Delft University Research Center of Intelligent Sensor MicroSystems (DISens)

A Delft University center for research and co-operative projects on Sensors and Actuators in MicroSystem Technology

DISens Symposium
Tuesday, 21 May 2002
Delft, The Netherlands
DISens is an institute of the Delft University of Technology for research and cooperative projects relating to sensor and microsystem technology with the business community and government. Researchers from the faculties Information Technology and Systems, Design, Engineering and Production, Applied Sciences and the Interfaculty Reactor Institute (IRI) participate in DISens.
Preface

Welcome to the First symposium of the Delft University Research Center of Intelligent Sensor Microsystems, DISens.

Sensor microsystem technology represents an important field of research within the Delft University of Technology. To a great extent, the foundation for this field of technology can be found at the DIMES research institute. In addition, several other faculties and institutions within the TU Delft contribute to the research on microsystems.

In order to present the research activities to the University as well as the institutions and industry operating in this field this first DISens symposium has been organized. The programs of the groups participating in DISens are summarized in this symposium book.

DISens was established in a constitutional meeting on September 28, 2001. The final agreement was signed by the board of DISens on January 16, 2002.

The objectives of DISens are:

- to strengthen the cooperation between research groups in this field within the TU Delft.
- to make the sensor microsystems research within the TU Delft known to both industry and society.
- to intensify the cooperation with industry, governments and subsidizing bodies by acting as a clearly recognizable point of contact.

Prof. Dr. ir. J.H. Huijsing   Prof. Dr. P.M. Sarro
Scientific director DISens   Managing director DISens
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1. Organization of DISens

1.1 DISens

**Delft University Center of Intelligent Sensor Microsystems**

“A centre for research and co-operative projects on Sensors and Actuators in Microsystem Technology.”

Address:
Mekelweg 4
ITS Building
2628 CD Delft
The Netherlands

Phone: +31 (0)15-278 5745
Telefax: +31 (0)15-278 5755
E-mail: DISens@TUDelft.nl
Website: [www.DISens.tudelft.nl](http://www.DISens.tudelft.nl)

Scientific director: prof.dr.ir. J.H. Huijsing
Managing director: prof.dr.P.M. Sarro
Secretariat: I. Duurkoop

1.2 Objectives

The objectives of DISens are

- to make the Delft University of Technology known, to both society and industries, as a profound scientific player and partner in the research field of sensor microsystem technology

- to intensify co-operation with industries, governments and subsidizing bodies by acting as a clearly recognizable point of contact as to increase possibilities for externally financed research

- to strengthen the internal co-operative relationships and to improve the coherence between research groups in this field, that are affiliated to various Delft faculties, research schools and/or interfacultary research clusters.
1.3 Research program

DISens has allocated the Delft sensor research to three scientific themes. These themes match carefully with those addressed in the STW programme as essential for sensor research in the Netherlands. The three themes of DISens are also closely related to the core themes of the research policy that is adopted by the Delft University of Technology. This program will focus on, but will not be limited to, themes of large impact on society and on national industrial realities, such as

- Medical and (bio)chemical instrumentation,
- Soil, water and air monitoring,
- Transportation and logistics monitoring,

1.4 Participants

The following faculties and institutions are currently involved in DISens. In the near future, more faculties and research groups may join DISens.

Faculty of Information Technology and Systems
Department of Micro Electronics
Electronic Components, Technology and Materials Lab./DIMES
Prof.dr. C.I.M. Beenakker
Prof.dr. P.M. Sarro

Electronic Instrumentation Laboratory
Prof.dr.ir. J.H. Huijsing
Prof.dr. P.J. French

Faculty of Applied Sciences
Laboratory of Inorganic Chemistry
Department of Chemical Technology
Section for Anorganic Chemistry
Prof.dr. J. Schoonman

Bio Technology Department
Section for Analytical Bio Technology
Prof.dr.ir. G.W.K. van Dedem
Prof. dr. G.M. Schalkhammer

Faculty of Design, Engineering and Production
Medical Technology and Mechatronics Department
Section for Man-Machine Systems
Prof.dr.ir. P.A. Wieringa
Prof.dr.ir. C.A. Grimbergen
Section for Structural Optimisation and Computational Mechanics
Prof.dr.ir. A van Keulen

Section for Micro-mechatronic systems and production technologies for micro-mechatronic systems
Prof.dr.-Ing. habil B. Karpuschewski
Dr. ir. M. Tichem
Prof. dr. ir. J. van Eijk
Prof. ir. O.H. Bosgra

Interfacultary Reactor Institute (IRI)
Radiation Technology Department
Prof.dr.ir. C.W.E. van Eijk
Dr.ir.R.Hollander
2. The DISens research programs

2.1 Microsystems Technology

Faculty of Information Technology and Systems
Electronic Components, Technology and Materials Lab./DIMES
Prof.dr. P.M. Sarro
Prof.dr. C.I.M. Beenakker, Prof.dr. J.N.Burghartz, Prof.dr.L.Nanver,
Ing.B.Goudena

The importance of microsystems, i.e. systems which combine electronic functions with mechanical, optical and others and that employ miniaturization in order to obtain high complexity in a small space, has been widely acknowledged. The advantages related to the use of conventional IC processes to fabricate the various components of a microsystem have been often underlined. This integration is challenged by constrains imposed by the IC process selected and the very tight control on material properties required to produce functioning electronic devices. This requirement, generally referred to as IC compatibility, is one of the most important issues in the development of process flows for integrated sensing microsystems and become of vital importance when moving from demonstrator to product, i.e. when yield, reliability and cost issues are crucial. The approach chosen to satisfy these requirements is to start from a standard baseline IC process and develop post-process modules.

In the ECTM laboratory the Integrated Sensors and MEMS technology group works very closely with the DIMES IC process group on the technology developments fundamental for the integration of sensors and microsystems. At the DIMES Technology Center a well equipped, modern, silicon process facility is available. A 100mm wafer full process line, mask fabrication facility, bipolar and CMOS processes as well as some packaging facilities are accessible to the design community. The DIMES base processes are listed in Table 1.

<table>
<thead>
<tr>
<th>Process</th>
<th>Technology</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIMOS</td>
<td>CMOS</td>
<td>1.5µm</td>
</tr>
<tr>
<td>Dimes-01</td>
<td>Bipolar</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Dimes-03</td>
<td>Bipolar</td>
<td>20 GHz</td>
</tr>
<tr>
<td>Dimes-04*</td>
<td>Bipolar</td>
<td>25 GHz</td>
</tr>
<tr>
<td>Dimes-SiGe*</td>
<td>Bipolar</td>
<td>60 GHz SiGe-BJT</td>
</tr>
<tr>
<td>Dimes-SOA*</td>
<td>Bipolar</td>
<td>Si, SiGe-BJT on SOA</td>
</tr>
</tbody>
</table>

* not yet fully released
In this advanced technological environment research on microsystems technology is carried out. The research focuses on the development of IC-compatible process modules to realize intelligent (micro) sensors and microsystems as well as for integration of RF components in silicon. The DIMES bipolar and CMOS IC processes form the base process to which these modules are added on. Several research programs within DIMES research school as well as within the University and in collaboration with other national or international groups, institutes or companies are supported by this research.

New or modified process modules for microsensors and microactuators; mechanical, optical and electrical characterization of the devices or structures realized, novel etching and deposition techniques, are among the research topics pursued. This wide range of activities in combination with the excellent infrastructure have strengthened our expertise on silicon bulk and surface micromachining, 3D micro-structuring (micro-wells, glass etching, through-wafer holes, through-wafer interconnects), high-ohmic silicon processing for radiation detectors and thin film technology. Some characteristics the process modules are summarized in Table 2.

### Table 2: Process modules for integrated sensors and microsystems

<table>
<thead>
<tr>
<th>Process</th>
<th>Technology</th>
<th>Structures</th>
<th>Dimensions</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk micro machining</td>
<td>Wet etching KOH/TMAH</td>
<td>Si membranes</td>
<td>Membrane thickness</td>
<td>Post-process compatible to Bipolar/CMOS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si beams</td>
<td>≥2µm, SiN: ≥300nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SiN membranes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface micro machining</td>
<td>Sacrificial oxide etching</td>
<td>SiN, poly-Si membranes/atoms</td>
<td>Thickness: Poly-Si: 0.2-1µm SiN: 300-800nm</td>
<td>Partial compatibility Bipolar/CMOS</td>
</tr>
<tr>
<td>Epi-micro machining</td>
<td>Sacrificial oxide Etching, Porous Si</td>
<td>Si, epi-poly membranes/atoms</td>
<td>Poly-thickness 1-10µm</td>
<td>Compatible to Bipolar/CMOS</td>
</tr>
<tr>
<td>Thin film</td>
<td>Thin films technology</td>
<td>SiN, SiO, SiC, poly-Si</td>
<td>Layers thicknesses 0.2-2 µm</td>
<td>Low stress as-deposited films</td>
</tr>
<tr>
<td>Glass</td>
<td>Wet etching</td>
<td>Channels/recesses</td>
<td>Shallow: 1-10µm</td>
<td>Smooth etched surfaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deep: 10-500µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wafer Bonding</td>
<td>Anodic Fusion</td>
<td>Si-glass, glass-glass Si-Si</td>
<td>Intermediate layer</td>
<td>Low temp fusion bonding</td>
</tr>
</tbody>
</table>

Several research projects aiming at developing post-process modules as well as characterizing novel material and microstructures are currently in progress. A few of these projects are briefly presented here.
2.1.1 Silicon Bulk Micromachining for RF applications

Leader: P.M. Sarro
Scientists: J. Burghartz
Post Docs: E. Boellard
PhD students: N.N. Pham
Sponsor: STW

Bulk micromachining of silicon is investigated to develop post-process modules for integration of RF devices. The modules can provide a blanket ground plane at an optimum position beneath the wafer surface, trenches to suppress cross talk through the conductive silicon and the integration of large passive components beneath circuitry for a much reduced chip area, lowering chip size and cost.

Currently, two post-process modules, one for blanket metal and the other for patterned metal are available to designers. The post-process modules are applied to the backside of processed wafers. A specific characteristic of this module is the use of an optimized process for pattern transfer in and across deep etched cavities (down to 400µm). Several resist coating techniques, i.e. modified spin coating, direct spray and electroplating are investigated. Several microwave components and structures, such as narrow microstrips, trench isolation and sub-surface inductors have been successfully fabricated using these post-process modules. Research is currently focussing on further improvements of the pattern transfer on high topography surfaces and on alternative etching methods to increase integration density.

