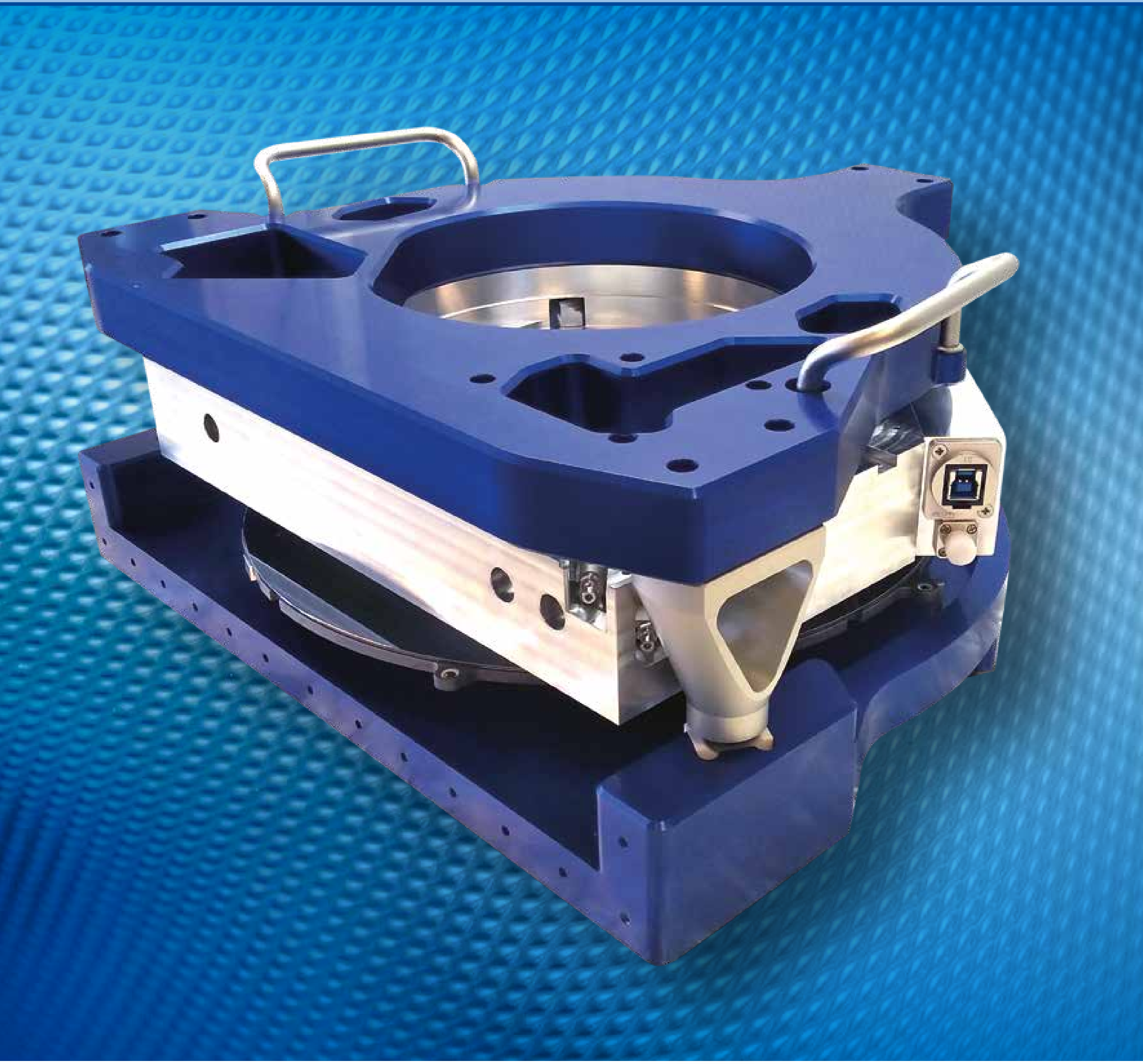
DSPE MIKRONIEK

2022 (VOL. 62) ISSUE 1
PROFESSIONAL JOURNAL ON PRECISION ENGINEERING



- THEME: HIGH-TECH SYSTEMS
- HIGH-NA EUVL THE NEXT MAJOR STEP IN LITHOGRAPHY
- TEACHING DESIGN PRINCIPLES AND MACHINE DYNAMICS
- WIM VAN DER HOEK'S BROAD VIEW

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

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.

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Publisher
DSPE
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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 image (featuring the design of a level sensor for the semiconductor industry) is courtesy of Hittech Multin. Read the article on page 5 ff.

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FEATURES

IN ADDITION TO SYSTEMS ENGINEERS, MORE SYSTEMS THINKERS ARE NEEDED

We are facing major transformations. Look at the energy transformation needed to combat climate change. These kinds of major transformations require a more systemic approach. A change for the sake of our future and the future of our children. For those complex changes, you also need systems thinkers: non-technicians who look at the larger system, together with systems engineers and others. In the end, we all work on subsystems that are interconnected.

As a Brainport region, we are champions in systems engineering for high-precision equipment. Take ASML's lithography machine. The making of that machine consists of many subsystems that ingeniously have been brought together. As a systems thinker, I understand this way of thinking and its language.

Look at connected, coordinated and autonomous mobility. This promises to be a solution for the major mobility challenges. Yet, why is it often limited to initiatives at a small-scale level? I believe this is due to its complexity. Since it is not just the technology to make that car drive independently, but a whole sequence of links, including traffic systems, a charging infrastructure, a road structure, the vehicle and road users. Coordination of all those links also requires a systemic thinking approach.

With those major transformations, you see that there is no problem owner for the bigger, complex, but necessary system change. There are problem owners for the subsystems, but there is no one for the overall architecture. This is the independent role that we assume. Someone who takes care of the integration in existing systems like society. Without it, we will never take the big steps to realise autonomous driving, for example.

Take the Brainport region. Also a large ecosystem, with different interests. One has to bring these together to achieve a common goal. Thinking from a systems perspective, you look at how these interests relate to each other. On the one hand, you have technological solutions, on the other, you have social issues that also require a solution.

That is similar to what a systems engineer does. That role and responsibility determination at the front. As a non-technician, a systems thinker, you can also look at a system, and together we can create common knowledge, which makes it easier for us to place ourselves in the world of experience of the other. Without judgement.

Systems thinkers are not omniscient. As a systems thinker, I realise that we are part of a larger system. Our region is again a subsystem in the system of the Netherlands in the system of the world. A systems thinker is continuously open to connecting with another system. That's why our work is never finished. There is always new information coming in that we have to post again. Then it's back to the common ground and determining what needs to be adjusted to move forward. Always make it manageable and understandable for others.

Systems thinking, in my view, is a skill that we should be exposed to at a young age. Maybe even as a subject in primary school. It is necessary to be able to take on the major transformations in our increasingly complex world.

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AFFORDABLE STABILITY IN HEIGHT MEASUREMENT

In a proof-of-concept study, Hittech Multin successfully designed and built a cost-efficient level sensor, specifically aimed at semiconductor applications, using mostly off-the-shelf parts and a self-developed processing algorithm. The target measurement stability was 50 nm. Experiments on a 300-mm wafer showed a short-term instability between 6.4 nm and 10^2 nm, at the centre and the edge of the measurement range, respectively. The next research stage will focus on bringing stability performance within specification throughout the entire range. Finally, the sensor's ability to also measure wafer tilt (Rx and Ry), for counteracting tilt-dependent wafer height measurement errors, will be investigated.

THOMAS OOMS AND FRED COUWELEERS

Technical introduction

The most critical step in the fabrication of a computer chip is lithography. In this step, the pattern of the electric circuits is 'written' on a wafer. A lithography system essentially projects an (electron-) optical image onto a resist-coated wafer. (Note: exposure using either photons (light) or electron beams is possible.) The top surface of the wafer must be in the (electron-) optical focal plane throughout the exposure or else the written pattern will be blurred, which would result in a non-functioning chip. The axial range in which the image is sharp is called the depth-of-focus (*DOF*), which can be calculated using the expression:

$$DOF = \lambda / (2 \cdot NA^2)$$

Here, λ is the wavelength of the light used and NA is the numerical aperture at the image side of the (electron-) optical system [1]. Lithography systems of the deep-UV generation use light with a wavelength near 200 nm. To write patterns as small as possible, these systems have an NA as large as 1 [-]. The *DOF* is then approximately 100 nm.

Capacitive sensors are available commercially that have a resolution as small as a few nanometers [2]. It is therefore possible to measure and (with proper actuation) control the wafer height with sufficient precision. However, to avoid a volume conflict with the (electron-) optical column, these sensors must be outside this column. The height measurements done at those locations only lead to the correct height at the centre of the column when the wafer is sufficiently flat. An optical sensor can measure on the (electron-) optical axis. A sensing light beam can travel at an angle towards the (nominal) intersection of (electron-) optical axis and wafer top-surface, reflect and then travel to a detector at the other side of a level-sensor (LS) module (Figure 1).

We decided to include the development of a "Level Sensor for application in Semiconductor Industry" in our internal technology development programme. The aim was to design and build an optical level sensor based on low-coherence interferometry, using standard parts, that is capable of measuring wafer height changes of 50 nm (resolution), over a vertical range of 300 µm (peak-to-peak). It turned out that deriving the wafer height from the optical sensor signals (signal processing) is not a trivial task in the presence of noise and changes in signal shape related to wafer height.

Hittech Group

Hittech Multin, located in Den Haag (NL), is part of the Hittech Group, which comprises nine companies in the Netherlands, Germany and Malaysia, and has a turnover of €140 million. Hittech is a first-tier system supplier in mechatronic and optical systems, and is active in the semicon, medical and lab equipment markets. The development group at Hittech Multin was responsible for the design and realisation of the level sensor within the framework of the "Sensors for Semicon" part of Hittech's Technology Program, under the supervision of Pieter Kappelhof, director Technology of the Hittech Group.

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Thomas Ooms holds a Ph.D. degree in Applied Physics (2008) from Delft University of Technology (NL). He has worked at Mapper Lithography and Hittech Multin, and currently works at ASML. His expertise is in the design of (optical) metrology solutions to accomplish accurate positioning in high-tech systems.
Fred Couweleers holds a Master's degree in Applied Physics (1990) from Eindhoven University of Technology (NL). He has worked predominantly in the field of (optical) metrology in industry and contract research organisations with a focus on production. Currently, he works as a senior optical designer at Hittech Multin on various optics projects, including microscopy, beam shaping and data merging.

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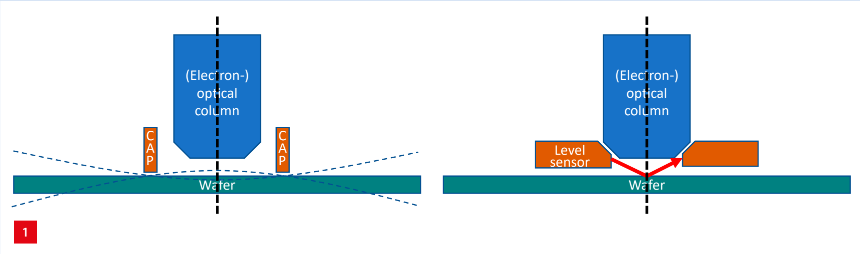


Off-axis measurement using capacitive sensors (left) versus on-axis measurement by an optical sensor (right).

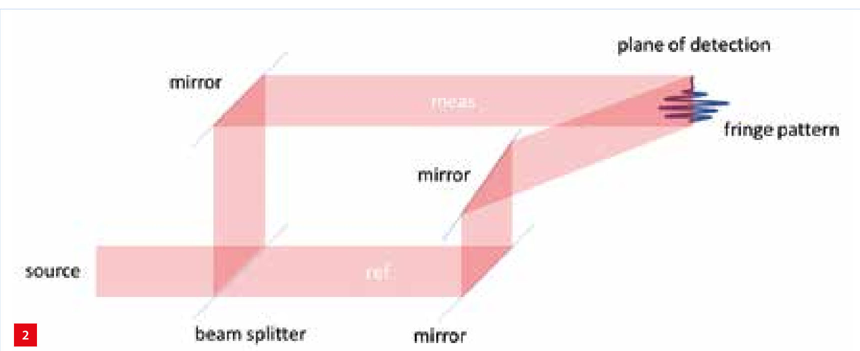
Concept design

To reach the required resolution, the sensor technology was based on interferometry. A single optical power measurement (one measurement using one photo-detector) is insufficient to generate a reliable height measurement, e.g. because the single power measurement would depend on the unknown wafer reflectivity. Instead, it is necessary to record a pattern with multiple fringes. This is realised by varying optical path length (*OPL*) within the interferometer.

The *OPL* can be varied as a function of time, for example by a scanning mirror in the reference branch. But the *OPL* can also be varied as a function of space, for example by letting the two interferometer beams combine at an angle onto a pixel-array sensor (camera) in a Mach Zehnder-like design (Figure 2). The second option was chosen so as to minimise the number of parts required and avoid having to generate small, but very reproducible, movements.

Although the typical light source for interferometry is a laser, such a highly coherent light source would result in a signal that is periodic over a large wafer-height range. In this case, it would be impossible to redetermine the wafer height after the measurement beam has been interrupted, for example during a wafer swap, because there is no way to tell how many fringes the signal has shifted after interruption with respect to the signal before interruption. To avoid this ambiguity, the sensor uses a low-coherent light source.

As the light source has low coherence, the fringe pattern will only appear where the *OPL* of the two interferometer beams is almost equal, as shown in Figure 3. When the wafer is at the bottom of its range, the measurement beam wavefront arrives 'late' at the detector, compared to the corresponding reference beam wavefront. The fringe pattern then forms near one edge of the detector. When the wafer is at the centre of its range, the fringe pattern forms at the centre of the detector. When the wafer is at the top of its range, the fringes form near the other side of the detector. See Figure 3.



