



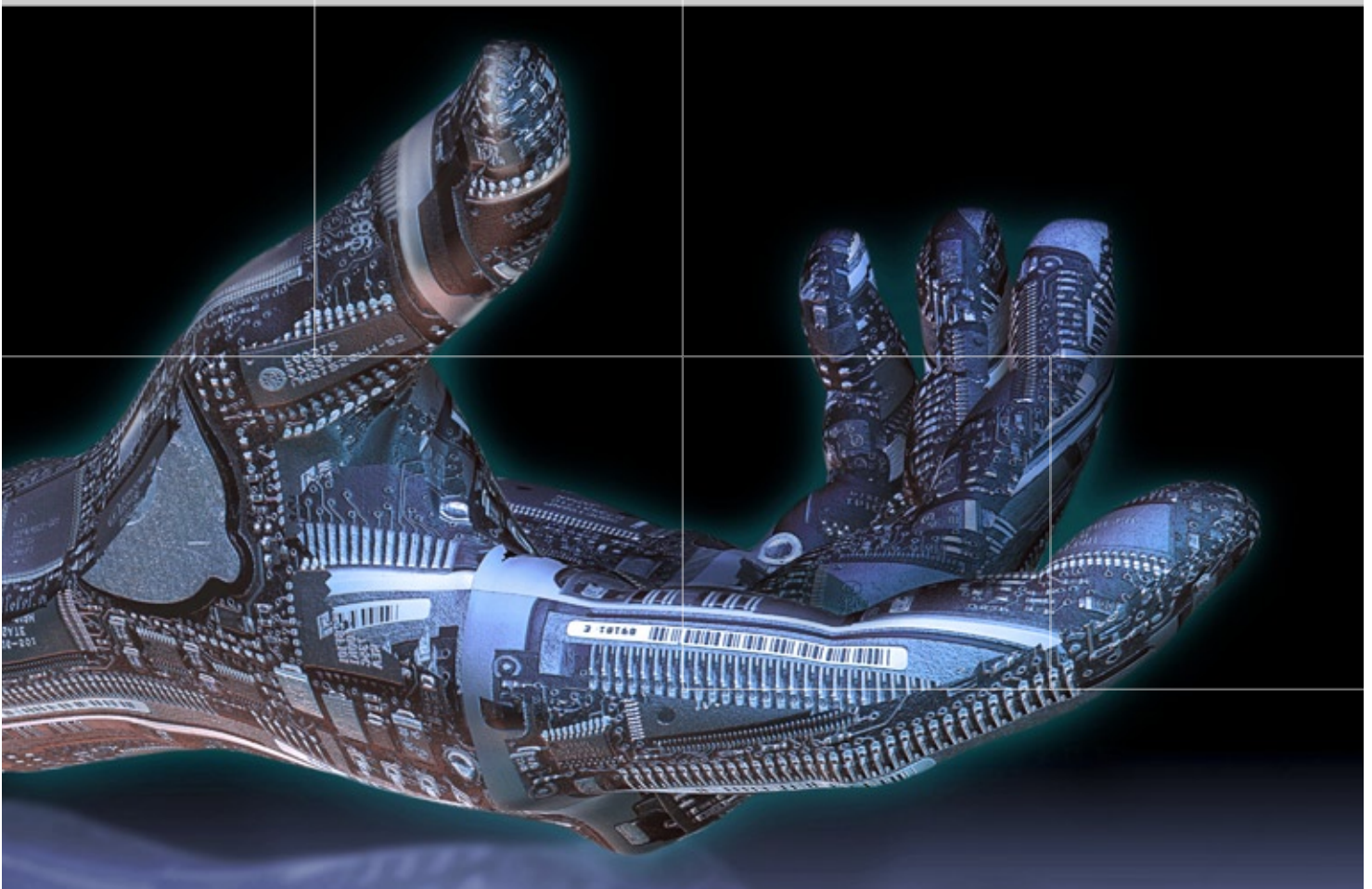
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Nordic Innovation Centre

March 2008

COSMOS - Components and Smart Machines with Micro-Nano Surface Embedded Sensors

- Joining Nordic forces to enable next generation man-machine interfacing
- First step achieved: Prototype of a thermal micro-sensor under wear resistant coating on stainless steel



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Title: Components and Smart Machines with Micro-Nano Surface Embedded Sensors (COSMOS)		
Nordic Innovation Centre project number: 06060		
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Abstract: The present COSMOS project (Components and Smart Machines with Micro-Nano Surface Embedded Sensors) has successfully merged two non-overlapping core competences: (i) clean room based sensor design and fabrication represented by Acreo Sweden and SINTEF in Norway, and (ii) tribology related hard coatings represented by VTT in Finland and Danish Technological Institute in Denmark. The main objective of the COSMOS project was to develop a prototype of a sensor, buried under a wear-resistant coating. The development was based on the know-how and the fabrication facilities of the involved partners. The main obstacle by creating an embedded sensor is related to the fabrication of a sufficiently insulating intermediate layer to be deposited on e.g. stainless steel as known from traditional wafer processing. A series of sensor fabrication experiments was conducted applying a shadow-based masking technique. Based on this series of experiments it was possible to quantify the insulating properties of the underlying isolation layers. An insulating layer composed of only Atomic Layer Deposition of Al₂O₃ or only Dual Magnetron Sputtering of Al₂O₃ appeared to be insufficient isolation for sensor fabrication. The best result was obtained for a multilayer coating system composed of either (i) Atomic Layer Deposition of Al₂O₃ followed by Dual Magnetron Deposition of Al₂O₃, or (ii) Several layers of Diamond Like Carbon (Ta:DLC), or (iii) a multilayer system composed of several layers of Al₂O₃/Cr₂O₃. Pure sensor adhesion to the underlying insulating layer was observed to be improved significantly by treating the substrate with implantation of oxygen. The final surface embedded temperature sensor was buried under Diamond Like Carbon (DLC) revealing promising properties in industrial applications. The ideas and the visions of the COSMOS project were communicated to relevant industrial partners in Europe. The development and implementation on more complicated geometries will be continued in COSMOS II.		
Topic/NICE Focus Area: Nordic MINT (Micro- and Nanotechnology) / Everyday Nano		
ISSN:	Language: English	Pages: 42
Key words: Surface embedded sensors, low-friction and wear-resistant coatings, PVD. CVD, magnetron sputtering, arc-DLC, sensor design		
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Executive summary

The purpose of the present COSMOS project was to merge non-overlapping core competences in two different topics, i.e. in the field of tribology and sensor fabrication, respectively. Tribology related issues are typically characterized by functionally optimized coatings deposited on three-dimensional machine components and devices typically made from stainless steel. Contrary hereto, sensor design and fabrication is only linked to a more or less two-dimensional silicon-based technology platform.

These two worlds were merged in order to fabricate surface embedded micro and nanosize sensors buried under hard, wear-resistant coatings. Focus was on fabrication of a temperature and/or a pressure sensor.

The project revealed that it was not straightforward to deposit a sufficiently electrical-insulating coating on to stainless steel. The isolation properties were improved by combining different coatings and good results were obtained for: (i) several layers of Ta:DLC, (ii) Atomic Layer Deposition of Al_2O_3 followed by dual magnetron sputtering of Al_2O_3 (iii) and multilayer $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$.

A final COSMOS-I prototype was fabricated by burying a Pt100 type temperature sensor under a non-conducting Ar IBAD DLC-like, low friction, wear-resistant coating.

The purpose of the COSMOS project was:

The main purpose of the present COSMOS project was development of a generic micro/nano-structured temperature sensor, embedded under optimized wear-resistant coatings to be deposited on a three-dimensional industrial relevant machine component fabricated from e.g. stainless steel. The temperature sensor (Pt100 or Cu/constantan) will be sandwiched between insulating layers and buried under a wear-resistant coating. Secondly, the COSMOS project would facilitate communication and networking between the involved partners and the European industry.

The concept of a sensor embedded under wear-resistant coating developed within the COSMOS project can be incorporated in numerous applications such as inside a plastic moulding form quantifying on-line the moulding temperature inside critical geometries ensuring optimal performance. Another application area could be in devices where surfaces are in direct contact such as in gliders, rollers and even bearings. Here an on-line quantification of the surface temperature would enable optimal performance and even prevent costly breakdowns by on-line regulation of process parameters.

The study has achieved this aim by:

The COSMOS project has successfully achieved this by combining the core competencies and the available equipment at the involved partners. Key achievement being:

- Elucidating and quantification of different isolating properties of different types of insulators.
- Developing a first generation of an embedded temperature sensor buried under wear-resistant coatings
- Applying different techniques available at the involved partners.
- Facilitated communication with a group of interested industrial partners in all four countries (S, N, Fin and DK).
- Applying and successfully archiving continuation of COSMOS-I in COSMOS-II.

Applied methods:

The applied methods in the COSMOS project are based on experimental techniques available at the involved partners and associated networks. In short, they are based on different coating techniques relevant for the fabrication of tribological coatings and different cleanroom processing techniques applied in connection with sensor fabrication. In all cases, the involved partners have access to a wide variety of state-of-the-art techniques.

Main results from the COSMOS project:

The main results can be summarized as:

- Overcoming the material gap between silicon and stainless steel.
- Overcoming the dimensional gap between traditional flat 2D wafers and more complicated thicker steel samples.
- Quantification of the properties of different electrical insulating layers deposited on stainless steel. The best result was obtained for ALD- Al_2O_3 followed by dual magnetron Al_2O_3 and for several layers of Ta:DLC.
- Sufficient electric insulation was observed for ALD- Al_2O_3 followed by dual magnetron Al_2O_3 and for several layers of Ta:DLC.
- It was observed that the adhesion of sensor metal structures to Ta:DLC was insufficient but could be increased significantly by oxygen implantation.
- Sensor structures have been fabricated and buried under low friction diamond-like carbon coatings.
- Proof of concept has been achieved for fabrication of flexible shadow masks suited for deposition of sensor structures onto three-dimensional components.
- Interchange of samples between the world of tribology and the world of cleanroom processing.
- Facilitating contact and networking between the involved partners and industrial end-users in several European countries.

The following conclusion can be drawn from the COSMOS project:

- ALD Al_2O_3 alone is not having sufficient isolation properties for sensor fabrication on stainless steel.
- 1-2 micrometer of dual magnetron deposited Al_2O_3 alone is not having sufficient isolation properties for sensor fabrication on stainless steel.
- ALD Al_2O_3 combined with dual magnetron Al_2O_3 reveal superior isolation properties.
- Several layers of Ta:DLC reveal sufficient isolation properties for sensor fabrication.
- Metal adhesion is poor on Ta:DLC. In fact so poor that it is not possible to deposit sensor structures directly on Ta:DLC.
- Metal adhesion to Ta:DLC can be increased significantly by treating the Ta:DLC substrate with oxygen implantation.

Recommendations for continued studies:

In order to successfully fabricate surface-embedded sensors under functionally optimized wear-resistant coatings it is important to entangle the issues related to the deposition of electrically insulating coatings on three-dimensional steel items. The successes appear to be highest when adding several isolating layers, lowering the overall pinhole/defect density. The present studies have showed the highest success for: (i) ALD Al_2O_3 combined with sputter deposited Al_2O_3 , and (ii) several layers of arc Ta:DLC. The result of COSMOS-I will be extended in COSMOS-II where

the involved partners will develop sensor fabrication on even more complicated geometries approaching real industrial applications.

