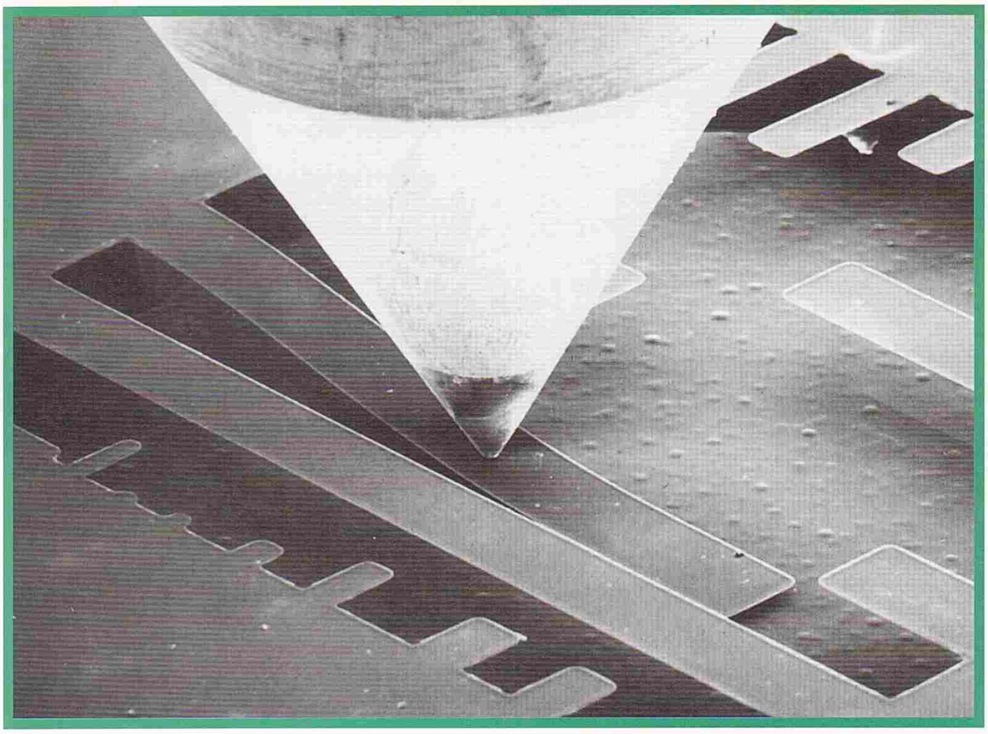
MICRO STRUCTURE BULLETIN

Newsletter for Swedish Micro Structure Technology No. 1 Feb 1994

Silicon Wet Etching



Beams and bridges created by dopant selective etching. The bridge is 0.2 mm wide.

The main topic of this issue is etching. Because of the well-ordered structure of crystalline materials you can fabricate several interesting geometric shapes using selective etching. Membranes and walls with controlled thicknesses, and deep wells, are three frequently used shapes. Combining these building blocks into more complex structures unfolds numerous possibilities to create many useful designs.

Pages 3 and 4

Monolithic Accelerometer

Environmental and reliability requirements of the military industry compare with those of the automotive industry. An essential difference is that an essential priority in military applications is miniaturization, while in automotive applications it is low cost. In both cases Micro Structure Technology is a viable alternative. The initiative for the presented accelerometer came from industry, at first to learn about micromachining. However, the performance of the device was such that it is now scheduled to be included in applications.

Page 2

MST has turned out to be one of the key technologies for developing components used in Bofors´ systems. Bofors has established a close cooperation with Chalmers University of Technology at the front end of key technologies, including micromechanics, primarily in silicon.

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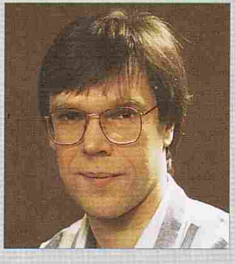
EDITOR'S NOTE

This issue of *Micro Structure Bulletin (MSB)* features the first of a series of articles on micromachining basics. Fabrication steps, materials, applications areas, etc. will be introduced one at a time in an informative way. The first article deals with etching, one of the most essential manufacturing steps.

The response to the first issue has been very positive, outside Sweden also. Naturally, the intention is to meet these high expectations. More than 35% of the foreign addressees have expressly requested future issues of *MSB*. Let's try to beat this percentage in Sweden. We also encourage you to put *MSB* on circulation within your organization.

One purpose of *MSB* is to stimulate MST and micromachining. The workshop *MSW '94* has the same purpose, so make sure to reserve March 24-25. Note also the possibility for you to present your MST-activity at *MSW '94*.

