MICRO STRUCTURE BULLETIN

Newsletter for Nordic Micro Structure Technology, Vol.7, 99:4–00:2, Nov 1999

25th MSB

This is the 25th and last *Micro Structure Bulletin* (*MSB*) for this millenium. It is a suitable chance to offer the readers some extra reading. As always, the spirit of *MSB* is to set the readers in focus.

Six years has passed since the idea of national MST-newsletters emerged during a wine tasting reception at the *MME* conference in Neuchâtel, Switzerland. The idea was so attractive that the next day at the Nexus General Assembly I dared to announce Sweden's intention and suggested that other nations follow. Three months later, *MSB 93:1* reached the readers.

MSB was initially targeted only at Sweden. After the first year *MSB* was extended to the Nordic region. In 1998, the Editorial Board was extended to better emphasize the Nordic sphere of interest.

More came out of the Neuchâtel-visit. As MST was maturing at several locations it felt important to gather people together, and the first *Micro Structure Workshop* (*MSW '94*) was held half a year later (repeated in 96 and 98). An intended biennial course-series (*MSK*) was also introduced, but only *MSK '95* could be held due to the difficulty of finding lecturers.

My target was to create media based on how I would like to receive information myself. This is a tough criterion since I seldom read general information sent to me, and immediately throw away or return mail that has an advertisement purpose, whether obvious or subtle. Most important has been the well-received neutrality and objectivity, implying that the key players behind *MSB/K/W* should not themselves be active or have commercial interests in the MST-area. Your comments support that a fundamental reason for *MSB*'s success is that Colibri fulfills this requirement.

Other important, but not easily combined, key-terms include: quality, professionalism, locally rooted, an informal personal touch, and forum-based instead of a cobweb. The target is to also reach those only peripherally interested in MST.

MSB/K/W have been commented in very positive terms. There was basically only one exception, an author was upset that his project did not get the space it 'deserved'. However, *MSB*'s main loyalty is to the readers, not to the authors.

Although being a very time-consuming and expensive hobby, it has been fun promoting the MST area. Now it is time for me to move on and focus more on Colibri's core business. *MSB* will have a 'time-out' during at least the first half of next year. This will be a test on how full-fledged Nordic MST is, and if *MSB/K/W* still are needed.

Jan Söderkvist, initiator and coordinator of MSB/K/W

MSB's *first issue published in December 1993.*

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EDITOR'S NOTE

First, I would like to express my thanks to the team that has made *MSB* possible. Knowing that my weak point is my memory, I prefer to not mention anyone specific.

It has been difficult to identify a Nordic long-term alternative that can strengthen and evolve the *MSB* concept without jeopardizing the well-received neutrality and objectivity. It has felt essential to look for solutions in which *MSB*, *MSK* and *MSW* are part of a larger scheme for technology promotion, and that are based on the same criteria that have created the spirit of *MSB*, some of which are listed on the front page.

MSB/K/W has been difficult to combine with Colibri's core business of system-level, dimensional-independent troubleshooting. Time has come to accept the consequences. I sincerely apologize that this will affect the future of *MSB/K/W* in a negative way. I hope that you understand and respect my decision although I am certain that some of you would have liked the outcome to be different.

Best wishes for pleasant Christmas reading, and *a Happy New Millenium*.

Building Awareness

One question has turned out to be fundamental when looking into *MSB*'s future: *On a national and Nordic level, who should be responsible for promoting the industrial awareness and development of a new technical area?*

Conflicting Dilemma

Traditional organizations have limitations when it comes to being unbiased at providing advice regarding new technologies. For example:

- No industry in the Nordic region has such a position that they can afford taking a very broad external perspective on MST.
- Universities' priority should be high-quality students, publications and theses. They are not always updated on the industrial status, and are less inclined towards external activities and tough deadlines.
- Research institutes are well suited for supporting projects and for creating the fundamental toolbox. However, when promoting a new technical area they often encounter the conflicting nature of objectivity and promoting their own organization.

It is best when customers are recommended optimal, 'low'-risk solutions, which often means conventional, 'low'-tech approaches and traditional subcontractors. This slows down the creation of competence at research institutes, which hinders one of their main purposes – to provide competence to industry. A conclusion is that research institutes must, per definition, be somewhat unbiased in their recommendations in order to advance their own competence. Although most likely favorable on a long-term, national perspective, this might involve 'sacrificing' individual projects and ideas along the road.

Need for Unbiased Info

I am often involved in critical phases of projects where unbiased information is of utmost essence. I routinely avoid information sources for which I cannot rule out that they primarily try to promote their own activities. I have met research institutes that offer to take over project-leadership with the sole objective to increase their own competence, despite that the project's market window and cost-pressure did not allow for such a learning-phase.

Many companies hesitate looking into the possibilities of new technologies. To form their own opinion they need sources of broad, impartial and realistic advice and information. Credibility is reached best if the sources themselves do not have interests in the technology. *MSB/W/K* has tried to fill this need for the MST-area.

Dedicated Individuals

An alternative to industry, research institutes and universities is to focus on individuals. In fact, it is essential to use dedicated persons if these tasks are to be handled efficiently. Unfortunately, it is difficult to find an individual that is updated on both the industrial and academic status, and that has sufficient spare time to 'sacrifice'.

A larger obstacle is the limited possibility to pay the dedicated individual anything but a symbolic compensation. This is especially difficult if the neutrality requirement is stressed since it will rule out his/her employer as a financier as these activities then clearly fall outside their business focus. Note that this type of information dissemination ought to be free of charge in order to reach a larger sphere, and advertisement can only be a small source of income. An undesired consequence is that the promotion mission most likely ends up as a costly and time-consuming hobby.

Where to Go?

Promoting the awareness of important new technical areas is of national and regional interest and should be handled accordingly. As it appears that most existing organizations focus at positioning themselves, there is a need for an inter-organization force. This stresses the importance of national strategies and resources. *Where do we wish to be five years from now?*

A natural suggestion is to handle the early stages of technology awareness promotion with a small group of very skilled generalists not connected with existing organizations, commissioned by and reporting to a national (or Nordic) authority. Such a group can handle several technology areas, and also advanced troubleshooting if needed. It should complement and pave the ground for industry and research institutes, and should not target at expanding or in any other way lose its neutrality and objectivity.

Jan Söderkvist

Statistics for MSB / MSK / MSW

My initial plan was a photocopied newsletter with at most 400 subscribers. Today, the mailing list contains three times as many individuals that actively have asked to receive *MSB*. A policy has been to not market *MSB* outside the Nordic region. Each issue is printed in 2,000 copies. *MSB 99:3* was distributed as follows:

741	to Sweden
99	to Denmark
98	to Finland
79	to Norway
138	to the rest of Europe
23	to the rest of the world

Copies are also distributed at various activities in-between the main mailings, and to authors, editors, supporting organizations, etc. The Swedish subscribers are split as follows:

58%	industry (223 locations)
21%	university
5%	research institutes
3%	hospitals
3%	governmental org.
3%	journalists
7%	private addresses

The original plan for *MSW* of a half-day informal gathering rapidly grew into a two-day activity. Statistics for *MSK* and *MSW* are (industrial percentage within parenthesis):

MSK '95: 52 attendees (44%)

MSW '94: 70 attendees (36%)
MSW '96: 81 attendees (37%)
MSW '98: 117 attendees (41%)

Jan Söderkvist

MicroSystem Technology

Are we not all fascinated by the craftsmanship of the Swiss watchmakers with their high precision mechanical systems so small that magnifiers are needed during assembly? Now, there is a need for even smaller devices, e.g. in consumer, industrial, IT and medical applications.

The wonders of microprocessors constantly change daily life, with products such as microwave ovens and computers. To function as desired they need information from their surroundings. Only recently, partly due to the evolution of micromachining, has it become economically feasible to include sensors in these products.

The MST Community

The technology push for MST is now complemented by a market pull. Many companies involved in MST are found in the U.S.A. and Japan. Dominating the rapidly expanding MST activity in Europe are Germany, France and the U.K.

A specialized sensor industry consisting of SMEs has evolved. Also, a few large companies in the semiconductor and automotive areas have launched product series based on their own MST activities.

Micromachining

The production technology behind MST, micromachining, is based on processes originating from the semiconductor industry. Typical devices have features smaller than feasible by traditional manufacturing, with dimensions measured in micrometers, sometimes in nanometers, and rarely in millimeters. Apart from the more advanced process steps, such as integrating electronics on the sensor chip (one-chip solutions), the technology today is sufficiently mature to slowly become industry driven.

Micromachining comes in two varieties, bulk and surface micromachining (BM and SM). Both date back to the 1960's, but the toolbox for SM has been more complicated to create and has taken longer to mature into commercial usage. BM tailors the substrate wafer itself into the desired geometric shape, while SM forms the desired structure via depositing and etching of thin layers on one side of the wafer. The material selectivity during etching is essential for SM in the same way as BM relies on the anisotropy of the etching.

Processing Steps

The fabrication of fully three-dimensional microscopic structures includes processes such as etching, deposition and bonding, all originating from the semiconductor industry. Recently, the borderline to neighboring production technologies has become diffuse as several processes used in precision mechanics have been modified to suit MST.

The dependence of the etch rate on the etch direction offers an excellent method for detailed tailoring. Sacrificial layer etching and etch-stop techniques add flexibility, enabling free-floating structures and membranes. Joining methods, e.g. bonding, facilitate features such as cavities and packaging of sensor chips.

MST Materials

Silicon is the most frequently used material in MST. Here, deflections are often detected capacitively or piezoresistively, and movements often excited electrostatically, thermally or magnetically. Although not always the best choice, silicon is a general and flexible material that can be used for a large number of components. This has made silicon the favorite for some large companies focused on a broad range of MST-based products, which has influenced universities and financiers to focus less on alternative materials. The investment in know-how and production equipment creates an inertia similar to that when silicon became the favorite for semiconductors.

Quartz has found its own niche in frequency applications where its piezoelectric effect, inertness and temperature stability make it the unsurpassed choice. The most successful micromachined product, all categories, is the quartz watch crystal. It is manufactured in six-digit quantities each hour, at a very low cost.

Other very promising materials are being explored for MST, such as metals, polymers and diamond. Here, we have only seen the tip of the iceberg (see pages 16 and 20).

Conclusion

While the last decade can be defined as the Decade of *Microelectronics*, there are signs that the Decade of *Microsystems* soon might come.

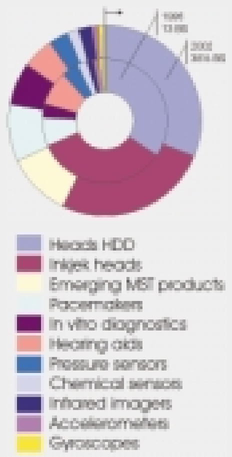
(Based on MSB*'s very first article in 1993)*

Jan Söderkvist

This micromachined quartz angular rate sensor from Temic (and Colibri) will function as the heart of vehicle dynamic control systems. Typical is that the micromachined part forms only a small part of the MST-based system (courtesy of Temic, Germany).

This 0.89 mm long M0.18 screw (pitch and width of slot: 0.05 mm) is mass-produced with high precision machining at a very low cost. It illustrates the diffuse borderline between precision mechanics and MST (courtesy of Björkgren Mekanik AB, Sweden).

MST Markets



Market forecast made by NEXUS in 1998 (see *MSB 98:4* and NEXUS website).

When MST?

Is MST useful? Check if your company wishes to:

- miniaturize existing systems
- increase reproducibility or robustness
- optimize performance or add new functionality
- reduce system-costs for high-volume applications
- minimize energy, sample or resource consumption
- acquire new strategic competence areas

False Hopes for MST's Industrialization?

Hopes for a MicroSystem Technology (MST) revolution are high, but reality does not match the expectations.

A different perspective to that presented on the next page could be that those involved in the early days of MST erroneously focused on the *technology* and on *MST-based companies* when presenting MST.

I will try to elaborate on this. My viewpoints are based on my contacts with *MSB*'s readers, my experience from interdisciplinary consulting since the mid-80's, and from having performed research in two different fields at two universities.

Cultural Clash Delays MST

In marketing, one must know the target group: Buyers seek functionality, reliability and price more than production techniques. Suppliers aim for simple, low-risk, high-yield solutions. Researchers look for challenging, publishable topics more than system aspects, and are often amazed by the simplicity of successful products ('old-fashion' technologies and designs have a surprisingly strong ability to survive).

This highlights the always-present cultural clash between academy and industry: "*A good scientist is a person with original ideas. A good engineer is a person that works with as few original ideas as possible*" (Freeman Dyson). Tailor MST-presentation accordingly.

One of universities' responsibilities is to share its know-how. Unfortunately, it is easier to present information based on one's own experience than at adapting it to the listeners. To succeed one must use industry's own terms when addressing industry, and vice versa ("*When in Rome, do as the Romans*").