Content

1. Introduction.....	3
2. Materials.....	3
2.1. Substrate.....	4
2.2. Electrical isolating coating.....	4
2.2.1. Available COSMOS relevant techniques for insulator fabrication.....	5
2.2.1.a. PECVD (Danish Technological Institute):	5
2.2.1.b. DC Sputtering (Danish Technological Institute):	5
2.2.1.c. Magnetron sputtering with DC pulse-technology (Danish Technological Institute):.....	5
2.2.1.d. Arc-DLC (VTT):	6
2.2.1.e. IBAD DLC (Danish Technological Institute):	7
2.2.1.f. ALD (UiO and Planar):	7
2.2.1.g. Hybrid combinations:	8
2.3. Type of insulators	8
2.3.1. Dual magnetron AlN (DTI):	8
2.3.2. PECVD Si ₃ N ₄ (DTI):	8
2.3.3. Dual Magnetron Al ₂ O ₃ (DTI):	9
2.3.4. Al ₂ O ₃ /Cr ₂ O ₃ multilayer coating (CemeCon AG):	10
2.3.5. Al ₂ O ₃ and TiO ₂ by ALD (UiO and Planar):	11
2.3.6. Hybrid materials by ALD (UiO):	11
2.3.7. Non-conductive IBAD-DLC (DTI):	11
2.3.8. Ta:DLC (VTT):	11
2.4. Sensor principle and materials	12
2.4.1. Temperature:	12
2.4.2. Pressure/Force:	12
2.4.3. Suitable elastic/ dielectric material, in particular Hybrid materials (UiO):.....	13
2.4.4. Suitable elastic/dielectric material, in particular hybrid materials (UiO):.....	13
2.4.5. Stress/strain sensor:	13
2.4.6. The “Mihara” pressure sensor:.....	13
2.5. Wear-resistant coatings	14
2.5.1. a-DLC (VTT):	14
2.5.2. PVD-DLC (Danish Technological Institute):	15
2.5.3. CrN (Danish Technological Institute):	15
2.5.4. TiAlN Multilayer (Danish Technological Institute):.....	15
3. Sensor design	16
3.1. Flex mask	17
3.2. Etched metal shadow mask	18
3.3. Actual design.....	18
3.4. Contact pads.....	18
3.5. Resistive temperature sensor.....	19
3.6. Thermocouples.....	20
3.7. Capacitive pressure sensor	21
3.8. Twin arc pressure sensors	22
3.9. VTT design	22
3.10. Test structures	23
3.11. Comparison of mask versus design.....	24

3.12. Comparison of deposition versus design	26
3.13. Electrical measurements	27
3.14. Design rules	27
4. Results.....	28
5. Final embedded sensors – the “real” demo	30
6. Collaboration with industries	32
7. References.....	33

1. Introduction

The objective of the present project is to merge mutual non-overlapping technologies to fabricate product embedded sensors buried under hard wear-resistant coatings. The non-overlapping core competences are production of tribological coatings on three-dimensional (3D) surfaces, which is represented by VTT in Finland and Danish Technological Institute. Sensor design and fabrication by state-of-the-art clean room processing on flat silicon wafers is represented by Acreo in Sweden and Sintef in Norway.

Fabrication of an embedded temperature sensor will prevail over both the material gap and the dimensional gap. The material gap is represented by a transition from sensor fabrication on industrial relevant steel surfaces versus more or less trivial sensor fabrication in connection with flat silicon wafers. The dimension gap is overcome when we are capable of fabricating a sensor unit on a more complex geometry as opposed to on a two-dimensional (2D) silicon wafer.

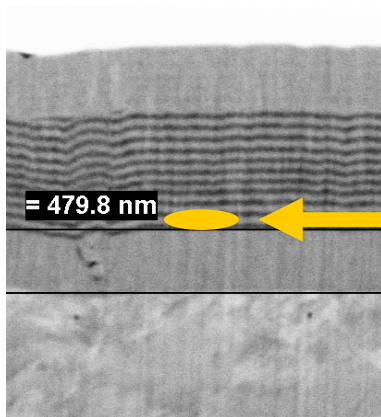
So far, there have only been very few attempts to fabricate product embedded sensors in connection with bearings and metal tools. Current state-of-the-art technology is represented by hand-held prototypes produced in academic surroundings. These examples are not at all ready for commercial applications (see e.g. Fraunhofer Institute or Mihara et al.).

The present COSMOS project will rely on the competences and fabrication techniques available at the involved partners' facilities as well as in their respective networks.

During the 2-year project there has been an extensive dialogue with relevant industrial partners, which has further solidified the need and interest for product imbedded sensors even further. The project will be extended by additional two years in the framework of MNT ERA-Net, funded by Nordic Innovation Centre (NiCe), the Research Council of Norway (RCN, Norway), and Tekes (Finland).

2. Materials

Product embedded sensors in bearings, moulds, extruders and other critical components will involve machined three-dimensional substrates, made from materials such as e.g. stainless steel, moulmax, etc. A common hurdle of all these substrates, is not only that they are three-dimensional but also that they are electric conductive in their nature. Hence, in order to incorporate a sensor circuit on such complex geometries, it is not only necessary to be able to handle 3D geometries but it is also of outmost importance to be able to deposit a pinhole and defect-free electrical isolating coating on top of these geometries prior to sensor deposition. Subsequently, the sensor structures have to be buried under hard wear-resistant coatings optimized for the specific operation before the integrated sensor device will be fully operational. In applications where the sensor structure will be buried under an electric conductive wear-resistant coating, it would again be necessary to deposit an isolating top-coat prior to burying the sensor device under the protective conductive wear-resistant tribological coating. Below (figure 1) is shown a schematic illustration of a sensor unit buried under a hard wear-resistant TiAlN/TiN multilayer coating.



Principle of surface embedded sensors

- ◆ Temperature
- ◆ Pressure
- ◆ Electrical properties
- ◆ Magnetic properties
- ◆ Thermal properties
- ◆ Visional properties
- ◆ Optical properties

Figure 1: SEM image illustrating an embedded sensor under a multilayer TiAlN/TiN wear-resistant coating.

Below is given a summary of the different material combinations, fabrication technique, sensor designs etc. which have been involved in the challenge of fabricating product embedded sensors in the present COCMOS-project.

2.1. Substrate

From the extensive network of VTT and Danish Technological Institute's Tribology Centre a survey of relevant substrate materials has been conducted. Special emphasis has been put on segments related to production equipment and machine components. Most often these components are made from austenitic, ferritic, martensitic and austenitic-ferritic (duplex) steels, such as AISI316L, Sverker 21, high speed tool steels (HSS), low-alloyed hardenable steels, etc. In applications, where the heat conducting properties of the base material is important, highly conducting materials such as copper based (moulmax) and aluminium-based alloys may be applied.

The surface finish will in most applications be applied directly from machining. In more critical applications the surfaces have either been mechanically grinded, electrochemically polished or polished mechanically to improve the surface finish.

Based on this survey, the COSMOS project decided to start on making a surface embedded sensor on polished AISI316L disks.

2.2. Electrical isolating coating

On a standard clean room processing platform it would be straight forward either to grow a thermal SiO₂ oxide on a silicon wafer or alternatively deposit an electrically isolating coating. Typical barrier or electrical isolating coatings deposited in standard wafer processing would be PCVD or LPCVD deposition of silicon nitride, boron/phosphor doped SiO₂ or pure SiO₂ from Si containing procurers such as e.g. SiH₄. However, since the substrates relevant for the COSMOS project have geometries far beyond flat silicon wafers, and further, a limited process temperature window, the above mentioned deposition techniques would clearly be inapplicable mainly due to incompatible geometries, process temperatures and the danger of cross contamination of existing clean chambers or clean process lines.

2.2.1. Available COSMOS relevant techniques for insulator fabrication

Different deposition techniques for various electrical isolating coatings have been tested, bearing in mind that the different techniques in question should be applicable on COSMOS relevant substrates. Special relevant issues being the process temperature and the 3D-nature of the items to be coated. Below is given a short introduction to the different deposition techniques applied within the COSMOS project in order to grow a defect-free electrical isolating layer on top of AISI216L steel surfaces.

2.2.1.a. PECVD (Danish Technological Institute):

As a possible setup for plasma-assisted chemical vapour deposition (PACVD) of Si_3N_4 , a commercial hot-wall Rübig PACVD system (PC 35/80) was re-configured to deposit Si_3N_4 films from SiCl_4 . The plasma was controlled by a bipolar DC-power generator capable of alternating the plus/minus configuration as well as adjusting the time lag (pause) between adjacent pulses. The pulsating plus/minus is needed in order to handle non-conductive coatings. The process parameters, i.e. gas flows (SiCl_4 : 0.5 - 1.0 slh, N_2 flow: 0.5 - 1.0 slh, H_2 flow: 200 slh, and Ar flow: 5 slh), voltages (200-1000V), temperatures (300-550 °C) and total pressures (0.5-5 mbar) were varied systematically within a relevant process window to deposit different Si_3N_4 films.

2.2.1.b. DC Sputtering (Danish Technological Institute):

Reactive sputtering is a well-known physical vapour deposition (PVD) technique applied routinely in connection with deposition of wear-resistant coatings. However, most of the deposited coatings (e.g.: CrN, TiN, TiCN, TiAlN) are fairly good conductors. Applying reactive DC-sputtering in the case of non-conducting coatings such as AlN, Cr_2O_3 , TiO_2 or Al_2O_3 appeared not to be trivial due to a phenomenon named “disappearing anode”. Basically, the non-conducting coating is also deposited on the anode which gradually gets more and more isolating. As a consequence hereof one pole, the anode, in the dc-circuit is gradually disappearing eventually closing down the sputtering process. Figure 2 shows an illustrative example, where a gradually decreasing ion current is observed during the deposition of AlN. For a comparison a normal and stable DC-run has been superimposed.

2.2.1.c. Magnetron sputtering with DC pulse-technology (Danish Technological Institute):

In order to overcome the technological limitation of conventional reactive DC-sputtering in connection with deposition of non-conducting coatings, two pathways were investigated in greater details: (i) interfacing the existing DC-sputter technology at DTI with an external alternating plus/minus power supply, and (ii) conducting an analysis of possible external suppliers of non-conductive coating. The first solution will solve the disappearing anode issue since the cathode/anode configuration will alternate during a sequence of positive and negative pulses, continuously cleaning the alternating cathode/anode configuration effectively. Concerning external supplies capable of depositing non-conductive coatings on an industrial relevant production scale it was only possible to find one supplier within Europe. A series of test runs were conducted on a CemeCon SinOx setup in Germany equipped with state-of-the-art DC-pulse technology.

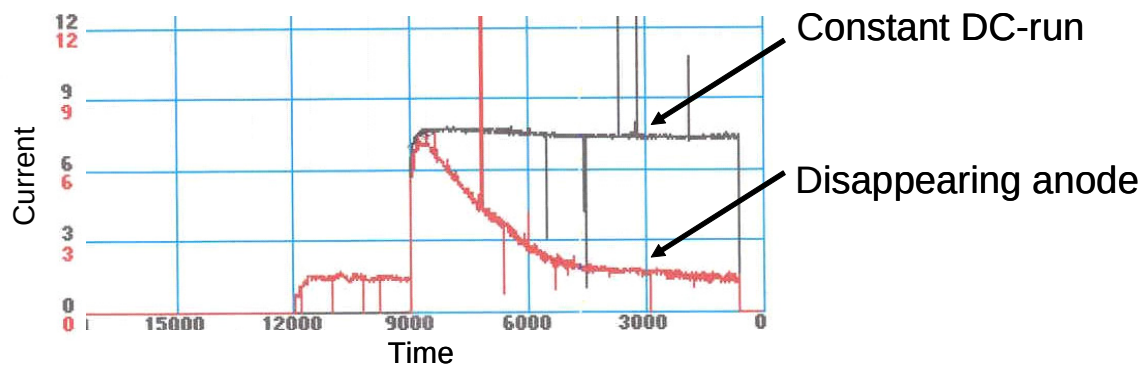


Figure 2: Comparison of magnetron current in two different runs: (i) Stable DC-sputtering of conductive coatings (black) and (ii) deposition of a non-conducting AlN coating (red) where the current is gradually decreasing due to coating of the anode.

2.2.1.d. Arc-DLC (VTT):

At VTT the arc deposition has been applied in order to deposit tetrahedral amorphous carbon (ta-C) coatings. The ta-C coatings were deposited by a pulsed vacuum arc discharge method where a cylindrical graphite cathode provides the carbon species for the plasma through an arc discharge. (See figure 3). A capacitor arrangement was applied to provide a current pulse, which accelerated the carbon species towards the substrate surface, situated at 300 mm distance from the cathode. In order to improve the adhesion of the coating, a thin titanium layer was deposited as an intermediate layer on the substrate by using a continuous current arc device with curved magnetic field to deflect the plasma. Prior to the deposition the substrates were sputter-cleaned *in situ* by argon ions. The pressure was in the range of 3×10^{-4} to 3×10^{-3} Pa and the deposition temperature was typically below 80 °C. The nominal deposition rate was about 0.5 $\mu\text{m/h}$. The ta-C coating is non-conductive.