Layout of a Mach Zehnder-like interferometer.

The essence of data processing is to determine the position of the fringes on the detector. The wafer height $\tilde{Z}_{waf}$ can then be estimated by multiplying this position with a proportionality factor.

Detailed design

Hardware

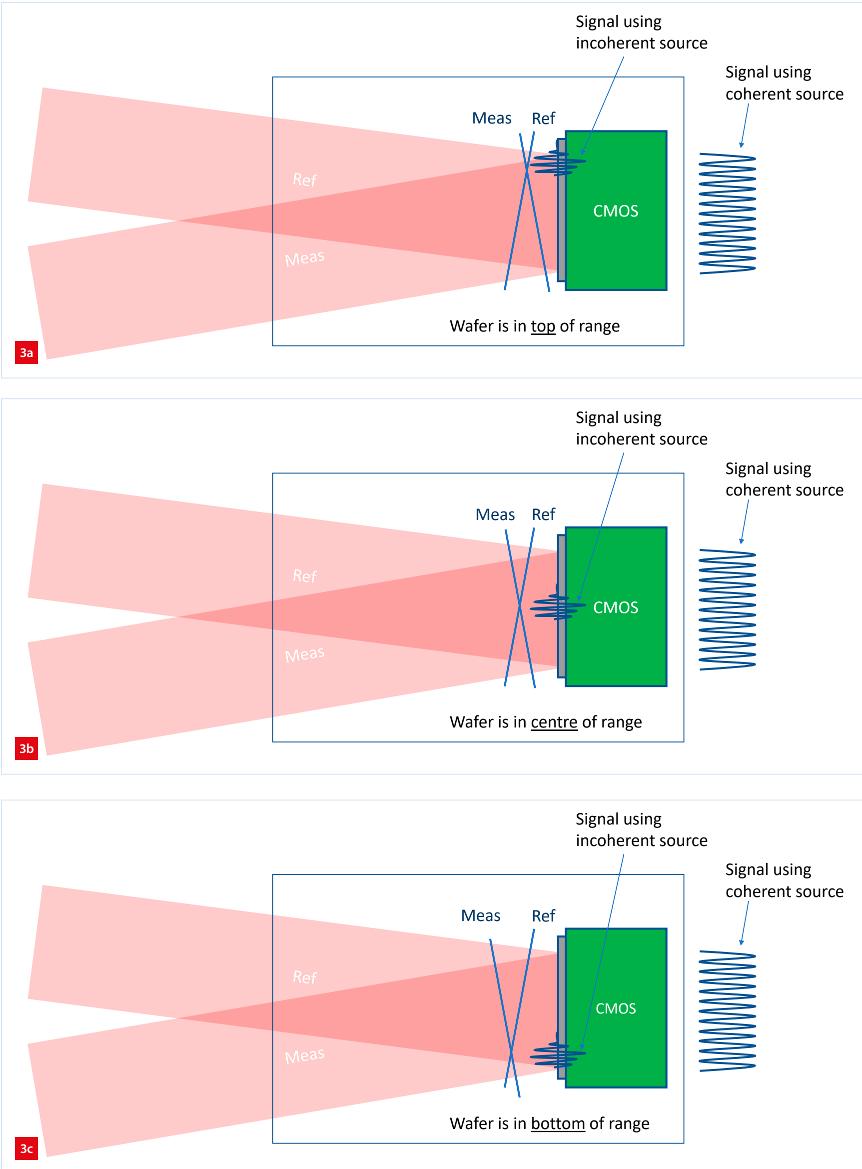
After the measurement concept had been validated in a breadboard set-up, the detailed design of the LS prototype commenced. The LS prototype was designed to consist of two modules, an 'electronics box' and a 'ring'. The ambition was to use commercial off-the-shelf parts, apart from a custom part to position the optomechanical parts with respect to each other and to serve as an interface to the environment (e.g. the lithography tool).

The electronics box contains a low-coherent infrared light source (super luminescent diode, SLD [3]), which emits light through a polarisation-maintaining (PM) single-mode (SM) fibre. An 840 nm wavelength was chosen because the SLD with this wavelength has a particularly large bandwidth, which leads to a narrow interference pattern (i.e., with relatively few fringes; an *OPL* difference of 5.3 wavelengths reduces the fringe contrast by only 50%), which reduces the chance of making a height measurement error due to an *OPL* measurement error of one or more exact wavelengths. A laptop PC performs real-time data analysis and displays the results.

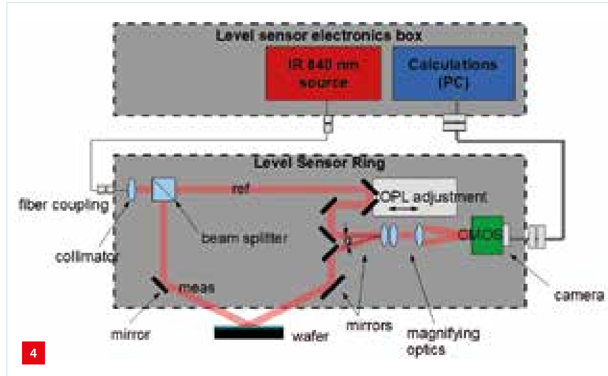
The ring receives light via a PM SM fibre. Inside the ring body, light is collimated and split into a measurement branch and a reference branch. Light in the measurement branch travels (via mirrors) to the wafer (angle of incidence *AOI* with respect to the normal is 68°), reflects and travels to a 'primary interference plane'. This large angle of incidence is derived from the volume claim in an earlier project and provides ample space for an (electron-) optical column in the centre of the ring. The change in *OPL* as a result of a change in wafer height is:

$$dOPL = 2 \cdot dZ \cdot \cos(AOI)$$

In this geometry, the result is: $dOPL = 0.75 \cdot dZ$.



The effect of wafer height on the fringe pattern on the sensor for a coherent and an incoherent source.



The level sensor consisting of two modules: the electronics box and the ring.

The reference beam travels via mirrors to the same interference plane. The *OPL* of the two branches must differ by less than a few μm. In this prototype, a sufficiently small difference in *OPL* between the reference and measurement beam cannot be accomplished by the stacking of manufacturing tolerances, so a mechanical OPL-adjustment was added in the reference beam (Figure 4). This is used for a one-time adjustment to be executed during sensor production.

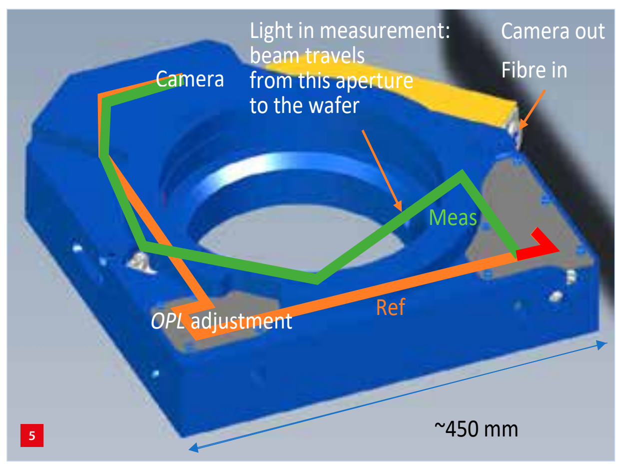
A compromise had to be found between ensuring that the sensor is able to resolve the interference pattern and ensuring that the measurement range requirement is met. If two beams of light with wavelength λ arrive at a plane under angles $+\alpha/2$ and $-\alpha/2$, respectively, the period in the interference pattern in that plane, p, is given by:

$$p = \lambda / (2 \cdot \sin(\alpha/2))$$

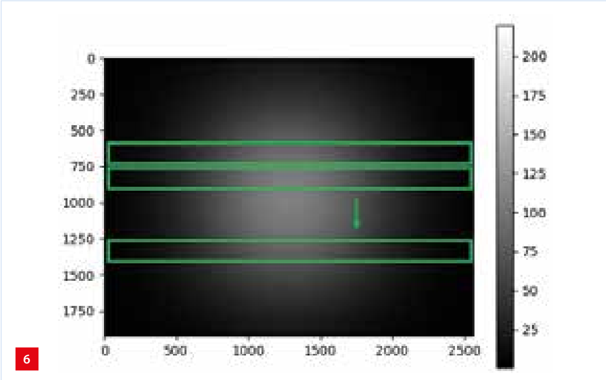
We do not account for the facts that we need to see the complete fringe pattern, the *OPL* matching is not perfect, and there is a wafer placement error with respect to the 'zero' position. Then, in first order, the wafer height measurement range is the sensor size multiplied by a proportionality factor between *OPL* and wafer height, divided by the period in the interference pattern. A small angle α will give a large period, which is easy to resolve but will give a small measurement range, while a large angle α will give a small period in the interference pattern, which is difficult to resolve but will give a large measurement range.

The values for the different parameters describing the design are listed below:

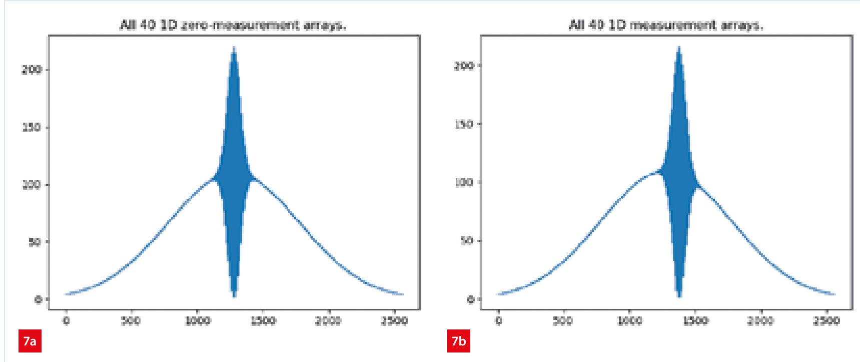
- Angle between beams in primary interference plane $\alpha = 16°$ → period $p = 3.0$ μm.
- Magnifying optics magnification $M = 2.5$ [-] → period on camera $p = 7.5$ μm.
- Camera has $N_x = 2{,}560$ pixels with distance $d_{pix} = 2.2$ μm [4] → size of camera = 5.6 mm; one fringe is 3.4 pixels (in compliance with the Shannon-Nyquist sampling criterion: to be able to fully reconstruct a signal, it must be sampled at a rate at least twice the highest (spatial) signal frequency [5]); measurement range is



Sensor ring: the central part is empty to provide volume for an (electron-) optical column.



A simulated image of the irradiance of two interfering spots on the CMOS sensor. The xy-axes of the figure represent the xy-position on the CMOS-sensor in pixels. The scale bar is 8-bit intensity. One data set (green box) contains ten pixel rows. Forty of these sets are used per recorded frame.



Two simulated examples of recorded irradiance. The horizontal axis represents x-position on the CMOS-sensor, as unit pixels. The vertical axis represents irradiance, normalised to a scale 0-255 [-].
(a) Zero measurement.
(b) Actual measurement.

((5,600/7.5) – 2·3·5.3)·0.84 – 10 – 50 = 540 µm in terms of *OPL* → according to the equation (d*OPL* = 0.75·d*Z*) derived previously, the range is 720 µm in terms of wafer height.
- Beam diameter = 3.3 mm.

A 3D model of the sensor ring is shown in Figure 5 (path of reference and measurement beams indicated by orange and green lines, respectively).

Processing algorithm
The essence of data processing is to determine the position of the fringes. This position is converted to an estimated wafer height by multiplication using a proportionality factor. More specifically, the data processing determines the displacement of fringes with respect to a 'zero measurement'. So, the sensor actually measures a wafer height change (dZ_{waf}) between a zero measurement and an actual measurement. The steps of the data-processing algorithm are described below.

For every frame, forty sets of ten rows (of 2,560 pixels each) are evaluated (Figure 6) – not all pixel rows are used. Within each set, the average over the ten rows is determined, to suppress noise. The result is 40 1D irradiance arrays (as function of x) per recorded frame. We arrived at these numbers by trial and error, compromising between noise suppression and contrast loss.

According to theory, the recorded irradiance distribution at any point on the detector, I_{tot}, which is actually $I_{tot}(x,y)$, can be expressed as:

$$I_{tot} = I_{meas} + I_{ref} + 2\sqrt{I_{meas} \cdot I_{ref}} \cdot \cos(\phi_{meas} - \phi_{ref}) \cdot \Gamma(\phi_{meas} - \phi_{ref})$$

Here, I_{meas} and I_{ref} are the irradiance of the measurement and reference beam, respectively, while ϕ_{meas} and ϕ_{ref} are the phases of these two beams, respectively, (leading to an interference term) and Γ is a function that expresses light source coherence as a function of phase difference (reducing the interference term as the phase difference increases). Two theoretical examples of I_{tot} are presented in Figure 7, showing simulated image intensity along a pixel row for two different wafer heights.
The two graphs in Figure 7 show that – for different wafer heights resulting in different fringe positions – the shape of the fringe pattern is different (the left side of Figure 7 is horizontally symmetrical, while the right side is not). The fringe pattern is modulated by the position-dependent I_{meas} and I_{ref}. This shape change hinders the data-processing task of determining the fringe pattern displacement. The solution is to include a normalisation step, which removes the shape change. The result is a normalised irradiance I_{norm}:

$$I_{norm} = \frac{I_{tot} - (I_{meas} + I_{ref})}{2\sqrt{I_{meas} \cdot I_{ref}}}$$

After this step, the fringe pattern will (theoretically) be as shown in Figure 8.

