benchmarked against national and international standards.

The Lab has been the key element behind a number of scientific and industrial success stories originating from KTH and ACREO research. Some of the more prominent are: world record high speed and tuneable lasers for fiberoptics, IR-imaging arrays, high speed silicon-germanium bipolar transistors, silicon carbide high power devices and microfluidic sensors for medical applications. Hundreds of people are currently working with the industrial exploitation of these results. Thus, the Lab serves as an effective company incubator in the "innovation and growth system" in Kista.

The Lab is a financially independent unit at KTH with an annual budget of approx. 35 MSEK. KTH and ACREO share the costs according to usage, currently approximately 50% each. The Lab organization itself provides the environment and infrastructure and has only about 10 employees. Machine use and maintenance is distributed to the various user groups to ensure tight coupling to the project needs. The Lab coordinates the use and has special responsibility to introduce new users and user groups to the facility. Despite its age, the Lab still has a very good general quality, as best demonstrated by the pilot production of large area detector arrays and power devices.

Equipment renewal has in the past been possible through grants from the Wallenberg foundation and other sources. However, this is becoming increasingly difficult and in addition there is an increasing need to replace old (> 10 years) standard equipment which is not possible to finance directly through projects nor by leading science motivations. To somewhat alleviate this problem a cooperation with Chalmers and Uppsala Universities was initiated during last year to encourage nationwide use of expensive equipment.

Gunnar Landgren	Nils Nordell
Vice president of KTH	Lab Director
Chairman of the Lab board	

Introduction

In 1987 the Institute of Microelectronics (IM) established a laboratory for semiconductor research and development in the Electrum building in Kista. When IM was reorganized in 1993, the research oriented activities and the semiconductor laboratory were transferred to KTH. The activities oriented towards industrial development were continued within a new institute, the Industrial Microelectronics Center (IMC). In 1999 IMC merged with the Institute of Optical Research (IOF) and formed Acreo.

Since 1993 the KTH Semiconductor Laboratory has developed to become a resource for education and research for departments at KTH, mainly the Department of Electronics (from 2001 Department of Microelectronics and Information Technology, IMIT) and the Department of Signal Sensors and Systems, S3. The lab is also open for researchers from other universities than

KTH, and we have had a few users from Mitthögskolan, through a collaboration between Mitthögskolan and IMIT.

Simultaneously the lab has established itself as a resource for industrial development and small scale production, mainly for Acreo and its customers. During the last years the lab has been a vital resource for new start-up companies emanating from both KTH and IMC/Acreo, such as ADC/Altitun, Optillion, Comlase, Silex, etc. Companies are also given the opportunity to rent clean room area including connections to the common media supply, in order to install their own equipment and establish their own processes, if there is free area available. For some years Nordic Solar Energy rented 20 m^2 under this conditions, and ABB Corporate Research did use the lab as a platform to establish a 300 m^2 cleanroom area for development of SiC based power electronics.

Today the lab can provide five different full process lines, for manufacturing of devices and microstructures all the way from substrates to chip level, for research or small scale production. The process lines are for Si electronics, Si MEMS, SiC electronics, GaAs and InP optoelectronics. New processes, which could be built from the steps available within these categories, could readily be established. This makes it fairly easy to start process development in new areas, which gives the lab a very high degree of flexibility.

The lab has more than 160 registered individual users, of those about 70 are Acreo employees, or industrial users, the rest are KTH users, mainly Ph.D. students (about 60), but also some research leaders (20), diploma workers (10) and engineers (5). In total the users spend more than 40 000 hours per year in the cleanroom.

Organization

The lab is organized as a Center at the IMIT Department at KTH. As a center the work at the lab is directed by a board, appointed by the president of KTH. In the board the main user organizations are represented (today IMIT, S3, and Acreo). The lab has an executive manager, who reports to the board in matters regarding the usage and development of the lab resources, and to the director of IMIT in administrative matters such as organization, personnel, economy and work environment. Financially the center is a separate unit at KTH.

The board points out the strategy for the lab development and decides on the overall rules for lab usage, infrastructure investments, safety and quality standards, and defines the principles for calculating the lab fees.

The lab manager heads a relatively small group of about ten persons with the task to coordinate the lab activities, to facilitate communication between the users and to form a common interface to the surrounding world.

The lab group also has the responsibility to coordinate the safety work in the lab, which has proven to be a considerable undertaking, due to the many different processes, chemicals and users in the lab. The fact that the users belong to different employer organizations, makes this work further demanding. A high standard on the lab safety work is a prerequisite for maintaining the authority permits to handle flammable and toxic gases and chemicals. The lab group maintains the common documentation for the lab as a whole, which makes it possible for the lab to act as one single unit in the contacts with authorities in these and other similar matters.

Other tasks for the lab group are to maintain the basic functionality of the lab, which includes delivering of media, and providing the user groups with utensils, chemicals etc., to distribute information about equipment and lab status and activities to the users, to give courses in lab safety and cleanroom infrastructure, to coordinate lab usage, and to make the economic accounts for the common part of the lab resource.

The tasks of the employees of the lab group could be specified as follows:

- **Management and economy** (1 person)
- **Maintenance and service of buildings and media delivery systems** (2 persons)
  - House media (gases, DI water, cooling water, compressed air, vacuum, drain, etc.)
  - Climate
  - Purchase of utensils, gases and chemicals
- **Coordination of lab use** (4 persons)
  - Work environment and safety
  - User registration
  - Courses and education
  - Following and adopting to legislation
  - Maintaining authority permissions
  - User information and booking of equipment (web-page)
  - Cleanroom workshop with tools and spare parts
- **Mechanics workshop** (2 persons)

In addition to the lab group, which is employed by the Center, the lab has more than 160 registered users, with the permit to work in the lab. They are employed by the user organizations, or by companies with contracts with the user organizations. The responsibility to maintain the functionality and process quality in the process equipment lies on the users. Hence each equipment is appointed a machine responsible person, and each room a room responsible person, employed by one of the main lab user organizations. The responsible organization has the full responsibility for the functionality, process control, safety and documentation for the equipment or the room. The room- or machine responsible organization is obliged to keep these machines at a minimum standard of functionality, so that they are useful for the own group or for other lab users. The user organizations also have the main responsibility to attract and run the projects in the lab.

This organization with a small lab group, which has the responsibility for the common premises, media delivery, safety and general lab coordination, in addition to a large user group with responsibility for processes, equipment, and lab quality is highly efficient. In this way only the processes which are demanded will be maintained, and only equipment which is used could stay in the lab. Simultaneously all users have access to a high quality lab environment.

Resources and equipment

The lab has a 1300 m^2 clean room area, with cleanroom classes 100, 1 000 and 10 000. There are also external labs for chip mounting and characterization. The lab has five full process lines, for production of microelectronic devices from semiconductor substrates, using the specific process technologies for

- Si electronics: IC and MOS devices, 100 mm diam. wafers
- Si MEMS, 100 mm diam. wafers
- SiC electronics, 50 mm diam. wafers
- GaAs optoelectronics, 100 mm diam. wafers
- InP optoelectronics, 50 mm diam. wafers

Some of the process equipment, but not the full process lines, could be used for other substrate sizes. The available process equipment could also be used for new processes, not defined as being a part of the process lines, as long as the standard processes are not affected.

Process equipment available for Si processes:

- Stepper lithography, (XLS i-line 0.5 µm, DSW g-line 0.7 µm)
- Contact 1:1 lithography (Karl Süss, up to 150 mm diam. wafers, Canon)

- Automatic photoresist and developer stations (Optitrack)
- Manual spinners and hotplates (Convac, EMS)
- Metallization (MS sputter, Leybold and Balzers evaporation)
- Dry etch (STS ICP, Omega RIE)
- Si/SiGe epitaxy (ASM, up to 200 mm diam. wafers)
- SiO_x plasma deposition (STS)
- Oxygen plasma barrel reactor (TEGAL)
- Furnace processes (Bruce diffusion, oxidation, deposition)
- Ion implantation (Varian)
- Rapid thermal anneal (Heathpulse)
- A wide variety of wet etch and cleaning processes (Mainly PM-plast)
- Die mounting and bonding

Process equipment available for compound semiconductor processes:

- Stepper lithography, (Canon 0.7 µm)
- Contact 1:1 lithography (Karl Süss, up to 150 mm diam. wafers)
- Automatic photoresist and developer stations(Optitrack)
- Manual spinners and hotplates (Convac, Solitech, BLE)
- Metallization (Alcatel sputter, Alcatel and Balzers evaporation)
- Dry etch (Oxford plasma ICP, VacuTech RIE, Nordico CAIBE)
- Oxygen plasma barrel reactor
- Epitaxy
  - Aixtron MOVPE for InP/InGaAsP(N)
  - Emcore MOVPE for GaAs/AlGaAs
  - Aixtron HVPE for InP/InGaAsP
  - Emcore and Epigress VPE for SiC
- SiO_x and SiN_x plasma deposition (Oxford Plasma and VacuTech)
- Ion implantation (Danfysik)
- Rapid thermal anneal (Heathpulse)
- Furnace anneal (Tempress)
- A wide variety of wet etch and cleaning processes (Mainly PM-plast)
- Lapping and polishing (Logitech)
- Die mounting and bonding

Characterization equipment

- X-ray diffraction (Philips)
- Photoluminescence

- Hall-effect measurements
- C-V etch profiler (BioRad)
- Electron microscopy (Jeol, Leitz SEM, Link EDS analysis)
- Optical microscopy (Nikon, Leitz, Olympus)
- Ellipsometer (Rudolph Research)
- Surface profilometer (Tencore)
- Atomic Force Microscopy, AFM
- Secondary Ion Mass Spectrometry, SIMS (Cameca)
- Probe station for I-V and C-V measurements
- Optical characterization of lasers

Lab usage

The lab is open for all users who qualify, i.e., the user must pass an introduction program, mainly focusing on lab safety and clean room working routines. The user must belong to one of the major user organizations of the lab (IMIT, S3, or Acreo), or have an agreement with one of these organizations, in order to obtain the proper supervision, and an organizational seat for legal and work safety matters.

In order to use an equipment the user has to obtain a driving license for that equipment. Primarily standard processes should be used, but process development is encouraged, given that the process variation is belied to contribute to the project success. Simultaneously precautions are taken towards contaminants and process alterations which could severely endanger the standard processes.

This open attitude towards new users and new processes or process variations have been of great importance for the development of new concepts and process solutions. It has been equally important for research as for device development with commercial goals. The flexible usage of equipment also contributes to an efficient equipment utilization, and hence a low cost per run.

University Research and Education

The lab resource is open for all interested academic researchers, even though most of the academic users belong to the KTH user groups at IMIT or S3. The researchers active in the lab are mainly Ph.D. students, and their research projects dominate the activities in the lab. These projects cover the broad filed from electronics to optics and photonics, micro systems and nanostructures. The activities also range from prototyping and applied research, to fundamental physics and materials science.

All the research groups active in the lab have international reputation, and produce a considerable number of publications in internationally recognized journals and of conference presentations. The number of Ph.D. and lic. exams, based on work in the cleanroom process lab, were eleven during year 2000 and is expected to be around fifteen during year 2001.

In order to increase the interest for clean room labs and experimental research and development, and as a part of the introduction to microelectronics and process technology, undergraduate students from Universities in Stockholm and Mälardalen are encouraged to make visits at the lab. Hence the lab environment is shown during a one-hour tour, and hundreds of students participate in such tours every year. Of those undergraduate students who continue their studies with courses in Microelectronics and Microstructure technology, about 50 carry out laboratory exercises in the lab annually.

Also senior high-school students in natural sciences are frequently given the possibility to visit the lab, usually as a part of KTH's PR activities, with the goal to attract students to the undergraduate programs.

In order to give an overview of the broad variety of the current academic research projects using the Semiconductor Laboratory, brief presentations of the groups and projects are given below.

IMIT Laboratory of Semiconductor Materials, 7 projects, 25 scientists

Key research areas are crystal growth, characterization and processing of materials and structures needed for advanced photonic and electronic device fabrication.

The group has collaboration with domestic and foreign companies, e.g., Ericsson Microelectronics, Comlase, Zarlink Semiconductor, Optillion, ADC-Altitun, Thomson CSF, Alcatel, CNET-Bagneux, German Telecom, NTT, Multiplex, Inc., and Agilent. The academic collaborations cover all major Swedish technical universities, and around ten different groups at universities abroad. There are also guest researchers, and Ph.D. students from abroad invited to work with projects in the cleanroom.

Current projects are listed below:

- ***Novel InP based QW-Structures***

Novel quantum well structures for 1.3 µm wavelength lasers, by using the InGaAsP/ InGaAlAsP alloy system, where the addition of Al is supposed to increase the conduction band offset without large effects in the valence band.

- ***White LEDs for Lighting***

A prestudy regarding solid state lighting using wide bandgap III-Nitride (GaN etc.) semiconductor materials. Blue LEDs have been fabricated and characterized. The compatibility with existing processes was shown to be good.

- ***Long Wavelength Vertical Cavity Lasers***

The development of long wavelength vertical cavity lasers (VCSELs) for emission in the 1.3–1.55 μm regime is a major activity, which is based on the world leading competence in epitaxial growth using MOVPE, and the device processes available.

- ***SiGe Chemical Vapor Deposition***

Selective and non-selective growth of Si/SiGe layers for HBT and MOSFET applications is studied in detail. New device concepts have been developed, and a large effort is made in studying segregation of dopants in device structures.

- ***Semi-insulating Materials and Selective Epitaxial Growth***

Growth of semi-insulating materials for the use in high speed optoelectronic devices is developed, which usually requires a multiple step epitaxial approach. Fe and Ru doping of InP, as well as growth behavior and simulation of doped structures is undertaken.

- ***Ion Beam Etching of III-V compounds***

Etch techniques using new chemicals in Reactive Ion Beam Etching (RIBE) and Chemically Assisted RIBE (CAIBE) are developed to diminish the etch induced damage. One application of this etch technique is the formation of 2D photonic crystals for integrated photonic circuits.

- ***High Resolution Electrical Characterization of Semiconductors***

Development of the Scanning Capacitance Microscopy technique for characterization of semiconductor materials and devices on a nano-scale. Measurements have been performed on doped Si, SiC and InP structures, grown or implanted.

IMIT Laboratory of Photonics and Microwave Engineering,
7 projects, 20 scientists

The research covers a wide spectrum from basic physics, such as quantum optics and electron waveguide physics and devices to photonic transmission systems and networks. Leading research themes are low dimensional photonics and electronics, integration of electronics and photonics, physically and conceptually, high speed electronics and novel photonics integrated circuits.

The group collaborate with several industrial partners, e.g., Ericsson Microelectronics, Optillion, IMEC, Acreo, Zarlink Semiconductor, Alcatel OPTO+, Cisco, Zenastra Photonics, Inc. There is also close collaboration with more than forty research groups at universities all over the world, including guest researchers invited to use the lab facility.

The project using the cleanroom are:

- ***Design, Modeling and Characterization of Semiconductor Lasers***

The performance of edge and surface emitting semiconductor lasers is improved with respect to increased transmission capacity by using new active materials, process techniques and novel design concepts, by systematic modelling, fabrication and characterization of devices.

- ***Rare Earth Doped Optical Devices***

Rare-earth doped silicon dioxide waveguides for signal amplification are produced, with the focus on short, densely Er-doped waveguides providing a gain at 1.55 μm for future telecommunication systems.

- ***Photonic Crystal Devices***

Photonic crystals, i.e., optical material with the dielectric constant periodically modulated on the scale of optical wavelength, are investigated. One dimensional structures are fabricated by multi layer stack depositions and two dimensional structures by advanced etch techniques.

- ***Nanoelectronics***

Electron waveguide devices, such as switches for logic and signal processing, where the concepts are borrowed from photonic analogies, are fabricated and characterized. There is also an activity on devices utilizing the spin properties.

- ***Photonic Integrated Circuits (PIC)***

Silica-on silicon technology is developed and integrated photonic devices are fabricated for future multichannel optical communication systems. This includes studies of the influence from technology parameters on the properties of deposited films and processed waveguides.

- ***High-Speed Photonic Technology and Devices***

Optical modulators based on inter-subband transitions in quantum well structures are developed with the final goal to reach wavelengths around 1.5 µm for optical communication. Monolithic receivers for high capacity TDM and WDM communication have been fabricated.

- ***Very High Speed Electronic Integrated Circuits***

High speed InP based heterojunction bipolar transistors have been fabricated, characterized and modeled, with the goal to fabricate monolithic opto-electronic integrated circuits. This project is currently run in close collaboration with ETH, Zürich.

IMIT Device Technology Laboratory, 4 projects, 30 scientists

The research focus is on device physics, physical device modelling, and fabrication technology. Primarily the application areas are high frequency silicon technology, silicon power device modeling and silicon carbide and wide bandgap device technology for high power and microwave power devices.

The group collaborates with a large number of companies, e.g., IBM, IMEC, Semikron Elektronik GmbH, France Telecom-CNET, VTT, ABB Corporate Research and Ericsson Microelectronics, and more than 20 universities world wide.

The projects using the clean room lab are:

- ***High Speed Silicon Bipolar Technology***

New processes for high speed SiGe HBTs are developed and new device concepts evaluated. The project includes processing, characterization, evaluation, design and modeling of the devices.

- ***Simulation, Devices and Process Technology in SiC***

The project focus is on high voltage switches, high frequency bipolar transistors and contacts for devices. Device structures, made in SiC and GaN based materials have been evaluated, and both ohmic and Schottky contacts on n- and p-type substrates have been developed.

- ***$Si_{1-x}Ge_x$ Channel for PMOSFET***

The incorporation of Ge into the channel of a sub-100 nm PMOSFET is investigated, with the goal to increase the hole mobility in the channel. This has been achieved in a CVD process, which allows selective deposition of SiGe with a Ge content above 20 %.