I want to conclude with a saying which describes the early days of micromachining: "The only way to discover the limits of the possible is to go beyond them into the impossible" (Larke's second law, the essence of research).



Jan Söderkvist

A Simple Monolithic Accelerometer

The development of this monolithic silicon accelerometer started as a study of MST technologies in 1987. Bofors decided to gain knowledge about MST by making an accelerometer. The reason for choosing an accelerometer is obvious: acceleration is one of the most important parameters needed to verify that a missile is moving. The accelerometer signal is integrated to obtain the velocity. For some applications a second integration, giving the distance flown by the missile, is of interest. You can use this further information in the safety and arming devices of the missile.

The entire project consists of two hardware realizations: one accelerometer and one Application Specific Integrated Circuit (ASIC) for signal conditioning. This article focuses only on the accelerometer die.

Design

The design of the accelerometer is really straight forward. The principle part is a piezoresistive device that handles linear acceleration as opposed to non-resonant piezoelectric accelerometers with primarily AC-response.

The sensor consists of a seismic mass with a cantilever beam on one side. A frame surrounds the mass and cantilever and supports the cantilever. A single sided supported mass ensures well-defined temperature characteristics. If you use twin-sided supported mass with two or four cantilevers you cannot predict the sign of the temperature coefficient of the sensitivity. This is because beams buckle unpredictably, either upwards or downwards, when exposed to thermal expansion. With a single-sided supported mass the buckling tendency due to thermal expansion is eliminated.

This design, however, gives you a non negligible cross-axis sensitivity, especially to acceleration along the cantilever. In our application this is of no importance. If cross-axis sensitivity is important to your application you may need a two- or even a four-sided support of the mass. In this case you might need a smart shape of the cantilevers to have well-defined temperature behavior.

Electronics

The electrical circuit on the accelerometer is a conventional Wheatstone bridge with open ground for optional offset adjustment. The entire bridge is integrated on the die so that all the resistors have the same temperature characteristics. This minimizes the temperature coefficient of the sensitivity.

No extraordinary dimensions or dopant levels are used. The dopant level chosen optimizes the Temperature Coefficient of Resistance (TCR) and π_{44}, which is the piezoresistive coefficient used in this device.

Damping

The accelerometer is damped with silicon oil to survive accelerations within specifications at the first order mechanical resonance frequency. The oil also provides good shock resistance. The silicon manufacturing process is less critical and less expensive for liquid-damped compared to air-damped accelerometers. Naturally you have to take good care in handling the silicon oil ... .

Packaging

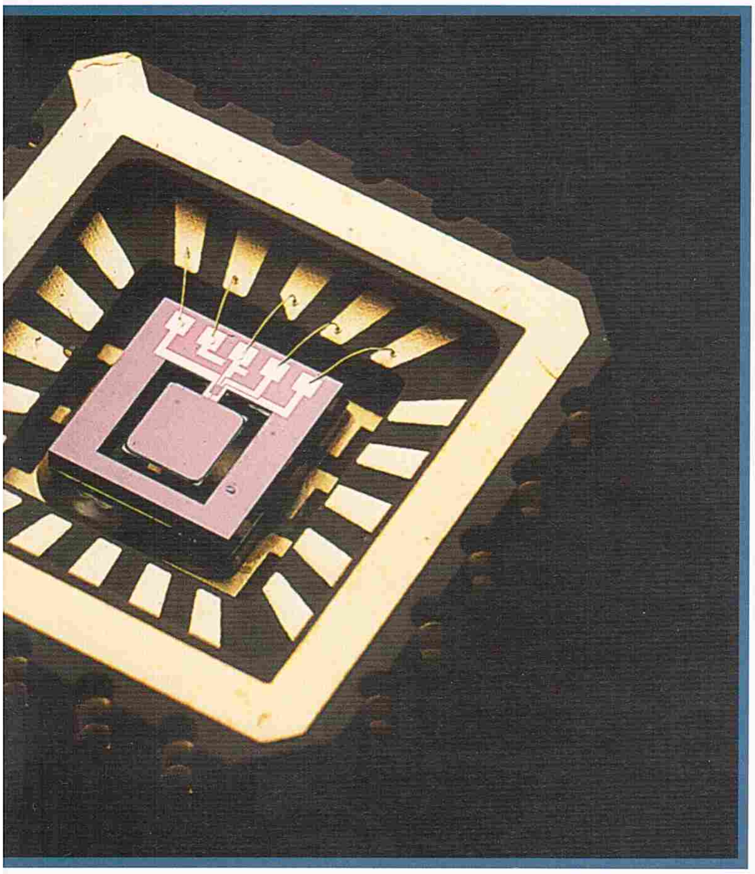
Just as most manufacturers of micromechanics we put a lot of effort into finding a suitable package. The prototypes use the Ceramic Lead-Less Chip Carrier (CLCC) shown in the photo. With this package we could not fill the device with silicon oil in a cost-effective way since this package is intended for "dry" electronic circuits. Nevertheless, we did fill the device and could test the prototypes. They performed excellently!