The next data-processing step truly determines the fringe pattern shift (position difference between zero measurement and actual measurement). Consider the normalised irradiance of the zero measurement, $I_{zero}(x)$, and the actual measurement, $I_{act}(x)$. They have the following Fourier transforms:

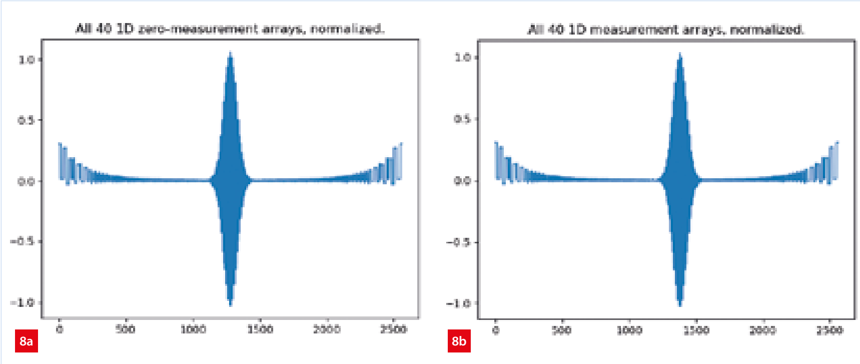
$$\mathrm{FT}(I_{zero}(x)) = J_{zero}(k)$$

$$\mathrm{FT}(I_{act}(x)) = J_{act}(k)$$

Here, k is the spatial frequency in increments of $1/(2 \cdot d_{pix} \cdot N_x)$ [m^{-1}].

We know that $I_{act}(x)$ is (in theory) a shifted copy of $I_{zero}(x)$. The shift is equal to the wafer height change (dZ_{waf}) times a proportionality factor γ:

$$I_{act}(x) = I_{zero}(x - \gamma \cdot dZ_{waf})$$



Fringe patterns after normalisation. The horizontal axis represents x-position on the CMOS-sensor, as unit pixels. The vertical axis represents irradiance, normalised as explained in the text. The shape of the two fringe patterns is (approximately) the same. The 'blocky' signal at the edges is a result of highly amplified noise.
(a) Zero measurement.
(b) Actual measurement.

The nominal value of γ is known, as it follows from sensor hardware parameters (angle of incidence at wafer, angle of interference, wavelength, magnification of lens set, pixel spacing). This nominal value γ is used in further calculations.

The relation between the two Fourier transforms is [6]:

$$J_{act}(k) = J_{zero}(k) \cdot (-\, i{\cdot}k{\cdot}\gamma{\cdot}\mathrm{d}Z_{waf})$$

Multiplying $J_{act}(k)$ by the complex-conjugate of $J_{zero}(k)$ yields:

$$C(k) = \overline{J_{zero}(k)} \cdot J_{act}(k) = \overline{J_{zero}(k)} \cdot J_{zero}(k) \cdot \exp(-i \cdot k \cdot \gamma \cdot dZ_{waf})$$

or

$$C(k) = |J_{zero}(k)|^2 \cdot \exp(-\, i{\cdot}k{\cdot}\gamma{\cdot}\mathrm{d}Z_{waf})$$

Note the term $|J_{zero}(k)|^2$ is real and that therefore the information of interest ($\mathrm{d}Z_{waf}$) has a very simple and direct relation with the phase of $C(k)$ (i.e. $\phi_C(k)$). That relation is:

$$\phi_C(k) = -k{\cdot}\gamma{\cdot}\mathrm{d}Z_{waf}$$

The phase of $C(k)$ can be calculated using an arctan-function. The slope in k-space ($-\gamma{\cdot}\mathrm{d}Z_{waf}$) can be found using a line fit in a k-ϕ_C-plot. Division by $-\gamma$ then yields the estimated wafer height change $\widetilde{dZ}_{waf}$.

The above-described process is shown graphically in Figure 9. Although this appears straightforward, there are unfortunately a few difficulties. The first difficulty is that when the phase data $\phi_C(k)$ is calculated using an atan2-function [7], the resulting data is wrapped modulo 2π. This can be solved with unwrapping algorithms (which are readily available or can be self-written).

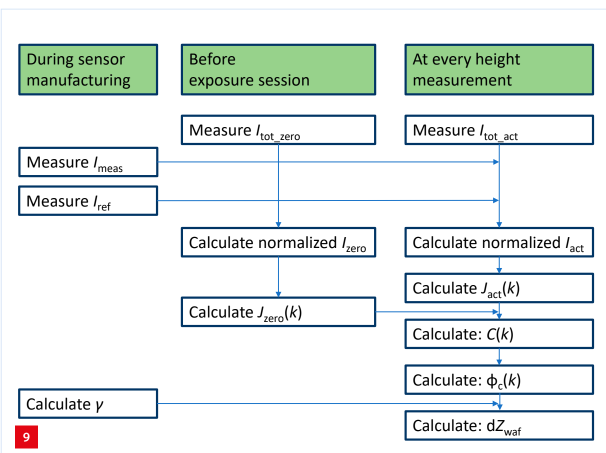
A second, more severe issue is that $C(k)$ only contains useful (non-zero) data within the peak at the spatial frequency of the fringes; see Figure 10. At most other spatial frequencies, $C(k)$ is nearly zero and calculation of $\phi_C(k)$ yields useless data when using:

$$\phi_C(k) = \mathrm{atan2}(\mathrm{real}(C(k)),\mathrm{imag}(C(k)))$$

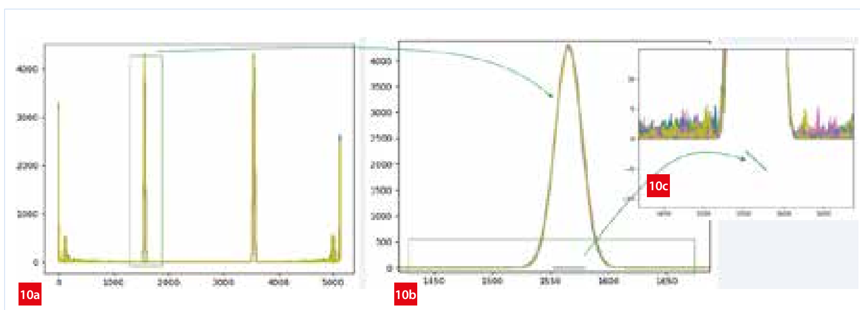
It is possible to evaluate data within the peak and a correct line fit can be done, but the accuracy of this line fit is poor because the k-extent of the peak is small.

The phase relation predicted by theory ($\phi_C(k) = -k{\cdot}\gamma{\cdot}\mathrm{d}Z_{waf}$) implies that points $(k,\phi_C(k))$ lie on a line that passes through the origin. Snapping the line fit to the origin would improve the accuracy of the line fit, because the origin is relatively far away. The problem is that – at the peak – merely $\phi_C(k) + 2\pi N$ is available, where N is an unknown integer. So, extending the line fit leftwards will generally not intersect the y-axis at the origin, but at a point $(0,2\pi N)$, where N can be any integer.

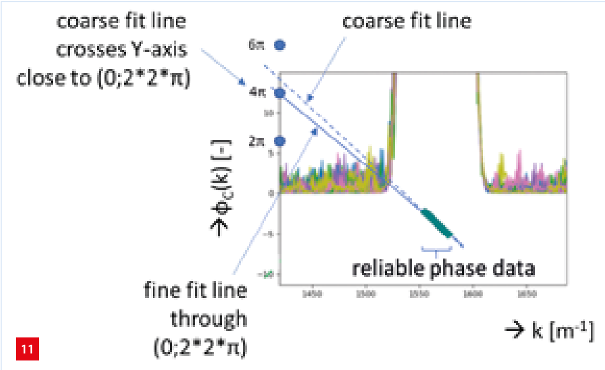
Fortunately, it turns out – for the realised sensor – that the coarse, leftwards extrapolation always intersects sufficiently closely to the correct 'y-axis-intersection point'. We therefore let the line fit snap to the $(0,2\pi N)$-point that is closest to the



Data-processing steps.



Irradiance plots. The horizontal axes represent spatial frequency: unit is $1/(2{\cdot}d_{pix}{\cdot}N_x)$, where d_{pix} is the pixel spacing and N_x is the number of horizontal pixels, 2,560). The vertical axes represent irradiance amplitude in arbitrary units, respectively phase (for the upper right green/cyan plot); unit is radians.
(a) $|C(k)|$.
(b) Horizontal zoom-in (at the spatial frequency of the fringes) of $|C(k)|$ and $\phi_C(k)$, which can be seen in green/cyan below the central irradiance peak.
(c) Vertical zoom-in of the phase data $\phi_C(k)$.



Coarse and fine line fit to phase-spatial frequency data.

Assembled sensor. The sensor ring (aluminium colour) is suspended from the top frame (blue), which stands on the bottom frame (blue), which in turn carries a 300-mm wafer (only the edge visible on the left).
(a) Rendering.
(b) Realisation.

intersection of the coarse line fit and the y-axis (Figure 11). Then, using a least-squares criterion, we fit the line to the $\phi_C(k)$-points that lie within the peak. The result is a line that passes through one point of the series $(0,2\pi N)$ and as close as possible to the points $\phi_C(k)$. This yields a 'fine' estimate of the line slope, which is subsequently divided by γ to yield the estimated wafer height change $(\widetilde{dz}_{waf})$.

Assembly

The review process in the system design led to a high-quality mechanical design and no surprises were found in the assembly of the sensor (Figure 12). The adjustable folding mirrors were locked in their kinematic mounts using adhesive. The rest (parts and sub-assemblies) was mounted and locked using locking screws. *OPL* alignment ensured that fringes were formed in the centre of the detector when the wafer was at the centre of the sensor's vertical measurement range.

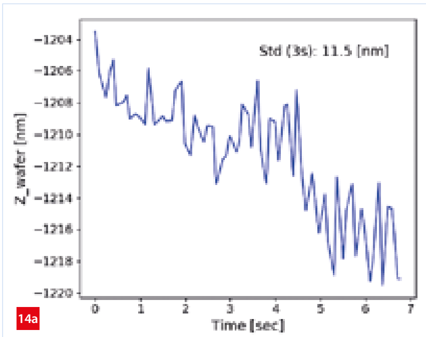
To enable sensor testing (with respect to functionality and stability), a dedicated frame and a stationary wafer, mounted on a wafer table, were added, as shown in Figure 13. A statically determined mounting with ceramic balls and V-grooves was used to position the frame holding the sensors with respect to the frame holding the wafer table.

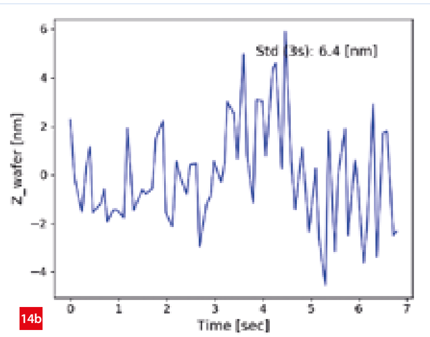
Assembly of the sensor.
(a) Inside the flowbench.
(b) Optical fibre inside ring module.
(c) Ring module shown upside down.

Height measurements were performed at one point in the centre of the wafer, as there was no xy-stage.

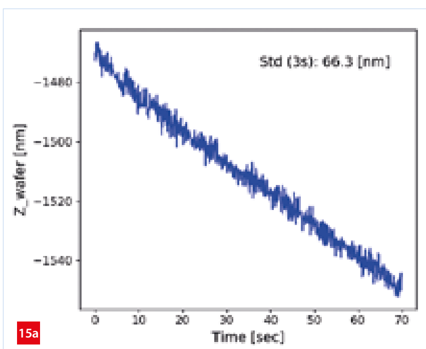
Testing

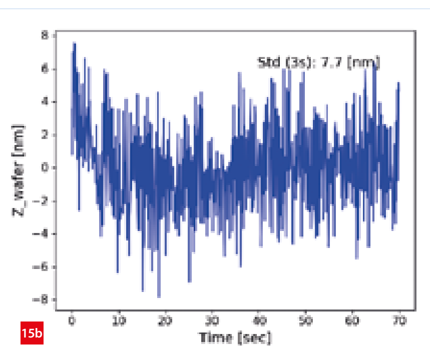
At our production facility, stability tests were executed inside a flowbench. During various time durations, ranging from 1 to 300 seconds, frames were recorded onto a PC hard drive. This data was analysed offline using the previously described data-processing algorithms. Time scales in the order of seconds or even a few minutes would correspond to the time a wafer spends in a lithography tool for one exposure. When recording seventy frames in 7 seconds, the observed stability (3σ standard deviation, std) was 11.5 nm, and 6.4 nm after a linear detrend of the data; see Figure 14.



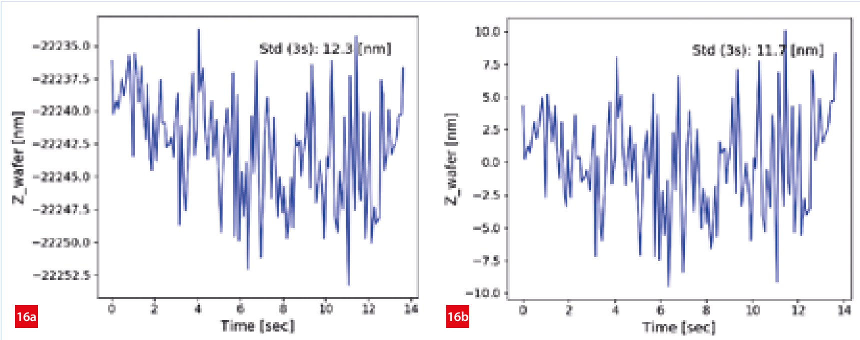


Wafer height measurement during 7 seconds.
(a) Raw data.
(b) Data after linear detrend.