- ***CMOS Technology for Analogue Applications***

pMOSFETs with effective gatelengths down to 250 nm have been successfully fabricated, and 100 nm gates will be fabricated in the near future. This relies on selective epitaxy, ultra shallow junction formation, with high doping levels etc. Device design and characterization is also performed.

IMIT Laboratory of Solid State Electronics, 9 projects, 25 scientists

The research focus on group-IV semiconductors, i.e., predominantly silicon, silicon-germanium and silicon carbide, and the research programs may be characterized as material- and process oriented physics, with the goal to carry out application motivated basic research.

The group collaborates with the following companies: Lucent technologies, ABB Corporate Research, IBM, IMEC, Ericsson Microelectronics, and mote than 25 universities world wide.

The research projects using the clean room lab are:

- ***New X-ray Imaging Sensors (XIMAGE)***

X-ray imaging sensors with highly improved sensitivity, for e.g., materials characterization and dental imaging are developed. Hence pixels have been formed by etching deep pores in a silicon matrix, which then are filled with scintillating tantalum doped cesium iodide.

- ***Devices Based on Silicon Nano Structures***

The properties of porous silicon and of silicon nanocrystallites for light emitting purposes are investigated. Controlled fabrication of sub-20 nm structures is performed by a combination of oxidation and electrochemical etching, and the structures are characterized by, e.g., photoluminescence.

- ***Micro Fabrication by Electrochemical Etching***

For, e.g., medical electrodes, channel plates and micro fluidic devices, the control of the etch technique is improved. By light-assisted electrochemical etching, and lithographically defined structures on the substrate backside, pillars or micro-pores are readily defined.

- ***Diffusion and Defects in Group IV and III-V Compound Semiconductors***

Several aspects are studied within this project, i.e., ion implantation doping, defect evolution and irradiation-enhanced diffusion in SiC; interaction between hydrogen and dopants in SiC and Si; point defects migration during quantum well intermixing of GaAs/AlGaAs heterostructures; dopant diffusion, interdiffusion and shallow thermal donors in strained and relaxed Si/SiGe/Si heterostructures; defect evolution in ion-implanted and annealed Si; p-type dopants and oxygen impurities in epitaxial layers of GaN; and defect and impurity diffusion in SiC during reactive ion etching.

- ***European Network of Defect Engineering of Advanced Semiconductor Devices***

The control of enhanced diffusion related to ion implantation in silicon based devices is studied, as well as the unwanted defects which affect the tolerance of silicon based detectros in harsh environments.

- ***High Voltage SiC Diode***

The material quality and device processing skills necessary to manufacture diodes capable of 10 kV reverse bias are developed. This includes optimization of device design and production of test structures for Schottky-, p-n-junction- and junction barrier Shottky diodes.

- ***Ion Implantation of SiC***

Ion implantation for planar SiC devices is studied, with focus on lattice damage with the goal to understand the damage build-up process and to optimize the implantation and post-implant annealing parameters to minimize residual damage.

- ***Contact Metallization using Silicides for Deep Sub-Micron Technology***

Experimental and theoretical studies are carried out to investigate the transition region between silicon and silicide. This covers contacts between Si and $TiSi_2$, with and without Nb addition. Also NiSi has been studied as an alternative to $TiSi_2$.

- ***High-K Gate Dielectric for Future CMOS Technologies***

The physical and electrical properties of ZrO_2 films are studied as high-K gate oxide for MOSFETs. Both experimental and theoretical investigations are made. The evaporation process for ZrO_2 deposition has been optimized with respect to both crystallinity and stoichiometry.

IMIT Condensed Matter Physics, 4 projects, 6 scientists

The competence of this group is in single crystal growth and thin film fabrication and evaluation, e.g., for super conducting materials, ferroelectrica, and thin ferrite films.

The group collaborates with Agilent Technologies, and more than 10 universities all over the world.

The research projects are:

- ***Epitaxial Complex Oxide Thin Film Heterostructures***

Complex multilayers of thin oxide films, compatible with standard planar IC-technology, are sintered at high temperatures, and studied with respect to physical properties, e.g., electric field effect, giant magnetoresistance and spin dependent interfacial electron scattering.

- ***Smart Ferrite Films for Microwaves and Magnetooptics***

Ferrimagnetic Yttrium Iron Garnet materials are studied for use in magnetostatic wave technologies and magneto optical devices, with the objective to engineer "smart" epitaxial ferrite thin film heterostructures and to test their feasibility for applications.

- ***Piezoelectric Materials for Actuator Device Applications***

Studies of bulk and thin film piezoelectric materials are performed for actuator applications. Techniques for piezoelectric characterization are developed, with the aim to build theoretical and technological foundations for use of piezoelectric materials in future applications.

- ***Fabrication of Bulk and Thin Films of Niobate, Tantalate, and Titanate for Industrial Applications***

Dense ceramic targets, and high performance thin ferroelectric films are fabricated by pulsed laser deposition and magnetron sputtering. The films are characterized with respect to the microcrystalline structure and functional properties.

S3 Microsystem Technology 10 projects, 20 scientists

The major research field is Micro Electro Mechanical Systems (MEMS) with special focus on applied sensor technology utilizing microelectronics fabrication techniques and micromachining of silicon. Currently the research fields of biotechnology, data- and telecommunication and wireless applications are dominating.

The group has collaboration with a number of industries in the field, e.g., Pondus Instruments AB, Biosensor Applications Sweden AB, and Datex-Ohmeda, Instrumentarium Corp., and a number of university groups.

The current projects are:

- ***Flow measurement and control of turbulent gas flow***

New types of hot-wire based anemometer sensors for turbulent gas flows in one, two or three dimensions are developed and fabricated. The fabrication relies on a robust, small radius polyimide V-groove joint (PVG).

- ***Micro-robotic devices based on PVG joint actuators***

Two locomotive micro-robot devices, a conveyance system and a walking micro robot, have been fabricated and extensively tested. Both systems are based on arrays on movable robust silicon legs raised from the substrate using polyimide V-groove (PVG) joint actuators.

- ***Nanochemistry***

This research program involves innovative tools, technologies and methodologies for chemical synthesis, analysis and biochemical diagnosis, performed in nanoliter or femtoliter domains. The current focus is on micromachined mass spectrometer injection tips.

- ***Microfluidic Devices***

A valveless diffuser pump has been designed and fabricated. The pump handles both gases and liquids, and is suitable for biochemical applications, e.g., pumping of living cells. Design and fabrication of electrostatically controlled pneumatic valves is also part of the project.

- ***Integrated Micromachined Concentrator and Sensor Chip for Biosensor Applications***

A micromachined biosensor with extremely high sensitivity and integrated with a sample concentrator is developed. The detection principle is based on antibodies attached to the surface of a piezoelectric crystal, and released when reacting with molecules in the sample.

- ***Micromachined Filter-chamber Array with Hydrophobic Valves for Biochemical Assays on Beads***

A filter-chamber array which enables real-time parallel analysis of three different samples on beads in an volume of 3 nanoliters on a 1 cm^2 chip is designed, fabricated and evaluated. The device is microfabricated in silicon and sealed with a Pyrex lid to enable optical analysis.

- ***Spiked biopotential electrodes***

Sharp micro-scaled spikes designed to pierce the outer skin layer of living subjects are manufactured at wafer level using new three step deep reactive ion etching. The electrodes show extremely low electrode-skin-electrode impedance, suitable for EEG recordings.

- ***Flow Sensors for Anesthesia and Respirator Systems***

Flow sensors specially adopted to for the use in medical equipment such as anesthesia and respirator systems are designed, fabricated and evaluated. A static turbine converts the volume flow into a torque, giving a bi-directional, profile independent volumetric flow meter.

- ***Ultra miniaturized Pressure Sensors for Intra- Vascular Applications***

Very small piezoresistive surface micromachined silicon pressure sensors are designed, fabricated and commercialized for the use in catheter based medical equipment for intravascular pressure measurements.

- ***Uncooled Infrared Focal Plane Arrays***

A new integration method for uncooled infrared focal plane detector arrays is established in collaboration with Acreo. In this technique the detector array and IC wafer are aligned and bonded in a low temperature polymer bonding process, before interconnects are established.

Biomedical and X-ray Physics, 1 project, 2 scientists

The group apply modern physical methods and technology to solve problems in biology, medicine, and materials science. One important field of research is soft x-ray science and soft x-ray optics, e.g., for sub-visible-resolution x-ray microscopes and high resolution projection lithography systems.

Only one project from this group is currently using the lab:

- ***Diffractive X-Ray Optics***

New diffractive optical components for X-ray microscopy are designed and fabricated to be used for high-resolution imaging of samples, several microns thick, in their natural aqueous environment. Typical resolution at the present is ~25 nm.

Research institute collaboration

In addition to the academic groups, the KTH Semiconductor Laboratory is used by Acreo, a research institute with activities in the fields of electronics, opto-electronics and micro-systems. Acreo has about 100 employees in Kista, and conducts contract research, development and small scale production within its competence areas. A primary goal for Acreo is also to contribute to the growth of small and medium size companies in Sweden, both by supporting existing companies with new technology, but also by encouraging Acreo employees to start spin-off companies based on innovations or technologies developed within Acreo.

Acreo's activities in the lab covers the fields of imaging, photonics, micro system technology, and silicon carbide technology. These activities and their importance for industry and academia are presented below.

- ***Imaging***

The core competence include imaging sensor technology, detector physics, CMOS circuit design and optically based information processing. Among the applications are night vision for the automotive defense field, medicine, computer and multimedia technologies.

One of the unique technologies developed by Acreo (part of the development was made by the predecessors IM and IMC) is the Quantum Well Infrared Photodetector (QWIP). This device has been taken into production on a small scale in the cleanroom lab. In the form of 640 × 480 pixel arrays, the QWIP is as a key component for long wavelength IR (8-9 μm) video cameras. New development is conducted to reach shorter wavelengths, i.e., 4 - 5.5 μm IR, and Acreo has demonstrated arrays operating in this range. In the field of uncooled detectors, such as microbolometers, a collaboration between Acreo, FOI and S3 at KTH is started.

An expanding filed is that of Spatial Light Modulators. These are pixelled devices similar to the detector arrays, with the difference that each pixel is an individually controlled light modulator. Acreo have demonstrated modulation in the GHz range, by applying a multi quantum well technique.

The Imaging Department at Acreo have several customers and financiers, among them are FLIR Systems, FMV, Saab, Ericsson, Photonyx, Telia Research, Autoliv, SEMCO and TCO.

- ***Micro System Technology***

The Micro System Technology department work over a broad field of applications, such as sensors, telecommunication and biomedical devices.

Microfluidic structures are developed and fabricated. They are used to study flow behavior and velocity distribution with applications to single molecule selection and DNA sequencing. Both industrial companies and medical scientists have shown interest in the work.

Radio Frequency Micro Electro Mechanical Systems (RF-MEMS) technology has been implemented for switching applications, where low loss, high isolation and zero standby power consumption is of importance.

As an example of a biomedical application, a system for neural recordings, which makes it possible to record multiple signals from neural tissue has been developed.

The Micro Systems Technology Department at Acreo have several customers and financiers, among them are Karolinska Institutet, NUTEK, Amersham Pharmacia Biotech, Ericsson Microelectronics, EU and IRECO.

- ***Photonics***

Among the projects at the Photonics Department, optical building practice and laser technology for various applications rely on the semiconductor lab resources for the projects.

The laser technology area is dominated by telecom applications, and together with researchers from KTH, Acreo has developed and patented a new versatile concept for miniature lasers, applicable to diode pumped solid state lasers. The design has prospects for cost efficient volume productions, and is a good example of the combination of laser technology with optical building practice.

Among the Photonics Department customers and financiers are Ericsson, NUTEK, Telia, Proximion, Wallenberg Foundation, and The Knowledge Foundation.

- ***Silicon Carbide Technology***

The Silicon Carbide Electronics Department have activities in the fields of high power microwave transistors and MOSFET based gas sensors. The microwave transistors could operate up to 35 GHz or at temperatures above 700°C. The sensors, developed together with Linköping University, could operate at extreme temperatures. They could be used for example to measure hydrocarbon emission in petrol engines, to optimize the fuel to air ratio.

Among the Silicon Carbide Technology Department customers and financiers are Whirlpool, Personal Chemistry, Office of Naval Research, Applied Sensor, EU and VINNOVA.

Industrial collaboration

The main industrial usage of the lab is organized within collaboration projects between the user organizations and their industrial partners and customers. Those collaboration partners are mentioned above in the project overviews. In these projects the processing work is conducted by the lab user organizations, and the results are eventually presented or sold to the partner or customer.

There is also a way for external industrial partners to come in and work with their own personnel in the lab. Hence they use the lab equipment under the same conditions as other lab users. To become accepted as a user, the industrial partner need a contract with one of the main lab user organizations, and from the lab's point of view the people working for the industrial partner in the lab are regarded as being employed by the main user organization, with which they have a contract.

Currently four companies work under these conditions in the lab; **ADC-Altitun, Optillion, Comlase** and **Silex,** with five to ten active lab users each. The first three companies work on lasers for opto-communication, and the last one on microsystem devices. Except for Comlase, they are spin-off companies from one or more of the main lab users.

One reason for a spin-off company to stay in the lab is the access to processes which the personnel might have established as employees at KTH or Acreo during an earlier research- or development stage. Another driving force to use the lab is that full process lines are available, to a reasonable cost, and that process development is allowed and also encouraged. These arguments are valid during a start-up and development phase, where the lab could act as an incubator for the new company. However, when the start-up company reaches the production phase, then process control and reproducibility becomes crucial for results and survival, and venture capital could be readily available. In his phase the start-up companies usually chose to build their own lab facilities, and leave our lab.

Until now only companies with some connection to this lab, or with employees used to this environment have been using the lab under the above described conditions, but also other companies, without any previous connection to the lab are welcome to establish processes here. A basic requirement is that they accept to work in the lab under the same conditions as the other lab users. For the lab it is a way to renew the competence and to use the excess process capacity in an efficient way.

An alternative approach has been for companies to set up their own equipment in a lab area, more or less closed to other users. As this exclusive right to use the lab area does not to a notable extent give positive contribution to the other lab users, the lab policy is hence to charge a higher cost for that area. This has been found to be a good solution when lab area is inefficiently used, and an industrial customer regards this environment suitable for a small scale activity in research, development or prototyping.

The major contract we have had in this direction has been with ABB Corporate Research, which had the goal to develop and produce high voltage silicon carbide devices. The contact was established as a continuation of a research activity financed by ABB at IMC (later Acreo). In this case ABB adopted a 300 m^2 lab area totally to their demands, and installed their own equipment. The collaboration has been beneficial for both parts, but the contract is ended during year 2002, as ABB quitted silicon carbide development.

Economy

The economic result for year 2001 and a preliminary budget for year 2002 are presented in a brief form below. This overview only presents the figures for the Center, and in addition the users have costs for maintaining their own lab equipment (including personnel, spare parts, service contracts, chemicals and lab fees). They also have costs for using lab equipment maintained by other user groups. Of course, the user groups which maintain equipment could also get an income from those, even though the costs for using equipment should reflect the actual costs to keep the machines and processes at a reasonable standard. Please note that the costs for equipment and its maintenance is covered directly by KTH departments or Acreo, and not included in the lab budget.

The incomes to the lab are mainly coming from the user fees. These are calculated using a formula based on the number of registered users at each organization, the number of hours the users spent in the cleanroom and the lab area each organization have to its disposal for equipment it has the responsibility for. The prices are adjusted, to balance the budget. The goal with these calculations is to distribute the common lab costs (which are to a very large degree fixed costs, independent of the lab usage) in proportion to the lab usage. In order to encourage the KTH research projects to use the lab, KTH supports the user groups with 10 MSEK. This support is distributed among the KTH users in proportion to their lab fees.

For the year 2001 the ABB project still pays for the lab usage, but as ABB leaves the lab by year 2002, the main lab users will have a corresponding raise in their costs.

In addition to the user fees, the user also pay for the lab for their use of house gases and the most common generally used chemicals, which are purchased by the lab. Project specific chemicals and gases are always paid by the user groups.

External sales is the income to the lab from the mechanic workshop, office space rented to external customers, consulting made by lab employees etc.

The lab expenses are dominated by fixed costs, i.e., the premises, the personnel, and the power for running the ventilation fans, climate and cooling systems and (to a lesser extent) for the process equipment. Also the costs for gases are predominantly fixed, as gas is constantly flowing through many process equipment, regardless if they running or not. The cost for KTH services is calculated as a percentage on last years expenses, and could be regarded as a fixed cost as well.

The variable costs are costs for the (mainly wet) chemicals used in the lab, the external services (which include computer service, external service techni-

	Result	**Budget**
Incomes	**2001**	**2002**
ABB user fee	7650	0
Acreo user fee	10250	15500
KTH user fee	1450	4500
KTH support	10000	10000
Chemicals	850	900
Gases	2850	3000
External sales	2550	4300
Sum 1	**35600**	**38200**
Costs	**2001**	**2002**
Personnel	5900	6100
Gas	2850	3000
Chemicals	850	900
Power	3200	3350
Premises	8400	8500
KTH services	2450	3400
Ext. services	900	950
Material	3200	3300
Sum 1	**25750**	**29500**
Deprecations	7200	8000
Interests	650	700
Sum 2	**35600**	**38200**

cians and workmen). The material consumed in the lab include both spare parts and consumables for the media delivery systems, utensils, clean room gloves and wipes, garment, and material used in the mechanic workshop.

Most investments are depreciated over five years, and the current deprecations are covering process equipment purchased as a common lab resource, including a 0.5 μm resolution stepper, wet chemistry benches, characterization tools etc. There are also investments made in the lab environment and infrastructure, e.g., new fans for improved ventilation, improved media delivery systems and a toxic gas detection system.