Fear of Entrance

At the end of a project one often says 'If we had known of all the trouble we had to face, we never would have started the project'. A conclusion is: 'telling too much too early might hinder good ideas from being tested'.

Many 'outsiders' assume that the entrance fee in know-how is high, and that they need their own production facility. Here, it is important to present the pros and cons relative to conventional production methods instead of the details of the technology. MST is just one of many production methods and should be treated as such.

MST-Based Companies?

Is Autoliv MST-based considering their automotive safety products that rely on microcomponents? Has Analog Devices turned MST-based with its one-chip accelerometers?

The answer is subjective. 'MST' was originally defined via its underlying production technology, micromachining. 'MST-based' companies are even today often associated with production possibilities. Thus, not many companies are, or will be, MST-based despite high hopes in this direction.

A comparison: Most companies use electronics in their products but very few are called 'microelectronic companies', not even those using ASICs. Lessons learned include that the number of companies that can benefit from MST is huge, that the number of companies profiting from micromachining-based production is small, that 'design houses' will be the link to production facilities, and that it suffices with a cursory knowledge of micromachining since the competitive edge comes from the system level. The same conclusions can be drawn by comparing MST with precision mechanics.

In the diversified MST-arena, the term 'MST-based' ought to be replaced by application-oriented sub-fields, such as µ-biotechnology, µ-chemistry, µ-fluidics, µ-optics, µ-mechanics, etc., each with its own requirements on MST.

Application-Focus is the Key

There are three types of MST-related organizations:

Production and equipment providers: Newcomers will be few due to the large investment-requirement. Most survivors from MST's early days have allayed with application-oriented companies as the technology itself did not provide a healthy business foundation. The trend is towards foundry services.

Support providers: These will grow as production providers become fewer and stronger. New 'fab-less' MST-design houses will appear.

Application-focused users: National efforts spent on promoting MST can be expected to have the largest effect on this group, and especially on SMEs. Their growth potential is much higher than that of technology-focused spin-off companies lacking the application foundation. Larger companies are harder to 'push' new technology upon.

Industry-Academic Mix

There are some striking differences in the Nordic region.

Finland and Norway are both world-leading producers of micro-accelerometers, despite that their universities previously were weak on MST. Strong industrial-oriented research institutes has compensated for this.

Denmark started out with MST by creating a research institute with the important mission to promote SMEs. Industrial companies are often project leaders in collaboration projects.

Sweden is organized differently with a strong university-based platform, but with a weaker industrial MST-side.

The competence-base provided by universities is essential. Nevertheless, creating a too strong university-base too early involves the risk of suffocating and delaying the industrialization, since awareness programs run the risk of not addressing topics important to industry, system aspects might be overlooked as these could lead to solutions outside the researchers' own field of interest, and project leadership will come from universities.

A lesson learned is that a well-balanced mix between industry, research institutes and universities is essential. To compensate for the apparent imbalance, *MSB* has for the last two years worked on further strengthening its industrial base at the expense of its academic base, both regarding articles and organization.

A Stronger Nordic Position?

The large difference in organization between our countries means that a closer Nordic collaboration would benefit our region. A Nordic strategy could involve more efficient coordination of actions, stimulation of Nordic industry-academic collaborations, strengthened information spreading, joint research programs, etc. The Nordic region will be competitive only in a very limited number of cases if this natural step is not taken.

It is important to also recognize that many of the success stories for MST have started as, or via, SMEs, catalyzed by a competent, industrial 'daredevil' with visions, intuition and entrepreneurship.

Some Proposed Actions

The following is an incomplete list of items I think might lubricate the industrial use of MST:

- Mentor-programs for industrialization and for MST.
- Industrial advisory board.
- Industrial leaderchip in collaboration projects.
- Map suitable applications.
- Information channels/forums.
- "When in Rome …"
- Long-term industrial awareness programs for those not knowledgeable about MST.
- Incitements to first-time users and to those exploring MST's possibilities via pre-studies (simular to FUSE).
- Possibility for persons with industrial experience to take a sabbatical in academia.

In short, there is a need for a strategy, and for a plan for how to reach the targets.

MST is Not a Necessity – it is an Opportunity

MST has come to stay. It is just a question of how fast it will evolve. Do we wish to grab the opportunity?

Suitable for the Nordic region is that MST often involves niche markets where relatively small application and market focused industrial players can thrive, if they have the right product at the right time and at the right price.

Jan Söderkvist

Industrialization Takes Time

History always has important lessons to teach us, such as: 'Industrialization takes longer than expected and is taken in well-defined steps'.

1st Wave – Pioneers

Researchers showed early that micromachining had an industrial potential via cost and added functionality. Several companies popped up dedicated at mass-producing a few 'simple' components, typically pressure sensors (medical applications) and accelerometers (automobiles). The initial success of these companies created major hopes for MST's future. Some predicted that MST rapidly would become more important than microelectronics.

However, not much happened in the decade(s) thereafter. Accelerometers and pressure sensors still dominated the MST-market in 1994. The original companies did not seem capable of opening up new markets or application areas. Possible explanations could be that the market was not yet ready for MST or that the technology was not sufficiently mature.

2nd Waves – Optimists

New spin-off companies from universities came hoping for opportunities to provide support to the industrial MST growth. However, they too were not able to increase MST's rate of growth. Obviously, some ingredient was missing.

Most initiatives so far originated from academia and were focused on the technology. The cultural difference between academy and industry created many situations where universities did not realize why industry was indifferent to the sensor designs offered to them. To gain industrial success one needs detailed knowledge of the application, system and market. As disappointing as it might be, it is seldom the best technical solution that wins the battle for market share.

3rd Waves – Slow-Starters

Slowly, in the background another force began to pick up momentum. A few large microelectronics companies, such as Analog Devices (ADI), Bosch and Motorola, decided that the timing was right to test micromachining-based production. Most notably are ADI's one-chip accelerometers. Their success had a great PR impact on those unfamiliar with MST, but was achieved via very resource consuming R&D. These companies could afford projects with a long payback time, they had application experience, and they had formed marketing strategies while observing the area. In short, they were well prepared. It is like Microsoft and their internet browser – let other companies take the first blow and move in with force and low risk when the timing is right.

Also, some of the MST dedicated companies from the first wave had survived, often via strong alliances with their customers. They were fortunate to have entered the MST arena when 'rudimentary' designs were accepted and economical margins were larger. Much experience was gained the hard way in a manner not possible in today's maturing MST arena. Key people from the early days are today technology leaders.

4th Wave – Application Focus

The previous waves created the necessary infrastructure for a grand fourth wave triggered by application focused companies entering the arena. For them, micromachining is just one of many competing production technologies that will be used only if its advantages clearly surpasses its risks and costs.

Application focused SMEs are often dynamic and keen on seeking information and evaluating new technologies. They can be expected to propel this wave forwards, although they only on rare occasions can afford their own micromachining facilities. Larger application-oriented companies will, in most cases, move in slower.

Technology oriented start-up companies lacking an application focus face a very tough future. To survive, they need to build around a technology breakthrough, while gaining applications and marketing know-how the hard way.

This micromachined $1 \times 5 \times 0.1 mm^3$ silicon sensor element has found a plethora of uses in pressure sensors, accelerometers, force sensors etc. It is still in production at SensoNor today, more than 20 years after its market introduction.

Restructuring

MST actors from the early waves will face a restructuring arena when the application oriented companies put pressure on production facilities, e.g. regarding availability, standardization, reproducibility and cost. A few larger facilities will survive. Smaller facilities will ally with component or system suppliers (e.g. VTI Hamlin with Breed Technologies). Equipment manufacturers and companies providing support will face new missions.

The diversified MST-related industry might well end up being organized as is the microelectronics industry.

Jan Söderkvist

WHEN IT ALL STARTED

Micromechanics is older than most people think. One starting point was the discovery of the piezoresistive effect in the early 1950's. Silicon sensors were fabricated ten years later. Around 1970, researchers at Westinghouse were using sacrificial layers to form capacitive sensors and electrostatic actuators.

The group at Stanford University, headed by Professor Jim Angell, probably had the greatest influence on the early development of micromechanics. The gas chromatograph on a single wafer, and other demonstrators, really demonstrated the potential of this new field. The achievements of Kurt Petersen, then at IBM, in designing and fabricating a number of innovative devices also served as an inspiration source.

In Europe, Philips had a very early start in miniature pressure sensors. The predecessors of SensoNor in Norway were industrially active already in the early 1970's producing silicon cantilever beams for use in medical equipment. Unknown to many is that micromachining techniques for three-dimensional structures, such as the LIGA technology, can also be traced back to the 1970's and the research laboratories of Siemens.

(From MSB 94:2*)*

Bertil Hök

Gas chromatograph developed at Stanford in the 1970's. The 2-inch wafer contains a 1.5 meter capillary column and associated plumbing for the injection system. (courtesy of Steve Terry)

History.no

The semiconductor technology activity in Norway started at SINTEF, former SI, in 1960. Initially, the focus was bipolar technology, and the development of mechanical sensors was only a minor part of the total activity. Nevertheless, in 1965 a silicon sensor with integrated piezoresistors was developed for pressure, force, and acceleration measurements. The same year, some scientists left SI to establish Akers Electronics (ame) and continue development on the silicon sensor. As a spin off from ame, SensoNor was established in 1985 as a company focusing solely on silicon for mechanical measurements.

The silicon sensor originating from 1965 has been produced by SensoNor for a variety of different sensor applications. The first generation of air-bag accelerometers is one example. Orders for other applications are already signed for production into the next century.

SensoNor is now supplying and developing a variety of micromechanical sensors, most of them in high volumes for the automotive industry. Best know is the SA20 air-bag sensor that has been the market leader in Europe for several years. A tire pressure sensor was introduced on the market, and a silicon gyroscope is in the pipeline.

ame has focused their activity on silicon-based opto-components, opto-hybrids and MCM. It is today one of the OSI System Companies, including amongst others, UDT Sensors Inc. in California. ame's activity has expanded during the last years and the company had a turnover of 80 MNOK over the last 12 months.

In the 1990s, four new companies have spun off from the microelectronics activity at SINTEF in Oslo. These companies, Ide, Chipcon, Presens and Fifty-four point Seven, are further described on the next page.

Anders Hanneborg, SINTEF

Microsystem Volume Production:

Present and Future Challenges

The industry of micromachined devices has emerged during the three last decades. At first these devices were mainly a technological spin-off from microelectronics and integrated circuit technology. Sensor applications provided the main market pull, batch processing was the key to reach high quality at low cost, and silicon micromachining established itself as a unique process technology with distinctive features. Today, production of these devices has matured into a separate industrial sector with its own market and manufacturing infrastructure, including micromachining of silicon and the use of deposited thin films. The devices are used in systems with widespread applications, ranging from low cost, high volume automotive applications to high cost, low volume instrumentation applications.

Key success factors for this industry include:

- Batch organized planar processing technology
- Microelectronics manufacturing infrastructure
- Rapid uptake of research results from solid state technology and other related fields of microelectronics

However, microsystems technology has during these years shown a much slower learning curve than microelectronics in general, turning MST devices into bottlenecks for performance and cost improvements in system applications. The most important inhibiting factors are:

- Slow market acceptance
- Low production volumes
- Immature industrial infrastructure for the specific materials and processes

Significant growth of the emerging microsystems industry requires a business focus on short as well as medium term results and on long-term R&D. To obtain success in this dynamic field, active participation and guidance by owners, board members and top management is a prerequisite.

SensoNor asa is an independent company operating as an OEM-supplier located in Horten, Norway. The company's business idea is to develop, manufacture and market microsensors, preferably for high volume applications, based on silicon microsystems technology. The company offers application specific sensors for mechanical quantities such as pressure and acceleration. Over the past 15 years, SensoNor has been in the technological forefront of offering microelectromechanical systems (MEMS) solutions to customers. Over these years a broad technological base has been built up. SensoNor has been able to introduce MEMS solutions to replace traditional sensors in the fields of avionics and precision metrology. Even more importantly, significant advances have been made in high volume applications such as the automotive area. SensoNor is today a leading independent supplier of pressure sensors and accelerometers for automotive applications, and has to date delivered more than 34 million units of the SA20 Crash Sensor.

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Industrial Foundry Service at SensoNor

SensoNor has since 1997 offered external customers a foundry service based on the technologies used for their OEM microsystems for volume production. SensoNor is involved in Europractice and is a coordinator of NORMIC – the Nordic Microsystems Manufacturing Cluster. The services give customers access to:

- Qualified industrial microstructuring processes
- Microsystem technologies proven in high volumes
- Processes supported by engineering kits, technology files for major CAD platforms, and a library of models and elements from basic building blocks to complete sensing elements.
- Volume as well as prototyping/low-volume (MPW) manufacturing
- A network of design houses and support centers
- Front-end and back-end processes

Examples of microsystems manufactured for external customers include pressure sensors, ink-jet printer heads, microphones and flow sensors.