![Patterned resist lines and contact windows in and across 375µm-deep cavities using direct spray coating](image)

![Inductor defined in electroplated photoresist on 4µm Al in a 400-525µm-deep cavity](image)
2.1.2 Post-processing surface micromachining for microsystems applications

Leader           P.J. French, P.M. Sarro
Technical staff   C. de Boer, M. Laros, H. Schellevis, T. Scholtes, P.J. Trimp, C. Visser
Post Doc          Dr. H. Yang
PhD students      H. T. M. Pham, L. Pakula, A. Bagolini
Sponsor           STW (project DMF.5103)

Compatibility of surface micromachining with conventional IC processing is essential for the realization of smart micromechanical devices. Using a post-processing approach for the surface micromachining process can preserve this compatibility. In order to achieve this, the mechanical layers must be deposited and patterned at the end of the conventional process and thus only processes using temperatures below 400ºC are allowed. On the other hand the post-processing character gives a larger freedom in the selection of materials, especially metals that can be used as mechanical layers. This project deals with materials properties, process modules development and microstructures fabrication.

2.1.2 a Low stress PECVD SiC thin films

This sub-project focuses on research and process development of materials that will be applicable as mechanical layer for post-processing surface micromachining. Among the structural materials that can be deposited at temperatures low enough to preserve compatibility with conventional IC processing, PECVD silicon carbide is an attractive candidate due to its high mechanical strength, high thermal conductivity, low friction and wear resistance, and inertness in harsh environment.

For proper design of microstructures and micro-sensors it is necessary to investigate the influence of the deposition parameters on the electrical, thermal and especially mechanical properties of silicon carbide. Moreover, it is important to extend the study to structural properties of silicon carbide in order to understand the relationship between its properties and the deposition process for a range of applications.
Thin films of undoped and in-situ doped SiC are deposited in a conventional PECVD reactor, a Novellus Concept One System. Deposition parameters such as temperature, pressure, power and gas flow are varied and their influence on the layers properties mapped out. Post-deposition treatments and the under-layer on which the SiC layers are deposited have an effect on the mechanical properties as well. In order to understand the effect of doping on the mechanical properties of the films structural analysis are performed. Further optical and electrical properties of these layers are investigated and the relation to deposition parameters studied.

2.1.2 b Post-processing modules and devices

The advantage of post-processing is that a wide range of materials can be used for fabrication of sensing and/or actuating structures. Several of test devices, including simple cantilevers, bridges, membranes, pointers for strain measurement, under-etch rate tests has been designed and fabricated to evaluate the mechanical properties of the layers and to characterize the process modules. FEM simulations based on initial experimental data are now being used to improve the design of many inertial sensors.

Two process modules, one using PSG as sacrificial layer and a wet release etch and the other using polyimide as sacrificial layer and a dry release etch, have been successfully developed. Several materials, such as silicon carbide, polysilicon or metals are used as mechanical layers. The fully released structures are fabricated and characterized. The data collected so far is used to design novel microstructures and inertial sensors.
2.1.3 High-density through-wafer interconnects for chip stacks

Leader                  P.M. Sarro
Scientist              C.I.M. Beenakker
Post Doc              N.T. Nguyen, L. Wang, E. Boellaard
PhD students   G. Craciun, V. Kutchcov
Sponsor                EU (project CORTEX)

Chip stacks are vital for parallel processing and system-on chips because of the ultra-high density they can offer. As the Cortex project investigates the applications of molecular wires for 3-D computers, the formation of through-wafer high-density interconnections is a crucial element in the research program. Our research focuses on the formation of through-hole copper plugs using a modified electroplating technique.

Test chips including pad arrays and several test structure to be used for investigation and evaluation of molecular electrical interconnections, such as structures for resistance and cross-talk measurement of the molecular wires, are realized. Three approaches have been selected to study the filling feasibility of Cu into high aspect-ratio vias: 1) trench filling; 2) metal bonding and bottom-up filling; and 3) one-side plating and bottom-up filling. The first method concerns filling before wafer thinning, while the other two approaches are related to filling after wafer thinning. Very promising results are achieved with the third method. Successful filling of vias with an aspect ratio up to 7 has been achieved. The filling ability of our technology for smaller size vias (<5 µm) and to characterize the electrical properties of the copper plugs is now under investigation. Next, wafer thinning by lapping and polishing will be combined with the Cu-plug formation process to work towards a 3-layers chip stack demonstrator.

Through-wafer Cu plugs: a) arrays of circular and square vias after deep dry etching; b) array of Cu-filled circular vias; c) cross-section of a filled via.
2.1.4 Wafer Level Packaging of Sensors

Leader: Dr. ir. A. Bossche
Technical staff: J.R. Mollinger
PhD student: V.G. Kutchoukov

For the development of autonomously working systems, low-cost and small-size sensors are required to provide the system with information from the environment. Therefore these sensors are often integrated on-chip. For reliable measurements most sensors should be brought in close contact with the environment to be monitored. This means that the sensor packages often require environmental access pads to the active sensor areas of the chip. At the same time, however, the package must protect the chip adequately, so that the environment does not degrade or destroy the sensor or its electronics.

This research has developed different through-wafer interconnect methods, intended to be applicable to most sensor and actuator devices. They are aimed to transfer the metalization to the back side of the wafer without open through-holes. This separates the electrical contact pads from the, often aggressive, sensor environment at the front side of the chip.

Bottom view (SEM images) of the chips with realized through-wafer interconnects and corresponding cross section (schematic view)
2.2 Intelligent Sensor Microsystems

Faculty of Information Technology and Systems
Electronic Instrumentation Laboratory/DIMES
Prof.dr.ir. J.H. Huijsing, Prof.dr. P.J. French

Fully automated production machines, consumer products, transportation vehicles, and other tools, need the functions of many sensors, signal processors and actuators. To implement this in a systematic way, greater intelligence must be built into the sensor and actuator systems. However, large-scale application of intelligent sensor and actuator systems is often not feasible today since such systems are too complicated, too expensive, too heavy, too large and use too much power. Therefore the development of fully automated systems is being hampered.

To solve problems and speed up development, the Electronic Instrumentation Laboratory within DIMES initiated a research program on Integrated Microsystems. The goal of this theme is to enable major breakthroughs in intelligent sensor and actuator systems in regard to size, costs, weight, power consumption and handling complexity.

The approach the EI laboratory has chosen is to combine the functions of: sensors, actuators, interface electronics and intelligence in integrated microsystems. The scientific challenge is the integration of these many functions in a single small, light and low-cost package while improving reliability and power efficiency.

The program has four sub-programs, and of course, the components have strong interactions. These are detailed below at the program and project level:

The four sub-programs are:
1. Medical and (bio)chemical instrumentation (French, Bossche)
2. Scientific instrumentation (Vdovin)
3. Industrial instrumentation systems (Huijsing, Meijer, French)
4. Human computer interfacing (Meijer)

These integrated microsystems are only achievable using the combination of a number of disciplines available in DIMES:
- Technology (Sarro, French, Vellekoop, Bossche),
- Sensors and actuators (French, Vellekoop, Vdovin, Bossche),
- Interface electronics (Huijsing, Meijer),
- Signal processing Software (Dewilde),
- Wireless communication (Den Dulk, Bossche),
- Wireless power supply, Packaging (Bossche).
2.2.1  Medical and (bio) chemical instrumentation

Leader  Prof.dr. P.J. French
Scientists  Prof.dr. P.J. French, dr.ir A. Bossche

Greater use of minimal intervention techniques will allow measurements to be made in the body with minimal tissue damage and minimal influence on the parameters to be measured. This means that a range of new sensors will have to be developed. In addition, an increasing number of implanted sensors are being used. These sensors should remain in the body for long periods (years). Implanted sensors can serve as feedback to control systems, long-term research and also restoring the use of lost senses. There are two important aspects. The first is to ensure that the device and packaging can survive these long periods and the second is the power and read-out of the devices. Wireless systems will enable both the activation and the read-out of the device to be achieved.

High-speed screening (HSS) is a technology for rapid testing and development of pharmaceutical lead compounds. The transfer from milliliter to nanoliter sample-volume asks for re-engineering of the measurement instruments. New integrated systems are being developed containing on-chip fluidic systems, multisensing arrays and dedicated fast readout circuitry.

New nanoscale fluidic devices with integrated electrical and optical sensors for the detection and manipulation of single molecules are being developed. This opens up new avenues for studying biomolecular interactions at the single-molecule level and is expected to have major impact on applications, for example in precision pharmaceuticals.

2.2.1.1  Multi-parameter Sensor System with Intravascular Navigation for Catheter/Guide Wire Application

Leader  Prof.dr. P.J. French
Scientists  Prof.dr. P.M. Sarro
Technical staff  Ing. P.J. Trimp
Post Docs  Dr.ir. J.F.L. Goosen
PhD students  D. Tanase M.Sc.
Sponsor  TU Delft / DIOC 9
Collaboration  Academic Medical Center, Amsterdam
Academic Hospital, Rotterdam
Faculties of OCP and TNW, Delft University of Technology

Interventional radiology is a medical specialty, which uses medical tools such as guide wires and catheters to diagnose and treat vascular diseases. To navigate these tools to the place of intervention, X-ray imaging is extensively used, creating an important health risk to the medical staff and to the patient. To reduce the radiation dose, an electromagnetic navigation
system is currently being developed. Once the correct position has been attained with the guide wire, the catheter can be brought into place. In many cases, the intervention radiologist requires a number of measurements to assess the situation and the treatment required. To achieve this, a multi-sensor chip has been developed for blood flow, pressure and oxygen saturation level, with dimensions suitable for catheter applications.

The project concerning the fabrication of the multi-chip sensor has finished in June 2001. However, the research has been extended to the fabrication of a sensor for measuring CO₂. The aim of this work was to measure CO₂ without using chemical sensing techniques. Therefore, the technique employed here uses infrared absorption. The difference from the oxygen measurement is that the gas has to be separated from the blood. This was achieved using a fine sieve, through which gas passes but not the blood. In the initial set-up a commercial infrared source and sensor were used. Liquid systems have been built, but blood measurements still have to be made.

Schematic representation of the intravascular navigation system
2.2.1.2 High-speed (bio)chemical analysis

Leader
Dr. A. Bossche

Scientists
Dr. M.J. Vellekoop, dr. A. Bossche

Post Docs
Dr. S.S. Lee, dr. B.L. Gray

PhD students
Ir. F. Laugere, V. Iordanov M.Sc., ir. J.H. Nieuwenhuis
P. Turmezei M.Sc.

Sponsor
DIOC (TUDelft)

Collaboration
Kluijverlaboratorium TUDelft, Applied Physics TUDelft

This project can be defined as devices that determine chemical properties of a fluid by measuring physical properties of, or phenomena in that fluid. They do not need a chemical interface where adsorption or desorption of molecules takes place. This concept has attracted increased attention because it lacks the need of a complex chemical interface. It allows a dramatic faster development of commercial devices, compared to so-called direct chemical sensors. The sensors measure thermal, optical, mechanical or electrical properties and effects in the fluid. For some applications, a physical pre-separation is performed in order to enhance selectivity. Examples are contactless electrical conductivity in capillary electrophoresis, nano-electrophoresis for single molecule detection, thermal conductivity in gas chromatography, optical-array particle shape and size detection, fluorescence detection, spectrometers, viscosity, density, and sound velocity in fluids, heating value, and applications in combinatorial chemistry such as high speed screening (HSS).