For the next year a necessary investment in the lab infrastructure will be made, to improve the safety standard in the lab, in order to comply with the demands from the authorities for maintaining the permits to handle flammable and toxic gases, and other chemicals, as well as an adaptation to new environmental legislation.

As a whole, the lab operation is fully paid by user fees, even though the research projects are generally under-financed, and rely on a central support from KTH. As the costs are predominantly fixed, and the lab resource is currently not fully used, there is a strong incitement for all the user groups to encourage increased usage of the lab, and to attract new user groups. An increased usage will directly lower the cost per user, which will be beneficial for all users. On the other hand, the financial situation also makes the operation extremely sensitive to the loss of one major user or customer, which will immediately rise the cost for all remaining users.

Challenges and future development

The fundamental prerequisite for the lab to survive and to develop, is to keep the current user groups, and to attract new users. Hence, the lab has to continuously adopt to the ever increasing demands from the users, as well as from authorities. Some of the most important success criteria are:

- Highly qualitative lab environment
- Access to highly qualitative and flexible processes
- Fast adaptation to new user demands
- Sufficient quality and quantity in media delivery
- Fulfillment of authority demands to maintain permits for the activity

Some ways to reach the overall goal – to attract users – are discussed in the following.

The user demands become increasingly specific, which is most obvious in the groups working on prototyping and small scale production. As soon as the process is established, and the production phase starts, demands on stable processes are raised. This is an issue in our multi-user environment, which traditionally has been flexible and open to process development and new materials, etc. In order to keep both production and research users satisfied, our solution has been to dedicate process equipment for specific use. Recently Acreo has established a few processes in their own equipment, open only for standard processing, and with very small possibilities for others to make alterations to the process parameters. An increased lab usage opens a possibility to establish basically separated process lines for production, development and research/education. In this scenario an incubator for start-up companies with demands on a stable process environment could be an important addition to the lab services. This will simultaneously give the development and research projects a more flexible environment, with increased possibilities to make experiments and to develop the processes.

There are currently increasing demands on equipment renewal in the almost fifteen years old lab, where many of the most used machines are between ten and twenty years old. It has simultaneously become difficult to receive grants from the Wallenberg Foundation, SSF, the Swedish Research Council or other financiers of expensive equipment in the field of microelectronics and microfabrication. Especially tools for the standard processes, e.g., for

- plasma deposition
- dry etch
- metallization
- standard lithography
- furnace processes
- wet chemistry
- electron- and optical microscopy
- electrical characterization,

which are necessary for fabrication of any device or microstructure, are impossible to renew in the current situation. To some extent Acreo could finance equipment in this category through contracts with industry, but also with the restrictions that the equipment only should be used for industrial projects in the incubator environment, where research and process development will be restricted.

The demands from authorities on a high degree of safety in the lab operation could also be read as a demand on infrastructural improvements. As well as for most equipment in the lab, the infrastructure suffers from being almost fifteen years old. The standards of installations have developed considerably during this time, and modern installations have the potential to deliver higher media quality, and are constructed by regarding modern safety standards. For the next years we plan to make the necessary improvements to the infrastructure, primarily demanded by the authorities in order to maintain our permits to handle toxic and flammable substances. The investment is calculated to a cost of minimum 10 MSEK, and includes:

- new gas cabinets to replace cabinets from mid-1980's
- new delivery lines for house gases to replace gas bottles in the lab
- catastrophe scrubber for handling a major toxic gas discharge
- modernized media installations
- renewal of wet benches
- recycling station for lab waste
- sedimentation of acid drain

A new way to attract lab users, is through the collaboration between us, the MC2 lab at Chalmers and the Ångström lab at Uppsala University. The collaboration is based on the open attitude to easily share the most expensive and specific process equipment at each lab. This could be accomplished by sending samples for processing between the labs, or even to educate people to handle the process equipment at the other labs. This will broaden the process portfolio which each lab could provide with the key processes at the other labs. In this way a network for processing of microelectronic devices and microstructures in Sweden is built.

In addition to the user groups active in the lab today, with focus on microelectronics and microstructures, we wish to attract user groups also from other fields of science, e.g., biotechnology, medicine, chemistry. We would also like to deepen the collaboration with groups both within KTH and with groups at other universities in Sweden and abroad. However, these new user categories would need a lager support from the lab in terms of practical supervision from experienced lab engineers.

As pointed out above, the research projects at KTH do not get the full financing from the funding agencies to pay the lab operation necessary for the projects. This is a fundamental issue in the funding system for experimental research. For the KTH researchers, KTH adds an extra grant for the lab operation. A more appropriate solution would be full financing of the research projects, where the actual lab fees are covered. An alternative would be a base financing grant for the lab operation. The grant could, depending on the size, also be used for necessary renewal of equipment or infrastructure, and to facilitate processing of samples from research groups at other universities in Sweden and abroad, and from other research fields.

Appendix 4

Report from the Ångström Laboratory

The Microfabrication Facility at the Ångström Laboratory Uppsala university

Scientific activities and Financial situation

Report to the Swedish Research Council
(December 2001)

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Background – the Ångström Laboratory

Semiconductor research started at Uppsala university already at the end of the 60th. The head of the Electronics dept. at that time, professor P-A Tove, did carry out R&D concerning semiconductor radiation detectors based on high resistivity Si-wafers. Originally these detectors were all based on Shottky barriers as rectifying contact. Therefore mostly evaporation and sputtering were used to fabricate these devices. In the middle of the 70th the first lithography equipment was installed and it became possible to fabricate smaller structures, mostly based on lift-off technique. In the 80th, the Swedish National Microelectronics Program (NMP) made it possible for this department to re-build the laboratory and set up a small clean-room facility. Also the R&D became more focused on MES transistors. 1984 we presented the first CMES structure fabricated on Si. In parallel to the electronic device research a group was formed active in MEMS technology. At the end of the 80th we fabricated the smallest pressure transducers ever made intended for measuring of blood-pressure in the human vane. The number of people involved in microstructure fabrication did steadily increase. However, it was realized that it was not possible to expand the laboratory at the present location. At the same time it was also realized that a large number of departments in natural science needed to expand their laboratories. In particular the professors in materials chemistry (J-O Carlsson), materials science (J-A Schweitz) and in electronics (S.Berg) argued for a solution where these groups should be transferred to a new building instead of making multiple ad-hoc solutions at the existing laboratories. The "dead-end" could only be pushed a few years ahead with a local solution. The faculty finally accepted this suggestion and recommended the university administration to build a new facility and collect activities having similar need for experimental conditions under the same roof. This should also encourage interdisciplinary work. This is how it was decided to build the Ångström Laboratory.

Resources

The laboratory was officially opened April 1997. It is about 30.000 sq.m offices and laboratories all together. The clean-room area is about 1700 sq.m of which 200 sq.m is class 100. However, installations etc did go on the whole year and the clean-room facility was not in full operation until beginning of 1998.

The following equipment are now generally available at the Ångström Laboratory.

- Laser Pattern Generator for mask fabrication
- Mask aligners single and double sided
- Wet chemical etching
- Professional cleaning baths
- Evaporation units
- Several sputtering units (cluster systems)
- Dry etching
- Deep Dry Etching for high aspect ratio MEMS
- Owens for diffusion, oxidation, nitriding and deposition of poly-Si.
- Ion implantation
- CMP , Chemical Mechanical Polishing
- Bonding
- Thickness monitors
- Four point probes
- Ellipsometer
- A dedicated SEM for inspection inside the clean-room area

In addition we have a large number of analysis equipment, SEM, TEM, Auger, ESCA, RBS, XRD, STM etc + soon installing a new FIB (focused ion beam).

Accessibility

The laboratory is generally available to all scientists that are able to handle the equipment. However, there are also equipment in the laboratory that belongs to special research teams and dedicated to their R&D activities. Since the opening of the laboratory the intention has been to successively make all equipment available to all scientists. However, this has not been fully realized yet.

As a part of this process some of the service-engineering personnel has been allocated to carry out service for the general available equipment. The remaining service personnel still belong to their original divisions and take care of their special dedicated instruments. Some of the general available instruments are still handled by scientists and Ph.D. students as part of their contribution to keep the service costs down to a minimum. This arrangement, however, frequently causes problems due to other commitments that this more qualified personnel have(teaching, visiting conferences etc. etc.) Due to such collisions of interests the down-time for some equipment sometimes may be unacceptable long. Down-time of key-instruments may affect a large number of projects. Originally the number of projects were not so big. However, today the activity has grown to a level where this type of ad-hoc service organization no longer can be accepted.

Scientific activities

The academic year 2000-2001 a large number of projects were carried out in the clean-room at the Ångström Laboratory. Primarily all were sponsored by national or international R&D agencies in competition with other scientists or directly sponsored by industrial partners. Some major projects are listed below:

Large area selective deposition
Reactive sputter deposition of complex compounds
Interface formation during thin film growth
Growth of piezoelectric thin films
Ångstrom Solar center – Smart windows prototype
Ångstrom Solar center – CIGS Thin Film Solar Cells
CIS Thin film solar cells on flexible substrates
Production of large area CIS based solar cell modules
Controlled surface structuring for tribological improvements
TixAlyNz coatings for temperature control of spacecraft's in space

Thin film coatings with variable emittance
Novel plasma devices
Microwave electro-acoustic devices
RF-CMOS –high-ε dielectrics
Metal gate electrodes
RF-Power transistors
LDMOS Devices
High voltage SOI technology
Quartz direct bonding
Miniaturized X-ray source
Hybrid micro propulsion thrusters
Nano satellite
RF-MEMS
Xenon feed microsystem for propulsion technology
Micro-pyros technology
E-field sensor
Low temperature wafer bonding
High aspect ratio MEMS
Fluid cell
DNA capture device
Membrane based microwave receivers
Ion track nanolithography
Wafer heterobonding
Diamond based micromechanics
Novel micromachining processes
Diamond based microoptics
AlN BAW high frequency resonators
GaAs microoptics
Microoptics for biofluidic MEMS
Biofluidic MEMS for mass spectroscopy
BCB based microoptics
Quartz and Si ion track technology
Paraffin microactuators
Piezoactivated microsystem
MINIMAN (Miniaturized robots)
Space qualification of direct bonded silicon microsytems
Oxygen plasma wafer bonding
Chip mounting and interconnection in multi chip modules for space applications

Undergraduate courses and use of students from other universities

About 50 undergraduate students annually carry out their laboratory exercises in the courses microelectronics and microstructure technology at the Ångström Laboratory. Next year this number will increase since we have started a new branch in the engineering science program focused on Biotechnology. From courses in this program further 40 students will carry out laboratory work in the clean room. There are also a number of students from the engineering programs that carry out their 6 months of diploma work in the clean room facility.

In addition also a number of scientists from smaller local universities are dependent on the fabrication facility at the Ångström Laboratory

Mitthögskolan	1 professor and 2 PhD –students
Mälardalens högskola	1 professor and 2 PhD students
Högskolan Gävle/Sandviken	Laboratory exercises – Undergraduate students (≈ 20/year)

Industrial collaboration

In addition to the academic groups the following companies are or have been working or sponsoring work in the Angstrom process & analysis laboratory since 1998:

Amersham Pharmacia Biotech AB
Ericsson Microelectronics AB
ABB Corporate research
Gyros AB
Radi Medical technology AB
Ericsson Radio Systems AB
Piezomotor Uppsala AB
Spectrogon AB
Åmic AB
Nordic Solar Energy
Biacore AB
Datex Ohmeda AB
ACR Electronics AB
Pyro Sequencing
Silex AB
Gnothis
Sense Air AB
Ericsson Microwaves AB
Nova diamant AB
Evox-Rifa AB

The annual fee from external users for work carried out by their own personnel in our laboratory is estimated to ≈ 2.3 MSEK this year (2001). Notice that primarily all these companies have made contacts direct to scientists that they already know. No coordinated advertising for inviting external companies have been carried out so far. However, we estimate that we are still able to offer a substantial part of the experimental equipment to more internal and external users. However, to be able to do so we need to establish a permanent contact and service organization for our laboratory.

Formal organization

At the Ångström Laboratory there exists a committee handling common businesses concerning equipment, personnel etc in the clean room. This committee reports to the board of the Materials Science Department. The committee consists of the head of divisions for materials science and electronics, the main responsible clean room supervisor, a representative from the companies that uses our equipment and a representative from the Ph.D. students.

We plan to organize the clean room and the persons involved in support of this laboratory as a separate division. As soon as we obtain adequate funding for initiating our plans this will be carried out. This new clean room organization will "sell" services and processing to internal and external users of the laboratory However, this can only be done if the up-time of all instruments will be significantly improved. To do this we need more engineering support and the improved organization that can handle this increased operation. Unfortunately there are no funding available at the university that can be used for this purpose. This is partly why we need financial support from the Swedish Research Council. During the whole planning period for the future of this laboratory we have used the NNUN in USA as a model for how we want the operation to be organized.

Fee for working in the laboratory – cost sharing

Sharing the same equipment between many persons implies that they have to share the costs for running the equipment unless these costs are paid from other sources. This is mainly how the running expenses are paid for today. All spareparts, chemicals, pump oils, gases etc are paid for from a special account. Also salaries for some of the generally available engineering persons are paid for from this account. Special chemicals, gases and specific project oriented products are paid for directly by the user. Wafers are bought jointly to get a good price. These are sold internally to the users. So is also done with photoplates for the laser pattern generator. Based on the history of the last years spending a preliminary fee has to be paid by all users. The fee for a scientist that belong to the Ångström Laboratory is at present SEK 135 000 per year. For external users (commercial companies) we also include costs for housing and depreciation of equipment. The cost for one person from this group is SEK 350 000 per year. The smallest period one may sign up for is 4 months. It should be pointed out that a 4 months fee has to be paid for a diploma work in the laboratory. This fee is almost equal to the salary cost the supervisor has to pay to the student.

The fee to the clean room facility is considered quite high for most users. In particular this is true for internal users. The grants from the Swedish research councils do not satisfactory cover for this type of costs. This may cause that some scientists can not afford using this facility as much as they would like. In particular this is true for preliminary tests of new project ideas not yet financially supported by any research funding agency. This seriously counteracts the idea of optimum utilizing of the laboratory facilities. The goal must be to try to find a solution where the fee for working in the laboratory is significantly reduced. In order to reach this goal we need some external basic funding for running this facility.

Financing

Below is outlined the specific annual costs for the microfabrication processing facility at the Ångström Laboratory. This does not include rent for offices for service and engineering personnel. It only includes direct costs for their salaries. For the activities carried out the academic year 2000/2001 we estimated the costs as the following (SEK).

Laboratory rent (clean room)	12 000 000
Service personnel	5 000 000
Running expenses	4 000 000
	21 000 000

This sum is balanced by taxation from internal and external users and from funding supplied from the university for the general activity for the Material Science Department. It should be noticed, however, that this cost level significantly restricts other activities at the department in general as well as for the individual scientist who has to pay his/her share direct from R&D founding grants. It is not financially possible for the Department to increase the personnel for service and maintenance without obtaining some external funding for this activity.

To be able to run the facility more satisfactory we need to increase the number of service personnel (+ 5) and to hire a responsible laboratory supervisor. We expect this to add another MSEK 5 to the expenses for the coming years. Since the purpose of hiring more personnel to the laboratory is to make it possible for an increased activity we also expect the running expenses to increase accordingly. Below is shown the expected budget for the 3 coming years (kSEK)

	2002	2003	2004
Laboratory rent	12 000	12 000	12 000
Service personnel	8 000	10 000	10 000
Running expenses	6 000	7 000	8 000
Total	26 000	29 000	30 000

We estimate the need for annual investments in new equipment to be ≈ 5–10 MSEK/year. However, the costs for these investments are normally paid for by special governmental or private funding and will therefore not show up in the cost statements for the running expenses.

It is expected that the costs level will stay approximately constant at 30 MSEK/year after year 2004. In order to offer reasonable basic service and maintenance of the laboratory to the users we need some basic financial support for this. As can be seen from above the department can accept a significant external contribution in order to reduce the internal costs for the clean room activities.

In the preliminary application to the Swedish Research Council (May 2001) we suggested that this Council should contribute with 12 MSEK/year to cover our costs for laboratory activities. This corresponds to ≈ 40–50% contribution to the basic costs for running the clean room operation. However, if such a substantial contribution is considered to be too high we are prepared to negotiate for a reduced financial support. We must point out, however, that we are facing serious financial problems if an adequate support can not be obtained.

Industrial impact

It should be pointed out that there is a significant activity in bio-medical and biotechnology in the Uppsala region. This region is considered to be the most expansive area in this field of R&D in Sweden. As a result a large number of small and medium sized companies have been established in this area. This is expected to increase even further in the near future. A large number of new devices in this area of research need to be miniaturized and need therefore to have access to a microfabrication facility. For new and small companies it is very attracting to be able to carry out the preliminary experiments and prototyping before making costly investments. Access to our laboratory may therefore play an important role in the process of developing this field of technology in this region of Sweden.

The Technology Link Foundation (Teknikbrostiftelsen) in Uppsala is an organization that supports commercialization of new products and assists in developing small and medium size companies based on contacts between industry and university. In particular this organization acts in the best interest of start-up companies in this region. The Technology Link Foundation in Uppsala is very interested in an arrangement that makes the clean room microfabrication facility at the Ångstrom laboratory more accessible to companies in this region. In order to increase the up-time of equipment and assist in establishing the new laboratory organization this agency will financially contribute with 1 500 000 SEK for the year 2002 for speeding up of hiring of more service and maintenance personnel. Unless the financial problem for the laboratory will be solved before the end of 2002 they will consider future funding for this purpose. The important factor for the Technology Link Foundation is that the laboratory must be able to offer fast and reliable microfabrication services to companies in the region.