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MPW, 3RD RUN

NORMIC offers a Multi Project Wafer service including support for device design and testing. Silicon processing will be made at SensoNor asa. The deadline for reservation of chip area is February 1, 2000.

For more information, please contact the MPW-coordinator.

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Fifty-four point Seven is a new Norwegian microsystem company spinning off from SINTEF Electronics and Cybernetics in Oslo. 54.7 started operations on September 1, 1999. The business idea of the company is development, manufacturing and marketing of microsystems, with a patented scheme for photoacoustic gas sensing silicon microsystems as its first venture.

The venture evolved during the ESPRIT project TESS (Total Environmental Surveillance Sensors), and is now followed up in the EUREKA project PAMPAS (Practical Applications of Microminiaturized PhotoAcoustic Sensors). The associated patents are licensed from SINTEF, and two of the three key inventors behind the scheme have joined 54.7: Alain Ferber is Chief Scientist, and Per Ohlckers is heading the company. Ralph Bernstein, the third key inventor, is a member of the Board of Directors.

The technical details of the photoacoustic gas system was presented in *MSB 96:1*.

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Chipcon Group AS is a spin-off from the microelectronics research activities at SINTEF. It was founded in 1996 and now employs 18 people focusing on the development and sales of application specific and standard integrated circuits.

Chipcon AS, which is one of two sister companies, is specialized in customized integrated circuits for a broad range of applications, including automotive, telecommunication, and industrial. The company utilizes both analogue, digital and mixed signal design techniques to obtain a high level of system integration, and has successfully completed a large number of products. A significant number of these designs are targeted for low-noise sensor readout applications.

Chipcon Components AS, the second company within the group, was founded in 1999. Focus is on standard ICs for short-range radio communication. The first product, a two-way radio transceiver (CC400), is already available on the market and is distributed to customers world-wide.

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Integrated Detector and Electronics AS (IDE) is active in the field of radiation detection technology. The Company designs and manufactures advanced ASICs and hybrids, and develops and manufactures radiation detection systems based on ASICs and solid state semiconductor sensors. Founded in 1992, IDE has its origin from the research institutes around the University of Oslo and CERN in Geneva. Currently, 20 highly skilled persons are employed at its office near Oslo.

IDE's systems are based on the integration of externally sourced semiconductor sensors and in-house developed ASICs and system electronics. The IDE technology provides high-quality and high-resolution digital radiation images (see e.g. *MSB 99:1*). The primary strength is predominately in developing low noise front-end electronics for solid-state sensors. Most of IDE's sales have traditionally been products for physics and astrophysics applications. IDE is currently concentrating primarily on the fields of nuclear medicine, X-ray diagnostics and autoradiography.

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PreSens AS was founded in August 1996 and has, as of September 1999, three full-time based employees.

PreSens was established as a result of several years of development efforts by SINTEF in Oslo. PreSens is at the development and qualification stage of its patented sensing principle for silicon piezoresistive high-pressure sensors. The first commercial deliveries were performed in August 1998. PreSens AS has licensed its technology and collaborates with other leading sensor companies.

PreSens is aiming to become a significant sensor manufacturer in Europe in selected market segments. Primary market opportunities exist in the automotive, industrial and military sectors.

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NMC Norwegian MST Center

The activity within microtechnology in Norway since 1960 has resulted in a build-up of core competencies, which today form a good platform for future expansion. This platform has the potential to foster new enterprises and to accelerate the technology shift facing the instrumentation industry. A national initiative has now been launched to put Norway among the best in industrializing research results within microtechnology.

SINTEF has established the Norwegian Microtechnology Center (NMC), where NTNU, UoO and SensoNor will be partners sharing common laboratories and equipment. NMC should consist of three operatons in Oslo, Trondheim and Borre focused on silicon based microsystems, micro photonics, and integrated microsystems, respectively.

NMC should be directly involved in advanced R&D projects both at the universities and in industry. Microsystem design services, based on both custom design and foundry-processes will be offered as well as prototyping and small scale manufacturing.

During the period 1999–2003, the Norwegian Research Council (NFR) is expected to contribute with 150 MNOK towards investments in the NMC-laboratories, including approximately 20 MNOK annually in funding for research programs at the universities and SINTEF, and 25–40 MNOK annually in support for industrial development projects within microtechnology.

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Some MST-active companies and organizations in Norway:

- SensoNor (www.sensonor.no)
- ame (www.ame.no)
- SINTEF (www.oslo.sintef.no/ecy/)
- UiO (www.fys.uio.no/elg/fysel)
- NTNU (www.fysel.ntnu.no)
- PreSens (frode.meringdal@presens.com)
- Chipcon (www.chipcon.no)
- Ide (www.ideas.no)
- Fifty-four point Seven (www.fys.uio.no/~poe/54.html)

and many others.

Browsing Minor Mechanics for Minor Life Forms

It is difficult not to admire the cunning of the male Fowler's toad as it, eager to compensate for its shorter vocal cords and smaller oral cavity, heads for a cold pond to make its voice deeper and improve its chances with females. With a spectrum of size for living things ranging over 21 orders of magnitude (from Mycoplasma, 0.1 pg, to the blue whale, 0.1 Gg), there are, however, plenty of size effects much more important than the mating or non-mating of a toad to explore. Besides, a cold bath might just be the way to lessen the desire.

Being a micromechanic, I find it particularly interesting to study nature's smallest mechanical systems and to compare them with those from man's artificial microstructure technology. Before sharing with you some of my findings, I will try to briefly introduce you to the theory of scaling, a most useful and fascinating aid in the understanding of size-related phenomena.

Scaling

When an object grows bigger, or shrinks, its surface and volume (or weight) change at different rates. This is easy to visualize if the object is a cube. Doubling the length of the edge results in a four-fold increase in the surface area and an eight-fold increase in the volume and weight. It might be trickier to see that this holds also for a ball or a toad, but as long as the shape is preserved, the surface area is proportional to L^2 and the volume/weight to L^3, respectively, where L is an arbitrarily chosen linear dimension of the object. Since some forces and matter exchange (e.g. adhesive forces and diffusion) act through the surface and some forces (e.g. gravitational and magnetic) act on the volume, the relative importance of them will alter with size.

A bridge, for instance, is hanging from wires or resting on pillars whose cross sectional areas are governed by the maximum stress allowed by the construction material and the expected load (the mass of the bridge itself, cars, pedestrians etc.). Should a perfectly engineered Lilliputian bridge be scaled up to our twelve times larger world, the load would be 1728 (12^3) times heavier, whereas the cross sectional area of the foundation would increase by a factor of 144 (12^2) only. There must be a considerable design safety factor in the original structure not to cause yielding or fracturing of the enlarged one by the much greater stress. For living creatures the bone structure is, therefore, much more slender for small specimens, like the hummingbird, than for larger animals, such as the elephant. An ant can easily carry many times its own weight, and a house fly resting on the ceiling can trust the weak van der Waals forces. (With diving beetles being one exception, very few insects use the suction cups your parents probably proposed.)

Forces acting on a body vary with its size (e.g., gravity follows L^3, pressure L^2, and surface tension L^1). The intersection corresponds to a fly resting on the ceiling.

Since heat is lost or gained through the surface, but dissipated or generated through the body, a tiny mammal like the mouse spends most of the day eating while a human being has plenty of leisure. For the same reason, insects need no circulatory organs, but instead rely on diffusion for transport of air via tracheas. Moreover, in small organisms nutrients like proteins and sugars diffuse several micrometers, which is a significant distance in the body, in a few seconds. People trying to combine their morning cereals with a foot bath, on the other hand, would need several centuries before the nutrients reach their brains (or should this ever be attempted, let's call it ganglion) by diffusion.

Now, let's see what we have learnt concretely from Mother Nature when it comes to microstructure design.

Friction

Most of you are probably familiar with those really small electrostatic motors capable of running at thousands of rpm, but wearing out in a fraction of an hour due to friction.

Friction has always posed a major difficulty in our field. Nowadays, many have abandoned bearings and sliding contacts in their micromechanics. Instead they make use of the friction in so called inch-worm motors, working by firmly attaching to a surface with one half of a body, then extending the spine (or middle part) of the body, before anchoring the other half of the body, releasing the first grip, shortening the spine, swapping the grip, and so on, mimicking an inch-worm or caterpillar.

Caterpillars (courtesy of William T. Hark).

Surface Tension

Although some insects, like the pond skater, benefit from surface tension, whereas larger animals largely ignore it (a human being would need a truly ridiculous foot perimeter of two or three kilometers to walk on water), it's a real pain for others. An ant faced with a water droplet for instance will find it difficult to penetrate and, should it succeed, even worse to get out. So, it's no coincidence that nature has eliminated tiny animals with a taste for showers and baths, and instead encouraged dry cleaning and built-in straws.

A spider thread with sticky beads, and a silicon nozzle (see MSB 97:2*) with a broken ink jet.*

Surface tension, with a little help from small perturbations, is able to split a thin jet of liquid into droplets – a phenomenon utilized in one of MST's most prospering applications: the ink jet printer. The exact advantage of this in the creation of a spider web, where a less volatile substance spun on a fast drying carrier thread breaks up into tiny beads, is not really clear though.

Attitude Control

In controlling its flight, especially yawing and perhaps less likely pitching and rolling, the higher Dipteras, whereof the housefly might be the best known member, use their oscillating vestigial hind wings, the halteres, as a sort of gyroscope similar to a Foucault's pendulum. The shear forces emanating when the plane of vibration is forced to change affect the amplitude of the main wings and stability is regained. The difficulty of scaling down ordinary rotating aircraft gyros to fit in microsystems was probably

A miniature quartz gyroscope (courtesy of J. Söderkvist), and the halteres of a crane fly (located right behind its wings).

perceived early. The miniature Söderkvist gyro with the geometry of a tuning fork was shown in *MSB 96:2*.

Aviation

Because of its favorable scaling properties, flying ought to be a promising way of conveyance in the microworld. Most flying insects stay aloft by flapping, giving a lifting force going as L^2 that counteract gravity that is proportional to L^3. So, a wasp having perhaps one third the length of a hovering hummingbird has indeed only around one tenth the lifting strength, but weights almost thirty times less.

Currently, the main hindrance for airborne MST seems to be the power supply. The most efficient insects benefit from a higher glucose concentration in their blood, and have their whole thorax working at resonance; the latter of which has been noticed and used by I. Shimoyama *et al* in their silicon/polyimide aircraft.

A microflight mechanism fabricated from polyimide and nickel (photo from I. Shimoyama et al, MEMS '94*), and a typical insect thorax engaged in wing beating (red: contracted muscle, blue: relaxed muscle).*

Swimming

For really small creatures, flying and swimming are very similar. For most motion in viscous media the Reynolds number, roughly defined as the ratio between inertial and viscous forces, serves as a good performance indicator. Insects and swimming microstructures qualify as low Reynolds number swimmers, and according to E. Purcell, the best we can do to come close to their situation is to immerse ourselves in a swimming pool full of a molasses and not move our limbs faster than say one centimeter per minute. The flow around the body is so smooth and laminar that any mixing of the fluid is reversible. Under such circumstances one cannot move by rowing or paddling. One would only end up where one started.

Part of a primitive animal, a Paramecium (courtesy of Y. Tsukii), and a hypothetical MST cilia (green: relaxed, blue: stroke, red: return stroke).

Single-cell-organisms use flagella or cilia to propel or whip themselves forward, while small insects use brush-like wings to dig through air or water. Many microactuator designers have adopted ciliary motion, and all kind of cantilevers has been used. If one uses a trenched silicon beam which is pretty stiff in the driving stroke and limp during the return, one comes even closer to nature's solution.

Optics

Insect vision has not yet rendered much attraction in MST. The compound eye is indeed an architectural masterpiece and seemingly a clever substitute for the diffraction limited iris eye, but is unfortunately a little deceptive to its master since objects look bigger but also dimmer on approaching. (This might explain why so many kinds of fragile, flying fauna tend to find a light bulb such a good place to land and die on.)

As mentioned by F. Nikolajeff in the latest *MSB*, one could however learn from the moth in designing a subwavelength grating for antireflection purposes.

A photonic 300-nm-grating (courtesy of J. Nole, Holgraphic Lithography Systems), and the compound eye of an ordinary housefly.

Communication

The potential of massive parallelism, i.e. an armada of gnat sized robots doing the work of a much bigger machine (like a vacuum cleaner), has often been put forward as an argument for MST, but close to no one has addressed the challenge of autonomous communication between its members. In nature, body language and pheromones are used excessively. And just like the exited weaver-ant rubs its belly to the ground to create an odor trail to guide its fellows to enemies, the inch-sized robots of H. Aoyama *et al* leave behind them a magnetic footprint detectable by their comrades and fading with time. (These robots are in addition a good example of inchworm motion.)

A miniature robot following the magnetic trace (the pheromones) of another one (courtesy of H. Aoyama).