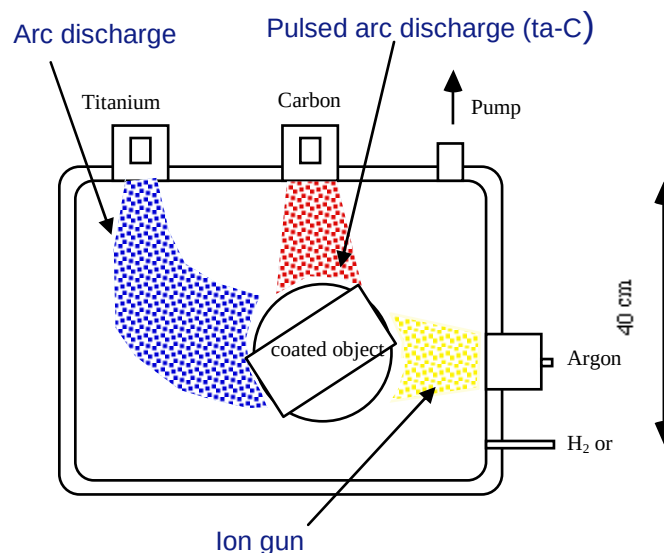


Figure 3: Principle of the VTT arc discharge equipment for the ta-C coating deposition.

2.2.1.e. IBAD DLC (Danish Technological Institute):

Another type of non-conductive tribological coating applied in the COSMOS project is Ion Beam Assisted Deposition of Diamond-Like Carbon coating (IBAD-DLC). This coating contains a mixture of sp^2 and sp^3 carbon atoms created by shooting between 50 keV to 200 keV energetic ions into vaporized oil. The result of this process is a hard low-friction IBAD-DLC coating with a unique adhesion to the underlying substrate. When the decomposition of the vaporized oil is driven by argon ions the resulting DLC coating will be non-conductive. This type of tribological coating will be especially relevant as an on-top protection of underlying sensor structures since the adhesion to the underlying coating as well as the buried sensors is expected to be very high. Furthermore, the non-conductive nature of the argon IBAD-DLC would clearly be an advantage in connection with the underlying sensor structures.

2.2.1.f. ALD (UiO and Planar):

ALD is a chemical vapour-phase deposition technique that relies on alternating self-hindered gas-to-surface reactions [1-8]. This enables the thickness to be controlled at an atomic level over large area substrates with neglectable gradients. This technique has almost unique surface covering characteristics, making it possible to coat intricate shapes evenly. Moreover, deposition can be done at relatively low temperatures (25 – 600 °C, most often in the range from 150 to 300 °C). ALD is excellent for production of multilayered structures since limited interdiffusion is expected at these deposition temperatures.

The ALD technique has proven excellent for production of electrically insulating materials. It has from the beginning of its invention in 1973 [6-8] been used for deposition of electrically insulating Al_2O_3 in solid state electroluminescent displays. The technique has been widely used to produce electroluminescent displays without the need of clean rooms since it will coat dirt on the substrates conformally. The ALD process enables production of pinhole free films without use of clean rooms, since also the dust particles are covered evenly. The ALD technique is currently used to deposit Al_2O_3 or HfO_2 as replacement for thermally oxidized SiO_2 as insulating layers in transistors and has as such enabled the 65 and 45 nm technologies.

The ALD technique shows excellent scalability properties to large area substrates and to high volume production, including roll-to-roll processing. The ALD technique has been demonstrated to coat 50 pieces of glass plates with a dimension of $40 \times 50 \text{ cm}^2$ evenly with Al_2O_3 within one run.

The thin film research group at UiO has broad experience in synthesis and characterization of complex oxides by different means. In 1995 UiO initialized ALD activities in collaboration with Helsinki University of Technology and at present three ALD reactors are operative at UiO. The research group at UiO has also been the first to prove that the ALD technique is well suited for deposition of organic-inorganic hybrid materials with a large freedom with respect to type of organic and inorganic building units [1, 2].

In connection with the COSMOS project 500 nm thick ALD- Al_2O_3 from Planar (Finland) has also been investigated as a candidate for electrical isolation of the underlying substrate.

2.2.1.g. Hybrid combinations:

Different combinations of the above mentioned deposition techniques have also been tried in order to improve the quality of the added non-conductive layer. So far the best result has been obtained by combining a thin ALD- Al_2O_3 layer with a dual magnetron PVD Al_2O_3 overlayer.

2.3. Type of insulators

Below is given a short introduction to the different isolating coatings deposited within the COSMOS project. The coatings have all been deposited by the techniques summarized above.

2.3.1. Dual magnetron AlN (DTI):

Several series of AlN runs have been tested. Figure 4 below shows a FIB-SEM image of an AlN deposited sample on which a Cu test structure has been deposited. All test measurements reveal that it was not possible to achieve a sufficient electrical isolation to the substrate. Most likely due to pin-holes and other point-defects in the coating.

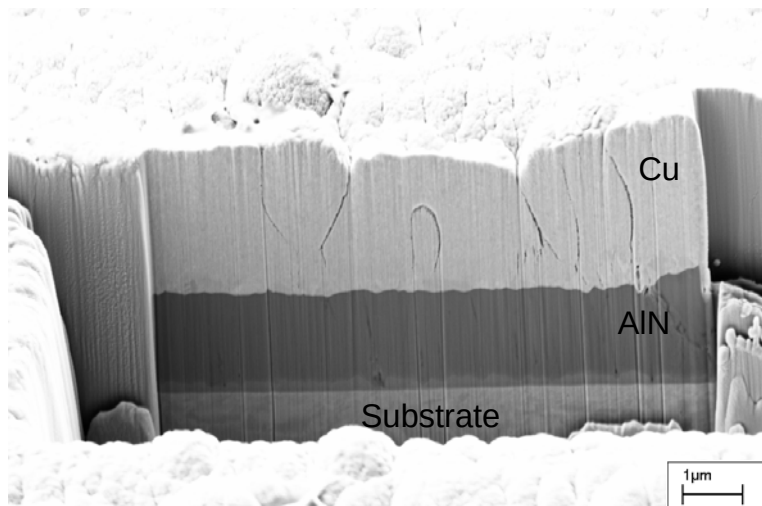


Figure 4: FIB-SEM image of a Cu/AlN/Al multilayer coating deposited on a steel substrate.

2.3.2. PECVD Si_3N_4 (DTI):

Several series of PECVD Si_3N_4 coatings have been deposited with different experimental parameters. Different “less good” regimes appear to be present in the parameter space giving either poor adhesion to the substrate or “SiN”-coatings containing a fairly large amount of stress. Nevertheless, regimes were found, where it was possible to deposit 1-3 micrometer thick Si_3N_4 coatings. However, it was not possible to get sufficient defect-free Si_3N_4 coatings to ensure a reasonable yield – most likely due to the cleanness of the PECVD chamber. The figure below shows a Rockwell C test revealing proper adhesion of the Si_3N_4 coating to the substrate. Also shown is an AFM image illustrating a typical pinhole into the growing Si_3N_4 coating.

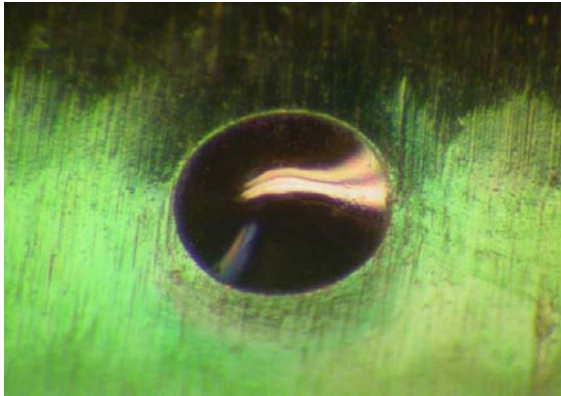
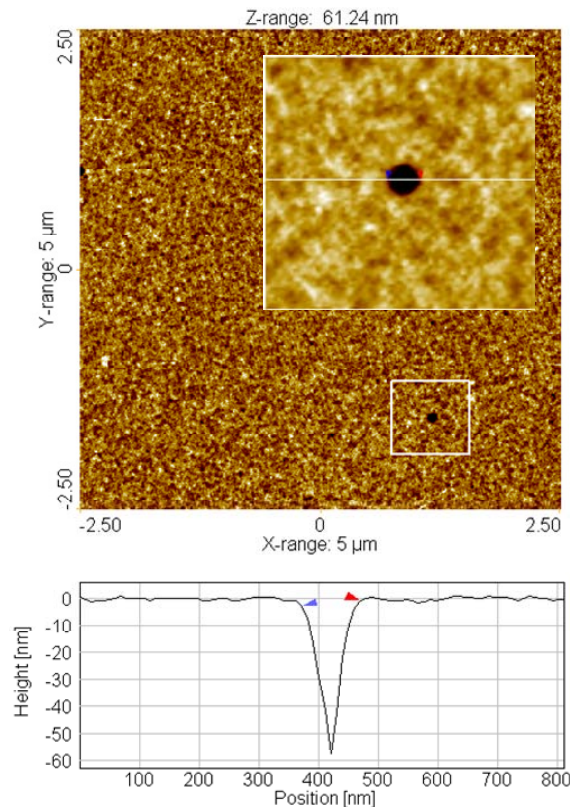


Figure 5:
Daimler-Benz adhesion test of grade 1 in
~1 μm Si_3N_4 film deposited on a High Speed
drill with a hardness of 62 HRC.

Right: Representative AFM image ($5 \times 5 \mu\text{m}^2$) of the Si_3N_4 film deposited on silicon. The overall roughness is below 1 nm. On the insert is shown a zoom of the selected area (white square) revealing a typical pinhole. The depth of the pinhole is depicted in the cross-sectioned line scan. The depth and width of the pinhole is estimated to 70 nm and 60 nm, respectively.



2.3.3. Dual Magnetron Al_2O_3 (DTI):

The magnetron sputtering setup at DTI was modified in order to run non-conducting Al_2O_3 coatings in the dual magnetron configuration with an external power supply. The conclusion of this series of experiments is that it is indeed possible to deposit Al_2O_3 under stable condition in the dual magnetron configuration. However, sufficient electrical isolation towards the substrate was still not possible due to a too large number of pinholes or other point defects in the deposited coatings. The defect density could be lowered significantly by adding an intermediate etching step facilitating nucleation and growth of new Al_2O_3 crystallites. Below (figure 6) is shown a representative FIB-SEM image of a grown Al_2O_3 coating.

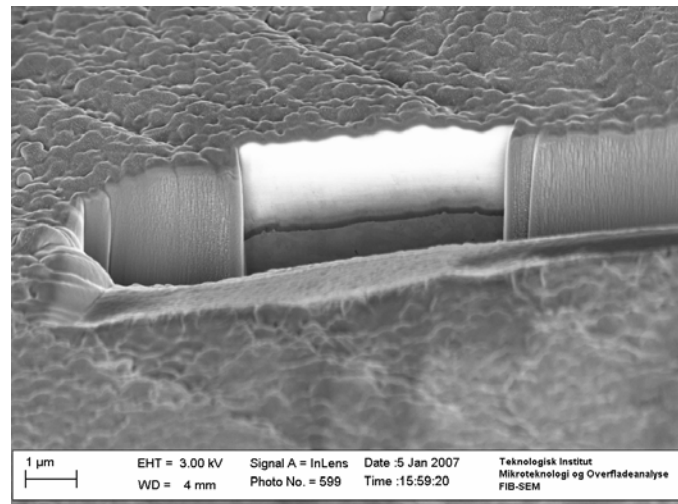


Figure 6: FIB-SEM picture of dual magnetron deposited Al_2O_3 . The profile has been created *in situ* in the FIB SEM by ion milling.