Summary

A large number of scientists at the Ångström Laboratory are strongly dependent on the equipment in the microfabrication facility in the clean room. The cost level for individuals for carrying out work in this laboratory seriously restricts the use of their individual R&D grants. The direct cost-share principle makes it almost impossible for young scientists to initiate a preliminary project without first having obtained some financial support from a research council. The fee for working in the laboratory must be reduced. To afford a better service and maintenance level without increasing the costs for the scientists we need to find some financial support for basic service in the laboratory. A better service level will also make it more attractive for external users (companies and other academic institutions) to use the laboratory. There is also a strong interest from start-up and small companies in the region in having access to the microfabrication facility at this laboratory.

Short form description of projects at the Ångström Laboratory

Project title: **MINIMAN**
Project leader at UU: Stefan Johansson
Deparment: Materials Science
Phone: +46 18 471 30 86
E-mail: Stefan.Johansson@Angstrom.uu.se
Project description:
The aim is to build an advanced mobile micromanipulator (miniature robot) that is driven by piezoelectric actuators and uses micromachined tools for manipulation of microparts. Manipulation can be made autonomously by particular vision sensors and algorithms. The movement is controlled by specially developed ASIC's and as a first test of making miniature robots a cm-sized piezoelectric robot with integrated electronics has been built. The project is based on advanced piezoceramic microstructures and the mechanical structuring as well as studies of the materials properties are crucial to the project. Surface texturing and deposition are needed for improved performance (depends on delivery time of instrument).
External funding:
(duration, size and source): 1998-2002, 316 kECU/3.25 year at UU (2.096 kECU in total), EU financing

Project title: **MiCRoN**
Project leader at UU: Stefan Johansson
Deparment: Materials Science
Phone: +46 18 471 30 86
E-mail: Stefan.Johansson@Angstrom.uu.se
Project description:
An European collaboration that will begin in 2002 (contract negotiations occurs at present). Can be considered as a continuation of MINIMAN. The project aims at developing miniature sized autonomous robots with advanced actuators for both locomotion and manipulation. The robots will have integrated sensors for force and position feed-back. Clusters of robots with communication

and power modules onboard will perform advanced manipulating tasks using micromachined tools. The project is based on advanced piezoceramic microstructures and the mechanical structuring as well as studies of the materials properties are crucial to the project. Surface texturing and deposition are needed for improved performance and global positioning. The actuator components have to be optimised with respect to size and the mechanical properties will determine the limits.

External funding:
(duration, size and source): 2002-2004, 315 kECU/3 year at UU (2.100 kECU in total), EU-financing

Project title:	**Piezoactivated microsystems**
Project leader at UU:	Stefan Johansson
Deparment:	Materials Science
Phone:	+46 18 471 30 86
E-mail:	Stefan.Johansson@Angstrom.uu.se

Project description:
A national collaboration project (LTH, UU, SCI, Gyros, Astra and APB). Development of materials, components and systems for fluid handling. The main focus has been the development of a flow-through dispenser for transfer, enrichments and separation of biochemical substances. The project will be directed towards the integration of smartness for continuous process analysis. Piezoceramic microactuators are assembled on silicon or other microcomponents. The actuators are fabricated with new techniques, and materials investigations as well as mechanical evaluations are needed. The possibility to deposit and pattern electrodes on the actuator will give new insight in the performance limitations of the components.

External funding: (duration, size and source): 1997-2001 (an application for continuation is under preparation), 0.7 MSEK/year, VINNOVA

Project title:	**Microfluidic bioanalysis system based on ultra-sonic manipulation**
Project leader at UU:	Stefan Johansson
Deparment:	Materials Science
Phone:	+46 18 471 30 86
E-mail:	Stefan.Johansson@Angstrom.uu.se

Project description:
An application for a national collaboration project (LTH, and UU) has been submitted. The aim is to develop an extremely fast system for microanalysis of

biochemical particles and beads. The project will be based on innovative solutions. Piezoceramic actuator structures are used for ultrasonic handling and the analysis is made contactless within a fluid cell. The size restrictions and high power requirements will make it necessary to optimise structures, materials and processes.
External funding: (duration, size and source): 2002–2204, 4 MSEK/year SSF (application).

Project title: **Tribological surface ennobling**
Project leader: **Sture Hogmark**
External funding:
(duration, size and source): 2002–2004, 1.4, 1.0 and 1.0 MSEK/year, VRT

The performance of bearings and seals, the effectiveness of cutting or grinding tools, the life-time of artificial hip joints, and the reliability of magnetic storage systems, all depend critically on tribology. At the Tribomaterials Group at UU, the tribological research and development is closely linked to fields such as materials science, surface engineering, surface mechanics, surface physics and chemistry, etc. In this project, all aspects important for the development of surfaces with improved tribological behaviour are represented; coating materials, micro-topography, formation of tribo-films, running-in, load bearing capacity, friction, wear and lubrication response, etc.

One important means to improve the tribological performance of lubricated sliding components is to apply a microscopic surface pattern to the surface or coating. This can be achieved in the most controllable way through lithography. One student working in this project will focus on surface texturing including lithography and surface coating by PVD.

Project title: **Textured surfaces with low friction properties and high wear resistance**
Project leader: **Staffan Jacobson**
External funding:
(duration, size and source): 2001–2005, 0.5 MSEK/year, SSF

For a number of years, structured surfaces have been used in applications ranging from hard disc reader heads to rolls for steel sheet rolling. However, the adopted structuring techniques do not allow high definition and micron scale sizes of the recess shapes. This prevents the contact surfaces from being designed on scale of the areas of real contacts. This project has three main objectives:

- To understand the relation between the texture and the friction properties of surfaces.

- To develop techniques that allow for manufacturing of textured surfaces with a very high definition, allowing very small and densely distributed recesses.

Produce surfaces with a topographical texture optimised for low friction and high wear resistance, primarily for mechanical components in dry, boundary lubricated and marginally lubricated sliding contact.

Achieved results
Textured surfaces of silicon have successfully been manufactured with the lithographic technique. The surfaces have been evaluated in lab tests involving reciprocal sliding between a steel ball and the textured silicon surface under starved lubricated conditions. The texture design had a strong influence on the wear resistance of the surfaces. Studies in SEM also showed the tribological functions of the recesses, including trapping of wear particles and storage of lubricant.

In the following, the research will be concentrated to the investigation of textured diamond coatings produced by CVD.

Project title: **Ångström solar center – cigs thin film solar cells**
Project leader: Lars Stolt
Department: Solid State Electronics
Phone: +46 18 471 30 39
E-mail: lars.stolt@angstrom.uu.se
Project description:
This project concerns the development of thin film solar cells based on $Cu(In,Ga)Se_2$ (CIGS). The work is divided in two main tasks: *CIGS production technology* and *Next generation CIGS.* In the first task a baseline cell fabrication process is operated. The objectives are to improve reproducibility, throughput and cell performance. The baseline does also serve as a stable reference for the research activities. Other work packages in the first task are process control for the CIGS co-evaporation process and long term stability of the devices. In the second task research on aimed at thinning down the CIGS absorber layer and increasing the deposition rate is carried out. An other research area is the formation of the heterojunction in this kind of solar cells, addressing in particular the replacement of the thin CdS-layer which is commonly used today.
Funded by:
The Swedish Foundation for Environmental Strategic Research (MISTRA) and the Swedish Energy Agency.
Annual funding: MSEK 10

Project title: **Production of large area CIS based modules – procis**
Project leader: Marika Bodegård
Department: Solid State Electronics
Phone: +46 18 471 72 49
E-mail: marika.bodegard@angstrom.uu.se
Project description:
This is a collaborative project with the objective to develop the CIGS thin film solar cell technology further in order to facilitate industrial production. The R&D work packages are: (1) low temperature CIGS fabrication, (2) thin CIGS layers with reduced indium content, and (3) Cd free and dry buffer formation. Solid State Electronics participates only in the second of these tasks where the work is coordinated with the other solar cell project – Ångström Solar Center. The work in this project consists of using bandgap profiles in the CIGS absorbers which allows reduction of the thickness with minimal sacrifice of cell performance, i. e. conversion efficiency, and development of techniques for enhancing the light absorption by optical confinement.
Funded by: European Commission
Annual funding: 75 000 Euro

Project title: **Metal gate for RF-CMOS**
Project leader: Jörgen Olsson
Department: Solid State Electronics
Phone: +46 18 471 30 35
E-mail: jorgen.olsson@angstrom.uu.se
Project description:
The project aims at finding a one-metal solution for gate electrode material for advanced sub-µm RF-CMOS transistors. The project involves reactive sputter deposition of metals and metal compounds, which will be evaluated both regarding CMOS process compatibility and also regarding electrical properties characterized using of one-dimensional test structures and MOS transistors. In particular we try to develop a process which results in very low gate resistance and complementary workfunctions for NMOS and PMOS, respectively.
Funded by: The project is part of the High Frequency Silicon program funded by SSF.
Annual funding: MSEK 0.8

Project title: **High-K gate dieelectrics RF-CMOS**
Project leader: Jörgen Olsson

Department: **Solid State Electronics**
Phone: +46 18 471 30 35
E-mail: jorgen.olsson@angstrom.uu.se
Project description:
The project aims at finding a dielectric material with high dielectric constant in order to replace the current silicon dioxide as gate dielectric in sub-mm MOS transistors. Promising candidates as tantalum oxide, hafnium oxide and zirconium oxide are investigated both regarding deposition techniques and process compatibility, as well as regarding the DC and high frequency electrical behavior.
Funded by: The project is part of the High Frequency Silicon program funded by SSF.
Annual funding: MSEK 0.7

Project title: **LDMOS**
Project leader: Jörgen Olsson
Department: Solid State Electronics
Phone: +46 18 471 30 35
E-mail: jorgen.olsson@angstrom.uu.se
Project description:
In this project a novel design of a LDMOS transistor is investigated. The transistor offers both high-voltage operation and performance in the GHz region. The transistor is investigated for different microwave applications, such as mobile base station amplifiers, microwave lighting and heating. The project requires many test structures to be developed, especially for measurement of physical transistor parameters, such as channel length, and for measurements of high frequency behavior of the silicon substrate.
Funded by: The project is part of the GHz Power Transistor program funded by SSF.
Annual funding: MSEK 1

Project title: **Diamond microelectronics**
Project leader: Jan Isberg
Department: Solid State Electronics
Phone: +46 18 471 58 21
E-mail:
Project description:
In this project basic diamond semiconductor structures are investigated. Processing steps for microelectronic structures on single- or poly-crystalline diamond

substrates will developed, including etching and patterning. Uni-polar devices, such as MESFET, MOSFET and Schottky diodes will be fabricated and electrically evaluated. In particular the electrical behavior of the diamond surface will be studied with respect to different processing conditions and surface terminations.

Funded by: ABB.
Annual funding: Not decided yet

Project title: **Microthruster**
Project Leader: Lars Stenmark
Department: Ångström Space Technology Centre
Phone: +46 18 471 72 35
E-mail: lars.stenmark@angstrom.uu.se
Project description:
This project aims at demonstrating a totally integrated cold gas micropropulsion system. In order to meet the requirements, precise shaping of silicon in three dimensions is necessary. Furthermore, the complex assembly of the microsystem parts have to be thoroughly investigated: solder joining, wafer bonds, etc. Material deposition, namely of electric conductors on complex surface constellations will also be necessary, as will surface texturing in difficult places.
Funded by: The European Space Agency
Annual funding: MSEK 4
Access to clean room processes and equipment:
Mask generator, åhotolithographic equipment, wet chemical etching and cleaning, DRIE, RIE, metal etching, plasma cleaning, resistive and e-beam evaporation, sputtering equipment, ion implantation, thermal processes, bond aligner, electroplating equipment, dicing saw, scanning electron microscopes, white-light interferometric profilometry, and IR inpection equipment.

Project title: **Micropyros technology**
Project Leader: Johan Köhler
Department: The Ångström Space Technology Centre
Phone: +46 18 471 72 53
E-mail: johan.kohler@angstrom.uu.se
Project description:
This is a collaboration between 5 European partners, headed by LAAS, Toulouse. The aim is to develop, characterise, and begin qualification on a miniaturised pyrotechnic actuator for micropropulsion. One of our tasks includes the

intricate problems of low temperature wafer bonding for the actuator matrix assembly. The other is to experimentally characterise the micropyros device in order to verify models of operation.

Funded by: The European Community: Information Society Technologies Programme

Annual funding: MSEK 0.8

Access to clean room processes and equipment:

Bond aligner, plasma equipment, equipment for wet chemistry, evaporation equipment, electroplating equipment, lithography. IR inpection equipment.

Project title: **Quality assurance/Product assurance of microsystems for space**

Project Leader: Lars Stenmark

Department: The Ångström Space Technology Centre

Phone: +46 18 471 72 35

E-mail: lars.stenmark@angstrom.uu.se

Project description:

The Quality Assurance and Product Assurance of Microsystems for space applications aims at maturing complex microsystems technology in order to meet the extreme requirements from the spaceflight conditions. Analysis of process sequences and development of strict laboratory protocols are major items in this work.

Funded by: The European Space Agency

Annual funding: MSEK 0.65

Access to clean room processes and equipment:

This project is an integral part of all other activities of The Ångström Space Technology Centre, and thus use all equipment of those projects. A specific area of interest are process monitoring, i.e. inspection equipment of all kinds are primary.

Project Leader: Ulf Lindberg

Department: The Ångström Space Technology Centre

Phone: 018-471 62 22

E-mail: ulf.lindberg@angstrom.uu.se

Project description:

This project aims at developing a demonstrator of a micromachined silicon Xenon Feed system for ion propulsion engines. Apart from generic micromachining issues, the project deals with utilising gas dynamics phenomena in microscale features.

Funded by: The European Space Agency
Annual funding: MSEK 0.6
Access to clean room processes and equipment:
Mask generator, åhotolithographic equipment, wet chemical etching and cleaning, DRIE, RIE, metal etching, plasma cleaning, resistive and e-beam evaporation, sputtering equipment, ion implantation, thermal processes, bond aligner, electroplating equipment, dicing saw, scanning electron microscopes, white-light interferometric profilometry, and IR inpection equipment.

Project title: **Thin Film Sun Sensor**
Project Leader: Lars Stenmark
Department: The Ångström Space Technology Centre
Phone: +46 18 471 72 35
E-mail: lars.stenmark@angstrom.uu.se
Project description:
This project aims at developing a novel miniaturised sun sensor for spacecraft. It contains the task of depositing multilayered patterns of thin film onto curved surfaces.
Funded by: ACR AB
Annual funding: MSEK 0.65
Access to clean room processes and equipment:
photolithography, resistive and e-beam evaporation, sputtering equipment, wet chemical etching, RIE, inspection equipment.

Project title: **Variable Emittance Panels**
Project Leader: Lars Stenmark
Department: The Ångström Space Technology Centre
Phone: +46 18 471 72 35
E-mail: lars.stenmark@angstrom.uu.se
Project description:
These devices are developed for thermal control on spacecraft. The clean room equipment are used for interconnecting the thin film structure to form a complete system.
Funded by: The Swedish National Space Board
Annual funding: MSEK 0.4
Access to clean room processes and equipment:
Photolithographic equipment, resistive and e-beam evaporation, sputtering, wet etching and cleaning, electroplating equipment.

Project title: **3D-Multichip Modules**
Project Leader: Lars Stenmark
Department: The Ångström Space Technology Centre
Phone: +46 18 471 72 35
E-mail: lars.stenmark@angstrom.uu.se
Project description:
The dense packaging of electronic devices in a 3D constellation is of prime importance to future space missions, and also has great promises in terrestrial applications. The major items of research are component demonstration. Future activities include multifunctional integration, space-hardening techniques for electronics, thin film interconnection technology, and durable silicon carrier structure development.
Funded by: The Swedish National Space Board
Annual funding: MSEK 0.2
Access to clean room processes and equipment:
Mask generator, åhotolithographic equipment, wet chemical etching and cleaning, DRIE, RIE, metal etching, plasma cleaning, resistive and e-beam evaporation, sputtering equipment, ion implantation, thermal processes, bond aligner, electroplating equipment, dicing saw, scanning electron microscopes, white-light interferometric profilometry, and IR inpection equipment.

Project title: **Miniaturized X-ray source**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se
Project description:
To build miniaturized X-ray sources by advanced microfabrication. The focus 2002 will be on fabricating and characterizing X-ray source chips vacuum encapsulated in wafer scale.
Funded by: SUMMIT/VINNOVA+faculty
Annual funding: MSEK 0.6 2002

Project title: **RF-MEMS**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se

Project description:
Initializing projects on RF-MEMS during 2001: to evaluate what fields in RF-MEMS to concentrate on from 2002

Funded by: SUMMIT/VINNOVA
Annual funding: MSEK 1 year 2001

Project title: **Membrane based microwave recievers**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se
Project description:
EU financed INCO/COPERNICUS project that ended with 2001. The objected was to integrate InP Schottky diodes on BCB membranes

Funded by: EU
Annual funding: MSEK 0.2 year 2001

Project title: **Ion track lithography**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se
Project description:
Several sub-projects on ion track lithography where SSF/AME and EU finance. Micromachining by ion track etching, electroplating in ion track pores and thin film lithographically defined flexible circuitry for magnetic recording and bio-analytic applications

Funded by: AME/SSF, EU
Annual funding: AME MSEK 0.8 year 2002, EU 1,000 yearly

Project title: **Wafer heterobonding**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se
Project description:
Project objectives to integrate InP epilayer optoelectronics on Si.