Conclusion

This was just a short account of some associations evoked while browsing minor mechanics for minor life forms. There should be much more out there and plenty of possible coalitions between biology and MST. And who knows – in the future MST might not be larger than life.

I guess we can chose to get inspiration or confirmation from nature's smaller life forms. Either way will do, but not adjusting to a playground staked out through millions of years of natural selection is foolish and maybe even offensive. Or, as Lewis Carrol puts it:

"I should like to be a little longer, Sir, if you wouldn't mind", said Alice: "three inches is such a wretched height to be."

"It is a very good height indeed!" said the Caterpillar angrily, rearing itself upright as it spoke.

Greger Thornell

MST getting a footing among medium-sized life forms (illustration by K. Åstrand).

History.fi

The late seventies and early eighties marked the beginning of silicon micromachining in Finland. At that time **Vaisala** decided to invest in a cleanroom in order to start in-house manufacturing of CMOS circuits for radiosondes, the most important product of the company. It was clear from the beginning that the cleanroom facility would also be used for the manufacturing of silicon micromechanical pressure sensors for the sondes. In 1982, a researcher on silicon micromachining was hired and sent in early 1983 to the Fraunhofer Institute in Munich to learn micromachining and to transfer the technology to the company. In 1984, the first capacitive silicon sensors were sold to a customer for telecom cable monitoring, and further development of the sensors continued. The present applications include precision pressure measurements in radiosondes, industry and interplanetary probes. In 1987, the first micromachined capacitive silicon accelerometers were designed and manufactured. This activity turned out to be a real success story: the current world leader in capacitive micromachined accelerometers, **VTI Hamlin Oy**, was founded for the mass production of the sensors in 1991.

The leading position of **Okmetic**, the Finnish silicon wafer manufacturer, is partly due to the early demand by Vaisala of micromechanical double sided polished wafers.

In 1991, **VTT Electronics** hired a research professor for the development of silicon sensors and microsystems. In close cooperation with Finnish companies and funded by Tekes and VTT, the research team has developed several microcomponents, such as an electrically tunable Fabry-Perot interferometer for IR-gas analysis, thermopile IR-detectors, electrically modulatable wide bandwidth IR-emitters, very sensitive differential capacitive pressure sensors and microphones, and an all silicon miniaturized IR-spectrum analyzer utilizing the developed components (*MSB 98:1*). Several of these components have been commercialized.

The **Helsinki University of Technology** has commenced basic research, development and education in microsystem technologies.

The funding for microsystems research and development in Finland is well organized. **Tekes**, the National Technology Agency, has played a crucial role in funding both individual research projects and large research programs. VTT Electronics has carried out its own microsystems programs for the development of technologies needed in the development projects.

The latest initiative comes from the **Espoo-Vantaa Institute of Technology**, which is planning to build a microelectronics manufacturing factory for the education of existing and future personnel for companies using modern electronics manufacturing technologies. The factory will also have a research unit specializing in packaging, assembly and testing of microcomponents and systems developed elsewhere.

Ari Lehto

Focused Ion Beam Applications

Focused ion beam (FIB) technology has been rapidly emerging particularly in the micro-electronics field. FIB is based on a finely focused ion (commonly Ga^+) beam that can be manipulated by electrostatic lenses in the same way as an electron beam in a scanning electron microscope (SEM). FIB equipment, like the Micrion 2500 recently installed at the University of Oulu's Microelectronics Laboratory, has an ion beam spot size as small as 5 nm, thus enabling submicron imaging resolution. The image is acquired by detecting secondary ions or electrons scattered from the sample surface.

Contrary to a SEM, the higher mass of the ions, and thereby the higher kinetic energy achieved by the acceleration voltage (typically 30–50 kV), makes it possible to utilize FIB for the precise ion milling and chemically assisted etching and deposition of various materials. The etching can be carried out by mere ion milling, or it can be enhanced by feeding a proper precursor gas into the chamber. Metal deposition is based on the reduction of tungsten hexacarbonyl gas in the focal spot of the ion beam. The conductivity of the deposited tungsten film is high enough for making electrical connections. Furthermore, it is possible to deposit SiO_2 with electrical characteristics sufficient enough to act as a capacitor dielectric.

A free-standing cantilever structure milled in silicon. The length of the cantilever is 50 µm and the width is 2 µm.

This ability to etch and deposit conductive and insulating submicron features puts FIB technology at the leading edge of innovation in microsystem development. Typical applications of the FIB are integrated circuit modifications, transmission electron microscopy (TEM) sample preparation and micromachining. One existing commercial application is hard disk drive magnetic head trimming. Other applications are quantum wire fabrication, microtool fabrication for medical purposes and (TEM) sample preparation. In addition, silicon microsystem research has been carried out for novel sensor applications.

The current FIB research activities in the Microelectronics laboratory are circuit modification and combined laser chemical vapor deposition (LCVD) of copper and FIB technique. The research is funded by the Technology Development Centre of Finland together with the companies Nokia Mobile Phones Oy, Tellabs Oy, Nokia Telecommunications Oy, VLSI Solution Oy and VTT Electronics. Future topics will include micromachining and microsystem technology applications as well as quantum device research.

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TEM sample of an integrated circuit prepared by FIB milling. The sample thickness is 70 nm. The slice location can be chosen anywhere on the sample and the preparation takes about an hour to carry out.

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MST for Future Communications Products

Telecommunications is one of the fastest growing industries. As a vendor of communications products, Nokia is actively searching for new technologies and solutions for wireless terminals and network products.

Microsystems for Wireless and Optical Communications

Future wireless terminals will provide connectivity to new type of services, data and images. In addition, the end-users are interested in new functionality and features. Extreme miniaturization of electronic components and systems is required. Micro-electro-mechanical components and microsystems provide possibilities for reducing the size and cost of the current implementations. They also provide possibilities for new architectures, e.g. of radio systems and power management. Furthermore, microsystems enable integration of new functionality into wireless terminals.

Multi-mode terminals required for the operation in different radio interface standards tend to increase the complexity of radio interface implementation. Micromechanical components create opportunities to reduce the number of necessary components in radio implementations by increasing the level of integration and by creating possibilities for tuning the components. Device concepts for micromechanical tunable capacitors and switches, VHF resonators and high Q value inductors exist. These elements will enable new solutions for fully IC-integrated tunable filters, micromechanical mixers, and voltage controllable oscillators in 1–2 GHz applications. In the millimeter wave range, integrated antennas, antenna arrays, tunable phase shifters, etc. can also be realized by micromechanics.

New technical solutions for user interfaces and power management are required for future wireless terminals. Micromechanical sensors and microphones are available as components, and they can be seen as building blocks for more complex smart systems consisting of several integrated sensor elements. Micromirrors create new possibilities for projection displays in wireless terminals.

In optical network systems, the best existing solutions for optical switching are based on optomechanical switches having limitations in accessible switching speed and in the integration possibilities with other optical components. Several groups have already developed micromechanical optical switches and prototypes of small-scale switch matrices (4x4). Micro-opto-electro-mechanical systems (MOEMS) are clearly an alternative for a faster and more reliable implementation of future optical network elements.

New Requirements

Fabrication processes capable of the large volume production of micromechanical components have been defined according to the requirements of the sensor applications. Communications systems create new requirements on microsystem technologies: 1) smaller dimensions, 2) new materials, and 3) increased complexity.

At high frequencies, series resistance, stray inductance, and parasitic capacitance determine the device performance. Careful layout design may partly solve the problem. However, requirements on the conductivity of thin films and the properties of dielectric materials are more critical than they are in the sensor applications. Necessary dimensions are also demanding. For example, a capacitively coupled micromechanical VHF resonator requires a separation between the capacitor plates of less than 1 µm.

Both optical and RF microsystems require the integration of micromechanical components into complex systems together with integrated optics or integrated circuits. Optimal solutions for building microsystems based on both monolithic and hybrid integration must be found. Flexibility to combine different functions according to the requirements of the particular application or product is also needed.

MST Research at Nokia

Nokia is studying the use of potential microsystems. Important are to identify the key applications where microsystems add value to the end-user and to determine how microsystems should be used in new system architectures. Nokia also sees it as important to be capable of designing and characterizing MEMS components, as well as being capable of defining new fabrication processes. The cornerstone of our MEMS work is the collaboration with research institutes, MEMS foundries, and IC vendors.

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New Tekes-Program

Tekes, the National Technology Agency, is the main financing organization for applied and industrial R&D in Finland. The funds for financing are awarded from the state budget.

Tekes has just launched a new program, Presto, on MEMS and related precision mechanics. Its goals are to:

- create new components and solutions based on MEMS
- facilitate the large scale use of micromechanical components
- develop Finnish research in companies, research institutes and universities
- facilitate the implementation of micromechanical products in existing products
- create new business in the manufacturing, assembly and design of micromechanical products

Tekes' goals also include the creation of an international network of partners to supplement the national know-how, to educate for industry and research, and to facilitate the exchange of researchers.

The focus is not only on traditional micromachining but also in related micro and precision milled components, production and auxiliary equipment.

The total volume of Presto is 160 MFIM (roughly 26 MECU) during the period 1999–2002. Another program, EMMA, which more focused on research was presented in *MSB 99:3*.

Ari Lehto

www.fi

Companies and organizations in Finland active in microsystems technologies include:

- Vaisala Oyj (www.vaisala.com)
- VTI Hamlin Oy (www.vti.fi)
- Okmetic Oy (www.okmetic.com)
- VTT Electronics Microelectronics Center (www.vtt.fi)
- VTT Automation (www.vtt.fi)
- Helsinki Univ. of Techn. (www.hut.fi)
- Univ. of Oulu (Microelectronics lab., www.oulu.fi)
- Nokia Research Center (www.nokia.com)
- Espoo-Vantaa Inst.of Techn. (www.evitech.fi)
- CSC Center for Scientific Computing (www.csc.fi)
- Tekes (www.tekes.fi)
- Academy of Finland (www.aka.fi)
- Otaniemi Technology Park (www.innopoli.fi)

and many others.

What has Been Presented in

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Crystal structure of Si (µBas1)
Silicon wet etching (µBas2)
Monolithic accelerometer
MST@Bofors

MSB 94:2
Detection methods (µBas3)
Gas flow sensor
MSW ’94
MST@KTH

MSB 94:3
Optics in MST (µBas4)
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Swedish MST history
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MST@Linköping Univ.

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MSB 95:4
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1996, Volume 4

MSB 96:1
Excitation methods (µBas7)
Photoacoustic gas sensor
SUMMIT
MST@CKD & IMC

MSB 96:2
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MST@Quartz Pro

MSB 96:3
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CD-based MST-replication
Passive alignment within BRO
IR gas sensing
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Is size important? (µBas9)
Gas flow in micro-channels
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MST@Lund Univ.

MSB 97:3

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MSB 97:4

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Microcar
MST@CKD & NMC

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MSB 98:1

MST in Finland and U.S.A.
Silicon wafers
CO_2 and pressure sensors
MST@VTT Electronics

MSB 98:2

MOEMS (µBas11)
Optics-based sensors
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MST@VTI Hamlin

MSB 98:3

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Polyimide joints
MST for hearing and space

MSB 98:4

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Simulation, X-ray
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MSB 99:4

Nordic country reports
Past and future
General MST
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Bird's Eye View of MST

Red-tailed hawk
(photo: Jim Morton)

MST, it is said, is a maturing field of technology, moving from academia to industry.

The Global Scene

MST still attracts PhD students, now perhaps more organized ones in contrast to the wild ones during the pioneering years. Research as such is also more organized and is approaching big science. To run a decent research program in MST today, you need strategic support on the national, and even the international, level. Ten years ago most decisions were manageable within the local university. Formerly cozy workshops are now big conferences with hundreds of participants and documentation requiring a CD format to be manageable.

On the other hand, for us who were present 15 years ago the scenery is not all that different. The main topics of scientific and technological interest are still valid, and many challenges remain just that. To name a few 'eternal' questions: When will we see fully integrated microsystems, truly interchangeable and mass-produced devices comparable to resistors, transistors and ICs found in the electric domain, or universal simulation and design tools?

True, we did see a number of significant breakthroughs. 'Almost' truly three-dimensional, multifunctional, still batch processed devices, the exploitation of the remarkable material properties of silicon, and not only silicon, and the creation of extremely complex microsystems with thousands of individual substructures. Some, if not all, of us have been quite clever and successful.

Meanwhile, industrial MST development has, predictably, become the silent workhorse that does not receive the loving care and attention it used to when it was younger. Industrialists nowadays are more loudspoken about the high R&D costs of MST devices than they are about the fascination of the technological achievements and possibilities. Some will argue that this is about time. Economically speaking, we were never very successful in generating large profits. The number of MST billionaires is not large.

Still, the silent workhorse is doing his job, planting accelerometers, gyro's and micromotors in your car, tuning forks in your watches, printheads in your PCs, pressure sensors in your veins, drowse alarms in your eyeglasses (if you were not alerted before…).