The key to success when going from silicon structures to a working device is to consider all aspects, including packaging. Most universities do not take this global view. The reason is obvious: at university you deal with phenomena, not with industrial components. The packaging aspect is especially important when using silicon oil, gel, or rubber in your application. The reason for care is that low molecular silicones creep or outgas oil etc. These properties will give you trouble with solderability or increased contact resistance in relays etc. Though, if handled with care silicon oil is a wonderful thing!

Development Strategy

If you are not working at a company experienced in and focusing on MST, you will do well to cooperate with a university in developing the silicon structures. Meanwhile, consider the package from all aspects:

- space
- mounting
- bonding
- compatibility with manufacturing equipment



The piezoresistive silicon accelerometer in its Ceramic Lead-Less Chip Carrier (CLCC). The seismic mass and the thin supporting cantilever beam are fabricated with wet etching.

This accelerometer is a cooperative effort between Bofors and Chalmers. The Bofors company is responsible for the design of the accelerometer die and the package. Chalmers University of Technology developed and machined the silicon structures. We conclude by stating that this is a very (cost-) efficient way of running an MST project!

Hans Richert ■

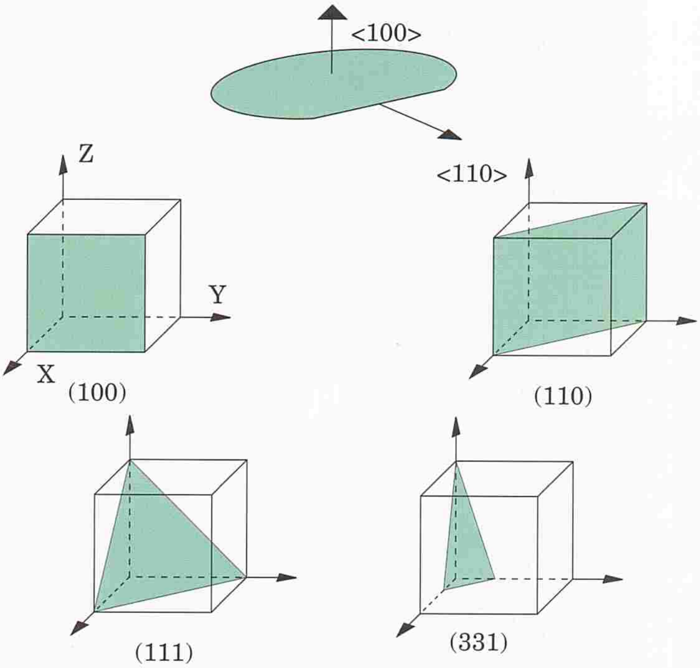
PIEZORESISTIVITY

The resistivity of semiconductors depends, normally, on the stress in the material. In silicon, the effect is mainly due to a direction-dependent change in electron mobility, and exceeds stress-induced dimensional change by a factor of about 50.

The relative change in resistivity equals a constant, π, times the mechanical stress. The stress may also generate asymmetries. In consequence, a voltage, proportional to a shear stress, may appear perpendicular to an applied electric field. This is defined as the shear piezoresistance component, π_{44}.

Micromachining Basics Part 1:

On the Crystal Structure of Silicon



A silicon wafer is monolithic; which means that it is a single crystal - if you know how the atoms are arranged in one area of the wafer, you automatically know how all atoms in the wafer are arranged.

Silicon has the same crystallographic structure as diamond, i.e. every atom is bound to four neighbors in a tetrahedral configuration. This is a strong structure because of the covalent bonds between the atoms.

There are three fundamental atomic planes in the silicon crystal, identified by their so called Miller indices, {100}, {110}, and {111}. There are also higher order crystal planes, such as {331}. Think of the structure as a cube with {100}-planes as its sides. You get a {110}-plane by cutting away a cube edge, and a {111}-plane if you cut off a corner.

