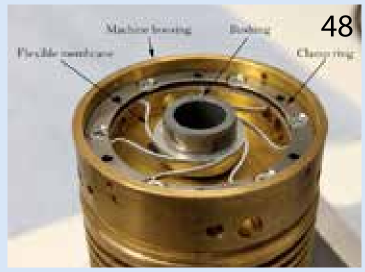
DSPE MIKRONIEK
2021 (VOL. 61) ISSUE 6
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING

- THEME: CONTAMINATION
- GAS BEARING WORKSHOP 2021 REPORT
- THERMAL DESIGN FOR SOURCE OF MEDICAL RADIOISOTOPES
- PRECISION FAIR 2021 REPORT – THE FUTURE OF PRECISION ENGINEERING

MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING – WWW.DSPE.NL

IN THIS ISSUE

THEME: CONTAMINATION



FEATURES

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics. The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

DSPE
YOUR PRECISION PORTAL

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Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

Mikroniek appears six times a year.

ISSN 0026-3699

The cover illustration combines a photo of taking a sample for measuring contamination (lower left, courtesy Fastmicro) and a drawing of the EBL2 research facility (courtesy TNO). See pages 19 ff. and 31 ff.

DSPE UPDATE

Last month, the Precision Fair took place on 10 and 11 November. Luckily, the event could be organised in the Brabanthallen in Den Bosch (NL), which offered the fair a spacious environment to ensure maximum safety with respect to Covid-19. It was great to meet people face-to-face after almost two years of limited physical contacts. From our DSPE perspective, the two award ceremonies were among the highlights of the fair.

The Wim van der Hoek Award for the best master's thesis in the field of precision engineering was presented to Nick Habraken, who graduated from Eindhoven University of Technology on the redesign of a robot for microsurgery. Kees Verbaan earned the Ir. A. Davidson Award as an acknowledgement for his work as a system architect at first-tier system supplier NTS in Eindhoven (NL). In his position, he focuses on design challenges related to accurate positioning in complex machines. For the entire precision engineering community, it was, as always, a pleasure to put these award winners, and the six other nominees for the Wim van der Hoek Award, in the limelight.

At the fair, the annual general meeting offered us an excellent opportunity for updating the members on DSPE affairs. Julie van Stiphout, working as our office manager since February 2020, was introduced and the monthly online DSPE lunch meetings were reviewed; many thanks to the people from MI-Partners for coordinating the hosting of these meetings. Also, this year, the DSPE website has been refreshed with an appealing look & feel and a clear structure that is ready for adding new functionality.

Covid-19 has hampered knowledge sharing, but we hope to get back on track. Avoiding contamination has been a growing issue in the past decades, with the ongoing shrinkage of IC patterns in the semiconductor industry. Other industries also have a growing need for contamination control. DSPE is helping precision engineers to obtain more knowledge about this subject. This *Mikroniek* issue is dedicated to contamination control and last month a new knowledge day on contamination control has been organised.

A new edition of the DSPE Optics Week is under construction in collaboration with the German photonics network Optence. Our underlying goal with this week is to promote Dutch-German collaboration in the field of optics. The DSPE Optics Week consists of a one-day seminar and the three-day Optomechanical Systems Design course, which already has been successfully organised several times by DSPE.

Last but not least, DSPE wants to thank Hans van Eerden for his outstanding job in realising our great *Mikroniek* magazine.

Hans Krikhaar
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ACTIVE CONTAMINATION CONTROL FOR EQUIPMENT AND SUBSTRATES

High-end manufacturing equipment has to support increasing levels of cleanliness. First-tier high-tech system supplier VDL ETG is pro-actively developing capabilities in product design as well as in production process design to support increasing requirements on cleanliness. Where knowledge gaps exist, VDL ETG supports research to further the state-of-art, for example in the ACCESS project: Active Contamination Control for Equipment and SubstrateS. In this project, VDL ETG and Eindhoven University of Technology (TU/e) work together as a multidisciplinary team, to deepen the fundamental understanding of generation, transport and removal of particle contamination.

TON PEIJNENBURG , PAUL BLOM, LUUK BERKELAAR AND JAN-JAAP KONING

Introduction

With constantly increasing requirements on accuracy, productivity and yield, high-end manufacturing equipment has to support increasing levels of cleanliness. Sensitivity for particle, molecular and ionic contamination of advanced processes like semiconductor photolithography and electron microscopy increases with the capability for finer details and higher magnifications. The achievable cleanliness of equipment depends, on the one hand, on specific product design decisions and, on the other hand, on tight cleanliness control of parts manufacturing, assembly and integration processes.

As a tier-1 supplier to many high-end equipment OEMs in semiconductor, analytical, photonic and healthcare industries, VDL ETG, having its own design and engineering capabilities, is pro-actively developing capabilities in product design as well as in production process design to support increasing requirements on cleanliness. Where gaps in knowledge exist, VDL ETG will support research to further the state-of-art, in this case the ACCESS-project. ACCESS is the acronym for Active Contamination Control for Equipment and SubstrateS.

In the ACCESS-project, VDL ETG and various TU/e research groups work together as a multidisciplinary team, to deepen the fundamental understanding of generation, transport and removal of particle contamination. The scale of contamination affects processing of current- and next-generation semiconductor devices, and various kinds of analytical techniques such as electron microscopy, mass spectrometry and spectroscopy.

The project has been designed to be executed by 3 PhD students in combination with 6 PDEng (Professional Doctorate in Engineering) trainees, such that fundamental research activities can be combined with application-driven validation measurements and prototypes.

Background

With scaling continuing in different forms, e.g. shrink according to Moore's law, albeit currently at a reduced pace, and More-than-Moore initiatives such as multiscale packaging and 3D integration, the processes to manufacture semiconductor devices become more and more sensitive. The need for sufficient yield becomes more prominent with increasing sensitivity coupled to increased equipment cost. Also, more process steps become contamination-sensitive. Even more so, increasing the number of layers on a semiconductor wafer (like 3D NAND structures require), increases the susceptibility to contamination. In this highly demanding business environment, it is essential that equipment designers and equipment manufacturers develop deep understanding of particle (and other kinds of) contamination to guarantee sufficient cleanliness and sufficient yield of the production process.

Higher cleanliness reduces the sensitivity for contaminants. Contaminants can be divided into several classes [1]:

1. Particles.
2. Metal ions.
3. Chemicals.
4. Airborne molecular contaminants (AMCs).

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Ton Peijnenburg is also fellow at the TU/e High Tech Systems Center (HTSC), now part of the Eindhoven Artificial Intelligence Systems Institute at Eindhoven University of Technology (TU/e). Jan-Jaap Koning provides research support at the HTSC, and is ACCESS project coordinator.

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In semiconductors, the presence of contaminants can cause three major defects:

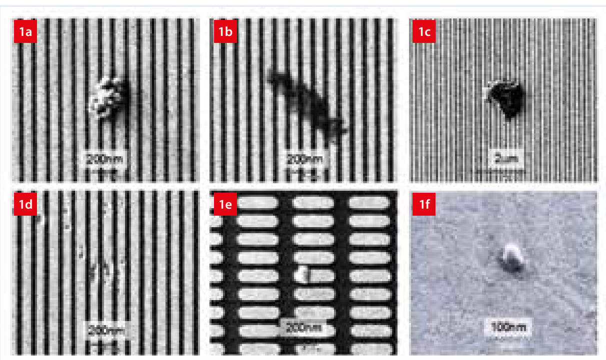
1. Device yield
   This is the most obvious defect and can easily be detected. Contaminants can cause the die to fail electrical tests and thus reduce yield.
2. Device performance
   Contamination can cause a lowering of device performance with time. This is a more serious problem because it causes lowering of device life.
3. Device reliability
   This is the hardest to detect because this can lead to failure, at some point in operational life.

Airborne contaminants (gases and particles) pose serious threats to high-tech industries with the critical dimension of e.g. a microelectronics chip quickly shrinking to nanoscale and the glass substrate of an LCD panel substantially growing to 1.9 m by 2.2 m. In theory, the best strategy to control the contaminants is to locate the emitting origin and to terminate the releasing source. The contaminants mainly originate from two sources: (a) incoming outdoor air, and (b) internal activities (Figure 1). Contamination is the main cause of a killer defect, that is any particle or any crystal defect that causes a disruption in an intended microcircuit pattern

The mechanism of contamination, e.g. in a semiconductor manufacturing environment [3]:

1. The source of contamination.
2. The transportation of the contamination.
3. The location of the contamination: surface, bulk.
4. The evolution of the contamination: how to remove it? Does the cleaning remove the contamination?

In semiconductor equipment, allowed contamination levels depend on productivity. Particle contamination characteristics for high-productivity lithographic equipment



Examples of surface contamination; the common defects induced by post-cleaning [2].
(a) Slurry abrasive particle remains.
(b) Organic residue.
(c) Polisher debris.
(d) Corrosion.
(e) Dendrites.
(f) Small residue defects.

Table 1
Progress over time in particle contamination characteristics for high-productivity lithographic equipment, in terms of particles per wafer pass (PWP) / size.

PWP / size	2015	2018	2022
wafer topside	0.5 / > 60 nm	0.5 / > 40 nm	0.05 / > 20 nm
wafer backside	2,500 / > 0.5 µm	1,750 / > 0.5 µm	600 / > 0.5 µm

are shown in Table 1. For metrology tools in a semiconductor manufacturing environment, having a lower productivity, a lower achievable PWP (particles per wafer pass) has been demonstrated by VDL ETG; 0.08 PWP / > 60 nm. Future requirements, in the next decade, however will even be stricter.

In scientific and analytical equipment, where high electric field strengths are used to generate an image (e.g. the optical path in electron optics), a single particle on a critical location already severely disturbs the image quality due to charging and arcing effects. When higher electric field strengths are implemented, the susceptibility to particle contamination even gets more critical.

Research approach

The purpose of the ACCESS project is to deepen our fundamental understanding of the (1) generation, (2) transport, and (3) removal of particle contamination. The scale of contamination affects processing of current- and next-generation semiconductor devices, and various kinds of analytical techniques such as electron microscopy, mass spectrometry and spectroscopy.

The work in the ACCESS research projects (see also the following articles) is carried out by three PhD students in various TU/e research groups, namely:

(1) Research project 1: Particle generation
    Research group: Mechanics of Materials (Mechanical Engineering department)
(2) Research project 2: Particle transport
    Research group: Turbulence and Vortex Dynamics (Applied Physics department)
(3) Research project 3: Particle cleaning
    Research group: Elementary Processes in Gas Discharges (Applied Physics department)

Each of the PhD students is assisted by two PDEng trainees to design and build experimental validation tools and prototypes. One of the PDEng trainees works in the Electrical Energy Systems research group at the TU/e Electrical Engineering department. The PhD students and the PDEng trainees are supervised by a technical project leader at the TU/e High Tech System

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VDL ETG development lab. (Photo: Bram Saeys)

Center (HTSC) to facilitate the multidisciplinary collaboration between VDL ETG and the various research groups at the TU/e. Supervision by VDL ETG is organised by management under (1) overall supervision of the first author, and (2) various topic leaders with relevant academic backgrounds. Regular meetings and sessions are organised at VDL ETG, where development labs (Figure 2) and project facilities are used for field tests and joint work.

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INFORMATION
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FROM MACRO TO MICRO

Phenomenological wear models are widely employed to extract design guidelines for engineering components, but do not provide information about the underlying mechanisms that cause surface degradation through wear particle generation. To investigate the formation of wear particles in lithography modules, a microscale scratch model has been established that reflects the contact situation of the wafer handler. Since an experimental approach poses significant challenges, a computational strategy is introduced to study the mechanics involved in wear particle detachment from scratch simulations.

SVEN SPERLING, JOHAN HOEFNAGELS, KASPER VAN DEN BROEK AND MARC GEERS

Wear models that describe the macroscopically observed loss of material are widely available in the literature and constitute the basis for most analytical and numerical calculations concerning lifetime predictions of engineering components. While these phenomenological wear models do provide well-founded design guidelines for structural machine parts, they do not shed light on the micromechanical mechanisms that govern the formation of wear particles. The mechanics and physics at the microscale attract increasingly more attention in research to generate physically motivated wear models that accurately describe tribological aspects of bodies in contact [1].

It is important to note that each contact situation is different. Hence, to relate microscale phenomena to macroscale events, one has to consider the topology of the bodies in contact at the intermediate (mesoscopic) scale. The schematic provided in Figure 1 illustrates the three relevant scales of a wafer in contact with a diamond-like carbon (DLC) coated pin from the wafer handler module. Considering the relative difference in surface roughness between the wafer and the DLC-coated machine part, a simplified microscopic contact model has been established that acted as the subject of this study.

The considered microscale contact situation, also referred to as single-asperity model, can provide insights into the mechanisms that govern wear particle generation by investigating the scratch response between the bodies. Note that the boundary conditions involved in these scratch tests, e.g. the force p and velocity v, are imposed through the macro- and mesoscopic scales.

To summarise, a simplified single-asperity model has been established to investigate the mechanisms of wear particle generation. Because the geometry and boundary conditions of this microscale scratch model result from the macro- and mesoscopic scales, a realistic situation in the wafer handler module is reflected, thus providing insights into small-scale mechanics that occur in lithography machines.

Computational perspective

In this study, part of the ACCESS project (see the overview on page 5 ff.), a joint undertaking of VDL ETG and Eindhoven University of Technology (TU/e), a numerical approach has been chosen. Of course, experimental verification is key in creating a physically valid model. However, information about the evolution of mechanical quantities that determine physical mechanisms is

AUTHORS' NOTE

Sven Sperling (Ph.D. candidate), Johan Hoefnagels (associate professor) and Marc Geers (full professor) are all associated with the Mechanics of Materials research group in the department of Mechanical Engineering at Eindhoven University of Technology (TU/e). Kasper van den Broek is a contamination control architect at VDL ETG T&D.

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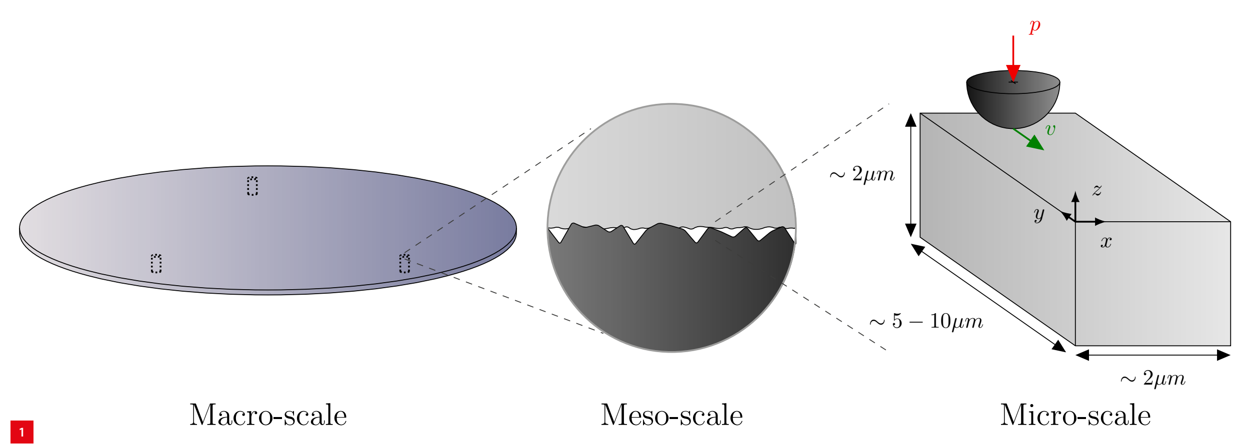
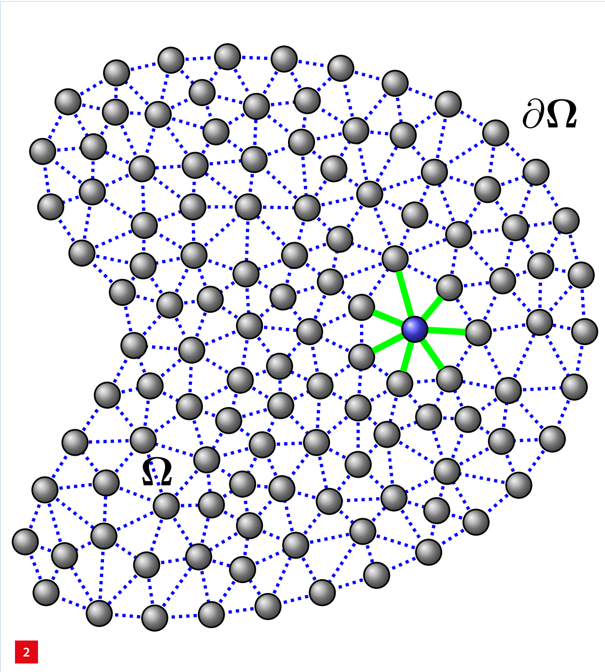


1 *Scale separation of a wafer in contact with a DLC-coated machine component.*



Sketch of a body Ω discretised into a series of particles including bonds.

sometimes extremely complex or even impossible to extract from experimental observations. Simulations can provide significant insights into the progression of, for instance, stresses and their influence on fracture events that govern material detachment.

In constructing a numerical description of the microscale scratch model, there are two essential ingredients: (i) the computational methodology, and (ii) the constitutive representation of the material behaviour. Logically, there is a set of requirements that govern the choices in these ingredients, the former of which is the first topic of discussion. The most accessible choice for (i) is the well-known Finite Element Method (FEM), which has proven to be an indispensable tool in industry and research. However, for this particular problem where complex fracture events translate to arbitrary discontinuities, employing a continuum-based methodology will pose significant obstacles.

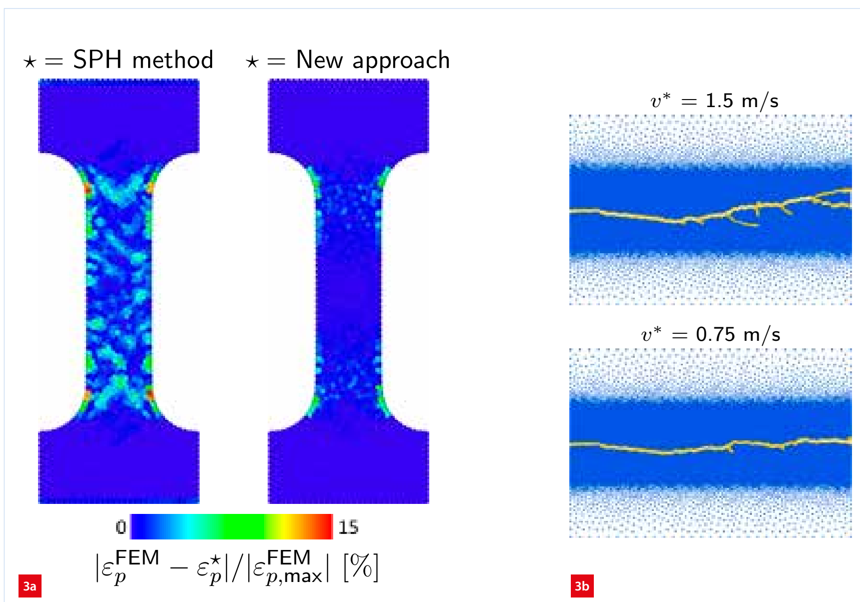
On the other hand, Molecular Dynamics (MD) maintains the discrete nature of materials and can accommodate arbitrary discontinuities by eliminating pairwise interactions between atoms in order to simulate fracture. Nevertheless, modelling a mechanical problem at the microscale via atomistic methods is still unfeasible with current computational resources. So, a hybrid solution is considered where one can exploit continuum-level material descriptions, while still being able to incorporate arbitrary discontinuities to capture complex fracture events followed by material detachment. Methods that combine these requirements can be found in the realm of so-called particle methods, for which the most prominent examples are Discrete Element Method (DEM), Smoothed Particle Hydrodynamics (SPH) and Peridynamics.

Most particle methods are employed within the scope of linear elastic-brittle materials. Moving beyond this scope by including nonlinear material behaviour, e.g. plasticity, will result in apparent numerical deficiencies that compromise simulation results. The origin of these numerical deficiencies resides in the mathematical formulation that approximates the material behaviour in particle methods [2-4]

Since microscale indentation experiments for silicon have proven that pressure-induced phase transitions dominate the material's mechanical response [5], it is unavoidable to take a step beyond the scope of linear elasticity in the silicon scratch model. This motivates the development of an alternative particle method formulation using arguments adopted from continuum mechanics to preserve the constitutive flexibility of a finite-element model while maintaining the powerful fracture properties of particle methods.

Proof of concept

The novel particle approach is based on a two-level description: (i) particles that each carry a fraction of the body's mass, and (ii) the bonds between pairwise sets of particles that interact with each other. A schematic representation is provided in Figure 2. One can trivially simulate fracture with this approach by simply deleting bonds between particles after exceeding a physically-based bond criterion, similar to classical particle methods. Here, the deformation corresponding to a particle (blue) is determined



Two numerical benchmark examples.
(a) Comparison of plastic, irreversible strain from tensile bar tests for SPH and the new approach, relative to FEM at 2.5% elongation.
(b) Crack paths resulting from two different loading velocities acting on the top side of the numerical specimen with a fracture toughness of 250 J/m^2.

via an averaging procedure involving the relative displacements of the bonded (green) nearest neighbours.

Note that the difference between the new approach and existing particle methods lies in the adopted averaging procedure that is used for the approximation of particle deformations. A deeper discussion about the numerical and mathematical discrepancies regarding existing particle methods and the approach presented here can be found in [6].

The goal in developing this alternative particle method is to combine constitutive flexibility with the ability to model complex fracture events. This is demonstrated with two numerical benchmark examples: (i) an elasto-plastic tensile bar, and (ii) a crack-branching problem. Figure 3a shows the results of an elasto-plastic tensile bar simulation for the new particle scheme and the previously mentioned SPH method. The absolute error in the calculated plastic strain over the deformed tensile bar is shown relative to a FEM simulation, which serves as a reference here. One can conclude that the new approach better reproduces a continuum-equivalent solution than SPH since it is closer to the FEM solution and does not show any artificial inhomogeneities within the gauge section of the bar. Secondly, Figure 3b shows the fracture results of a thin elastic-brittle plate where the top side is moved upwards with a velocity v^* and the bottom is fixed. The branches observed have been modelled without any additional fracture criteria or domain enrichment, hence this complex cracking behaviour is captured naturally through the dynamics of the new particle approach. The ability to naturally simulate complex fracture events such as branching is one of the key advantages of particle methods.

The next steps

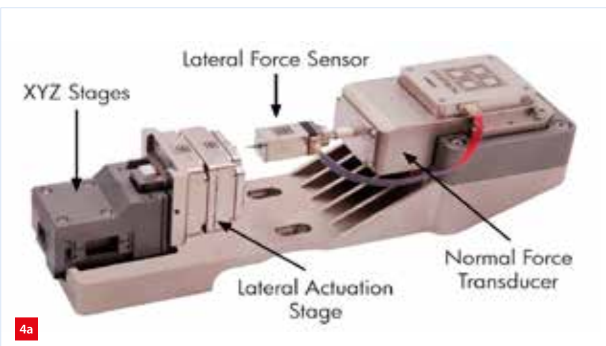
The new computational methodology has been established and evaluated against two distinctive numerical examples that prove its potential. The next challenge is to establish the scratch simulation with this novel particle method and then validate the model with experiments. A brief discussion on the upcoming tasks and tools is provided below.

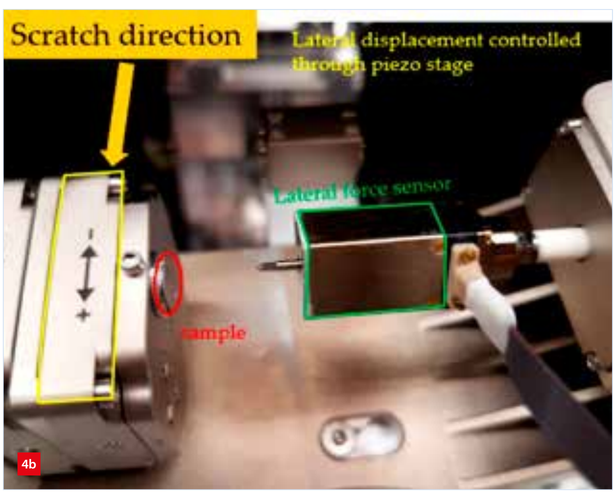
High-performance three-dimensional implementation

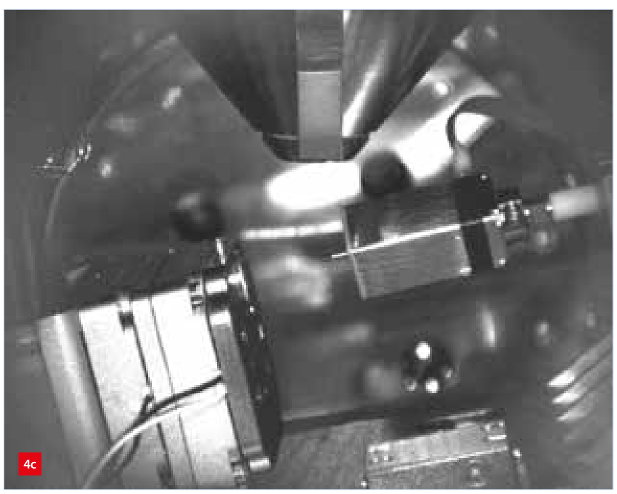
The current simulations that have been executed and shown in Figure 3 are two-dimensional. But, when it comes to indentation and scratch simulations, a two-dimensional simplification of the problem is inadequate. Hence, a three-dimensional implementation is required. Additionally, to reach maximum computational efficiency, a parallel routine of the numerical scheme is being implemented in the open-source program LAMMPS, which is a molecular dynamics simulator suitable for various types of particle simulations.

Constitutive model

The second ingredient for the numerical model, the constitutive material representation, must account for the pressure-induced phase transitions that are observed in silicon indentation experiments. To achieve this, a state-of-the-art continuum plasticity description will be adopted from the literature that tracks the volumetric inelastic strain in loaded and unloaded conditions [7].







The Hysitron (Bruker) In Situ PI 88 PicoIndenter instrument.
(a) Indication of the different components (stages and transducers).
(b) A concentrated view of an indentation sample and the tip set-up.
(c) Installation inside a ZEISS Gemini SEM.

Experimental validation

To experimentally validate the model, VDL ETG, participant in the ACCESS project, invested in a nano-scratch instrument that can be inserted in a scanning electron microscope (SEM) to extract in-situ experimental data from scratch tests. After intensive investigation of the necessary device specifications, it was found that no commercially available nano-scratcher satisfies all the extremely strict requirements regarding, e.g., load sensitivity and position accuracy. However, after careful evaluation of the scratch conditions, the device specifications could be adjusted to the limits of the current state-of-the-art. As a result, the Hysitron (Bruker) In Situ PI 88 PicoIndenter instrument, shown in Figure 4, has been procured and will be installed in the Multi-Scale lab affiliated with the TU/e Mechanics of Materials research group. A SEM image of a scratch experiment executed with the new experimental apparatus is shown in Figure 5. In the coming months, the scratch response and topology will be investigated for varying loading conditions and the experimentally obtained data will be compared to numerical simulations.

Conclusion

After intensive evaluation of the computational requirements for silicon scratch simulations, it was concluded that currently available numerical methods are not suitable for the considered problem. Hence, a novel particle scheme has been introduced and the numerical requirements have been demonstrated by means of two examples: (i) an elasto-plastic tensile bar, and (ii) a dynamic crack-branching problem. Example (i) elucidated the constitutive flexibility of the new approach, while example (ii) illustrated the capability to include complex fracture events. These properties are essential because the nonlinear material description, accounting for pressure-induced phase transitions, will govern the fracture behaviour, while the orchestra of crack initiation, propagation and coalescence shall determine the detached wear fragment.