Sweden's Role

What position will small countries, like Sweden, take on this contradictable scene? Being small also means having less money than the larger nations. Nothing is very new here, it will probably be the same tomorrow. On the other hand, a consoling fact is that the relationship between R&D expenditure and outcome is neither linear nor monotonous. It may even be negative.

Another thing that we cannot say for sure is that success is more likely in the fields of our present strength. Swedish researchers used to be pioneers in computer science (in the 1950's), its industry made a strong effort, and it flopped. Instead, almost against all odds, two Nordic countries have taken a world lead in mobile telecom. Was it predictable? Informed sources at Ericsson claim that it was, at least in one sense: The anarchistic company regime allowed this activity to grow, and build up strength. A very helpful conclusion.… Having thus depreciated the value of predictions, we should neither refrain from trying to predict, nor in trying to help others to avoid the mistakes that we made.

A bird's eye view of the present Swedish MST arena looks as follows: Several university based research groups have acquired international recognition. The activities in Lund and Linköping have grown fast in recent years, with chemical/biosensors and nerve cell-silicon interfacing as important highlights. In Göteborg, new automotive sensors have been brought forward, and in Stockholm, microfluidic and other devices for 'nanochemistry' are being developed. In the joint Uppsala-Stockholm center of competence, SUMMIT, strong efforts are directed towards 'exotic' materials such as polymers, ceramics, quartz and diamond. The PhD school, Advanced Microengineering (AME), in Uppsala is directed towards microsystems in space, medicine and optics. Sweden has two industrially oriented institutes: ACREO in Stockholm, and IMEGO in Göteborg.

Swedish industry has an 'hour glass' structure: Quite a few important large companies, a large number of very small companies, and very few in between. The large ones with strong MST interests are telecom, automotive, or pharmaceutical. These companies are acting on the global arena, both in their marketing and in their R&D activities. In order to stay competitive, nothing but top rank partners will be considered for their strategic development. More often than not, such partnerships are nonexclusive and have a network character. Ericsson, to give one example, has built up a tightly spun national network during the last decade, infiltrating all technical universities, institutions and organizations on the national levels, including the governmental. What's good for Ericsson is also good for Sweden?

Our large pharmaceutical companies have, by and large, left the country. Contradictory as it may seem, Swedish MST may come out as one of the winners. The plans of the 'leftovers', Amersham-Pharmacia Biotech and Biacore, appear to possess all of the ingredients for future success (see page 21).

Ruby-throated hummingbird
(photo: Terry A. Danks)

For small companies, the situation is different. Most university/small company relations are bilateral, and strongly personal. The role of universities should not be to subsidize product development. On the other hand, without industrial relations, academic research will really become academic. And without the impulses from the scientific frontline, fewer product innovations will be generated and pursued. Our ability to successfully perform this balance act will determine the future of MST in this country.

Future

What are the directions for future research? Microtechnology recently turned into nano, will pico be the next? Probably not. At least it will not be the largest issue. Size is important, but at some point, the investments to carry this one step further will not be paid back. No straight line, even Moore's law, goes on indefinitely.

More probable is that we will be forced to look upon MST in a new perspective. One driving force could be our understanding of complex systems. What makes living, biological systems viable? Why are our computer networks so unreliable? The answers to questions like these will have profound impact on MST evolution. New architectures for microsystems will have to be developed. Perhaps the Architect of these will be *our* Bill Gates? Will she be a Swede? Why not?

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History.se

The history of Swedish R&D in micromechanics and MST started as industrial activities.

In the early 80's, Ericsson Telecom developed a fiberoptic switch based on a silicon V-groove structure that was mounted in a conventional relay. This was probably the first Swedish micromechanical product, and was used primarily to achieve redundancy in fiberoptic networks. Replacement of a blown-out laser diode could then be performed in a matter of milliseconds completely automatically.

At the same time, ASEA put in a substantial R&D effort in fiberoptic sensors, which resulted in a family of systems for measuring temperature, vibration, pressure, current, voltage, and magnetic fields, among other parameters. A few of these sensors are still commercially available. One of the accelerometer designs used a cantilever beam of GaAs-AlGaAs fabricated by selective etching. The acceleration signal resulted from variations in reflectance, and photoluminescence due to band-band recombination in GaAs provided a reference signal.

Academic research started in 1984 as a cooperative effort between ASEA and Uppsala University. Two lines of research started, including investigations into the mechanical and thermal properties of micromechanical elements, and the development of new speculative devices. Early highlights included the demonstration of the superior strength of silicon cantilever beams, high-speed fiberoptic multiplexing by means of a silicon scanning mirror, and a fiberoptic pressure sensor for biomedical applications, later to be commercialized by Radi Medical Systems.

A fiberoptic accelerometer with a micromachined cantilever beam made of GaAs-AlGaAs, designed and fabricated in 1983 (courtesy of ABB Corporate Research).

(Updated text from MSB 94:3*)*

Bertil Hök

MST@UU

www.mst.material.uu.se

www.ame.material.uu.se

www.summit.material.uu.se

WWW.SE

Some MST-active companies and organizations in Sweden:

- ACREO (www.acreo.se)
- Amersham Pharmacia Biotech (www.apbiotech.com)
- Biacore (www.biacore.com)
- CelsiusTech (www.celsiustech.se)
- Chalmers (www.ic.chalmers.se)
- Ericsson Components (www.ericsson.se/components)
- IMEGO (www.imego.com)
- KTH (www.s3.kth.se/instrlab)
- Linköping Univ. (www.ifm.liu.se/Applphys)
- Lund Univ. (www.elmat.lth.se)
- RADI Medical Systems (www.radi.se)
- Samba Sensors (www.samba.se)
- Spectrogon (www.optics.org/spectrogon)
- Telaire Europe (www.telaire-europe.com)
- Uppsala Univ. (www.mst.material.uu.se)
- XaarJet (www.xaar.se)
- Åmic (www.amic.se)

and many more.

New, exciting, and expanding, IMEGO, a new center for microsystems R&D, was founded in 1998, with the ambition to spearhead microsystems technology globally. Our activities, of which 60% are contracts financed by industry, focus on sensor systems for the automotive, environmental, security, communications, and medical industries. Our strategic location on the Chalmers University of Technology campus in Gothenburg makes us a dynamic link for microsystems between industry, academia, and government.

THE IMEGO INSTITUTE
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ACREO AB is a merger between IMC (Industrial Microelectronics Center) and IOF (Institute of Optical Research). Through this merger a powerful industrial research institute, comparable with the best ones in Europe, is formed. The organization is a liability-limited company owned by an industry group, FMOF, and the state-owned holding company, IRECO. ACREO has 130 employees in Kista and Norrköping.

ACREO specializes in market-driven applied research, development and consulting services in microelectronics and optics. ACREO also carries out small-scale production as a natural step after a successful development project. A basic mission for ACREO is to create a fruitful cooperation between universities and industry. Research results from universities should reach industrial applications, and demands from industry should have influence on university-based research.

ACREO has seven departments: Imaging, Photonics, Interconnect and Packaging, Silicon Carbide Electronics, Microsystem, Surface Characterization and Business Services.

The rapidly expanding Microsystem department today has a total of 20 employees working in two different groups, development and productification. Typical application areas are sensors, optical microbenches, microfluidics and RF-MEMS based on silicon technology.

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Silicon Technology Forever?

The answer to the question in the heading above is obvious to many people. It certainly seems obvious to me. But lately I have come to realize that the answer is not at all obvious to everyone, and there exist trends which, taken by themselves, appear to contradict my own conviction. The Editor of this Newsletter has for some time now tried to persuade me to give my own view on the issue. Though I have been hesitant, feeling that I would just kick down an open door, I will here try to express my thoughts about it.

Inertial Mechanisms

Stone was the basis of our primeval materials technology many thousands of years ago. Looking around, we still find stone to be a very important construction material in roads, dams, buildings etc. Stone-based composites such as bricks, tiles and concrete are produced in huge quantities. The Stone Age actually never ended, it is still with us, as are all of the other stages of technological development in human history. Similarly silicon technology is here to stay. But to achieve better and better functionality and ever higher efficiency (technical as well as economical), and to conquer new application areas for MST, alternative materials and new technologies must be added. But there exists inertial mechanisms in the MST community opposing such a development.

Let me illustrate this point with an example from a completely different field in the materials science realm. From a materials technology viewpoint, modern ceramic tools for metal cutting are inherently superior to the conventional high-speed steels (HSS). For this reason, ceramics were predicted as far back as the seventies to take over the cutting tool market. But this did not happen, mainly because the huge competence and know-how existing in the HSS field made it possible, time and time again, to “sharpen” the HSS just enough to maintain an advantage over the new ceramics. In microelectronics, a similar situation has existed in the relation between silicon and the III–V compounds, for instance.

Silicon? Yes, but not Always!

The question is: will the same thing happen on the MST scene? Will the enormous previous investments and accumulated know-how in silicon technology effectively suffocate alternative materials and new processing for MST?

Some such tendencies can be seen, but still I do not believe that this will happen. The reason can be condensed into one sentence: *The extreme diversity of MST*. In the HSS vs. ceramics conflict, the objective is efficient metal cutting, nothing else. In the silicon vs. III-V conflict, the objective is efficient signal processing, period. In the case of MST, on the other hand, a plethora of objectives exist in a broad variety of disciplines and application areas, not only in engineering. Silicon certainly is a wonderful material, but *no single material is superior enough to meet all the diverse demands appearing in MST.*

Recent development in watch resonators and microgyros for automotive applications give illustrative examples of how an inherently superior material – in this case crystalline quartz – is challenged by silicon. Quartz is dominant in these applications today, being an excellent materials choice for such components. But looking at the recent publications and industrial efforts, it is obvious that silicon is gaining ground in spite of its fundamental shortcomings. The reasons are of economical nature, processing and integration advantages, etc. It is probable that silicon will “win” this contest in the case of modest performance requirements, but that quartz will stand its ground in high-performance resonators.

New Materials Technologies

I wish to highlight another two emerging materials technologies for MST from two extreme ends of the materials property map. Both are based on microreplication from silicon preforms, hence illustrating how “old” technology provides a basis for advanced, new technology.

My first example is diamond. Diamond displays extreme properties: it has the greatest hardness, highest heat conductivity, lowest friction and widest optical transparency window of all materials, yet is chemically inert and insulating but can be made to be semiconducting. Today, this remarkable material may be replicated at reasonable cost levels from micromachined preforms of other materials using vapour deposition techniques. Silicon is an excellent preform material, which can be easily micromachined with high precision, and the diamond replicas are true to shape with high accuracy. Multilayer and sacrificial layer processing is possible, and high-aspect ratio structures and hollow structures such as tubes and capillaries can be achieved. It is also possible to make the diamond surfaces hydrophilic for microfluidic applications. Numerous applications can be envisaged in microoptics, microfluidics, microtribology, microcooling systems, microtools for secondary replication, microanalysis systems etc.

My second example is microreplication in polymeric materials. It is probable that significant contributions towards future MST are to be found in this field. It exploits the literally endless variety of material properties possible to achieve by advanced polymer synthesis and compounding. It also opens up the possibility for high-volume, low-cost, mass production of MST components in telecom, microoptics, sensor technology, medical analysis and many other areas. The telecom industry provides one good example. In order to realize cheap broadband communications with global coverage, the world has to be covered by a finemeshed network of single mode optical fibers. This network must include vast numbers of fiberoptical modules and interconnects. Even if these are possible to design and batch fabricate in silicon, the price per piece will be too excessive. The solution might be to mass-produce them cheaper in polymeric materials by a microreplication technique, similarly to how the optical track on CD records is mass duplicated today.

In Conclusion ...

… silicon technology is here to stay, we all know that, but there is no reason to go fundamentalistic about it. Much of future MST will be based on non-silicon technology, and only limited parts of today’s silicon-based MST will be prominent in the future.