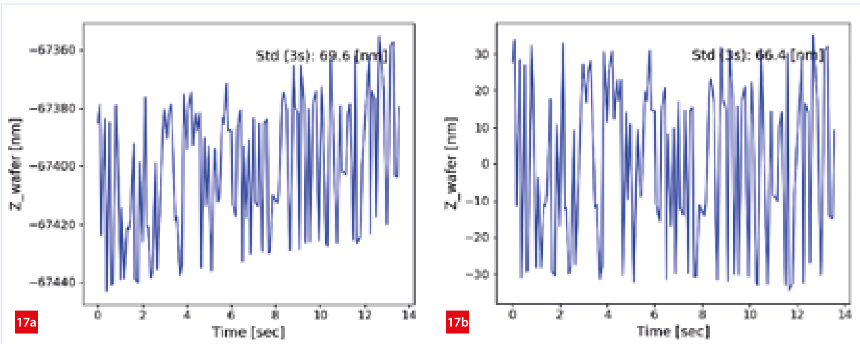




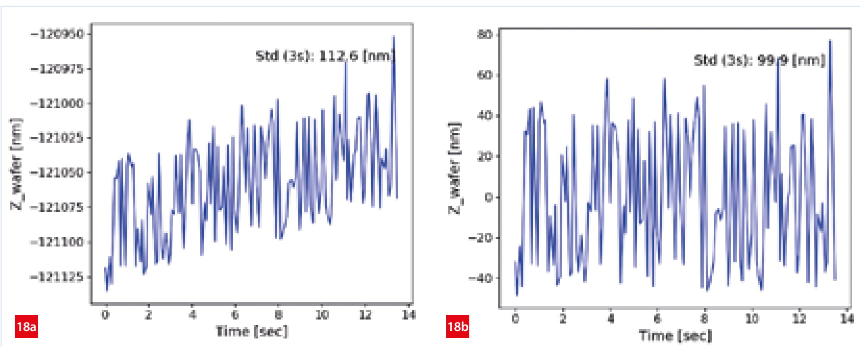
Wafer height measurement during 70 seconds.
(a) Raw data.
(b) Data after linear detrend.



Wafer height measurement with the wafer effectively lowered by about 20 µm.
(a) Raw data. (b) Data after linear detrend.



Wafer height measurement with the wafer effectively lowered by about 60 µm.
(a) Raw data. (b) Data after linear detrend.



Wafer height measurement with the wafer effectively lowered by about 120 µm.
(a) Raw data. (b) Data after linear detrend.

Note: in Figures 14 to 18, Std (3s) denotes Std (3σ)). It is not known precisely whether the linear trend originates from the sensor or from the environment (frame or wafer table). A longer measurement (700 frames during 70 seconds) revealed a comparable result (Figure 15). The raw height measurement contained a clear trend/drift, which led to an observed instability (3σ std) of 66.3 nm. The instability after linear detrend was a mere 7.7 nm.

Tests were also conducted to check whether the required measurement range (300 µm peak-to-peak) was reached. The wafer was lowered virtually by raising the sensor ring by placing shim plates between the top and bottom frames. In a first test, the ring was raised by about 20 µm. This resulted in an observed instability of 12.3 nm (3σ std); see Figure 16. As there was no linear trend/drift, the instability of the detrended data was about equal.

In a second test, the ring was raised by about 60 µm (compared to the case without shims). The observed instability was 69.6 nm (3σ std); see Figure 17. As there was only a small linear trend/drift, the observed instability of the detrended data was about equal.
In a third test, the ring was raised by about 120 µm (compared to the case without shims). The observed instability was 112.6 nm (3σ std); see Figure 18. The observed instability of the detrended data was 99.9 nm.

Conclusions and outlook

The test results show that the short-term (linearly detrended) instability of the sensor can be as low as 7.7 nm. This is a very satisfying result when compared to the maximum permitted instability of 50 nm. It also became clear that during longer measurement sequences (70 seconds), the observed drift can be as large as 60 nm per minute. It is not currently known whether this behaviour originates from the sensor ring or from its environment (frame + wafer). The next stage of research will focus on bringing stability performance within specification throughout the 300 µm range.

In this respect, it is also relevant to clarify how the stability of the environmental temperature in the executed tests relates to the stability of the temperature inside a semiconductor lithography tool (which is generally very tightly controlled). To that end, sensor drift will be measured in an environment with improved temperature stability (< 20 mK). Depending on our findings, we will decide whether to invest in a thermo-mechanical redesign of the sensor.
Finally, the test results show that the short-term stability of the sensor increases significantly when the wafer height difference (between zero measurement and actual measurement) increases. The cause of this effect is not currently understood. We will invest in understanding this behaviour, because the largest observed short-term instability (99.9 nm) significantly exceeds the maximum permitted instability of 50 nm.

Further research will explore the simultaneous measurement of wafer height as well as wafer tip/tilt (*Rx* and *Ry*) by also measuring the angle of the interference pattern on the camera and the pitch of the fringes in the interference pattern. The tip/tilt parameters relate linearly to the fringe spacing and fringe orientation on the detector, which can both be extracted from the recorded 2D image. Applications can benefit from this additional functionality, for example in counteracting tilt-dependent wafer height measurement errors (e.g. Abbe errors).

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NEXT MAJOR STEP IN LITHO – THE IMEC PERSPECTIVE

In the course of 2025, we expect to see the introduction of the first high-NA extreme ultraviolet (EUV) lithography equipment in high-volume manufacturing environments. These next-generation lithography systems will be key to advance Moore's Law towards the logic 2-nm technology generation and beyond. In this article, imec scientists and engineers involved in preparing this major next step in semiconductor lithography (driven by equipment maker ASML) discuss challenges and opportunities. They highlight recent insights and progress obtained in developing the patterning processes, metrology and photomasks needed for enabling the high-NA EUV lithography infrastructure.

DANILO DE SIMONE, GIAN LORUSSO, VICKY PHILIPSEN AND KURT RONSE

A leap in resolution

2019 marked an important milestone for extreme ultraviolet (EUV) lithography: ASML's EUV lithography systems were for the first time deployed in the mass production of logic chips of the 7-nm technology generation. Inserted to pattern the most critical layers of the chips' back-end-of-line, it enabled printing metal lines with pitches as tight as 36-40 nm.

With an extremely short wavelength of 13.5 nm, EUV lithography was introduced to succeed 193-nm (immersion) lithography as the most cost-effective manufacturing solution for the most advanced chip nodes. This transition was dictated by the Rayleigh equation for resolution: $R = k_1 \cdot \lambda / NA$, with k_1 a constant (process factor), λ the wavelength and NA the numerical aperture. According to this equation, the resolution of a lithography tool – and thus its ability to print features with a certain half pitch or critical dimension (*CD*) – can be improved by using light with smaller wavelength during wafer exposure. Moreover, the complex, expensive multiple-patterning requirements of 193 nm – which involve splitting a chip pattern into two or more simpler masks – could be moved back again to single-patterning EUV.

On the development side, researchers have been continuously trying to push further the single-print capability of today's most advanced EUV full-field scanner, ASML's NXE platform. Last year, for example, imec and ASML were able to demonstrate 28-nm-pitch single-exposure patterning readiness for lines/spaces, corresponding to critical back-end-of-line metal layers of a 5-nm logic technology node. This brings the current scanner close to its resolution limit for high-volume manufacturing, which is around 13 nm (26 nm pitch). Along with the evolution in logic, memory manufacturers are increasingly looking at using EUV lithography for meeting the high-density requirements for future memories – for example for patterning critical DRAM structures.

At the same time, multiple-patterning EUV lithography options are being explored to advance EUV to the next nodes. While these 'tricks' offer more relaxed pitches, they also come with a downside: an increased number of processing steps, adding to the cost, complexity and processing time of the patterning step.

2023 will mark a new milestone in the evolution of EUV lithography. By then, the first new generation of EUV lithography tools is expected to enter the scene: a high-NA EUV lithography scanner – projected to print the most critical features of 2-nm (and beyond) logic chips in a smaller number of patterning steps. The transition towards high-NA lithography is again justified by the Rayleigh equation, which provides a second knob for improving the resolution: increasing the *NA* of the projection lens. The *NA* controls the amount of light (more precisely, the number of diffraction orders) that is used to form the image, and thus controls the quality of the image.

Transitioning to higher-NA imaging equipment has been applied before, remember the move from 193-nm dry to 193-nm immersion lithography. At that time, the optical trick of replacing the air between lens and wafer with water allowed a 45% increase in *NA*. In the case of EUV, ASML will move from the current *NA* of 0.33 to 0.55 (i.e., a 67% increase) by redesigning the optics within the lithography system. 0.55NA EUV lithography promises to ultimately enable 8 nm resolution, corresponding to printing lines/spaces of 16 nm pitch in one single exposure.

AUTHORS' NOTE

All authors work at imec, a leading nanoelectronics research centre based in Flanders (B). Danilo De Simone is the principal staff member leading the research on patterning materials for EUV lithography, Gian Lorusso is a principal scientist working on EUV and metrology, Vicky Philipsen is a lithography engineer, and Kurt Ronse is the Advanced Patterning Program director. This article is a slightly abridged version of a longread that was published last October on the imec website.

www.imec-int.com/en/reading-room
www.imec-int.com/en/articles/high-na-euvl-next-major-step-lithography

An ambitious timeline

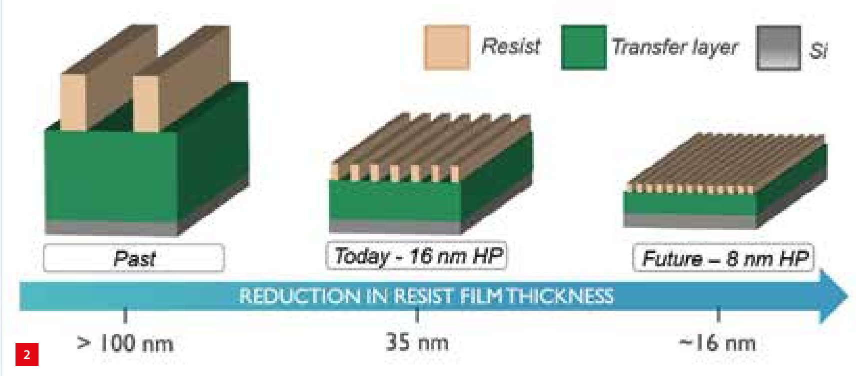
0.55NA EUV lithography will push the patterning towards features smaller than what is possible with current 0.33NA EUV lithography systems. But the road forward is ambitious. The development of EUV lithography systems goes back to the 2000s, with a ten-year time span between the installation of the first pre-production EUV scanners and the recent introduction of EUV lithography in high-volume manufacturing. For high-NA, the ambition is to compress that time frame to only three years, with a first prototype (the EXE:5000; Figure 1) foreseen for 2023.

1

Rendering of ASML's EXE:5000 high-NA EUV lithography scanner. (Courtesy of ASML)

Prior to the availability of the first high-NA tool, dedicated lab equipment and current-generation EUV lithography tools and materials are being pushed to their limits to prepare and derisk the new high-NA EUV lithography technology as much as possible.

Simultaneously, imec is partnering with ASML to open a joint High-NA Lab, where a high-NA system will be linked to a coat and development track and surrounded with metrology equipment. Together, they will pioneer the ecosystem for the industry to meet the process requirements and establish the infrastructure that goes along with high-NA tool development – including anamorphic imaging, new mask technology, metrology, resist screening and materials development for thin-film patterning, etc. In addition, chipmakers will have access to the High-NA Lab to develop their private high-NA use cases.



2

Evolution of the reduction in resist film thickness (HP = half pitch).

Process and metrology needs

The tendency towards thinner resists (Figure 2) will continue with the advent of high-NA EUV lithography, which ultimately aims at printing lines/spaces of 16 nm pitch, corresponding to printing lines with widths as small as 8 nm. This calls for resist films thinner than 20 nm to maintain the ideal aspect ratio of 2:1 (defined as the ratio between the height and the width of the line). With thicker resists, the aspect ratio would increase, and with it the risk of line collapse.

High-NA EUV lithography brings a second reason for using thinner resist films. Following a second Rayleigh equation, the depth-of-focus (DOF) – i.e. the resist height across which the (aerial) image is in focus – decreases by the square of the numerical aperture. Simulations predict an effective decrease of DOF with a factor of 2-3 with respect to current 0.33NA lithography. A transition from thicker to thinner resists is therefore needed to cope with both a lower DOF in high-NA EUV lithography and a reasonable aspect ratio.

The reduced resist thickness requirements bring new needs for the high-NA EUV processes as well as new challenges to the metrology. For example, when the resist becomes ultrathin, the amount of material within a printed line becomes so small that it can hardly be 'seen' with the currently used metrology tools. For the widely used CD-SEM (CD scanning electron microscopy), for example, using thinner resists translates into a strongly reduced image contrast. Recent experiments revealed that the type of underlayer (i.e., the layer underneath the photoresist film) can positively affect the SEM imaging contrast. But using a different underlayer to improve the metrology will in turn impact pattern transfer, calling for optimised etch processes. To continue optimising pattern transfer, improved metrology tools or optimised tool settings will be needed to reliably image the patterns.

Below, we present a grasp of some recent insights in both patterning and metrology.