2.3.4. $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ multilayer coating (CemeCon AG):

An $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ multilayer test coating was performed at CemeCon AG. Below is shown the SEM images of this coating. The electrical isolation of this coating was observed to be better due to the multilayer nature of the coating.

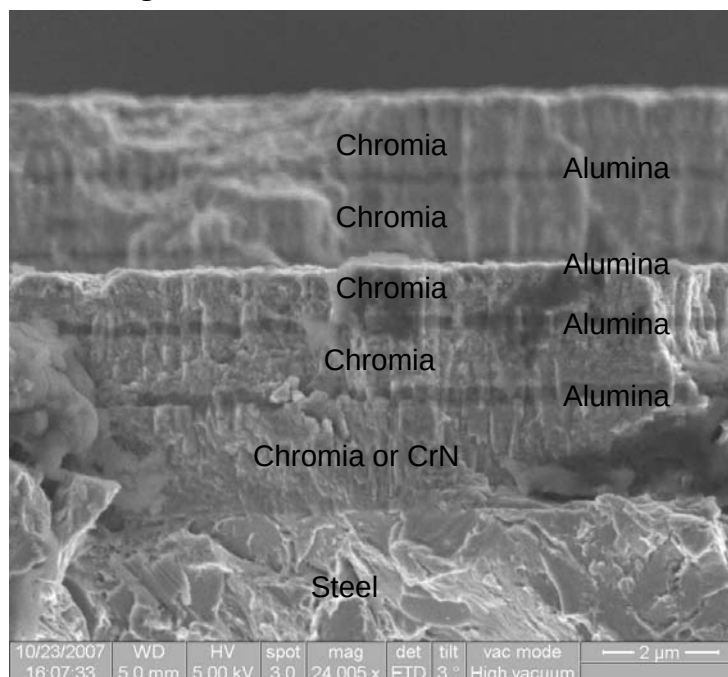


Figure 7: SEM image of a multilayer $\text{Cr}_2\text{O}_3/\text{Al}_2\text{O}_3$ coating.

2.3.5. Al_2O_3 and TiO_2 by ALD (UiO and Planar):

Both Al_2O_3 and TiO_2 are wide band gap insulators with high dielectric constants. ALD deposited Al_2O_3 is widely used as electrically and chemically insulating materials for electronic purposes. The electrically insulating properties can be further enhanced by depositing these materials as multilayered stacks. Other potentially interesting insulating materials are ZrO_2 and HfO_2 . Atomic layer deposition (ALD) from UiO in Norway and the company Planar in Finland has been involved in the COSMOS project depositing 500 nm ALD Al_2O_3 . The UiO test substrates have been deposited by ALD using TMA (trimethyl aluminium) and water at a deposition temperature of 300 °C or TMA and ozone at a deposition temperature of 200 °C. Both depositions were performed using two runs where approx. 150-200 nm of Al_2O_3 was deposited, separated by a cleaning step. An *in situ* cleaning procedure using ozone was also applied prior to all depositions.

2.3.6. Hybrid materials by ALD (UiO):

The organic-inorganic hybrid materials combine the properties of the organic and the inorganic building units. When these are chosen from units that conduct electrons poorly, the resulting film becomes a highly resistive material. These films also have a rather high growth rate as compared to similar growth processes of purely inorganic materials and do also produce surfaces with neglectable surface roughness. This class of material shows promise as a sensor-material to be further investigated in the present projects. In particular, a simple capacitive sensor design is included in the mask-set produced in the current project.

2.3.7. Non-conductive IBAD-DLC (DTI):

A special modification of the IBAD-DLC process has been applied to deposit a non-conducting DLC-like wear-resistant coating. The basic deposition principle of this coating is to decompose an oil vapour by impinging high energy ions facilitating nucleation and growth of a DLC-like coating.

2.3.8. Ta:DLC (VTT):

Ta-C coatings are hydrogen-free, hard, and mostly a sp^3 bonded carbon coating. The ta-C films were studied for the insulation purposes, since the coating is hydrogen-free and as such, non-conducting. Due to the coating deposition process, the coating structure typically has pin-holes. Therefore, the ta-C films were deposited as a multilayer system to avoid overlapping pin-hole structure and to increase the isolation properties of the coating. Several multilayer structures were studied. A coating composed of more than 5 layers of ta-C DLC appeared to provide the necessary electrical isolating properties for sensor application.

2.4. Sensor principle and materials

A very wide range of sensor principles and different materials may be used to detect physical parameters. In the COSMOS project we are restricted to thin film solutions. The reader may find most of the principles discussed here covered in greater details in the Handbook by Fraden, [Fraden, Handbook of Modern Sensors, 2nd edition]. In the following section we are covering the different sensor principles to be found on the first generation shadow mask.

2.4.1. Temperature:

Thermo-Resistivity is one of the most useful sensor principles, that the electrical resistivity of a given material (usually platinum) is a well known function of the temperature. A sensor design, using the simplest form (termed Resistance Temperature Detectors) only requires a well defined volume of defined material (Pt-alloy) mounted in or on an electrical insulator in thermal contact with the surroundings. Within a defined temperature range the temperature coefficient of resistance will follow a simple mathematical model (often near-linear in the case of Pt and W).

It is also possible to measure the temperature by the Seebeck principle as used in common thermocouple devices. In short, any conductor (such as a metal) subjected to a thermal gradient will generate a voltage which is also known as the thermoelectric effect or the Seebeck effect. Using dissimilar metals to complete the circuit, this will generate a small voltage available for measurement, which increases with temperature. This difference can typically be between 1 to about 70 microvolts per degree depending on the applied materials. In the COSMOS project it would be possible to deposit Copper and Constantan (Cu/Ni) corresponding to a T-type thermocouple which is suited for measurements in the -200 to 350 °C range. The positive conductor is made of copper, and the negative conductor is made of constantan. As both conductors are non-magnetic, Type T thermocouples are a popular choice for applications such as electrical generators which contain strong magnetic fields. Type T thermocouples have a sensitivity of $\sim 43 \mu\text{V}/^\circ\text{C}$.

2.4.2. Pressure/Force:

For the COSMOS project the relevant class of pressure and force sensors is often termed “tactile sensors” as we are restricted to thin films and such films have been employed in robotics to mimic the human “touch” sensor principle in our skin. An external force may be sensed in a piezo-resistive material (as used for stress-strain sensors), in a piezoelectric material or by using i.e. a change in the electrical resistance or capacitance between two electrical conductors that are moved closer together.

The electrical resistance between 2 conductors mounted in a semi-conducting material is partly a function of their separation distance. Thus, a simple tactile sensor may be based on a compressible semi-conductor with embedded conductor lines. Another versatile approach is to measure the capacitance between such conductors, i.e. plates separated by a non-conducting (dielectric) material.

The capacitance between two conductors is proportional to the dielectric constant of the material that separates them and the effective area of interaction, while the capacitance is inversely proportional to the distance between the conductors. An external force will induce a strain in a restricted elastic material, thus changing the effective capacitance between two conducting thin

films sandwiching the material. The ability of detecting pressure and force is then partly a task of finding a suitable elastic dielectric material.

2.4.3. Suitable elastic/ dielectric material, in particular Hybrid materials (UiO:)

The organic-inorganic hybrid materials refer to a rather large group of materials where the organic and inorganic building units can vary widely and given special functional properties such as polarity or chemical reactivity. This class of materials is excellent for producing materials amenable to alteration of thickness or polarity upon pressure changes. They are therefore most suitable as candidates for pressure sensor materials based upon alterations in capacitance or simply as piezoelectric compounds. Most of the organic-inorganic materials also show good electrical insulating properties.

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2.4.5. Stress/strain sensor:

A Strain-Gauge is usually made from a resistive, electrical conductor (usually a Cr/Ni alloy) that has a well defined change in resistance as a function of mechanical strain, i.e. elongation in a bending mode. As such, it is termed “piezoresistive”. The design is usually a meander-shaped wire or thin-film conductor such that the gauge is most sensitive in one single direction. A dedicated Strain-Gauge design is not included in the current project but is high on the list of demonstrators for COSMOS II and other follow-up projects.

A material that is “piezoelectric” will respond to a mechanical strain by a an electrical surface charge that is proportional to the strain, thus functioning as a strain sensing material with the added benefit of being able to function passively, i.e. not requiring a sensing signal. The most commonly used thin film piezoelectric material is the polymer PVDF. The integration of piezoelectric thin films (PZT-class) in MEMS is of major interest worldwide, and is an important research area for the SINTEF group taking part in COSMOS, see i.e. www.sintef.no/mems-pie. However, it has not been of primary relevance to the COSMOS project.

2.4.6. The “Mihara” pressure sensor:

Dr. Mihara at Musashi Institute in Japan has developed the thin film sensor for pressure measurement in journal bearing in order to study the lubricant film pressure acting in the journal bearings. He has applied aluminium oxide (Al_2O_3) as the electrical isolating material and manganin (Cu/Mn/Ni) as the piezoresistive material. The layered sensor structure and the sensor design used by Mihara can be seen below. This design has been included in the COSMOS mask layout.

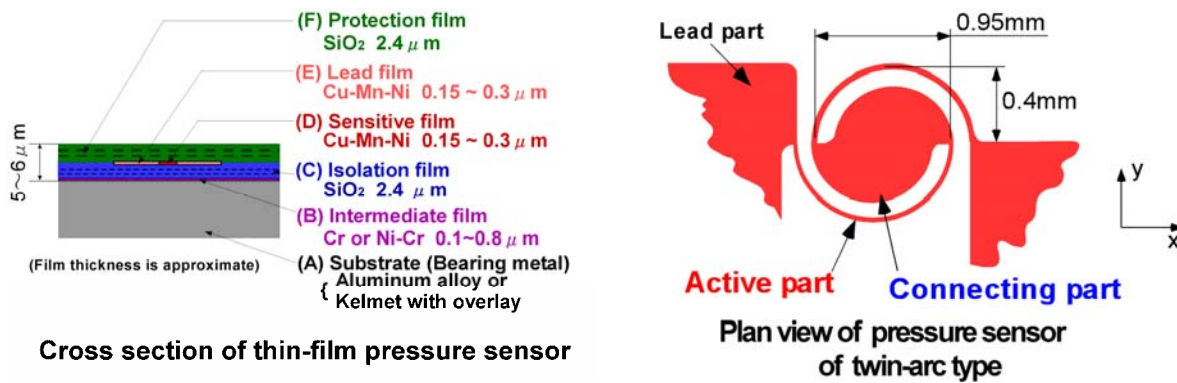


Figure 8: Cross section of thin film pressure sensor and the twin-arc design of the pressure sensor used by Mihara [Someya, T., Mihara, Y., New thin-film sensors for engine bearings, In: CIMAC Conference 2004, Kyoto, Japan. Paper no 91, 16 p.].

2.5. Wear-resistant coatings

Below is given a short introduction to the different hard wear-resistant coatings available in connection with the fabrication of surface embedded sensors in the COSMOS project.

2.5.1. a-DLC (VTT):

Diamond-like carbon (DLC) coatings have low friction and high wear resistance compared to bulk materials and to other wear-resistant coated surfaces. The surrounding environment, gas atmosphere, humidity and temperature, affect dramatically the friction and wear performance of DLC-films. In dry and inert atmospheres the highly hydrogenated DLC-films typically exhibit low friction performance, but the hydrogen-free DLC-films have high friction accompanied with increased wear. In humid environment the friction coefficient of both types of DLC-films is similar varying in the range 0.05 to 0.2 and the best wear resistance can be achieved with hydrogen-free ta-C films. At elevated temperatures the advantageous tribological properties of hydrogenated DLC-films may be disturbed due to effusion of hydrogen and graphitization of the film structure at rather low temperatures. The hydrogen-free ta-C films on the other hand can survive in higher temperatures, even though the friction coefficient reaches higher values.