To establish the scratch simulation, an efficient three-dimensional implementation of the newly developed computational methodology is needed in combination with a tailored elasto-plasticity model that can simulate the observed phase-transitions in silicon. To validate the model, numerical simulations will be compared to experimental scratch tests.

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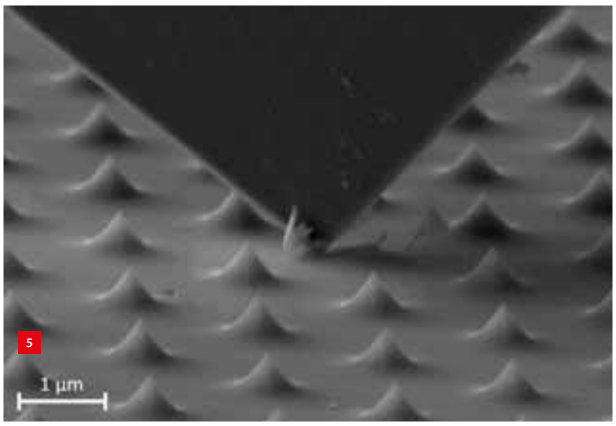


SEM image of a sheared asperity after the test on a Silicon TGT1 calibration grating sample. A diamond three-sided cube corner indenter tip (50 nm radius) was used for this scratch experiment.

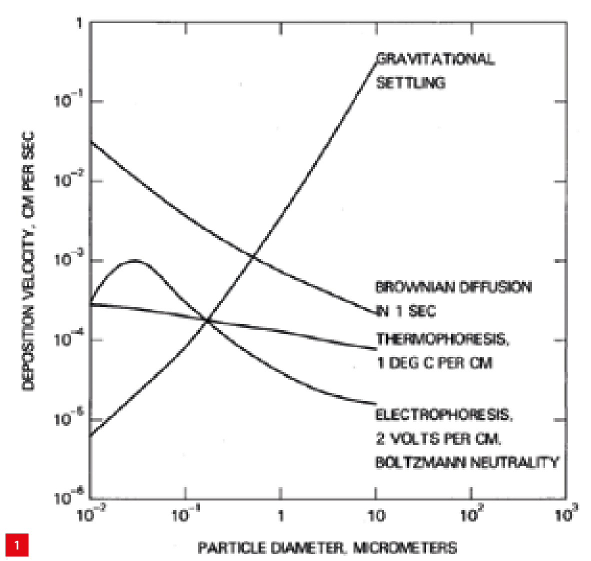
MODELLING SUB-MICRON PARTICLE TRAJECTORIES

High-tech manufacturing processes require very high accuracy and precision, which makes these processes extremely sensitive to contamination at ever-reducing size scales. The use of complex mechatronic systems in manufacturing, such as dynamic robots and moving stages, unavoidably results in the transport of particles.
A numerical model will be developed and subsequently integrated into a classical Computational Flow Dynamics tool, for more accurate prediction of sub-micron particle trajectories in particle contamination transport. An experimental set-up has been developed for model validation, including a visualisation tool for accurate measuring of particle dynamics.

DMITRI SHESTAKOV, WERNER COOIJMANS, ANKITA KALRA, RALF REINARTZ AND HERMAN CLERCX

Introduction

Manufacturing processes in the semiconductor, analytical and pharmaceutical industries require very high accuracy and precision, which makes these processes extremely sensitive to contamination (particles, chemicals, biomaterials) at ever-reducing size scales. For example, one high-tech industry concern is counting particles of 1 nm to 100 nm in size.
To assure high quality of manufacturing, complex mechatronic systems are needed, which necessarily involves mechanical movements (motors, robot arms, vacuum gates, micro-stages, pumps, gas and liquid flows) and unavoidably results in the transport of particles by means of gas drag force, inertia, turbulent diffusion, electrostatic force and thermodiffusion [1]. The role of these forces is particle-size- and condition-dependent, as can be seen from the particle deposition velocity (Figure 1).



1 Comparative effect of various factors on particle deposition velocity versus particle diameter [1].

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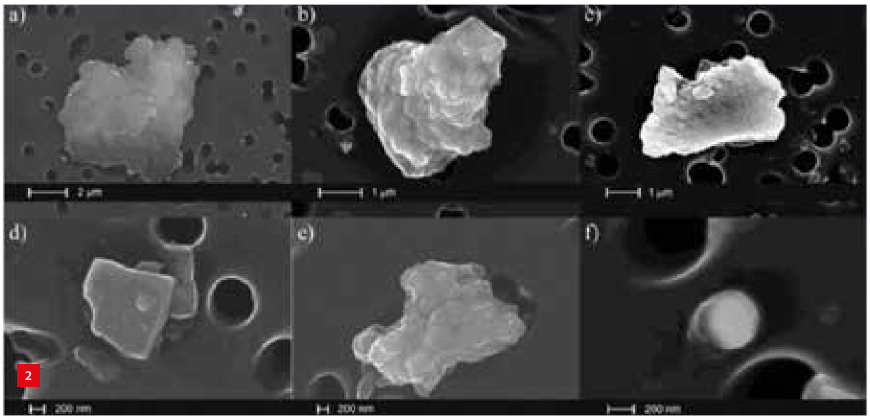
While the particle transport mechanism is quite well understood for particle size > ~10 μm [2], the dynamics of smaller particles (size < 10 μm) and especially sub-micron particles (size < 100 nm) is still a big challenge [1,3]. Besides the particle size, the shape is also an important factor (Figure 2), which is often ignored in studies because of the extra complexity that comes with it.

The interaction between a particle and gas molecules is also dependent on the relation between the particle size and gas concentration. The so-called Knudsen number (K_n = free mean path / particle radius) is the key parameter here to compare various cases with one another. From the particle-gas interaction perspective, there are four different regimes (continuous $K_n < 0.01$; slip $0.01 < K_n < 0.1$; transient $0.1 < K_n < 10$; and free molecular $K_n > 10$) that are relevant for contamination control in the semiconductor industry (Figure 3).

Already at atmospheric conditions, classical Navier-Stokes-based Computational Flow Dynamics (CFD) is not accurate for particles < 10 μm. But it can be updated with slip correction factors and still be used even for wafer loadlocks and vacuum wafer handlers, down to a vacuum of a few Pa. (Note: with some extra conditions applicable.) But CFD becomes less and less accurate and will eventually fail, when going deeper into vacuum. The situation could be greatly improved by using advanced methods such as Lattice-Boltzmann (LBM), Direct Simulations Monte Carlo (DSMC) or their combinations [4].

After considering all other practical aspects of this study, CFD + DSMC was chosen to solve the contamination transport problems. This combination means that standard CFD techniques will be used for the larger system under

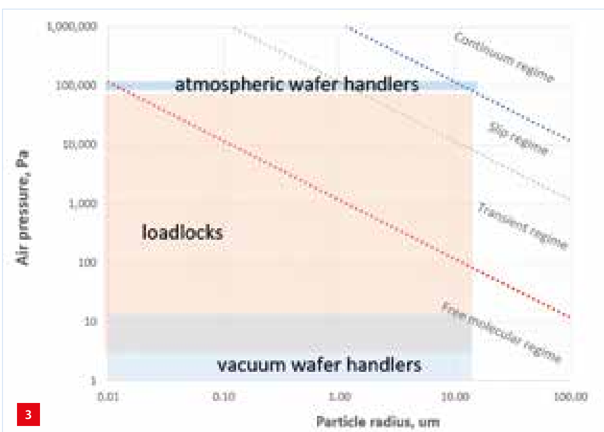


Examples of (sub)micron particle shapes.

consideration, while DSMC will be used to fundamentally understand how particles react to macroscopic quantities such as velocity, heat flux and stress tensor.

This fundamental behaviour needs to be validated by means of experiments to obtain accommodation coefficients, which are a direct input in the DSMC simulation to model the gas-wall behaviour. These accommodation coefficients tell us how much information, in terms of momentum and energy, a gas molecule takes from the wall. The combination CFD + DSMC is being developed and experimentally tested at conditions of their natural merge, the transient regime (Figure 3).

For accurate measurements, very precise control of the experimental environment is needed (temperature stability of ~10 mK, pressure stability of ~10 Pa, no natural/forced convection, etc.). An additional challenge is the lack of commercial (optical) measuring techniques for the motion of sub-micron particles in vacuum. Therefore, development of dedicated optical and image processing tools also became a part of this study.



Particle-gas interaction regimes with relevant examples from lithography sub-systems.

Experimental set-up to study the particle-gas interaction with the possibility to control pressure, temperature and temperature gradient. The photo shows all the main components of the set-up: the vacuum chamber (in the middle) on top of an optical table, and a special cover (black box above the chamber) closing the chamber during the experiment for safety and optical background reduction [5].

Objective

This study is part of the ACCESS project, a joint undertaking of VDL ETG and Eindhoven University of Technology (TU/e); see the overview on page 5 ff. The key objective is to create a validated analytical model for sub-micron particle transport, which includes complicating factors such as shape, slip factor, thermodiffusion and electrostatic forces, dynamic pressure ranging from 1 Pa to 10^5 Pa, and dynamic flows. This model will be a tool for accurate prediction of the contamination transport in ultraclean

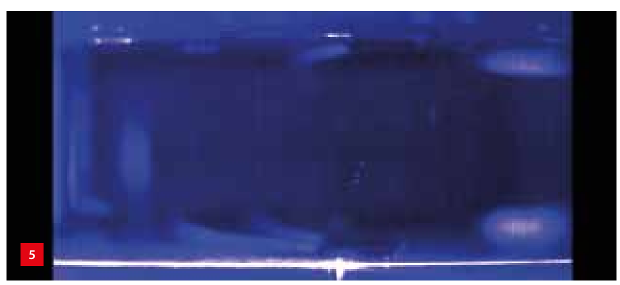
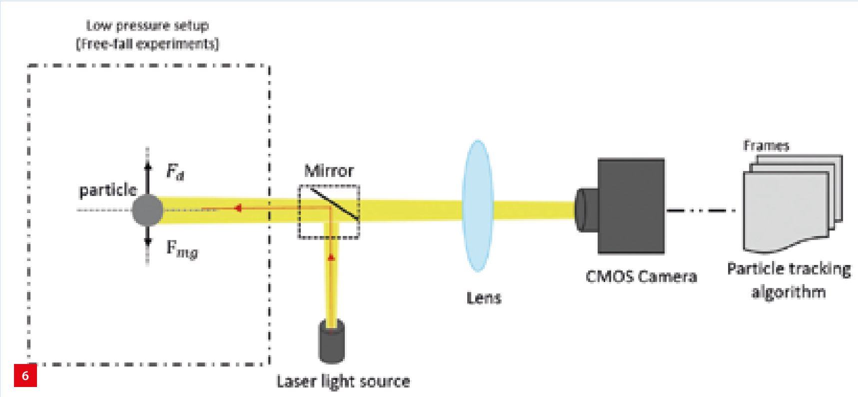


Image from the experiment: balancing the thermophoretic force and gravity, the cloud of 2-μm particles (in the centre) is levitating in vacuum [5].



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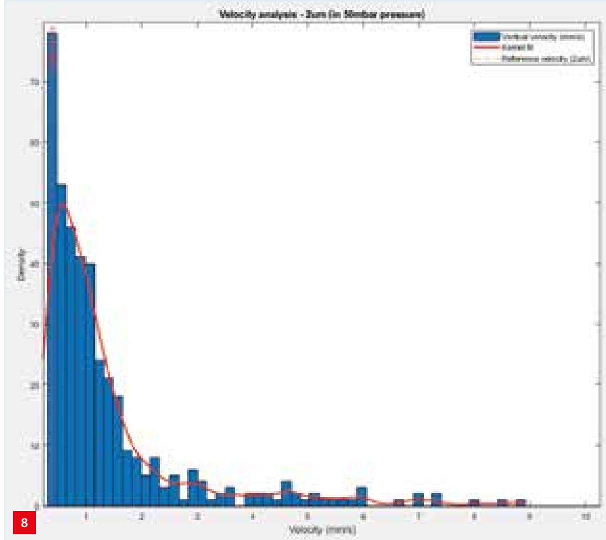
The imaging system is placed outside the vacuum chamber and consists of a laser light source, optics and a CMOS camera. The in-house developed software code enables image processing and data extraction from the recorded videos [6].



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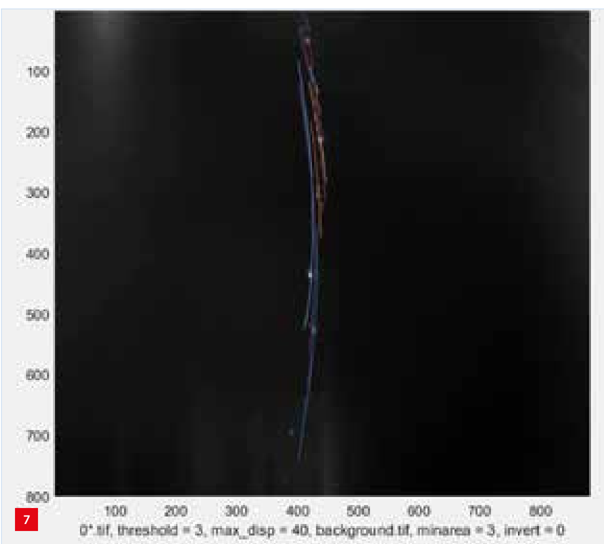
Experimental result showing the vertical velocity distribution of all the detected particles that are freely falling in a vacuum of 50 mbar pressure. The vertical dotted line represents the expected single-particle velocity calculated from theory (0.369 mm/s). The actual distribution demonstrates the presence of particle clusters of various sizes, which can also be a subject of separate study [6].

systems. The theoretical part of the work is performed in the Fluids and Flows research group at the TU/e Applied Physics department. The supporting experimental work is performed at VDL ETG T&D, together with the development of special techniques needed for measuring the sub-micron particle transport.

Goals

1. A developed and validated numerical model will be integrated into the CFD tool for more accurate prediction of the sub-micron particle trajectories in rarefied gas. In this way, it will become a part of the ACCESS project.
2. An experimental set-up will be used for validation of the numerical model.
3. A visualisation tool will be used for accurate measuring of the particle dynamics in vacuum.



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Example from the experiment: particles are falling in a vacuum of 50 mbar pressure as captured by the camera. The software draws the coloured lines on the image to show individual particle trajectories [6].

Results so far

The experimental set-up (Figure 4), capable of controlling pressure, temperature and temperature gradient, was built within one year of the work starting. It can also serve as a platform for other control parameters to be implemented in the future, such as electrostatic force or rarefied flow. For now, the vertical temperature gradient is used to stabilise, stop or even reverse the particles falling inside the vacuum, while accurately measuring their velocity in two directions (Figure 5).

To make these measurements possible, a new high-resolution visualisation tool was developed (Figures 6, 7 and 8). This tool enables the detailed measurement of the sub-micron particle trajectories and velocities at low pressure.

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TAMING THE BEAST

To become a leader in contamination control, VDL ETG is aiming at the development of a new in-situ, non-contact technology to remove particles from a system. To this end, a concept is investigated in which particles are electrically charged and trapped in a plasma and then removed. This research involves the design of a plasma seal, a high-cleanliness-vacuum wafer-handling robot, and a test set-up to compare sealing concepts with respect to both particle and molecular contamination.

PAUL BLOM, JUDITH VAN HUIJSTEE, FEDERICO MEDINI, ROBERTO GARCIA ROCHIN, RICK BAADE AND JOB BECKERS

Introduction

Since many years, VDL ETG has been investing in understanding and controlling contamination in equipment for semiconductor, analytical, integrated photonics and other applications. When looking at high-tech equipment, the need for contamination control quickly increases from generation to generation, to support sufficient yield.
VDL ETG has strong ambitions to become the leader in contamination control, and is aiming at the development of a new in-situ, non-contact technology to remove particles from a system, to prevent them from reaching surfaces such as a wafer or surfaces in direct line of sight of a charged particle beam. Figure 1 shows examples of particles degrading the imaging quality of a wafer system and an electron microscope.

Justification

There are existing technologies to clean substrates and other surfaces. In general, these cleaning technologies require extra equipment, which must be mounted onto a vacuum chamber, and require the vacuum chamber to be opened. Other techniques for cleaning require contact with the surface that needs to be cleaned. Therefore, a need exists for an in-situ non-contact cleaning technology that does not require opening of the vacuum chamber (reduction of downtime) and prevents damage to the substrate (increase of yield). This need is addressed in the ACCESS project, a joint undertaking of VDL ETG and Eindhoven University of Technology (TU/e); see the overview on page 5 ff.

AUTHORS' NOTE

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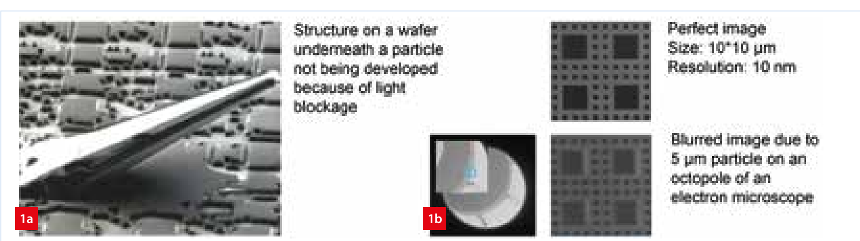


Effect of particles on system functionality.
(a) Wafer illumination.
(b) Electron microscope imaging.

Objectives

The RCR (Release, Confine, Remove) concept of the Elementary Processes in Gas Discharges research group at the TU/e Applied Physics department provides a promising path towards particle removal. In the RCR concept, particles are electrically charged and trapped in a plasma, and then removed with the aid of an electrical field, gravity component and/or gas stream. This concept is still not used by any industrial party, and thus creates opportunities for this project.

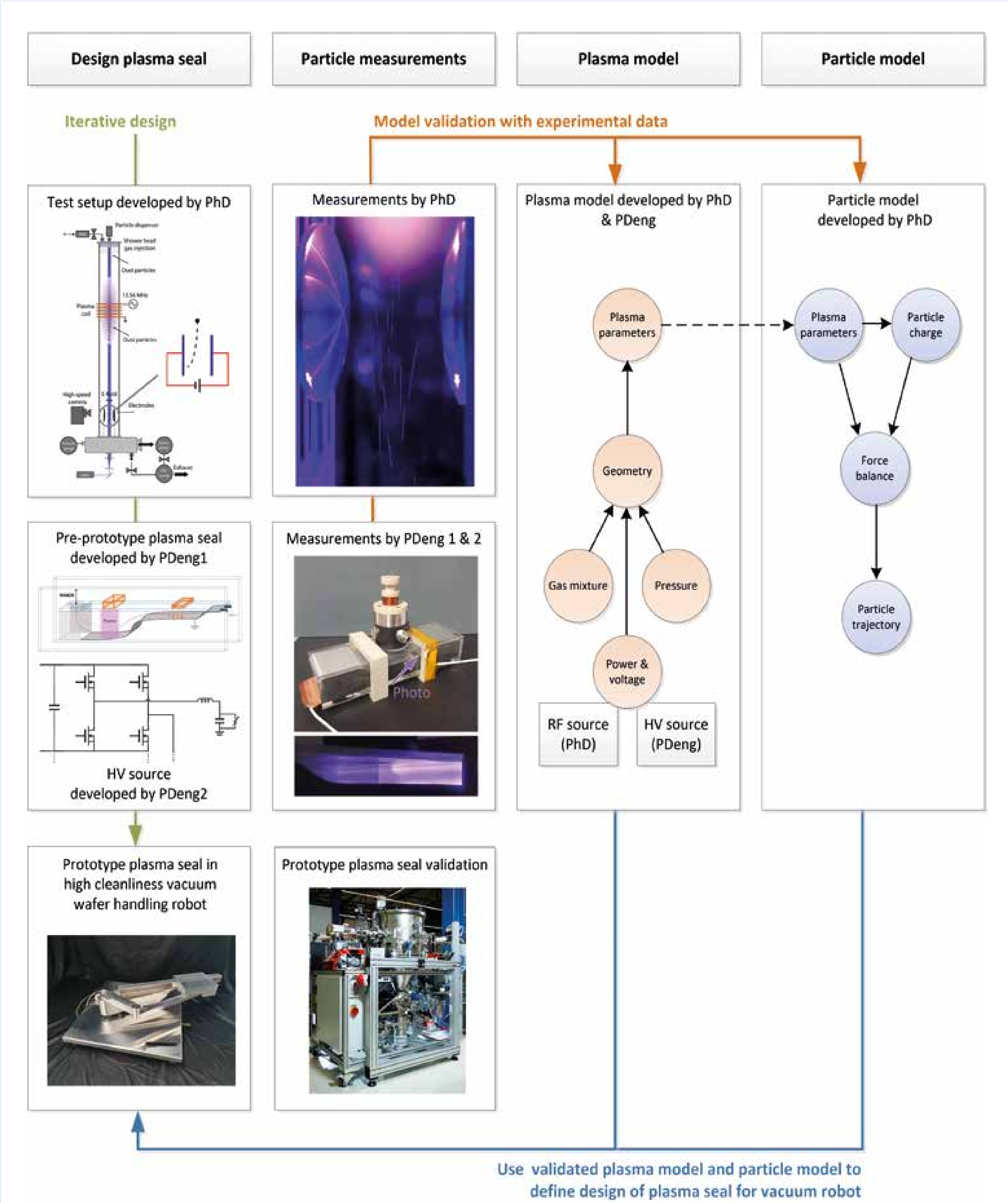
The industrial application of a plasma discharge for contamination control requires a reliable, low-cost, and flexible high-voltage source. The Electrical Energy Systems research group at the TU/e Electrical Engineering department is specialised in the design of such high-voltage sources, where the high-voltage source is electrically matched towards the plasma reactor. The flexibility of the high-voltage source, with a tuneable shape of the voltage signal, determines the plasma characteristics and the plasma power.

Goal

The RCR concept and the high-voltage source are combined in the design of a plasma seal that can be built into the rotational joints of a prototype of a high-cleanliness-vacuum wafer-handling robot (HCVWHR). Sealing-off of particle transport through these feedthroughs can be achieved by differentially pumped seals or by magnetic rotary seals. However, a solution based on plasma filtering of contamination can result in enhanced contamination suppression, lower costs and a lower volume claim.

Results

Figure 2 shows an overview of the R&D activities related to the plasma seal. On the left side of the graph, the various iterative design steps for the plasma seal are described. It starts with the plasma particle charging investigation (PPCI) set-up developed by the PhD student, which is used to better understand the relation between the particle charging process and the plasma characteristics.



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R&D overview for the plasma seal.

In a second step, two PDEng trainees develop a compact pre-prototype plasma seal (PPPS) that can operate in the environmental conditions defined by the HCVWHR. In a last step, the PDEng trainees will develop a prototype of the plasma seal, which can be implemented in the HCVWHR, and tested for effectivity. As part of the project, a plasma and particle model of the plasma seal will be developed. Measurements on the PPCI and the pre-prototype of the plasma seal will be used to validate both models, which can then be used to make a final design of the prototype plasma seal. The various items of Figure 2 will be discussed in more detail below.

Plasma particle charging investigation set-up (PPCI)
The PPCI set-up [1-4] is developed to investigate fundamental plasma interaction with micrometer-sized particles and to measure residual particle charges with a precision as good as a few elementary charges only.
The set-up consists of the following main elements:

- The flow tube: a 1-m-long glass tube of which the cross-sectional shape is square with inner dimensions of 100 mm x 100 mm. The pressure and the gas velocity (in the downward direction) inside the tube can be controlled independently in the respective ranges of 1-100 Pa and 0.01-1 m/s. The base pressure of the system is ~$5 \cdot 10^{-5}$ Pa. Micrometer-sized particles can be injected (from the top) by a particle injection system. The velocity of the particles is determined by the balance between gravity and the drag forces exerted by neutral gas particles.
- The plasma: a radio-frequency (RF) coil outside the tube is used to ignite and sustain an inductively coupled RF plasma at low pressure inside the tube. The driving frequency of this plasma is 13.56 MHz and the deposited power can be set between 5 and 100 W.
- Particle deflection and imaging: at a certain distance below the RF coil, two Rogowski electrodes induce a horizontal electric field of 0-5 kV/m that deflects the dispersed and plasma-charged particles. A high-speed camera system images the laser-irradiated particle trajectories at a frame rate of 3,200 frames per second. Via data post-processing, horizontal and vertical components of the velocity and acceleration of the particles can be determined, from which the charge on the particles can be deduced.

Pre-prototype plasma seal (PPPS)
The PPPS is developed to test the plasma-assisted removal of particles from a gas flow in the desired application environment. It is an intermediate step towards the final prototype, meeting the need for (1) flexibility to test different conditions, and (2) optical access to get qualitative and quantitative information about the particle trajectories.
To achieve this, a linear prototype has been developed.
The set-up consists of the following main elements:

- The plasma seal chamber: it mimics the shape of the plasma seal as it will be built into the HCVWHR. It is designed to create the appropriate pressure regimes to generate a plasma area for charging the particles, and a drift area where the particles are removed from the volume (50-200 Pa), and to separate these two areas from the vacuum wafer-handling environment (2 Pa). To achieve this pressure separation, an external gas flow is needed, which results in a gas velocity distribution across the PPPS (1-5 m/s).
- The plasma: this is a dielectric barrier discharge that is operated by an electrode on the glass top plate of the plasma seal. The metallic bottom part of the plasma seal serves as the counter electrode. The top electrode is driven by a special high-voltage source optimised to maximise the plasma intensity and minimise the amount of heat flux towards the substrate transfer mechanism.

Prototype plasma seal (PPS)
The translation of the linear PPPS into a circular geometry, which is needed to fit the HCVWHR, will lead to the prototype plasma seal (PPS). The same gas flow used in the PPPS is here provided to the HCVWHR, leading to the same pressure and gas velocity distributions across the seal. Following experimental results from both the PPCI and the PPPS, and insights from the plasma and particle models, the PPS will be tuned to make sure it meets the process requirements. The PPS will be installed in the HCVWHR, and as such validated on the BEAST (described below).

High-cleanliness-vacuum wafer-handling robot (HCVWHR)
Wafer-handling robots are among the key modules of substrate handling systems, responsible for wafer transport throughout the semiconductor manufacturing tools. Contamination control is critical in the design of wafer-handling robots, given the vast amount of substrate transfers that occur during the life of a wafer. Most commercially available substrate-handling robots show the classical SCARA design, where cleanliness is achieved by the addition of contamination seals. The seals must shield the contamination sources in robotic joints, e.g. rolling-element bearings, drive trains and cabling, from the clean process environment, while allowing relative motion between the two bodies connected to that robotic joint. These seals add mass and complexity to the design, thereby negatively affecting cost and performance requirements.

A novel wafer-handling robot is being developed as part of a PhD project in a collaboration between VDL ETG and the TU/e [5,6]. An alternative closed-loop kinematic structure was created that provides high out-of-plane stiffness and allows for actuation at the robotic base, eliminating the need for drive trains through the robotic mechanism. The absence of a drive train in the robot arm removes a significant contamination source. Linear joints are included in the kinematic chain, providing high stiffness. These linear joints are implemented as magnetically suspended bearings. The contactless nature of the magnetic bearings removes the need for contamination sealing. A technology demonstrator of the linear axis of motion has been realised and is currently being integrated and tested.