The limits of pattern transfer

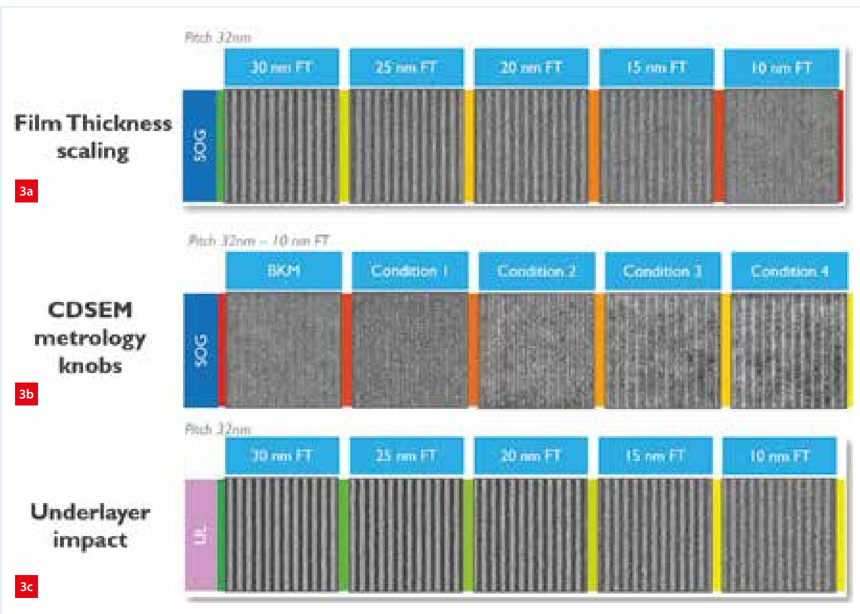
In anticipation of the first high-NA EUV prototyping system, imec uses an advanced 0.33NA EUV lithography system, the NXE:3400B, to predict the performance of thinner resists – for both lines/spaces and contact holes. Earlier, imec and ASML were able to print the smallest pitch possible with this NXE:3400B scanner (i.e., 24-nm pitch lines/spaces and 28-nm pitch contact holes).

By using this tool, the team showed, for example, that the line-edge and line-width roughness (LER/LWR) – among the most critical parameters for patterning lines/spaces – tend to increase when using thinner resist films. In these experiments, chemically amplified resists (CARs) were used, a type of resist that relies on chemical amplification of electrons formed within the resist when EUV photons hit the surface.

For high-NA lithography, however, the industry might need resists beyond CARs, with better resolving power. We therefore see an emergence of novel photoresist materials such as metal-oxide resists (MORs). Our first experiments seem to indicate that these MORs have indeed a better pattern transfer capability for smaller features and thinner resists. Imec collaborates with multiple material suppliers to develop these concepts and assess critical issues such as contamination risks and process integration challenges.

Metrology

Imec sees two ways to address the issue of decreasing image contrast of presently used CD-SEM tools, and to continue measuring very small lines printed with ever thinner resists. A first approach is to tweak the tool's settings. Playing with some of the knobs of the CD-SEM tool (such as the scan rate) turns out to positively affect the imaging contrast – making patterns visible even at film thicknesses down to 15 nm (Figure 3). A second approach is to explore alternative metrology techniques, in close collaboration with metrology suppliers. Very promising in terms of resolution are for example low-voltage SEM, helium-ion microscopy, and scatterometry.



Impact of reducing the resist film thickness (from 30 to 10 nm) on the CD-SEM image contrast.
(a) Negative effect.
(b) Improvement by playing with CD-SEM metrology knobs.
(c) Improvement by using different underlayers.

Apart from lines of e.g. 10 nm width, there are even smaller features within the pattern that need to be imaged. As scaling continues, it has become more difficult to measure parameters like LER and overlay performance (i.e. how well one layer is aligned with the next one) – requiring image resolution far below 10 nm.

And then there is defectivity, more particularly, the appearance of stochastic print failures: random, non-repeating, isolated defects such as microbridges, locally broken lines and missing or merging contacts. They are believed to arise from the fundamental relationship between energy and wavelength. With the wavelength getting shorter, the energy from the light source is distributed over less photons. Consequently, there are just a few photons to create a pattern. Besides this 'photon shot-noise effect', stochastic effects originate from the molecular nature of matter, and the probabilistic behaviour of their interactions.

The advent of high-NA EUV lithography with further increasing resolution and reduced resist thicknesses will further drive this evolution. Imec and ASML have been developing methodologies to systematically quantify the defect levels in the EUV materials and learn about the many factors contributing to the failures. Key is the development and improvement in wafer inspection strategies, which traditionally rely on optical techniques.

More recently, e-beam based inspection is gaining increased attention. Although it looks very promising for finding small defects, it comes with a major drawback: a dramatic increase of the time needed for inspecting the full wafer – calling for solutions for enhanced tool productivity and throughput. Meanwhile, ASML is working on a fast multi-beam inspection tool that leverages several of ASML's core technologies: advanced stages, computational technology and advanced electron optics.

Besides, electrical tests of metallised patterns are increasingly being set up to look for correlations with data obtained with optical and e-beam inspection techniques. This allows to increase learnings on stochastic patterning failures and to gain more insights in the way they impact yield.

Mask technology

The photomask is an essential component for the manufacturing of chips as it holds the design layout information intended for the final device. Ideally, this information is contained in dark (i.e., absorbing) and bright (i.e., reflecting) areas on the mask. Now that progressively smaller features are being printed, deviations from the ideal mask are increasingly impacting the final wafer pattern. Mask-specific challenges therefore need to be addressed. These include, amongst others, a reduction of the mask 3D effects, an enhanced understanding of the mask lifetime and of its contribution to printing stochastic failures. On top of that, the introduction of anamorphicity (see below) within the high-NA EUVL optical system brings along additional complexities to the mask industry.

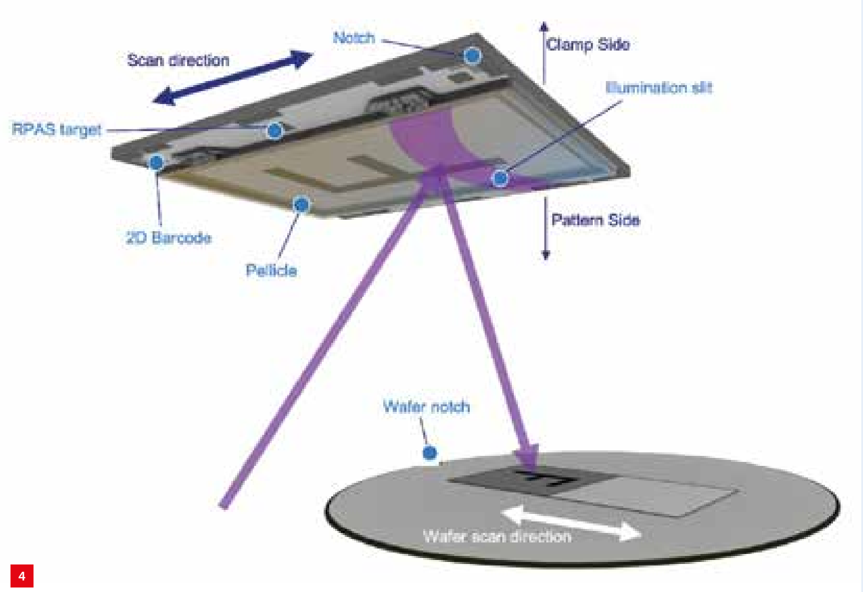
In close collaboration with ASML and with its material suppliers, imec contributes to the design optimisation and qualification of photomasks intended for high-NA EUV lithography. This work is described in more detail below.

New absorber materials

Today's EUV photomasks consist of a ~300-nm-thick reflective multilayer stack, formed by 40 to 50 alternating layers of silicon (Si) and molybdenum (Mo), capped with a thin ruthenium layer. On this stack, the absorber made of tantalum-boron-nitrate (TaBN) carries the pattern. While the multilayer of Mo and Si reflects the incident light, the absorber blocks the reflection and this combination defines the features on the wafer.

Current Ta-based absorbers are typically about 60-70 nm thick, designed to absorb a sufficient amount of light. This thickness is large compared to the 13.5-nm exposure wavelength of the light. Consequently, light that hits the mask under a certain angle of incidence (centred around 6° in conventional EUV lithography) and reflects from the multilayer is sensitive to the 3D topography of the 'thick' mask, undergoing for example multilayer- and absorber-induced phase deformations. This distorts the aerial image – the pattern of light that finally is transferred in the photoresist – and reduces its image contrast. These so-called mask 3D effects also come with increased feature-dependent variations in placement and best focus on the wafer. This presents additional challenges for high-NA EUV lithography, that already suffers from a reduced DOF budget.

Originally, innovations in source illumination and mask design were applied to compensate for the mask 3D effects. In recent years, attention is shifting towards improving the mask material as the parameter to control mask 3D effects on the wafer and thus help to increase high-NA DOF. This has driven imec's research into exploring new absorber materials, that either have a different EUV refractive index (low-*n* materials such as RuTa or PtMo allowing for attenuated phase shifting) or a high EUV extinction coefficient (high-*k* materials such as PtTe or Ni with high absorbing capability). For each of the material types, thickness optimisation is required to give the best imaging trade-off.



4
Schematic representation of an anamorphic mask, and main orientations of mask and wafer during printing on a 0.55NA scanner. (Courtesy of ASML)

Anamorphicity

High-NA EUV lithography comes with a significant redesign of the optics within the scanner, allowing light with larger angles of incidence to hit the wafer – giving the system a higher resolution. At equal scanner magnification (actually, demagnification), this would come with a draw-back. Light with higher angles of incidence will hit the mask as well and, without action, this would dramatically worsen the 3D mask effects.

One approach to overcome these additional shadowing effects would be to increase the mask magnification from its historical 4x to 8x, in combination with using larger mask blanks. But abandoning the original 6-inch x 6-inch mask dimensions while preserving a high mask quality would dramatically impact the mask industry.

To minimise that impact, ASML and Zeiss have introduced anamorphic optics, with different magnification in the *x*- and *y*-directions (4*x* and 8*y* (*y* being the scanning direction), respectively). The 6-inch mask is preserved, but its design is stretched in one direction (Figure 4). The increased magnification (in one direction) cuts the image field size (i.e., the part of the wafer that is exposed in one step) to one half, so the scanner may end up printing the features on only part of the device. This is especially true for chips with larger die sizes, imposing a constraint on how these chips need to be designed.

For the chips with larger die sizes, chipmakers must resort to a technique called stitching. One part of the pattern is exposed with one mask, the next part with a second mask, and the two masks are stitched together. Imec investigates methods for improved stitching, for example by reducing the so-called transition zone that inherently exists between both masks. On the hardware side, ASML has worked towards accelerated mask and wafer stages to compensate for the loss of productivity caused by the half-field imaging.

Pellicle development

In lithography, the photomask is usually mentioned in the same breath with the pellicle – the membrane used to protect the mask from contamination during high-volume semiconductor manufacturing. It is mounted a few millimeters above the surface of the photomask so that if particles land on the pellicle, they will be too far out of focus to print.

Developing an EUV pellicle is however not straightforward. A major challenge generic to all EUV scanners is to make the pellicle absorb as little as possible to maintain the throughput and economics of EUV lithography. In addition, the pellicle must be able to survive exposure to the increasing EUV power of future lithography tools, including the high-NA EUV lithography tools – for which the 8x magnification comes with the benefit of reduced power density on pellicle and mask level.

ASML has engineered a pellicle with 90% transmission, which can handle 380 W source power and is fully compatible between the low-NA and high-NA platforms. While imec, in collaboration with its partners, has developed an innovative CNT-based pellicle solution (Figure 5) that has potential to survive scanner powers beyond 600 W. The CNT (carbon nanotube) pellicle feasibility was already successfully demonstrated through use on the EUV NXE:3300 scanner at imec. The team is now working to extend the lifetime to enable a high-productivity pellicle solution suitable for next-generation EUV lithography tools, including high-NA, with its strongly increased reticle acceleration.

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A full-sized CNT-based pellicle similar to those exposed in imec's NXE:3300B.

More mask issues

The imec team also focuses on other mask-specific issues, such as mask lifetime. Masks are subject to carbon growth when stored, and this affects the critical dimension of features printed on the wafer. The effect is observed to depend on the storage conditions and can be reversed by EUV exposure.

Another challenge relates to the increasing contribution of mask deficiencies to the stochastic failure probability. The surface roughening of the mask's multilayer, which increases with mask ageing, is observed to play a crucial role. This drives the research of alternative multilayer 'mirror' materials. In addition, more than before, small mask imperfections translate into errors observed after wafer printing, as a direct consequence of scaling. All this urges the need for massively quantifying the mask contribution to the wafer imaging performance.

In addition, other methods for writing the masks with more precision and smaller resolution are being investigated, including multibeam mask writing, which allows for different (so-called curvilinear) mask shapes.

AttoLab

The need for speeding up learnings on thin-resist imaging was one of the reasons why imec decided to invest in AttoLab, a joint project with US-based KMLabs. The lab allows us to explore the fundamental dynamics of photoresist imaging under high-NA EUV lithography conditions before the first 0.55NA EXE:5000 prototype from ASML becomes available. Within the AttoLab, the high-NA exposure at 13.5 nm is emulated with a bright, coherent, high-harmonic EUV source in an interference-type of set-up.

Recently, with a Lloyd's-Mirror-based interference set-up for coupon (test specimen) experiments (Figure 6), 20-nm pitch lines/spaces could for the first time be successfully imaged at imec in a metal-oxide resist. In this arrangement, light reflected from a mirror interferes with light directly emitted by the 13.5-nm high-harmonic source, generating a finely detailed interference pattern suited for resist imaging. The pitch of the imaged resist pattern can be tuned by changing the angle between the interfering light beams. This set-up supplies the critical learnings for the next step: expansion to a 300-mm wafer interference exposure that theoretically can go down to an unprecedented 8 nm pitch.