Miniaturization by silicon integration of the sensors is attractive because of the potential advantages: smaller sample volumes, high-speed handling, faster response, more different simultaneous tests, on-line monitoring possibilities (instead of lab testing), and low costs (lower sensor costs, less sample, faster measurement).

Our investigations in these multidisciplinary subjects are often done in cooperation with (bio)chemists, both national and international. Besides the measurement principles and technology, important aspects in our research are the application of electronic circuitry at the sensing device, micro fluidic behavior, and chemicals-resistant design and packaging.

2.2.2 Scientific instrumentation

Leader
Dr. G. Vdovin

Scientists
Prof.dr. P.J. French, prof.dr. P.M. Sarro

MEMS technology for combining silicon sensors with signal conditioning circuitry brings many benefits into the field of scientific instrumentation. Micromachining techniques combined with integrated electronics were applied to development of advanced integrated spectrographs, color sensors, adaptive optical systems and spatial light modulators for scientific applications, including astronomy, ophthalmology, ultrafast optical sciences and confocal microscopy.
2.2.2.1. **CMOS sensor for dynamic optical profiling**

Leader  
**Dr. G. Vdovin**

PhD students  
**D.W. de Lima Monteiro M.Sc.**

Sponsor  
**STW (DOE.5375)**

For wavefront profiling we use the Hartmann method because it allows straightforward measurement of an incoming wavefront from the displacement of light spots. The concept is simple: a wavefront is sampled by a mask with an array of holes, which results in a 2D pattern of spots on a detection plane placed behind the mask. If the wavefront is flat the spot centroids form a grid with the same pitch and pattern as that of the holes in the mask. If, however, the wavefront is distorted, the spots will be displaced from the original grid according to the local distortions. Traditionally a CCD camera is used to register the spot positions but image processing hinders real time operation. We then implemented a dedicated sensor for fast and direct read-out of spot displacements. It has been fabricated in standard CMOS (DiMOS) and features 256 pixels grouped in 64 position-sensitive elements that can be addressed randomly. The sensor supports complete signal scanning in less than 0.5 ms, which allows profile changes at a rate higher than 2 kHz. Also, wavefront sensitivity can be as good as \( \frac{1}{50} \) rms (\( =633\)nm), provided that enough light power is available.

![Diagram of wavefront and imprinted wavefront](image)

2.2.2.2  **Technology of silicon-based liquid crystal wavefront corrector**

Leader  
**Dr. G. Vdovin**

Scientists  
**Prof.dr. P.J. French, prof.dr. P.M. Sarro**

PhD student  
**Ir. M. Loktev**

Sponsor  
**STW, project DOE.5490**

Collaboration  
**P.N. Lebedev, Physics Institute of the Russian Academy of Sciences (Russia), University of Durham (UK)**

![Photograph of wavefront imprinted by a lens](image)
Liquid crystal (LC) phase modulators for real time wavefront control is an important new technology for inexpensive adaptive optics. At present, only piston-type LC phase correctors are available, however the implementation of the modal approach brings much higher correction performance, comparable to that of deformable mirrors. It is shown that the modal LC corrector can have several degrees of freedom per physical actuator and that the number of degrees of freedom depends on the control technique used. This feature did not appear in any known type of modal wavefront correctors and provides extra functionality in the realization of adaptive optical systems. Besides, an application of silicon technology for the realization of modal LC correctors allows integration of the LC device and control electronics in a single chip.

The first design of a modal LC corrector with silicon backplane was made and submitted to DIMES. The structure consists of 4 layers. The first metallic layer (Al/Si alloy) contain contact pads and control contacts; the second one provides wiring between them; PECVD oxide layer provides isolation between two metallic layers, and a high-resistance layer (sheet resistance $\sim$5 M$\Omega$/sq.) on top of the contacts serves as a control electrode with distributed resistance. We consider doped silicon carbide as a possible material for the manufacturing of the resistive layer; this possibility can be realized in DIMES. However, there are companies manufacturing highly resistive coatings using other technologies, such as amorphous silicon.

One of the corrector’s prototypes manufactured earlier was tested in close-loop operations. To control the corrector we used two DAC boards. Real Time Linux driver was developed to generate rectangular pulses with maximum frequency 4 kHz and maximum peak-to-peak amplitude 10 V on 37 channels. Wavefront was measured using CCD-based Hartmann sensor. Closed-loop correction was performed with 1 Hz frequency. In this experiment we observed reduction of RMS aberrations from 0.53 to 0.20 waves.

Design of 39-channel modal LC corrector; (a) view from top; (b) cross section.
2.2.2.3  High definition micromachined silicon displays

Leader  Dr. G. Vdovin
Scientists  Prof.dr. P.J. French, prof.dr. P.M. Sarro
Technical staff  Ing. P.J. Trimp
PhD students  Ir. S. Sakarya
Sponsor  STW, project DEL.3945
Collaboration  DIMES, TUDelft

Within this project, we investigate two approaches: the first one using pixelated nitride membranes and the second based on deformation of viscoelastic layers. During 2001, we focused on the latter approach. To fabricate the modulator structure, we bond two silicon chips using a viscoelastic intermediate layer and then etch away the top chip. This results in a very high optical quality viscoelastic layer “deposited” directly on top of the bottom chip. Light modulation is achieved by deforming the deposited viscoelastic layer using electrodes integrated into the bottom chip. Before bonding, the top chip is coated with an 80nm layer of aluminum and 50nm layer of nitride, that serves as the etch stop and reflector at the same time. The elastic material is deposited on the bottom chip as a droplet, into which the top chip is pressed, yielding a uniform 5 μm layer. After hardening at 150°C for 15 minutes, the device is put into a 33wt% KOH solution at 85°C for 6 hours to remove the bulk silicon. The thin nitride layer functions as the etch stop. Special technology has been developed to provide low-stress side and back protection from the etchants. The continuous reflective membrane results in a 100% optical fill factor, enabling the modulator to handle relatively high optical loads. Also, given a sufficient bias voltage, the voltages on the electrodes should be in the range of 15-30V, making integrated solutions possible. Applications lie in the field of optical communication networks and projection displays.
2.2.3 Industrial instrumentation systems

Leader
Prof.dr.ir. G.C.M. Meijer

Scientists
Prof.dr.ir. J.H. Huijsing, prof.dr. P.J. French, prof.dr. P.M. Sarro

This program concerns the sensor systems and the instrumentation systems related to sensor applications. Industrial sensors and instrumentation systems process physical/electrical/electronic signals, while operating in a harsh physical/chemical environment. This environment can create huge problems for the accuracy, speed and reliability of the systems:

- Mechanical shocks and stress can cause inaccuracy, unreliability or even breakdown of the sensors.
- Aggressive chemical material will cause unreliability and fast breakdown of the sensors.
- At high temperatures (e.g. >200 °C) leakage currents will disturb a proper biasing of the active components.
- Often the input signals are small. Therefore, parasitic elements and cross effects can easily disturb the sensor accuracy.

To solve the first two problems, a good packaging is required. However such packaging is expensive, isolates the sensors from the environment in which it has to perform its function, and due to cross sensitivity, causes inaccuracy. Moreover, packaging induces mechanical stress, which affects the accuracy of integrated sensors.

To solve the high-temperature problems special technologies, such as SiC technology, can be applied. However, this will lead to expensive solutions. It could be an interesting alternative to use special circuit designs, implemented in low-cost CMOS technology.

A specific field of application concerns “Sensors for Metrological Applications”. For these application special physical sensors, such as wind sensors, humidity sensors, pressure sensors, radiation sensors and temperature sensors are developed. The development includes investigation and application of MEMS technology.

A close cooperation with industrial companies is considered to be important for a proper scientific feedback for an evaluation of the results of the research activities. Often the help of these companies is essential to enable expensive long-term experiments in the field.
2.2.3.1 Dedicated Admittance Sensors

Leader
Prof.dr.ir. Gerard C.M. Meijer

Technical staff
H.M.M. Kerkvliet

PhD students
B.P. Iliev, M.Sc.

Sponsor
STW

Collaboration
Shell, Martil Instruments, Enraf

The project concerns the development of novel techniques for non-invasive measurements of the specific admittance of oil products and blood. The admittance-measurement data forms an important indirect measure for the composition, humidity, contamination and other physical properties of the products in a non-invasive way.

When applied in the oil-field industry the system will be operated in a harsh environment, where the temperature can be as high as 250°C, while still a high accuracy and reliability is required. It is shown that this challenging combination of desired properties can only be obtained with dedicated design for specific applications. Two of these applications are considered: a) Application in high-temperature oil-spores, for down-hole monitoring and troubleshooting in oil wells; b) Applications in a system for non-invasive measurement of oil/water mixture ratios.

The dedicated design will be made following the object-oriented approach, where existing high-performance knowledge, software and hardware will be re-used as much as possible. The dedicated parts are mainly concentrated in the front-end and output parts of the system.

The application for blood measurements concerns an indirect measurement of blood viscosity in catheters and heart-lung machines.

![Red blood cells (erythrocytes)](image)

The equivalent electrical circuit of blood

Red blood cells (erythrocytes)  The equivalent electrical circuit of blood
2.2.3.2  A universal sensor interface

The new Universal Sensor Interface (USI) has a complete analog front end for low frequency measurement applications, based on a period-modulated oscillator. The USI converts the signal of the sensing element into the period-modulated signal (time interval) that is a microcontroller and DSP-compatible signal. The USI can provide interfacing for:

- Capacitive sensors: variable range up to 300 pF, Platinum resistors Pt100, Pt1000, Thermistors 1 kΩ - 25 kΩ, Resistive bridges 250 Ω - 10 kΩ with maximum imbalance +/- 4% or +/- 0.25%, Conductivity: 0 µS – 100 µS, Thermocouple: 0 mV – 200 mV, ±200 mV, ±25 mV, ±2 mV, Voltage: 0 V – 1 V, 0 mV – 200 mV, ±200 mV, ±25 mV, ±2 mV

In the USI, the continuous auto-calibration of offset and gain of the complete system is performed by using the three-signal technique. The low-frequency interference is removed by using an advanced chopping technique.

![A diagram of the USI](image-url)
2.2.3.3 Dynamic CMOS temperature sensors and bandgap references

Leader Prof.dr.ir. G.C.M. Meijer
Technical staff H.M.M. Kerkvliet
PhD students G. Wang M.Sc.
Sponsor STW
Collaboration Smartec, Philips, Alcatel

This project investigates the concepts, opportunities and limitations of temperature sensors and voltage references realized in CMOS technology. A full temperature characterization of pnp substrate transistors fabricated in a CMOS technology is performed. A novel interface circuit for thermocouple-signal processing is developed. It is shown that bipolar substrate transistors are very suited to be applied to generate the basic $V_{BE}$ and PTAT voltages. Furthermore, it is shown that dynamic element matching and auto-calibration can solve the problems related to mismatching of components and 1/f noise. The effects of mechanical stress are a major source of inaccuracy. In CMOS technology the mechanical-stress effects are small, as compared to those in bipolar technology. It is found that with low-cost CMOS technology rather accurate voltage references and temperature sensors can be realized.