Funded by: SUMMIT/VINNOVA
Annual funding: MSEK 0.4 year 2001 (ended now)

Project title: **Diamond based micromechanics**
Project leader: Klas Hjort
Department: Materials Science
Phone: +46 18 471 31 41
E-mail: klas.hjort@angstrom.uu.se
Project description:
By diamond based biofluidic material, in collaboration of the large scale facility of IMM in Mainz, Germany (funded from EU 2001 by 200 kSEK to be spent at IMM)
Funded by: group for work at Uppsala
Annual funding: SEK 100 000

Company: Ericsson Microelectronics
Project leader: Fredric Ericsson
Department: Materials Science
Project description:
High-resolution materials analyses of nano-IC components
Supervisor Ulf Smith at 20% for Ericsson Microelectronics
Funded by: SUMMIT/VINNOVA
Annual funding: MSEK 0.8 (+ MSEK 0.92 from Ericsson Microelectronics)

Project title: **HV-DMOS**
Project leader: Jörgen Olsson
Department: Solid State Electronics
Phone: +46 18 471 30 35
E-mail: jorgen.olsson@angstrom.uu.se
Project description:
Within this project a novel solution for highly integrated high-voltage transistors is developed and investigated. The goal is to develop a one-chip solution for auto-motive electronic applications. By using silicon-on-insulator (SOI) substrate material and deep trench technology the high-voltage device could be completely isolated from the low voltage circuitry. In particular the project investigate the trench formation, chemical mechanical polishing (CMP), and implementation of high-voltage RESURF technology.
Funded by: The project is part of the AUTO-IC program funded by SSF.
Annual funding: MSEK 1.2

Access to clean room processes and equipment:
Full process flow: mask fabrication, lithography, sputtering equipment, wet chemical processes, dry-etching equipment, high temperature furnaces, CVD-equipment, ion implanter and CMP-equipment.

Project title:	**Quartz direct bonding**
Project leader:	Ylva Bäcklund/Greger Thornell
Department:	Materials science
Phone:	+46 18 471 30 23 +46 18 471 30 31
E-mail:	ylva.backlund@angstrom.uu.se greger.thornell@angstrom.uu.se

Project Description:
Investigation of our developed direct bonding of crystalline quartz, and its application to high-stability resonators.

Funded by:	TFR, Vetenskapsrådet
Annual funding:	2000: SEK 298 000 2001: SEK 298 000 2002: SEK 350 000

Project Title:	**Interface phenomena during thin film growth**
Project Leader:	Ilia Katardjiev
Department:	Solid State Electronics
Phone:	+46 18 471 72 48
E-mail:	ilia.katardjiev@angstrom.uu.se

Project description:
The main objective of the project is to study the initial nucleation growth stages of thin films during reactive sputter depostion. Of prime interest is the influence of the nucleation processes on interface evolution, preferred orientation, residual stresses, interface mixing, etc. Understanding of the initial growth stages of thin films will result in developing deposition processes for film with improved properties as well as low growth temperatures.

Funded by:	The project is part of the Swedish Consortium on low temperature thin film processing funded by SSF.
Annual funding:	MSEK 0.7

Access to clean room processes and equipment:
Sputtering equipment, lithographic processes, mask fabrication, RIE-processes as well as wet chemical and cleaning processes, HRTEM and SEM analysis.

Project Title: **Microwave electro-acoustic devices for mobile and land based communications**
Project Leader: Ilia Katardjiev (Project Coordinator)
Department: Solid State Electronics
Phone: +46 18 471 72 48
E-mail: ilia.katardjiev@angstrom.uu.se
Project description:
The main goal of the project is to develop the next generation fabrication technologies for the manufacture of high frequency electro-acoustic filters operating in the microwave region. These devices are to be based on thin film technologies, as oposed to the standard single crystalline technology. Technological processes for the synthesis of thin piezoelectric films are be developed. Filter prototypes will be designed, fabricated and incorporated in a real communications system, which will then be used to test and evaluation the potential of the new thin film technology.
Funded by: The project is a EU project in the 5th Framework.
Annual funding
(for Uppsala only): MSEK 1.5
Access to clean room processes and equipment:
Sputtering equipment, lithographic processes, mask fabrication, RIE-processes as well as wet chemical and cleaning processes, HRTEM and SEM analysis.

Project Title: **Thermally compensated high frequency BAW resonators**
Project Leader: Ilia Katardjiev & Klas Hjort
Department: Solid State Electronics
Phone: +46 18 471 72 48
E-mail: ilia.katardjiev@angstrom.uu.se
Project description:
The main goal of the project is to develop thermally stable thin film bulk acoustic resonators (TFBAR) operating in the microwave region. The devices will be fabricated using thin piezoelectric films of AlN. Thermal compensation will be sought by combining materials with oposite thermal coefficient of frequency. In the first instance thermal compensation will be sought in the region 25 to 125 degrees Celcius. A long term objective is thermal compension down to -70 degrees Celcius.
Funded by: The project is funded by SUMMIT.
The project starts in year 2002.
Annual funding : MSEK 0.45

Access to clean room processes and equipment:
Sputtering equipment, lithographic processes, mask fabrication, RIE-processes as well as wet chemical and cleaning processes, HRTEM and SEM analysis.

Project title: **Quartz and Si ion track technology**
Project leader: Greger Thornell
Department: Materials science
Phone: +46 18 471 30 31
E-mail: greger.thornell@angstrom.uu.se
Project Description:
Using etching of swift-heavy-ion induced damages together with micro lithography to create high-aspect ratio microstructures in insulators and semiconductors.
Funded by: AME
Annual funding: MSEK 0.1
Access to clean room processes and equipment:
Photolithography, wet etching and cleaning processes.

Project title: **Paraffine microactuators**
Project leader: Greger Thornell
Department: Materials science
Phone: +46 18 471 30 31
E-mail: greger.thornell@angstrom.uu.se
Project Description:
Paraffine is integrated with pliable microstructures of silicon, polyamide, or polycarbonate. The expansion following from a thermally activated phase transition is used for high-stroke, large-force displacement.
Funded by: AME
Annual funding: MSEK 0.3
Access to clean room processes and equipment:
Photolithography, wet and dry etching processes, thin film deposition.

Project title: **Fluid cell**
Project leader: Ulf Lindberg
Department: Materials science, Solid state electronics
Phone: +46 18 471 62 22
E-mail: ulf.lindberg@angstrom.uu.se
Project Description:
A new fluid cell has been developed by Biacore under the program SUMMIT.

This cell has been investigated and charaterized in co operation with Uppsala University. New flow cell will be manufactured and tested at the Ångström Laboratory as the program proceeds.

Funded by: VINNOVA, Biacore
Annual funding: MSEK 1.5

Project title: **Low temperature wafer bonding**
Project leader: Ulf Lindberg
Department: Materials science, Solid state electronics
Phone: +46 18 471 62 22
E-mail: ulf.lindberg@angstrom.uu.se
Project Description:
Wafer bonding is a key technology in micromachining. Since many applications use temperature sensitive details such as compound semiconductors. Metals, and diffusion layers, it is essential that high quality interfaces can be accomplished at low temperatures. Here at the Ångström Laboratory , we are studying the influence of different surface pretreatments and after treatments of the bonded wafers, on bond strength and defect distribution at the interface at low temperatures. The surface treatments could be wet chemical or different types of plasma treatments. We are also looking at the possibility of using designed monolayers for low temperature wafer bonding. Bonding at reduced atmospheric pressure for vacuum encapsulation is also investigated. The after treatments of the bonded wafers include annealing temperature and time.

Project title: **Capture device**
Project leader: Ulf Lindberg
Department: Materials science, Solid state electronics
Phone: +46 18 471 62 22
E-mail: ulf.lindberg@angstrom.uu.se
Project Description:
The manufacturing and testing of a capture device. This device can trap charged biomolecules in a channel by applying a voltage over the channel. The applications of this device will be tested at the Protein Analysis Center, Karolinska Institutet.

Funded by: Karolinska institutet
Annual funding: MSEK 0.2

Short description of companies with access to the laboratory.

Åmic

Åmic is a company based on micro replication technology. I develops and produces microreplicated devices to mainly Swedish life science and telecom industry. Seven persons have direct access to the cleanroom and uses it extensively. The relationship between Åmic and Ångström is mutual beneficient, since some of Åmics equipment is placed in the cleanroom and Ångström personal can use it.

ACR

ACR develops Microsystems for space applications under ESA contracts. They are dependent on facilities in Ångström and have allocate two persons full time there.

Piezomotor

Piezomotor is a spin of from Uppsala University and manufactures and sells piezoelements. Some of their development is done in Ångström.

Silex

The business idea of Silex is to produce MEMs based device as an OEM producer. Silex rents labspace in Ångström. They intend to expand their operations in Ångström during 2002.

Radi Medical

Radi sells medical equipment world wide. One of the items they sell is sensor for pressure measurement in the coronary artery. They participated heavily in the Summit program and had two persons 2000-2001 placed at Ångström because of the clean room facilities.

The company also give financial support for a PhD student salary (industridoktorand), Niklas Strid, at Ångström.

Biacore

Biacore develops, manufactures and sells bioanalytical instruments based on the Surface Plasmon Resonance effect. Their instrument are the top of the line instruments for studying biomolecular kinetics. They allocated Mattias Tidare to carry out research in the Summit program. The research concerns a flowcell that improves the performance of the latest instrument. The manufacturing and some of the testing of new versions of the flowcell will be done at Ångström.

Amersham Biosciences

Although they have some microfabrication facilities they uses Ångström for certain processes they lack. There use of Ångström is very irregular in time but the very existence of Ångström is a factor that influenced their decision to build there own facility.

Piezomotor Uppsala AB

Piezomotor is a spin-off company from the microactuators research at Uppsala University. The company was founded 1997 and develops and produces small linear motors based on patented technology. The motors are driven with piezoceramic material that creates controlled stepwise movements and by frequency variations a high dynamic velocity range is achieved. The solid material and friction contact during movement makes it possible to reach high forces as well as precise positioning.

Nordic Solar Energy AB (NSE)

NSE is a company owned by Uppsala University Holding AB and the Technology Link Foundation in Uppsala (Teknikbrostiftelsen). NSE is developing thin film solar cell production technology in collaboration with Ångström Solar Center. Fabrication of devices is done in the cleanroom of Ångström Laboratory using a set of deposition system specifically assigned to fabrication of CIGS thin film solar cells as well as general sputtering equipment, photolithografic processing, and thin film analysis equipment.

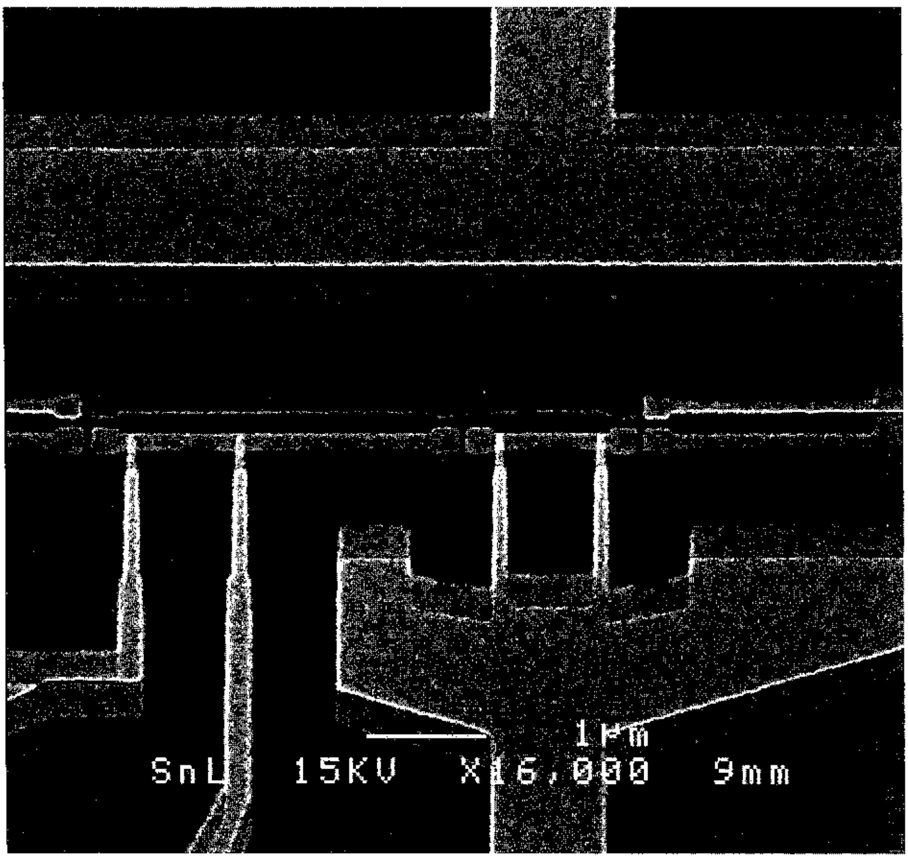
Solibro AB

Solibro is founded by researchers from the Ångström Solar Center at Solid State Electronics. The objective is to develop and demonstrate large scale production technology for CIGS thin film solar cells. Solibro will use the cleanroom at the Ångström Laboratory for development and evaluation of materials and processes.

Notice! Several other companies depend on Ångström in an indirect way. These are for instance some customers of Åmic and Silex for whom the microfabrication facilities enhances their choice of future technologies significantly. Åmic and Silex have informed us that they do use the microfabrication facility at the Ångstrom laboratory carry out development contracts with the following companies; Ericsson, Nokia, Gyros, Pyrosequencing, Gnotis.

Appendix 5

Report from MC2



Summary

This report presents the activities, the output and the present economic situation of MC2. It is written for an evaluation performed by the Swedish Research Council of the microtechnology process laboratories at Swedish universitites. The substance is taken mainly from a report analysing the economic situation of MC2 entitled "Increasing MC2 Income", from the brochure, "Growing Smaller" describing the research within the centre and from MC2 output data collected in the period 1997 - 2000.

Cost analysis shows that, in order to run the MC2 Process Lab with reasonable economy in relation to investments, income from internal and external sales on a level of 44 MSEK/year performed by a cleanroom work force of 30–40 persons is necessary for break-even. This will probably lead to two-shift work. Break-even in Profit/Loss account is assumed after five years.

Income from sales is expected to arise from:
- Internal research groups,
- Industrial service,
- Products
- Spin-off companies.

Cost-free income as grants is suggested to come from three different sources:
- Governmental institution (e.g. the Swedish Research Council),
- Chalmers Foundation
- Industrial supporting group.

The consequences of the economic five-year plan presented in the report are:
- The total external sales shall increase by a factor of 4
- 70% of sales are external
- Internal sales to research groups shall double in the same period.

It is argued that, in order to achive these goals, a number of strategic measures need to be taken. These include specialization of process lab personnel, starting a commercial unit in connection with MC2 and, most important, creating a powerful new organization of the total activities within the centre. The need for continous marketing of MC2 is pointed out.

Background and present situation

History

Ten years of discussion, arguing and planning among the Chalmers research groups and administraton, resulted in 1994 in a Government decision to allocate 38 MSEK per year for running a new facility in microelectronics at the university. This governmental action started the project to design the new building. Prolonged discussions in connection with the privatization of Chalmers delayed the project and the MC2 building was finished and occupied by scientists and technical/administrative personnel, totaly 220 persons, in the summer 2000. In the fall 1999, after reconsidering the decision from 1994, the Government withdrew the funding for MC2. This unusual act gave rise to a problematic situation, that has influenced the strategic planning of MC2, described in this report.

Organization

In the present organization of MC2 (Fig. 1), the centre is led by a Director, reporting to the President of Chalmers. The Director is responsible for the MC2 resources, the utilization of the MC2 Building and the development of the Process Laboratory. The Director also has the task to start up novel research under the headline of the centre within fields not directly fitting into existing structure. An Advisory Council with international representation, academic and industrial, influences strategic decisions and long term economy. The research groups are organized within and are reporting to the Schools of Physics, of Electrical Engineering and of Chemistry, depending on the domiciles of the specific groups. Twelve of the senior research group leaders belong to an executive group, chaired by the Director, for decisions of operative nature. The Advisory Council meets 4–5 times per year and the Executive Group has one meeting per week.

The vision, mission and the values of MC2 were formulated in the *MC2 Action Plan,* latest revised 2000-05-01 (see *www.mc2.chalmers.se/concept/index.html*). In order to define a direction of the centre, the concept of Microtechnology was formulated as

> Microtechnology at MC2 is centred around knowledge of materials, devices and basic systems for collection, manipulation, transport and presentation of information. Microelectronics, including photonics, micromechanics and nanoscale engineering play major roles.

and the role of the Executive Group was formulated in the following way:

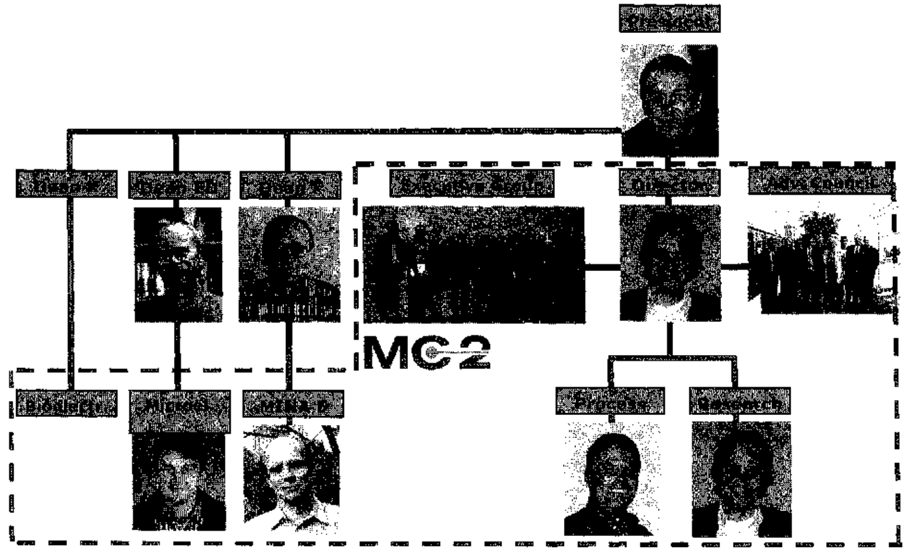


Fig. 1 Present MC2 organization

MC2 is a centre for strengthening the research activities at Chalmers in the field of microtechnology. The MC2 Executive Group has the responsibility to develop the microtechnology area along the directions given by the vision, mission, goals and strategy and in accordance with the values of the centre.