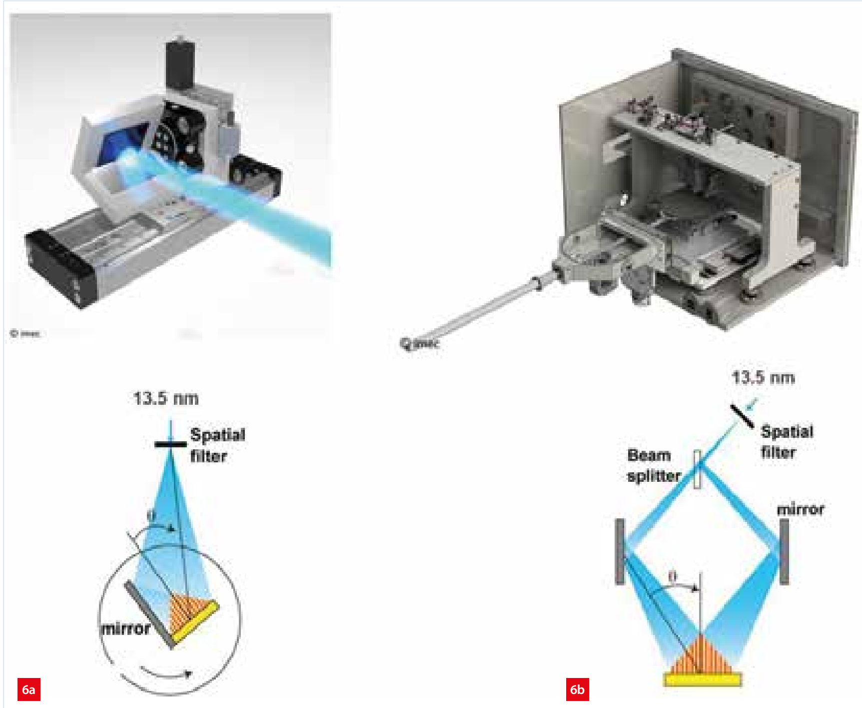
While ASML's scanners are designed for mass production of chips, the interference type of tools as used in the AttoLab will never achieve the required full-field throughput. But with these 13.5-nm femtosecond-enveloped attosecond laser pulses, imec is pursuing a different goal, i.e., using a variety of techniques, to study EUV photon absorption and ultrafast radiative processes that are subsequently induced in the photoresist material, and learn more about the critical stochastic print failures.

Conclusion

The move to high-NA EUV lithography presents a major opportunity for the lithography community to jointly tackle the challenges and to prepare for the tool's introduction in only a very short time frame. Together with ASML in a joint High-NA EUV Lab, imec is focusing on the infrastructure preparation that comes along with high-NA scanner development. For that purpose, imec is relying on and invites all material and equipment suppliers to contribute to the establishment of a complete high-NA ecosystem. The reward for all these efforts will be big, as the 0.55NA EUV lithography tool promises to advance Moore's Law towards 2-nm technology generations and beyond.

Acknowledgements

This work is the result of the collaborative effort of the imec advanced patterning team, in close collaboration with imec's equipment and material suppliers.



Schematic representations (not to scale) of AttoLab measurement set-ups.
(a) Lloyd's Mirror set-up for high-NA EUV interference coupon experiments.
(b) Interference chamber for full 300-mm wafer experiments.

PICOSECOND ULTRASONICS

Applying ultrasound in the Megahertz range for the investigation of the human body is a well-known medical practice. But using ultrasound to study nanometer structures requires ultrahigh sound frequencies in the Gigahertz range. Delft University of Technology researcher Gerard Verbiest and his team succeeded in reaching vertical nanometer accuracies thanks to the photoacoustic effect. But achieving these accuracies in lateral directions required a second trick: the application of an atomic force microscope.

FRANS ZUURVEEN

In the field of nanotechnology, structures have to be investigated with a resolution of a few nanometers. Existing imaging methods working with either electrons or photons have the disadvantage of not being able to penetrate deep into materials. Moreover, materials like silicon are totally opaque for electrons or photons – i.e. at visible wavelengths; silicon becomes transparent at a wavelength of ~1 μm wavelength, which is however too large for nanometer-scale imaging. And the situation is even worse for metals, which is why ultrasound can help to 'look' deeper into materials with nanometer resolution.

Photoacoustics

Already in 1880, Alexander Graham Bell experimented with sound waves, aiming to reach long-distance signal transmission. He invented the 'photophone', which enabled the transmission of vocal signals by reflecting sunlight from a moving mirror to a selenium-based solar receiver. The essence of his discovery was the awareness that absorbed visible light may cause structural changes inside materials, resulting in the emission of acoustic waves.

Bell did not really understand the origin of these acoustic signals, but today we know that they originate from the local heating of the lattice structure inside materials. This so-called photothermal mechanism causes the generation of acoustic waves in materials, which can be observed by sensitive sound sensors.

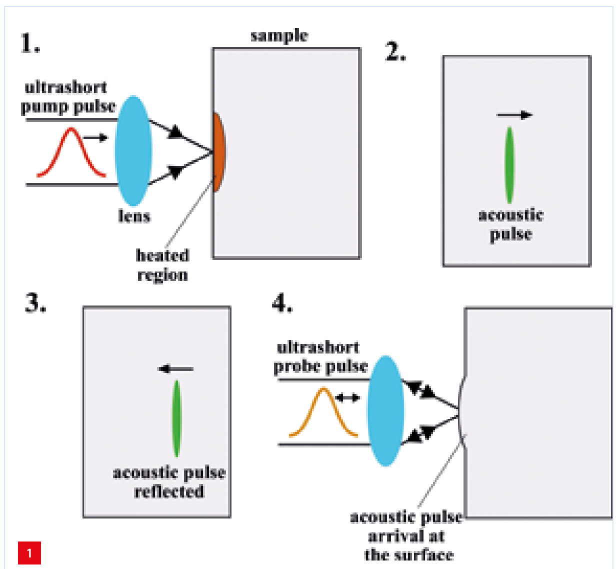
From piezo to light

Already for a few decades, acoustic waves, generated by piezo transducers, have been applied in a highly useful medical aid utilising acoustic 'echoes'. Among other clinical applications they facilitate the widely practiced examination of pregnant women. The frequencies involved here correspond with wavelengths of about 0.1 to 1 mm, depending on the material. For example, in water the wavelength at a medical ultrasound frequency of 10 MHz would be 1,500 ms^{-1}/10 MHz = 150 μm.

Upgrading the ultrasound resolution to the nanometer range requires acoustic signals with extremely short wavelengths, even down to 100 nm, and thus frequencies in the GHz range. In water, see the example above, a wavelength of 150 nm (i.e. a factor of 1,000 lower) would require a frequency of 10 GHz. Piezo transducers are not able to generate such short acoustic waves, so the photoacoustic effect is employed, using femtosecond light pulses. Such pulses are absorbed by the material within 1-2 ps, resulting in an acoustic wave with a duration of 1-2 ps. This research field is therefore called 'picosecond ultrasonics' [1].

Ultrashort optical pulses

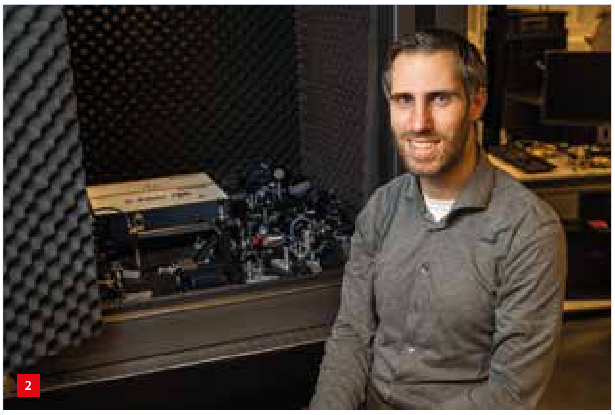
These ultrashort optical pulses are called 'pump pulses'. When these pulses hit the surface of an opaque solid,



The principle of photoacoustics.
(1) A pump pulse of light induces changes in the material structure (heated region).
(2) An acoustic pulse is generated and starts travelling through the material.
(3) The acoustic pulse is reflected from an (internal) interface.
(4) The reflected pulse ('echo') arrives at the surface and is 'detected' by an ultrashort probe pulse; see the text for a more detailed explanation of the detection principle.

AUTHOR'S NOTE

Frans Zuurveen, former editor of Philips Technical Review, is a freelance writer who lives in Vlissingen (NL).
This is his last contribution to Mikroniek; see also page 32.



Gerard Verbiest with his photoacoustic set-up. (Photo: TU Delft)

some optical energy is absorbed and converted to heat. Figure 1 illustrates this process, with the final panel showing the reflected acoustic pulse returning (as a kind of 'echo') at the material surface.

Gerard Verbiest (Figure 2) and his team in the Precision and Microsystems Engineering department at Delft University of Technology (TU Delft) participate in this research field and succeeded in realising the emission of these ultrashort acoustic waves by means of the photoacoustic effect.

This phenomenon is highly effective in the investigation of thin films and nanostructures because the acoustic penetration depth is much larger than the optical absorption depth of 10 to 50 nm. The generated acoustic pulse can be modelled as a superposition of longitudinal plane waves of different wavelengths travelling normal to the surface, which is fundamental for the realisation of depth resolutions with nanometer accuracy. When, for example, two interfaces within the material under study each generate a reflected signal ('echo'), the time elapsed between the detection of the two successive echoes can be converted into the distance between these two interfaces by bringing the (material-dependent) velocity of sound into the equation.

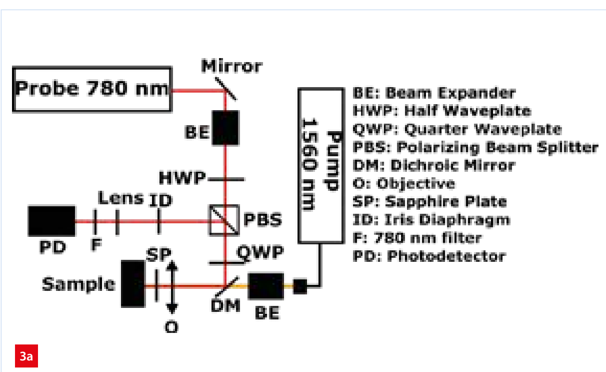
Practical realisation

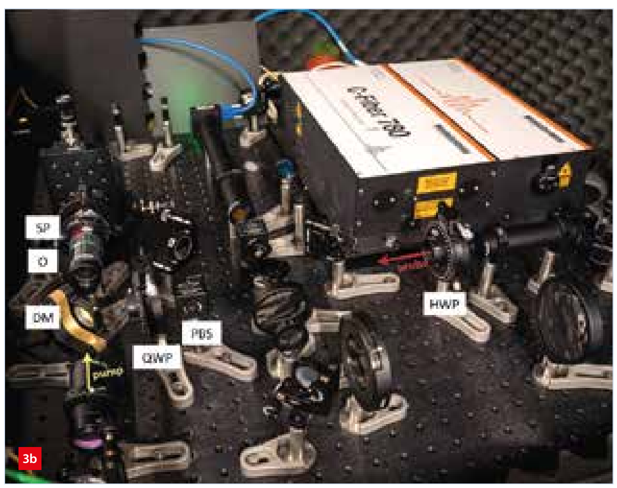
Among other researchers, the Delft team succeeded in translating the theoretical principles described above into an experimental set-up [2]; see Figure 3. The detection of the acoustic pulses essentially builds on the set-up of a conoscope, an optical instrument designed to study surfaces by exciting interference patterns in (visible) light. In this application, an objective lens focuses light onto a sapphire crystal, which exhibits two different refractive indices (birefringence).

Figure 3 shows the Delft set-up with two femtosecond erbium laser systems: a 1,560-nm laser pump and a frequency-doubled 780-nm probe laser. The drawing shows how the probe beam is expanded to an appropriate size and passed through a half-wave plate HWP to achieve the correct polarisation for the polarising beam splitter PBS. A quarter-wave plate QWP then shifts the polarisation into an elliptical state, which is required to exploit the birefringence.

After passing a dichroic mirror DM, where the pump path joins the probe path, the two beams are focused on the sample through a sapphire plate SP. The pump beam is absorbed by the sample to generate acoustic waves in the sample and a part of the probe pulse, modulated by the acoustic echo signal, is reflected. The conoscopic interferometry takes care of the detection of the reflected probe pulse: the quarter-wave plate QWP restores the linear polarisation, while PBS filtering then leaves one polarisation direction to hit the photodetector.

The silicon-based photodetector has a bandwidth of 250 MHz and is able to detect individual probe pulses. The ultimate aim is to reach vertical nanometer accuracies in opaque materials. To demonstrate the performance, the Verbiest team simultaneously developed another application example; see the text box on the next page.





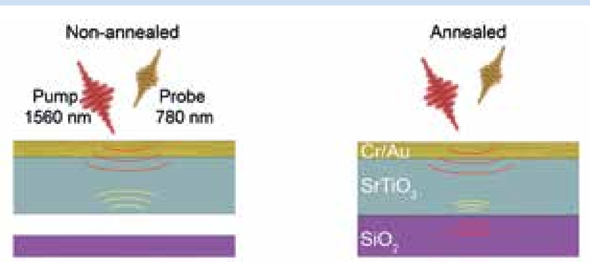
Photoacoustic set-up, with labelling of the main components.
(a) Schematic drawing; see the text for explanation.
(b) Practical set-up.

Demonstration

In Delft, photoacoustics have also been applied to improve pressure sensors for MEMS technology (microelectro-mechanical systems) [3]. The challenge was to find ultrathin membranes that show absolutely no gas leakage. 2D sheets of graphene (a regularly arranged configuration of carbon atoms, with one-atom thickness) promised to be ideal for this application, but have not been available in a sufficiently convenient format up until now.

Figure 4 shows how Verbiest tested the adhesion of a new pseudo-2D material: free-standing $SrTiO_3$ (STO, for short). STO is mechanically robust, just like graphene, and can be produced easily in large sheets using epitaxial crystalline growth, which reduces the risk of gas leakage. However, similar to the traditional 2D materials, free-standing STO has a weak (non-bonded) van der Waals interaction with the substrate causing gases to leak along the interface. For microscale pressure-sensing applications using 2D materials, this leakage is a major problem. Better adhesion between the 2D material and the substrate was expected to improve the resistance against leakage.