Bi-contamination equipment aerosol seal tester (BEAST)
Moving mechanical elements, e.g. bearings and cables, are the main sources of internally generated contamination. In many applications, contamination seals are applied close to the contamination source to prevent contaminants from spreading throughout the manufacturing equipment. In certain applications a contamination source can be sealed by a static seal, for example a bolt-on cover in combination with an O-ring. However, there are other applications where a dynamic seal is required, for example when a rotation between two bodies is needed. Various types of dynamic seals are commercially available, each type based on different physical concepts. Examples are ferro-fluidic seals, differentially gas pumped seals and the plasma seal as presented above.
In a VDL ETG - TU/e collaboration, a measurement set-up has been realised that is aimed at quantitatively comparing sealing concepts for particulate as well as molecular contamination. The set-up contains two individual vacuum chambers that share a common vacuum wall. A flange port in this common vacuum wall allows different types of seals to be mounted effectively in between both vacuum environments. Gases and particles can be injected in one of the vacuum chambers, while the other vacuum chamber contains measurement facilities to measure migration of both particles and gases through the seal. A measurement set-up containing a high-speed camera and a laser source is used to count particles (similar to the PCCI set-up described above). A residual gas analysis instrument (RGA) is used to measure molecular contamination.

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SURFACE PARTICLE CONTAMINATION MEASUREMENT AT MICROSCALE

In the high-tech industry, cleanliness demands are tightening, making it more and more challenging to achieve the right cleanliness at predictable cost, while defectivity challenges are also increasing. Defectivity discovered in the later stages of the semicon value chain will result in significant uptime and productivity losses. With the current global supply chain sourcing challenges and the ramp-up in chip manufacturing, it is more important than ever to supply first time right by checking cleanliness early. For that purpose, Fastmicro has developed a high-throughput, easy-to-operate solution for fast and accurate surface particle contamination measurement at microscale.

Optomechatronic systems require higher and higher accuracy and hence are becoming more and more sensitive to contamination. Improved surface particle cleanliness and defectivity control, preferably at micron-level accuracy, is required to keep their performance and yield at the right level. This poses a big challenge – concerning qualification and monitoring of cleanliness in the supply chain – on equipment suppliers, with their first-tier system suppliers and the related second- and third-tier suppliers as well as the cleaning houses. Process engineers and quality engineers have to define the right cleanliness specifications for products and processes, and subsequently secure control during manufacturing through incoming and outgoing inspections.

Manual ways of working

Possibly the most used measurement solution for surface particle inspection on products is the manual use of UV-light and bright-light methods. While it may be cumbersome to secure the pre-condition of a dark room, the biggest problem is that there is no objective quantification of the results. Moreover, the methods are time-consuming and man-dependent, and not suitable for smaller particles, possibly leading to discussions with the customer about the cleanliness or to unneeded rework or overcleaning.

Airborne

While process validation standards are based on airborne-particle counters, awareness is increasing about the need to measure the cleanliness on or near critical surfaces. Particles on both product surfaces and workplaces in the cleanroom can cause defects. Typical airborne process validation is specified at a maximum particle count for sizes from 0.5 μm upward. However, there was no fast, quantified and easy-to-operate measurement method at this lower micrometer scale for particles on the surfaces.

Sniffers

Airborne particle counters do have the low-microscale capability and, in combination with sniffers, can be used to perform surface particle measurements. However, due to the nature of physics the smaller-size particles stick to the surface a lot more than the bigger particles, which means that this method is not useful for determining the surface particle count at the lower microscale. After all, these small particles remain stuck at the surface and cannot be measured airborne.

1 *Stray light, as caused by the sun illuminating dust particles in the air*

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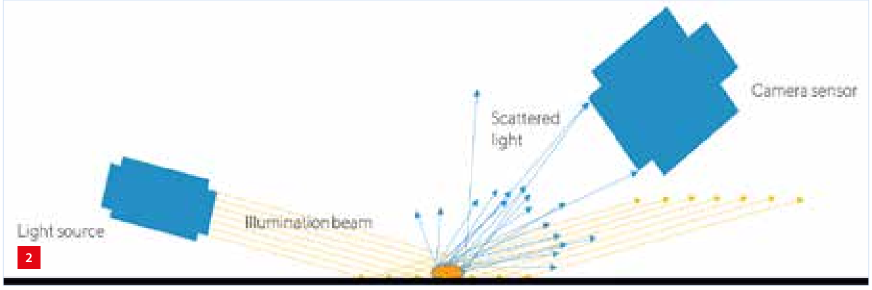


2

Principle of Mie scattering.

Standards

Many industries are driven by standards, such as ISO14644-9 in the case of surface particle measurement. Different industries have different specifications. Several industries

3

Fastmicro's Sample Scanner.

(such as the automotive industry) have specifications for surface particles from 50 μm upward. While the semicon lithography industry is ahead with its cleanliness needs, other industries are moving in the same direction and relevant standards will follow over time. While the ultimate cleanliness specs in semicon litho are even at nanoscale, the metrology for this is very expensive, slow and difficult to operate.

About Fastmicro

TNO, the Dutch applied research organisation, has worked with Lans Engineering on products for the high-end cleanliness industry for many years. About five years ago, awareness started to grow that measurement at micron level could be the right focus to enable fast and quantitative measurements in manufacturing environments. While functional models and prototypes were manufactured in the first years, demand was growing for a new OEM dedicated to delivery and service of industrialised metrology solutions. In 2019, Fastmicro was founded to provide equipment for surface particle measurement with global support.

While this article focuses on maintaining cleanliness in the supply chain for equipment manufacturing, by using the Sample Scanner, Fastmicro also offers the Product Scanner (Figure 4). The Fastmicro Product Scanner measures directly on the product as long as it has a smooth flat surface, enabling fast measurement of large surfaces. It is targeted for applications such as reticle blanks and backsides, pellicles from both sides, wafer blanks and backsides, and displays. It is available as a stand-alone version for academia and R&D departments, an automated, customisable inline cleanliness monitoring sensor for fabs and other clean manufacturing environments, and a white-label solution for system integrators.

For monitoring critical areas in cleanrooms and workplaces, and under duration tests, Fastmicro has developed another product range, Particle Deposition Monitoring, targeted at monitoring particle fallout from the air, both in ambient and in vacuum. In addition, Fastmicro is collaborating on the development of a scanner for particle measurement in vacuum (see the following article).


4

The Fastmicro Product Scanner.

Scattering metrology

The above challenges called for a metrology solution with the right throughput, objectivity and sensitivity to enable improved cleanliness control at the low micron level. Fastmicro (see the text box) has developed a solution based on an improved version of Mie scattering technology (named after the German physicist Gustav Mie). Basically, it comprises a light source and a camera. When the light hits the particles, stray light is generated, similar to what can be seen when dust in the air is illuminated by sunlight (Figure 1).

The scattered light is recorded by the camera sensor (Figure 2). It works extremely well with smooth product surfaces, as rough surfaces add too much noise to the measurement signal. The method can be calibrated for high accuracy using PSL (polystyrene latex) test particles with identical shape and optical properties, provided by NIST (National Institute of Standards and Technology).

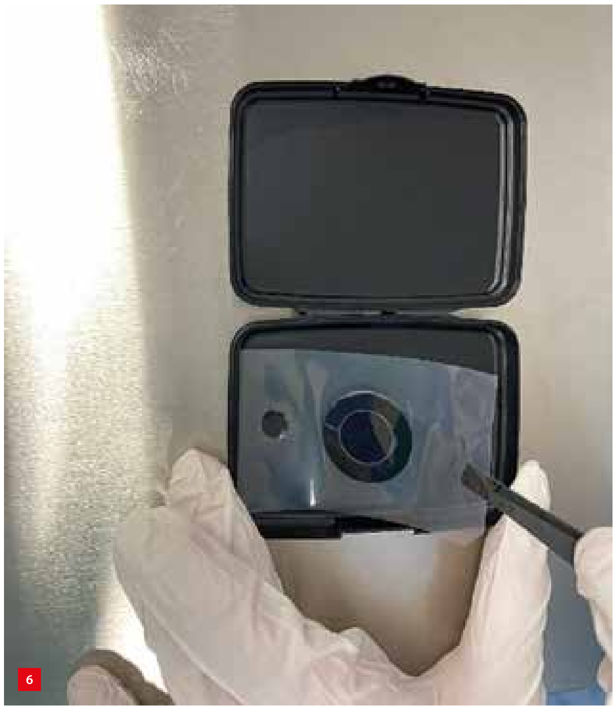
Sample scanner

Drawing upon the Mie scattering technology, Fastmicro developed the Sample Scanner (Figure 3) for measuring surface particle contamination levels indirectly using samplers, so-called Particle Measurement Cards (PMCs). By pressing these samplers with the sticky side on the

5

Taking a sample.

measured surface, the particles are collected (Figure 5). These samplers enable the user to take particle samples at any time on various equipment areas, even at places difficult to reach or from relatively rough surfaces. No measurable residue is left behind. The samples can be measured within seconds in the Sample Scanner, for a measurement area of 225 mm^2. The output is the quantity, location and size of particles. The samples can also be transported in a clean sampler holder (Figure 6), for later remeasurement and further analysis.



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Putting a sample in a clean holder.

Benefits

Unlike metrology solutions such as microscopes, SEM/EDX, AFM, Infrared and OCT, which are used in labs and R&D departments, the Fastmicro technology can also be applied in manufacturing environments. In Industry 4.0, cleanliness information is a vital element of the digital factory. Therefore, Fastmicro devotes a great deal of effort to ease of operation and extensive software options. This includes qualification with OK/NOK reports based on comparison with standards, connections to SPC/MES (Statistical Process Control / Manufacturing Execution System) monitoring databases. Because the Fastmicro technology is non-destructive, follow-up measurements using other metrology methods are possible.

To conclude, the Fastmicro sample-scanning technology all in all offers a number of benefits.

Scanning

1. Fast: imaging in seconds, also with large surfaces.
2. Quantitative results.
3. Easy to operate:
   (a) Qualification by operators in production.
   (b) Analysis by advanced users in R&D.
   (c) Continuous monitoring and SPC.
4. Accurate: high-resolution measurement of quantity, position and size; calibrated from 0.5 µm upward.
5. Consistent: clean, objective, contactless measurements, constant over time and across the supply chain.
6. High throughput: no interruption of the production process.

Sampling

1. Robust with relatively rough surfaces.
2. No measurable residue left behind.
3. Samples transportable with clean transport box (sample holder).
4. Measurement area of 225 mm^2.
5. Measurement of difficult-to-reach places.
6. Repeat measurements and further analysis enabled.

Launching customer

"Fastmicro has transformed our inspection capability business significantly. Before migration to this new inspection tool, we saw a 50% variation in the particle count measurements. This is now reduced to less than 10% in combination with a particle detection limit that went down significantly by more than one order of magnitude to 500 nm. We have confidence in the Fastmicro scanner to help us with finding an excellent quantification of the surface cleanliness of critical parts. As a valued customer, I know that the integration of Fastmicro has allowed us to reach our required machine defectivity performance. Besides accurate measurements, the tool offers ease of use and high throughput features. We appreciate the professional service and collaboration with Fastmicro to extend the capabilities of the tool further in the future."

Dr. ir. L.H.A. Leunissen, cleanliness project manager, ASML

COUNTING PARTICLES INSIDE THE CHAMBER

With the increasing need for vacuum environments in the semiconductor industry, the cleanliness of parts and subassemblies is becoming more and more critical. This requires testing their cleanliness and contamination properties in vacuum, for example by counting particles. Until now, measurement procedures at ASML were cumbersome and contamination sensitive. Therefore, a scanner for particle measurement inside a vacuum chamber has been developed, in collaboration with Fastmicro, a specialist in surface particle contamination measurement at microscale.

LEO HENDRIX AND ROBERT SWINCKELS

For vacuum applications, hardware has to be tested and qualified at the part and subassembly level. This involves 'mechaphysical' quantities such as: pressure/vacuum, temperature and flow; dynamical behaviour of components and the impact on connectivity; and tribological aspects such as friction, wear and particle generation. Preferably conducted under 'real-life' conditions, i.e. in vacuum and various other, ASML-specific environments, measurements concerning particle deposition, the effect of gases such as hydrogen, the quality of seals, etc. have to be performed 'on the fly', to investigate new design concepts and mitigate the risks associated with vacuum applications.

Unclear about cleanliness

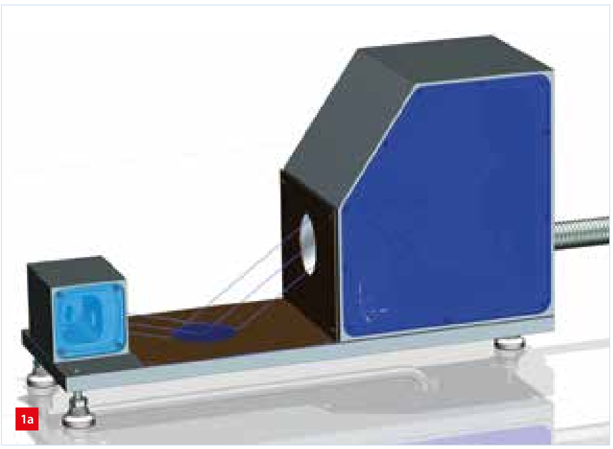
Until now, procedures at ASML were cumbersome. A 300-mm wafer, used as a kind of 'witness plate', was placed inside a vacuum chamber, after which experiments were conducted, the wafer taken out of the chamber and measurements performed in a particle scanner under atmospheric conditions. The risk of unwanted contamination was huge, so there was no certainty whether the particles measured were related to the experiment at hand or due to contamination that occurred underway between the vacuum chamber and particle scanner.

Optical measurement

Fastmicro had already developed an innovative scanning technology for particle measurement under ambient conditions (see the previous article), so ASML decided to contact Fastmicro to collaborate on the development of a scanner for operation in vacuum (see Figure 1). The idea was to adopt the same measurement principle: using a light source to illuminate a surface on which particles are deposited, and a camera to measure the stray light coming from these particles to determine their number and dimensions.

Vacuum-compatible

The main challenge was to develop a vacuum-compatible set-up for the optical measurement principle. This involved designing leak-tight light-source and camera modules, and solving the 'heat problem'. Any light source and camera



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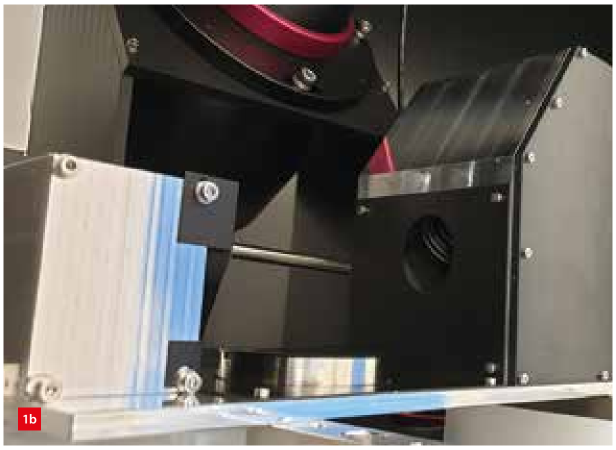

1b

The scanner for particle measurement inside a vacuum chamber, with the leak-tight light source and camera (on the right in both views).
(a) Schematic.
(b) Realisation.

AUTHORS' NOTE

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The standard vacuum test set-up developed by ASML.

module generate heat, which affects the experimental conditions, as heat cannot be extracted easily in vacuum. Therefore, it was decided to create atmospheric conditions inside the light-source and camera 'boxes', which were connected to each other via a tube and with the ambient world via a hose through which the heat can be vented.

Advantages

Compared to various measurement procedures currently used, the new concept has several advantages. It is non-destructive, involves no contact with the measurement area, exhibits no cross-contamination of the sample, and prevents contamination of the measurement area by particle generation due to friction and wear & tear on moving parts.

Specifications

The new particle counter can detect particles with dimensions of > 0.5 µm. The scanner is calibrated using PSL (polystyrene latex) test particles provided by NIST (National Institute of Standards and Technology). These test particles are perfect spheres with typical sizes of 1, 3 and 5 µm.

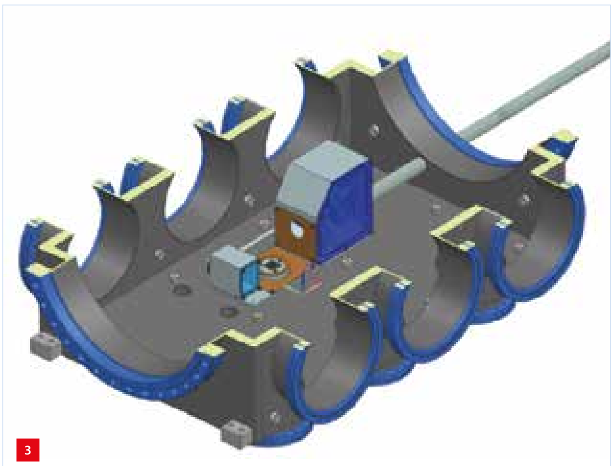
Platform for vacuum testing

The particle counter will be placed inside a vacuum chamber that is the result of the development of an ASML platform technology for vacuum test set-ups. This initiative was aimed at preventing elaborate custom development of set-ups, which can be time consuming and costly, by providing a standardised modular vacuum test set-up that can be customised efficiently using standard modules for specific test objectives.

The vacuum chamber (Figure 2) is provided with standard mechanical, electrical and software interfaces, to which various modules can be connected. These interfaces include two 500-mm doors, flanges, viewports and connectivity feedthroughs. The set-up is completed with three turbomolecular pumps for various vacuum pumping strategies. Inside the chamber, standard mounting facilities are available for test tables, sensors and, of course, the particle counter (Figure 3).

Acceptance

The development of the scanner at Fastmicro in Geldrop (NL) has been successfully completed. Now, Fastmicro is preparing for the site acceptance test at ASML. When this has been concluded, the system is ready for operation and serial production can begin for the dissemination of in-vacuo particle counting within ASML and its supply chain.



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CAD drawing of the new scanner mounted inside the vacuum chamber of the standard test set-up.

SURFACES, CHAINS AND MEASUREMENTS

In mid-October, the Dutch Association for Contamination Control VCCN organised the Product Cleanliness 2021 symposium. About 130 participants attended lectures on product cleanliness and visited the exhibition. It was a special moment to be able to meet each other face to face after such a long time. The meeting highlight was the presentation of the first issue of the VCCN Guideline 12: Product Cleanliness.

JOS BIJMAN

Guideline

ASML's latest (EUV) lithography machines require such high accuracy, and therefore such high levels of cleanliness, that the entire semiconductor production chain must be compliant with respect to cleanliness. Cleanliness of products is also important in many other industries, such as optics, automotive, nuclear, aerospace, medical devices and life-science products. Suppliers in these industries are increasingly being asked to provide clean products. Surface cleanliness is also playing a progressively more important role here, both in terms of particulate and chemical contamination. OEM companies are setting stricter requirements for surface cleanliness, and their suppliers must accommodate these in their own production and logistic processes and be able to prove that they can meet these standards. This has created the need for a definition of product cleanliness for both OEMs and suppliers.

Thus, with the help of the OEM companies that set the requirements for product cleanliness, as well as suppliers and knowledge companies, VCCN has drawn up Guideline 12. This publication defines the requirements and harmonises the language used regarding product cleanliness (see also the following article).
The VCCN Guideline 12 was produced by the VCCN Workgroup 23: Nano Micro Product Cleanliness. It began on 1 November 2017, and recently, at the VCCN symposium on 14 October 2021 in Eindhoven (NL), the first copy was handed over by VCCN chairman Eric Stuiver to Professor Vadim Banine, senior director Defectivity at ASML and part-time professor of Physics and Technology of EUV Lithography at Eindhoven University of Technology (Figure 1). Most of the workgroup members were present at this symposium, as either a participant or a speaker.
The theme of the lectures was "High demands on surface cleanliness challenge the entire supply chain".

Surface cleanliness

Philip van Beek, the chairman of the symposium and a member of Workgroup 23, introduced the new Guideline 12 and the lecture programme. The effects of contamination (particles and chemical) on products and means of production, such as failure, reduced long-term reliability and shortened lifespan of the means of production, have been known for a long time. That is why production and assembly increasingly take place in a cleanroom. While air particles in cleanrooms of a certain ISO class for cleanliness are often taken into consideration, surface cleanliness of a product (or part) is much more important.

Surface cleanliness relates to various areas, such as surface properties, manufacturing, cleaning, measurements, and measures to keep a product clean during assembly, storage and transport. Depending on the desired cleanliness of the product surface (with respect to particulate and/or chemical concentrations), more or less stringent methods must be used in the production flow to meet the specifications. Also, the design of the product should enable the realisation of a clean product.

This was what Dirk Trienekens, who is in charge of supplier cleanliness support at ASML, communicated with his presentation "Build clean, make clean & keep clean – Securing cleanliness from start to finish". He stated that ASML's most stringent cleanliness requirements, known as grade 1, are so challenging that focusing only on cleaning is not enough. Instead, cleanliness will have to be taken into account throughout the entire production chain.

Rients de Groot, senior system design engineer at Thermo Fisher Scientific, explained the important role surface cleanliness plays in the system assembly process and the manufacturing process of the various parts and modules that make up the final system. In his presentation, he highlighted the manufacturing aspects and also the specification and validation of cleanliness.

Covering the cleanliness chain

Surface cleanliness is already a concern during product

AUTHOR'S NOTE

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VCCN chairman Eric Stuiver (right) handing over the first copy of VCCN Guideline 12 to Professor Vadim Banine.

design, as the components to be manufactured as part of modules need to meet the desired cleanliness requirements. This was the theme of the lectures from both Koos Agricola, an expert in contamination control and cleanliness technologies on behalf of VCCN, and of Olof Teulings, process engineer at NTS Mechatronics.

Agricola pointed out that Guideline 12 is like a guide for making clean products (see also the next article). Cleanliness is about determining the acceptable amount of particulate and/or chemical (molecular) contamination on functional product surfaces. He explained that to achieve a specified cleanliness level, the entire manufacturing chain must be taken into account:

- Where can contamination occur?
- Can it be prevented or removed?
- Measuring and monitoring the surface cleanliness of (test) products help in understanding and tackling contamination.
- Cleaning processes are necessary for removing the unwanted contamination, but these will also affect the surface.
- Therefore, a good compromise will have to be found to prevent the disruption of the functionality of the product.

Teulings explained the challenge for suppliers when they need to supply multiple OEMs that each have different cleanliness demands. He showed how to manage the different demands in limited facilities and how to keep clean assembly under control. His conclusion was:

1. Realise that clean assembly is more than only having a cleanroom:
   - keep monitoring the cleaning of your incoming parts and the results of your own cleaning;
   - keep measuring and working on contamination control of your cleanroom(s);
   - keep training and creating awareness concerning assembly;
   - maintain a strong focus on your final cleaning and inspection.
2. Keep improving:
   - invest in facilities, people, research and knowledge.
3. Organise cleanliness:
   - be aware that there are a lot of individual contributors (production, facilities, supply chain, and design).

Standards and measurements

Just like VCCN, the global semiconductor industry association SEMI is focusing on surface cleanliness in its standards. This was demonstrated by Max van de Berg, senior project consultant at Festo and participant in SEMI activities in the field of gas delivery standards and component cleanliness. The semiconductor industry is very much relying on clean environments and clean components in their manufacturing equipment. As the size of the structures on a microchip decrease further and further, the presence of particles and other forms of contamination is driving many research programmes to detect smaller particles and all kinds of contamination. Van de Berg signalled that this development will also lead to new measurement methods for finding those contaminants and classifying them in a different way.

Freek Molkenboer, senior systems engineer at TNO, showed how important vacuum cleanliness has become in several applications. With vacuum it is possible to meet these high demands for cleanliness. In his presentation he showed, based on the well-known V-model for product development, why the right cleanliness level at the right location is needed, and how applying the right level at the right location can save costs.

Paul Krüseman, manager Cleanliness Qualification Lab at Eurofins Materials Science Netherlands, has a wide range of measurement techniques at his disposal in his lab. He showed several possibilities for determining the cleanliness of a product by performing an independent measurement. His presentation provided a global overview of the available measurement techniques and their application areas.

INFORMATION
To obtain VCCN Guideline 12, please check the website.
WWW.VCCN.NL/RICHTLIJNEN

PRODUCT CLEANLINESS

In various industries there is an increasing need for guidance on nano- and microscale surface cleanliness for product development, part manufacturing, surface treatment, assembly, cleanliness measurements and cleanroom services. A VCCN project group therefore prepared the VCCN Guideline 12: Product Cleanliness. It does not prescribe solutions but describes what should be considered when dealing with product cleanliness, which should, among other things, enable and align the communication on product cleanliness between suppliers and customers, in order to help industries to realise and improve product cleanliness.

KOOS AGRICOLA

Cleanliness of product (or part) surfaces is important in many industries, such as aerospace, automotive, microelectronics, semiconductors, optics, nuclear, medical devices and life-science products. Surface cleanliness involves topics such as surface properties, manufacturing, cleaning, measures to keep a product clean during assembly, storage and transport, and measurements. Depending on the desired cleanliness of the product surface (with respect to particle and/or chemical concentrations), stringent methods must be used in the production flow to reach the cleanliness specifications. The product design should enable the realisation of a clean product. In case of application in high and ultrahigh vacuum (HV and UHV), additionally the selection of raw materials and the design of the part can influence the outgassing of the part.

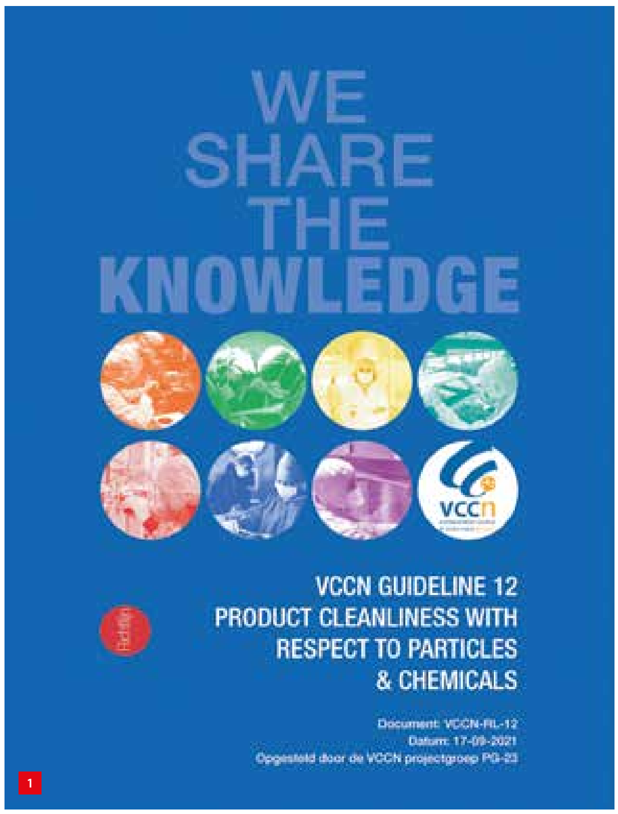
Overview

VCCN guidelines are associated with international cleanroom standards prepared and published by the technical committees ISO TC 209 (Cleanrooms and associated controlled environments) and CEN TC 243 (Cleanroom technology). They provide additional information on cleanroom technology and contamination or cleanliness control. The recently published VCCN Guideline 12 (Figure 1) describes surface cleanliness of parts and products with respect to particles and chemicals. For some applications (especially in UHV) the emission of vapours caused by chemical contamination is of interest (RL 12 Product Cleanliness - VCCN) [1].
For the specification, realisation and verification of surface cleanliness it is crucial to understand the functions and application of the product. This motivates the product cleanliness requirements. During manufacturing, from raw material to delivered specified part or assembled device, the required surface cleanliness should be achieved. In general, the design is the starting point, but to be able to design a clean product, product developers should have knowledge of all cleanliness aspects. Various aspects have impact on the product cleanliness (see Figure 2).