![A DEM Switched Capacitor amplifier, according to Wang](image-url)
2.2.3.4 Piezojunction effects in silicon

Leaders
Prof.dr.ir. G.C.M. Meijer, prof.dr. P.J. French

Technical staff
H.M.M. Kerkvliet, ing. P.J. Trimp

PhD students
dr. F. Frueutt, dr. J.F. Creemer

Sponsor
STW

Collaboration
Alcatel, Smartec

Mechanical stress affects the magnitude of base-emitter voltages of forward biased bipolar transistors. This phenomenon is called the piezojunction effect. The piezojunction effect is the main cause of inaccuracy and drift in integrated temperature sensors and bandgap voltage references. The aim of this project is twofold. Firstly, to find techniques that can reduce the mechanical-stress-induced inaccuracy and long-term instability. Secondly, to find how the piezojunction effect can be applied for new types of mechanical-sensor structures. To characterize the anisotropic piezojunction effect, systematic investigations are performed over wide ranges of mechanical stress and temperature. The experimental results are used to extract the first- and second-order piezojunction (FOPJ and SOPJ) coefficients for bipolar transistors. In 2001 the piezojunction coefficients were also calculated from fundamental physical principles. This enables the piezojunction effect to be calculated for any direction of current and/or stress. Devices with lower mechanical-stress sensitivity can be found by comparing their piezo-coefficients. The layout of the device can also be optimized to reduce the mechanical-stress sensitivity. The knowledge of the piezo-effects on device level can be used to predict and to reduce their negative influence on circuit level. This is demonstrated for a number of important basic circuits, including translinear circuits, temperature transducers and bandgap references. Finally, it is shown how the piezojunction effect can be used to fabricate stress-sensing elements.

Examples of calculated piezojunction effect (left) lateral pnp transistors on a {100} wafer subject to a uniaxial stress, X. This stress is either oriented in the longitudinal direction with respect to the current, or in the transverse direction. (right) First order stress sensitivity when both the stress direction and the transistors are rotated around the wafer plane.
2.2.3.5 The development of micromachined humidity sensors based on a dielectric of porous silicon

Leader  Prof.dr. P.J. French
Technical staff  Ing. P.J. Trimp,
Post Doc  Dr. E.J. Connolly
Sponsor  STW (DEL 4694)
Collaboration  KNMI, Mierij Meteo

The project is continuing with an investigation into other materials that are compatible with the (single crystal) porous silicon sensor platform: porous polysilicon and porous SiC. The advantage of using polysilicon is that, since its electrical conductivity is dominated by grain boundaries, it is possible to tune its response (by doping) so that it has a very small temperature coefficient of resistance. Preliminary results have shown porous polysilicon to be less sensitive to temperature changes than porous single-crystal Si. If this can be incorporated into a humidity sensor we should be able to reduce the effect of temperature on RH measurements. The response of a porous polysilicon RH sensor is quite large although there is some saturation at very high and very low RH levels. On the other hand, the advantage of using porous SiC is that it offers the possibility of a humidity sensor that could withstand very harsh chemical environments. Another advantage of the SiC is that it is not etched by KOH so that it is an automatic etch stop when making membrane structures. The porous SiC response is so far smaller than the porous polysilicon response but shows very good linearity over the whole RH range testes. Some hysteresis is also evident. Work is continuing to improve sensitivity and the hysteresis problems.

The normalized (to the RH value at RH=10%) response of a porous polysilicon humidity sensor.  The normalized (to the RH value at RH=10%) response of a porous SiC humidity sensor.
The development of the macro-porous technique for silicon micromachining and improvements of the process on p-type material are in progress. A further important development is a DNA chip fabricated by combining macroporous etching and oxidation. The device uses a channel with a large array of oxide columns with sub-micron spacing. It is this sub-micron aspect that is essential to achieve effective DNA separation. This can be achieved through the oxidation of the inside of the pores and removal of the remaining silicon between the oxide pillars. Hereby the distance between the pillars can be made considerably smaller than the lithographic resolution. Further processing involves the bonding of a glass capping layer to achieve the complete DNA chip.
2.2.3.7 Smart wind sensors

Leader Prof.dr.ir. J.H. Huijsing
Ph.D. student K.A.A. Makinwa M.Sc. M.E.E
Sponsor STW
Collaboration Mierij-Meteo, Bronkhorst Hightech

An integrated smart wind-sensor has been implemented in a 1.6 micron CMOS (DIMOS-01) process. The sensor is a square silicon chip on which a two-dimensional (2-D) thermal flow sensor and the required interface electronics have been co-integrated. The output of the sensor consists of three bit-streams that are decimated and processed by an external microprocessor. Using the sensor, wind-speed and direction may be determined with an inaccuracy of $\pm 2^\circ$ and $\pm 5\%$ respectively in the range 0 - 25 m/s.

The on-chip flow-sensing elements consist of four heaters, four thermopiles and a central diode. In operation, the chip is heated to a temperature above that of the flow and the thermopiles used to detect a flow-induced temperature gradient. The central diode is used to measure the chip’s absolute temperature. The flow-sensing elements, together with three comparators (located in the middle of the chip) are configured as three thermal sigma-delta modulators. These modulators control, and simultaneously digitize, the heat distribution in the sensor.

A common-mode modulator, incorporating the central diode and an external ambient-temperature diode, maintains the chip at a constant temperature above that of the flow. The other two differential modulators incorporate the thermopiles and act to cancel the flow-induced temperature gradient. Since the output of the thermopiles is at the millivolt level, auto-zero techniques are used to reduce comparator offset to less than 10 microvolts. The bit-stream output of the differential modulators is then a digital representation of the cancelled gradient, which in turn is a function of flow-speed and direction.

Chip micrograph

Block diagram
2.2.3.8 Low-power low-voltage analog-to-digital conversion

Leader: Prof.dr.ir. J.H. Huijsing
PhD students: Ir. L.J. Breems
Sponsor: Philips Research Labs., Eindhoven
Collaboration: Philips Research Labs., Eindhoven

A 1.8mW CMOS IF sigma-delta modulator has been designed in cooperation with Philips Research Labs. This chip incorporates an IF mixer and a continuous-time baseband sigma-delta modulator and is designed for use in GSM-based mobile phones. The mixer is placed in series with the input resistors of the first integrator stage of the sigma-delta modulator. The virtual ground nodes at the input of the first opamp ensure high-linearity mixing of the input current signal. The mixer converts the IF (intermediate frequency) input signal to a baseband signal that is digitized by a sigma-delta modulator. Two such modulators are used in a quadrature configuration. In a quadrature sigma-delta modulator, gain or phase mismatch between the two modulators results in a finite image rejection ratio. To mitigate the effects of mismatch a novel dynamic element-matching scheme has been devised. The scheme only requires the use of an EXOR gate and some additional switches. In the case of a 20% gain mismatch, this technique improves the image rejection from -20 dB to -60 dB without introducing any undesirable artifacts. Over a number of samples, the typical image-rejection ratio was 61 dB. The measured third-order inter-modulation distortion for two -64 dBV IF tones at 13 MHz (mixer operating at 13 MHz) is -84 dB (IP3 = +36 dBV). The chip only consumes 1.8mW from a 2.5 V supply, making the design very suitable for battery-powered applications.

2.2.3.9 Smart temperature sensors in CMOS with high uncalibrated accuracy

Leader: Prof.dr.ir. J.H. Huijsing
Scientist: Prof.dr.ir. G.C.M. Meijer
PhD student: Ir. M.A.P. Pertijs
Sponsor: STW (project DCS.5668)
Collaboration: Philips Semiconductors, Delft, The Netherlands
Philips Semiconductors, Tempe, AZ, USA
Smartec, Breda, The Netherlands.

This project focuses on techniques to increase the initial accuracy (i.e. before calibration) of CMOS smart temperature sensors to ±0.4°C, such that for many applications calibration will not be needed anymore. A secondary goal of the project is to develop low-cost calibration techniques, such that for higher accuracy, a low-cost one-point calibration can be performed. A block diagram of a typical smart temperature sensor is shown below. It contains a PTAT source, which generates a voltage that is proportional to the absolute temperature (PTAT) of the sensor, and a bandgap reference. Both are based on bipolar substrate transistors. An analog-to-digital converter (ADC) compares the PTAT and reference...
voltage to find a digital representation of the sensor’s temperature. The non-linearity and sensitivity to process variations and stress of the bipolar transistors results in the mentioned limited accuracy.

**Block diagram of a typical smart temperature sensor.**

**Chip photograph of the smart temperature sensor with second-order curvature correction developed in cooperation with Philips Semiconductors**

### 2.2.3.10 Low-power sigma-delta modulators for medical applications

**Leader** Prof.dr.ir. J.H. Huijsing  
**PhD student** Ir. M. Djurica  
**Sponsor** STW  
**Collaboration** University of Amsterdam, Philips Research Labs, Eindhoven

A sigma-delta analog-to-digital converter for medical applications has been designed. The chip is battery-operated and can be used in different areas of medicine where bio-potentials (body potentials) are measured. The sigma-delta ADC is integrated on the same chip with a decimation filter. Attained SNR is 90 dB (15 bit) and the total power consumption is 9 mW from a 3 V supply.

### 2.2.3.11 Design automation for sigma-delta ADCs

**Leader** Prof.dr.ir. J.H. Huijsing  
**PhD student** Ir. O. Bajdechi  
**Sponsor** STW  
**Collaboration** Katholieke Universiteit Leuven, Belgium, Philips Research Labs, Eindhoven

A 14-bit sigma-delta A/D converter has been designed to read out the voltage output of an electret capacitor microphone. The converter is implemented as a single-loop, single-bit, fourth order sigma-delta modulator architecture. Using an oversampling ratio of 64 times, it attains a quantization noise limited dynamic range of more than 96 dB. The final design's dynamic range is white noise limited to 80 dB (13 bit) in the 11kHz signal bandwidth, thus masking the in-band tones with amplitudes of -115 dB.
2.2.3.12 Calibration and self-testing of an integrated thermal wind sensor

Leader Prof.dr.ir. J.H. Huijsing
PhD students S.P. Matova M.Sc.
Sponsor STW
Collaboration Mierij-Meteo

The integrated wind sensor measures wind speed and direction. It consists of two main parts an electronic device and its packaging (see figure). Main elements of the electronic device are four orthogonally disposed heaters, four thermopiles and a centrally located diode. The sensor is glued on a thin ceramic carrier and housed in the middle of an aluminum pedestal.

a) Cross-section of the sensor’s packaging; b) Schematic draw of the integrated wind sensor; c) Three-dimensional numerical model.
2.2.4 Human-Computer interfacing

Leader Prof.dr.ir. G.C.M. Meijer

Keyboards and mouses are the most frequently used devices for human-computer interfacing. Unfortunately, these devices have a large number of shortcomings: They are not suited and not fast enough to respond to the wide variety of signals produced by people to indicate their wishes, desires, to give commands or to express emotions. This project is intended to develop new tools and devices to improve the quality of the human-computer interfacing. In these projects systematic research will be performed to replace mouse and keyboard by 3-D gesture sensors. For this application acoustic, magnetic, capacitive and RF sensors will be used in combination with special interface circuits and data-processing circuits and systems.