DLC-films cover a wide range of different types of coatings with similar, yet differing tribological properties. The two major categories of DLC are the hydrogenated and hydrogen-free DLC films. The hydrogenated DLC-films typically have a hydrogen content from 20 to 40 at. % and the hydrogen-free DLC has only a small fraction of hydrogen present as a diluted impurity in the film structure. The composition of DLC-films has been described in a ternary phase diagram of hydrogen content, sp³ and sp² hybridization (see figure 9) [11]. Using this classification, the major groups of diamond-like carbon films that have been investigated mostly are hydrogenated amorphous carbon (a-C:H), amorphous carbon (a-C) and tetrahedral amorphous carbon (ta-C). A great interest has been addressed particularly to the tribological performance of a-C:H films deposited mostly with plasma assisted chemical vapour deposition (PACVD) processes, as discussed below. Studies on the hydrogen-free a-C films, deposited with sputtering processes, and the hydrogen-free ta-C coatings, deposited by vacuum arc or laser ablation processes, have also been carried out, but to a lesser extent. The friction and wear performance of DLC-films is greatly

influenced by the intrinsic coating properties, the functional parameters applied and the environmental conditions.

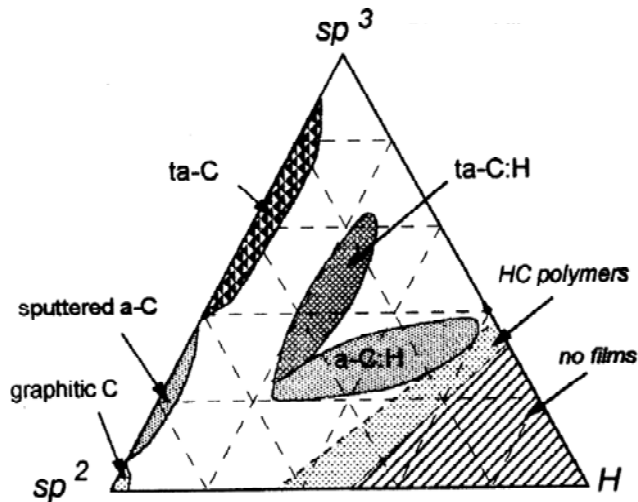


Figure 9: A ternary phase diagram of hydrogen content, sp^3 and sp^2 hybridization showing different types of DLC-films [11].

The ta-C coatings and IBAD-DLC and PVD coatings used in this study had a stable friction performance as the coefficient of friction typically varies against steel and e.g. alumina around 0.1. The wear resistance of t-c coatings is excellent and even better compared to a-C:H coatings due to high hardness of the coating.

2.5.2. PVD-DLC (Danish Technological Institute):

An electric conductive functional gradient PVD-DLC coating based on a combined PVD/”CVD” process is available for the COSMOS project. The coating is composed of CrN which is gradually converted into CrC after which follows a gas phase carbon reaction based on C_2H_4 .

2.5.3. CrN (Danish Technological Institute):

An electric conductive PVD CrN coating is available in two temperature versions, i.e. a low temperature version, where the deposition temperature is below 150°C and a high temperature version with a deposition temperature of around 450°C .

2.5.4. TiAlN Multilayer (Danish Technological Institute):

A series of hard wear-resistant TiAlN single and multilayer coatings could also be combined with the embedded sensor technology. The TiAlN coatings are available in a low temperature version and a high temperature version, respectively.

3. Sensor design

Thin film sensors in MEMS and microelectronic applications are mostly manufactured by thin film deposition and subtractive patterning of the deposited metal or isolator using photolithography techniques. This technology easily gives a pattern resolution of a few micrometer or better, but requires flat and smooth surfaces. MEMS and microelectronic applications mainly use substrates with perfect flatness, e.g. silicon or glass wafers. In machinery applications such patterning is not possible, which makes the application of thin film sensors with high resolution on 3D objects challenging and requires new and innovative approaches.

There are possibilities of depositing homogenously thick photoresist on 3D surfaces using electrodeposited resist. However, with short radius shafts or other machineries, where the sensor area has an expected deviation from a perfect flat surface to be measured in mm rather than μm , there will be a problem with exposure of such resist.

In the COSMOS project we have therefore chosen to work with shadow mask technology, where the sensor materials are directly deposited in the final pattern through a shadow mask as shown in Figure 10. Two different shadow mask technologies, flex-mask and etched metal shadow mask, have been evaluated and are described below.

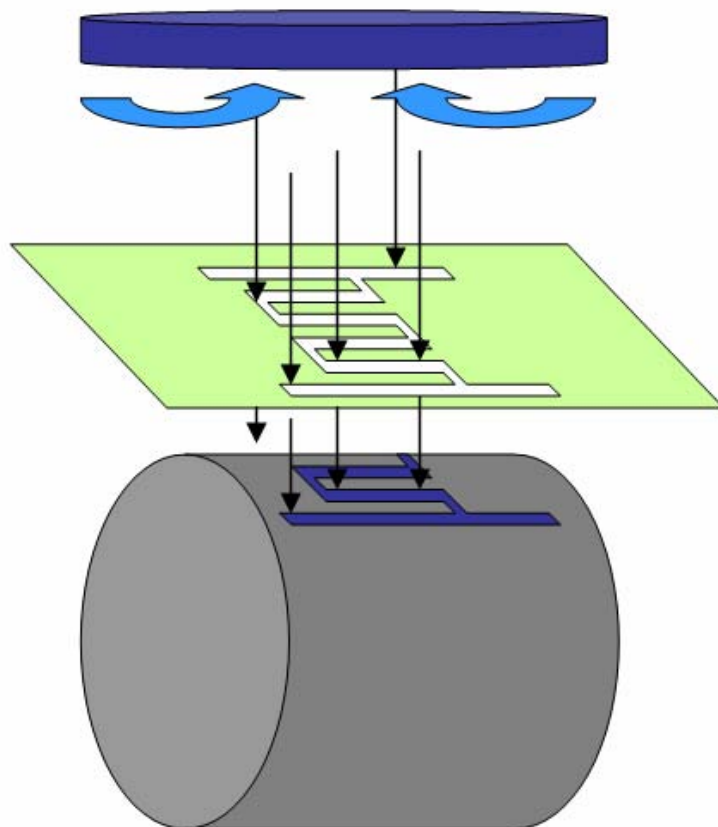


Figure 10: Principle of deposition through a shadow mask.

3.1. Flex mask

The idea with the flex mask solution is to use a technology called HiCoFlex. This technology makes it possible to apply microelectronic fabrication process, and resolution, onto flexible substrates.

Figure 11 shows the build-up of a HiCoFlex multilayer substrate. The sensor design pattern will be generated in the first layer (shown without vias in Figure 11). When released from the underlying rigid carrier this will create a very thin shadow. This mask is flexible and adjustable to any shapes of a machinery part.

In the original HiCoFlex process the first layer is only 14 μm thick. The sensor design pattern has been successfully reproduced in such a thin flex substrate. However, a shadow mask that thin is impossible to work with, when it shall be mounted on a substrate. Further development work will therefore be directed on making the mask easier to handle while keeping the flexibility of applying it onto the substrate.

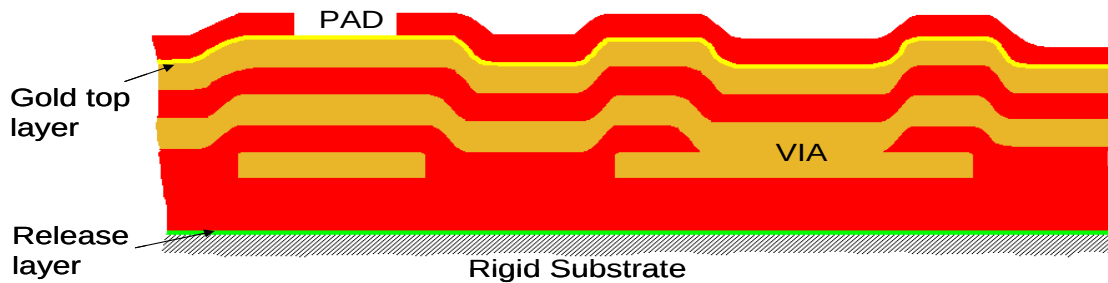


Figure 11: Cross section of HiCoFlex multilayer substrate.

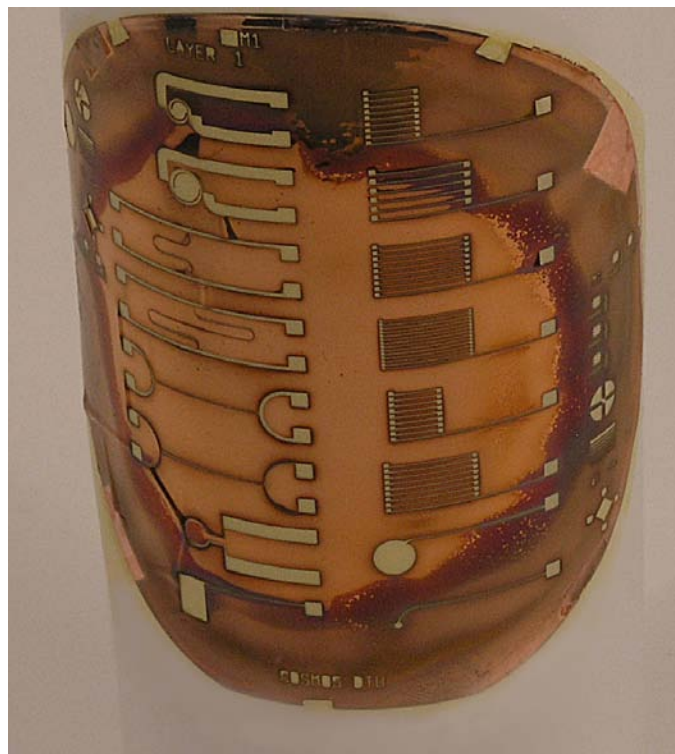


Figure 12: Picture of an early version of the flex mask development.

3.2. Etched metal shadow mask

Several different metal mask sets have been fabricated and one - “Acreo M1” – has been used for evaluation of the sensor fabrication process. The shadow mask is shaped as a 4” wafer with a standard sized primary flat. It consists of open structures in a 100 μm thick metal called 7C27Mo2 and is fabricated by HP Etch in Sweden. Each chip is $10 \times 30 \text{ mm}^2$ with up to 4 layers – 2 metal and 2 isolating layers – depending on the sensor design. The mask is held in place using several strong magnets on the backside of the substrate. A photograph of a metal shadow mask can be seen in figure 13.

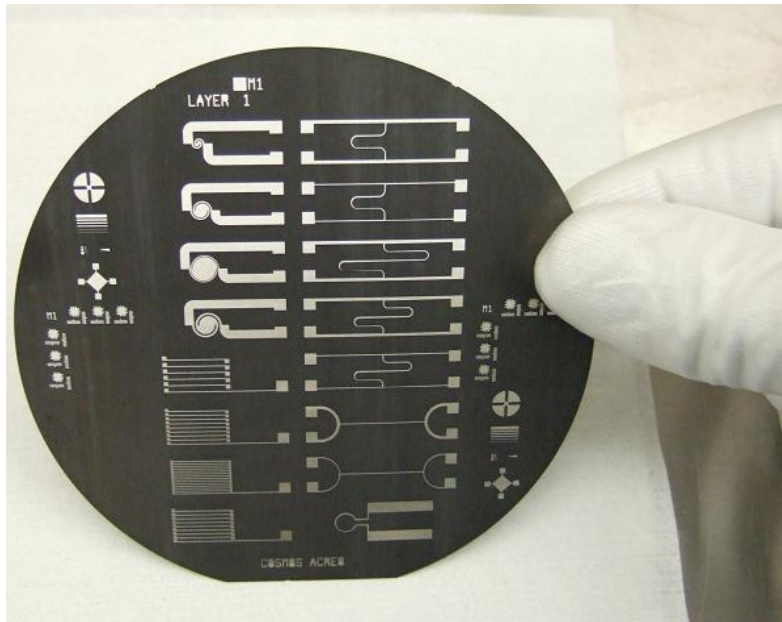


Figure 13: Photograph of the metal shadow mask with Acreo M1 sensors.