The following international standards on surface cleanliness are used [2]:

ISO 14644-9	Classification of surface cleanliness by particle concentration on surfaces, SCP.
ISO 14644-10	Classification of surface cleanliness by chemical concentration on surfaces, SCC.
ISO 14644-13	Cleaning of surfaces to achieve defined levels of cleanliness in terms of particle and chemical classifications.

Microbiological contamination topics are not specifically covered in the guideline, but various aspects such as design for cleanliness, specifications, assembly activities and controlled environments are also relevant for micro-



1 *Cover of the recently published VCCN Guideline 12 document.*

AUTHOR'S NOTE

Koos Agricola is an applied physicist with 35 years' experience in contamination control and cleanroom technology. He is product manager and contamination control specialist at the Brookhuis Applied Data Intelligence cleanroom division in Enschede (NL). In addition, he is active in education and various (international) societies, including VCCN, and technical committees, covering standards for cleanroom technology and other topics in this field.

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organisms. Their behaviour is comparable to that of particles (deposition, contact transfer) and molecular contamination (airborne transport of viruses), with the major deviations being the potential growth of micro-organisms and need for disinfection methods.
To achieve clean controlled environments, the following standards on air cleanliness with respect to particles and chemical concentrations can be used:

ISO 14644-1	Classification of cleanrooms.
ISO 14644-2	Monitoring air cleanliness with respect to particle concentration.
ISO 14644-8	Monitoring air cleanliness with respect to chemical concentration.

Additionally, ISO 14644 provides standards on cleaning, design, construction and start-up of cleanrooms, separative devices, as well as suitability of materials, consumables and equipment with respect to particle and chemical emission. For control of micro-organisms the use of EN17141:2020 "Biocontamination" is recommended [3].

VCCN Guideline 12 provides guidance on the major aspects of cleanliness of solid surfaces of parts, products, tools and equipment. The purpose is to align the communication between customer and supplier, on surface cleanliness specification and qualification and to provide guidance on means to reach and maintain specific cleanliness levels.

Surface cleanliness involves the determination, reduction and prevention of contamination by particles and/or chemical compounds and/or trace elements. Important aspects are:

- Specification — Expression of the required level of surface cleanliness with respect to particles and chemicals.
- Measurement — Determination of the level of surface cleanliness with respect to particles and chemicals as can be used in qualification and monitoring.
- Raw materials — Impact on surface cleanliness and outgassing behaviour.
- Manufacturing — Process conditions and part treatment during manufacturing with respect to surface cleanliness.
- Cleaning — Selection and evaluation of methods for cleaning to a specified degree of surface cleanliness.
- Assembly — Maintaining initial surface cleanliness by proper environmental cleanliness, operational procedures and working methods.
- Packaging — Impact of packaging on the surface cleanliness of solid surfaces.
- Design — Aspects that have impact on the achievable surface cleanliness and cleaning.

Surface cleanliness starts with the specification of the customer demands. During this phase, the requirements are set that must be met during a chain of activities. A typical chain of activities is shown in the process flow in Figure 3. The process flow of the manufacturing of a clean product starts with the specification of the raw material and ends with the delivery of a specified part or assembled device to the customer.

For specification of surface cleanliness, product functions and types of contamination that can harm the function or application of a part (or the function of the device in which the part is used) must be described. The contamination can consist of specific particles and/or chemicals. Particulate contamination can cause electric opens or shorts, geometric defects, obscuration and (micro)mechanical defects. Chemical contamination can cause unacceptable off-gassing or outgassing of a product and unacceptable chemical interactions, such as corrosion, and have an unacceptable negative impact on adhesion of coatings and adhesives, etc.

Surface cleanliness levels are expressed in contamination concentration (mass and particle area or number) per surface area. Levels are described according to the ISO standard or guideline the customer and supplier agree(d) to use. The next step is to select the appropriate measurement method(s). Preferably the surface cleanliness is specified with respect to the recommended measurement method.

Contamination control

The starting point of manufacturing is the raw material that is used to make a part. Composition, purity and structure will have impact on the achievable surface cleanliness. An important fabrication (material transformation) process is machining and this will have impact on the surface contamination and cleanability.

After transformation, a dirty or unclean surface needs to be cleaned to a specified surface cleanliness level. There are many cleaning methods that can be used to clean a part. The selection depends on the levels to be reached, type of contamination, the material and the acceptable level of damage by the cleaning process. For the selection of a cleaning method, the cleaning efficiency and/or effectivity of the cleaning method should be evaluated.

Clean parts can be contaminated during assembly of the product. Often, assembled surfaces cannot be cleaned afterwards. A risk assessment on the likelihood and consequences of contamination during product assembly will help to identify locations where contamination should be prevented. To limit and control unwanted contamination, a clean environment and specific operational measures are required. The complete set of measures to achieve and maintain relevant and sufficient cleanliness levels is called contamination control.

When a part is ready and its cleanliness has been verified, it can be packed and sent to the customer. The selection of packaging material with respect to emission of contaminants and surface cleanliness is important in retaining the optimal initial surface cleanliness. Packaging can also be used as an intermediate step to keep a part clean.

Looking at all cleanliness aspects, it becomes clear that product cleanliness can be less challenging to realise in case cleanliness aspects are taken into account during the design phase.

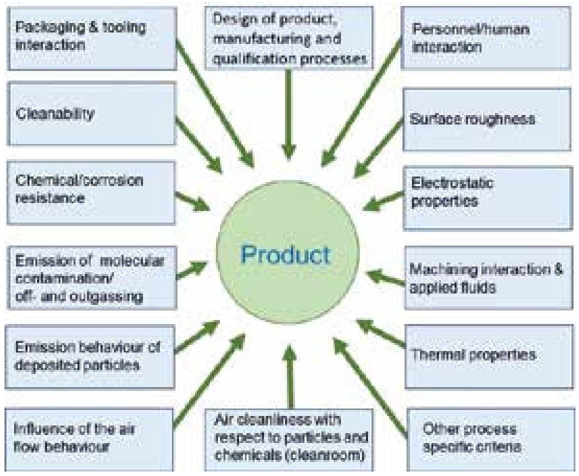
Standards

Many industries use surface cleanliness requirements that are derived from their own measurement method or measurable functional properties. For suppliers it is difficult to deal with the various different surface cleanliness definitions and specifications. Therefore, industries are encouraged to use ISO 14644 surface cleanliness standards, or at least to translate their requirements into these standards. Various exercises have demonstrated that this is possible.

The ISO 14644 surface cleanliness standards separate the specifications for particles and chemicals (molecular contamination). When this separation is not possible, it is recommended to express the total amount of contamination in g/m^2.

ISO 14644-9:2012 deals with the surface contamination by particles. It uses a particle size distribution in which the number of particles is inversely proportional to the particle size determined by the diameter D of the circumference of the particle silhouette on a surface. The surface cleanliness level is related to the number of particles ≥ 1 μm per m^2. The measurement result must be expressed in the cumulative number of particles ≥ D μm per m^2: N_D. The surface cleanliness level then is $N_D \cdot D$ for different particle sizes. The maximum surface cleanliness level for the considered particle sizes determines the overall surface cleanliness level SCL. In the ISO standard then the 10-log SCL is taken to determine the ISO SCP class.

The particle size distribution on a surface correlates with the contamination of a surface by particle deposition. However, when a surface just has been cleaned, most larger particles will have been removed and the particle size distribution becomes inversely proportional to D^p, where $p > 1$ and up to 2-4. During exposure of the surface to particle deposition from the air, the p value will move towards 1.



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Aspects of product cleanliness.

ISO 14644-10:2013 deals with surface cleanliness by chemicals. The surface cleanliness level is given by the mass of the chemicals of interest or group of chemicals of interest in g/m^2. Some measurement methods do not give the contamination in mass, but rather state the number of molecules. In that case, the number of molecules is multiplied by the molar mass and divided by the number of Avogadro. In that way, the molecular contamination can be expressed in g/m^2. In the ISO standard then the 10-log of the surface mass is taken to determine the ISO SCC class. Since the mass is < 1 g/m^2 the ISO SCC classes will be negative.

Measurement methods for surface cleanliness are discussed in VCCN Guideline 12 and also in the mentioned ISO standards.

Manufacturing chain

For product cleanliness, the complete manufacturing chain should be known. This starts with the way the raw materials are made, followed by the transformation processes, such as machining, then various cleaning, interconnection and assembly processes. Sub-assemblies or parts can be transformed again, etc. In the complete chain, one should be aware of potential contamination sources. In case these are critical, they should be measured to be able to keep them within an agreed limit or they should be avoided.

A cleaning process can be a decoupling point in the chain, but depending on the vulnerability for chemical contamination in particular, one should still know potential contamination sources. Contamination sources can be found on surfaces, in liquids, gases and air within the processes concerned or in surrounding processes, or on other products made in the observed facility of a supplier. The impact of these sources can be reduced by prevention and removal by filtration and cleaning of process media and environment.

Cleanliness strategy

The cleanliness strategy will be a combination of preventing or limiting unwanted contamination and removing contamination by cleaning. Each process will contaminate the product. One can analyse the product cleanliness backwards, from the final cleanliness towards the start of the manufacturing chain. In the final process, the initial surface cleanliness should be better than the final surface cleanliness. The difference gives the acceptable contamination. This knowledge is used to develop the measures to limit the contamination within the given process latitude. During cleaning, the surface cleanliness is reduced depending on the initial surface cleanliness and the cleaning efficiency. Unclean products can also become a source of contamination for subsequent products and/or the environment.

The cleanliness strategy determines where contamination control measures are taken and where cleaning processes are required. The optimal strategy depends on product design, quality of processes, suppliers, transport, storage, available cleaning facilities and monitoring of product cleanliness. Analysing costs and risks of quality loss, the optimal cleanliness strategy can be determined.

Cleaning

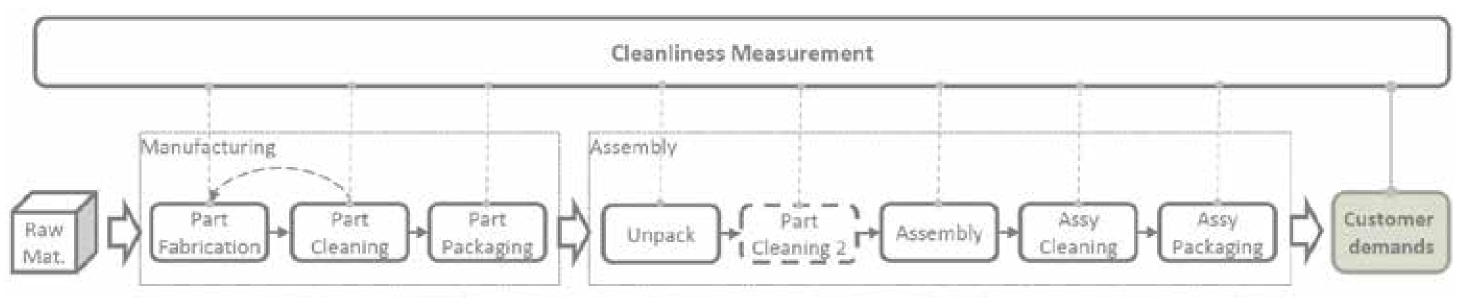
Cleaning processes are applied to remove particulate and chemical contamination. A dirty product first needs precleaning since cleaning processes that remove particles and/or chemicals need a sufficiently low initial surface contamination level to be able to reduce this contamination level sufficiently. A cleaning process has a specific cleaning efficiency depending on the cleaning method, process parameters and products to be cleaned. A cleaning process will have a negative impact on the product surface. It is therefore selected in such a way that the surface damage by the cleaning action is acceptable. The cleaning action is a combination of mechanical and chemical energy. In addition, cleaning temperature and time are important. Cleaning parameter settings can be interdependent.

ISO 14644-13 describes the way to select a cleaning process and gives a simplified overview of cleaning techniques. An important aspect is the investigation and testing of the suitability of a specific cleaning method for the intended application. Cleaning processes can be either wet or dry. The major cleaning action can be either chemical or physical (including mechanical and thermal).

Cleanroom

Cleanroom technology can be applied to control surface cleanliness and to prevent and limit contamination during assembly of clean products. The basics of contamination control is the creation of a separated clean space and controlling the cleanliness of everything that enters this space. The space is under overpressure and it has entry locks to prevent introduction of contaminants by air. Within the space only goods and equipment that are suitable with respect to the allowed emission of contamination are admitted, while the surface cleanliness of everything that enters should be within set limits.

Within the clean space, airborne contamination is diluted and removed by ventilation with clean air. All surfaces should be cleaned efficiently and frequently. A very important factor is personnel. Their number should be as low as possible. Ideally, they should be hygienic, non-smoking, without cosmetics and able to follow entry and working procedures. Personnel should wear clean(ed) occlusive cleanroom clothing to shield the environment from human contamination. Working procedures should be developed to minimise contamination during assembly. The goal is to limit deposition of particles and chemicals onto vulnerable product surfaces.



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Process flow of manufacturing a clean product.

The VCCN project group that prepared the new VCCN Guideline 12. Fifth from the right, the author of this article, Koos Agricola.

Monitoring

Various cleanliness parameters should be monitored to visualise the quality of the manufacturing chain with respect to cleanliness. For this, data on surface cleanliness of product, tools and equipment, media and environment can be used. With respect to particles in a controlled environment, the air cleanliness, particle deposition rate and surface cleanliness should be monitored. A light-scattering airborne particle counter can be used real time to provide information on particles < 10 µm. A real-time particle deposition monitor can be used to monitor particles > 10 µm, especially particles > 25 µm that are not removed by the ventilation system. ISO 14644-17:2021 gives guidance on the interpretation and application of the measurement results of particle deposition rate.

All surfaces in a clean environment can introduce particles into the air when agitated by activity and turbulent air flows. Therefore, also the cleanliness of floors, work benches, tools and equipment should be monitored.

With respect to chemicals, it is important to prevent unwanted chemicals to enter the clean space. Surfaces should be cleaned in case there is a chance of unwanted chemicals. Surface samples should be taken to measure the cleanliness. The air cleanliness can be measured by taking air samples in absorption tubes and analysing these in advanced measurement equipment for chemicals.

Conclusion

The VCCN Guideline 12 was prepared by a VCCN project group (Figure 4) with members from the various stakeholders. It does not prescribe solutions but rather describes what should be considered when dealing with product cleanliness. Considering the various topics that are addressed, industries should be able to realise and improve product cleanliness. The guideline can enable and align the communication on product cleanliness between suppliers and customers. It also includes a few examples.

It is important to develop a helicopter view on potential contamination during the complete manufacturing process and to understand the impact of design and process options on the product cleanliness.

REFERENCES
[1] *www.vccn.nl/rl-12-product-cleanliness*
[2] *www.iso.org*
[3] *www.nen.nl/en/nen-en-17141-2020-en-275425*

EBL2 FOR EUV, AND MORE

Producing extremely small and powerful microchips with the help of extreme ultraviolet light (EUV) is an impressive achievement. But the manufacturing process faces some tough challenges, such as preventing contamination. To solve this problem, TNO has built an impressive research facility (EBL2), which is used to help the chip industry control contamination. How does this work exactly? Freek Molkenboer, senior systems engineer at TNO, explains this in detail.

MENNO DE BOER

The very advanced equipment that the chip industry works with nowadays is particularly susceptible to contamination. EUV does not pass through the atmosphere, so the EUV-based lithography process must take place in an ultra-clean vacuum. If the equipment doesn't provide these conditions, you'll face contamination and it will be difficult – or in fact impossible – to produce microchips that function properly.

Crucial vacuum

Vacuum is the 'big enabler' – not only for the semiconductor industry, but for many areas of research. For example, take CERN, where the researchers of that particles laboratory would never have been able to demonstrate the existence of the Higgs particle without vacuum. The ITER nuclear fusion project also requires a very large vacuum chamber, in which the plasma is created. Quantum computers require microchips that are placed in a vacuum chamber, close to absolute zero.

Critical cleanliness

Contamination is the term used to describe lack of cleanliness in a system or at a surface, to such an extent that the system can't be used in the desired and designed manner. That's why every application has requirements in terms of permissible contamination, and for each application this will be different. The first step is therefore to determine the required level of cleanliness and to ensure that all parties involved understand why this is a critical success factor.

Hefty price tag

In EUV lithography, a dirty vacuum can cause contamination on mirrors. To prevent such contamination, equipment manufacturers may go to extremes and work with ultra-clean vacuum systems, where it is very important to know exactly which molecules may and may not be present in the vacuum system. They may choose to focus on thoroughly cleaning the machines and all other material involved in the lithography process in order to achieve this. But the risk is to go too far with such measures. Those who choose to clean everything to extremes may always be certain of optimum cleanliness conditions, but they'll face huge additional cleaning costs.

How clean should it be?

To increase the cleanability of a design, and with that to save costs, it is useful to include the cleaning of components in the design phase of systems and parts. The first question to be answered is: how clean should a system be? Only when you have a clear idea of this you can implement the systematic approach that minimises the risk of contamination to the desired level at the desired costs.

Regular checks

The first step is to determine how clean the end product has to be. On that basis, you can then conclude how clean the sub-products and the production process have to be. It's important to check regularly during the manufacturing process, whether the chosen approach is meeting the set requirements. And an inspection of the end product is of course also part of this process.

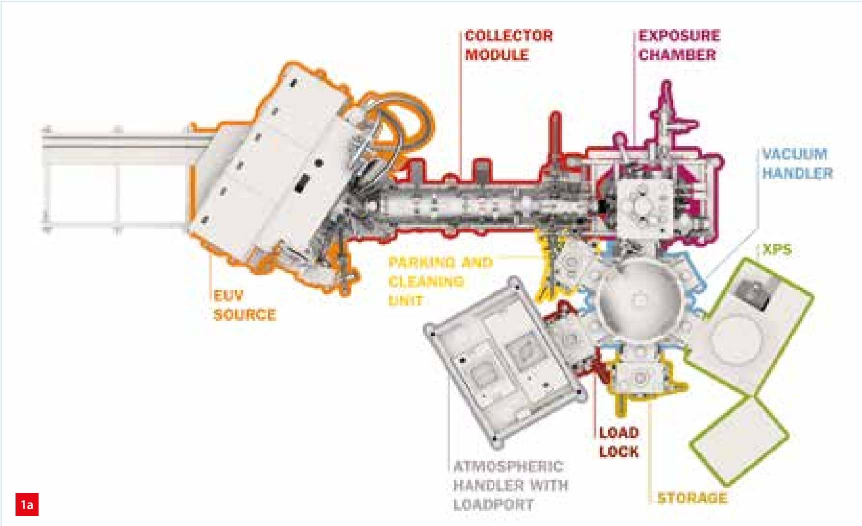
Advanced research facility

At TNO, we've learned a lot about contamination control over the last 25 years. We've also built advanced machines to investigate the challenges of contamination control, and the EUV Beam Line 2 is our greatest pride and joy. This is a large, costly and very complex research facility that we built in 2017. It is now in constant operation and we will continue using it over the coming years. (See Figure 1 and the video [V1].)

EBL2 enables us to simulate the environment of, for example, an EUV lithography machine and to determine the effect of high EUV dose on specific samples and the degree of contamination that occurs. Different vacuum chambers of the EBL2 system ensure that such a sample cannot accidentally become contaminated in an uncontrolled manner during its passage through the various parts of the EBL2 system. (See Figure 2 for the attainable vacuum in the various chambers.) This is vital because if it happens, we cannot say with certainty whether the contamination measured corresponds to the situation in practice at chip manufacturers.

AUTHOR'S NOTE

Menno de Boer is a freelance text writer. This article, based on an interview with Freek Molkenboer, senior systems engineer at TNO, was commissioned by TNO.



Overview of the EUV Beam Line 2 (EBL2).
(a) Layout:
- EUV chamber: 3 W power at 3 kHz, 1-30 mm spot diameter;
- hexapod positioning stage: < 250 μm positioning accuracy, < 100 μm reproducibility;
- in-situ imaging ellipsometer: 15 mm x 15 mm field of view, 0.1 mm imaging resolution;
- XPS (X-ray photoelectron spectroscopy) system: 152 mm x 152 mm sample capability, energy resolution 0.1 eV;
(b) In TNO's cleanroom.

Solving tricky puzzles

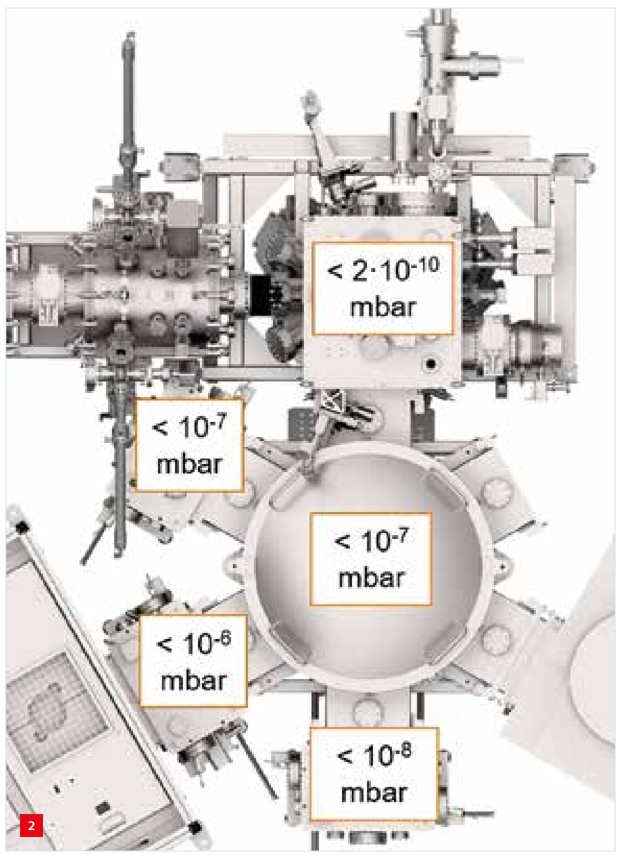
EBL2 contains all kinds of ingenious components for ensuring that the samples to be tested move through the system in the correct way. Many of these components were made specifically for this research facility and consist of many parts, which meant that our mechanical engineers had to be inventive to ensure their creations do exactly what they are designed for.

The materials used in the construction of EBL2 also posed a considerable challenge. Not every material can be cleaned and kept clean at the required cleanliness of EBL2. There are many restrictions in that respect when it comes to ensuring the right test environment. In some cases, when we really have to use a specific material, we have to adapt the design of EBL2 in such a way that the use of such a material does not cause any problems. For example, we have a reflectometer that contains a material with a contamination risk. We've developed a separate vacuum chamber for this device, which we will attach to the EBL2, with a very small vacuum connection to the exposure chamber of EBL2 to prevent contamination of EBL2.

All in all, it meant solving quite a puzzle, but that's something we engineers like to do. And in the end, we found a suitable solution for every problem, which is why we currently have a unique machine at TNO. To my knowledge, there's no other party that can measure the contamination of EUV lithography processes so accurately.

Cost savings

At TNO, we don't keep the contamination control knowledge to ourselves. We share that knowledge, so that chipmakers and other parties in the industry can optimise their equipment, production methods and cleaning regimes. I imagine that information about contamination risks will also form an important part of agreements between chipmakers and their suppliers. After all, the cleaner the parts that chipmakers are supplied, the less time and money they spend on the cleaning process. This also results in less delay and can have a positive effect on the lifespan of equipment. Even a seemingly marginal improvement in those areas can mean cost savings of millions of euros for chipmakers.



The attainable vacuum in the various EBL 2 chambers; see Figure 1a for reference.

Quantum computers / internet

And what about the future? Vacuum facilities will continue to play a major role. Vacuum is essential for quantum computers and in future, vacuum facilities will be necessary for sending and receiving information via the quantum internet. Once the technology matures, we will enter an interesting next phase of quantum computers and internet, in which contamination control and vacuum technology will play an important, enabling role.

The vacuum of space

We'll apply the knowledge about contamination control acquired in the semiconductor industry in our new Calibration Space Instruments (CSI) facility. Take Earth observation satellites, for example. After being launched, they end up in a vacuum environment where it may be cold or hot, depending on their position, though a satellite may also end up in a location where the temperature changes constantly. To ensure that these satellites do their work in the way that they're supposed to, they're tested on Earth in an environment that resembles space as closely as possible. A contamination budget is drawn up throughout the production process of such a satellite. This budget describes clearly how much contamination is permitted for each step of the process. Before a satellite in production moves on to the next step, there are checks to determine whether that step is clean enough. And that also applies to the facility in which it is calibration that checks whether the satellite is functioning as it is intended to do.

An ultra-clean facility

TNO is currently building a new facility for this step: the CSI. This is a vacuum chamber that has been designed and built using the contamination-control know-how that we've gained in the world of semiconductor industry. And because space projects are subject to cleanliness requirements that are already strict, and becoming ever stricter, we have designed and procured an ultra-clean facility.

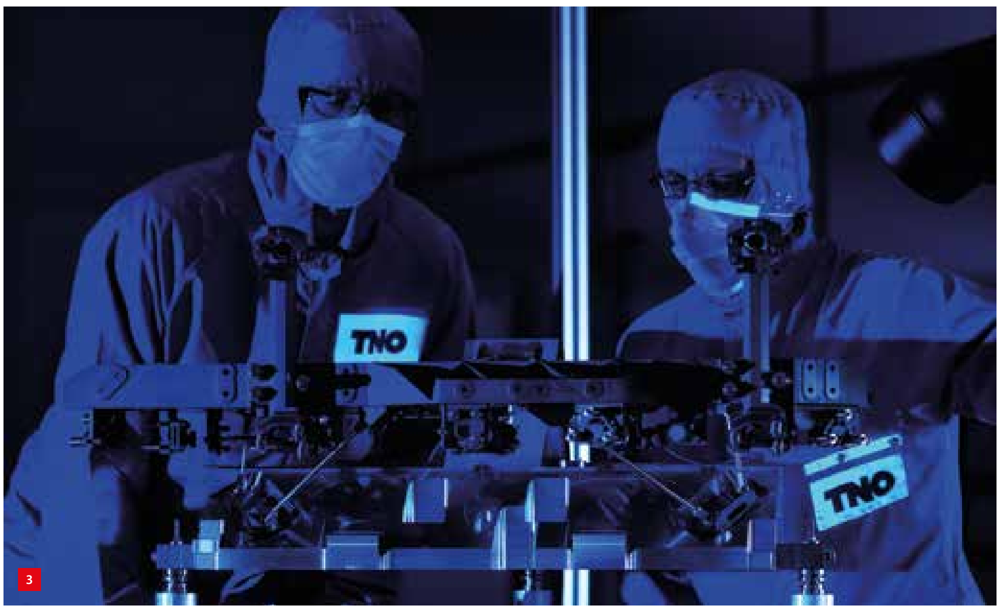
1.5 million kilometers

Space projects always appeal to the imagination; for example the Gaia mission, which became operational in 2013 for creating an ultra-precise three-dimensional map of stars in our Galaxy. (See Figure 3). I will mention one more nice example of the importance of contamination control: the new James Webb Space Telescope, which will go into space at the end of this year as the successor to the Hubble Space Telescope. This very costly observatory will not be circling the Earth like its predecessor; instead, it will be put into orbit around the Sun. This means that it will be 1.5 million kilometers from the Earth. If something breaks down there as a result of unforeseen contamination, you can't just send a few astronauts to fix it.

In short: contamination control in vacuum environments remains a key success factor, both for the current semiconductor industry and the quantum computers and space projects of the future. It's great that at TNO, we have ever more ways of accurately measuring that important factor.