This schematic figure shows how ultrafast acoustic pulses can be applied to measure the adhesion of STO to a substrate of SiO_2-covered Si. Moreover, the set-up was used to investigate the effect of annealing of the STO. Did it help



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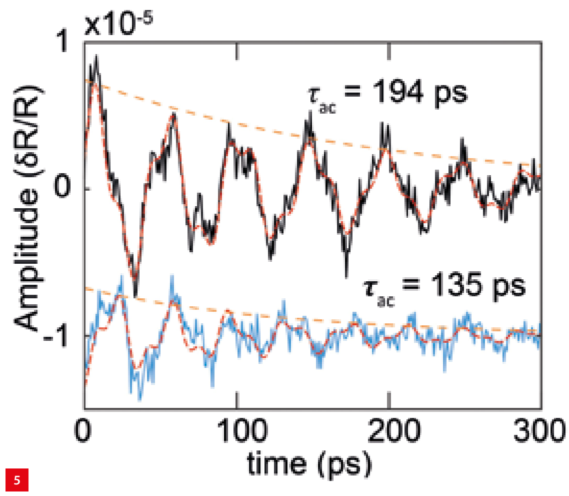
Cross-sectional illustration of pump-probe measurements in a non-annealed $SrTiO_3$ (STO) sample on the left and an annealed STO sample on the right. Here, the STO layer measures 82 nm in thickness, while the gold layer on top measures 33 nm.

to improve the resistance to leaking? Yes, because it appeared that annealing causes the forming of extra oxygen combinations between STO and SiO_2 molecules, such that they 'share' oxygen atoms.

Figure 5 shows the results of the acoustic measurements: amplitude-versus-time curves for different annealing conditions. Without going into greater details of the meaning of the various curves, the meaning of the general trend highlighted by the dashed lines can be explained as follows. The red dashed curves are fitted to a superposition of damped sine functions and the orange ones depict the exponential decay. This exponential decay is a measure for the energy loss of the acoustic waves at the STO-SiO_2 interface, which strongly depends on the adhesion. From the exponential decay time τ_{AC}, this adhesion can be quantified, with the decrease in Figure 5 showing that the annealing greatly improves the bonding between the STO and SiO_2.



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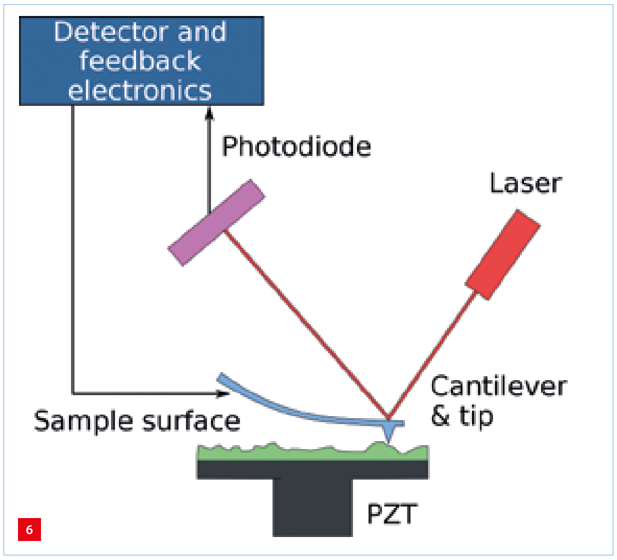
Graphical output of measurements with the set-up of Figure 4, showing the effects of the sound waves reflected from the STO-SiO_2 interface and optically sampled at the top surface of the sample. The black curve is for the non-annealed sample, the blue one for the annealed sample. See the text for further explanation.

Atomic force microscopy

Ultimately, the research resulted in the practical realisation of a vertical (Z-direction) nanometer-resolution opto-acoustic material inspection tool. Nevertheless, a solution still had to be found to reach lateral nanometer accuracy. It was not necessary to find a fresh, new approach to this problem because lateral nanometer accuracy can already be achieved with an atomic force microscope (AFM).

The resolution of an AFM as realised in practice, enabled by accurate piezo-electrical drives in the lateral X- and Y-directions, depends on the dimensions of an extremely sharp cantilever tip. Its radius amounts to only a few nanometers. In the AFM, an optical beam deflection method can be applied to maintain a constant distance between the tip and the surface of a sample, see Figure 5. In this set-up, the tip is mounted at the end of a beam of which the nanometer displacements are detected with



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Schematic drawing of a cantilever-based AFM. PZT (lead-zirconate titanate) is a piezoelectric ceramic widely used for nanopositioning (in this case, in the lateral directions). (Source: Wikipedia / OverlordQ).

a four-quadrant photodetector measurement system. This results in a nanometer-resolution height map of the sample surface.

Integration of an AFM into the picosecond ultrasonics set-up of Figure 3 means that the sample is replaced by an AFM cantilever system, as shown in Figure 6; see also [4]. The backside of the cantilever tip is then simultaneously illuminated by a laser for the conventional AFM optical beam deflection measurement and the pump and probe pulses for photoacoustic measurement. Thus, the integration enables a two-stage probing process: an AFM tip probes the 'real' sample, in either contact or oscillating non-contact mode, while the picosecond ultrasonics set-up probes the acoustic reflections coming from the tip and the sample. Further details of this combination of interferometry and optical beam deflection cannot be provided here.

To conclude

Looking into non-transparent materials appeared to be an absolute impossibility in the realm of nanotechnology. But Gerard Verbiest and his Delft team are now set to make it reality by building on the 'old' expertise of photoacoustics as explored by the famous 19th-century inventor Bell. By combining the high vertical resolution enabled by photoacoustics with the high lateral AFM resolution, they are developing a new nanometer-resolution inspection tool for which novel applications can be explored.

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THE BRAINPORT WAY

The Brainport region is a world champion in manufacturing high-tech advanced machines. Just look at ASML's lithography machines or Philips products in healthcare, says Naomie Verstraeten, chief Innovation & Technology at Brainport Development. Staying a world champion is another thing; it does not just require knowledge of the various disciplines. There is an entire system behind it. Hardware and software play a role in this, but so do the various engineers within the companies and their suppliers. In short, systems engineering connects those disciplines and the people around them.

CORINE SPAANS

Rare

In Naomie Verstraeten's view, a systems engineer plays a crucial role in the success of this region. "Such a person possesses a rare competency. Often it is linked to individuals and the knowledge remains within one company."
That it is a rare competency is demonstrated, for example, by the number of vacancies for systems engineers or systems architects in the Brainport region. "That number only continues to rise, these vacancies are difficult to fill," she says.

What is systems engineering (SE)?

SE is a structured way of working to develop complex systems. It is a key technology and a core competency that underlies the success of the high-tech ecosystem in the Brainport Eindhoven region. Being able to work systematically and to create an overview is the basis on which increasingly complex systems and machines can be developed in the region. From that overview, it is possible to zoom in on details and zoom out again, organise information differently, make connections and act on them. It, therefore, contributes significantly to the various key technologies such as Artificial Intelligence (AI). Being able to deal with this multidisciplinary nature, which is increasingly demanded of the high-tech industry, is an SE issue par excellence.

Verstraeten is not the only one to be convinced of the importance of SE for the region. April 2021, she signed a collaboration agreement with Wouter Leibbrandt (TNO-ESI), Marc Hamilton (High Tech Systems Center (HTSC), TU Eindhoven), Hans Meeske (Holland Innovative), and Hans Evers (VDL ETG); see Figure 1. Their goal is to achieve a better definition of the concept, promote the exchangeability of SE processes in the region, and set up a more focused education system.

"Bumping your nose in a controlled way"

Step one in this collaboration was to arrive at "a clear description of the Brainport way of systems engineering". This phase was completed at the end of last year. Bert van Appeven, programme manager at Holland Innovative, and Joris van den Aker, SE programme manager at TNO-ESI, were the project leader and project architect, respectively. Mira Dreessen was responsible for the project at Brainport Development. Together with systems engineers from ASML, Philips, Thermo Fisher Scientific, and Canon Production Printing, the three made a blueprint of what makes SE unique within the Brainport region.

SE is not something you only learn from books, according to Van den Aker. "You learn it mainly by doing." Within TNO-ESI, Van den Aker provides education and training in the field of SE. "You want to get people to turn their noses up in a controlled way." Training is necessary, but Van den Aker says it is mostly a cross-pollination between industry and education. "It's good to eventually develop a curriculum for SE. But what it should look like, both in terms of content and work formats, that's still a challenge."

Van den Aker has worked in the high-tech world for more than 20 years. "If there's one thing I've learned there, it's that things don't become a success by themselves. You have to have a plan for the future to remain a market leader. Determine where you want to win the race and how. A plan that justifies the investments that are needed. The investments in the high-tech industry are huge. SE has a clear added value in all of this."

Competitions

The high-tech world is characterised by complexity (Figure 2) and dynamism, says Van den Aker. "It's much more than developing a high-quality product such as an electron microscope or a wafer scanner. Of course, it's already a challenge to develop good mechanics, electronics, and software, but you also have to be able to place that

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At the High Tech Campus Eindhoven, after the signing of the collaboration agreement, from left to right: Naomie Verstraeten (Brainport Development), Wouter Leibbrandt (TNO-ESI), Hans Meeske (Holland Innovative), Rutger van Poppel (Brainport Development), and Marc Hamilton (HTSC). Not in the photo: Hans Evers (VDL ETG). (Photo: Bram Saeys)

in a broader market and business perspective. Within this whole range, the complexity and dynamics are enormous."

For Van den Aker, an important question for the Brainport region is which "games" to play. "Which competitions do we want to win within our ecosystem of companies, government, and educational and research fields? What does this require of our way of collaborating? How and where will we earn our living in the future? What needs to happen for that to work out as we want it? A systemic approach is important here. To me, that is SE."

Like Verstraeten, Van den Aker believes that the Brainport region is a world champion in making highly advanced systems "where knowledge, capital, and people come together." It's all about companies that sell their products all over the world, in a globalising market, he states. "That game is getting more and more complex. It's important to know what we're all about. Developing one language. Knowing why we do things the way we do. Finding the connection between market, business, and technology."

2

Developing a complex wafer handler for ASML calls on VDL ETG's systems engineering expertise. (Photo: RGB Producties)

Culture

Van den Aker, Van Appeven, and Dreessen did a survey among systems engineers from ASML, Philips, Thermo Fisher Scientific, and Canon Production Printing, asking them to describe what SE currently entails within their companies. To do this, the three used the so-called BAPOC model: Business, Architecture, Process, Organisation, and Culture. Van den Aker: "This is not a new model; we have been using it for years to organise and structure information. We are distinctive in this region primarily because of the culture, and this is reflected in the way we develop systems."

Dreessen: "It was nice to see that the people who are already experts in SE heard from the others how they look at it. Where one expert thought that something was quite normal, it turned out that this was not yet the case for the other. That gave a nice insight into why it's sometimes difficult to work together in the value chain."

For Van den Aker, the outcome was actually a confirmation of what he already thought. "We're indeed seeing a very creative, experience-driven, professional way of SE again. The knowledge is primarily secured in people and in relationships between people. To a lesser extent in rigid processes and standards." A difference with, for example, the SE approach from the aerospace industry in the US. "That approach is much more based on a process and works with formal approaches. Although newcomers, such as Space X, have a different, disruptive approach."

Human-driven

Van Appeven: "You see a very big 'can do' and 'no nonsense' mentality in this region. Not getting too hung up on processes. People here talk about the result and the issues that come with it." Another characteristic appears to be a highly developed project organisation. "The project team is a clear reflection of the product that has to be made. If, for example, it's about a superfast printer, then there is an owner in the team for each of its functions. This isn't entirely unique in the world, but it gives you an organisation with clear responsibilities, without blind spots or overlaps."

What does make this region unique, according to Van den Aker, is the human-driven way of working, based on professionalism (Figure 3). "That's actually typically Dutch. It enables us to build complex systems. We're allergic to hierarchy. If you're very hierarchical or very process-oriented, then bureaucracy and slowness come in. Slow isn't something you want to be in this rapidly changing high-tech world."

For Van Appeven, this blueprint – which, for now, is not yet intended to be shared with the outside world – marks the start of a brief period of "reflection", in his own words. Whereas the blueprint focused on the major stakeholders in the region, the next phase will focus on the entire supply chain. "How do you make sure they're hooked up in the SE process?" Exactly what the assignment for that phase will be, remains to be seen. Phase 3 is about defining a curriculum. "In whatever form it takes. That could be in a bachelor's, master's, or a post-graduate, we don't know right now."

Visible

"I think it's especially interesting to look at how you can give SE a place in lifelong development early on," Dreessen adds. "Here you can think of an additional master's degree or programme, or also modules that can be added to existing programmes."

According to Verstraeten, the blueprint makes the specific Brainport elements clear. That is necessary to make ideas into something visible and tangible. "People who are a systems engineer or systems architect by nature are hard to find. The more we become aware of the characteristics, the better we can train people to become real systems engineers."

What makes this region unique, according to Joris van den Aker, is the human-driven way of working, based on professionalism. (Photo: Brainport Development)

ProCleanroom – flexible specialist for cleanrooms and laminar flow cabinets

ProCleanroom specialises in cleanroom and laminar flow solutions for tech companies and research organisations in various industries. The company is located in Valkenswaard (NL) in the heart of the high-tech region in the Benelux. ProCleanroom offers design, manufacture, installation and validation of cleanrooms and flow cabinets, and operates in accordance with the strictest European regulations.

ProCleanroom has its roots in the high-tech industry. As true professionals, they understand better than anyone else the needs and requirements relating to handling critical processes. Their aim is to create the most innovative solutions for energy-efficient operation in an ultra-clean environment. ProCleanroom presents itself as a partner in the field of contamination issues, helping customers to develop and maintain their expertise, as well as excel in their field.

Cleanroom solutions

ProCleanroom provides a full range of clean air solutions, ranging from entry-level, compact, mobile cleanrooms to large-scale, high-end, fully-flush hardwall cleanrooms for the most demanding applications. It is ProCleanroom's philosophy that the best cleanrooms and flow units are built around the developments taking place within the environment itself, taking the critical processes of its customers as the starting point for the development of cleanrooms and laminar flow units. Using their broad knowledge and experience, the ProCleanroom engineers analyse the critical processes and define the requirements the products need to meet, to create an optimal solution that seamlessly fits the customer's needs.