Profile and output

With a total personnel of 220 persons divided into 10 departments, including 12 full professors, about 20 associate professors, another about 20 assistant professors, 120 PhD students and, in addition, technical and administrative personnel, it is natural that the centre has a broad profile (Fig. 1). However, the big number of scientists covering a wide range along the dimension basic – applied also certifies a considerable depth. Comparing the Process Lab with other facilities like those at Cornell University, MIT, Rensselear, North Carolina State University, Georgia Tech and Stanford University, we find that the MC2 Process Lab facilities are on the same level, or even higher. With one of the largest groups in the field of microtechnology and one of the best process labs among the universities in the world, we feel that MC2 has great opportunities for the future. The research groups are active within the following fields:

- Microwave electronics for high speed devices based on III-V compunds, SiC and Si.
- Silicon technology for novel processes and devices, including MEMS

- Photonics including semiconductor lasers, fiberoptical transport phenomena and diffractive optics
- Bioelectronics for novel information technology and medical applications
- Physical electronics and photonics for novel nanoelectronics
- Superconductive materials and devices
- Experimental mesoscopic physics for single electron transistors heading towards quantum computing
- Liquid crystal physics for new materials and devices
- Applied semiconductor physics for heteromaterials of the III–V family
- Theoretical studies in applied quantum physics for new information technology.

In the years 1997–2000, the research groups of MC2 produced on the average per year:

- 200 papers in scientific journals with referee system
- 170 conference contributions, including 37 invited
- 980 citations in scientific journals
- 10 PhDs
- 80 MSEK in external grants.

The number of visiting months by guest scientist was on the average 230 per year in the same period.

The MC2 Process Laboratory

The main cleanroom, in total 1000 sqm, contains 25 sqm of class 1 space, approximately 140 sqm of class 10, about 200 sqm of class 100 and the rest of class 1000 space. In the complementary Training Lab, with an additional cleanroom area of 240 sqm of class 10,000, students- as well as start-up activities are taking place. Additional classified areas are the component MBE, the laser ablation area and the rooms for chemical preparation and CMP/dicing. All the supporting media are supplied from the basement. The cleanroom concrete floor, divided into 3 parts, rests on vibration isolated steel pillars anchored directly in the underlaying bedrock without touching the surrounding, providing an extremely low vibration environment for the fine nanometer-line work. The standard of the vibration is set to 3 µm/sec (standard curve E) which is met with good margins. The laboratory has humidity control within +/– 3% RH, and temperature control within +/– one degree (around the e-beam column +/– one-tenth of a degree C). Ultra-high purity process gases are distributed

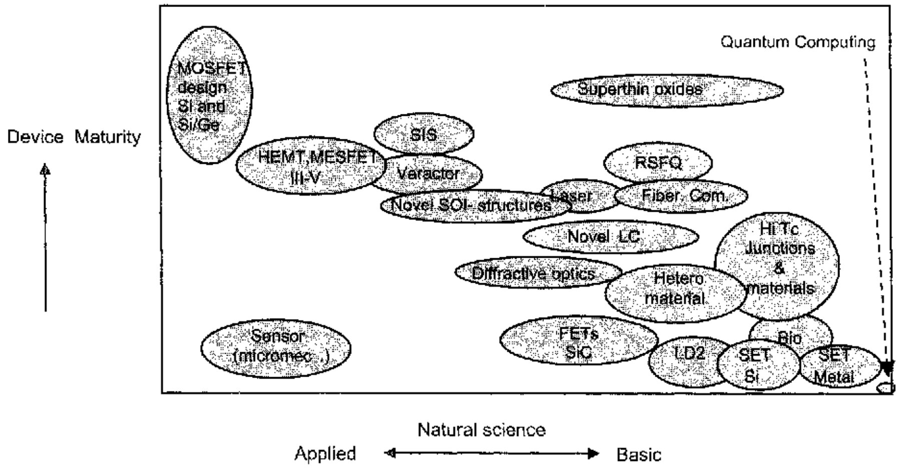


Fig. 2 MC2 Research Landscape. The maturity of devices, for which the research is aiming, is plotted as a function of the need of natural science; applied to the left and basic to the right. Every region corresponds to a research group led by a senior scientist. Explanations to some of the acronyms:

SIS = superconductor – insulator – superconductor structure
LD2 = low dimensional devices based on III-V and silicon materials
SET = single electron transistors

throughout the labs using electro-polished, stainless steel delivery systems. Excellent safety features include centralized smoke, fire and toxic gas monitoring systems – along with rigorous safety training program and detailed operating procedures – to safeguard staff against potential dangers. From an installation in a special gas building outside the main building, the laboratories are outfitted with automatic gas cabinets with remote shut down, automatic laboratory shut down and notification, and multiple contained process systems. The facility and process equipment are maintained by a staff of four service- and maintenance technicians and eleven process engineers. The process engineers are also responsible for the quality and safety of the standard processes and development of new state-of-the-art processes.

The Process Lab is equipped with the following machines and steps:

- Two JEOL electron beam lithography systems. One of those is of the company's latest design, presently the only existing at any university in the world.
- Metrology
- Diffusion/oxidation module for 6 inch silicon wafers
- Liquid Crystal Module (most advanced at any university in the world)

- Thin film module for silicon
- Thin film module for nanostructures and III–V compunds
- Wet processing modules for silicon, nanostructures and III–V compunds
- Optical lithography modules for silicon, nanotechnology and III–V compunds

Present economic situation of the MC2 resource

As a consequence of the breach of faith by the Swedish Government, when withdrawing the commited grant of 38 MSEK/year, MC2 is met by economic situation that has motivated a new strategic action. This will be further discussed below from economic as well as technical and organizational viewpoints. First, the present economy will be presented in Table 1 as profit/loss accounts for the closing of the books for fiscal year 2001 and also as the budget for 2002.

Table 1 depicts the total economic profit/loss situation of MC2, as if the centre were a free-standing economic unit. The large differences between

Table 1 Profit/loss accounts for the closing of books, fiscal year 2001, and for the 2002-budget

	Closing of books 2001	Budget 2002
INCOME		
Income from government source	500	500
Chalmers Foundation	27 189	36 000
Depreciation contribution (KAW etc.)	7 928	19 112
External sales	1 148	5 000
Internal sales (research groups)	3 500	6 000
Income, rentals and cleaning	17 164	24 900
Total income	**57 429**	**91 512**
COSTS		
Salaries	8 803	12 648
Running costs, process lab	11 298	20 647
Rental and cleaning	28 101	31 967
Depreciations	12 031	26 250
Total costs	**60 233**	**91 512**
RESULT	**–2 804**	**0**

budgeted values for 2002 and actual values for 2001 are due to the fact that the Process Lab was started up in the summer 2001. Depreciation contributions are coming from grants, mainly from the Knut and Alice Wallenberg Foundation (KAW), but also from the Chalmers Foundation for investment in the Process Lab facility itself and its equipment. These grants have been partitioned into ten-year depreciation portions. It should be noted that 2001 was not a full year from economic point of view because the Process Lab was started up in the second half of the year.

Rental and cleaning costs are for the whole MC2 building and are full year costs. Rental costs are administrated by MC2 management, meaning that the research groups pay rentals to MC2 (income), which in turn pays to "Akademiska Hus" (cost). This gives freedom in distributing rental costs by internal MC2 decisions.

Table 2 shows accumulated investments in MC2 from the start of the project until february 2002.

The use of the MC2 Process Lab

An important demand on the Process Lab is that it should be organized so that the PhD-students can use it effectively. Therefore, we have tried to find a way of charging the groups independent of time spent in the lab. We have introduced a "season card" principle, where the price tag is proportional to the total value

Table 2 Accumulated investments made in MC2 by February 2002

	Source			
Item	Chalmers Foundation [MSEK]	KAW [MSEK]	Swedish Governm. [MSEK]	Total [MSEK]
Start-up investment	20			20
Cleanroom	120	50		170
Equipment (1996)		50		50
Equipment (2000)	30	40		70
P/L losses (2000–2002) (8+30+27)	65			65
"MC2-research" (2000–2003)	2			2
Building			375	375
Artwork			1	1
Furnishing			25	25
Totalt	217	140	401	758

of such projects that are considered as "process intensive". For year 2001 the charges payed to the Process Lab were 15% of these amounts. With this charging principle the members of a research project can spend as much time as they want for processing. The basis for the price calculation in 2001 were 53 different, externally financed research projects with a total economy of 26 860 701 SEK.

Before entering the clean rooms, all users must pass a one-day course on general clean room behavior and before using a specific machine, a "driver licence" is requested. About 200 persons have taken the course so far and more than 300 driver licences have been issued.

Six months after opening the Process Lab, one of the largest international companies on the electronics market has signed a four-year contract with MC2 (totally 14 MSEK) and another about five small or medium size companies have signed contracts or asked for quotations in the interval 100 kSEK to 2.7 MSEK).

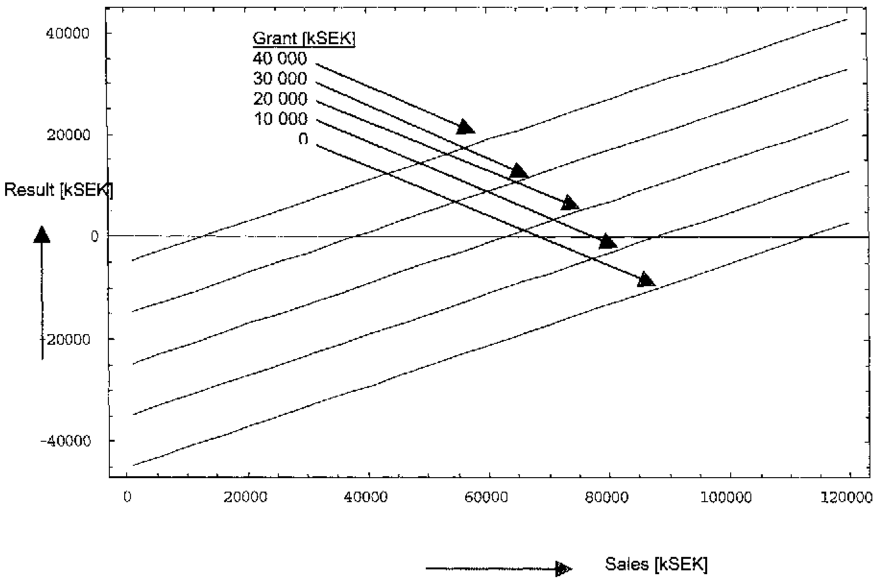
Cost analysis

In an earlier economic analysis (Status Report 2001-05-26) a number of different economic scenarios were investigated. It was shown that if MC2 would replace the government funding of 38 MSEK/year by external and internal sales, taking into consideraton the costs associated with such an activity, the income would have to be more than 100 MSEK/year. Even if such a scenario would be possible to realize, it would change the profile of MC2 from being a research centre to an almost pure commercial production unit. Therefore, we conclude that MC2 income must be built up by a mix of sales and grants. From budget work, we have assumed a simplified relation describing the income/cost relation when increasing the activity volume in the MC2 Process Laboratory. We found that within reasonable expectation of accuracy one may assume that volume dependent cost increase is 60% of increased volume dependent income. Together with corresponding volume independent parameters, one can express the economic *Result* of a predicted P/L account in MSEK/year as

Result = Grant + Volume dependent income – [0.6 x (Volume dependent income – 8000) + 39 900]

This expression is based on an assumed rental cost for the Process Lab of 6 MSEK/year. Furthermore, the "Depreciation contribution", mentioned in Table

Fig. 3. The economic result as a function of total sales (external + internal) for different grant levels

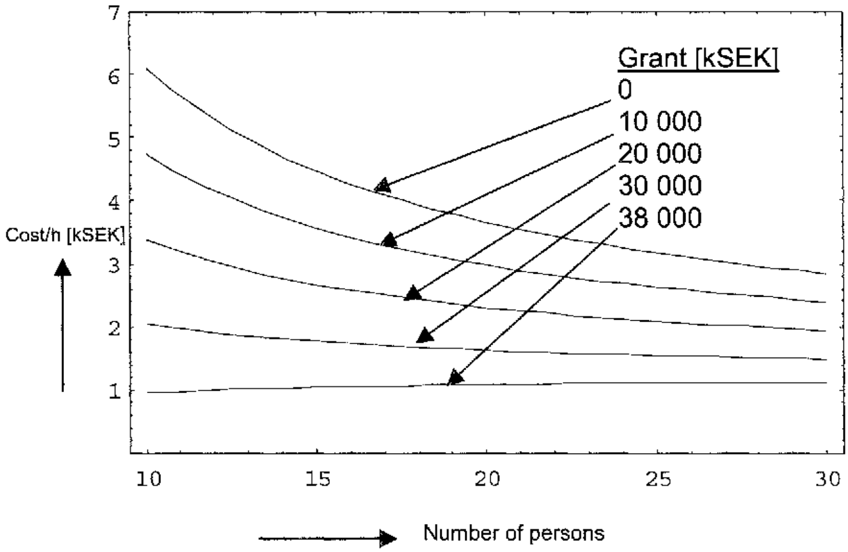


1 (19 112 kSEK budgeted for 2002), has been deducted from the income side and correspondingly from the cost side of the P/L account. This was made in order to obtain a more transparent economic model.

In Fig. 3, *Result* is plotted as a function of volume dependent income (=*Sales*) for different levels of *Grant*. Break-even (zero level crossing) occurs for sales between about 12 000 and 112 000 kSEK for grant injection levels between 40 000 and 0 kSEK. The graphs in Fig. 3 are linear as a result of the first order estimation represented by the expression above. This is of course a simplification limiting the accuracy. The interesting part of Fig. 3 for the present reasoning, however, are the intersections with the line where *Result* = 0, giving an estimate for the need of future income levels.

An estimated cost per working hour in the Process Lab is obtained by starting from the same expression as used in connection with Fig. 3 above. Assuming that a certain *Number of persons* work 8 hours per day with 100% efficiency to cover orders exactly corresponding to the sales needed for break-even in Fig. 3, the cost per working hour is shown in Fig. 4. The cost figures are highly dependent on grant injection levels and approach asymptotically 1200 SEK/h with increasing *Number of persons*. Assuming a grant injection of 30 MSEK, the cost per hour is about 2000 SEK, weakly dependent on the number of persons in production within the abscissa interval shown in Fig 4. For this case, which is suggested below, a suitable price to external customer may be 3000 SEK/h.

Fig. 4. The cost per hour and person for work in the MC2 Process Lab as a function of the number of persons performing productive work. The persons are assumed working an ideal 100% available 8 hours per day to cover orders needed for break even at different grant injection levels.

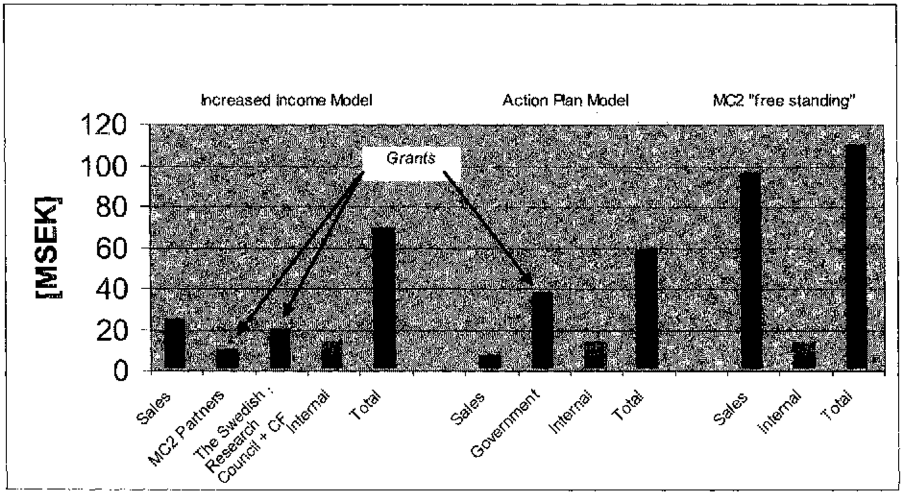


It is interesting to observe that with the grant of 38 MSEK, as initially decided by the Government, the cost would have been about 1200 SEK/h allowing for a competitive price of about 2000 SEK/h.

Income: Four sources for break-even

Fig. 5 shows income scenarios for break-even. The middle set of bars shows the "Action Plan Model", which was the original estimate as given in the MC2 Action Plan under the assumption that the Government promise would hold. In order to reach economic break-even, this situation requires an external sale of 7 MSEK/year, and an internal income (from the research groups) of 14 MSEK/year. To the right in Fig. 5, the income distribution for a "free standing" case without government contribution is shown. As mentioned above this case includes a total sale of 110 MSEK/year. The imbalance between internal and external sale is obvious when depicted this way. To the left in the same diagram, the "Increased Income Model" is demonstrated. Apart from the internal sale to the research groups, still kept at 14 MSEK/year, the three contributions of "the Swedish Research Council/Chalmers" ("the Swedish Research Council&CF"),

Fig. 5 Income distributions for break-even for three different scenarios. The middle bar set, "Action Plan Model", represents the situation originally assumed in the MC2 Action Plan. The set to the right, "MC2 free standing", is the result of missing government contribution. In the "Increased Income Model" to the left, the income is distributed across three external sources. This is the model suggested, to be further discussed in text.



"MC2 Partners" and "Sales" are shown at the levels of 20, 10 and 25–30 MSEK/year, respectively. These external income sources are the "Four sources for break-even" to be discussed below.