Jan-Åke Schweitz

MORE MST-READING

MICROMACHINE (Japan)
www.iijnet.or.jp/MMC/magazine.htm

Micromachine Devices (U.S.A.)
r.cassidy@cahners.com

mstnews (Europe)
www.vdivde-it.de/mst/IMSTO/mstnews.html

Journal of Microelectromechanical Systems
www.ieee.org/pub_preview/mems_toc.html

Journal of Micromechanics and Microengineering
www.ioppublishing.com/Journals/Catalogue/JM/

Sensors and Actuators A
www.elsevier.nl/locate/sna

Words You Might Wonder About

Actuator: Device converting energy (electric, chemical, etc.) into mechanical work.
AFM: Atomic Force Microscopy. Visualizes features on an atomic scale.
Anisotropic etching: Direction-dependent etching. Often based on the periodic order of crystalline materials (anisotropy).
Anisotropy: Different material or processing properties in different directions.
Anodic (field-assisted) bonding: Bonding conductive to non-conductive materials (e.g. silicon to glass) using heat and high-voltage-generated electrostatic forces.
ASIC: Application-Specific Integrated Circuit. Chip specially designed for a certain customer and application.
Batch: Production of many components at the same time.
Bonding: Joining of parts in a permanent way.
Bulk micromachining: Tailoring structures by machining a wafer's interior.
Cleanroom: Ultra-clean area with a controlled environment.
CMOS: Complementary Metal Oxide Semiconductor. Type of integrated electronics often used in one-chip solutions.
CVD: Chemical Vapor Deposition. Deposition through chemical reactions at the surface.
Dielectric material: A non-conducting material.
Direct wafer bonding: Bonding wafers without using an intermediate adhesive material.
Dry etching: Processes based on chemically aggressive gases (e.g. RIE), plasma, and particle-bombardment.
EDM: Electro Discharge Machining. Milling using electric sparks.
EDP: Ethylene Diamine Pyrocatechol. An alternative to KOH for wet etching of silicon.
Electroplating: Deposition of metals using an electric current and an electrolyte solution.
Electrostatic force: Mechanical force caused by a voltage between two electrodes.
Epitaxy: Atom by atom growth of layers that adjust to the crystallographic orientation of the substrate (a single crystal).
Etch stop: Technique of stopping the etching at well-defined locations, e.g. at silicon-insulator interfaces or P-N junctions in semiconductors.
Etching: Removal of material, often with chemical processes.
Evaporation: Deposition using a heated source that sublimate or boil. Low pressure ensures high directionality of the vapor condensing at the substrate.
Fab: Factory for microstructures (nickname similar to lab).
FEA & FEM: Finite Element Analysis & Method. Simulation procedure for analyzing multi-physics behavior.
FIB: Focused Ion Beam. Finely focused ion beam (often Ga^+) used for imaging, milling and deposition.
Fused silica: Non-crystalline (amorphous) quartz.
GaAs: Gallium Arsenide. Semiconductor with optical and piezoelectric properties.
HF: Hydrofluoric acid. Ingredient in etchants that attack SiO_2 (incl. quartz).
Hydrophilic: A drop of water will wet a hydrophilic surface.
Hydrophobic: The opposite to hydrophilic.
Isotropic etching: Direction-independent etch-speed.
KOH: Potassium Hydroxide. The most common etchant for wet etching of silicon.
LCVD: Laser-assisted CVD.
LIGA: Lithographie, Galvanoformung, Abformung. Synchrotron radiation is used to form high-aspect ratio polymeric structures suitable for metal filling by electrodeposition and as masters for replication.
Lithography: Copying a mask-pattern onto a surface, e.g. using light or X-ray.
Lorentz force: Mechanical force caused by an electric current in a magnetic field.
LPCVD: Low Pressure CVD.
Mask: Pattern to be copied with etching or deposition.
MCM: Multi Chip Module.
MEMS: MicroElectroMechanical System (see MST). Acronym primarily used in U.S.A.
Micromachine: See MST. Word primarily used in Asia.
Micromachining: Processes for microstructure fabrication. Originating from the semiconductor industry's processes.
Microstructure: Structure featuring small geometries (sub-µm to mm). Often fabricated using micromachining.
Microsystem: System including one or more microstructures or assembled using microtechnology.
µ-TAS: Miniaturized Total Analysis System. Integrated chemical sensor system.
MOEMS: MicroOptoElectroMechanical System.
MPW: Multi Project Wafer. Several projects share the space and cost of a wafer.
MSB: Micro Structure Bulletin.
MST: MicroSystem Technology (regionally also MicroStructure Technology). See microsystem. Acronym primarily used in Europe.
MSW: Micro Structure Workshop. Nordic biennial workshop first held in 1994.
OEM: Original Equipment Manufacturers sell to system manufacturers instead of directly to customers.
One-chip solution: Sensor element and its electronics integrated on one chip.
PCB: Printed Circuit Board.
Photoresist: Substance used to protect areas not to be etched. Patterned via lithography followed by removal (etching) of exposed (or unexposed) areas.
Piezoelectricity: Mechanical stress generated by electric field/charge, and vice versa. Present in strongly anisotropic dielectrics, e.g. quartz.
Piezoresistance: The dependence of resistivity on mechanical stress. Involves mainly semiconductors, e.g. silicon.
Plasma: Cloud of ionized gas and electrons.
Polysilicon: Silicon consisting of crystalline grains. Often deposited via CVD or PVD.
PVD: Physical Vapor Deposition. Deposition processes such as sputtering and evaporation.
PZT: Lead Zirconate Titanate. Large-strain piezoelectric ceramic.
Quartz glass: See fused silica.
Quartz: Crystalline SiO_2. An inert, highly stable, and piezoelectric material.
Replication: Duplication of an original using casting, embossing or molding.
Resonator: Mechanical structure that vibrates, sometimes at a resonance frequency.
RIE: Reactive Ion Etching. Dry etching based on a plasma with chemically active gas ions.
Sacrificial layer etching: Removal of a buried fast-etching layer used, for example, to create freely movable structures.
SEM: Scanning Electron Microscopy. Features too small for optical microscopy made visible by scanning the sample with an electron beam.
Sensor: Device providing useful output to a specified stimulus. May react also to other stimuli, e.g. temperature.
Silicon fusion bonding: High-temperature hermetic bonding. Its atomic nature means high-quality bond interfaces.
Silicon: The most popular material in micromachining.
SME: Small to Medium-sized Enterprise (company).
SOI: Silicon On Insulator. An oxide layer sandwiched between two silicon layers, used in etching as an etch stop barrier and sacrificial layer.
Sputtering: Deposition based on bombarding a source by ions from a gas plasma. Knocked out atoms lose their directionality when passing through the plasma on their way to the substrate.
Stiction: Undesired adhesion of movable solids in very close proximity, caused by forces such as Van der Waals, capillary and hydrogen bridging.
Surface micromachining: Forming structures via deposition and etching of thin layers on the wafer's surface.
TEM: Transmission Electron Microscopy. Visualizes details in thin slices via the transmission of an electron beam.
Transducer: Device, e.g. sensor or actuator, converting energy from one domain to another, calibrated to minimize conversion errors.
Wafer: Thin slice of material suitable for batch processing. Normally circular with diameters in the 50–300 mm range.
Wet etching: Etching using chemically aggressive liquids.
Wire bonding: Making electrical connection by attaching thin gold or aluminum wires.
Yield: Fraction of functioning components after processing.

Jan Söderkvist

History.dk

Microsystems technologies got off the ground in Denmark relatively late. Nevertheless, it is today one of the focus areas in the national research strategy of the National Research Councils.

Early activities involved only the former Semiconductor Laboratory Institute at the Technical University of Denmark (DTU), in collaboration with Ferroperm A/S and Brüel & Kjær A/S. A coordinated national effort emerged after the formation of an MST group at Danfoss A/S at the end of the eighties, and the establishment of MIC in 1990. The establishment of MIC was based on a governmental analysis of Denmark's industrial potential within microelectronics and microsystems. DELTA started activities within the MST area in mid-90's.

Mikroelektronik Centret, MIC, is an autonomous research center for advanced microtechnologies in semiconductor materials, which currently has approximately 70 employees and PhD students. MIC is affiliated with DTU and has a 3-fold mission:

- education of engineers within the framework of DTU
- scientific research at the front edge
- technology transfer to Danish industry through joint research projects

MIC has a 560 m^2 cleanroom with state-of-the-art silicon processing facilities, in addition to well-equipped characterization laboratories. MIC has been operational since 1992 with an initial budget for investment in laboratory space of 60 MKR, for equipment of 60 MKR, and for recurring expenses of 24–27 MKR/year. This budget is supplemented with support from DTU.

In its first phase of existence, MIC has built up basic competence in silicon processing in a national collaboration project with the Danish companies NKT Research Center, Danfoss, Grundfos, Brüel & Kjær and Topsil.

In its second phase MIC, has focused on research and innovative technology development projects together with a range of Danish companies including Microtronic, DME – Danish Microengineering, Grundfos, Danfoss, as well as the service institute DELTA and the Institute for Processing Technologies (IPT) at DTU. In the meantime, MIC and its partners have entered collaborations with microsystems manufacturing sites in Europe, among others is the Europractice's Nordic Manufacturing cluster NORMIC (*MSB 98:1)* and the ESPRIT project HISTACK in the 4th Framework Program (*MSB 98:2)*, and recently in NORMIC2 and SESiBon in the 5th Framework Program.

MIC currently trains approximately 10 master, 10 PhD and 5 post-doctoral researchers. MIC is committed to double these figures over the next 4 years.

Siebe Bouwstra

MIC's office building

COM's office building

MIC's cleanroom facilities

The CAT building

The cleanroom extension for prototyping (projected)

www.dk

Some MST-active companies and organizations in Denmark:

- Brüel & Kjær (www.bk.dk)
- Danfoss (www.danfoss.com)
- DELTA (www.delta.dk)
- Dicon (hh@pe.dk)
- DME (www.dme-spm.dk)
- Grundfos (www.grundfos.com)
- HMT (jk@mic.dtu.dk)
- Ibsen (www.ibsen.dk)
- Ionas (www.ionas.dk)
- MIC (www.mic.dtu.dk)
- Microtronic (www.microtronic.dk)
- NKT Research Center (www.nkt-rc.dk)
- Topsil (www.topsil.com)

and several more.

New Initiatives

COM: MIC's photonics research program has joined forces with telecommunication programs at other DTU institutes to form the COM Center (Communication, Optics and Materials). The COM Center is located in DTU-owned buildings adjacent to MIC. For integrated optics technology COM researchers continue to use MIC's cleanroom facilities.

CAT (Center for Advanced Technology) established an industrial research office building in 1998, including microsystems and photonics packaging laboratories. MIC's and COM's industrial partners are now housed together under one roof in the new CAT building at DTU also adjacent to MIC.

Sensor Initiative: The Council for the Advancement of Industry (Erhversfremmestyrelsen) has initiated a program called Sensor Initiative. The program will run for 4 years from the summer of 1999 onwards, and is funding so-called Centercontract collaborations between service centers (e.g. DELTA and FORCE) and industry, as well as industrial PhD education. An agency called the Center for Sensor Technology has been established which coordinates existing sensor activities at 5 Danish service institutes and administers the above-mentioned funded projects.

Start-up companies: The year between the summer of 1999 and the summer of 2000 has witnessed the establishment of 4 start-up companies at MIC. Within the area of MST the start-up company Hybrid Micro Technologies ApS was established on July 1, 1999 with Jochen Kuhmann as director. HMT provides services in advanced stacking and metallization technologies for MEMS and optoelectronic systems, and has products under development.

MST-Structure in Denmark

Denmark has practically no background in microelectronics manufacturing. Starting a microtechnology-based industry in the country can, therefore, be likened to a bootstrapping exercise where MIC is expected to play a central, catalytic role.

The specific way in which MIC and industry collaborate can be expressed by stating that MIC is not working for industry but with industry. Collaboration projects with industry ensure that the companies themselves build up expertise in microtechnologies, while MIC gives equal weight to all three aspects of its mission (see left).

Microsystem Technologies is now one of the focus areas in the national research strategy of the National Research Councils.

contact.dk

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Industrial Participation

All major collaboration projects have at least two industrial partners, rather than only one, ensuring that such projects deal with innovative technologies and demonstrators rather than products. A particularly important feature of the MIC model is that many of the industrial researchers working within these collaboration projects are stationed at the institute.

The Danish governmental funding programs favor public-private collaboration where the partners are on an equal footing. The absence of large companies in Denmark and the abundance of small and medium sized enterprises may be an explanation for the existence of this type of program. Also, most of Danish industry is export-oriented and typically operates in niche markets. As a result, many of these companies do not have competitors in Denmark and are, therefore, willing to collaborate with each other. Besides, a large part of the equity in these companies is in Danish possession. All in all, exposure in collaboration projects does not render Danish companies vulnerable.

PhD Collaborations

Most of MIC's industrial partners have first started collaborations with MIC through Denmark's industrial PhD education program. In this program, the candidate is hired by the company for the 3-year duration of the education, and the education covers academic as well as industrial aspects, including thesis work.

In most cases, these smaller collaboration projects result in larger collaboration projects. Also, established partners often initiate further PhD education projects within microsystems in order to evaluate new directions for the company.

Benefits

As a result of the direct collaboration between MIC and industry as sketched above, industry is able to share technical information, MIC staff is kept aware of the challenges that private companies face, and students learn about these challenges first hand from direct contacts with industrial researchers. A bonus of this model is that recruitment by the industrial partners is highly effective. Above all, by operating as a group, Danish companies gain clout when dealing with MST manufacturing sites.

Siebe Bouwstra

Prototyping: a Necessary Bridge

Experience in the past few years has shown that it is difficult to repeat the successful fabrication of a demonstrator. Therefore, MIC has recently initiated prototyping activities. On February 1st, 1999, MIC, the service institute DELTA, and the private companies Danfoss A/S, Grundfos A/S and Microtronic A/S launched the 3-year collaboration project, SUM. The objective of this project is to bridge the gap between the research these companies have been doing at MIC and the industrial production at a silicon foundry by focusing on one demonstrator device for each company.