2.2.4.1 Smart sensors for art applications

Leader Prof.dr.ir. G.C.M. Meijer
Technical staff H.M.M. Kerkvliet
PhD students R.N. Aguillar M.Sc., G. Chao M.Sc.
Sponsor STW
Collaboration Smartec, Enraf

The research project concerns the development of new low-cost sensor systems, which enable human-computer interfacing for various art applications. The sensor systems will be applied in and for art performances as well as for art development. The field of art includes dance, painting and multi-media dance/sound/light performance. The project will take advantage of the present activities of TUDelft in the field of smart sensor systems and will be focused towards the development of gesture sensors and personal position sensors. The personal detectors are based on the use of acoustic position measurement. This system is intended for use in special prepared rooms, such as studios. The gesture sensors make use of micro-machined capacitive accelerometers. A large number of these very small sensors are connected to body parts of art performers, for example dancers. Local reference resistive and capacitive sensors are used for position and speed reference. The work will be organized in two sub-projects: a) smart accelerometer systems and b) smart acoustic detection, as described now.

**Smart accelerometer systems**
Small micro-machined smart sensors will be used to measure 3-dimensional acceleration. After integration and double-integration also speed and position information are found. To determine the integration constants, additional (reference) measurements are required. These additional measurements are performed at certain reference positions and moments, using special reference sensors. The whole sensor system
should be fast enough to enable real-time use in art performances. The (sub-)project will include the following research items:

- The overall system architecture in relation with the intended applications.
- The selection, development or fabrication of low-cost accelerometers. When possible, existing elements will be used.
- The selection, development or fabrication of low-cost reference sensors to measure starting position and speed. When possible, existing elements will be used.
- The development of the hardware for low-cost signal-processing circuits.
- The development of dedicated software for the real-time smart data processing. The software will be implemented in microcontrollers, digital signal processors (DSP’s) and personal computers.

**Acoustic position detection**
In this sub-project the position of persons or body parts will be detected, using ultrasonic transmitters and receiver.

![Diagram of inertial system using inertial sensors.](image)

*A scheme of inertial system using inertial sensors.*
2.3  Anorganic Chemistry

Faculty of Applied Sciences
Laboratory of Inorganic Chemistry
Department of Chemical Technology: DelftChem Tech
Section for Anorganic Chemistry
Prof.dr. J. Schoonman

Research on sensors in the Laboratory for Inorganic Chemistry is focused mainly on electroceramics for Nernst- and Taguchi-type gas sensors. The Nernst-type sensor is based on measuring the difference in gas concentration between a reference compartment and a measuring compartment. The sensor consists of a measuring electrode, a selective ion conducting solid electrolyte, and a reference electrode. The potential difference is established according to Nernst law. Electrode and electrolyte materials have been studied for $O_2$, $H_2$, $SO_x$, $NO_x$, and $CO_x$. The Nernst sensor is very selective, but not very sensitive.

The detection principle of the Taguchi sensor is based on changes of the resistance of a thin film of an oxidic semiconductor upon adsorption of the gas molecules to be detected. The gas-solid interactions influence the density of electronic species in the film and thereby the resistivity. Ceramic semiconductors for the detection of CO and NO have been studied. The Taguchi sensor is very sensitive, but not very selective. More recently, a catalytic asymmetrical Nernst-like sensor (CANS) for methane has been designed. In addition, nanostructured composites of metals and polymers and metal oxides and polymers are being investigated.

The research on materials for chemical (gas) sensors is financed by the University and the Netherlands Foundation for Research.

2.3.1 Materials for Taguchi-type Gas Sensors

Smooth thin films of semiconducting metal oxides are usually employed in Taguchi-type gas sensors. These sensors need to be operated at elevated temperatures. While this type of gas sensor is very sensitive, it is not very selective and a major effort in literature is focused on improving its selectivity. A variety of catalysts has been applied to the surface of the smooth metal oxide semiconducting films. In another approach arrays of Taguchi sensors are employed.

Little attention has been given to the effects of surface morphology. Increasing the effective gas-solid surface area would not only improve the sensitivity, but also the selectivity, as the catalyst activates a larger surface area.

The surface morphology of semiconducting metal oxides can be controlled by the Electrostatic Spray Deposition (ESD) technique, developed in our laboratory. In the ESD technique, a liquid containing the precursors for the desired oxidic film is forced to flow through a small metal nozzle, which is
subjected to a high electric field. The liquid will leave the nozzle in different forms or modes due to different electrohydrodynamic mechanisms. In order to obtain fractal and reticulate surface morphologies, the cone-jet mode is very effective.

For oxygen sensor applications ESD of titanium dioxide films with reticulate surface morphologies have been studied in detail.

### 2.3.2 Catalytic Asymmetrical Nernst-like Sensor for Methane

Although a large number of sensors has been developed for methane detection, none of the existing sensors and applications meet the requirements for methane detection in natural gas, i.e., detection of methane in high concentrations in the absence of oxygen. The catalytic asymmetrical Nernst-like sensor (CANS) converts methane into another (detectable) product, i.e., hydrogen, using the CO$_2$-reforming reaction

\[
\text{CH}_4 + \text{CO}_2 \rightarrow 2 \text{CO} + 2 \text{H}_2.
\]

The detection principle of the CANS is based on the difference in catalytic activity of two metals for this reforming reaction. The sensor comprises a proton-conducting solid electrolyte and two different electrodes, i.e., the catalytic or working electrode and the counter electrode. The working electrode has a high catalytic activity for the CO$_2$-reforming of methane, while the counter electrode has a significantly lower catalytic activity than the working electrode. Therefore, a difference in hydrogen partial pressure is created in-situ at the electrodes. This chemical potential difference creates an electrochemical potential difference across the proton-conducting solid electrolyte, which can be measured as a potential difference. The amount of produced hydrogen is proportional to the amount of methane present. Hence, the CANS works as a Nernst-type hydrogen gas sensor, where the hydrogen is produced in-situ from methane and CO$_2$. A schematic picture of the CANS is given in Figure 1.

![Figure 1. Schematics of the catalytic asymmetrical Nernst-like sensor (CANS). The solid electrolyte is CaZr$_{0.9}$In$_{0.1}$O$_{3-x}$. The figure includes SEM micrographs of this solid electrolyte and the electrolyte - electrode interface, i.e., Ni-CaZr$_{0.9}$In$_{0.1}$O$_{3-x}$ (CERMET) film and the interface with the solid electrolyte.](image-url)
Figure 2. The potential difference of the CANS for methane corrected for the CO\textsubscript{2} concentration at 600°C

The long term stability of the CANS for methane at 600°C and 10 vol.% CO\textsubscript{2} is better than 960hrs.

2.3.3 Metal-polymer Nanostructured Composites

In a collaboration with the Karpov Institute of Physical Chemistry, Moscow, nanostructured composites comprising metal-polymer and metal oxide-polymer are being studied as chemical sensor. The nanostructured composites are Sn(SnO)/PPX, Ti(TiO\textsubscript{2})/PPX, Cu(CuO)/PPX, and Al\textsubscript{2}O\textsubscript{3}/PPX. In the vicinity of the percolation threshold MeO/PPX composites exhibit a dramatic increase in the electrical conductivity. Several applications as chemical sensor are currently being studied.
2.4 Bio-chemical Sensor Microsystems

Faculty of Applied Sciences
Bio Technology Department
Section for Analytical Bio Technology
Prof.dr.ir. G.W.K. van Dedem
Prof. dr. G.M. Schalkhammer

“Sensor” programs within Kluiver Laboratory. In all cases, the Kluiver laboratory participates in these projects. The numbers of postdocs and PhD students listed below are for the total project.

2.4.1 STW BIOMAS

Leader: Prof. G.W.K. van Dedem
Ph.D student: R. Guijt van Duijn, F Laugere
Collaboration: DIMES, ITS, MESA+, University of Twente, IMT Neuchâtel
Sponsor: STW
Start/end date: Jan 1997-Jan 2003
Funding per project: 5 PhD, 1 Postdoc salary+investments+running costs

Objective: real-time measurements of relevant analytes in fermentation and cell culture systems by sampling, component separation and quantification on integrated microdevices.

Results: Integrated microdevice for separation by capillary electrophoresis and conductometric detection was designed and built. Furthermore, fluid manipulation on these devices was further developed using (indirect) osmotic pumping.

![Figure 1. Separation of organic acids on integrated device](image)

1. Fumaric
2. Citric
3. Succinic
4. Pyruvic
5. Acetic
6. Lactic

Sample concentration (1 mM each)
Injection @1000 V (0 sec)
Separation @1000V
Sample diluted in 10% buffer
2.4.2 Intelligent Molecular Diagnostic Systems (IMDS)

**Leader**
IT Young

**PhD student**
R. Moerman, V. Iordanov, E. van Sommeren

**Sponsor**
TU Delft (DIOC5)

**Collaboration**
Pattern Recognition Group, DIMES, ITS, Univ. Leiden, NV Organon

**Start/end date**
Jan 1997-Jan 2003

**Funding per project**
5 PhD, 2 Postdoc, 2 technicians
salary+investments+running costs

**Objective:** Design and build a platform for the generation of high-density discrete analyses and their interpretation.

**Results:** Enzyme levels can be measured on chips in which small reactors (typically 5 nl) are prefilled with the necessary reagents. The chips are stored and can be used by applying (diluted) enzyme test samples and covering. Read-out is by measuring fluorescence, emanating from NAD(P)H using an adapted microscope and a sensitive CCD camera.

*Figure 2. Testing device for induced electro-osmotic pumping*

*Figure 3. CCD image of highly fluorescent 5 x 5 wells array*
2.4.3 Rapid sampling

Leader  JJ. Heijnen  
PhD student  finished  
Sponsor  Ministry of Economic Affairs (BTS)  
Collaborations  Applikon Dependable Instruments  
Start/end date  Apr 1997-Nov 2001  
Funding per project  1 PhD, 1 technician salary+investments+running costs  

Objective: Design and construction of a system to sample from a fermentor in such a way that the metabolism of the cells is stopped within less than a second.

Results: “Bioscope” sampling device to obtain a continuous sample at a precisely-known time-interval after a step change in conditions. Preliminary data on samples have shown usefulness of this approach.

Figure 5. Schematic of “Bioscope” principle
2.4.4 Stimulus Response Technology

Leader: JJ. Heijnen
PhD student: S. Picioreanu
Sponsor: Ministry of Economic Affairs (TS)
Collaborations: Applikon Dependable Instruments, DSM
Start/end date: Mar 2002-Mar 2006
Funding per project: 4 PhD/Postdoc salary+investments+running costs

Objective: to study rapid processes in fermentations in more detail i.e. looking at the metabolome, the transcriptome and their interdependencies.

Results: Projects just started in March 2002.