Source 1: Internal research groups

The income to the Process Lab from internal research groups has been budgeted to 6 MSEK for the year 2002. As this is the central activity for the Process Lab and the reason for the process faciltity to occur in the present outfit, the volume of research connected processing should be expected to increase. Our goal is 14 MSEK/year within 5 years. This requires increased external financing of the MC2 research as a whole, which implies a considerably increased activity to take part in projects with EU financing. Strategic and organizational measures will probably be necessary to obtain such a situation.

Source 2: The Swedish Research Council/Chalmers grant

Operating a facility of our type without contributions in the form of cost-free income is very unusual; to the best of our knowledge it is non-existing among similar facilities in the world. Therefore, as long as the Process Laboratory is dedicated mainly to research, a certain amount of grant is necessary. One would expect that the Government at the end would take some responsibility for their economic promises. A deal between Chalmers and the Government on a shared burden of 20 MSEK/ year might be expected possible if Chalmers in addition guarantees for absorbing MC2 losses during the first five years. Such an agreement would set an end to the disturbing controversy over failed Government promises. This requires an action to approach the governmental Department of Education.

In the winter 2001/2002, an evaluation of the Swedish microtechnology laboratories will be performed under the commission of the Swedish Research Council. This will probably give grants to MC2. A realistic estimate, however, is that the level will be around 5–10 MSEK/year, meaning that other complementary sources are necessary. Assuming that Chalmers Foundation accepts to contribute with an additional grant, a total of 20 MSEK/year along this lane would be a realistic estimate.

Source 3: MC2 Partners

The third source involves establishing a group of "MC2 Partners" consisting of influential industry people on the CTO level into a sponsoring society under the agreement of giving the sponsoring firms "first priority" to MC2 knowledge and facilities. This group would be composed of:

- 3 service providers (banks, revision firms, lawyer firms)
- 4 international investor companies
- 4 international companies within the MC2 area of activity

The offers given to MC2 Partners could be:

- Priority cleanroom use
- Scientific competence support
- Early information about scientific progress
- Network to other MC2 Partners
- Exclusive possibility to invest in MC2 research results ("First Right of Refusal")
- Annual scientific/commercial symposium ("The MC2 Sci-Com Symposium")

With a member fee of 1–1.5 MSEK/year it might be reasonable to obtain a total "injection" of 10 MSEK/year into MC2. In the year 2002, Chalmers plans for a second fund-raising campaign under the headlines of Environment, Bio, IT and

MC2. The efforts to create the MC2 Partners program will take place within this activity.

Source 4: External sales

Present situation

Six months after the opening of the MC2 Process Lab, the value of external orders are higher than expected. Contracts have been signed to a value of about 5 MSEK and, at the moment of writing this report, discussions are going on for orders valued to about an additional 3 MSEK (Table 3). If the latter agreements will be signed, which we consider probable, we will exceed the budgeted 5 MSEK which is our value for 2002. This has been achieved without any international marketing. Three of the orders are from abroad. Orders 1, 2, 4 and 5 in Table 3 are of the "industrial service" type while 4 and 6 are of the "product type". Orders 2 and 3 are research orders including PhD students and with a heavy process activity from big international companies

Table 3. External orders for the year 2002 on the date of this report. Actual orders will start being executed in January 2002. Estimated orders are considered probable. Discussions are going on in all these cases.

Business area	Technology area	Actual order [kSEK]	Estimated order [kSEK]
(1) Bioelectronics	Bio-MEMS	2 700	1 000
(2) High speed transistors	SiC	2 000	
(3) Communication	QD VCSEL		475
(4) Process service	e-beam litho		1 000
(5) Optical	Diffraction optics		200
(6) Sensors	Superconductors		500
Total		**4 700**	**3 175**

Industrial service

In the four smaller cleanrooms that existed on Chalmers campus before opening the MC2 Process Lab, a certain amount of industrial service was performed. This included the sale of process time in specific equipment, either performed by our own personnel or by industrial representatives themselves. We consider this kind of service to continue and to increase in volume. With increased marketing we set the goal at an income level of 15 MSEK/year to be reached in 5 years.

Products

We believe that it will also be possible to utilize the MC2 Process Lab for making special types of products. This must be high value units with prices above about 10 000 SEK/unit. Series production of low-price products is out of reach and will have no possibility to fit into the pattern of other activities within the centre. After discussions with the senior scientists of MC2, five possible technology areas have crystallized. We put a priority as shown in Table 4 to our list and assume that an income level of 8 MSEK/year is possible after 5 years.

Marketing

With an assumed income distribution as suggested in Fig.5, where the mainpart comes from external sales, it is important to realize that MC2 is a player on a competitive international market. Adapting to the rules of the game in such an environment is necessary and must be dealt with in a professional manner. Active marketing, therefore, is necessary to make the MC2/Chalmers trademark attractive for customers around the world. This kind of activities, which so far have been limited to the Swedish market, will now broaden into an international activity.

Spin-off companies

In recent couple of years, three spin-off companies have started, based on ideas from persons within the centre. The bioelectronics order, mentioned in Table 3 is from one of those companies starting up. Also the other two companies plan for processing activities in the Process Lab and have asked for quotations. In order to lubricate the rise of start-up companies, we are planning to create a fund, owned by venture capital organizations. This may become a central Chalmers fund or it may be a fund specialized in the microtechnology area. In the Fall of 2001 we have been visited by about 10 venture capital firms interested in different parts of the product cycle, from financing early projects in the Process Lab to final stages of the product cycle in start-up companies.

Economic summary: Five-year goals

Inserting assumptions about reasonable steps to reach the goals set for the next five year period, we obtain the data summarized in Table 5 and Figs 6–8 below.

Table 4. Suggested technology areas for production in the MC2 Process Lab

Technology area	Product, application and our possible differentiation	Market guess
(1) Micromechanics directed towards bio-chips	Devices for manipulating living cells. To start with we specialize along the direction of the spin-off company Cellectricon and build on the knowledge of the bioelectronics research group.	The medical market is huge and growing.
(2) Diffractive optics	Diffractive optical elements for use in displays and optical equipment	Small market but few actors
(3) GaN material	Starting material for producing blue/green light emitting diodes and lasers. Based on combined research activities with other Swedish universities, our niche would be in producing a material with superior quality.	Products exist on the market since a couple of years. Starting materials have serious needs for improvement, which fits our competence well. A big market increase is expected in two to four years.
(4) SiC and GaN transistors	Microwave transistors for high power. Mobile communication. Our niche: Higher quality due to high quality research.	Due to the possibilities of increased output power, these transistors will find a market as soon as they reach a final development.
(5) Quantum dot materials and lasers	Starting material for producing lasers with low threshold current and high efficiency for local area networks. Our niche: First on market with high quality material	No products on the market yet. The whole area is in a state of initiation and research. A pronounced market increase may be expected in a five years period.

Fig. 6 Graphical representation of assumed annual development of the six income sources in Table 3

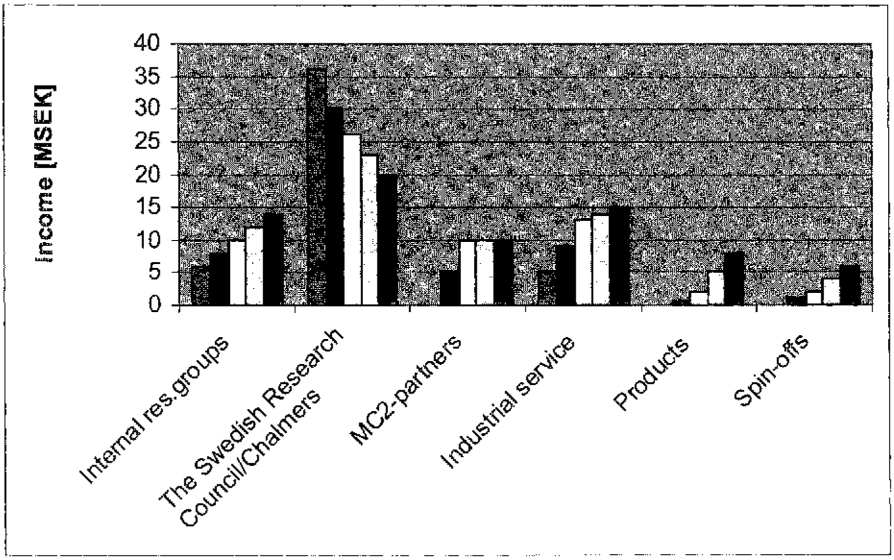
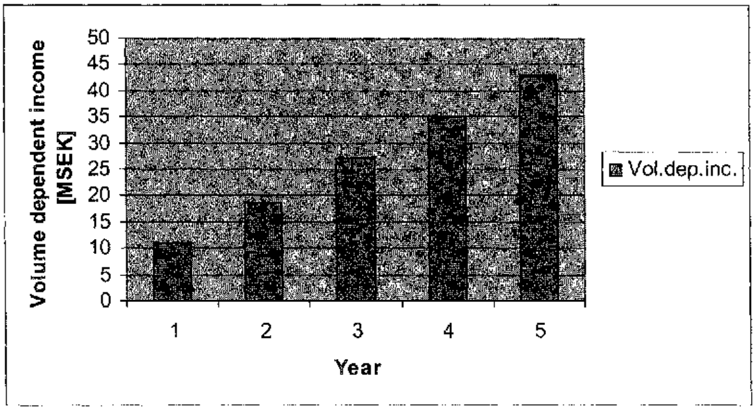


Table 5. Resonable steps for approaching the five-year goals for the different income sources discussed in Section 3. All values in MSEK.

Year	Internal res.groups	The Swedish Research Council/ Chalmers	MC2-Partners	Industrial service	Products	Spin-off service	Total income	Volume dep. inc.
1	6	36	0	5	0	0	47	11
2	8	30	10	9	1	1	59	19
3	10	26	10	13	4	2	65	29
4	12	23	10	14	6	4	69	36
5	14	20	10	15	8	6	73	43

Fig. 7 Distribution of the income sources in Table 3 sorted by year

Fig. 8 Assumed annual volume dependent income (the sum of sales to internal research groups, industrial service, products and spin-off companies)



Strategic measures

The economic five-year goals described in Section 5 can be summarized briefly as:

- total volume dependent income shall increase by a factor of 4
- 75% of volume dependent income is based on external sales
- internal income from research groups shall double.

This change will not happen without:

- strict planning based on strategic and commercial thinking
- efficiently utilizing the skills of all personnel of the centre, scientific as well as technical and administrative
- flexible thinking outside traditional academic tracks

The concrete strategic measures to be taken for the next couple of years would be the following:

1) I order to be able to deliver within the strategic areas stated in Table 4, a number of specially directed competences should be built up in the Process Lab.

Strategic measure: For each of the following areas (a)–(e), at least one process engineer should be allocated and trained:

(a) Bio-MEMS
(b) Diffractive optics
(c) GaN material preparation
(d) High speed transistors
(e) Quantum dot materials and devices

2) One of the most steeply increasing business areas in semiconductors presently is based on GaN materials and the related alloys InGaN and AlGaN. By combining research efforts within the MC2 groups with those of other universities in Sweden, specialized on materials problems, we would be able to build a constellation with a very high international strength serving MC2s design of high power and photonic devices. Discussions have started and a concrete interest for such an activity exists among the research groups. This requires investment in process equipment for epitaxial growth.

Strategic measure: Inspire a research activity between MC2 groups and the groups at other Swedish universities. Invest in MoCVD equipment for GaN preparation.

3) The number of employees in the Process Lab is to be considerably increased within the five-year period. Probably 40 persons are needed in direct processing activities. As a first step, the present crew of 10 process engineers are planned in our budget to be increased by 5 persons within 2002. At some point of time, a couple of years from now, this requires the introduction of double shift work. Due to the difference in salary levels between universities and industry, we recognize problems when reqruiting people of this category.

Strategic measure: Increase salary levels of MC2 Process Lab personnel by at least 15 %.

4) Creating the MC2 Partners group is a subtle task which is planned to be done within the Chalmers Fundraising Campaign.

Strategic measure: Take initiatives within the fundraising project to obtain a powerful activity for attracting the right persons to MC2 Partners.

5) The extraordinary possibilities and goals challenging MC2, as referred to above, demand tools for empowering all personnel such that every individual feels an ownership in the totality of results created by the centre. A necessary requisite therefore is an organizational model for inspiring and educating personnel towards the common and overriding goals and for executing decisions with precision and speed and to adjust the course of MC2 in those directions which are needed for reaching and keeping a front position in a competitive environment.

Strategic measure: Bring the personnel of MC2, presently belonging to the line organizations of the Schools, into one new line organization of the centre.

6) The increased external activities require a pronounced marketing and sales activity. A problem that must be handled carefully is the balance between the internal needs for research related processing in the Process Lab and the external processing for sales. This is further described in Section 6 below.

Strategic measure: Build up a commercial unit in connection with the technological activities of MC2.

7) The competence and equipment present in the MC2 building is expected to be attractive for venture capital. In order to fertilize the growth of start-up

companies with roots in MC2, a special fund, owned by venture capital firms should be established. Further details are discussed in Section 6 below.

Strategic measure: Take action in building up a fund for capitalizing spin-off companies.

Organizing a business and development unit

Changing a university organization with old traditions and habits in the directions suggested in Section 5, Point 5 above is a task that may extend outside the time scale for carrying out the measures suggested in this report. The present organization has a built-in problem due to the separate economies for the Schools and MC2, respectively, and with the Executive Group being more a group of customers than a formal, common steering unit. Due to the necessity of an increasing and economically dominating external activity in the Process Lab, there is an obvious risk that the needs of the research groups will become second priority in such a situation. This can be handled by letting the commercial unit operate outside the MC2 organization to become a separate limited company, owned by Chalmers and eventually the employees. The balance between research and commercial process work can then be controlled by formal agreements between the university and the new company.

On the other hand, for a situation, where all members of the centre belong to one and the same line organization with a formal executive group and with a common economy, there will be easier to handle research vs. commercial balance. For this case, it is everyone's interest to contribute to the same economic result which makes the commercial activity more acceptable from the researcher's point of view. In this situation, the unit is better placed inside the MC2 organization.

The two cases are depicted in Figs 9 and 10, respectively. Arrows symbolize the stream of money. Apart from the status of the commercial unit, the two organizational charts are mainly the same. The commercial "Business & Technology Development" unit should house personnel for professional interaction with industrial customers in marketing, negotiations, sales and delivery.

Figs. 9 and 10 also show the relation between MC2 and the fund planned for supporting the creation of spin-off companies. In such activities, the role of MC2 will just be that of a catalyzer. For practical support to the start-ups, other parts of the Chalmers Innovation System (Chalmers Invest AB, Chalmers Innovation, Chalmers School of Entrepreneurship, Connect Väst AB) will be involved.

Conclusions

With a total of 220 persons populating our new building, a cleanroom area of 1240 sqm and superior equipment, MC2 is in a starting position with outstanding possibilities. Our way of acting at this moment will have a decisive influence on our future among similar competing establishments. Some of the measures proposed in this report require a great deal of initiative, uncommon in the university environment. However, we have just started an activity with big investments from a platform that was pulled away from under our feet. This forces us to transit a road of our own construction to pass economic break-even. That challenging journey will certainly shape up and further strengthen the competitive power of MC2.

Fig. 9 The organization of MC2 for a case where the line organization of the research groups is part of the schools

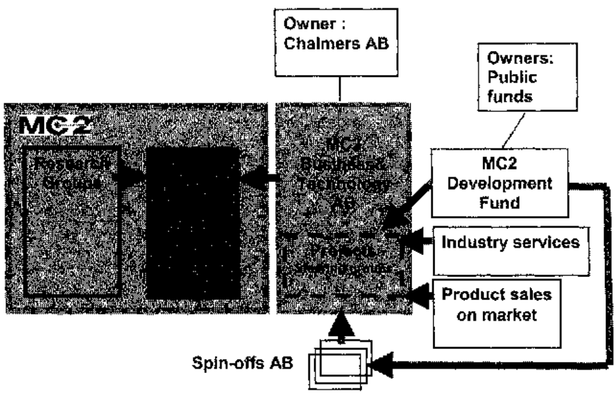
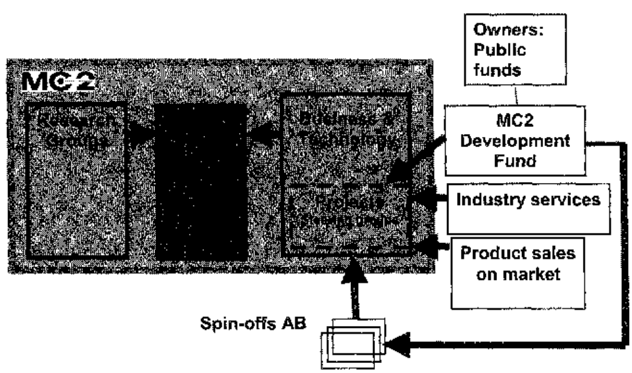


Fig. 10 The organization of MC2 for a case where the centre has its own line-organization separate from the schools



Appendix 6

The SPIN Document

Agreement on founding a Swedish Microtechnology Process Integration Network (SPIN)

The following document, which has been translated from Swedish, is an agreement including the basis for founding a network between the process laboratories in Uppsala, at KTH and at Chalmers. The Swedish version was signed in September 2000 by the presidents of the three universities: Bo Sundqvist, Anders Flodström and Jan-Eric Sundgren.

Translated from Swedish:

2000-08-22

SPIN

(Swedish Microtechnology Process Integration Network)

This document is the basis for co-operation between the three larger process laboratories in microtechnology at KTH, Chalmers and Uppsala University. The aim is to start a network, "Swedish Microtechnology Process Integration Network" (SPIN), between these laboratories in order to utilize big investments more efficiently by co-ordination.