Silicon wafers available on the market are usually cut so that their surface coincides with one of the three fundamental planes, and are named thereafter. Hence, a "(100)-wafer" has a "cube side" as its surface. An additional reference for the circular wafer is given by a missing segment, the "wafer flat". These two reference directions give all essential information on the orientation of the crystal.

For being a single crystal, a high quality silicon wafer is remarkably free of dislocations and other imperfections. Taking into account that micromachined devices have very minute dimensions, statistics tell us that these devices have a fair chance of being defect free at critical places. This gives a construction material that can be many times stronger than steel.

Lars Rosengren
Uppsala University

■

Micromachining Basics Par

Silicon Wet Et

When working with micromachining you need to both add and remove material in a controlled way. Adding material can be done physically, e.g., by bonding two wafers together or by epitaxial growth on a wafer. Material can also be added chemically, e.g. by electroplating or by chemical vapor deposition (CVD).

Removing material is done almost exclusively by chemical etching, where atoms are removed one by one. This can be done either in a liquid (wet etching and chemical polishing), or in a plasma, (dry etching).

Chemistry of Wet Etching

The chemical mechanisms behind silicon wet etching are not fully understood. One explanation is that the removal of a silicon atom in an alkaline solution takes place in two steps. In the first step four electrons are injected into the silicon bulk:

$Si + 4(OH)^- \rightarrow Si(OH)_4 + 4e^-$

The $Si(OH)_4$ is dissolved in the solution. In the second step the electrons are released back into the solution according to:

$4e^- + 4H_2O \rightarrow 4(OH)^- + 2H_2$

Anisotropy of Wet Etching

Many etchants etch silicon anisotropically, i.e., at different speeds in different crystal directions. The final shape of an etched wafer depends highly on the relative etching speed of the different crystallographic planes.

The {111}-planes are almost inert to these etchants, while the relative etching speeds for other planes depend on the etchant, temperature, concentration, additives etc. Potassium hydroxide (KOH), for example, etches {110}-planes faster than {100}-planes; but, if isopropylic alcohol (IPA) is added, this relationship is reversed: {110}-planes can be revealed while {100}-planes are etched away faster.

However, there are etchants that etch silicon isotropically, at the same speed in all directions. These etchants come in handy when the desired etch pattern does not coincide with the crystallographic planes, e.g., for a circular hole. The isotropic etchants are usually based on hydrofluoric acid, acetic acid and/or nitric acid.

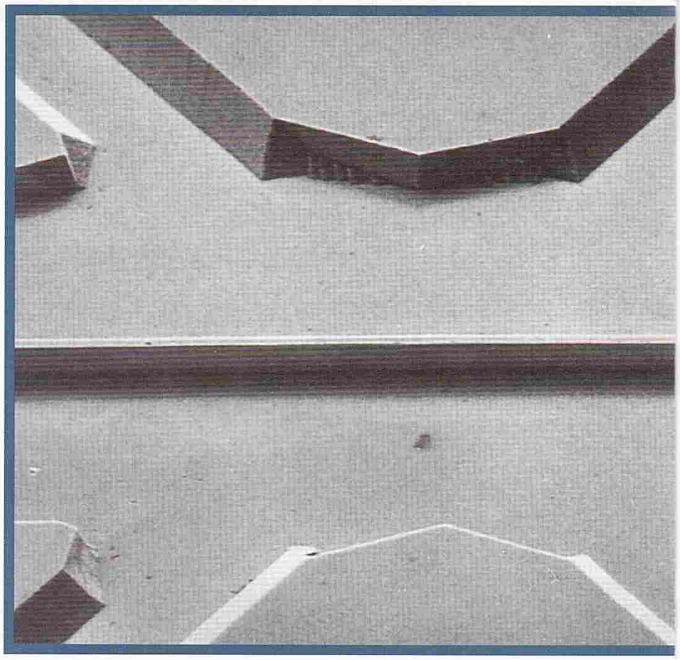
Etchants

Several etchants exist with various merits and drawbacks. KOH, the most commonly used etchant, has the disadvantage of containing potassium, which contaminates wafer and furnace. Potassium and sodium destroy the electric properties of silicon and are not sweetly looked upon by the semiconductor industry. Ethylene diamine pyrocatechol (EDP) is an etchant, which, unlike KOH, does not contain potassium or sodium contaminants, but is poisonous and nasty to work with. Ammonium hydroxide solutions have been tested, but these etchants do not as yet produce smooth surfaces nor are they widely used. Still the most simple and versatile etchant is KOH, if you can live with the potassium contamination.