2.4.5 DIOC Lifetech

Leader: T. Schalkhammer
PhD student: T. Schalkhammer
Sponsor: TU Delft (DIOC)
Collaborations: Biophysics group
Start/end date: Jan 2001-Jan 2005
Funding per project: 3 PhD, 2 Postdoc salary+investments+running costs

Objective: “Making the bio-recognition tools of tomorrow”, sub-project: single molecule arraying.

Results: this sub-project has not yet started.
### 2.4 6 FOM Physics for Technology: nano-scale electrophoresis

**Leader**  
A. Bossche  
  
**PhD student**  
G. Gaudin, F. van der Heyden  
  
**Sponsor**  
FOM  
  
**Cooperations**  
Biophysics group, Pattern Recognition Group, ITS  
  
**Start/end date**  
Jun 2000-Jun 2008  
  
**Funding per project**  
6 PhD, 3 Postdoc salary+investments+running costs  
  
Objective: Study molecular movement in nanometer-scale channels and applying this knowledge to e.g. single molecule isolation and detection, the study of single enzymes or enzymes in functional arrays.

Results: Enzymes (trypsin) could be reversibly immobilized on self-assembling monolayers on top of gold surfaces while maintaining their activity.

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**Figure 6.** Schematic of a self-assembling monolayer  

**Figure 7.** Gold surface as viewed by atomic force microscope
2.5 Man-Machine Systems
Sensors and Actuators in Medical Catheters

Faculty of Design, Engineering and Production
Medical Technology and Mechatronics Department
Section for Man-Machine Systems
Prof.dr.ir. P. Wieringa
Prof.dr.ir. C.A. Grimbergen
Prof.dr. J. Dankelman

Optimal use of catheters is one of the most important subjects in medicine of the near future presenting a big challenge for (microsystem)-technology. The minimal damage of healthy tissues in treatments and the consequent minimal hospital stay and recovery period of the patient is of utmost importance also in view of the patient population growing older. The challenge for technology is to convert the present primitive catheter with its poor steer ability and limited therapeutic function into a controllable catheter equipped with several sensors and actuators needed for diagnosis and treatment. Moreover, the catheters should also be miniaturized to reach vessels with smaller diameters (< 1mm).

To meet these challenges, there is a great interest in medicine in the application of microsystems. The catheter already being an expensive, disposable tool, makes it feasible to equip the catheter with relatively cheap microsystems. As soon as these microsystems are able to increase the success rate of the treatment or decrease the number of catheters to be used, it is also economically useful to apply them. In first instance one should think of (multi)-sensors for pressure, flow, temperature, saturation, pH and O₂- en CO₂-concentration, preferably measured in a volume as small as possible. In addition to these, also actuators could be designed like micro pumps for drug application and the more standard methods based on balloons, electricity, heat and (laser) light.
In the projects M5 ("Mechanical steering of catheters in minimally invasive interventions") and M6 ("Miniaturization of sensors, actuators and interface-electronics used in catheters") of the MISIT-program (Minimally Invasive Surgery and Interventional Techniques) of DIOC9, research is being done on the use of catheters in minimally invasive interventions.

Design of microsystems is generally much more complex as compared to classical systems. Caused by the change of dimensions, many interactions and disciplines are involved and to be accounted for. Therefore adequate design and simulation techniques have to be developed. The MEMS-project, which is closely related to the DIOC9-program, will focus on multi-disciplinary simulation, design and optimization of micro-systems. The techniques being developed will be used for the design of micro catheters.
2.6 Micro-mechanical Systems

Faculty Design, Engineering and Production
Structural optimisation and computational mechanics
Prof. dr. ir. F. van Keulen

The Structural Optimization and Computational Mechanics group is participating and contributing to the Mechatronics and Control programme of the Faculty for Design, Engineering and Production. The main research activities of the group are devoted to the development of new simulation techniques, e.g. applicable to micro-systems, and optimization techniques. The latter involves the mathematical algorithms for shape, sizing and topology optimization. Shape optimization refers to the optimization of the shape of a structure or system without changing its topology. Topology optimization has become popular during the last decade and is focusing on the optimization of the layout of structures. Apart from simulation and optimization, the group has ongoing activities on design sensitivity analysis. This refers to cost effective techniques to estimate the effects of small design changes.

Part of the Mechatronics and Control programme is involved with micro-systems. These very small systems are usually under 1 mm in size and can contain mechanical, electrical, optical, fluidic, thermal etc. components. They are used for sensing, actuation, structural components, integrated optics, chemical analysis and even signal processing. Their small size, low power requirements, and the scaling effects of the laws of physics makes it possible to design micro-systems to achieve things that can not be done by larger, macroscopic systems.

Micro-systems, often know as micro electromechanical systems (MEMS) are fabricated using a variety of techniques, generally derived from IC processing and frequently make use of photolithography to achieve the small feature sizes required. The fabrication processes for such systems are complex and have a very large influence on the design and functioning of the final system. This makes designing such system difficult and time consuming.

Part of the research efforts is directed towards assisting the designer of micro-systems. This will be done along different routes. First, new simulation and design sensitivity techniques will be developed to enable cost effective and reliable simulations. Herewith the number of costly experimental trial-and-error steps can be limited. This requires simulation techniques that are multi-disciplinary and which can account for manufacturing induced effects. Second, once reliable simulation techniques are available, they can be combined with optimization techniques. These techniques need to be adapted and expanded to be applicable to micro-systems. As mentioned, not only are multi-physics necessary in the analysis of the systems, the importance of the
fabrication process on the system behaviour dictates that such influences must be included as well.

Figure 1 Typical example of topology optimization. The layout of this structure, shown in black, has been created automatically.

In contrast to macroscopic structures, micro-structures are to a much larger extent determined by the manufacturing processes used. This implies that in the optimization manufacturing constraints must be taken into account. These are of entirely different nature and complexity as compared to similar constraints for macroscopic structures.

The simulation and optimization techniques will be applied to biomedical applications. Micro-systems provide new possibilities in minimally invasive procedures, as their size makes it possible to place whole systems inside the human body. Within this medical speciality, there is a special interest in catheters and guide wires. Projects on measurements inside the body using sensors placed in a catheter are done in collaboration with the Electronic Instrumentation Laboratory of the faculty of ITS and the Man-Machine-Systems Group. These projects will help the physician to better diagnose and treat ailments of the cardio-vascular system. The design of active guide wires which can actively bend and change their shape, will make the procedures easier and safer.

Figure 2. Guide wire and catheter inserted into a blood vessel for the diagnosis and treatment of a stenosis (partial blockage of blood vessel).
2.6.1 Design, modeling and optimization of SMA actuators for active catheters.

Structural optimisation and computational mechanics, Faculty Design, Engineering and Production, TU Delft
Ir. Matthijs Langelaar, Ph.D.
Dr. ir. Hans Goosen
Prof.dr.ir. Fred van Keulen, Promotor

In minimally invasive medical procedures guide wires or catheters are pushed through the blood vessels to the point of interest inside the body, without the need for surgery. One problem with these instruments however, is the navigation of the guide wire through the maze of blood vessels. This presents problems in both steering the guide wire into the proper branch of the vascular tree and in pushing it through the twists and turns, resulting in dangerous mechanical loads on blood vessel walls. To alleviate these problems an actively controlled guide wire can be used that can actively deform to move into the chosen vessel branch and reduce the load. In order to achieve this functionality, actuators are needed that fit in the instrument and are capable of bending it. One good candidate for this actuation is a shape memory alloy (SMA) actuator.

The design of such Micro ElectroMechanical Systems (MEMS) presents a challenge for designers, due to the multi-physics involved and the close interaction between fabrication and functional design. This often results in less than optimal designs. The aim of this research is to extend existing topology optimisation methods, and include multi-physics, production-induced effects and manufacturing constraints for the design of MEMS.
To achieve this, models and numerical, multi-physics simulation techniques are formulated that are capable of predicting the system characteristics. Experiments will be carried out to validate this model. Then, to use these in a topology optimisation setting, taking into account production effects and the many requirements related to the field of application. As this obviously varies with the application, the SMA actuator for an active catheter is chosen as a test case. A concept image of the actuator is shown in Fig. 2.

![Concept of SMA actuators for active catheter](image)

**Figure 4. Concept of SMA actuators for active catheter**

### 2.6.2 Propulsion and active shape adaptation of guide wires and catheters

In minimally invasive medical procedures, catheters and guide wires are used for diagnosis and treatment inside blood vessels, without the need for surgery. To avoid mechanical damage on the vessel wall and ease negotiating the blood vessels, active guide wires and catheters are needed that can change and control their shape. Either to propel themselves through the blood vessels, or to conform to the shape of the blood vessel. For this, a micro actuator is needed. Shape memory alloys are mostly used for this, but they have several disadvantages such as relatively high temperature for actuation and no intermediate actuation states. As the proposed application needs actuators along the full, or a substantial part of the length, and constant actuation is needed, such temperature-controlled actuators can not be used. In particular in very small guide wire with diameters in the order of a few hundred micron other solutions are needed.
The aim of the research is to design a micro actuator with embedded sensing, that can provide both the actuation and the feedback needed. For this purpose, electrostatic distributed actuators will be used. Electrostatic actuators use little power, stay cold and can more easily be controlled due to the inherent feedback possibilities offered by position sensing in the actuator itself. However, both the load and the range of motion are very limited for a single actuator.

By placing many simple actuators in series and in parallel, their work will be added, giving the required motion and load (see figure 1). Such distributed actuators solve many of the problems faced by micro actuators, and enable partial activation of basically one big actuator in order to achieve the required shape of the guide wire. A proposal of a distributed electrostatic actuator structure is shown in figure 2.

For the fabrication of such large arrays of very small structures, photolithography and IC processes are very appropriate. However, such a distributed electrostatic actuator calls for a 3-dimensional microstructure, which is difficult to fabricate in the mainly planar IC technology. As the dimensions are limited to 50-80 um in depth, advances in MEMS technology provide new possibilities for the manufacture of such structures. Processes such as deep reactive ion etching (DRIE), electrochemical etching, macro-porous silicon formation, and polymers such as SU-8 can easily form structures with the required dimensions.
The high activation voltage, which is often considered a large disadvantage of electrostatic actuation, can be lowered by the proper design. By choosing a smaller gap width to lower the actuation voltage, motion of one actuator is lost, however, within the same space of a distributed actuator, more ‘gaps’ will fit, making up for the smaller motion. By shaping the gap appropriately, the actuation voltage can be lowered even further. Capacitance measurements on the actuation plates will enable a shape feedback, which can be used in local active adaptation of the shape to reduce loads on the vessel wall.

Figure 2. Example of (a) the passive and (b) active distributed electrostatic actuator array
2.7 Micro-mechatronic systems and production technologies for micro-mechatronic systems

Faculty Design, Engineering and Production

One of the main research focuses in the Faculty of Design, Engineering and Production is the area of micro-mechatronic systems. Micro-mechatronic systems are miniaturised mechatronic systems which perform tasks on micro-level. In the field of micro-mechatronic systems two areas meet. On one hand, products in the macro-domain undergo miniaturization in order to increase function density of products, or to improve energy efficiency or material usage. Also, micro-mechatronic systems, when incorporated with macro-systems, will result in new product performances. On the other hand, the traditional MST domain focuses on monolithic systems, the field is dominated by micro-electronics. Increasingly, hybrid micro-systems receive attention, which can be considered micro-mechatronic system, leading to a focus on micro-mechanics.