VIDEO

[V1] "EBL2, the unique EUV exposure and analysis facility at TNO", *www.youtube.com/watch?v=jDFucd0vN-Q*



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UV testing for contamination of the accurate space interferometer BAM developed by TNO for the Gaia mission. (Photo: TNO / Fred Kamphues)

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IS THE RELIABILITY OF ELECTRONICS AT STAKE?

Over the last decades, the amount of man-made noise has grown substantially, driven by the need for power efficiency and (more) compact electronics design. On the other hand, signal levels with electronic devices have come down from several volts peak-to-peak to less than a volt. As semiconductor device scaling goes on into the nanometer region (Moore's law), the vulnerability to electrostatic discharge increases proportionally. Another threat involves storage and data integrity problems due to small ionising particles in our atmosphere. This article aims to raise awareness among engineers about EMI contamination problems, as their design choices may impact the EMI sensitivity of products and systems.

MART COENEN

Introduction

Driven by the need for power efficiency and (more) compact electronics design, numerous products and systems have been developed that contribute to the contamination of domestic, office and industrial environments with electromagnetic interference, from low frequencies upwards into the multi-GHz-regions. These products and systems range from LED lamps with their switching drivers, PWM motor controls, and wired and wireless battery chargers for all kinds of products, such as hoverboards and electric bikes, cars, buses and trucks, all of which contain switching electronics, to photo-voltaic (PV) power converters, electric trains and wireless internet-of-things (IoT) devices.

On the other hand, signal levels in between electronic devices have come down from several volts peak-to-peak to less than a volt: e.g. LVDS (low-voltage differential signalling) enables GB data rates. Interconnect cable losses remain physically unavoidable, for example in ethernet CAT-7 or CAT-8 signals, where the maximum cable length has been limited to only 30 meters, which corresponds to 26 dB at 2 GHz, whereas CAT-6A did allow 100-meter length and 44 dB of loss at 500 MHz.

As semiconductor device scaling goes on into the nanometer region (Moore's law), the vulnerability to electrostatic discharge increases proportionally, as the insulation layers within these devices have also shrunk with scaling, leading to damage threshold levels of 10 V or less, while their operational bandwidth has increased to near THz-regions. Yet, man-made static discharge effects caused by the rubbing of synthetic cloths/shoes have not changed; they can still be represented by 4 to 15 kV test pulses with sub-nanosecond rise time.

Another threat involves storage and data integrity, as small ionising particles in our atmosphere carry more energy than the charge of a memory cell and are able to initiate a conductive path through gate-oxide layers, causing everything from single-event upsets to full damage of power electronic devices (when in operation).

Higher power efficiency

More power-efficient energy transfer in a smaller volume requires faster switching within sub-nanoseconds by using SiC- and GaN-devices, rather than multiple nanoseconds by using MosFets, or microseconds, using IGBT (insulated-gate bipolar transistor) and thyristor devices. These 'slow' electronic switches are used with high-power applications. Today, the power-efficiency performance is often above 95%, leading to fewer dissipative losses, also mostly at higher switching frequencies.

State-of-the-art, high-power AC/DC chargers (240 W, i.e. 50 V @ ~5 A, with USB-C (Release 2.1 spec)) have reached a power-efficiency performance of over 99% under maximum load conditions at optimal operational supply voltage, temperature, etc. This is quite different to the 5-V charging (up to 9-V fast charging) we use today for our smartphones and tablets. Despite the recent EU developments regarding unification of USB-C-based chargers, most of the manufacturers using USB-C adapters have dedicated protocols to enable their high voltage, i.e. high-power modes, depending on battery status.

Low-frequency interference

On the other hand, more and more sensing devices (for current, displacement, acceleration, distance, etc.) and touchscreens are used that operate in the frequency range

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of 10 kHz to several MHz, a range already being occupied by energy-transfer devices and their switching frequency harmonics. The minimum distance between such a sensing device and an energy-transferring device, required for reliable operation, i.e. compatibility, is mostly undefined.

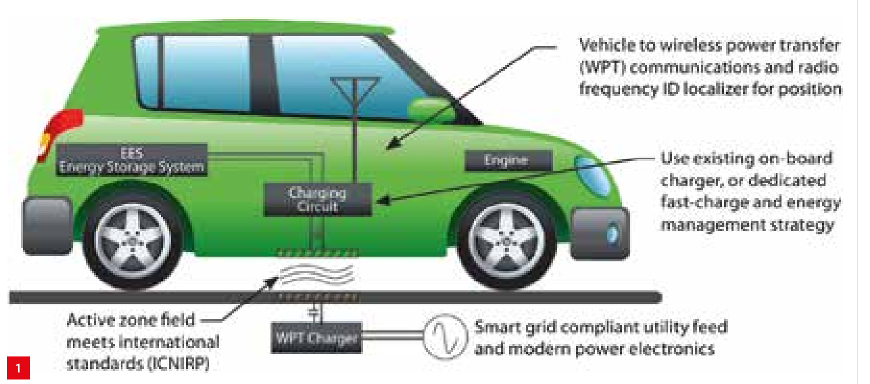
Smart solutions, such as changing the scan frequency slightly when ‘interference’ is detected in the designated band, are a technical way out. The opposite could be also done: changing the switching frequency of the power-conversion device slightly such that its fundamental frequency and/or harmonics do not interfere with any sensing circuit. Such an approach is, however, doomed when ‘spread-spectrum’ clocking techniques are already used within the power-conversion system to comply with the legally enforced EMC (electromagnetic compatibility) regulations.

Modern cars with an electric drive train no longer have an infotainment multimedia system that is able to receive long-, mid- and short-wave broadcast signals, because the interference from the on-board electronics is too high to enable undisturbed audio reception. Even the FM-band (87.5-108 MHz) is at stake. DAB+ (175-239 MHz) or internet radio, using the wireless communication services in the GHz bands (3G, 4G, 5G: from 850 MHz onwards), are required, along with playing MP3 files, to enable quality on-board audio.

Lagging standardisation

International standardisation and legislation cannot keep pace with recent developments, as consensus needs to be reached between manufacturers (= market push), end-users (= market pull) and the various national authorities. Though worldwide-applicable electrical vehicle regulations have been updated (UNECE R10, rev. 6, 2019), they do not incorporate any immunity requirement below 20 MHz, other than the electronic sub-assembly requirements as set out in IEC CISPR 25/ EN 55025 (2017). The latest IEC CISPR 25 pre-released version (2021) [1] has no requirements given below 150 kHz.

However, when a public road vehicle is passing a railway crossing where an electric train provided with an advanced (bi-directional) traction power supply system (ATPSS) is approaching, even long before the barriers come down the interference from the train (below 150 kHz) will be underneath the vehicle at less than 20 cm distance (train rail to vehicle bottom). This might upset CAN-bus or other signals used on-board the vehicle. Fast, orthogonal passing of the railway crossing might overcome unintended interaction, by causing only a short-lasting interference that might be self-recoverable, depending on the software. A vehicle full stop above the train rail at the crossing may be fatal.



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Wireless charging system for electric vehicles [2].

Products must comply with the relevant (EU/UNECE) regulations before they are allowed to enter the market. Whether these products satisfy the requirements concerning all possible phenomena as mentioned above is ‘nice to have’, but not mandatory. Furthermore, no regulatory requirements apply for any check-up after maintenance or repair, or for any component degradation over lifetime. Meanwhile, reports have been published about real performance degradation of the EMI filters as used on ‘bullet’ trains (TGV, ICE), leading to substantially higher noise when such a train passes by. Simple things like exchanging conventional lamps for LED lamps can already cause a functional failure, because the lower current drawn by the LED lamps is recognised as indicative of failure.

Wireless power transfer

Wireless power transfer for charging vehicles is not restricted to private areas, but will appear along public roads as well. Similarly, with inductive cooking at ~20 kHz, the power transfer is optimal when the pan is above the ‘antenna’. Any off-centre positioning leads to non-coupled magnetic stray fields and the cooking plate should detect and turn off when the inductive coupling to the pan is insufficient. Similarly, the wireless coupling to a vehicle being charged (wireless power transfer, WPT (Figure 1), 50-70 kHz, up to 17 kW) should also be optimised to avoid too-high stray fields being spread to all possible adjacent public road users. In-house wireless power transfer to drive LEDs that do not have wiring in between, over distances up to one meter, will be creating (intentional) huge stray fields, at or over the ICNIRP human exposure levels. Wireless changing of smart phones and tablets, on the other hand, is power-limited and remains local.

Shielded cables

Wired gigabit-signal transfer suffers from insertion loss of cables due to dielectric material loss and skin-effect losses. PFTE-foam dielectric, which equals near-air, shows the lowest losses, while silver-plated wiring gives the lowest skin-effect losses; examples are LEONI and GORE cables, which can easily satisfy the insertion loss figures as indicated above, in the introduction. Their main advantage remains that these cables are shielded and therefore less vulnerable to interference. Unshielded twisted pair (UTP) cable leaks about 20 dB more than shielded twisted pair (STP) cable, when properly applied. Similar to the STP case, requirements (*Kabelkeur*) apply for interference-free broadcast reception from the cable distribution network in combination with terrestrial signals (GSM, DCS, 3G, 4G, etc.). Shielding effectiveness of 90 dB and more is required for 'approved' coaxial cables.

The drawbacks of shielded cables are weight, stiffness and their limited range of flexibility compared to wireless interfaces. An alternative may be fibre-optical cables with their lower weight and stiffness. These fibre-optic drivers/receivers, however, require high power at both ends of the interface to transform photonic to electrical signals or vice versa. Further, these electrical signals are vulnerable to interference too, dependent on receiver gain corrections needed to compensate for the optical path losses. Wireless options with limited data rates are available, such as LORAN, Zigbee, BT-e, WiFi, UWB, etc., but they are all limited in their sensitivity due to man-made noise caused by nearby electronics and multiple reflections due to reflective objects and structures along the intended transmission path.

ESD protection

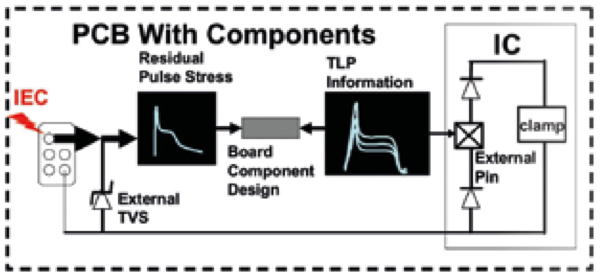
Decreasing semiconductor dimensions and lowering their gate insulation (for example in FinFETs) make these nanometer-scale devices vulnerable to electrostatic discharges, as the dielectric breakdown of the gate oxide is limited to a few volts at the most (local gate-oxide breakdown field strength is about 10^9 V/m). ESD (electrostatic discharge) protection measures need to be taken on the silicon die, but need to remain cost-effective with respect to the chip area required. With high-pin-count devices, however, the ESD protection device is weakened, and bond pad size is reduced to save area as these determine the circumference, i.e. die size, required for all I/O- and supply-pad protections and connections. With so-called 'glue logic', more than 50% of the silicon area must be used as ESD protection and bond pads, to meet JEDEC requirements.

As such, off-die ESD protections need to be added on the PCB to every IC pin that can be externally exposed to system-level ESD stress of 4-15 kV (Figure 2). These external ESD protection devices need to be fast enough to ensure that they clamp the overvoltage to a voltage level less than the maximum stress level that the IO pin can handle. Additionally, the off-die ESD protections need to have low stray capacitance too, to enable the required data-transfer rates into the Gb/s region. Mostly, on-die ESD protection (Figure 3) is designed to withstand (ANSI, JEDEC, ESDA, IEC) HBM (human-body model), CDM (charged-device model) and TLP (transmission-line pulse) pulses to the required voltage levels, but only for pulses with a maximum pulse duration of 100 ns, as the power-handling capabilities of the on-die protections are limited by thermal interconnect meltdown and insulation breakdown constraints.

Ionising particles

Another disturbing effect will be due to the thin insulation layers used with CMOS devices, solid-state drives and power devices, because ionising particles can change the content of memories when the particle energy is higher than the ½.$C.V^2$ (the charge energy stored in a memory cell). These ionisation effects are usually transient, creating glitches and soft errors, but can lead to the destruction of the device if they trigger other damage mechanisms (e.g. a latch-up).

Lattice displacement is caused by neutrons, protons, alpha particles, heavy ions and very-high-energy gamma photons. They change the arrangement of the atoms in a semiconductor crystal lattice, creating lasting damage. Though not man-made, ionising particles are part



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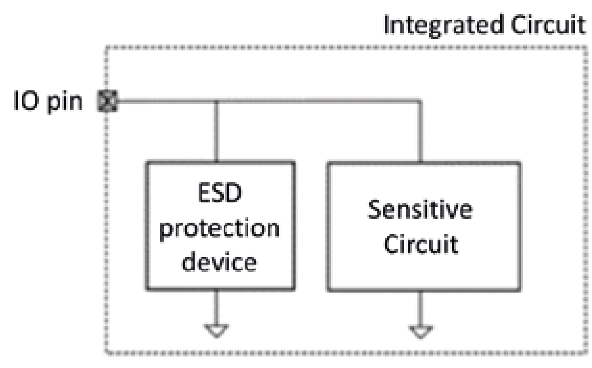

System-efficient ESD Design methodology [3] includes careful consideration of the interaction between the PCB protection and the IC pin transient characteristics.

of the contamination equation to be considered with regard to the future electronification and the expected increase of reliability requirements for existing and new applications.

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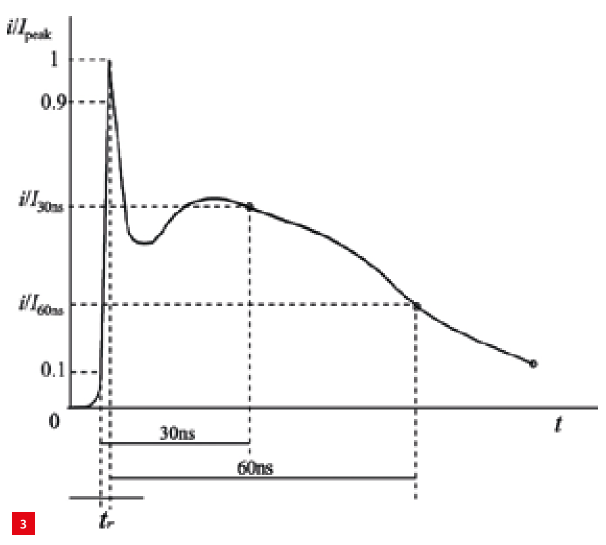

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System-level ESD pulse lasting for 30-60 ns halfwidth time, while its initial impulse rise time is 0.7-1 ns, lasting about 2-4 ns halfwidth time (IEC 61000-4-2 [4], ISO 10605). For most high-speed ICs, even the duration of the initial pulse is already longer than the functional bit time, and hence several bits will be corrupted with every ESD stroke occurring.

ULTRAFINE CLEANING

Rising requirements for particulate and film cleanliness are leading to a need for ultrafine cleaning solutions in companies from more and more branches of industry. High-purity sectors such as the semiconductor supply industry, optics and medical engineering are also undergoing a transformation.

DORIS SCHULZ

For many years, the automotive industry was seen as the driver for increasingly stringent cleanliness specifications, especially as far as particulate cleanliness was concerned. In precision cleaning, this role has now been taken over by producers of manufacturing equipment for the semiconductor industry. The development is mainly driven by extreme ultraviolet (EUV) lithography. Thanks to this technology, ever more powerful microchips no larger than a fingertip and capable of accommodating more than ten billion transistors can be produced.

In the nanometric and atomic percent range

It is therefore not surprising that specifications for particulate cleanliness now extend into the nanometric range. The specifications for filmic contamination are also extremely strict. When it comes to the outgassing of organic substances and liquids as well as surface analyses for residues of inorganic substances, permissible values can even be in the atomic percent range, depending on the component. For years now, the design of processes and equipment including part fixturing devices, as well as the environmental conditions for cleaning such components, has been a core area of expertise of UCM.

AUTHOR'S NOTE

Doris Schulz is a journalist. Her agency, based in Korntal, Germany, specialises in PR solutions for technical products and services. This article was commissioned by UCM, the division of the SBS Ecoclean Group that specialises in precision cleaning.

www.schulzpressetext.de
www.ucm-ag.com

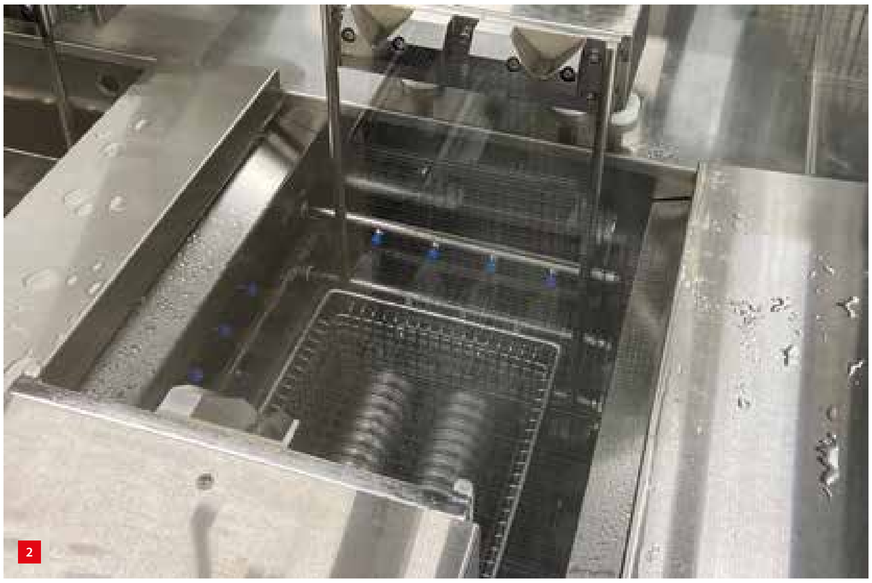
Round and flat optical components are increasingly made from acid-sensitive glass. To avoid glass corrosion with these sensitive materials, appropriately designed cleaning and water treatment systems and processes - including software - are indispensable. (Photo: Zeiss)

The starting point for designing multi-chamber ultrasonic cleaning systems and cleaning processes for specific tasks are the materials and geometries of the parts to be cleaned as well as the degree and type of contamination. Since outgassing limits are sometimes extremely strict, attention is also paid to selecting suitable cleaning chemicals. This, together with careful consideration of the materials and production processes used to construct the cleaning system, helps to prevent re- and cross-contamination.

New materials and processes drive requirements in optics

Two trends can be observed in the optical industry that are bringing about changes in cleaning requirements. For one, round and flat optical components are increasingly being produced from types of glass that are sensitive to acid. Depending on their acid resistance class, the materials react differently to the aqueous cleaning media and rinsing water used, which can lead to glass corrosion. To avoid this, the cleaning and water treatment systems and the processes must be appropriately designed (Figure 1). This includes ensuring that the dwell times of the glass components in the various baths, which are defined in the part-specific cleaning programmes, are reliably observed, and that prioritised processes can be carried out if required.

New tasks are also emerging in optics due to geometrically complex parts with holes and undercuts, for example ring laser gyroscopes made of glass ceramics such as zerodur. Cleaning solutions for these components must ensure that the internal surfaces of the geometries are reliably cleaned. This calls for specially designed part fixturing devices that also allow rotational or centrifugal movements during the cleaning process. Especially in the case of optics with 'super polish' surfaces, the ultrasonic frequency and output must be perfectly aligned when designing the process in order to prevent any change in surface roughness. The cleaning processes are verified, among other things, in specialised laboratories using measurement techniques capable of measuring surface roughness in the Ångstrom range.



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An immersion-type spray rinse tank sprays off the parts as they exit the bath for an improved rinsing result. (Photo: Philips Medical Systems)

Additively manufactured parts and the new MDR

Additive manufacturing is enabling enormous advances in medical engineering for patient-specific care. Cleaning plays a key role in this context. Parts manufactured using powder-bed-based printing processes can be cleaned of powder residues in a dry process after unpacking using vacuum technology, for example. For the subsequent wet-chemical cleaning step, chamber or in-line immersion systems can be used (Figure 2).

During the cleaning process, ultrasound and pressure-change technologies combined with a suitable medium ensure that contaminants and powder residues are removed from even the finest structures and complex geometries. New challenges for companies in the medical sector also arise due to the new MDR (Medical Device Regulation). Besides the cleaning result, this regulation also places higher demands on process validation, as well as on documentation and traceability.

Special solution or modular system concept

High purity applications in the semiconductor supply industry, optics, medical technology as well as the laser and sensor industry usually require individually designed processes and cleaning solutions that are correspondingly adapted for use in cleanrooms. For somewhat less demanding precision cleaning tasks which are becoming necessary in more and more branches of industry, UCM has developed a highly flexible and cost-efficient solution in the form of a series of ultrasonic immersion systems called UCMSmartLine (Figure 3).

This series is based on standardised modules, it includes integrated electrical and control systems for cleaning, rinsing, drying, loading and unloading processes, as well as a versatile transport system. The modules can be used to configure systems for pre-cleaning, intermediate cleaning and final cleaning, and also to extend them as required. Furthermore, these systems generally have shorter delivery times.

The solution that best meets the technical and economic requirements of the respective task can be determined through cleaning tests in the precision test centres of Ecoclean and UCM.

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Based on standardised modules, UCMSmartLine is a freely configurable system for numerous precision cleaning tasks. (Photo: Ecoclean / UCM)

ASML AND MORE

Precision engineering is one of the foundations of the Dutch knowledge and innovation economy. This became clear once again on 10 and 11 November 2021, during the 20th edition of the Precision Fair, organised by Mikrocentrum. A record number of exhibitors, 320, presented their innovations to visitors. The focus was on the future of precision engineering, culminating in the keynotes by Jelm Franse of ASML and Prof. Cheng of Brunel University. Naturally, the present and the past also received ample attention: in the lecture programme, on the exhibition floor and at the 20 Years Precision Fair expo.

The huge importance of precision engineering to our rapidly changing society was the common thread during the Precision Fair 2021 (Figure 1). Over the past 20 years, the fair has grown into the annual meeting point for the high-tech industry, playing an important role in the Dutch, and increasingly also the European, high-tech ecosystem. Also, the Precision Fair's collaborations with Big Science projects have resulted and continue to result in a large number of assignments for business.

As usual, the industrial liaison offers from the Big Science projects presented recent developments and upcoming tenders. In one of the newer fair items, the Young Talent Pitch programme, young talents from the universities of technology, the universities of applied sciences and the Leidse instrumentmakers School presented their innovative high-tech projects to the public. Belgium was this year's partner country, while Enterprise Europe Network organised another international Meet & Match in collaboration with Mikrocentrum.

Precision engineering challenges

Jelm Franse, senior director Mechanics at market-leading lithography machine builder ASML, delivered a keynote lecture about ASML's precision engineering challenges. Franse (Figure 2) discussed current topics, trends, barriers and urgent breakthroughs that need to investigated. Driven by Moore's law (the ongoing shrinkage of IC features), ASML's product performance roadmap for its lithography machines, regarding overlay, throughput and image quality, requires ever more accurate and faster movements, as well as more accurate and stable optical imaging capability, which must be achieved with modules and parts that exhibit low or even no wear. The overlay and throughput requirements are driving precision mechanics and mechatronics solutions from micrometer to nanometer and picometer regimes.

It all starts with applying the right design principles. Referring to a presentation of a 2025 update by precision engineering professors from the Dutch universities of technology, delivered at the Precision Fair 2019, Franse gave an overview of the 'ten commandments' of design principles for accuracy and repeatability:

- Kinematics design.
- Design for stiffness.
- Design for lightweight.
- Design for damping.
- Design for symmetry.
- Design for low hysteresis.
- Design for stability (long-term effects).
- Design for low sensitivity (short-term effects).
- Design for load compensation.
- Design for minimal complexity.

These design principles are applied to numerous (sub) modules and parts, in each case to enable one or more of the four types of precision engineering patterns that can be discerned within ASML machines, as summarised by Franse:

- Fast and precise motion, to be achieved with, for example, the wafer and the reticle stage.
- Stability and standstill, required for the metroframe, mechanical frames, and sensing and measuring modules.

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The 20th edition of the Precision Fair was held in a new, Covid-19-safe location: the Brabanthallen in Den Bosch (NL). (Photos: Mikrocentrum / Susanne van Doornik)

- Accurate photon delivery, through the optical (sub) systems, from laser to tin droplet in the EUV source (for EUV light generation), as well as in the projection optics box within the machine.
- Careful handling, concerning the mounting and clamping of reticle and wafer, and the prevention of particle contamination (using, for example, the pellicle assembly mounted in front of the reticle).

Next, Franse gave a casual overview of the gaps in the product performance roadmap and the required breakthroughs for each of the four patterns. These gaps range from thermal effects and micro-slip to defectivity and optics degradation. To address these gaps and create breakthroughs, ASML Development & Engineering has mastery of over 200 technical competences, including the aforementioned precision engineering principles, tribology and additive manufacturing, down to bolted components.

To illustrate the competence development required, Franse picked a few issues. The first one was concerned with the cable slab, which connects the fast-moving and accelerating wafer stage with the fixed outside world. This cable slab affects system performance by introducing disturbance forces on the short stroke of the wafer stage. In addition, the continuous deformation of the cable slab causes wear and hence particle generation by cables, hoses, clamps, end-stops and O-rings. In the end, this contamination leads to defectivity issues with the wafers produced in the machine.

The cable slab issue is part of the general dynamic links challenge. The number of dynamic links, for water, gases, vacuum, data and electric power, increases with each new machine generation, adding to the problem of unwanted forces (disturbances) that can be transmitted. This goes as far as the cooling-water flow inducing unwanted vibrations in the system.

A nice design principle example presented by Franse involved the well-known elastic elements. These are used in flexure supports that have to deal with large deflections in the newest machines, leading to a decrease of stiffness and fatigue problems. In collaboration with Delft University of Technology, ASML is investigating metamaterial- and origami-based beam flexures, for achieving large deflections with high support stiffness.

Franse also discussed a 'new' design principle. Until recently, damping was discarded because of the risk of position uncertainty due to hysteresis. But now, as the ever-higher control bandwidths required can no longer be achieved with the conventional stiff, lightweight design, passive damping comes to the rescue. At Eindhoven University of Technology, part-time professor

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Jelm Franse of ASML delivering his keynote lecture. The photo shows only half of one lecture room; two other lecture rooms were filled with Precision Fair visitors following the presentation via a video link.

Hans Vermeulen, senior principal architect EUV optics system at ASML, is conducting research on passive damping.

To conclude, Franse talked about the manufacturing challenges for producing precision parts in hard materials. He has high hopes for PECM (precision electrochemical machining), as it combines the advantages of conventional milling and EDM (electrical discharge machining). It is a relatively fast and low-cost process, which is non-contact (no tool wear) and burl-free (no defectivity issues), introduces no mechanically or thermally induced stresses in the product, and involves no copper (as with EDM), which is forbidden in the wafer area. According to Franse, PECM is an enabling technology for elastic elements as discussed above. Just to show that manufacturing technology, as an enabler for (new) design principles, is part of the future of precision engineering.

Ultraprecision machining

While Jelm Franse concluded his presentation with the manufacturing challenges of ASML, the keynote by Kai Cheng, professor in Manufacturing Systems at Brunel University, London (UK), was devoted entirely to ultra-precision machining. Prof. Cheng (Figure 3) discussed machines, systems and future perspectives for industrial-scale ultraprecision machining. This covered high-precision components and devices, such as ultraprecision machines, tooling, machining processes, in-process monitoring and measurement, and their seamless integration for forming ultra-precision manufacturing systems. In this way, Cheng combined the future of precision engineering with the future of manufacturing.