Within this project MIC is extending its processing capacity. In particular, plans have been made to extend the laboratory space with an extra 400 m^2 of cleanroom. Construction of this new facility, which will be largely dedicated to prototyping, is planned to begin in the year 2000. However, even before the new facility is available, MIC has launched an internal prototyping project to streamline its process information flow, and dedicated some of its equipment to optimized reproducibility rather than optimized flexibility. These activities are closely coordinated with the SUM project.

Photo: Karsten Damstedt

DELTA focuses on the packaging of microsystems (e.g. through conductive adhesive technologies), on development of known-good-die (KGD) testing schemes of MST components, and on building up competence in reliability and failure analysis of microsystems. These are important areas for taking the step from MST-demonstrators, via prototypes, over to production.

With the launch of the prototyping activity, MIC expects to lift Danish competence in microsystem technologies further, and to shift part of microsystem development from wafer processing and chip handling to CAD-tool based development. The long-term objective is to lower the entrance barrier for newcomers in this technology, so that a range of microtechnology based products and companies take root in Denmark.

Siebe Bouwstra

Replication – the Future of MST?

A breakthrough for emerging MST-applications in the biomedical and telecommunication areas is predicted in the coming years. These applications involve, for example, microfluidics and micro-opto-mechanics for which techniques other than conventional high-cost silicon or glass/quartz micromachining are needed. Here, different replication techniques are predicted to provide an enabling tool for future success.

MST in Life Science

Today, strong efforts are focused on the miniaturization of systems used in the life sciences market. The main driving force for biotech companies are high throughput per time unit, small sample volumes, and integrated functions. To fulfil these criteria, low cost mass-production of disposable micromachined devices is crucial.

A strong network has been established in the Uppsala-Stockholm region within the medical and biotechnology fields. Both larger multinational and smaller start-up companies, which have the knowledge and capability to develop and produce the needed microsystems and instruments, are found in this region. Two semiconductor laboratories for R&D and small-scale production are available (ACREO and Ångström), as well as mass production capabilities for replicated MST-products (Åmic).

Why Replicated MST?

The main advantages with replicated MST are:

- Cost effectiveness
- Choice of material
- Integrated functions
- Size independence

In mass production the cost savings can be on the order of 100 to 1000 times for the replicated component compared to components made from traditional silicon, glass or quartz based microtechnologies. Also, the possibility to replicate microsystems in different materials enables enhanced and even new functionality. New features can be integrated either into the master or into the molding process in a cost-effective way. The replicated parts do not necessarily need to be small. Integration can be facilitated easier via ‘designing for assembly’ when using replication than with traditional silicon micromachining.

Basics in Microreplication

The first step in the replication process is to fabricate a *master*. Several micromachining techniques are available. Silicon based processes, such as anisotropic/isotropic wet etching and deep RIE, are commonly used. Other IC-based lithography processes used are e-beam, laser and UV-exposure of thick resists. Also, sophisticated conventional workshop tools, e.g. micro-milling and micro-EDM, are important complementary techniques in order to fabricate micromold inserts with an interface to the macroscopic world.

The second step often includes electroforming of a *mold insert* in a rigid material that can withstand the molding process. Electroplating of nickel is most common, but other metals can be electroformed in addition.

The master structure is thereafter *replicated* in a micromolding process. Normally injection molding, hot embossing or casting is used (*MSB 96:3*). A wide range of thermoplastics and UV or thermally cured plastics are available. Microstructures with filled polymers, and even ceramics, are possible to fabricate. In addition, by repeating the electroforming process, metal microparts can be replicated with extremely high accuracy.

Finally some kind of *post processing* is often needed. Examples include the deposition of metal films for electrical connection or optical reflection, chemical treatment for surface modification, mechanical drilling of holes for liquid interfaces, bonding for closing structures, and filling capillaries for optical waveguides.

Future Challenges

A few replicated MST-products can be found today on the market, particularly in low-cost disposable and consumer applications. The big challenge remains to implement the technology in a wider field of applications and to build a reliable production.

Future R&D includes replication of more advanced materials. The increasing demands for thermal/mechanical stability and integrated electrical/optical functions, etc, necessitates combining polymer based composites and compounds, as well as non-plastic materials such as metals, alloys and ceramics, into a single replicated microsystem. Developers and producers with skills in a variety of processes will be able to manufacture high quality replicated microsystems cost-effectively.

Replicated MST will certainly be one important factor in bringing microsystems to the people.

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HISTORY OF REPLICATION

In 1838, a report on the reproduction of objects by electroforming was first presented. Some 80 years later the plastic revolution started slowly with bakelite parts for electrical insulation.

Two decades later, electroforming and plastic embossing merged in a mass product called the ‘vinyl disc’ for music distribution. The precision of the modulation of the grooves was in the sub-micron range. This was probably the first object where microreplication precision by today’s standards was achieved. Information storage demands have thereafter been one of the drivers in replication process development for small structures, especially after the introduction of the CD-platform (injection molding and nickel mold inserts). (*MSB 97:1*)

At the same time as the CD was introduced, the high-precision LIGA process for creating 3D microstructures emerged. Its high mastering cost (X-ray lithography) made replication of the parts necessary in order to reach an affordable cost-level for the fabricated component. Also, here electroplating of the masters was used to create the mold, which then was filled with various polymers.

In the 90’s, developers of silicon micromachined devices began to look towards replication in order to approach the broad market segments where both precision and low price are a must. The standard recipe for bringing the cost down for silicon based components has been to miniaturize. However, not all MST-applications can follow that recipe (e.g. most fluidic applications) which opens up for replication as the cost-saver.

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Microfluidics on a Plastic CD

There is currently a strong industrial drive for exploiting microfluidics in the fields of life science. The main reasons are the possibility to boost sample throughput and to reduce the overall cost of samples and consumables. For example, automatic microscale devices can provide the means for the ultra-high throughput screening of samples (combinatorial, genomic and proteomic). Other important reasons are the possibility to analyze extremely small quantities of materials as well as to create integrated disposable devices at low cost.

We at Amersham Pharmacia Biotech (APB) are investigating replication techniques on polycarbonate and other polymeric materials in combination with microstructures fabricated by silicon micromachining. The work is performed partly in collaboration with Åmic AB and ACREO AB. A microfluidic platform, to be used in numerous applications, is developed based on microreplicated compact discs (CDs), in which centrifugal forces are exploited to propel liquid through various fluidic channels.

Liquid Interfacing of CDs
The ability to carry out assays in parallel in a microarray format is essential for the success of a high throughput analysis system. To address microfluidic channels and arrays with a high degree of precision and accuracy, piezoelectric micro dispensers are being developed by APB, in collaboration with Lund University and ACREO. These permit the precise placement of droplets in the picoliter to nanoliter range, at a rate of a few kHz, without touching the target. By the drop-on-demand technique a certain predefined number of drops may be delivered, up to a flow rate of approximately 1 ml/min.

An injection molded polycarbonate microstructure.

Some CD Applications
There are many applications where we believe our CD approach will extend the limits of pharmacological research, some of which are given below.

Cell Based Assays
Miniaturized cell culture assays can offer new efficient tools and provide more information in primary and secondary screening, for example where cell availability is limiting. A small volume also maximizes the concentration of an analyte or messenger molecule, thus enabling detection of the molecule or its actions on a second cell population. Other applications are where the physical scale of the structure simulates a physiological environment, such as adhesion in cell lined capillaries and applications requiring very rapid addition of test agents to cells (e.g. 50 ms time resolution) with simultaneous measurement of the response.

SNPs
Pharmaceutical companies right now compete using pharmacogenomics (the understanding of the correlation between a patient's genotype and their response to drug treatment) to find new drug candidates.

The exploitation of single nucleotide polymorphism (SNPs) in pharmacogenomics requires accurate and cost-efficient methods for the scoring of multiple SNPs in large numbers of samples. This requires a reduction in scale to ensure low sample and reagent use, as well as integration and automation. In our CD approach, sample clean up, amplification, and analyses will be integrated, providing for faster processing times with nanoliter reagent consumption. The principle of pyrosequencing™ on a solid-phase is used as the detection method.

PCR
The low thermal mass of a CD microchannel can provide very rapid response to parameters such as temperature changes. We have used the polymerase chain reaction (PCR) to amplify DNA in microfluidic CD devices with volumes in the 100-500 nanoliter range.

Opportunities
It is now indisputable that microfluidics offers extensive opportunities for life science applications, and that miniaturization and high reliability are key factors for success in a market where increasing demands are put on cost, assay speed and throughput.

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EXPANDING INTEREST

Several additional companies in the Uppsala-Northern Stockholm region are interested in micro-replication:

Biacore (formerly Pharmacia Biosensor) was founded in 1994 as a spin-off from Pharmacia. Their mission was to utilize the latest technology advances to construct instruments able to measure biological activity. Silicon micromachining was considered from the start and is now a strategic know-how, especially for creating molds for some of the optical and fluid components in their instruments. A challenge is to combine a more efficient production with higher precision and new functionality. Replication of microstructures meets this challenge.

Ericsson: The (tele)communication industry is rapidly moving towards high bandwidth. Reducing cost for inexpensive optical components, such as fibers and access components, is a necessity. Plastic replication might prove to be a very interesting step in this direction (see *MSB 97:1*).

PyroSequencing was formed in 1997 as a spin-off company from KTH. This company intends to make simple, accurate and high throughput DNA sequencing quickly available to the expanding genomics and pharmaceutical research sectors, and later to the emerging medical diagnostics segment, a potential multi-billion dollar market (see above text from APB).

Toolex Alpha develops and manufactures equipment for information storage on optical discs (CD, DVD, etc) (*MSB 97:1*).

XaarJet AB (formerly MIT) focuses at producing printheads in high volume (*MSB 99:2*). Although being small-dimensioned devices, suitable materials are not easily micromachined. Material characteristics make silicon less attractive. On the other hand, plastic replicated parts offer opportunities.

Åmic AB provides technology as well as production capacity for replicated polymeric and metallic MST-products (*MSB 99:1*).

Radi Medical Systems AB: The description of medical-related companies in Uppsala would not be complete without mentioning Radi. Their micro-products include pressure sensors (*MSB 93:1* and *99:2*) and possibly also miniaturized X-ray sources (*MSB 99:3*). Unknown at the moment is if replication is a useful technology for their applications.

Jan Söderkvist

MME '99

The 10th *Micromechanics Europe* workshop was held in September in the Paris region. To enhance the workshop spirit, the 49 accepted papers (4 from the Nordic region) were presented as posters combined with short oral introductions. This resulted in many interesting and idea stimulating discussions.

Topics that were stressed included 'Materials and process technology' and Microactuators and microsensors'. To set the stage for discussions, each session included invited review styled oral presentations addressing topics such as electrodeposition, thick layer resists, ferroelectric thin films, InP-MOEMS, magnetic fluids, biomedical applications, and industrial MEMS on SOI.

For the next *MME*, see *MSB*'s last page.

Eurosensors XIII

The 13th *European Conference on Solid-State Transducers* was held in The Netherlands Congress Center in The Hague on September 12–15. The conference was splendidly organized by a team from the Technical University in Delft headed by Prof. Reinoud Wolffenbuttel. The conference was opened with an obituary by Prof. Peter Hauptmann, Uni-Magdeburg, and one minute of silence to commemorate the unexpected and tragic death of Prof. Wolfgang Goepel.

The technical program consisted of 3 keynote papers in a plenary session, followed by parallel oral and poster sessions with 12 invited papers, 120 regular oral presentations and 134 posters. The first keynote speaker was Dr. Jiri Marek, Robert Bosch, who gave an inspiring talk on the growing importance of microsystems for automotive applications, in particular for emission control, safety and comfort electronics. The level of integration of sensor and electronics is very high in all of these high volume applications. Microsystems offer reduction of cost, size and weight, as well as improvements in reliability and functionality.

The Nordic countries were well represented with a large number of delegates as well as scientific contributions, including two invited papers. Jochen Kuhmann, MIC, Denmark, presented advanced hybrid stacking technologies developed by MIC and LETI (France), which are now industrialized in the ESPRIT-project HISTACK. Ylva Bäcklund, Uppsala University, Sweden, presented the use of alternative materials such as diamond thin films and injection-molded thermoplastics, both using micromachined silicon as a mold.

All in all, the quality of the contributions was high, and in particular that of the posters. In parallel to the technical program there was a traditionally small exhibition with vendors of CAD-tools-for-MEMS, processing equipment and publishers, as well as a job market. There were 440 registered participants.

The conference ended with a lively, memorable plenary session with all participants cramped in a parallel session room without air conditioning. Best paper awards were presented and the venue and date of next year's *Eurosensors* conference was announced (see *MSB*'s back page).