3.3. Actual design

The sensor designs are divided into three main groups; resistive temperature sensors, thermocouples and pressure sensors. The resistive temperature sensor includes one single metal layer while the thermocouples and pressure sensors include two metal layers with a sandwiched isolator in between. Special alignment marks were developed to enable alignment of the different layers to each other. The following sections describe the individual sensor design in more detail. The CAD pictures presented in this document have the following layers:

Blue:	Metal 1
Red:	Metal 2
Green:	Isolator
Turquoise:	Top isolator
Red line:	Help layer to show chip outline

3.4. Contact pads

All contact pads used in the sensor designs are square shaped $1\text{mm} \times 1\text{mm}$. The pads are placed on the same location on all sensors to make measurements easier between different devices with exception for the resistive temperature sensors that have two additional contact pads. The pads are placed 2 mm from the short end and 1.5 mm from the long end of the chips.

3.5. Resistive temperature sensor

These sensors measure the temperature by detecting a change in the resistance of a thin conductor. To eliminate the influence of the resistance in the measuring wires, the sensor is designed with 4 point connections; two that are used for measuring the voltage and two for measuring the current, resulting in the resistance by Ohm's law. The design parameters for the resistive temperature sensors were performed according to known standards [12]. The length and width of TR1-2, TR4-7 are calculated to result in 100 ohm for a 1000Å thick Pt film. TR3 results in 200 ohm. Two types of temperature sensors can be seen in Figure 14 and Figure 15, respectively. The design data can be seen in Table 1.

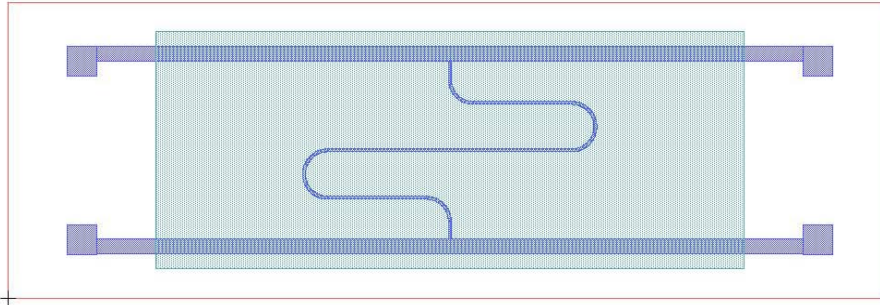


Figure 14: CAD design of resistive temperature sensor TR3.

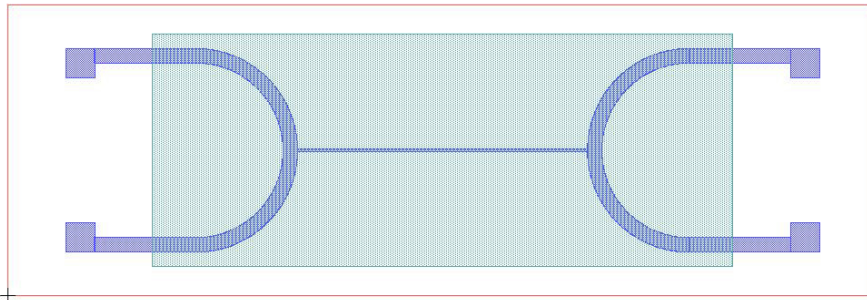


Figure 15: CAD design of resistive temperature sensor TR6.

Table 1. Design parameters for thermo-resistive sensors [μm].

Design#	Sensor Length	Sensor Width	Wire Length	Wire Width	Sensor Shape
TR1	15000	150	24000	500	H
TR2	15000	150	24000	150	H
TR3	30000	150	24000	500	H
TR4	20000	200	24000	500	H
TR5	20000	200	24000	150	H
TR6	15000	150	18000	500	X
TR7	15000	150	18000	150	X

3.6. Thermocouples

Thermocouples can be used for measuring internal temperature gradients. The read-out signal can be magnified by multiplying the amount of connections between the metals. The CAD pictures show an isolation layer between the metal layers, which does not need to be present for the device to function. This layer is intended as a possible extra precaution to prevent unwanted shortages between the metal layers in case the metal somehow gets deposited underneath the shadow mask. An example of the thermocouple design can be seen in Figure 16 and the design parameters for thermocouples are found in Table 2.

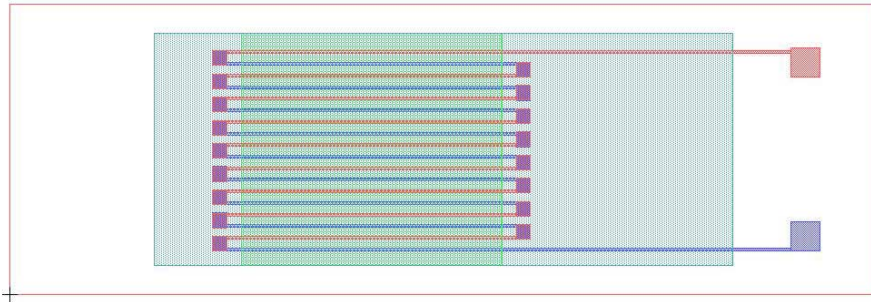


Figure 16: CAD design of thermocouple T3.

Table 2. Design parameters for thermocouple temperature sensors [μm].

Design name	Line Length	Line Width	Distance between lines	Pad Length	Pad Width	# of Line Pairs
T1	5000	150	250	550	550	9
T2	10000	150	450	750	750	6
T3	10000	150	250	550	550	9
T4	10000	150	100	400	400	14
T5	5000	200	200	600	600	9
T6	10000	200	200	600	600	9

3.7. Capacitive pressure sensor

The capacitive pressure sensors include two main designs; one with circular and one with rectangular sensor area. Each sensor consists of two overlapping metal layers with an isolator in between. It is important that the overlapping sensor area is well defined as this affects the measured capacitance and gives a value for the sensor-to-sensor reproducibility. The area control is improved by using rectangular metal areas perpendicular to each other which decrease the sensitivity to alignment errors. Sensor parameters are found in Table 3 and examples in Figure 17 and Figure 18.

Table 3. Design parameters for circular (C1-6) and rectangular (R1-5) capacitive pressure sensors [μm].

Design name	Sensor Diameter	Wire Length	Wire Width	Distance between wires
C1	150	21000	150	4800
C2	500	21000	150	4800
C3	1000	21000	200	4600
C4	3000	21000	200	4600
C5	5000	21000	200	4600
C6	1000/2000	21000	200	4600
R1	4000 x 150	16500-17400	200	2400
R2	4000 x 500	16450-17200	200	2550
R3	4000 x 1000	16300-16950	200	2800
R4	6000 x 4000	13450-14000	200	4600
R5	2000 x 1000	17300-17950	200	2800

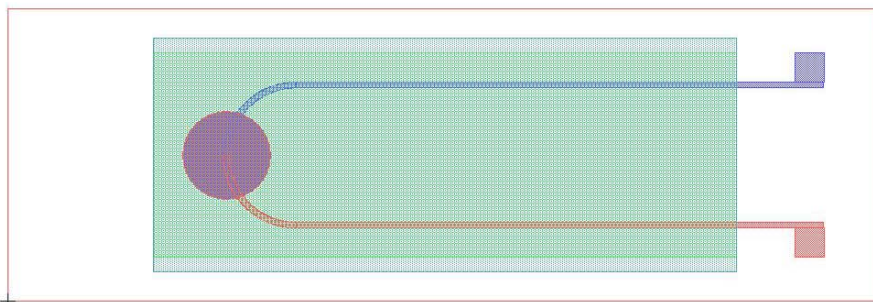


Figure 17: CAD design of circular pressure sensor.

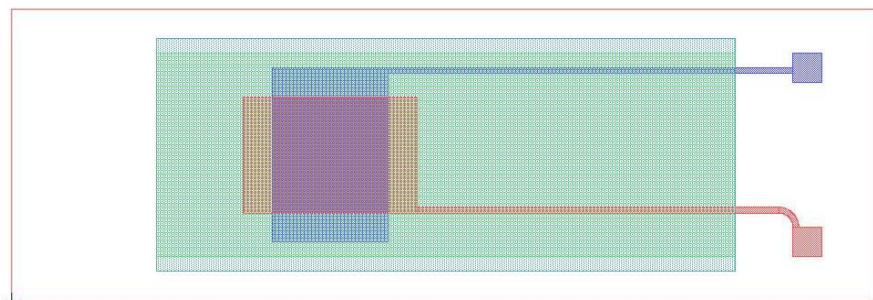


Figure 18: CAD design of rectangular pressure sensor.

3.8. Twin arc pressure sensors

We have designed some twin arc sensor devices with similar design as presented in “Paper No.: 91 New thin-film sensors for engine bearings”, Tsuneo Someya et al., CIMAC congress 2004, Kyoto. The design parameters are found in Table 4 and an example of the design is seen in Figure 19.

Table 4. Design parameters for twin arc pressure sensors.

Design name	Outer diameter	Sensor wire Width	Sensor/wire Distance	Wire Length	Wire Width	Wire Distance
X1	2000	200	200	13700-15000	1500	5000
X2	3500	200	200	13200-15500	1500	5000
X3	5000	150	150	11700-17000	1500	5000
X4	5000	300	300	11900-16800	1500	5000

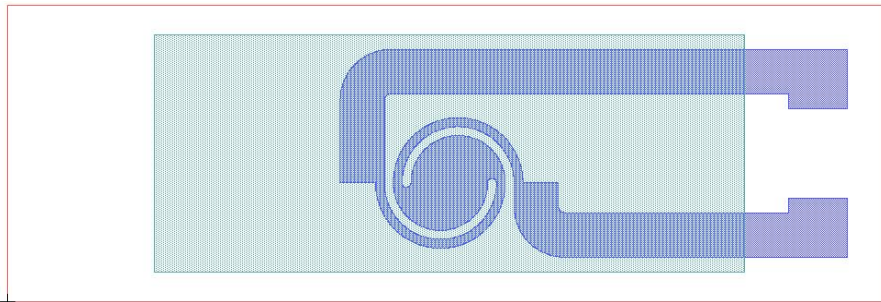


Figure 19: CAD design of piezoresistive pressure sensor X2.

3.9. VTT design

VTT had inputs on a new design they wanted to try with a 200 μm wide sensor and $2 \times 12 \text{ mm}^2$ connection wires as seen in Figure 20.

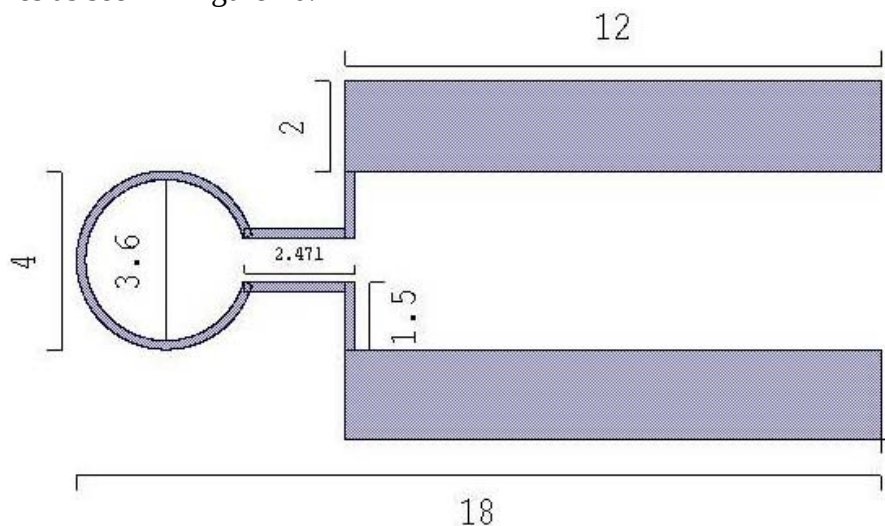


Figure 20: CAD picture of sensor design given by VTT. All measurements are in mm.

3.10. Test structures

We have included test structures on the wafer that are used for deciding the metal mask production resolution, metal deposition resolution and metal film quality. For this purpose we have designed five different structures with parameters shown in Table 5 and purpose shown in Table 6.

Table 5. CAD pictures and parameters of the test structures.