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Prof. Cheng talking about future perspectives for ultraprecision machining.

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PRIZE FOR MULTIDISCIPLINARY, ENTHUSIASTIC SYSTEM ARCHITECT KEES VERBAAN

During the 20th edition of the Precision Fair (see the report on page 40 ff.), the Ir. A. Davidson Award was presented to Kees Verbaan. Verbaan is a system architect at NTS Development & Engineering Eindhoven. He received the prize for his crucial contributions to complex NTS projects and his broad commitment to knowledge sharing and the development of his profession.

The DSPE board presented the Ir. A. Davidson Award to Kees Verbaan on Wednesday 10 November. The purpose of the prize is to encourage young talent by recognising the efforts of a precision engineer who has been working for several years at a company or institute and has a proven performance record that has been acknowledged both internally and externally. Candidates must have also demonstrated an enthusiasm for the field that results in a positive effect on young colleagues. The biennial prize, which was established in 2005 and was now presented for the eighth time, is named after an authority in the field of precision mechanics who worked at Philips in the 1950s and 1960s. The prize comes with a certificate, a trophy and a sum of money sponsored by DSPE. The trophy was created by the Leidse instrumentmakers School in the form of the handbook on precision mechanics that Davidson used as a foundation when forming the constructors community at Philips.

Critical contributions

Once again, the jury received a large number of nominations for the award; this year even ten. The jury's choice ultimately fell on Kees Verbaan. Verbaan studied Mechanical Engineering at HU University of Applied Sciences Utrecht and Eindhoven University of Technology, where he subsequently obtained his Ph.D. degree in 2015 with Prof. Maarten Steinbuch for research into the role of damping in the control of precision systems. He then started working as a system architect at first-tier system supplier NTS in Eindhoven (NL). In this position, he focuses on design challenges related to accurate positioning in complex machines. In doing so, he uses his extensive knowledge of design principles and in particular passive damping, the subject of his Ph.D. research. Also, in a leading role, he made crucial contributions to challenging projects that are very important to NTS.

"True" professional

According to the jury, as a system architect Verbaan can easily balance the required depth in the technology, and the cost price target and other preconditions from the customer. Due to his enthusiastic and constructively critical attitude, he always manages to get the project team on board. He is also not afraid to get his hands dirty – proverbially – by helping with assembly in the cleanroom if necessary or by providing pizza if the team has to work long hours. In addition, he is involved in knowledge sharing and competence building inside and outside NTS. He always makes time for coaching colleagues and students, and contributes to meetings of DSPE and international associations. In his specialist field, passive damping, he contributes as a teacher to two courses of the High Tech Institute via Mechatronics Academy.

All in all, Kees Verbaan can move easily through a wide range of disciplines and activities, both theoretically and practically. He does this with his characteristic helpfulness and enthusiasm, according to jury chairman Willem Tielemans. "He is interested in the direction in which his profession is developing and helps his employer to respond to this. In this way, he knows how to direct and connect others in order to jointly drive developments. All this makes him a true professional in his role, an asset to the field of precision technology and a deserved winner of the Ir. A. Davidson Award 2021."

Winner of the Ir. A. Davidson Award 2021, Kees Verbaan. (Photos: Mikrocentrum / Susanne van Doornik)
(a) Receiving the check that comes with the award from the hands of DSPE board member Erik Tielemans (left), managing director of Demcon Eindhoven.
(b) Proudly showing the certificate and trophy.

WIM VAN DER HOEK AWARD GOES TO TU/E ALUMNUS NICK HABRAKEN

During the Precision Fair, the Wim van der Hoek Award was presented under the auspices of DSPE. The prize went to Nick Habraken, who graduated from Eindhoven University of Technology (TU/e) on the redesign of a robot for microsurgery. According to the jury, his thoughtful design is not intended to replicate human motor skills, as often happens in robotics. "By looking closely at the application of the robot, Nick has arrived at a 'non-human', innovative topology (spatial structure, ed.), which is tailored to the function that the device has to perform."

Nick Habraken, winner of the Wim van der Hoek Award 2021, receives the certificate that goes with the prize from the hands of jury chairman Jos Gunsing. In the foreground, some of the award nominees. (Photos: Mikrocentrum / Susanne van Doornik)

The second day of the Precision Fair 2021, Thursday 11 November in Den Bosch (NL), featured the presentation of the Wim van der Hoek Award. This award (also known as the Constructors Award) was introduced in 2006 to mark the 80th birthday of the Dutch doyen of design engineering principles, Wim van der Hoek (1924-2019). The Constructors Award is presented every year to the person with the best graduation project in the field of design in mechanical engineering at a Dutch or Belgian university of technology or university of applied sciences. This award includes a certificate, a trophy made by the Leidse instrumentmakers School and a sum of money, sponsored by TU/e institute EIASI.

Criteria for the assessment of the graduation theses include quality of the design, substantiation and innovativeness, as well as the suitability for use as teaching materials. The jury, under the presidency of DSPE board member Jos Gunsing (MaromeTech), received a total of seven nominations from TU/e, Delft University of Technology and Fontys Engineering University of Applied Sciences in Eindhoven (NL).

Feasible, substantiated, fully developed

The Wim van der Hoek Award 2021 eventually went to Nick Habraken, who studied Mechanical Engineering at TU/e. This spring he graduated on the redesign of a robot for microsurgery. Medical technology company Microsure in Son (NL) has developed this robot for, among other things, breast reconstruction. In such an operation, blood and lymph vessels with diameters of less than a millimeter must be sutured; that precision is almost unattainable for a human being.

Habraken started with an extensive review of the application and the resulting technical and ergonomic requirements. Robotics often attempts to replicate human motor skills. However, Habraken chose not to do this and thus arrived at an innovative, 'non-human' topology, which is tailored to the function that the robot has to perform. The design was of high quality according to the jury. "Nick provided a feasible, substantiated and fully developed elaboration for all functions, both on a system and a detailed level. The emphasis was on a sophisticated control of the degrees of freedom of the robot, which must be able to move in a compact, sterile space. This is entirely in the spirit of Van der Hoek's design principles."

All seven nominees for the Wim van der Hoek Award 2021 received a certificate and were invited to attend the DSPE Conference on Precision Mechatronics 2023 and present their nominated graduation work.

DSPE KNOWLEDGE DAY
ENGINEERING FOR CONTAMINATION CONTROL

Contamination control is crucial for modern-day precision engineering. Two years ago, DSPE organised a first knowledge day about this topic, dedicated to engineering for particle contamination control. This successful event prompted DSPE to organise a second knowledge day in spring 2020, which however had to be postponed because of the Covid-19 pandemic... Fortunately, on 23 November 2021 the day could be organised as a live event at Mikrocentrum in Veldhoven (NL), attracting some 40 participants.

The knowledge day was organised by DSPE in collaboration with VCCN (Dutch Association for Contamination Control) and was devoted to various aspects of designing advanced mechatronics systems, such as dealing with contamination or minimising the implications of contamination. In addition, information was shared regarding tools that support the design (and test) phase of a project. For the current Mikroniek issue, which features the theme of Contamination, several contributions were elaborated into an article by the presenters concerned.

These presenters annex Mikroniek authors are senior system engineer Paul Blom, who talked about contamination control at VDL ETG (see page 8 ff.); Freek Molkenboer, senior systems engineer at TNO, who introduced the EUV Beam Line 2 research facility (see page 31 ff.); and Erik Vermeulen, CEO at Fastmicro, who delivered a joint presentation with Rob Lansbergen, senior system engineer at Lans Engineering, about their novel technology for surface particle contamination measurement at microscale (see page 19 ff.).

On behalf of the organisers, first DSPE board member Kasper van den Broek, contamination control architect at VDL ETG, opened the meeting, starting with a short presentation of DSPE and the Knowledge Day format. VCCN knowledge manager Jos Bijman then gave a brief overview of VCCN goals and activities, while also summarising the rationale behind this knowledge day: "Small, smaller, smallest requires clean, cleaner, cleanest."

Supply chain

Omneo Systems offers a reliable contamination control system, including products such as the Omneo PDM (Figure 1), for the entire supply chain in the high-tech industry and develops innovative cleaning concepts for large construction parts. Besides standards for particle measurement, CTO Cees van Duijn also talked about design-for-cleaning. Naturally, the parts included in the design are important, concerning their cleanliness and contamination properties. Another critical factor is the assembly scheme, which can be laid down in a flowchart that maps all the production steps and the flow of products between these steps, both within the factory and in the supply chain. Each step and each transfer come with their own contamination risk. Smartly rearranging the assembly scheme can help to reduce the overall risk.

Coating and cleaning

On behalf of total solution provider Settels Savenije, manufacturing engineer Jasper Smit and cleanliness engineer Thom Bijsterbosch gave a presentation on functional coatings, which are applied on high-tech products to modify, for example, their optical properties. Under the Dutch motto "Coaten is klote" (Coating is shit), they discussed the manufacturing and cleanliness challenges of coatings, or as they phrased it: "To obtain perfect layers, you have to send a lot of prayers."

Smit and Bijsterbosch presented an overview of the various steps in the coating process, pointing out that in every step things can go wrong, often in relation to the cleanliness of the product to be coated. When a product is not clean, a coating will not adhere to its surface optimally, while a non-perfect coating may generate particle contamination. "And don't forget about handling and transport."

So, coating is a critical manufacturing step, but in product development it is often treated as a black-box process, or only briefly addressed at the last minute. To prevent potential coating issues, thinking about coating and cleanliness should be integrated in the well-known V-model from the start, in the project initialisation phase, Smit and Bijsterbosch argued.
In conclusion, they presented a few cases to demonstrate that design-for-coating and design-for-cleanliness have a lot in common. This includes designing smooth surfaces and edges, incorporating flushing and venting holes for product cleaning, and reducing the number of contamination-sensitive features such as threaded holes. For example, a leafspring block turned out to be difficult to clean and coat due to sharp edges, deep holes and narrow gaps, and was therefore redesigned.

Following the success of this DSPE Knowledge Day, for next year an edition is planned that will be dedicated to molecular contamination control.

The Omneo Particle Deposition Monitor (PDM) measures and collects comprehensive particle deposition data at process-critical positions in production environments. Particle level and type are essential information for effective surface cleanliness management.

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IF YOU CAN'T STAND THE HEAT

Strictly speaking, the SMART project is not Big Science, but the collaboration of over 25 research institutes and high-tech companies working on a revolutionary technology for the production of radioisotope ^{99}Mo is definitely impressive. The technology comprises a large electron accelerator and huge irradiation and extraction facilities. At the heart of the system is a matchbox-sized target that is irradiated by a 3-MW electron beam. Alongside the radiative load on the target and exposure unit, the heat load on the target is among the key challenges of the SMART project. Demcon is developing an 'exotic' solution: cooling with liquid sodium.

PATRICK DE BRUIJCKER AND JOHANNES JOBST

AUTHORS' NOTE

Patrick de Bruijcker and Johannes Jobst are both senior mechatronic system engineer at SMART project partner Demcon, a developer and supplier of high-end products and systems with locations in Best, Delft and Enschede (NL), amongst others.

www.demcon.com
www.ire.eu/en/our-activity/ire/smart

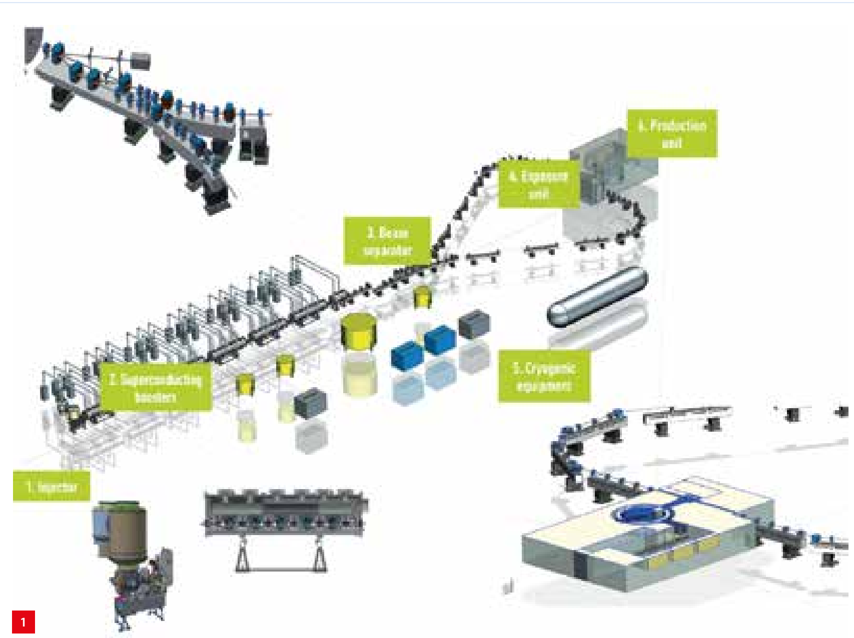
Introduction

In the past decades, driven by Moore's Law, ASML investigated several options for short-wavelength light sources for its lithography systems, ultimately leading to EUV. One of the alternative options that was discarded along the way was a free-electron laser, the origin of which was a high-energy electron beam. In 2015, ASML realised that this option could be adapted to produce the radio-isotope molybdenum-99 (^{99}Mo).

ASML decided to continue development of this so-called LightHouse principle externally. To that end, they engaged in a partnership with IRE (Institute of Radio Elements), headquartered in Fleurus (Belgium). IRE, world leader in the production of radioisotopes used for diagnosis and therapy, is one of the producers of ^{99}Mo, the most widely used radioisotope for diagnosis in nuclear medicine.

The ^{99}Mo isotope is produced in a nuclear reactor by irradiating enriched uranium. Worldwide, IRE is the largest of four suppliers of medical radioisotopes. It does not operate a reactor of its own, but relies on several reactors in Europe. The ^{99}Mo produced there is extracted by IRE and then supplied to hospitals. When the ^{99}Mo arrives in the hospital, it has partly decayed into the short-lived technetium-99m, the element that is administered to patients before a scan is made.

Production in a nuclear reactor is not a sustainable model. The reactors that are used currently for this purpose are nearing their end-of-life, which makes operation unreliable and hence jeopardises the reliability of supply, as no buffer stock can be created due to the rapid decay of ^{99}Mo. In addition, the uranium used in these reactors poses huge safety and waste problems.



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The LightHouse concept. Electrons are injected (1) into the accelerator that is provided with superconducting boosters (2). The electron beam is accelerated to 75 MeV and then split into two beams (3) that irradiate a target from both sides in the exposure unit (4). The superconducting boosters are cooled with cryogenic equipment (5), while the target is cooled with liquid sodium (not shown). In the production (harvesting) unit (6), the intended product, ^{99}Mo, is harvested from the target after irradiation. (Source: SMART)

LightHouse concept

In the LightHouse concept (Figure 1), ^{99}Mo is produced by irradiating the non-radioactive ^{100}Mo with an intense electron beam. Compared to nuclear production, this alternative is, in principle, reliable and cheaper, requires no radioactive uranium and produces hardly any waste. In addition, the technique is capable of producing quantities comparable to those produced by a nuclear reactor. Electron accelerators are already used to produce small quantities of low-specific-activity ^{99}Mo, but this does not meet the specifications for large-scale production of ^{99}Mo for nuclear medicine. That requires a superconducting, high-power linear electron accelerator. The electron beam it produces is split into two to expose a target composed of ^{100}Mo-enriched molybdenum from both sides, to achieve a relatively uniform activation profile. The high-energy electrons are stopped in the target, which produces *Bremsstrahlung* (high-energy gamma rays) that transforms the ^{100}Mo into ^{99}Mo. After irradiation, the ^{99}Mo is harvested from the target.

The LightHouse concept poses big physical and technical challenges. Therefore, financially supported by the Belgian authorities, IRE, with the technical support of ASML, integrated the LightHouse technology in the SMART project (Source of MedicAl RadioisoTopes), in which over 25 research institutes and high-tech companies participate. The various production components of the future LightHouse facility are developed by specialists. Research Instruments, based in Bergisch Gladbach (Germany), is an expert in the field of particle accelerators, while Demcon is developing the exposure unit, including the target, and the harvesting unit.

Target design

Cooling

One of the major project assignments was awarded to Demcon: developing a target that could survive the 3-MW heat load caused by the electrons. This is indeed a challenge, because the target is the size of a matchbox (the reason for this size will be explained below). The heat load, equivalent to the heat produced by three Formula-1 cars, requires massive cooling. Since only a small part of the power is used to create the ^{99}Mo, 2 MW of heat is generated in the target and 1 MW is lost in adjacent components of the exposure unit. Hence, both need to be cooled very efficiently. For cooling, liquid sodium was selected as the coolant, because sodium has a relatively low melting point and a high specific heat capacity. However, it is flammable and chemically aggressive, which makes it difficult to handle.

Modular

The design of the target is modular, based on the irradiation and harvesting procedures; each time highly irradiated parts (modules) of the target are harvested, the medium irradiated parts are rearranged within the target and fresh ^{100}Mo-containing parts are added. For confidentiality reasons, no further details can be shared.

Simulation

Extensive simulations were performed to verify the concept and investigate whether the target and the surrounding structures could survive the irradiation and the liquid sodium cooling. Experiments were conducted with a sodium-cooling test circuit to verify the simulations, and a 1:1,000 version of the SMART factory was built. Particular simulation problems included calculating the local heat load in the target and the complex target geometry, which led to high flow velocities and extreme pressure differences.

Materials

Material selection for the structural parts around the target was another issue. Insufficient data were available for the extreme heat and irradiation conditions; hence feasibility studies were performed with the most critical parts. For the target material itself there was no choice: it had to be ^{100}Mo. Unfortunately, little information was available. Concerning radiation damage, both embrittlement and swelling (components getting bigger, which is highly undesirable in complex machinery) are a problem. To gain insight into these matters, a visit was paid to the European Spallation Source, the Big Science facility based in Sweden that operates the world's most powerful neutron source.

Size

Determining the optimum target size was a trade-off between power density and the competition between ^{99}Mo activation and decay. A low power density is preferred to keep the accelerator and target manageable, while on the other hand a high electron current density is needed to achieve sufficient activation. The cross-section of the target was optimised to an area just under 10 cm^2 and its depth is related to the penetration depth of electrons in this specific target, which is in the order of centimeters. Hence, the 'matchbox'. If the target is too small, it will cook and evaporate under the heat load. If it is made larger, the yield will be lower, given the beam energy and current.

Exposure unit

The exposure unit is housed in a vacuum vessel. The target is surrounded by components designed to extract the 1 MW that is not absorbed by the target. A so-called power dump acting as a first layer around the target absorbs the high-energy radiation, while concrete shielding outside the vacuum vessel protects humans and machines against the 'low'-energy scattered radiation and the produced neutrons. As the extreme conditions will undoubtedly lead to damage, easy replacement of parts was one of the demands.

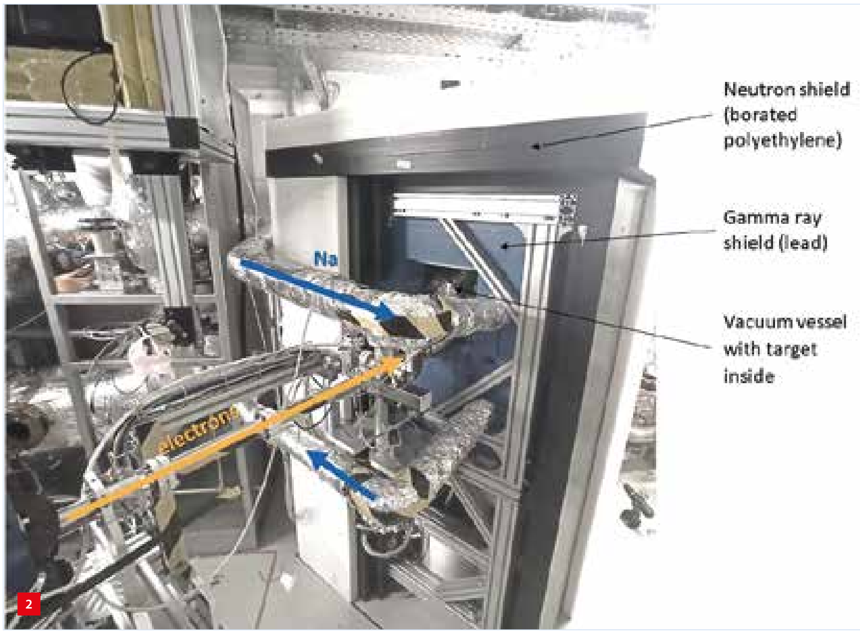
Harvesting unit

Demcon also elaborated the design of the harvesting unit, where the ^{99}Mo is extracted from the exposure unit and harvested, and substantiated this with analysis of test set-ups and tests on specific parts. Here, the radiation intensity is orders of magnitude lower, but components such as motors and sensors are highly sensitive to radiation damage. Therefore, the biggest design challenge was the 24/7 long-term reliability of the SMART factory.

A fast extraction procedure was required to minimise the loss of activated material due to natural decay. After irradiation for 23 h, extraction should be performed within 1 h. Accuracy for target positioning is in the range of 0.1 mm, which is relatively very precise, as the manipulation unit has a size in the order of several meters. Manipulation is fully automated; only the chemical processing of the harvested parts is performed manually, by an operator using a telemanipulator.

Outlook

Using the 1:1,000 miniature version of the SMART exposure unit (Figure 2), running with full power density, the first short-run test (several seconds) was done this year. This is proof of the thermal feasibility of the cooling concept. Later this year, Demcon plans a long exposure run to validate the structural integrity of the target including the long-term effects of exposure to radiation and liquid metal, after which development & engineering will be completed next year. In 2028, the revolutionary nuclear medicine production technology is scheduled to hit the market.



The 1:1,000 miniature version of the SMART exposure cell. It was installed at the ELBE electron accelerator at HZDR Dresden-Rossendorf (one of Germany's Big Science facilities). Power density, Na cooling and target materials are representative of the SMART target.

TURBO, SPINDLE, WAFER

The boundaries of gas-bearing applications are being stretched again and again. This was the main message from the fourth Gas Bearing Workshop, a Dutch-German collaboration that was organised last month. One of the focus areas was high-speed rotational bearings, especially for turbomachinery, where precision is not the primary goal. Of course, precision applications were still a common thread in most presentations, for example on low-speed spindles. A solar-wafer transport application was also presented.

JOS GUNSING

Introduction

In 2015, the first Gas Bearing Workshop was organised as a collaboration between DSPE, VDE GMM and the Bond voor Materialenkennis, and it has been a biennial event ever since. This year's workshop had to be postponed by eight months, but to no regret; thanks to the speakers and the audience, the fourth edition on 15 November 2021 in Düsseldorf (Germany) was a success.

Programme

- Opening words:
  Wolfram Runge, Beuth Hochschule für Technik, Berlin (DE);
- Keynote: Gas bearing supported small-scale turbomachinery – recent advancements,
  Jürg Schiffmann, EPFL, Lausanne (CH);
- Gas bearing applications for production equipment in semiconductor and solar industries,
  Jaap Beijersbergen, Levitech, Almere (NL);
- Active shape control in aerodynamic air foil bearing,
  Hossein Sadri, SADAP, formerly TU Braunschweig (DE);
- Experiences gained in air bearing design,
  Johan Jacobs, Simex-Technology, Eindhoven (NL);
- Keynote: Addressing diverse precision manufacturing challenges through airbearing design,
  Byron Knapp, Professional Instruments, Hopkins (MN, USA);
- Design, manufacture and test methods of gas bearings for ultra-low shaft errors in motion even at higher speeds,
  Ralf Dupont, Levicron, Kaiserslautern (DE);
- Design challenges in high-speed turbo compressors with herringbone gas bearings,
  Christof Zwyssig, Celeroton, Volketswil (CH);
- Tilting pad bearings; world record high speed,
  Marius Nabuurs, NabTech, Eindhoven (NL);
- High speed small turbomachinery gas bearing performances experimental investigation,
  Kostandin Gjika, Garrett Motion, Épinal (FR); Wanhui Liu and Jürg Schiffmann, EPFL (CH).

WWW.GAS-BEARING-WORKSHOP.COM

The chair for the day, Wolfram Runge, gave a short overview of what the topics had been for the previous three workshops. The first edition was characterised by classical precision engineering, with a focus on components and quasi-static operation. The second edition included new non-precision applications like web transport or floating parts, while standardisation was a discussion item for an expert panel. The third edition, and the 2021 edition reviewed here, established a further focus: high-speed rotational bearings, especially for turbomachinery. Here precision is not the primary goal; rather, the main drivers come from tribological challenges. Of course, precision applications have been a common thread throughout all the workshops.

The presentations were roughly categorised into: applied research; new technologies and components; design guidelines, methods and pitfalls; and special applications.

Applied research

Jürg Schiffmann's applied research at EPFL concentrates on small-size high-speed turbomachinery for applications such as heat-pump compressors, fuel-cell compressors, turbo-expanders for waste heat recovery in trucks, and also for turbochargers for the automotive industry.

Due to the fact that for all these applications, the combination of controlled lifetime, robustness of operation and low product cost is important, quite some research is being put into further fundamental understanding and control of the properties of the high-speed bearings inside. Schiffmann also emphasised that making more efficient use of the current concepts has enormous energy-saving potential.

Herringbone gas bearings offer good opportunities for application in high-speed turbomachinery, but with respect to shaft rigidity, the alignment sensitivity of the bearing bushing must be dealt with, while several aspects have not yet been well described in literature, such as:

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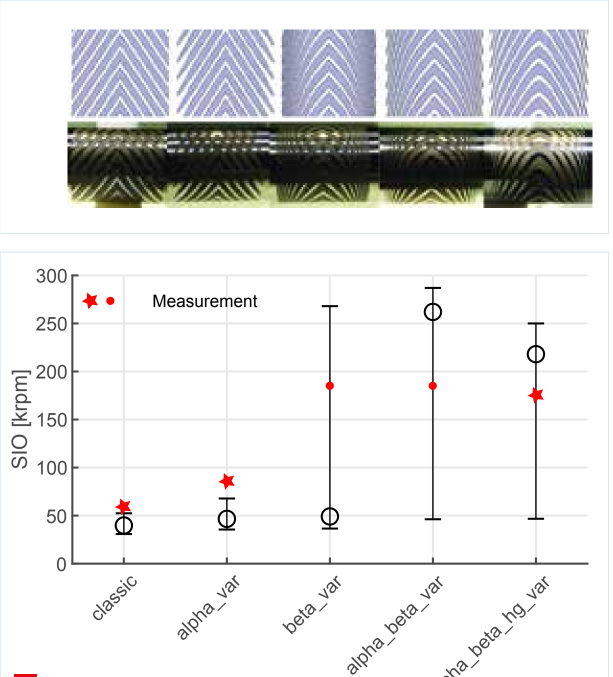

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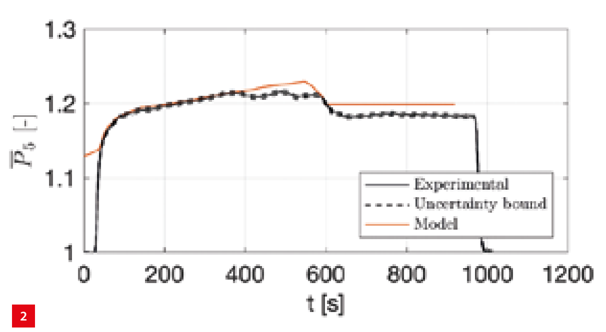
Experimental results concerning the speed of instability onset (SIO) in relation to herringbone bearing groove patterns. (Copyright ASME, Journal of Tribology [1])

- Optimisations of groove patterns in herringbone dynamic air bearings.
- Real gas effects:
  - Condensation; operation close to saturation depending on temperature, pressure and humidity:
    + 1- and 2-phase operation;
    + effects on load-carrying capacity and friction losses.
  - Effects of turbulence under higher pressures.
- Effect of bushing compliance on herringbone bearing operation.