Background

In recent decades, information technology has given rise to completely new conditions for industrial activity and has created a market for electronic equipment increasing by 10–30 percent per year. This development is based on integrated circuits and devices, mainly built on semiconductors. For silicon technology, which by volume dominates all IT systems, the market has increased by 15% per year since 1970. For other markets, photonic devices and high speed devices, even if their share of the total semiconductor market is considerably smaller, they have a decisive strategic importance for the properties of the systems. The whole area is still in an unretarded technical development and no ending can be seen on the exponential development of technology and performance.

From international point of view, Swedish microtechnology is presently establishing strength in a number of important niches. Mature industry, like Ericsson Microelectronics and Mitel Semiconductor together with a number of companies with roots in the research of the eighties and nineties (Altitun, Optronics, Radi Medical, FLIR a.o.) are presently in a powerful phase of expansion with large investment programs (hundreds of MSEK) and a fast increasing turnover. The importance of this potential for Swedish industry in microtechnology has also been observed by, among others, NUTEK that has suggested a "National Strategy for Microelectronics". Furthemore, through ISA, Microbind (Göteborg/Uddevalla) and other similar initiatives, work is going on for international investments in Sweden within this area.

For an industrial nation like Sweden it would be natural to invest for building up competence within such areas that have a fast growth of knowledge and market. Even if the share of Swedish gross national product allocated for R&D is one of the highest in the world, it is important to keep in mind that the absolute value is small from an international perspective. This means that we are always forced into an act of balance between the geographic distribution of resources and the needs of critical concentration. For cases where research requires big resources, the problem is especially pronounced. Therefore, investment in microtechnology research in Sweden has often been accompanied by priority problems.

The situation in Sweden

Measured per capita, Sweden has a strong research activity in microelectronics. Presently, investments are done that will have great influence on our possibilities to keep such a position in the future. In the last decade, KTH has been running a process laboratory of broad international top class with device tehnology in photonics, integrated circuits in silicon, micromechanics and power devices. Since a couple of years, there is a new laboratory at the Uppsala University directed towards microtechnology processes. At Chalmers today, four smaller laboratories are spread across its campus and at the beginning of 2001 the university will open a new process laboratory of highest internationall class for a powerful combination between electronic materials physics and microtechnology. A natural question is whether this total national investment corresponds to a real need. The answer should be given while taking into account predicted development of this technological field: In order to secure knowledge for Sweden in an area which has developed with unchanged acceleration for many decades, it is important to invest in such basic activities which provide and renew competence necessary for future industrial efforts.

For future Swedish research in microtechnology we believe that international competitional power can be obtained only by a a far-reaching industrial and academic co-operation in order to utilize big investments. Beside considerable investment in specific equipment, a driving force is investment in know-how and production experience. Placing multiple versions of expensive, heavy and not fully booked equipment at a number of laboratories would be particularly inefficient. Therefore, it is very important to distribute special type of equipment in an optimal manner and to co-ordinate its use.

Object

The idea of SPIN is:

- to co-ordinate the need of new, very expensive (>5 MSEK) equipment in order to strengthen the technological profile of each university and to avoid unnecessary multi-investments
- to increase common use of expensive process equipment between KTH, Chalmers and Uppsala University
- to offer universities outside the SPIN initiative the possibilities to use resources inside SPIN, not only within the area of microelectronics, but also within adjacent areas like medical and bio-technology.

SPIN will cover a broad spectrum of processes, from standard CMOS and bipolar processes to sophisticated process steps for microelectronics of tomorrow. In addition flexible processes for microstructure technology will be offered. This arrangement will ensure a geographically independent accessibility to a wide menu of processes.

Organization

In order to achieve the possibilities diescribed above, we will create a simple organization for the network with the following task:

- to prepare and co-ordinate proposals for the funding of expensive equipment with a purchase value higher than 5 MSEK.
- to create rules for common use of equipment
- to create rutines for fast communication and process service between the three units
- to make common proposals for the financing of improved process service

The activity shall be led by a board of three senior representatives on a level corresponding to Dean/Lab Board and with the three laboratory managers as operative parties. The chairman of the SPIN board should not have any preferential connection with any of the three universities. Initially the board has the following members:

Olof Engström, Chalmers
Gunnar Landgren, KTH
Sören Berg, Uppsala University
and
Sten Norrman, Chalmers
Nils Nordell, KTH
Jörgen Olsson, Uppsala University

As chairman of the board, we suggest
Olle Nilsson, earlier professor at KTH and Chalmers.

The board shall have meetings at least four times per year.

Existing co-operation

It is worth mentioning that co-operation and certan specialization of competence already exists together with a certain exchange of services. However, we believe that there is a considerable potential for increasing this kind of contacts. Examples of the existing distribution of process competence is the following:

- Electron beam lithography – Chalmers
- Molecular beam lithography – Chalmers
- CVD/VPE-technology – KTH
- Stepper lithography – KTH
- CMP – Uppsala University
- Laser lihography – Uppsala University

Also far reaching common project activities are going on within research programs in:

- Photonics
- High speed devices
- Silicon technology
- Micromechanics
- Quantum devices

These programs have a total economy of about 50 MSEK per year. In addition, there exist a number of smaller and informal co-operations. SPIN intends to strengthen and continue this kind of projects.

Process service exchange

In order to create a better economic base for research projects within SPIN, the activity needs to be funded. The contribution needed to realize the potential of SPIN is estimated to about 6 MSEK per laboratory and year, totally 18 MSEK per year. These recources shall be used to guarantee the accessibility to equipment and competent personnel for process service to the respective SPIN partners or for supervising personnel from universities outside SPIN. This funding should be transferred to SPIN annually with follow-up and correction depending on the extent of co-operation.

Conclusion

This agreement shall be understood as a distinct intention to a gradually increasing co-operation. Hence, its accomplishment is not depending on or connected with any singular activity or proposal. For proposals to public and ideal financing institutions, this document will be enclosed by all research groups included in SPIN.

Jan-Eric Sundgren	Anders Flodström	Bo Sundqvist
Chalmers	KTH	Uppsala Universitet

Appendix 7

Funding from KAW, VINNOVA, SSF and the Swedish Research Council

Overview of microelectronics R&D funding in Sweden

In Sweden, build-up of serious R&D capability within universities and institutes was initiated around 1980. The initiator was VINNOVA's predecessor STU (Swedish National Board for Technical Development). The total level of funding increased from around 5 MSEK to around 40 MSEK in three years. At that time there were only two small university labs and two small semiconductor manufacturers, RIFA (Ericsson) and ASEA-Hafo. STU designed, and the government launched in 1984, a larger programme: the National Microelectronics Programme (NMP) with a total level of approximately 530 MSEK million in 4 years. This programme consisted of four parts:

NMP1: Education in circuit design (UHÄ, 13 MSEK)
NMP2: Basic research in semiconductor technology (NFR, 40 MSEK)
NMP3: Applied research in components technologies (STU, 179 MSEK)
NMP4: Industrial developments, cooperative projects (STU, FMV, Televerket, ÖCB, 141 MSEK and 50% industry, 133 MSEK).

A result of these programmes was that small clean room facilities at the five major universities (KTH, CTH, LiU, LU and UU) were strengthened and that the Kista lab was built. Preliminary discussions concerning an integration of the small clean rooms of the Physics Department and Electronics and Computer Science Department of Chalmers were started.

Two years later (1986) another, systems-oriented, programme was launched, called the National IT-programme. This had a total size of around 1 400 MSEK for 4.5 years. This programme consisted of two parts:

IT3: Continuation of STU's programme (approximately 286 MSEK)
IT4: Industrial consortia (STU, FMV, Televerket, ÖCB, 495 MSEK and 50% industry, 600 MSEK). In reality it included a considerable proportion of semiconductor process technology (photonics and power electronics).

These programmes ended after approximately 4 years, with a return to a lower level of funding. In 1990–91 there was a new increase in funding (around

50 MSEK) of applied research in microelectronics, with industrial project co-ordination (consortia), almost at the same time as NUTEK was created out of STU and two other agencies. In 1995 the new research foundations, the Swedish Foundation for Strategic Research, SSF, and the Knowledge Foundation, KK-foundation, were created. In principle the foundations would contribute substantially to the funding of applied research and particularly to microelectronics. A correspondingly large part of the budgets for NUTEK and the research councils (NFR, TFR, MFR) was withdrawn by the government, so there has been no net increase in the funding in the last decade. The total public funding of microelectronics and information technology has grown from around 220 MSEK/year to around 300 MSEK/year from 1990 to 2000.

There has, however, been considerable government and other public funding of new clean room laboratories during the period: Linköping (IFM Department), Ångström Lab in Uppsala, ACREO AB in Norrköping, MC2 in Göteborg, and recently at Mitthögskolan in Sundsvall and Östersund (EU funding).

Scientific equipment from KAW

Since 1996 the Wallenberg Foundation has given major donations for equipment. Thus KTH has received 55 MSEK, the Ångström Lab 62 MSEK, and the MC2 lab 90 MSEK.

Research in microelectronics financed by the Swedish Foundation for Strategic Research

The Swedish Foundation for Strategic Research has financed a number of research programmes in microelectronics since 1999. The budgets of the research programmes have been at the same level during the years 1999 to 2002. They are shown in the table below.

In 2003 new programmes will start. The amounts allocated to different research areas are not yet determined, as the decisions on the new programmes will be taken during the autumn of 2002.

A reduction of the allocations from SSF will decrease considerably.

Research financed by the Swedish Research Council

The Swedish Research Council funds basic research of high quality. The funding for the research that at present utilizes clean room facilities is predominantly project support. A typical project runs for three years and has a funding of 650 kSEK per year, university administrative costs included. In most cases the major part of the project funding will cover the salary for a PhD student.

The total funding from the Swedish Research Council to clean-room-rele-

Financing of research in microelectronics/year 2001

Building practice	10
Photonics	29
High-speed electronics	16
System design	27
Microsystems	15
Nanotechnology	18
Silicon	15
Silicon carbide	16
	Sum 146

Financing of research in microelectronics/year 2003

Strategic research centres	50
Framework grants	28
Silicon programme	10
Microsystems	13
	Sum 101

vant projects is approx. 35 MSEK for 2002. This sum is likely to increase by a few MSEK during the coming two years due to additional support from the government to basic research in IT.

Research in microelectronics financed by VINNOVA

At present VINNOVA is planning a national strategy for the IT and electronics industry, with a particular emphasis on R&D for producibility. This strategy will include a substantial rise in funding for microelectronics, which after a 5-year build-up would be expected to reach a level of 500 MSEK per year above the present level plus industrial financing. The strategy is intended to have a 10-year perspective. Essential parts of the strategy are focusing and profiling on the national level and strengthening of selected technology areas, as well as attending to factors that influence the efficiency of the R&D system. The suggested strategy is intended to be presented to the government in June 2002.

Appendix 8

Performance criteria for centres

Performance criteria for centres

This appendix defines the performance criteria used to assess the efficacy of each individual participating facility that is a member of the Network. The Appendix also provides an outline for judging the efficacy of the Network as a whole. It is proposed that the metrics outlined below be collected and reviewed every six months. Every twelve months these metrics would then be used to distribute the 5 MSEK available annually to encourage effective resource-sharing. At the end of the fourth year, performance as judged by these metrics would determine whether the Network or individual facilities are to be continued after the fifth year.

The metrics to be used to assess performance are listed below. A number of terms are used in these. The suggested definitions for these terms are stated below.

In the case of each participating facility, it is suggested that its effectiveness in fulfilling its role be judged on the basis of the following criteria:

(1) Performance in the Specific Facility Utilization per Year
(2) Performance in the Facility R&D Utilization per Year
(3) Performance in the Facility Educational Utilization per Year
(4) Performance in the User Satisfaction Report
(5) Effectiveness in Attracting New Users.

The effectiveness of the Network in fulfilling its role will be judged on the basis of the following criteria:

(1) Performance in Total Network R&D Utilization per Year
(2) Performance in Total Network Educational Utilization per Year
(3) Overall Performance in the User Satisfaction Reports
(4) Effectiveness in Attracting New Users to the Network
(5) International R&D Users per Year.

The definitions used in these metric categories are as follows:

Facility Specialization: scientific and technological areas which are the responsibility of a specific facility, as established by the Swedish Research Council.

Potential R&D User: any person with R&D funding support from a government agency, foundation, university, or industry who requires micro- or nanotechnology processing or characterization equipment to carry out his or her work.

R&D User Application: form to be filled out by a potential R&D user at all facilities, stating use objective, tool set requirements, staff support needs, and use-time requirements. A user with multiple projects must fill out a form for each. The User Application must show whether the facility is to be used for the Facility Specialization or not.

Distinct R&D User: to be counted as an R&D user of a specific facility in an established reporting year, an individual must have utilized the facility for a minimum of 10 hours in the established reporting year. An R&D user may be a distinct user at multiple facilities.

Facility R&D Utilization per Year: number of distinct users in a facility in an established reporting year.

Facility Specialization Utilization per Year: number of distinct users in a facility working in the Facility Specialization in an established reporting year.

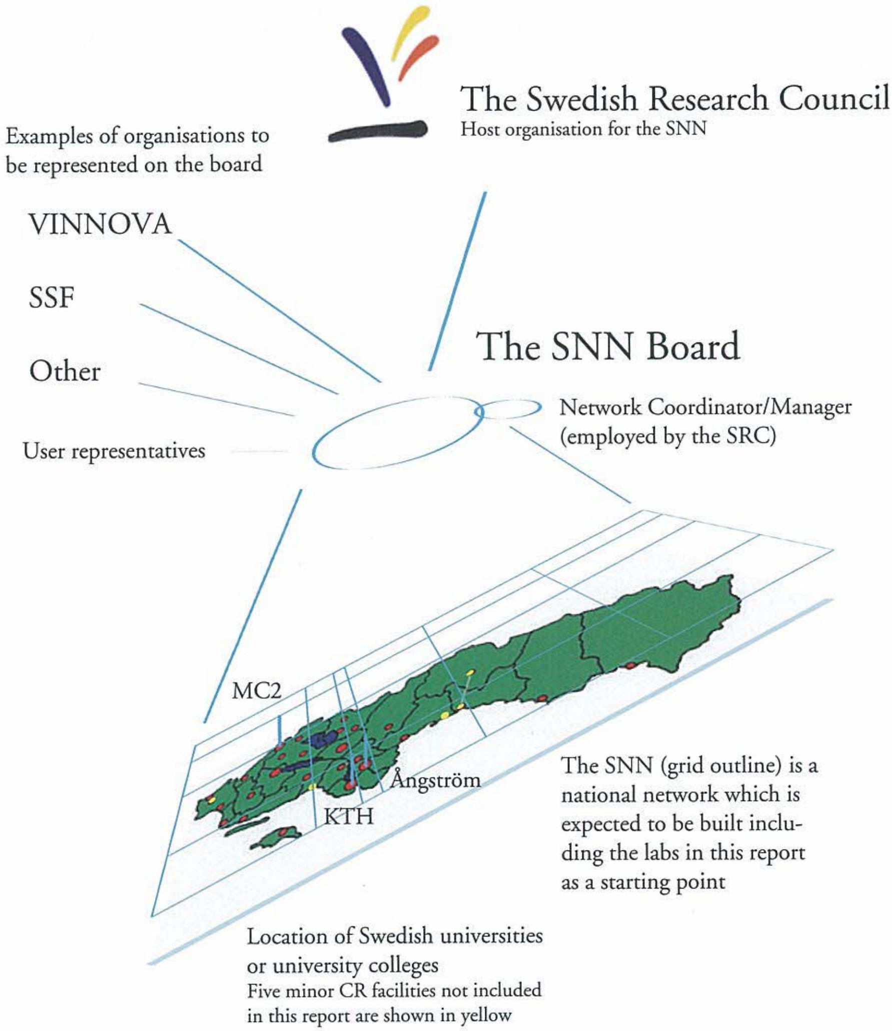
New User: an individual who has never before utilized micro- or nanofabrication, attracted to a facility in a reporting year.

Facility Educational Utilization: a criterion composed of three parts—(1) number of educational institutions using a facility for course support, (2) number of courses supported, and (3) number of students in these courses.

User Satisfaction Report: a standardized survey used at all facilities to measure user assessment of equipment availability, equipment status, and staff assistance. This survey is to be conducted each quarter at each facility.

Appendix 9

Swedish Nanotechnology Network (SNN) – Outline of Organization



Three major academic laboratories

The quality and future potential of three major academic semiconductor laboratories in Sweden—the Semiconductor Laboratory (the Royal Institute of Technology), the Ångström Laboratory (Uppsala University) and MC2 (Chalmers University of Technology)—are evaluated here. These laboratories are important for research and education in microelectronics, the field that underlies modern information technology. Because of ongoing rapid shifts in science and technology, the report also presents a broader perspective which emphasises microtechnology in general and the emerging nanotechnology. International comparisons are made and the role of the laboratories for academia and industry is assessed.

The three laboratories represent considerable investments in buildings and advanced scientific equipment with substantial running costs. The report suggests how the three laboratories should specialise in different areas and coordinate their activities to ensure efficient use of resources. Furthermore it is proposed that a Swedish Nanotechnology Network (SNN) be created. SNN will have the responsibility of serving academic research and industrial R&D on a national basis.

The Swedish Research Council, together with the Swedish Agency for Innovation Systems (VINNOVA), has appointed a committee of experts to perform the evaluation. The members of the committee were Klas-Håkan Eklund (Eklund Innovation, Sweden), Stephen Fonash (Penn State University, USA), Jørn Hvam (Technical University of Denmark) and Herman Maes (Interuniversity MicroElectronics Center, Belgium), with Karl-Fredrik Berggren (Linköping University, Sweden) as chairman.

The Swedish Research Council has a national responsibility for the development of Swedish basic research and information about research. The Council prioritises and finances basic research of the highest scientific quality in all fields of science. The goal is to ensure that Sweden holds a leading position as a nation engaged in research.

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