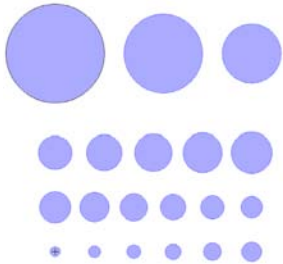
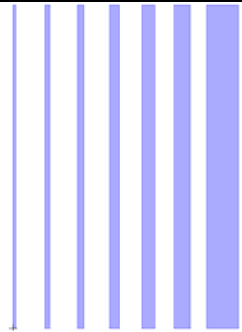
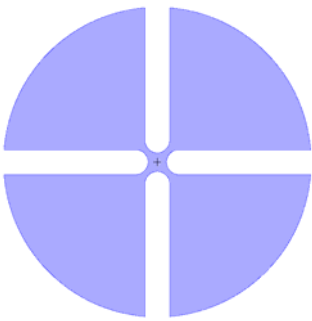
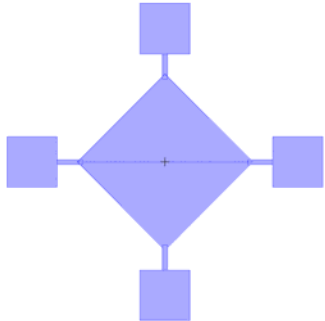
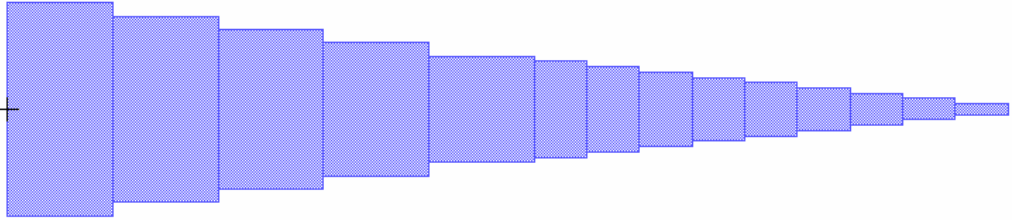
Design		Design	CAD picture
Circles: 50-500 μm Diameter		Lines: 50 – 500 μm width, 3 mm length	
Round van der Pauw: Small cross section		Square van der Pauw: Large cross section	
Arrow: 20– 400 μm width, 100 – 200 μm length per section, 2 mm total length			

Table 6. Purpose of the different test structures.

Design	Mask Production Resolution	Deposition Resolution	Film Quality
Circles	X	X	
Lines	X	X	
Arrow	X	X	
Round van der Pauw			X
Square van der Pauw			X

3.11. Comparison of mask versus design

The features on the masks have been measured using an optical microscope. For ID purposes the chip locations on the masks have been numbered with row = r and column = c put together as ‘rc’ according to Figure 21. The sensor structures included in mask “Acreo M1” is found in Table 7.

The mask has been measured both on the front and back side where the front side indicates the one where the text has correct reading.
Explanation of the table:

Bold values	Target values in CAD
The sign ‘-‘	Not measured feature
Double values, e.g. 150/150	Used for designs X1-X4 where
	- the first value indicates the gap width between metal body and hinge
	- the second value indicates the hinge width

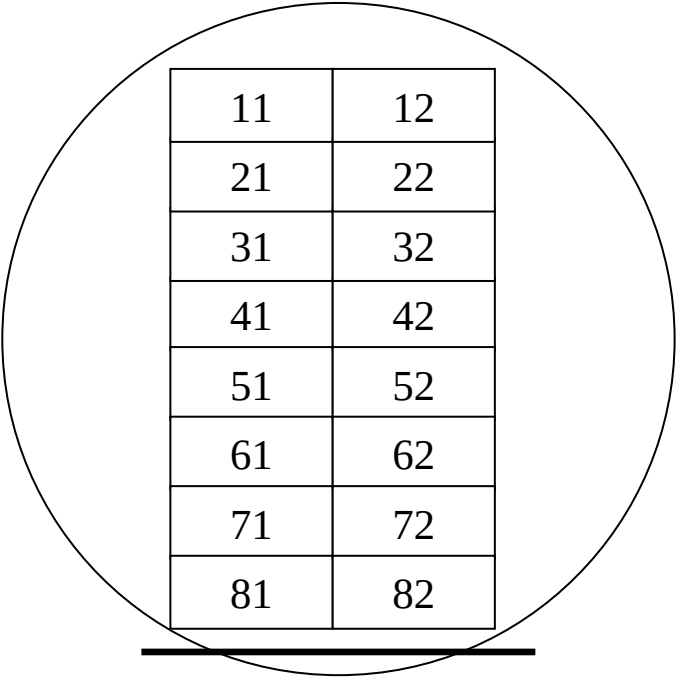


Figure 21: Chip locations on the wafer-shaped masks with the flat at the drawn line.

Table 7. Measurement values for the metal shadow mask "Acreo M1".

Chip pos	Sensor Design	Wire width CAD	Wire width back side	Wire width front side	Sensor width CAD	Sensor width back side	Sensor width front side
11	X1	1500	1533	1540	200/200	151/243	153/242
12	TR1	500	543	546	150	190	144
21	X2	1500	1530	1540	200/200	150/245	154/245
22	TR2	150	186	192	150	193	138
31	X3	1500	1526	1533	150/150	108/174	104/172
32	TR3	500	542	545	150	191	135
41	X4	1500	1530	1536	300/300	251/349	254/341
42	TR4	500	540	540	200	245	193
51	T2	150	188	194	150	193	184
52	TR5	150	185	188	200	245	197
61	T3	150	187	192	150	191	183
62	TR6	500	532	538	150	194	142
71	T4	150	191	192	150	187	184
72	TR7	150	179	189	150	193	140
81	T6	200	243	250	200	249	240
82	VTT	2000	-	-	200	251	245
Average Difference to CAD			+36	+38		+43	+17
Standard deviation			5	13		6	24

It is clearly seen in the measurement values presented in Table 7 that the openings in the mask are larger than designed in the CAD and can be explained by the etch process of the mask. The larger structures have in general a more even width on both sides of the mask compared to the smaller structures where differences up to 50 μm can be found.

The size of the standard deviation of the mask gives an indication of how controlled the etch process has been. The high values for the small structures show that the etch process has not been within the preferred processing parameter, usually called "the process window". We believe that the structures have been too small to be produced with control, using this technique. It might also be a question of adjustments of process parameters as this was the first time this technique was used for structures of this size.

3.12. Comparison of deposition versus design

By analyzing the measurement values in Table 8 it is found that the sizes of the structures on the substrate are in average about 41 μm larger than initially drawn in the CAD. This difference may originate from three different things; increased structure size on the mask, error in the attachment of the mask to the substrate or an error in the measurement of the structures. Comparing the structure size on the substrate and the mask we find an average increase of 10 μm on the wire structures with a standard deviation of 14 μm and a 20 μm average increase on the sensor structures with a standard deviation of 25 μm .

It is not probable that the structures on the substrate would be smaller than on the mask so the standard deviation resulting in a negative value is believed to originate from measurement errors. The small size of this negative part shows that the measurement values are found correct in general.

We believe that the attachment of the metal shadow mask to the substrate needs improvement. This is based on the standard deviation of the difference of structure sizes on the mask and the substrate. This deviation shows how the structure size differs from the mask and therefore is directly connected to how well the mask has been attached or how close the mask has been to the substrate surface. It is believed that the use of several magnets gives rise to a magnetic field, where some parts of the mask are repelled from the surface. This can be solved by using a different arrangement of the magnets and/or changing the size of the magnet(s).

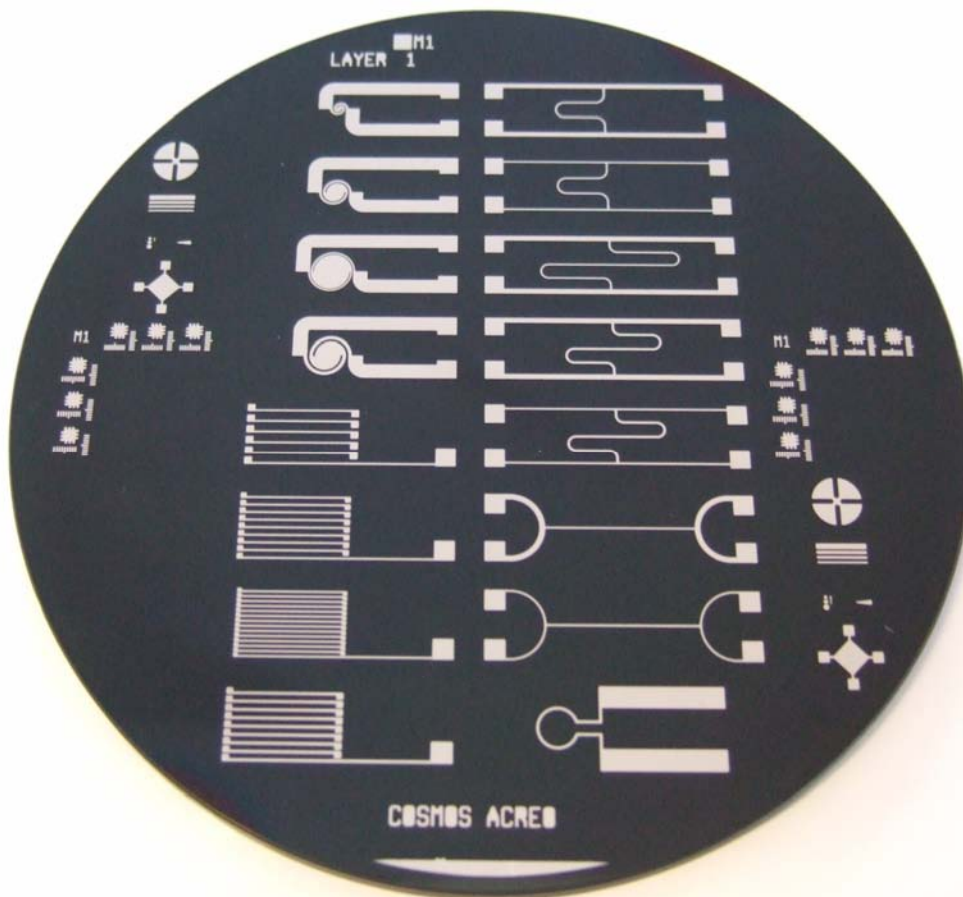


Figure 22: Photograph of wafer 6 deposited with sensor structures using metal shadow mask "Acreo M1"

Table 8. Measurement values of the sensor structures on wafer 6.

Chip Pos	CAD Wire	Wire Width	CAD Sensor	Sensor Width
11	1500	1560	200	241
12	500	564	150	197
21	1500	1533	200	241
22	150	181	150	183
31	1500	1530	150	156
32	500	559	150	175
41	1500	1543	300	356
42	500	551	200	243
51	150	192	150	183
52	150	188	200	241
61	150	183	150	175
62	500	545	150	185
71	150	188	150	175
72	150	179	150	186
81	200	285	200	256
82	2000	-	200	247
Average Difference to CAD		+45		+37
Stdev		17		13

3.13. Electrical measurements

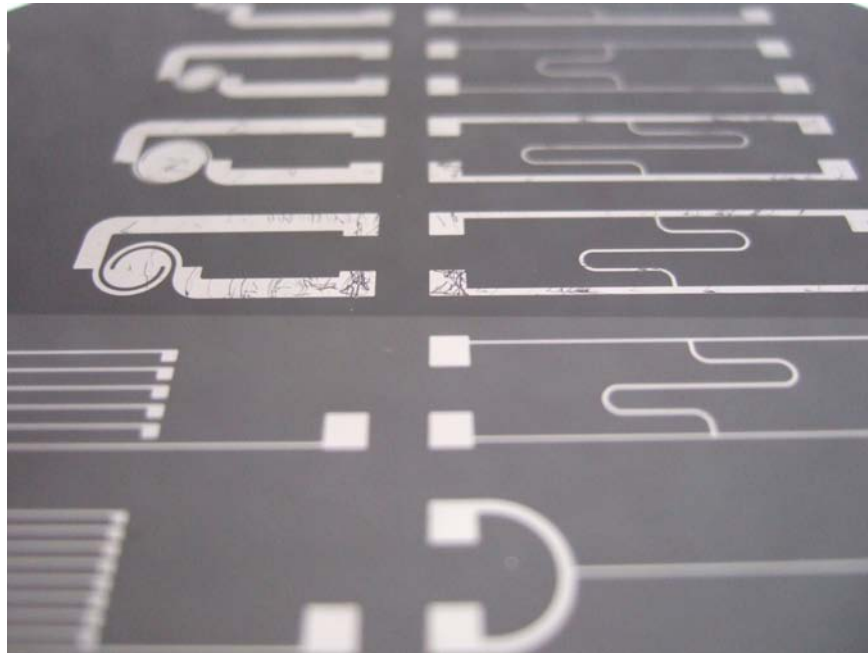
All structures have been measured electrically. The main reason has been to evaluate how well the isolation layer between the substrate and the sensor structures can be fabricated. The sensor structures have been measured using standard two-point resistance measurements, but no four-point measurements have been done. The reproducibility of the resistance (or capacitance) in the sensors has not been evaluated yet.