Siebe Bouwstra

PUBLICATIONS

- Adhesives in Micromechanical Sensor Packaging; O. Rusanen (VTT); *Doctoral thesis* (2000).
- Anodic Bonding for the Fabrication of Self-Testable Pressure Sensors; A. Cozma Lapadatu (SensoNor / K.U. Leuven); *Doctoral thesis*, ISBN 90-5682-185-7 (1999).
- Decreasing the Optical Path Length in an Optoelectronic Module Using Silicon Micromachining; Å. Richard, P. Rangsten, C. Strandman and Y. Bäcklund (UU); *J. Micromech. Microeng.*, **9**(2) (1999) 127–129.
- Evaluation of Mechanical Materials Properties by Means of Surface Micromachined Structures; J.-Å. Schweitz and F. Ericson (UU); *Sensors and Actuators A*, **74**(1–3) (1999) 126–133.
- Fabrication and Characterization of a Piezoelectric Accelerometer; R. de Reus (MIC), J. Ole Gulløv and P.R. Scheeper (Brüel & Kjær); *J. Micromech. Microeng.*, **9**(2) (1999) 123–126.
- In the Structure of Microstructure Technology; M. Vangbo (UU); *Doctoral thesis*, *Acta Univ. Ups. 475*, ISBN 91-554-4537-3 (1999).
- Mechanical Considerations in the Design of a Micromechanical Tuneable InP-Based WDM Filter; S. Greek, R. Gupta and K. Hjort (UU); *J. Microelectromech. Systems*, **8**(3) (1999) 328–334.
- MEMS Applications in Turbulence and Flow Control; L. Löfdahl (CTH) and M. Gad-el-Hak (Univ. of Notre Dame, U.S.A.); *Progress in Aerospace Sci.*, **35** (1999) 101–203.
- MEMS Packaging; O. Rusanen (VTT); *Proc. IMAPS Nordic 36th Annual Conf.*, Helsinki, (Sept. 19–22, 1999) 125–132.
- Microelectronics for Micromechanics; L. Johansen (MIC); *Doctoral thesis* (1999).
- Microstructure Technology in Silicon, Quartz, and Diamond; P. Rangsten (UU); *Doctoral thesis*, *Acta Univ. Ups. 484*, ISBN 91-554-4572-1 (1999).
- Multiple Through-Wafer Interconnects for Stacking of Microelectromechanical Devices; M. Heschel (MIC); *Doctoral thesis* (1999).
- Nordic Collaboration in Micromachine Technology; F. Grey (MIC); *Proc. 5th Micromachine Symp.*, Japan, (Oct. 28–29, 1999).
- Perforated Silicon Nerve Chips with Doped Registration Electrodes; in vitro Performance and in vivo Operation; L. Wallman[1], A. Levinsson[2], J. Schouenborg[2], H. Holmberg[2], L. Montelius[1], N. Danielsen[2] and T. Laurell[1] ([1]LTH, [2]LU); *IEEE Trans. Biomedical Eng.*, **46** (1999) 1065-1073.
- Porous Silicon Carrier Matrices in Micro Enzyme Reactors - Influence of Matrix Depth; J. Drott (LTH), L. Rosengren (UU, APB), K. Lindström and T. Laurell (LTH); *Mikrochimica Acta*, **131** (1999) 115–120.
- Residual Stress in Sputtered Gold Films on Quartz Measured by the Cantilever Beam Deflection Technique; G. Thornell, F. Ericson, C. Hedlund, J. Öhrmalm, J.-Å. Schweitz (UU) and G. Portnoff (Quartz Pro); *IEEE Trans. Ultrason., Ferroelect., and Freq. Contr.*, **46**(4) (1999) 981–992.
- Silicon Carbide Field-Effect Devices Studied as Gas Sensors for Exhaust Gas Monitoring; P. Tobias (LiU); *Doctoral thesis*, ISBN 91-7219-492-8 (1999).
- Tantalum Oxide Thin Films as Protective Coatings for Sensors; C. Christensen, R. de Reus and S. Bouwstra (MIC); *J. Micromech. Microeng.*, **9**(2) (1999) 113–118.

Dissertations

Courtesy of Ovako Stål

MSB wishes to congratulate the following individuals on their successful PhD work:

Matthias Heschel, MIC/DTU
Multiple Through-Wafer Interconnects for Stacking of Microelectromechanical Devices

This work applies to the interconnect wafer of a new packaging concept for integrated microphones (*MSB 99:3*).

The interconnect wafer is provided with multiple interconnects through the wafer, under bump metallizations (UBM), solder bumps, solder sealing rings on one side, and top surface metallizations for conductive adhesive bonding on the other side. The entire metallization system, including the patterning of the metallizations using an electrodepositable photoresist (EDPR), is based on cost-effective electroplating techniques. Several EDPR processes have been developed and optimized, and suitable etching and lift-off techniques have been investigated.

The feedthrough interconnects have been optimized for low series resistance and small parasitic capacitance. Their wire parameters and the coupling between adjacent feedthrough interconnects have been characterized electrically.

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Leif Johansen, MIC/DTU
Microelectronics for Micromechanics

Processes for monolithic integration of SOI CMOS circuits and surface micromachined electroplated nickel microstructures have been developed.

Compared to bulk CMOS, SOI CMOS requires less complicated processing and has several electrical advantages, such as the elimination of latch-up, low body-effect, reduced leakage currents and improved high temperature operation, which makes it attractive for sensor applications. For microstructures, electroplated nickel supersedes polysilicon in terms of mechanical properties, deposition rate and temperature, complexity and overall production cost.

The aim is a simple, robust SOI CMOS process with an add-on electroplating post-processing module for fabrication of e.g. comb resonators and accelerometers. The low temperature used in this add-on process makes it applicable to most fully processed microelectronics circuits, and it thus has potential of becoming a key technology for MST.

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Pelle Rangsten, UU
Microstructure Technology in Silicon, Quartz, and Diamond

This thesis addresses different fabrication processes for three completely different materials.

The work on single crystalline silicon includes a pressure sensor-based system, an electrostatic actuator structure, and a non-planar lithography technique.

For single crystalline quartz, more fundamental fabrication processes are treated. Experiments and simulation of wet etching in quartz, as well as quartz-to-quartz direct bonding are presented.

Processes and applications of the new and very promising MST material, diamond, are also presented. This part of the work includes a replication technique for microstructuring of polycrystalline diamond, as well as microfluidic applications and an X-ray source based on field emitting structures (*MSB 99:3*).

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Peter Tobias, LiU
Silicon Carbide Field-Effect Devices Studied as Gas Sensors for Exhaust Gas Monitoring

Metal-insulator-silicon carbide (MISiC) devices change their electrical characteristics when exposed to different gas ambients (*MSB 95:2*). Due to the short response time (milliseconds) they were found to detect exhaust pulses from individual cylinders when used as lambda-sensors in cars. Miniaturization is possible since the response does not scale with size.

The work includes the preparation and characterization of the sensor and the modeling of the detection process. A simple method for exchanging the gas within a millisecond is introduced for response time measurements. Results show that the response to hydrogen is faster than that to hydrocarbons, the response to oxygen is slowed down after a pulse of hydrocarbons, and the relationship between mass transport and surface reactions influences the response and determines which gas molecules are predominant on the sensor surface.

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Mattias Vangbo, UU
In the Structure of Microstructure Technology

This thesis focuses on microstructure technology in general. It coarsely delimits the technology and discerns a structure of five different aspects.

Knowledge about the materials is represented by an investigation on etching near-<111> planes of Si in a KOH solution. A method for high accuracy pattern alignment to the crystallographic orientation of Si and InP expands the set of processes that can be used to reign the materials. The art of proper shape design is assisted by an analytical analysis of the snap-through behavior of a double clamped beam. The realized beam also enlarges the set of functional elements available to combine microsystems from. Final consideration regards what function the microstructure has in our society. Here, a simple microstructure, a scanning mirror with the application to project computer graphics onto the eye's retina, is demonstrated.

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Coming Dissertations
The following two theses will be presented after *MSB 99:4* is sent to printing:

Adriana Cozma Lapadatu
SensoNor / K.U. Leuven
Anodic Bonding for the Fabrication of Self-Testable Pressure Sensors
This work deals with wafer bonding technologies as tools for the fabrication of stacked micromechanical structures. Emphasis is put on silicon-glass anodic bonding. Issues investigated include the electrostatic forces developed during bonding and their effect on flexible structures, and the electrical characterization of bonded silicon. These studies led to an improved bonding process with increased bond quality, speed and yield, and reduced negative effects on the bonded devices.

This technology is applied to the fabrication of pressure sensors with self-testing capabilities (*MSB 99:3*). The self-test function is implemented by means of an actuation process applied to the pressure sensitive membrane. Measurements performed on a double-membrane pressure sensor / bimetallic actuator prove the feasibility of the concept.

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Outi Rusanen
VTT Electronics
Adhesives in Micromechanical Sensor Packaging

This thesis presents knowledge for selection, use and reliability assessment of isotropically conductive adhesives (ICAs) in die and flip chip bonding, as well as a lifetime model of ICA flip chip bonds in thermal cycling. The lifetime of ICA bonds is shown to be less influenced by non-recoverable strain than is the lifetime of solder bonds. Thus, ICAs may outlive solder in applications of cyclic operation, such as underhood automotive electronics.

Adhesives in MEMS sensor packaging is also looked into. Evaluated MST applications include an IR spectrometer, a microphone and a differential pressure sensor. The effect of packaging on the performance of the microphone and pressure sensor was also evaluated by measurements. The results showed that the effect of packaging was negligible and that these devices can be used in a wide temperature range, e.g. between -40°C and +60°C.

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MICRO STRUCTURE BULLETIN NO.99:4–00:2 NOV 1999

Eurosensors XIV

The *Eurosensors* meetings, organized since 1987, is a forum with a twofold mission:

- The presentation of recent high-quality research in the fields of solid-state transducers and microsystems
- The gathering of, primarily, European researchers to enable efficient pan-European networking and interaction between industry and academia.

Next year's *Eurosensors* will be hosted by Denmark on August 27–30, 2000, with the venue in the center of Copenhagen. Deadline for the submission of abstracts is March 6, 2000. See below for contact information. Welcome.

MME '00

For more than 500 years, Uppsala has been an inspiring environment in the sciences, literature and art. We would like to share this atmosphere of tradition and inspiration with you.

Since 1989, the workshop on *Micromachining, Micromechanics and Microsystems* has traveled all over Europe in its aim to promote research and development in European micromechanics in order to prepare the microsystems community for international competition. In the year 2000 (Oct. 1–3), we'll meet again when Uppsala University hosts the 11th *MME* workshop.

See 'Future Events' for contact information. Welcome.

FUTURE EVENTS

MEMS-2000, Miyazaki, Japan, Jan. 23–27, 2000.
mems@mesago-jp.com
www.mesago-jp.com/mems

MSM 2000, San Diego, U.S.A., March 27–29, 2000.
wenning@dnai.com
www.cr.org/MSM2000

MICROMAT2000, Berlin, Germany, April 17–19, 2000.
michel@izm.fhg.de
www.micromaterials.com

Silicon Radiation Sensors (course), Oslo, Norway, May 4–5, 2000.
fsrm@fsrm.ch, www.fsrm.ch

μTAS 2000, Enschede, The Netherlands, May 14–18, 2000. *Abstract deadline: Jan. 8, 2000.*
mutas2000@cat.utwente.nl
www.el.utwente.nl/mesa/mutas2000

Micro Actuators (course), Uppsala, Sweden, May 25–26, 2000.
fsrm@fsrm.ch, www.fsrm.ch

ACTUATOR 2000, Bremen, Germany, June 19–21, 2000. *Abstract deadline: Nov. 30, 1999.*
actuator@messe-bremen.de
www.actuator.de

Eurosensors XIV, Copenhagen, Denmark, Aug. 27–30, 2000. *Abstract deadline: March 6, 2000.*
eurosensors@vanhauen.dk
www.eurosensors.dk

Microsensor Packaging (course), Lyngby, Denmark, Aug. 31–Sept. 1, 2000.
fsrm@fsrm.ch, www.fsrm.ch

MME'00, Uppsala, Sweden, Oct. 1–3, 2000. *Abstract deadline: June 15, 2000.*
mme00@angstrom.uu.se
www.mst.material.uu.se/MME00

Microsystems in Biomedical Engineering (course), Stockholm, Sweden, Oct. 2–3, 2000.
fsrm@fsrm.ch, www.fsrm.ch

Transducers '01, Munich, Germany, June 10–14, 2001.
oberm@mat.ee.tu-berlin.de

New NEXUS-EMSTO website: www.nexus-emsto.com

THE AIM OF the *Micro Structure Bulletin* (*MSB*) is to promote the industrial use of micromachining, microsystem technology and components based thereon, and to serve as an informal link between people in industry and academics actively working in this field. *MSB* is one part of a joint Nordic effort to disseminate scientific and technological information.

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