Masking

To remove material in selected areas, you need to protect the surface elsewhere. Silicon oxide (SiO_2) is a chemically resistant material easily formed by heating the wafer in an oxygen atmosphere. The oxide can be patterned by covering it with a light-sensitive film, called "photoresist". The photoresist is exposed to UV-light in selected areas through a photographic mask.

The exposed resist is easily removed revealing the underlying oxide. This oxide can, in turn, be removed by hydrofluoric acid (HF) which does not etch silicon significantly. If the wafer is now exposed to a reactive etchant, unprotected silicon atoms are removed, while the atoms protected by the oxide layer are left unaffected.



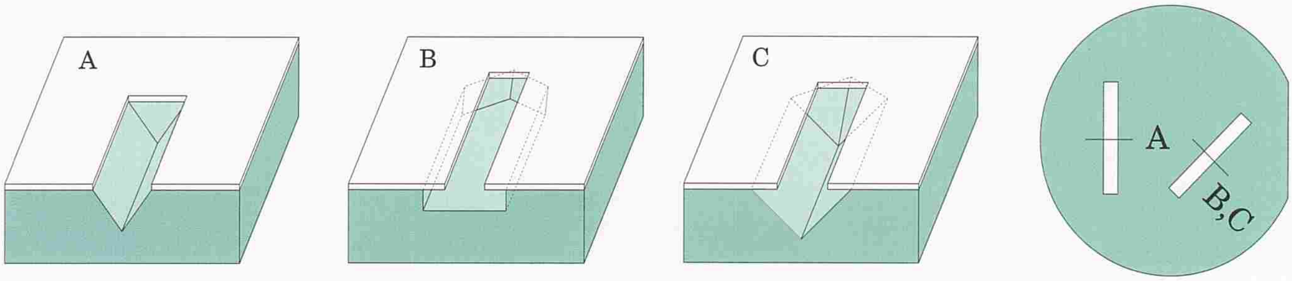
The anisotropic etching properties of silicon demonstated of a beam-s
Fibers are positioned in the diagonal V-grooves. Part of the light is re
in the center. The entire structure is made in just one etch step. The va
walls is due to the anisotropy.

Geometry

The shape of an etched concave corner, such as the bottom of an etch pit, is defined by slowly etched planes such as {111}. Other exposed planes etch away faster and leave the pit to these {111}-planes. The more prolonged the etch, the more the pit will be dominated by {111}-planes, since these are the most slowly etching planes of all.

A convex shape, such as an outer corner, is blunted by fast etching planes, such as {331}-planes, as illustrated above. Slow etching planes are attacked from the edges and are therefore removed. This makes sharp outer corners difficult to obtain without careful design of the etch mask.

In a (100)-wafer, four {111}-planes are inclined at 54.7° to the surface. Since anisotropic etching virtually stops at these planes, a square mask opening etched long enough produces a pyramidal pit. If the square is stretched to a long thin line, the etch pit will turn into a long groove with a V-shaped cross-section, (see groove A). This so-called V-groove can be used for positioning of e.g. optical fibers



2:

ching

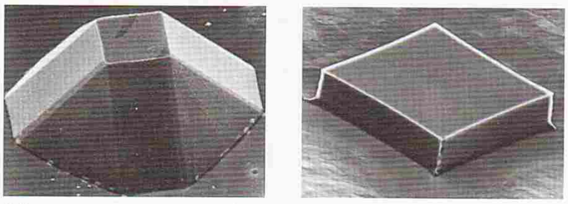
litter for optical fibers.
lected by the vertical wall
iation of the incline of the

or provide channels for distribution of fluids.

In fact, any mask opening in a (100)-wafer will turn into a square etch pit with four inclined {111}-walls if etched long enough.

In addition, if the etchant is KOH, {100}-planes are also etched relatively slow. If a square mask opening is rotated 45° relative to the wafer flat, these {100}-planes, vertical to the surface, are revealed (see groove B). If EDP is used as etchant (or, as previously mentioned, if IPA is added to KOH), {110}-planes etch slower than {100}-planes, resulting in V-grooves with a 45° angle to the surface (see groove C).

In a (110)-wafer, on the other hand, there are two, inert, {111}-planes perpendicular to the surface. If the V-groove mask is applied to this wafer, you can create very deep and narrow trenches. These trenches can be used, e.g., to maximize the area/volume ratio for cooling or for surface confined chemical reactions.