Schiffmann dedicates a lot of effort at EPFL to researching the various phenomena.



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Drop in load-carrying capacity when going from dual- to single-phase fluid behaviour due to the disappearing condensation effect when the temperature rises. P_5 is (indirectly) related to the load-carrying capacity. (Copyright ASME, Journal of Tribology [2])

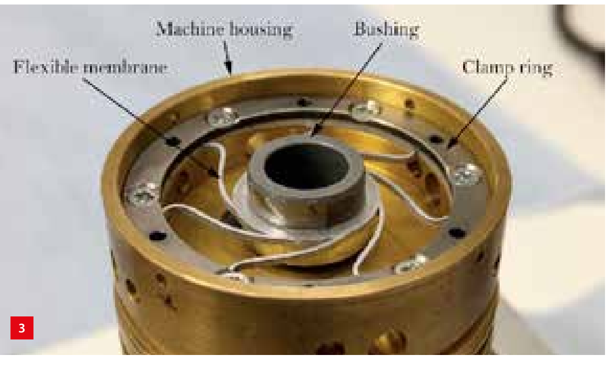
- Optimisations of groove patterns in herringbone bearing grooves:
  - Optimised patterns tested on the same rotor with the same bearing clearance.
  - Enhanced groove patterns allow for increased rotor speed as compared to classical grooves.
  - New patterns allow for a 50% increase in clearance.

  Results of modelled and tested groove patterns are shown in the graphs in Figure 1.

- Real gas effects:
  Schiffmann also described extensively his investigations into the effects of condensation, both in single- and dual-phase operation. There is very little to be found on this area in current literature; most research deals with more-or-less ideal gas behaviour. Along with this, his modelling and experimental research also covers bearing behaviour under (partially) turbulent conditions (Figure 2).

- Effect of bushing compliance on herringbone bearing operation:
  Herringbone bearings require very small clearances (5-10 µm for ø10 mm) to ensure stable operation and sufficient load capacity; hence the size and alignment tolerances cause high manufacturing cost. This requires research into the potential of flexible bushing support and modification of fluid-film behaviour.

  After some research and development, the concept of tuneable membranes for bearing bush support came up (Figure 3). During experiments with four probes (discerning tilting and translation; Figure 4) on the bearing bushing, an unstable bushing tilting mode was identified coupled to the flexible support bushing. The mechanism behind this phenomenon is:
  - The underlying mechanism is cross-coupled fluid-film behaviour in tilting.
  - Bearing bushing inertia on tilting springs experiences destabilising forces from fluid-film impedance.



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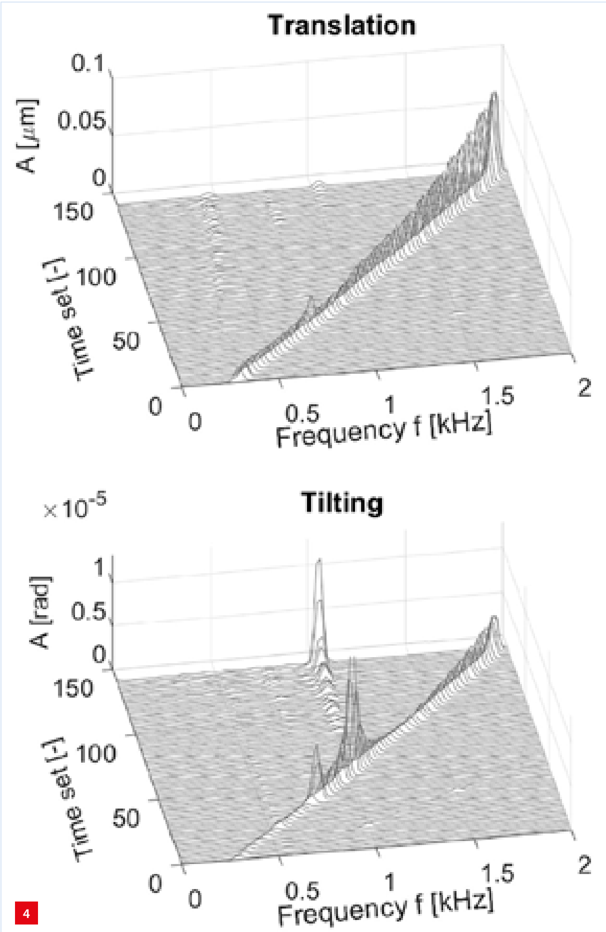
Tuneable flexible membrane bearing bushing. (Copyright Elsevier [3])



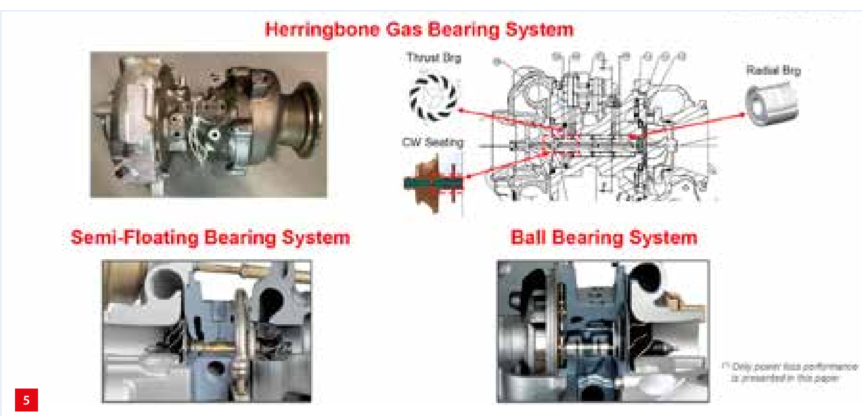
Dynamic translation and tilting of herringbone bearing bushing on a tuneable flexible membrane. (Copyright Elsevier [3])

Power-loss test rig: measurement principle and set-up.

Power loss in high-speed small turbomachinery
Kostandin Gjika presented an interesting experimental study on the power loss of different types of bearing systems applied to high-speed turbochargers, such as:

- semi-floating oil-bearing system;
- herringbone aerodynamic bearing;
- ball bearing.

All are shown in Figure 5.



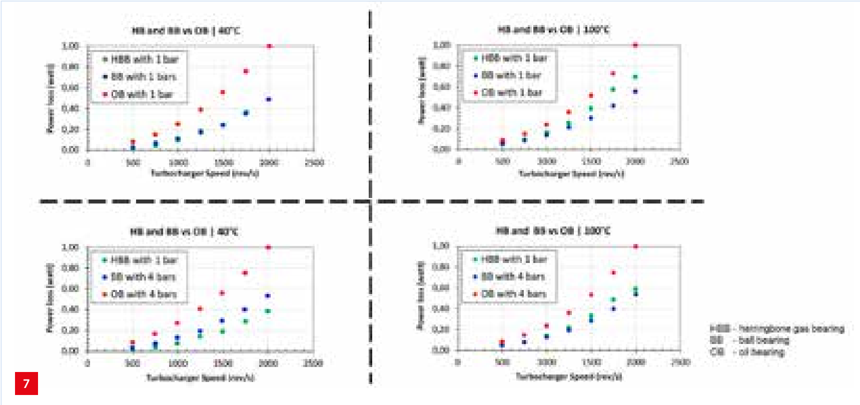
The different bearing types applied in a small high-speed turbocharger.

The total power loss of turbochargers has been measured on a dedicated Garrett test bench that has been upgraded for the design of the herringbone gas bearing (Figure 6). Extensive testing was carried out under steady-state operating conditions with inlet fluid temperature (oil or air) of 40 °C and 100 °C. The inlet fluid pressure was chosen based on the actual operating conditions of the bearing designs. The herringbone gas bearing has been tested with a gas-bearing air-inlet pressure of 1 bar, and the oil bearing and ball bearing as per their extreme oil inlet pressures of 1 bar and 4 bar.

The power loss of the oil- and ball-bearing turbochargers is compared with the power loss of the herringbone gas-bearing turbocharger at the operating speed range up to 2000 rev/s. Figure 7 summarises the dimensionless power-loss test data. It shows that:

- The increase in the air inlet temperature increases the power loss of the herringbone gas bearing because the viscosity of the air increases.
- The increase in the air inlet temperature decreases the power loss of the oil bearing and the ball bearing because the viscosity of the oil decreases.
- For the fluid inlet temperature of 40 °C:
  - The power loss of the herringbone gas bearing is equal to that of the ball bearing, but two times less than that of the oil bearing for an inlet pressure of 1 bar.
  - The power loss of the herringbone gas bearing is 28% less than that of the ball bearing and 60% less than that of the oil bearing for an inlet pressure of 4 bar.
- For the fluid inlet temperature of 100 °C:
  - The power loss of the herringbone gas bearing is 30% less than that of the oil bearing, but 25% greater than that of the ball bearing for an oil inlet pressure of 1 bar.
  - The power loss of the herringbone gas bearing is 40% less than that of the oil bearing, but 9% greater than that of the ball bearing for an oil inlet pressure of 4 bar.

Herringbone gas-bearing technology appears to be a competitive design.



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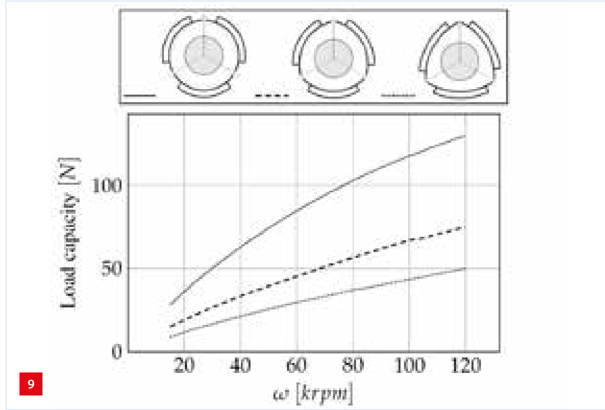
Dimensionless power-loss test data for turbochargers with semi-floating oil bearing, ball bearing or herringbone gas bearing; the pressures are the gas-bearing air-inlet or oil pressures.



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Effect of shape control on load capacity as a function of speed.

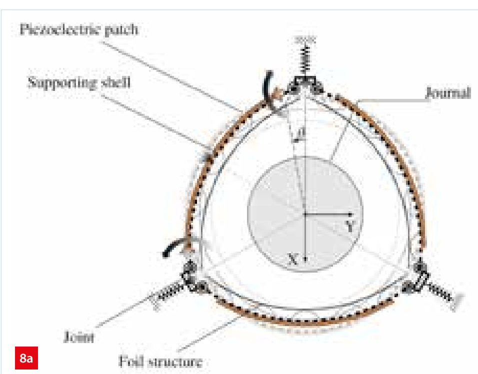
Next step of the study: to develop and test an air-foil bearing turbocharger for shaft motion, power loss and lift-off speed; thus extending the comparison of turbocharger bearing types.

New technologies and components

Hossein Sadri of SADAP took us on an enthusiastic journey on the development of active shape control of the bore geometry in aerodynamic foil bearings, which is on the edge of applied research and new component development. Active foil bearings will potentially be able to control lift-off capacity, load capacity and hydrodynamic preload (thus stiffness), and thus improve static and dynamic properties (Figures 8 and 9).

The foil bearing will be equipped with piezo-actuated elements in order to control the foil shape (conformity with respect to the shaft radius). Flexure joints are applied to avoid backlash effects.

It can be concluded that static and dynamic properties can be adapted/improved by way of active shape control. Subsynchronous motions can be reduced heavily (Figure 10), while increasing damping at higher rotational speeds.



8a

8b

Piezo-activated shape control of aerodynamic foil bearing shape.
(a) Concept overview.
(b) Realised design.

Marius Nabuurs of Nabtech took another route on improving the aerodynamic gas-bearing properties by applying tilting pad bearings. He redesigned a tilting pad journal bearing such that it can be produced more easily with improved properties. His bearing consists of a bearing bush holding three integrated pads supported on leaf-springs. The preload on the springs can be adjusted with a screw (Figures 11 and 12).

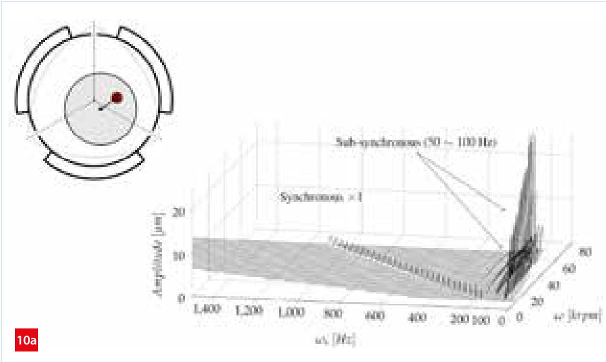
According to Nabuurs, experimental validation with the help of a dedicated test rig (Figure 13) showed that a number of properties can be influenced/improved, including load capacity, dynamic stability, thermal stability, position accuracy, power loss, imbalance response, shock impact/acceleration, instability speed onset, and dynamic stability.

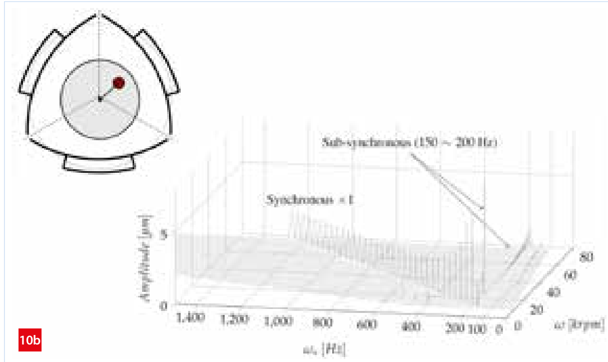
Nabuurs claimed a world record for his off-the-shelf adjustable tilting pad aerodynamic bearing, with 365,000 rpm for a 16-mm diameter journal gas bearing ($D{\cdot}n$: $5.85{\cdot}10^6$), where surface speeds are over 300 m/s (close to the speed of sound).

Design guidelines, methods and pitfalls

Johan Jacobs of Simex-Technology started with his history of air-bearing design at Philips, where many gas bearings were developed for all sorts of applications, even for mass-production applications such as the spiral groove bearing. Among other things, he worked on designs for a conical bearing for a particle foil trap in ASML's EUV beam equipment, a contactless wafer movement for atomic layer deposition (SoLayTec), and spherical bearings (Kugler). An example of his work is shown in Figure 14, which deals with increased stiffness and manufacturability for a thrust bearing with surface restrictors. This bearing has been applied in a high-speed turning spindle for manufacturing non-spherical optical elements.

What was very interesting in his lecture was the description/overview of the guidelines for design (loops) plus the pitfalls.

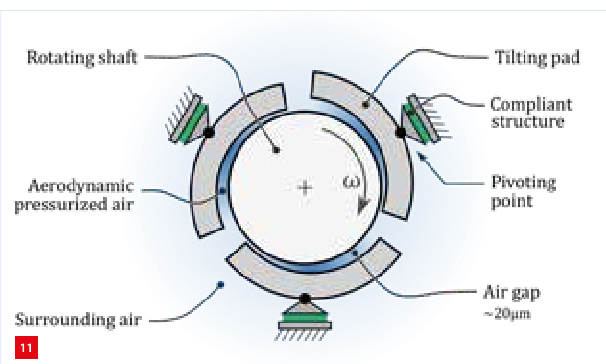




Effects of shape control on synchronous and subsynchronous motion of a shaft centre, with shape-control-reduced amplitude for non-synchronous movements over the whole frequency range.
(a) 50 ~ 100 Hz.
(b) 150 ~ 200 Hz.

Design loop:
- Determine load capacity, axial and tilt stiffness plus airflow:
  - Firstly, an estimation with basic formulas.
  - Secondly, optimisation with e.g. FEM/Ansys.
- Check airgap budget:
  - Geometrical variations: manufacturing size, shape and roughness specifications/tolerances.
  - Deformations: mechanical and thermal.
  - Boundary conditions: supply pressure and preload variations.
- Check stability (bearings with pockets).
- Choose the right material and coatings.

Pitfalls:
- Unnecessary use of gas bearings.
- Burrs/chamfers restrictors.
- Too-large pocket size, leading to unstable bearing and pneumatic hammer effect.
- Too-high pressure drop in supply lines outside/inside bearing.
- Unstable pre-load.
- Underestimation of mechanical deformation of bearing parts and support.
- Contamination caused by gas supply.

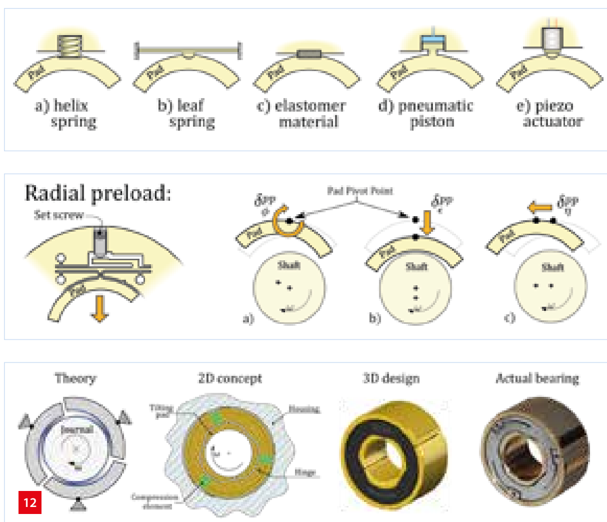


Concept of a tilting pad journal bearing with tilting pads and radial and pivoting compliance.

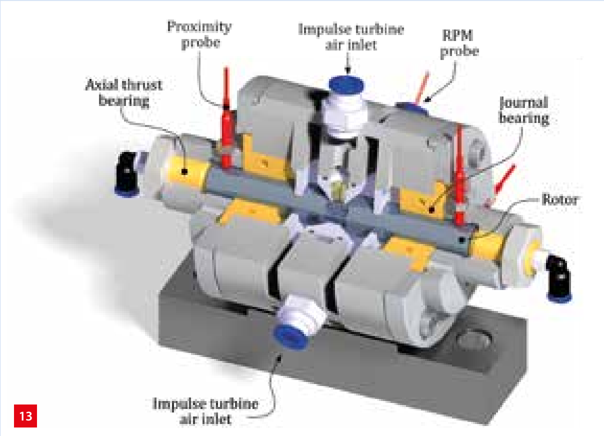
- Bearing stability in vacuum differing completely from that in atmospheric applications.

Ralf Dupont of Levicron in his presentation discussed several design concepts for a high-speed spindle, concerning among other things thrust-bearing position on the spindle shaft (front, mid and rear position), and the effects of tool holders both from a dynamic stability and a thermal perspective. In this report, the focus is on his work on thermal aspects.

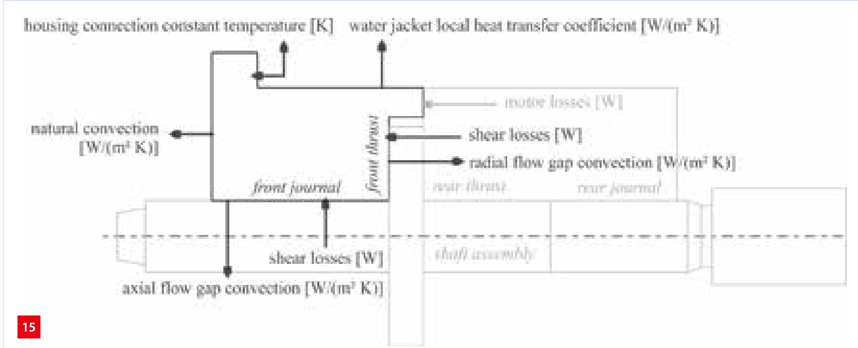
Dupont started by describing heat sources and dissipation (Figure 15). By way of integrating thin-film cooling, detached heat sources (bearings, motor), a symmetrical spindle shaft design and axial dilatation compensated by centrifugal shaft shortening, he succeeded in controlling the thermal aspects, including the time needed to reach equilibrium ('soak time'; see Figure 16).



Radial and pivoting compliance, from concept to bearing design. (Upper two rows: copyright KU Leuven)



Test rig for static and dynamic measurements up to extreme high speeds.



Heat sources in high-speed spindles.

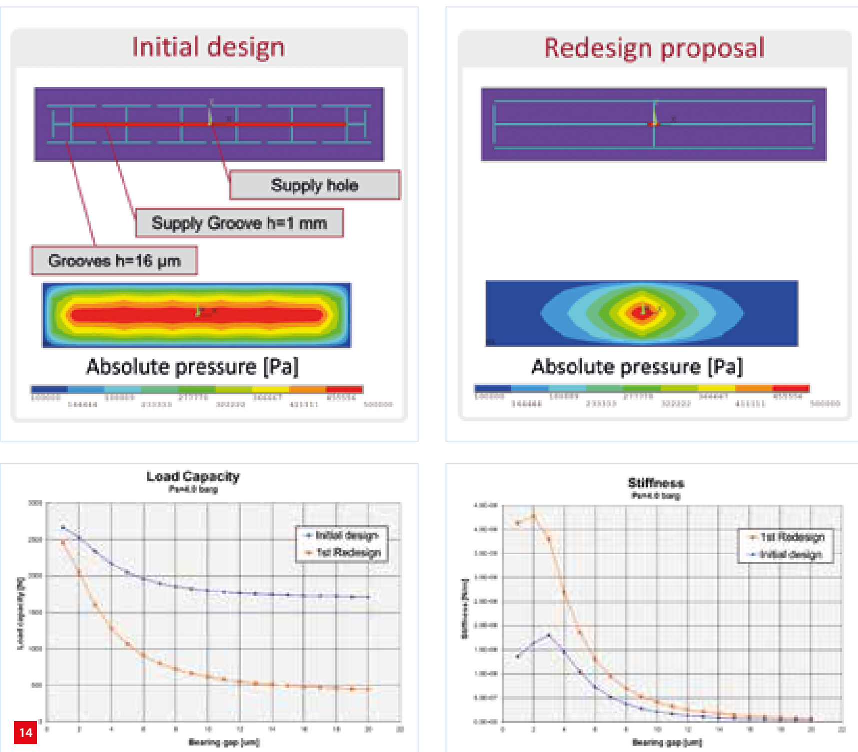
Bearings under shock load
Christof Zwyssig brought an extra dimension to dynamic loads on gas bearings; his case dealt with up to 20-g shock loads in high-speed compressors in mobile and automotive applications, specifically in vehicle fuel cells systems (Figure 17).

The application of herringbone gas bearings offers advantages in oil- and wear-free operation, robustness, and energy savings, provided that shock loads (acceleration capability; see Figure 18) can also be absorbed under all combinations of conditions. For example, high shock loads (a typical requirement is 10 g up to 400 times during 11 ms at low (–20 °C at cold start) or high gas temperature (up to 150 °C at steady-state bearing temperatures)), under a variety of pressures (e.g. operation at 0.7 bara in high altitude). These conditions are typical for high-speed vehicle turbo compressors.

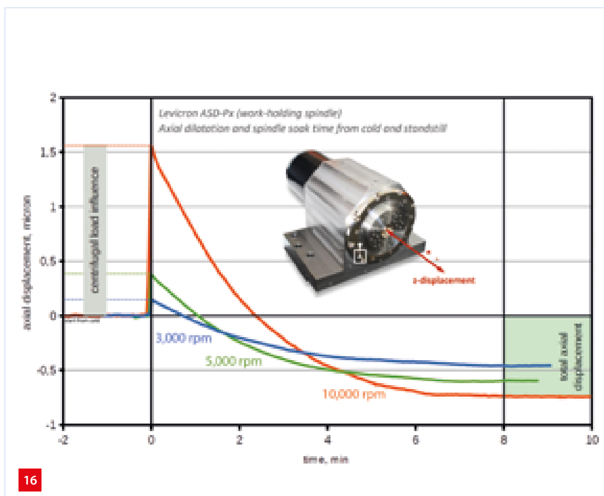
Based on simulation models, Zwyssig described how the axial and radial shock acceleration capability can be determined under a variety of temperature and pressure conditions (of both process and environment). Figure 19 shows the combined axial and radial load acceleration capability, where the orange area is a region of potential damage due to shocks exceeding 5 g acceleration.

Special applications

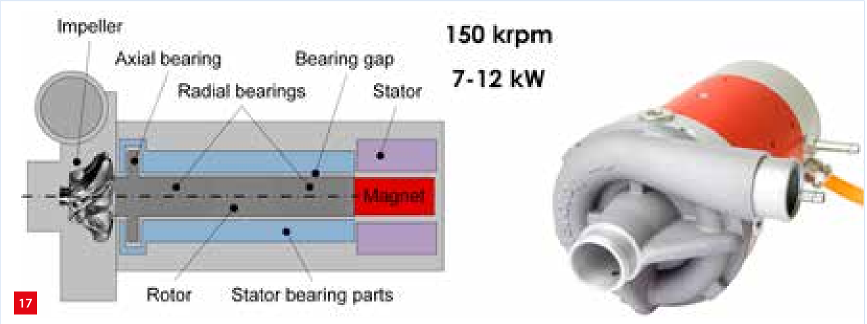
Working for Professional Instruments, a company with a rich history in ultraprecision machining, Byron Knapp addressed manufacturing challenges that can be solved through air-bearing design. One example was diamond turning of, e.g., freeform optics, for which he replaced bronze journal bearings with porous graphite sleeves to overcome concerns on the durability of air bearings especially in frequent start-stop operation. In this report, a special application for metrology purposes is picked out.



Results (load capacity and stiffness versus bearing gap) of a redesign towards higher stiffness of a thrust bearing, for better bearing manufacturability (and, hence, better manufacturing performance of a turning machine with the bearing inside).



Results (axial displacement over time, at various speeds) from a thermally healthy high-speed spindle design.

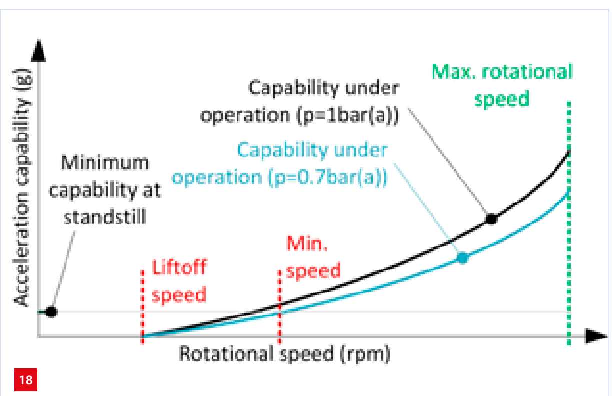


High-speed compressor for vehicle fuel-cell application.

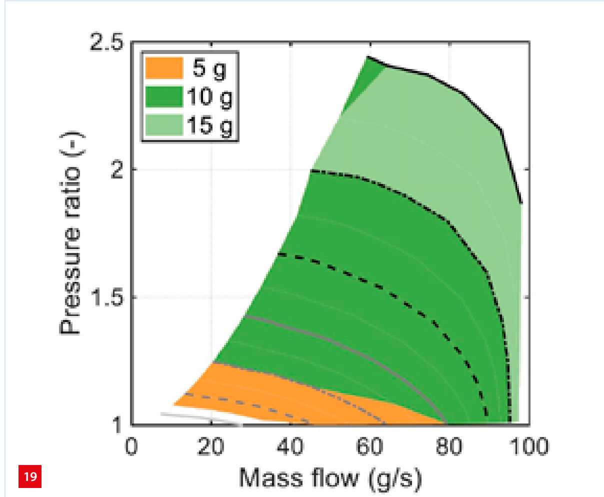
A rotary metrology application required a spindle (Figure 20) with low error motion (both the synchronous/repetitive error and especially the non-synchronous/non-repetitive errors in radial as well as axial direction). Spindle metrology could be used for feedback to refine the bearing compensation. Special attention had to be paid to the thermal effects at the required low speeds of approximately 0.3 rpm.