Various application fields can be identified, like photonics and opto-electronics (fibre to chip coupling, optical switches), bio-medical instrumentation (tissue handling, surgery, endoscopy, catheterisation), automotive (the application of micro-sensors and actuators for increased engine performance, safety systems) and consumer electronics (disk drives, reading head actuators).

Example micro-mechatronic systems: micro-motor (left), disk drive (right, EPFL)
Research in the field of micro-mechatronic systems focuses on two areas: (1) the functionality of micro-mechatronic systems and (2) the production and assembly of micro-mechatronic systems. A micro-mechatronic system can be considered to consist of a number of basic functions: actuation, sensor functions, communication and energy supply. Research focuses on developing solutions for these functions. The second area focuses on the production of micro-mechatronic systems. The parts of a micro-mechatronic system will in general originate in two technological domains that come together: micro-parts that are produced with “conventional” techniques, on a highly advanced level in terms of part size, accuracy, materials and part geometry complexity, and micro-parts that are produced using the technologies available from the MST domain. Micro-assembly brings the parts together into complete systems.

The scientific interest is mainly driven by the miniaturisation of the systems. The small system scale causes that other physical and material effects prevail, which are not dominant in the macro-domain. It is an important research objective to gain understanding of the fundamental principles in the micro-domain, and make use of these principles for the development of solutions. In some cases, the dominance of adhesion forces like electrostatic attraction or Van der Waals forces, is disturbing, resulting for instance in sticking between two parts in a micro-actuator, or part releasing difficulties in micro-assembly. Micro-mechatronic systems must be developed which minimize the disturbing effect. On the other hand, it is a challenge to make use of effects that are only dominant in the micro-world, e.g. part gripping using surface tension forces of liquids.

Developing micro-mechatronic systems and production and assembly methods for these systems apparently requires a different approach than in the macro-domain. The research and development of micro-mechatronic systems includes the development of solution principles, mechanical structures and material choice, production and assembly methods, and the realisation of demonstrators, all taking into account the particularities of the micro-domain.

Currently, research is being conducted on the following topics (for details of some of these initiatives see next pages):

**Basic functions of micro-mechatronic systems.** This research is part of the FUMMS project, Fundamentals of Micro-Mechatronic Systems. A current PhD project focuses on optical actuators.

**Magnetic bearing for ultra precise production processes.** The goal is to develop an active magnetic bearing system with nanometre precision for Optical Disc Mastering.
**Micro-part manufacturing.** The goal is to develop technology for the manufacturing of small parts with high accuracy, sometimes complex shapes, and often out of new advanced engineering materials. A current PhD project focuses on Micro Abrasive Air Jetting.

**Micro-assembly.** The goal of the micro-assembly research is to develop methods and techniques for the assembly of micro-mechatronic systems, and to develop design principles for micro-mechatronic systems focused on micro-assembly. In the micro-domain new methods and techniques can be applied, unknown to the macro-domain. Examples are self-assembly and self-adjustment, batch-wise assembly, sensor-controlled assembly, new micro-gripping techniques and many others. PhD research is soon to be started on self-adjustment of opto-electronic components. In a feasibility study for this research, the Laboratory for Production Technology and DIMES/ECTM have co-operated in the development of a micro-device which takes care of final alignment of optical fibres with an accuracy better than 0.1 µm, using micro-actuators integrated with the package.

![Diagram of in-package actuator and fully mounted device](image)

*a) Schematic drawing of the in-package actuator, a piezo-electric actuated cantilever beam*

*b) Optical image of a fully mounted device*

Alignment of optical fibres using in-package actuators based on MST, result of a feasibility study carried out by PTO and DIMES/ECTM.
2.7.1 FUMMS – Fundamentals of Micro-Mechatronic Systems

Advanced Mechatronics (Prof. dr. ir. J. van Eijk), Production Technology and Organisation (Prof. Dr.-Ing. B. Karpuschewski, Dr. ir. M. Tichem, m.tichem@wbmt.tudelft.nl), Systems and Control Group (Prof. ir. O.H. Bosgra).

The FUMMS project is a joint initiative of the three research groups mentioned above. The project has two main research directions: (1) the development of solutions for basic functions of micro-mechatronic systems (actuation, sensor functions, communication and energy supply), and (2) micro-assembly. Currently, one research project has been started, which focuses on opto-mechanical micro-actuators.

Micro-actuators

Prof. dr. ir. J. van Eijk, Ir. W.J. Venstra (PhD researcher, w.j.venstra@wbmt.tudelft.nl)

One of the basic functions of a micro-mechatronic system is actuation. In the FUMMS project, a variety of micro-actuators will be developed, serving several degrees of freedom, in which industrially relevant cases are used as a starting point. A clear focus point exists on opto-mechanical micro actuators. A recent example is a micromachined piezo-electric micro actuator, having one degree of freedom perpendicular to the wafer plane, for the optical fibre-alignment problem. A next step is to develop an actuator which moves within the plane of the wafer it is fabricated from. For this study, we use improved tracking control of a hard disk drive head as a case. Within the FUMMS project, a long term focus exists on opto-mechanical actuation, capable to actuate without being electrically connected to the outside world.

Opto-mechanical micro-actuators

Most micro actuators need electrical wires to supply the energy required for the actuation of the actuator itself and its payload. For stand-alone operation of a micro-mechatronic system, the energy supply poses a problem. The most significant advantage of a micro-mechatronic system without electrical connections to the outside world, would be the lack of a physical interface - which directly implies reduced complexity and increased flexibility.

A relatively unexplored concept to achieve actuation without electrical wires is the direct (non thermal) conversion of light into mechanical motion. Several materials revealing structural changes when exposed to irradiation have been discovered recently. Reversibility of the photo-induced dimensional changes is an important condition for application in a micro actuator.

Recently, contraction and dilatation in thin chalcogenide films has been discovered. The dimensional changes are reversible, and depend on the polarisation of the illuminating light. The physical phenomenon which
causes the opto-mechanical effect is not yet fully understood. Our research includes characterisation of these optically active thin films when applied for opto-mechanical actuation. The goals are to contribute to a better understanding of the involved physical effects, and to develop a functional opto-mechanical actuator. Within this project, we will deposit optically active thin films on pre-loaded micromachined flexure elements. In the end this should result in an actuator which can be applied as an optically actuated switch, e.g. an all-optical cross connect.

Attention is also paid to techniques for measurement of small displacements. For this project a new displacement sensor is developed at our laboratory, which will be able to measure displacements of mechanical parts having dimensions down to 10µm with an expected accuracy of 10nm.

### 2.7.2 Magnetic bearing for ultra precise production processes

Advanced Mechatronics, Faculty Design, Engineering and Production, TU Delft
Prof. dr. ir. J van Eijk, Ir. J.W. Spronck, Dr.ir. H. Polinder (ITS), Dr. M. El-Husseini (postdoc),
L. Jabben (PhD researcher), P. Overschie (PhD researcher, p.m.overschie@wbmt.tudelft.nl)

Large amounts of data such as financial data, medical data, experiment and simulation results or movies require data storage media with very high data density. Currently existing CDs (650 MB) and DVDs (4,7 GB) can not store these and future large data quantities. Therefore, the storage capacity of these optical storage media must be increased. Optical media are produced by replication from a master disc. For increasing the data density, a new generation of mastering systems needs to be developed. By cooperation of multiple disciplines in and around the section Advanced Mechatronics an ultra precise rotating Optical Disc Mastering (ODM) device is developed.

**Extreme Positioning Stability**

As can be seen in the figure, data is written on an ODM with a laser that writes pits in a photosensitive layer. The rotor rotates underneath the laser at a speed varying from 2000 rpm to 6000 rpm! The positioning accuracy of the laser with respect to the rotor is critical for increasing the data density on the ODM. The non-repetitive part of the rotor positioning must have an accuracy of smaller than 1 nm!! Air bearings, currently used in ODM devices, can not achieve enough rotor positioning stability to ensure these extreme accuracies. Therefore the use of Active Magnetic Bearings is researched for the next generation of Optical Disc Masters.
Active Magnetic Bearings
In Active Magnetic Bearings the transfer of disturbances like floor vibrations and air vibrations can be minimized by actively controlling the position of the rotor. The sensor is a critical component in the control loop, as sensor speed and accuracy are the limiting factors for the control performance. Only by optimizing all components of an active magnetic bearing system, an extremely high-accuracy system can be developed. Combined effort of design, optimization and implementation of a sensor system, electro-magnetics, control and a mechanical layout will result in a system that can fulfill the specifications for future data storage.

2.7.3 Micro Abrasive Air Jetting
Production Technology and Organisation, Faculty Design, Engineering and Production, TU Delft
Prof. Dr.-Ing. B. Karpuschewski, M. Achtsnick (PhD researcher, m.achtsnick@wbmt.tudelft.nl)

The main objective of the research project “Micro Abrasive Air Jetting (MAAJ) as a precision machining operation for brittle materials” is to increase the capability, reliability and fundamental understanding of the micro abrasive air jetting process for a wide sustainable introduction in the industrial environment. MAAJ is focussed on the interface between chemical etching, laser machining and conventional micro-cutting operations.
The process is based on the erosion of a mask-protected substrate by a high-velocity powder beam. MAAJ is capable of generating three-dimensional microstructures up to 100 times faster than other deep micro-machining methods. The minimum dimensions reachable with MAAJ are about 30 µm in width and down to 1 µm in depth. Depending on the material properties, aspect ratios of 1:5 are achievable.

The laboratory for Production Technology has realised a powerful and flexible air jet machine with a machining area of about 500x500x300 mm and a 3-axes sledge for nozzle movements. The abrasive powder, mostly Al2O3, has an average size of 3 to 150 µm. The powder flow as well as the air pressure are adjustable.

One of the main research activities in this project is the improvement of the machine components such the nozzle and the powder feeder, which have major influence on the process performance. Another research goal is to investigate the erosion behaviour of materials like silicon, glass or synthetics. In this context, the influence of the process parameters and appropriate modelling techniques, are the focuses of research.

The main field of application is the structuring of glass sheets for e.g. micro-fluid chips of LCD’s. New fields of use are photovoltaic and MEMS components, like sensors, pumps and reactors. Other projects for the well defined structuring of tribological or aerodynamically surfaces are intended.
2.7.4 Assembly-Net: a thematic network on precision assembly technologies for mini and micro products

Production Technology and Organisation, TU Delft
Prof. Dr.-Ing habil B. Karpuschewski, Dr. ir. M. Tichem
(m.tichem@wbmt.tudelft.nl)

In September 2001, the EU financed thematic network Assembly-Net started. The full title is Precision assembly technologies for mini and micro products. The network brings together about 30 participants from all over Europe; about 50% of the participants comes from industry, the rest from academic research institutes.