Mesa structures manufactured in a (100)-wafer from identical mask and wafer orientation by etching in a) EDP and b) KOH.

Etch Stop Techniques

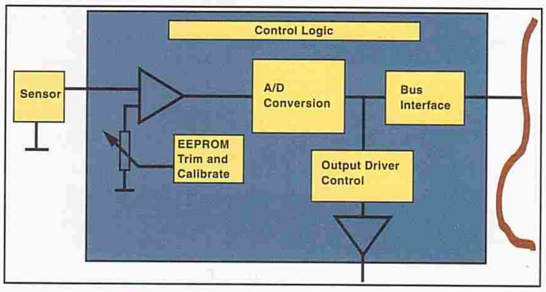
As mentioned earlier, a SiO_2 layer covering the silicon surface protects it from being etched. Another way of protecting the surface is to deposit a silicon nitride layer using CVD. This layer is even more resistant to most chemicals and etchants, such as HF and KOH. However, this resistance implies more complex patterning and removal processes.

Surface protection is often sufficient, but for some structures you need to treat parts of the silicon material itself to render it inert to the etchant, e.g. when etching beams and membranes. You can accomplish this by doping the material heavily with, e.g., boron. Silicon, boron-doped to around one atomic percent, is not etched by most etchants. A thin beam with a controllable thickness can be produced in this way if the wafer is doped in a beam pattern from one side. Etching the wafer from either side then reveals the beam since the doped areas are left intact (see front page figure).

There is a more subtle way of dopant selective etching. If a wafer has areas of both p- and n-type, and the wafer is biased with a certain electric potential relative to the etchant, the p-type material is removed, while the n-doped areas are left unetched.

By creatively combining all these crystal properties and manufacturing techniques in your tool box, you are well prepared to create a silicon wafer tailored to your specific design.

Lars Rosengren
Uppsala University ■



MEMS '94

The seventh IEEE Workshop on Micro Electro Mechanical Systems (MEMS '94) was held this year from January 25 - 28 in the Oiso Prince Hotel, Kanagawa, Japan. The workshop provides researchers an annual international forum for the presentation and discussion of the latest developments.

Focus is on the design, modeling, fabrication, operation and application of devices, machines and systems containing electromechanical elements in the micrometer to millimeter scale. During the meeting 3 invited speaks and 61 selected papers – 36 oral and 25 poster presentations – were presented to the 256 participants.

Interesting contributions in several different sessions dealt with: microfluid handling, modeling, sensors, actuators, fabrication methods, microrobotics, materials, teleoperation/micro-assembly, and devices/systems. Sweden was represented by Industrial Microelectronics Center (IMC). Their contribution was a fabrication method for capillary channels intended for chemical analysis. In addition, Uppsala University co-authored a contribution on etching with the University of Twente, The Netherlands.

Next year's MEMS workshop will be held in Amsterdam, The Netherlands.

Wlodek Kaplan, Industrial Microeletronics Center

MST at Bofors Missiles

Bofors started the activities in the MST area in 1987. The original aim was to gain knowledge about MST. MST has turned out to be one of the key technologies for developing components used in Bofors´ systems.

So far, one department in Gothenburg is responsible for designing and consulting of MST components and/or systems at Bofors. Bofors has established this department in Chalmers Teknikpark to enjoy close cooperation with Chalmers University of Technology at the front end of key technologies, including micromechanics, primarily in silicon.

The accelerometer has matured from a technology project to a component to be used in production. During this work a number of ideas were generated about new components and structures based on MST. This was possible partly due to a fruitful exchange of knowledge between Chalmers and Bofors; we have established a beneficial relationship in the interface between the academic and the industrial field.

At Bofors, all calculation and design, i.e. all theoretical modeling, are performed with knowledge about what is possible to achieve with given processes. We can thus optimize the performance of a device since we know all data about the system in which the device will be placed. Hence, we do not need to share the sensitive or classified information which often is required to design an MST-component adequately.

So far, Bofors has decided not to start a silicon fab to manufacture the devices. We believe that cooperation with a suitable department at a university or research institute is far more cost-efficient. Of course, you cannot bring a full-scale mass production task to a university since the university focuses on basic research. However, our experience is that small development and pilot scale projects are welcome. This really indicates that the research work performed can be used in ”real life”.