Extensive testing showed the following results (Figure 21):
- The standard design shows 6 nm synchronous and 1.4 nm asynchronous run-out at 0.35 rpm.
- Below 500 rpm, 0.5 nm high-frequency errors are observed, caused by air distribution axial grooves on the thrust-bearing surface.
- Axial supply grooves in the thrust bearing boost the stiffness and load capacity, but can be removed in this application to provide smooth motion.

Jaap Beijersbergen of Levitech took the opportunity to present two different concepts for keeping wafers floating in processes for semicon and solar applications. The semicon process is especially for heat treatment and coating processes, such as annealing oxidation, nitridisation and silicide formation. The concept of a floating wafer has been developed to enable rapid temperature increase and cooling of the wafer while keeping the temperature distribution even for reasons of shape control and avoiding cracks.



Qualitative acceleration capability (shock-absorbing capability) of a herringbone gas bearing under different rotational speeds.



Compressor diagram including allowed acceleration/shock at different operational points for defined operating conditions; in this case: –20 °C cold start at sea level (1 bara).

A furnace containing a single wafer is applied, then the wafer is transferred from a hot to a cool chamber, using the convection (constituting the larger part of the heat flow) of the helium bearing gas plus the additional radiation of the chamber walls and the wafer itself. Heating and cooling to and from temperatures of up to 1,200 °C are typically carried out within a few seconds with an air gap of 150 µm (Figure 22).

Another special process is the atomic layer deposition line for solar applications. In this process, solar wafers are passivated with aluminium oxide on the backside, using TMA (trimethylaluminium) in combination with H_2O (for the oxidation process) in a continuous flow.

The oxidation process has to be repeated several times to obtain a sufficiently thick layer of aluminium oxide, and thus several identical process chambers are placed in a row. The contactless solar wafer transport takes place by keeping the wafer floating on the gas film in combination with the use of gravity (Figure 23).

Spindle for metrology purposes with extreme demands on (non-)synchronous errors/(non-)repetitive run-out in axial and radial direction.

Wrap up

A lot of knowledge and insights were presented during the fourth Gas Bearing Workshop. It was obvious that the boundaries of gas-bearing applications are being stretched again and again. Along with this, potential new chapters (e.g. real gas behaviour such as condensation/saturation and also operation under shock load) are already maturing for the standard textbook *Air Bearings, Theory, Design and Applications* (Farid Al-Bender and co-authors, Wiley, 2021). In early spring 2023, the fifth edition of the Gas Bearing Workshop will be organised.

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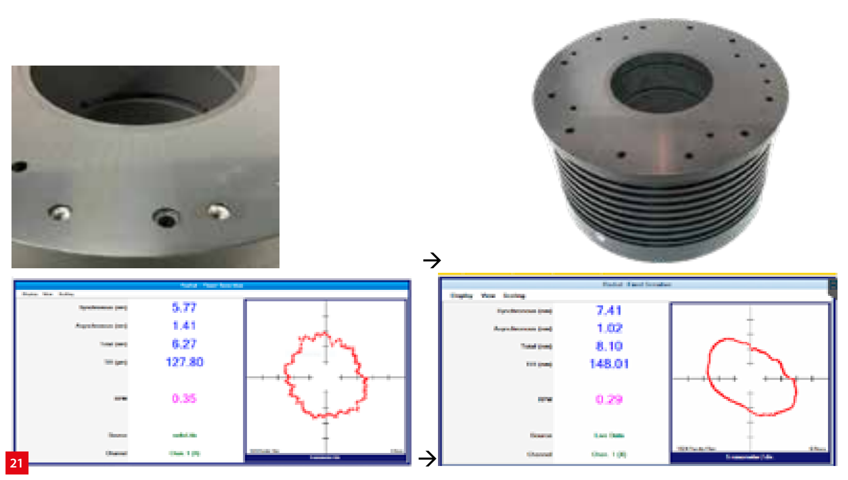
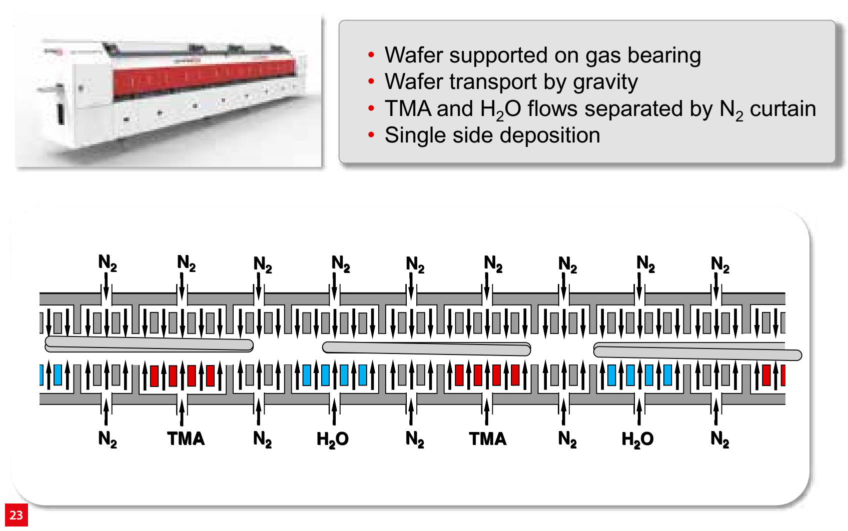
[2] Gueneat, E., and Schiffmann, J., "Thin Gas Film Isothermal Condensation in Aerodynamic Bearings", *Journal of Tribology*, vol. 141 (11), pp. 111701, 2019.

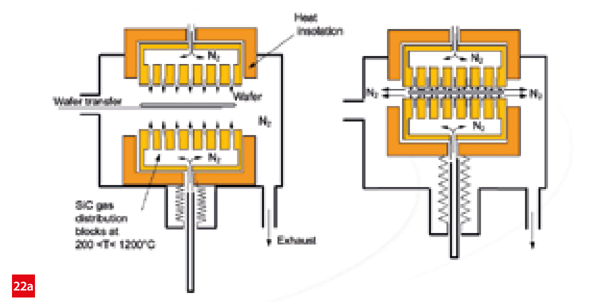
[3] Bättig, P., and Schiffmann, J., "Unstable tilting motion of flexibly supported gas bearing bushings", *Mechanical Systems and Signal Processing 162*, 2022,

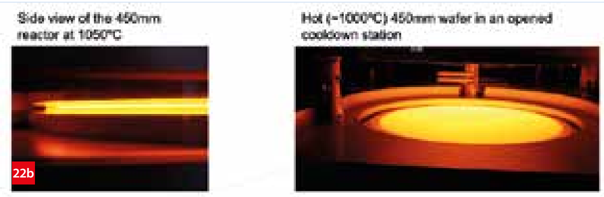


Test results for a thrust bearing: grooves (left) versus no grooves (right) yields 1 nm instead of 1.4 nm asynchronous error/non-repetitive run-out.



Continuous atomic layer deposition process.

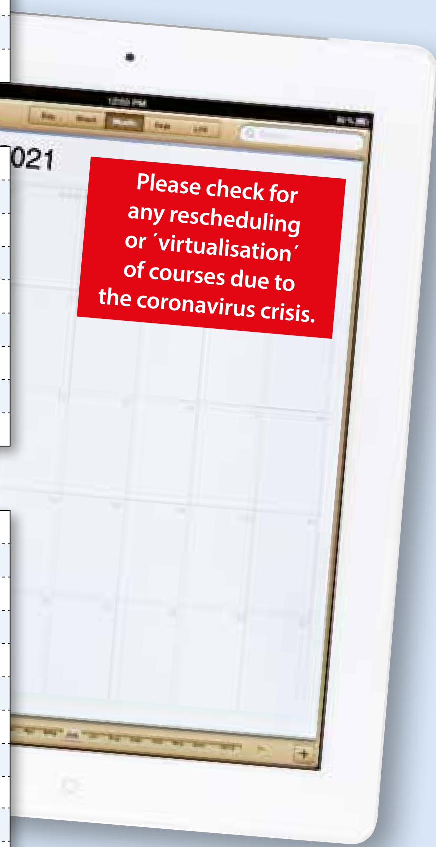




Floating-wafer hot process.
(a) Principle.
(b) A hot wafer in the process.

ECP² COURSE CALENDAR

COURSE (content partner)	ECP² points	Provider	Starting date
FOUNDATION			
Mechatronics System Design - part 1 (MA)	5	HTI	4 April 2022
Mechatronics System Design - part 2 (MA)	5	HTI	10 October 2022
Fundamentals of Metrology	4	NPL	to be planned
Design Principles	3	MC	9 March 2022
System Architecting (S&SA)	5	HTI	11 April 2022
Design Principles for Precision Engineering (MA)	5	HTI	20 June 2022
Motion Control Tuning (MA)	5	HTI	20 June 2022
ADVANCED			
Metrology and Calibration of Mechatronic Systems (MA)	3	HTI	22 March 2022
Surface Metrology; Instrumentation and Characterisation	3	HUD	to be planned
Actuation and Power Electronics (MA)	3	HTI	14 June 2022
Thermal Effects in Mechatronic Systems (MA)	3	HTI	to be planned (Q2 2022)
Dynamics and Modelling (MA)	3	HTI	to be planned
Manufacturability	5	LiS	31 January 2022
Green Belt Design for Six Sigma	4	HI	28 March 2022
RF1 Life Data Analysis and Reliability Testing	3	HI	14 March 2022
Ultra-Precision Manufacturing and Metrology	5	CRANF	to be planned
SPECIFIC			
Applied Optics (T2Prof)	6.5	HTI	to be planned (Q4 2022)
Advanced Optics	6.5	MC	24 February 2022
Machine Vision for Mechatronic Systems (MA)	2	HTI	upon request
Electronics for Non-Electronic Engineers – Analog (T2Prof)	6	HTI	to be planned
Electronics for Non-Electronic Engineers – Digital (T2Prof)	4	HTI	to be planned
Modern Optics for Optical Designers (T2Prof) - part 1	7.5	HTI	21 January 2022
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	28 January 2022
Tribology	4	MC	8 March 2022
Basics & Design Principles for Ultra-Clean Vacuum (MA)	4	HTI	20 June 2022
Experimental Techniques in Mechatronics (MA)	3	HTI	8 June 2022
Advanced Motion Control (MA)	5	HTI	21 March 2022
Advanced Feedforward & Learning Control (MA)	3	HTI	18 May 2022
Advanced Mechatronic System Design (MA)	6	HTI	to be planned (Q3 2022)
Passive Damping for High Tech Systems (MA)	3	HTI	to be planned
Finite Element Method	2	MC	3 March 2022
Design for Manufacturing (Schout DfM)	3	HTI	10 March 2022



ECP² program powered by euspen

The European Certified Precision Engineering Course Program (ECP²) has been developed to meet the demands in the market for continuous professional development and training of post-academic engineers (B.Sc. or M.Sc. with 2-10 years of work experience) within the fields of precision engineering and nanotechnology. They can earn certification points by following selected courses. Once participants have earned a total of 45 points, they will be certified. The ECP² certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP² title.

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First Dutch lab for extreme chip-assembly technology

The growing demand for computer chips is driven by the digital transformation of products and services. Recent chip shortages underline the importance of semiconductor supplies for the global economy. Delft University of Technology (TU Delft, NL) and the Dutch semiconductor equipment manufacturer ITEC (part of Nexperia) have launched X.AL, the first Dutch lab to research the next generation of green chip-assembly processes and equipment concepts. Following market trends and the requirement for sustainable technologies, new chip-assembly equipment must be faster, energy efficient and more compact.

"Mechanical limitations restrict the efficiency of today's chip assembly equipment", Marcel Tichem, associate professor in precision and microsystems engineering at TU Delft, and scientific leader of X.AL, comments. "A complex mechatronic machine needs to contact each individual chip before placing it. We will investigate contact-free methodologies in combination with extreme parallelisation of the assembly process."

The amount of chips in consumer products is rapidly growing; for example, LED screens comprise millions of chips. The next generation of chip-assembly machines must meet this growing demand for chips in a more efficient way. The team of TU Delft researchers, led by Marcel Tichem, Peter Steeneken and Massimo Mastrangeli, provides the knowledge and expertise to develop the breakthrough technologies for these new equipment concepts.

"Chips are assembled under very challenging conditions: extremely small chips must be picked-and-placed with great precision at a rate of 100 chips per second", Joep Stokkermans, innovation director of ITEC, located in Nijmegen (NL), adds. "Developing this technology requires a state-of-the-art lab, housing the latest technology as well as the most up-to-date knowledge of this technology. In the ITEC X.AL, we combine the expertise of TU Delft with the ITEC experience in semiconductor equipment and automation technologies. This allows us to realise the breakthroughs for a super-efficient chip-assembly process."

Tim van der Hagen, president of the board and rector magnificus of TU Delft, (left) and Marcel Vugts, general manager of ITEC, sign the agreement for X.AL.

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Dannis Brouwer (UT) recognised as ASPE fellow

At its annual meeting, last month in Minneapolis (MN, USA), the American Society for Precision Engineering (ASPE), recognised Dannis Brouwer, professor of Precision Engineering at the Universiteit of Twente (UT) in Enschede (NL), as a member of the ASPE College of Fellows. Election to the ASPE College of Fellows is an honour that is intended to recognise and honour those exceptional members of the society who have made outstanding contributions to the art and practice of precision engineering through original research, significant innovations, education and outreach, or service to the profession.

Dannis Brouwer received an M.Sc. degree in mechanical engineering, in 1998, and a post-master (PDEng) degree in mechatronic design in 2001 from Eindhoven University of Technology. In 2007, he received the doctoral degree in mechanical engineering from the UT. He has eight years of industrial experience with the Philips Centre for Manufacturing Technologies (CFT), Eindhoven (NL), and Demcon in Enschede (NL). He was appointed full professor at the UT in 2020 and is now chairing the Precision Engineering lab focusing on precision motion of mechatronic and robotic systems. His research focus is on flexure mechanisms, kinematics, macro- and micro-manipulators, variable-impedance robotics and precision engineering. For three years, he has served as a director-at-large for ASPE.

Among a total of six ASPE fellows to date are also Theo Ruijl and Alexander Slocum, both recognised in 2020. Theo Ruijl, senior mechatronics system architect at MI-Partners in Veldhoven (NL), is recognised for contributions to ultraprecision machine design. His work addresses numerous areas including thermal effects, high-precision metrology systems, control systems, damping techniques and system architecture in an industrial setting.

Alexander Slocum, professor of Mechanical Engineering at the Massachusetts Institute of Technology in Cambridge (MA, USA), is recognised for developing, teaching, and applying precision engineering principles to machine design, medical devices, and energy systems. His work has resulted in several hundred patents and technical publications, textbooks, and several generations of engineers trained in the principles and practice of precision engineering.

Last month, Dannis Brouwer, professor of Precision Engineering at the UT, was recognised as a member of the ASPE College of Fellows. (Photo: UT)

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Nobleo Technology acquires Ruvu Robotics

Nobleo Technology, a rapidly growing engineering firm in the field of autonomously intelligent systems with 95 employees, located in Eindhoven (NL), will take over Ruvu Robotics, a specialist in mobile robotics from Best (NL), as of 1 January 2022. In this way, the engineering firm is further fulfilling its national and international growth ambition.

“It is our ambition to be a leader in the field of autonomous and intelligent systems”, Gerrit Dijkhoff, CEO of Nobleo Technology, explains. “Within our organisation we distinguish three pillars: autonomy, intelligent systems, and high-tech systems. With the acquisition of Ruvu Robotics, we are strengthening the autonomy pillar.” In this field, Nobleo focuses on the domains of industrial inspection and cleaning, agriculture and logistics. “Within these domains, our proposition is to replace the dirty, dull and dangerous work – our three D’s – with autonomous solutions”, COO Rob Hendrix adds. “Ruvu Robotics has a lot of experience within the logistics market”, founder Rokus Ottervanger declares. “With the acquisition, we are adding this experience to the Nobleo Technology palette.”

Nobleo Technology headquarters in Eindhoven (NL).

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Sonion Poland's mechanisation division joins IMS Holding

As of 1 Demcember 2021, the mechanisation division of Sonion Poland is part of the IMS Holding. As an independent company, it will operate under the name Precision Systems Engineering (PSE). Sonion is an international and leading manufacturer of components for hearing aids. IMS Holding, based in Almelo (NL), consists, apart from PSE, of Integrated Mechanization Solutions (IMS) and ESPS. IMS develops and supplies production lines for the production of small sensors, actuators and micro-optics used in the automotive, smart devices and medical industries. ESPS is an experienced specialist in the field of industrial robotics and automation.

PSE's team consists of 40 experienced engineers and has specialised in the development and manufacture of equipment for the production of high-accuracy components. Under the Sonion banner, the focus was on components for hearing aids. In the new situation, as part of the IMS Holding, PSE sees good opportunities to start exploring new markets and applications, says managing director Marek Zaleski: "We are thinking for example in the direction of medical devices and special sensors. When it comes to micro-components in small batches, we are prepared to take on any challenge, from process development through conceptual design to implementation. In this regard, our entry into IMS Holding brings a win-win situation, as we can complement each other in terms of expertise and have access to each other's design ideas."

WWW.IMS-NL.COM

International gravitational-wave laboratory opened in Maastricht

Last month, ETpathfinder was officially opened in Maastricht (NL), in the south of the Netherlands, near the Belgian and German borders. The state-of-the-art physics laboratory will serve as a testing ground for the development of technologies for future gravitational-wave detectors. ETpathfinder's arrival also strengthens the border region's position as a candidate location for the new European gravitational-wave detector, the Einstein Telescope.

ETpathfinder is currently under construction at Maastricht University, one of the driving forces behind ETpathfinder alongside Nikhef, the Dutch National Institute for Subatomic Physics. The project also involves several other European knowledge institutions. ETpathfinder is realised with support from Interreg Flanders-Netherlands, funded by the European Union.

Physicists look to the future with ETpathfinder. A new European gravitational-wave detector should be ready around the year 2035: the Einstein Telescope. The Einstein Telescope requires an investment of approximately 2 billion euros and will be around ten times more sensitive than current detectors. This should result in hundreds of thousands or even millions of observations of gravitational waves per year. However, such a significant increase in sensitivity is not possible using current technologies.

The required technologies and techniques will therefore first be developed and tested using ETpathfinder. This includes for example new cooling techniques, mirror coatings and lasers, which will be developed by collaborating knowledge institutions and high-tech companies. The resulting innovations are expected to find other uses in industry as well.

The facility itself will consist of a large, dust-free hall with a stable temperature: a cleanroom. Various kinds of laser interferometers, the type of instrument used to measure gravitational waves, can be set up inside the cleanroom over the next 20 to 30 years. These set-ups consist of several towers containing all kinds of equipment, and 'arms' consisting of vacuum tubes of 20 meters long. These arms are not long enough to measure gravitational waves, but the set-up suffices for the development and testing of different kinds of technologies and their interplay.

WWW.ETPATHFINDER.EU

A 3D render of ETpathfinder. (Image: Nikhef / Marco Kraan)

Jan van Eijk receives ASPE Lifetime Achievement Award

As a representative of the Dutch precision engineering community, Jan van Eijk has received the ASPE Lifetime Achievement Award for broad-reaching advances in precision mechatronics and for promoting the active sharing of these advances throughout the technical community. Van Eijk served on the board of directors of ASPE, the American Society for Precision Engineering, for several years, as well as on the council of ASPE's European counterpart, euspen. In 2012 he was awarded the euspen Lifetime Achievement Award, and in 2016 DSPE presented him the Martin van den Brink Award for his leading role in the architecting of high-technology systems.

As a pillar of the precision engineering community, he has contributed by initiating and heading innovative applied research activities and by active sharing of industrial expertise. This collaborative spirit was first realised in 1989 with the creation of an in-house mechatronics training programme for Philips engineers, where industrial trainers taught new engineers how to work in multidisciplinary teams and to employ each other's technical strengths in order to reach the best overall result. This course has by now educated some 2,500 engineers and established a solid foundation as other training programmes were created to cover the additional disciplines. Beginning in 2010, these training activities were continued outside of the Philips organisation by the establishment of Mechatronics Academy.

Van Eijk started his education at Delft University of Technology with an M.Sc. degree in mechanical engineering. Following this, he spent three years abroad working at universities in Pakistan and Sri Lanka as a UNESCO associate before returning to Delft (NL) to complete a doctoral programme that included a dissertation on the design of flexure mechanisms. He received a Ph.D. in mechanical engineering in 1985.

Prof. Dr. Ir. Van Eijk then worked for 22 years at Philips in their Philips Centre for Manufacturing Technologies (CFT). Dutch company Philips has been a birthplace of advances in science and technology since the early years of the twentieth century, acting as the knowledge base for mass-production technology in Philips. Research at the famous Physics Lab ('Natlab') drove the development of high-throughput manufacturing machines, which proved to be an important factor in the decades-long growth of the organisation. Throughout his career, Jan Eijk has had the opportunity to build on this foundation and to work with many excellent engineers in the field of high-precision mechatronics.

Jan van Eijk at the DSPE Conference on Precision Mechatronics 2014.

His unique skills and expertise have arisen from the knowledge and experience gained from working at Philips, where he became CTO Mechatronics. While building a mechatronic technology centre of about 200 engineers, he made conceptual contributions to a wide range of applications, including optical-disc-drive systems and lithography systems. With the start of ASML in 1984, Van Eijk contributed to key concepts and the architecture of mechatronic elements of ASML's highly successful lithography tools. The use of a rigorous metrology concept, introduced in 1986, formed a significant contribution to the early lithography machines.

After leaving Philips in 2007, he founded his own company, Mechatronic Innovation and Concept Engineering (MICE), to continue to provide consultancy to world-class equipment manufacturers worldwide. From 2000 to 2012, he also was a part-time professor in Delft, where he supervised doctoral students on projects related to using active magnetic bearings for precision applications. He contributed to the book "The Design of High Performance Mechatronics", by Prof. Rob Munnig Schmidt, *et al.*, which gives an industrial perspective on the multidisciplinary knowledge used in mechatronic engineering.

WWW.ASPE.NET

Schunk Group has acquired ClimaTech

Via its subsidiary Weiss Technik Nederland, based in Tiel (NL), the Schunk Group has acquired the company ClimaTech, located in Nijkerk (NL). ClimaTech has been working as a turn-key cleanroom builder for more than 25 years, in the healthcare, pharmaceutical, electronics and precision industries.
Weiss Technik Nederland offers climate solutions for environments where people and machines are challenged: in industrial cleanrooms for precision production processes, measurement rooms, hospitals or in the pharmaceutical industry, but also in the IT and telecommunications industries. The Schunk Group is a global technology company; a leading supplier of products made of high-tech materials (such as carbon, technical ceramics and sintered metal), as well as machines and systems – from environmental simulation and air conditioning to ultrasonic welding and optical machines.

WWW.CLIMATECH.NL
WWW.WEISS-TECHNIK.NL
WWW.SCHUNK-GROUP.COM

ClimaTech, a turn-key cleanroom builder, has been acquired by Schunk Group.

The Eindhoven Engine OpenCall 2022 is open

Eindhoven Engine invites consortia to submit project proposals for the OpenCall 2022, which has a budget of 2.4 M€ in total (max. 500 k€ per application). Eindhoven Engine accelerates innovation in the Brainport Region (NL) through challenge-based research in its public-private research facility at the Eindhoven University of Technology Campus. Teams of the region's most talented researchers from industry, knowledge institutes and students cooperate in Eindhoven Engine research programmes to deliver breakthrough technological solutions.

Through the OpenCall 2022, innovation projects can contribute to address societal challenges, participate actively in the Eindhoven Engine community and use the co-location and student facilities that the Engine offers. Proposals must be notified before 20 January 2022, while the application deadline is 24 February 2022.

WWW.EINDHOVENENGINE.NL/OPENCALL/OPENCALL-2022

Buy-and-build- and Brexit-inspired acquisition

NMi, located in Delft (NL), has acquired Young Calibration, a UKAS accredited calibration laboratory and component testing laboratory, based in Shoreham-by-Sea (UK). Young Calibration specialises in thermal fluid systems testing, component cleanliness and air-flow calibration. This acquisition, closed on 26 October 2021, marks the first step in the buy-and-build strategy of NMi, a leading independent specialist for legal metrology testing and inspection services.

"The Young Calibration acquisition strengthens our UK footprint and broadens our testing and calibration capabilities", says Yvo Jansen, NMi CEO. New regulations in the automotive and motorsports sectors promise to usher in demand for increased testing requirements. Young Calibration managing director, Adrian Young, adds, "Given anticipated industry changes and the general growth of the calibration and thermal fluid systems market, NMi is a logical partner to help accelerate our growth with further accreditation services and expansion into the legal metrology field."
Additionally, with the pace of change in the electrical vehicle market, Young Calibration's UK facilities offer a solid basis to further expand NMi electrical vehicle charging system services and capabilities.

WWW.NMI.NL
WWW.YOUNGCALIBRATION.CO.UK

UPCOMING **EVENTS**

Please check for any rescheduling, online reformatting or cancellation of events due to the coronavirus crisis.

31 January - 4 February 2022, Zwolle and Leiden (NL)
LiS Academy Manufacturability course
5-Day course targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

WWW.LIS.NL/LISACADEMY

15-18 March 2022, Utrecht (NL)
ESEF 2022
The largest and most important exhibition in the Benelux area in the field of supply, subcontracting, product development and engineering, showcasing the latest innovations.

WWW.ESEF.NL

22-23 March 2022, Zürich (CH)
SIG Meeting Thermal Issues
Special Interest Group Meeting, hosted by euspen and dedicated to thermal effects as a major contributor to errors on precision equipment, instruments and systems within precision engineering. The local host is the ETH Zürich university, which has materials & manufacturing as one of its four strategic areas.

WWW.EUSPEN.EU

13-14 April 2022, Den Bosch (NL)
Food Technology 2021
Knowledge and network event about high-tech innovations in the food industry.

WWW.FOOD-TECHNOLOGY.NL

17 May 2022, Veldhoven (NL)
CLEAN 2022
This theme day, organised by Mikrocentrum, provides an expert's view on cleanliness, focusing on design, production, assembly and packaging.

WWW.MIKROCENTRUM.NL

30 May - 3 June 2022, Geneva (CH)
Euspen's 22th International Conference & Exhibition
The event features latest advances in traditional precision engineering fields such as metrology, ultra-precision machining, additive and replication processes, precision mechatronic systems & control and precision cutting processes. Furthermore, topics will be addressed covering robotics and automation, precision design in large-scale applications, and applications of precision engineering in biomedical science

WWW.EUSPEN.EU

8-9 June 2022, Den Bosch (NL)
Vision, Robotics & Motion
This trade fair & congress presents the future of human-robot collaboration within the manufacturing industry.

WWW.VISION-ROBOTICS.NL

End of June, Wetzlar (DE)
DSPE Optics Week 2022
Unique event comprising the DSPE Optics and Optomechanics Symposium & Fair, and the well-known three-day optomechanics system design course.

WWW.DSPE.NL

27-30 september 2022, Utrecht (NL)
World Of Technology & Science 2022
Four 'worlds' (Automation, Laboratory, Motion & Drives, and Electronics) and Industrial Processing will be exhibiting in the Jaarbeurs Utrecht.

WWW.WOTS.NL

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