The main goal of the Assembly-Net network is to improve the global competitiveness of European industry manufacturing mini and micro products. The Assembly-net aims to bring together, share and exchange critical technologies, research results and the latest information in precision assembly automation.

The activities are grouped in work packages, and cover:

- Strategy development and research advancement: analysis of trends, creation of a precision assembly roadmap, stimulate new projects in precision assembly;

- Information provision: website (www.assembly-net.org), brochures, newsletters, periodic electronic broadcasting, journal contributions;

- Training, education and international events: stimulate the development and delivery of new academic and training courses, annual summer school, organization of an annual precision assembly conference;

- Special interest groups: active, industry led discussion on areas of interest, internet based virtual workshops.
2.8 Radiation Sensor Systems

Radiation Technology Department
Section Instrumentation and Systems
IRI

Prof.dr.ir. C.W.E. van Eijk  Ing. R. Koornneef  Ing. J.T.M. de Haas
Dr.ir. R.W. Hollander  Dr.ir. R. Kreuger  Drs. M. Farahmand
Dr. P. Dorenbos  Ing. J. Huizenga  Drs. E.V.D. van Loef
Ir. J. Sonsky  Ir. T.L. van Vuure

Fundamental research in the section 'Instruments and Systems' of the Radiation Technology department of the Interfaculty Reactor Institute is aiming at the application and detection of radiation (electrons, positrons, pions, neutrons, light quanta (VUV - IR), X-rays and gamma quanta). The R&D include the development and improvement of complete systems, instruments and/or techniques for the (position sensitive) detection of radiation, besides data acquisition, data analysis and simulation studies.

The list of projects in the section 'Instrumentation and Systems' illustrates the range of activities:

TUD   fast-neutron dosimetry and micro-dosimetry
dosimetry
silicon micro-gap gas-amplification
gas electron multipliers and neutron detection
dating in archaeology
position sensitive thermal neutron detection

NWO   development of inorganic luminescent materials and
theory of scintillation and luminescence

STW   new inorganic scintillators and storage phosphors
silicon drift sensors and smart silicon sensors

STW   development of phosphors for displays

FOM   proton dosimetry

EC    Techni, European network for neutron instrumentation
Desy, characterization of scintillating materials
Esprit, VUV-phosphors for cpdp's

INTAS, program for Ukraine

Shell  X-ray transmission multi-phase-flow measurement

Gov.   mine detection, humanitarian demining
Sensor research is focused on new scintillators for gamma and neutron detection, large area position sensitive silicon sensors for low energy X-rays and scintillator light and gas-filled position sensitive sensors for thermal neutrons and X-rays based on GEM-preamplifier foils.

2.8.1 Silicon drift sensors and Smart silicon sensors and integrated electronics.

The silicon drift detector (SDD) joined the family of silicon detectors relatively recently. The key feature of a SDDs is its extremely low readout capacitance (~150 fF). This capacitance is determined by the small area of the n⁺ readout electrode and is essentially independent of the detector size. Therefore superb energy resolution can be achieved even for large detectors (area of several cm²).

We are developing a multi-anode linear SDD with a very good energy resolution (electronic noise < 10 rms electrons) for 1D-position sensitive detection (~250 µm) of low energy (180 eV to 2 keV) X-rays. The R&D include the integration of the front-end p-JFET, which plays a crucial role in the noise performance. The development of detector and electronics fabrication is being carried out in close collaboration with DIMES.

Fig.1. Potential gutters in MSSDD due to sawtooth shaped p⁺-strips (in green), which confine and direct the signal charge to the readout anodes (in red).
2.8.2 Position sensitive thermal neutron detection.

A micro-machined silicon-well scintillator detector has been developed for position sensitive thermal neutron detection. Deep reactive ion etching (DRIE) is used to produce wells in the 500 µm thick handle wafer of a SOI-wafer. Scintillation light is detected with a photodiode, produced in the thin (10 µm) bonded wafer. Signals from thermal neutrons has been observed well separated from the noise using $^6$Li$_2$Gd(BO$_3$)$_3$ as neutron absorbing scintillator inside the wells. These sensors are developed in close collaboration with DIMES and MESA.

2.8.3 Development of inorganic scintillation crystals

For efficient detection of hard X-rays and gamma rays relatively dense, high atomic number detection materials are required. A class of such materials is found in the group of inorganic scintillators, i.e. materials that scintillate upon interaction with radiation. A radiation detector is formed by coupling the scintillator to a photomultiplier or a (silicon drift) photodiode for transformation of light into an electric signal. Commercially available inorganic scintillators do not meet the requirements of e.g. systems to be employed in medical imaging. An extensive R&D program is carried out for the introduction of new scintillators.
The class of materials presently being studied are halides as bulk material for the interaction, doped with Ce ions as luminescence centres. Examples of new scintillators introduced by us are LaCl$_3$:Ce and LaBr$_3$:Ce. These materials show the best energy resolution ever observed with a scintillator. See figure 3. To better understand the basic scintillation mechanisms, we also studied for example Cs$_2$LiYX$_6$:Ce (X=Cl, Br). A model could be derived that can explain almost all the data. It is however not possible to give an explanation for the excellent energy resolution obtained with LaCl$_3$:Ce and LaBr$_3$:Ce.

We do not only use the Delft facilities, but also the synchrotron radiation facilities at HASYLAB, Hamburg, the Compton Coincidence Facility at Georgia Tech, Atlanta, U.S.A., and EPR at the University of Paderborn and ENSCP Paris. All samples are prepared at the University of Bern.

2.8.4 Micro-structured X-ray and neutron detectors.

For position-sensitive detection of soft X-rays, charged particles or neutrons, gas-filled detectors can be employed with micro-structures (1 – 100 µm) to obtain gas-amplification. R&D is focused on two types of detectors, the micro-gap chamber (MGC; fig. 4) and the gas-electron multiplier (GEM; fig. 5). The former is developed in collaboration with DIMES, using IC technology, the latter is obtained from CERN, Geneva.
In the framework of the construction of a neutron beam scanner, based on the MGC, we have produced radiation sensors with an active area of 5 x 5 cm² surrounded by bias resistors and coupling capacitors. Coupling capacitors are inserted between the Micro-Gap sensing electrodes and the read-out preamplifier chip to decouple the DC potential of about 400 V from the (AC) signal pulse. Since the separation of the readout channels of the detector is 1 mm, which is too small to use modular capacitors, and because many channels have to be read out, the coupling capacitors need to be integrated with the sensor. This has been achieved, using a 3 micron thick oxide layer as dielectric of a two-metal film capacitor. In addition, high and low ohmic protection resistors (10 MΩ and 1 kΩ) have been incorporated in the design. They have been realised as meander structures in 60 nm thick NiCr layers. The metal NiCr has been selected as resistor material because of its ability to survive high peak currents without a change of the resistance value, and compatibility with processing on glass wafers.

![An MGC consists of thin aluminium anode strips (pitch 0.2 mm) on silicon oxide insulator ribbons (top left) positioned on a segmented cathode plane. With an appropriate voltage between anode and cathode a very strong electric field results close to the anode. If an electron enters this region (from above by means of additional electrodes) gas amplification will occur. A signal is observed on the anode. MGCs are produced on silicon wafers, including coupling capacitors and preamplifier protection resistors. At the other ends of the anode strips (not shown) HV bias resistors are integrated.](image)

The production of MGCs on glass substrates may be compulsory to eliminate the crosstalk between the cathode channels via the (conducting) silicon substrate. It also reduces the cathode strip capacitance considerably, improving the matching between output impedance of the detector and the input impedance of the preamplifier.
In collaboration with the Central Electronics Service department of TU Delft we are developing preamplifier ICs. The first eight-channel chips showed rather good characteristics. Furthermore, a complete setup for the neutron beam scanner was designed.

With current generation GEMs we attained amplification factors of \(10^3 – 10^4\) for a single GEM, and \(10^5\) for 2 GEMs in cascade. A combination of GEM+MGC is also possible. This allows to run the MGC at a lower, and safer voltage, and offers the possibility for single electron detection. A large area position-sensitive GEM neutron detector employing a new gas mixture of \(^3\text{He}, \text{Xe}, \text{TMA}\), is under development.

![Fig. 5. Two GEMs in cascade. A GEM is a ~50 µm thick kapton foil with a thin copper layer on each side. If an appropriate voltage is applied across the foil, the ~ 80 µm diameter holes act as electrostatic lenses. When an electron enters from above, gas amplification occurs in the strong electric field inside a hole and many electrons leave at the lower side. A signal is observed at the bottom electrode.](image-url)
3. **Overview of main institutes on sensor technology**

**DIMES**
Mekelweg 4  
PO Box 5031  
NL-2600 GA Delft  
the Netherlands  
Phones: +31 (0)15 278 6234  
Telefax: +31 (0)15 262 3271  
E-mail: c.boers@dimes.tudelft.nl  
Website: www.dimes.tudelft.nl

**DISENS**
Mekelweg 4  
ITS Building  
NL-2628 CD Delft  
the Netherlands  
Phones: +31 (0)15 278 5745  
Telefax: +31 (0)15 278 5755  
E-mail: DISENS@TUDelft.nl  
Website: www.DISens.tudelft.nl

**Mesa**
University of Twente  
PO Box 217  
NL-7500 AE Enschede  
the Netherlands  
Phones: +31 (0)53 489 2715  
Telefax: +31 (0)53 489 2575  
E-mail: MESA@el.utwente.nl  
Website: www.mesaplus.utwente.nl

**Novem Utrecht**
Catharijnesingel 59  
PO Box 8242  
NL-3503 RE Utrecht  
the Netherlands  
Phones: +31 (0)30 239 3493  
Telefax: +31 (0)30 231 6491  
Website: www.novem.nl
Sensor Technology Club
FHI
Uraniumweg 23
PO Box 2099
NL-3800 CB Amersfoort
the Netherlands
Phones: +31 (0)33 4657 507
Telefax: +31 (0)33 4616 638
Website: www.sensorclub.nl

Syntens Den Haag
Laan van Ypenburg 90
PO Box 1183
NL-2280 CD Rijswijk
the Netherlands
Phones: +31 (0)70 4145 555
Telefax: +31 (0)70 4145 544
Website: denhaag@syntens.nl

TNO
PO Box 6050
NL-2600 JA Delft
the Netherlands
Phones: +31 (0)15 269 69 69
Telefax: +31 (0)15 261 24 03
E-mail: infodesk@tno.nl
Website: www.tno.nl

Technology Foundation STW
Van Vollenhovenlaan 661
PO Box 3021
NL-3502 GA Utrecht
the Netherlands
Phones: +31 (0)30 6001 297
Telefax: +31 (0)30 6014 408
E-mail: sensor@STW.nl
Website: www.stw.nl/sensor

WIB
Prinsessegracht 26
NL-2514 AP The Hague
the Netherlands
Phones: +31 (0)70 356 00 92
Telefax: +31 (0)70 356 00 74
E-mail: office@wib.nl