When prototypes of a new device are ready for manufacture, we bring the device concept to the facility with which we want to cooperate with. We begin by sharing the information needed to start thinking about the process flow, etc. Together we define the activities to pursue the task; this includes Bofors' unlimited access to the fab to follow the work. In this way we can discuss and solve difficulties together during the process flow. MST activities are growing continuously and we continue to establish new contacts for cooperation both in Sweden and abroad. Our ”idea of business” is always to focus on components for industrial use. We have seen that MST is very useful provided you consider that micromachining is only one, however important, aspect when designing the device. Always cogitate over how to design the micro-

PUBLICATIONS

The following list shows some Swedish MST-related results published during the last months:

- A Micromachined Enzyme Reactor in (110)-Oriented Silicon; T. Laurell (LTH) and L. Rosengren (UU); *Sensors and Actuators B,* 19(1-3) (1994).

- Characterization of Spontaneously Bonded Hydrophobic Silicon Surfaces; K. Ljungberg, A. Söderbärg (UU), S. Bengtsson and A. Jauhiainen (CTH); *J. Electrochem. Soc.*, 141(2) (1994) 562-566.

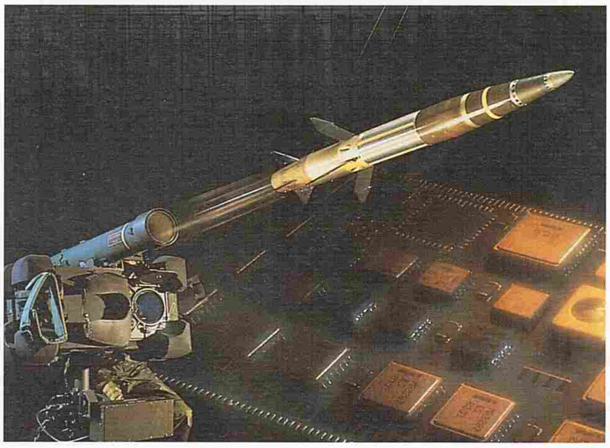
- Conducting Polymers as Artificial Muscles: Challenges and Possibilities; E. Smela, O. Inganäs and I. Lundström (LiTH); *J. Micromech. Microeng.*, **3**(4) (1993) 203-205.

- Micromachined Gyroscopes; J. Söderkvist (Colibri); *Sensors and Actuators A,* **43**(1-3) (1994).

- Micromachined Optical Planes and Reflectors in Silicon; L. Rosengren, L. Smith and Y. Bäcklund (UU); *Sensors and Actuators A,* 41(1-3) (1994) 330-333.

- Micromechanics — Fabrication Processes and Fluid Components; U. Lindberg (UU); Doctoral thesis, Acta Univ. Ups. #9 (Dec. 1993), ISBN 91-554-3196-8.

- Silicon Microstructures — Fabrication Techniques and Applications; L. Smith (UU); Doctoral thesis, Acta Univ. Ups. #8 (Dec. 1993), ISBN 91-554-3195-X.



AB

machined structure to be (re)produceable. Think about the assembly and packaging at the same time you think about microstructure.

So far, one person is fully engaged in coordinating MST activities. Since micromechanics is often used together with microelectronics, a close cooperation with these departments is natural. For more information please contact Hans Richert, Bofors AB, Chalmers Teknikpark, phone +46-31-772 41 46, fax +46-31-772 41 53.

Hans Richert ■

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The price of...

... electronics and sensors per luxury vehicle in the year 2002 is estimated by Ford Electronics Division to be about $2,600: $600 for engine controls, $1,200 for driver information services, and $800 for vehicle controls.

Over the last ten years their warranty service cost on sensors and actuators dropped a factor of ten. In the future, quality parameters will be measured in terms as small as car returns per (ten) million.

Micromachining is one of several technologies which will be used to meet the demands.

DISSERTATIONS

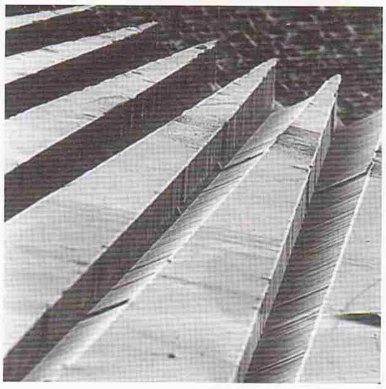
Recent Dissertations

MSB congratulates both Ulf Lindberg and Leif Smith, Uppsala University, on successfully having defended their theses on December 10, 1993.