3.14. Design rules

The main limitation of metal masks is the smallest possible structure size. This is due to the fabrication technique where the openings are etched in a thin metal plate. It is believed that the minimum controlled structure size is 200 μm . The over-etched structures seen in our masks can be compensated for in the fabrication tool. It may require some test runs to see how the etch works with the specific structures that are included in the design. There are no other known rules that restrict the structure design, other than the additional “fundamental” restrictions, e.g. no free islands of metal that fall out during etching.

4. Results

As the project developed and the properties of the different layers were further quantified it was realised that the sensor structure couldn't adhere sufficient to Dimond-Like Carbon. This was even the case when the Platinum (Pt) sensor layer was deposited ontop of a Titan (Ti) adhesion layer. This issue was solved by modifying the DLC surface layer by medium energy ion implantation of oxygen. Most likely this caused an enrichment of available oxygen atoms capable of bonding to the deposited Ti layer. Figure 22 below illustrates the improved adhesion obtained by oxygen implantation prior to sensor deposition.



Non conducting
Arc deposited Ta:DLC

Adhesion improved by
Ion Beam Implantation
with O⁺

Figure 22: Arc deposited Ta:DLC revealing reduced sensor adhesion except in the lower portion of the steel surface where the Ta:DLC has been modified by oxygen implantation.

Table 9 next page gives a list over the different steel samples processed in the COSMOS project.

Table 9. List over processed steel samples.

Steel substrate	Deposited insulator	Conclusion
1	Dual magnetron Al_2O_3 at DTI.	Sensor deposited including a Ti adhesion layer. Analysis of the isolation properties revealed that the highest resistance between the sensors and the underlying steel substrate was around 1000 Ω . Several of the 16 sensor structures showed a resistance below 100 Ω . Poor isolation.
2	Dual magnetron Al_2O_3 at DTI	As above no need for further analysis.
3	ALD at Planar	Sensor deposited including a Ti adhesion layer. Up to 1.6 M Ω isolation for a single sensor unit. Several of the 16 sensor structures showed a resistance below 500 Ω . Better isolation than the Dual magnetron Al_2O_3 although far from good enough. Poor isolation.
4	ALD at Planar + Dual Magnetron Al_2O_3 at DTI at DTI	Sensor deposited including a Ti adhesion layer. Perfect isolation 15 out of the 16 sensor structures revealed a too high resistance to be quantified. Perfect isolation.
5	ALD at Planar	Waiting.
6	CemeCon dual magnetron multilayer $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$	Sensor deposited including a Ti adhesion layer. A few sensors were perfectly isolated from the substrate whereas the remaining 11 out of 16 sensors revealed an ohmic shortcut to the substrate. Intermediated isolation.
7	Test sample for pure Al_2O_3 coating at CemeCon	Poor isolation quantified by Cu pads. Poor isolation.
8	Ac-H DLC at VTT Half area will be treated with O ⁺ in order to increase adhesion	Poor sensor adhesion (see figure 22) except in the portion treated by oxygen implantation
9	Ac-H, DLC at VTT, will get 5xDLC and sent to Aarhus for O ₂ implantation	Sensor deposited including a Ti adhesion layer. Perfect isolation 15 out of the 16 sensor structures revealed a too high resistance to be quantified. Perfect isolation.
10	5×5 cm ² steel-test sample for ALD at SINTEF	Deposited but isolation has not been measured.
11	5×5 cm ² steel-test sample for ALD at SINTEF	Deposited but isolation has not been measured.

Conclusion on steel samples:

From the sensor depositions and quantification of the obtained insulating properties it can be concluded that electric isolating coatings based on multilayer systems gives the best results. The highest resistance between sensor structures and the underlying steel substrate was obtained for the sample with ALD + dual magnetron Al_2O_3 and for the sample with several layers of Ta-DLC. The main reason for the improved isolation properties of the multilayer coatings is most likely due to the nucleation and growth of new crystallites when starting on the next layer. In accord with this it was also observed that a $\text{Cr}_2\text{O}_3/\text{Al}_2\text{O}_3$ multilayer coating revealed better isolation properties as compared to a single layer of Al_2O_3 with approximately the same thickness.

Based on the above results it was decided to deposit non-conducting Argon based IBAD DLC on sample 6 and 9. The best sample with ALD + dual magnetron Al_2O_3 insulator is saved until the COSMOS team has learned from the experiments performed on the other samples.

5. Final embedded sensors – the “real” demo

Two steel samples were fully processed to fabricate surface embedded temperature sensors. These samples were multilayer DLC (sample 9) and a CemeCon multilayer $\text{Al}_2\text{O}_3/\text{Cr}_2\text{O}_3$ sample (sample 6). A suitable candidate for further processing would also be the insulator based on ALD Al_2O_3 combined with dual magnetron Al_2O_3 sample (sample 6). However, as mentioned above this sample was saved for later experiments. The figure below shows successfully surface embedded “Pt100” temperature sensors buried under Argon based IBAD DLC. The contact pads have not been coated.



Figure 23: Buried “Pt100” temperature sensors under a low friction Diamond Like Carbon coating. Uncovered Pt bonding pads for electric connection can clearly be seen.

Figure 24 shows a closer look at the sensor structures revealing the fingerprint of the underlying Pt wires. One of the Pt sensors has been wired and the resistance has been measured as a function of

the temperature in the range from room temperature $\sim 25^\circ\text{C}$ up to 175°C . Figure 25 shows the measured temperature response.

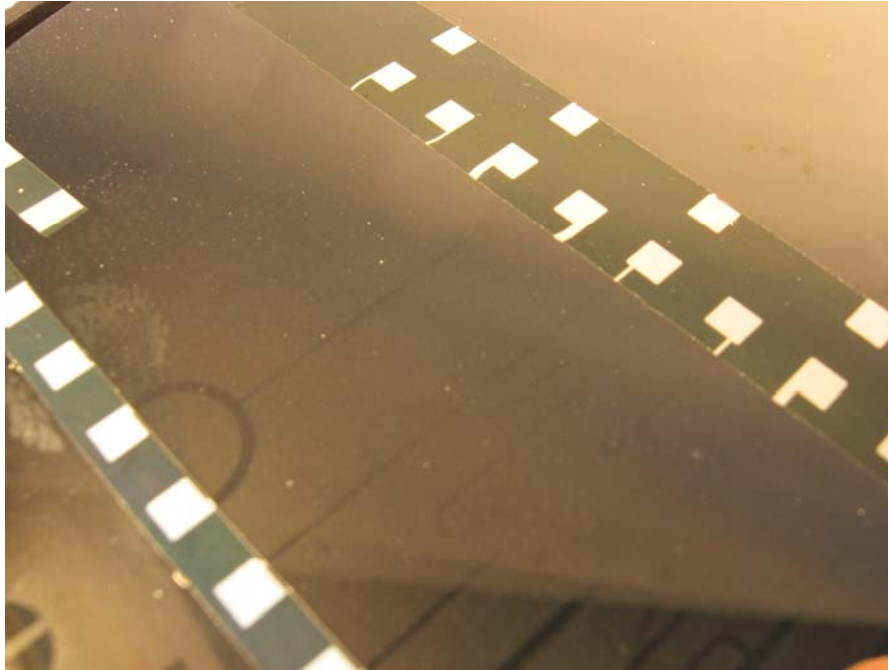


Figure 24: Close up image of the sensor structures revealing the fingerprint of the underlying Pt structures.

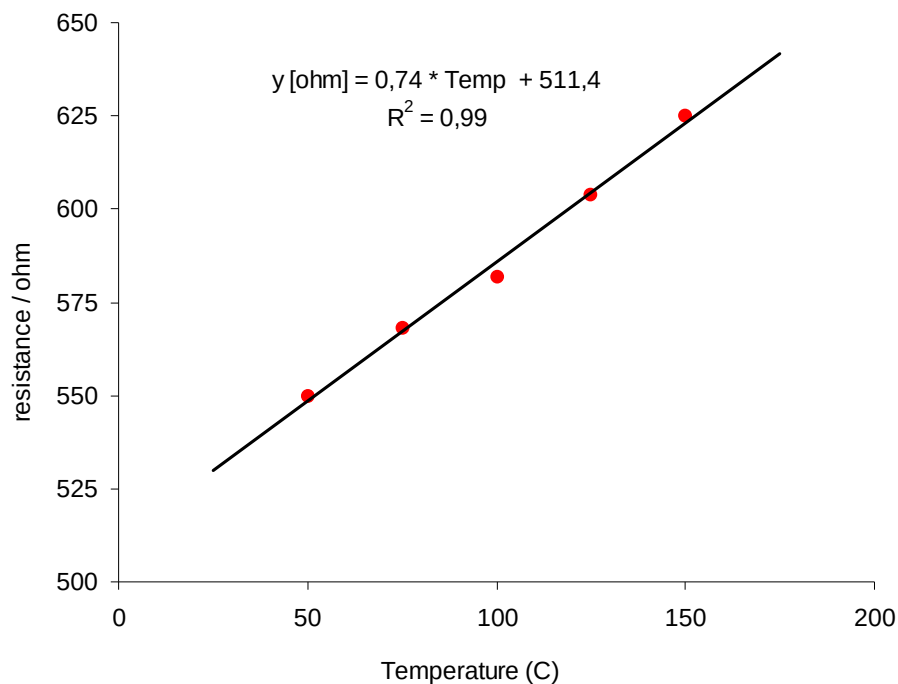


Figure 25: Temperature response for a surface embedded sensor sandwiched between multilayer $\text{Cr}_2\text{O}_3/\text{Al}_2\text{O}_3$ and a non conducting IBAAD DLC coating.

From Figure 25 it is evident that the buried temperature sensor is fully operational, and furthermore, that it is giving a close to linear signal as a function of the temperature. Obviously this reveals that within the framework of COSMOS it has been possible to fabrication a surface embedded sensor buried under wear resistant coatings on a steel sample.

6. Collaboration with industries

During the COSMOS project four meeting with external industrial partners have been arranged. The COSMOS-meetings were held in all four countries (Denmark, Norway, Sweden and Finland). The purpose of the meetings was to invite different industries both to participate in the meeting but also to give their opinion on issues where they can see the potential of surface embedded sensors buried under wear-resistant coatings. Below is summarized the companies which have been involved in these meetings.

Finland:

In Finland Planar Co. and Wärtsilä Finland were involved in the project and the information about the project and the minutes of the project meetings were distributed to several other industrial companies in Finland.

Norway:

The main industrial contacts in Norway include those parts of the industrial cluster at the Raufoss Technology Park. The following industrial companies will take part as active partners in the follow-up project COSMOS II:

1. Raufoss Industrial Tools AS
2. Plasto AS
3. Raufoss Technology AS

In addition, the start-up company "BALDUR coatings" has established relations with research groups at UiO and SINTEF and is motivated by industrial demand for ALD coatings and know-how.

Denmark:

In Denmark Sauer-Danfoss, Grundfos, Vestas, Novo and Alfa Laval have been involved in the project. The content of COSMOS has been communicated to a wide range of SMV's during meetings and national seminars.

Sweden:

In Sweden Volvo Aero and ABB has been involved in different meeting activities.

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Nordic Innovation Centre

Nordic Innovation Centre

The Nordic Innovation Centre initiates and finances activities that enhance innovation collaboration and develop and maintain a smoothly functioning market in the Nordic region.

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