Leif Smith

His thesis, *Silicon Microstructures — Fabrication Techniques and Applications*, comprises investigations from basic process technology through fabrication of advanced microstructures in silicon using silicon bulk micromachining. The processes investigated are silicon fusion bonding and electrochemical etching. The investigations have increased knowledge about bonding technology, and helped in the development of a novel etch stop technique based on accumulation of free carriers. Novel silicon microstructures presented are: beam-splitters (se figure on page 5), a non-reverse valve, and small orifices, fabricated using anisotropic and dopant selective wet etching. Also included are proposed designs for capacitive pressure sensors and an electrostatically driven bimorph actuator.

Further, design of an ultra miniaturized fiberoptic pressure sensor with an overall diameter of 0.35 mm is presented (ed. note: see last issue of *MSB*). This sensor has been investigated in terms of dynamic response, modulation, and stability, both theoretically and experimentally. In conclusion, the results of this thesis are promising for future applications, such as in: medical manometry, ink-jet printing, drug delivery, and computer communications.



Etched grooves in z-cut quartz. Measurements of the groove walls enable the generation of etch diagrams.

Leif Smith is now working mainly at RADI Medical Systems on the miniaturized fiber optic pressure sensor and partly at the Uppsala University on micromachining research.

Ulf Lindberg

The title of his thesis is *Micromechanics: Fabrication Processes and Fluid Components*. Regarding the fabrication processes, emphasis is put on anisotropic wet etching of quartz and silicon, and the influence of the silicon cleaning and etching processes on the wettability of silicon and its compatibility with insulin. Also shown was the feasibility of a buckling device, where both the magnitude and the direction of a deflection could be controlled. A Finite Element Analysis (FEA) as well as a general theoretical model were used to investigate this phenomenon.

The fluid handling components consisted of a microfabricated non-return valve and a microvial fabricated and evaluated in cooperation with the Analytical Chemistry department at KTH (The Royal Institute of Technology).

Coming Dissertations

Two additional dissertations in the MST-field will be given in Uppsala this semester: Johan Bergqvist on April 22 and Lars Rosengren on May 19.

Naturally, you are welcome to attend their dissertations. ■

• • • Return this slip by mail or by fax (+46-(0)8-510 116 15) • • • • • • • • • • • • • • •

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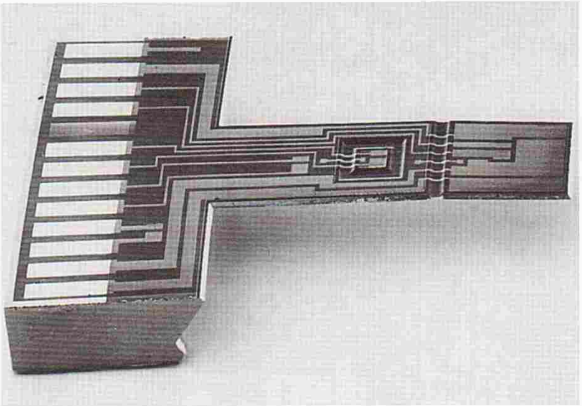
MICRO STRUCTURE BULLETIN NO. 1 FEB 1994

NEXT ISSUE



Some topics in the next issue will be:

- a micromachined gas flow sensor
- detection methods
- MST at The Royal Institute of Technology (KTH)

MSW '94, Micro Structure Workshop
Uppsala, Sweden, March 24-25, 1994

MSW is an informal workshop for those in Scandinavia interested in, or actively working with, MST. You are also invited to present your MST-activity. The official language is Swedish.

For more information return the slip below, or contact: Jan Söderkvist (+46-8-510 116 49) or Ylva Bäcklund, Uppsala University (+46-18-18 30 23).

FUTURE EVENTS

MSW '94, See separate note.

Eurosensors VIII in Toulouse, France, September 25-28, 1994. For information contact: Eurosensors VIII Secretariat, CNRS/LAAS-7, Fax: +33-61 33 62 08.

MME'94 (MicroMechanics Europe) in Pisa, Italy, September 5-6, 1994. *Abstract deadline: June 1.* For information contact: Prof. Dario, ARTS Lab., Pisa, Fax: +39-50-559 215.

MEMS '95 (Micro Electro Mechanical Systems) in Amsterdam, The Netherlands, January 30-February 2, 1995. *Abstract deadline: October 3.* For information contact: Ms. J. Spierenburg, Fax: +31-53 356 770.

Transducers '95 • Eurosensors IX in Stockholm, June 25-29, 1995. For information contact: Carin Palm, Phone: +46-18-18 31 48, Fax: +46-18-55 50 95.

THE AIM OF the *Micro Structure Bulletin* is to promote micromechanics and micro structure technology. It constitutes one part of Uppsala University's effort to share scientific and technological information

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