Benefits of ProCleanroom's clean-air solutions

- High efficiency and functional design.
- Small, entry-level to high-end, large-scale projects – fit for purpose.
- Both custom work and standard solutions possible.
- Lowest operational cost in the market.
- Compliance with the international cleanroom standard ISO14644-1/3.

Flow cabinet solutions

When a clean environment workstation is required, ProCleanroom offers a solution with its laminar air flow (LAF) units. Through unidirectional airflow, a particle-free environment is realised that allows critical processes to run according to the highest standards. The air in the LAF unit is (nearly) free from particles and micro-organisms, while the unit protects against harmful product and process contamination. Along with the standard programme, ProCleanroom also offers the possibility of customisation.

Accessories and consumables

In addition to the full design, manufacture, installation and validation of cleanrooms and flow cabinets, ProCleanroom supplies cleanroom furniture, equipment, accessories and consumables. A webshop offers access to thousands of specialist cleanroom products to support cleanroom needs.

High-level performance

ProCleanroom's case studies provide evidence of successful cooperation with many organisations in the Netherlands and Europe. For each sector and situation, ProCleanroom provides the best solution, driven to perform at the highest level. Its products score the highest for sustainability and efficiency, while the lowest operating costs and lowest cost of ownership are guaranteed.

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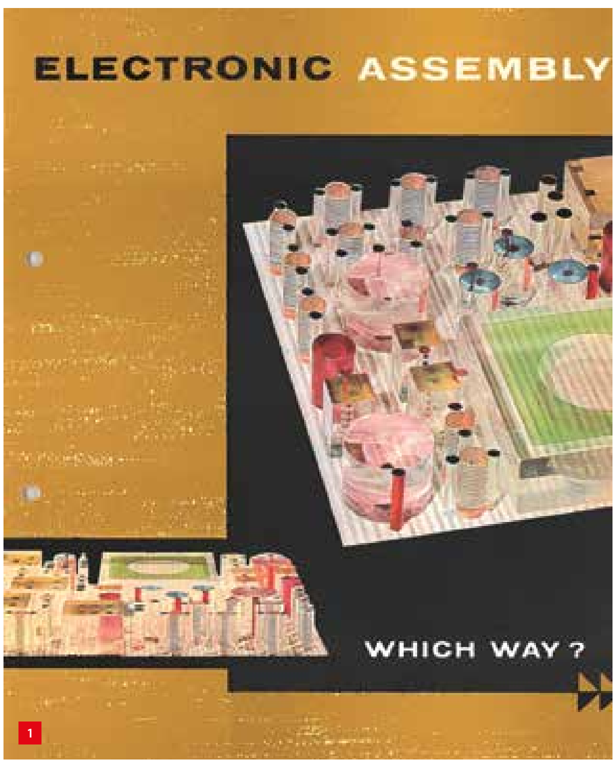
A BROAD VIEW: FUNCTIONAL THINKING AND CLASSICAL EDUCATION

The work of Wim van der Hoek, who with his principles of light, stiff and statically determined mechanical design is one of the founders of Dutch precision engineering, is an inexhaustible source of inspiration. In addition to his professional career, his personal life is also fascinating. The Dutch-language book "Wim van der Hoek (1924-2019) – A constructive life", published over a year ago by DSPE, bears witness to this. Mikroniek is starting a series of articles with an anthology to inspire beginner and advanced mechanical designers. This first article illustrates the broad perspective Van der Hoek always had in his life and work.

In 1949, when Van der Hoek had not yet completed his studies in mechanical engineering at Delft University of Technology (NL), he joined Philips in Eindhoven (NL). He started working in the department *Bedrijfsmechanisatie* (Production Mechanisation) of the Apparatenfabriek (Appliances Factory), later the *Hoofdindustriegroep* (Main Industrial Group) RGT (Radio, Gramophone and Television). It was here that he studied the dynamic behaviour and positioning accuracy of mechanisms and machines, because these machines needed to become increasingly faster and more accurate.



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In 1961, a brochure was published on 'Which Way', the umbrella vision of electronics assembly, co-developed by Van der Hoek, from the first radios to the distant future. (Source: Philips Company Archives)

"Electronic Assembly – Which Way?"

Gradually, in the 1950s, the first semiconductors made their appearance and Van der Hoek immersed himself in the assembly of electronic products. His work became characterised by progressive miniaturisation – symbolised by the portable, 'transistorised' radio – and the rise of integrated circuits (ICs). Together with his colleagues, Van der Hoek developed an overarching vision, which was published in 1961 in the brochure "Electronic Assembly – Which Way?" (Figure 1). It described production technologies in increasing degrees of miniaturisation and automation: from the manual assembly of classical components on a metal chassis to the automatic assembly of miniature components, and the at that time still-to-be-developed ICs on a standardised printed circuit board.

In 1968, Van der Hoek wrote about the great opportunities that technological IC developments offered the electronics industry. According to him, the main benefit was not to be found in switching technology, as almost everything could be realised conventionally, but in reliability and cost price, and therefore in economically viable mass production. It struck him, however, that the choice of which parts of a circuit to put on an IC was determined mainly by technical-physical considerations and not by function. An illustration of this, according to him, was the large number of outputs that an IC had.

Further integration

This observation led him to advocate for extending integration one step further to the level of FUs (functionally defined units). In FUs, ICs could be incorporated together with the parts that were missing in an IC, such as adjustable resistors, high-impedance and very-low-impedance resistors, large and adjustable capacitances, and self-inductances, as well as switches that were not part of an IC. Thus an FU was the "logical consequence and completion

At the Stedelijk Gymnasium Leiden, Wim van der Hoek followed a classical education, including "that damn Greek grammar". (Source: Heritage Leiden, www.rapleiden.nl/gebouw/gymnasium-43)

of the IC", functionally rather than technologically, and had a limited number of inputs and outputs. "This small number of connections means almost proportionally greater reliability in device assembly and fewer traces on the prints." Van der Hoek acknowledged that the necessary technological development still had to take place in the FU field. That is why he presented his memo as an introduction to an initial, exploratory discussion between technologists of various kinds: "What can we do for device designers, device manufacturers and service people; won't they benefit more from FUs than ICs?"

Broad alignment

Two years later, he added the suggestion that the development of FUs should be done in broad coordination between Philips' various main industry groups. Here, he referred to two dangers, resulting from two human weaknesses: a focus on the short term at the expense of the long term, and a focus on one's own (sub)goals at the expense of common goals.

By way of illustration, he mentioned 'Which Way', which had been broadly established as a coherent system for electronics assembly in collaboration between dozens of Philips laboratories and other business units.
It "subsequently degenerated into specific RGT and even specific pocket radio technology, only recently (ten years later) to become established as the basis for long-term development of electronic assembly in the main professional industry groups". In short, taking the long view and keeping a wide perspective were required when it came to far-reaching developments.

Classical training

A wide perspective was something Wim van der Hoek had from an early age. In 1937, at the age of twelve, he started studying at the *Stedelijk Gymnasium* in Leiden, NL (Figure 2). He already knew that he was going to study engineering, but he also wanted to gain some general knowledge, the reasons for which he later, looking back, was able to clearly explain. "Well, I knew I was an engineer and always wanted to be one, playing and building with Meccano while earning money in the process, as it were. I also felt that I could learn and understand technology, that it would come naturally. All those other things, art, culture, literature, languages, history; well, I had to get into these subjects while I still could, before technology absorbed me. A blessed decision. And I did it intensely, sometimes with tears of rage over that damned Greek grammar, but in the end reading books voluntarily that were not compulsory for technical types...
In those days, when I wanted to state something with great seriousness and emphasis, I unintentionally jumped into hexameters and bound prose."

"Wim van der Hoek (1924-2019) – A constructive life"

After the passing away of Wim van der Hoek, in early 2019, DSPE took the initiative to publish a book (in Dutch) about the Dutch doyen of design principles (Figure 3). It covers Van der Hoek's formative years, including World War II 'adventures', his career at Philips and Eindhoven University of Technology, where he developed his breakthrough ideas on achieving positioning accuracy and controlling dynamic behaviour in mechanisms and machines, and their reception and diffusion.
It concludes with his busy retirement years in which he continued to tackle – technical as well as social – design challenges, believing that technology should support people.

Lambert van Beukering & Hans van Eerden (eds.), "Wim van der Hoek (1924-2019), Een constructief leven – Ontwerpprincipes en praktijklessen tussen critiek en creatie", ISBN 978-90-829-6583-4, 272 pages, published by DSPE, €49.50 (€39.50 for DSPE members) plus €6.50 postage.

His specialism, dynamic behaviour and positioning accuracy, was the main subject of his part-time professorship at Eindhoven University of Technology, from 1961 to 1984. There, he undertook the endeavour to enthuse freshmen for the mechanical engineering profession and to teach fourth-year students (some 600, over the years) mechanical design: construction as a confrontation between criticism and creation. In his lecture notes, he built on his research at Philips. He collected examples of designs that were lightweight, sufficiently stiff and play-free with regard to dynamics in his famous "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP), which he presented as a source of inspiration for upcoming and experienced designers. Now, the book about Wim van der Hoek conveys the same enthousiasm.

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NEW TEACHERS, NEW MOTIVATIONS, NEW TRAINING COURSES

Inventas is a leading training institute in the Dutch high-tech ecosystem. Recently, it has employed two new teachers, updated its 'classic' Design Principles training and introduced two new dynamics training courses. Underlying these developments is the ongoing miniaturisation in high-tech systems and the associated need for ever higher accuracies and, hence, better predictability of dynamic behaviour.

Sixteen years ago, mechanical engineer Jos van Grinsven, then a teacher of design principles at Fontys University of Applied Sciences in Eindhoven (NL), founded the Inventas training institute in Nuenen (NL). Nowadays, Inventas employs over a dozen experienced freelance (part-time) teachers to provide a wide range of mechanical engineering training courses for companies, large OEMs as well as SMEs.

The Inventas training portfolio ranges from Design Principles, Reading Technical Drawings, and Tolerance Analysis, to Machine Dynamics, Design for Manufacturing, and Consultative Advising for Engineers. The target group includes engineers at intermediate technical, higher professional and academic level. All training courses are tailored to the training goals of the individual students and are preferably presented in a classroom setting, for live interaction with a small group of (a maximum of ten) students and with lots of practical exercises.

Design Principles

As the cornerstone of the Inventas training portfolio, Design Principles is firmly based on the famous Dutch canon of (precision) mechanical design, with teachers such as Wim van der Hoek, Rien Koster and Herman Soemers. This training is concerned with creating a mechanical design that is lightweight and has the right stiffness and the right degrees of freedom. Questions to be answered: What are well-functioning constructions and modules for (accurate) movement and positioning? How do you apply elastic elements in your design? How do you make smart use of sheet metal and other materials? And so on.

The ultimate goal is to achieve the required dynamic behaviour while avoiding precision-disturbing phenomena such as play, friction, hysteresis, micro-slip and wear. Even high-precision machines exhibit friction, which causes static position indeterminacy, also known as virtual play. This phenomenon and its avoidance are becoming increasingly important due to process and product miniaturisation.

While Van Grinsven for many years presented the Design Principles training on his own, he recently decided to further intensify personal attention to students by forming a duo with a teacher who is new to Inventas, Arne de Roest. De Roest graduated in mechanical engineering at Eindhoven University of Technology (NL), in the group of Nick Rosielle, one of the champions of the ideas of Wim van der Hoek. After having worked as a mechatronic system architect and mechanical engineer at Prodrive Technologies in Son (NL), he now is a freelance (lead) mechanical engineer and system architect.

De Roest decided to become a part-time teacher because of his passion for knowledge transfer (Figure 1), drawing on his experience in solving precision positioning challenges in his daily work. "That is also what we ask of our students, to immediately apply what they have learned during the training in their daily practice and come back to the following training days with practical examples, which we then discuss."

Van Grinsven: "If a student presents a practical situation in a training course, for example a set of drawings of a device, Arne quickly arrives at the core of the problem with a few specific questions. Not everyone has that much technical insight." De Roest: "In that respect, I follow the approach that Van der Hoek and Rosielle have advocated; each time trying to put yourself in the position of the object you are designing, to understand how it works by asking yourself: what do I feel, how am I being pulled at, what positions am I fixed at, in what degrees of freedom can I move? And so on."

Over the years, students have come up with new questions, Van Grinsven and De Roest observe. About the circular

EDITORIAL NOTE

This article was based on interviews with Inventas director Jos van Grinsven and teachers Arne de Roest and Jurnan Schilder.

Arne de Roest teaching Design Principles. (Photo: Inventas)

economy, for example. "We contribute to this based on Van der Hoek's philosophy of creating as much effect as possible with as little material as possible – lightweight – and making a sustainable design that does not need to be replaced every five years. The less friction and play you allow in your design, for example, the more wear is prevented. We do not focus on the end of the lifecycle, on recycling, but rather on the beginning: making smart constructions that are sustainable, lightweight and energy efficient."

Current demand for the Design Principles training is also driven in part by the need for new platforms for machines and devices. "Companies have sometimes been working for decades with a platform on which they have continuously developed new versions. But because it has to be smaller, faster and more accurate, such a platform will no longer perform at a certain point in time and a completely new platform has to be designed. Standard off-the-shelf components and modules then no longer suffice for this, so mechanical engineers have to develop these themselves from scratch. That is why they first attend our training."

Consequently, new questions arise together with new motivations to follow the training. At the same time, Van Grinsven and De Roest are working on renewing the training itself, including an update of the teaching materials to make these even more practical. This may lead to an extension of the training duration, now four days spread over four weeks.

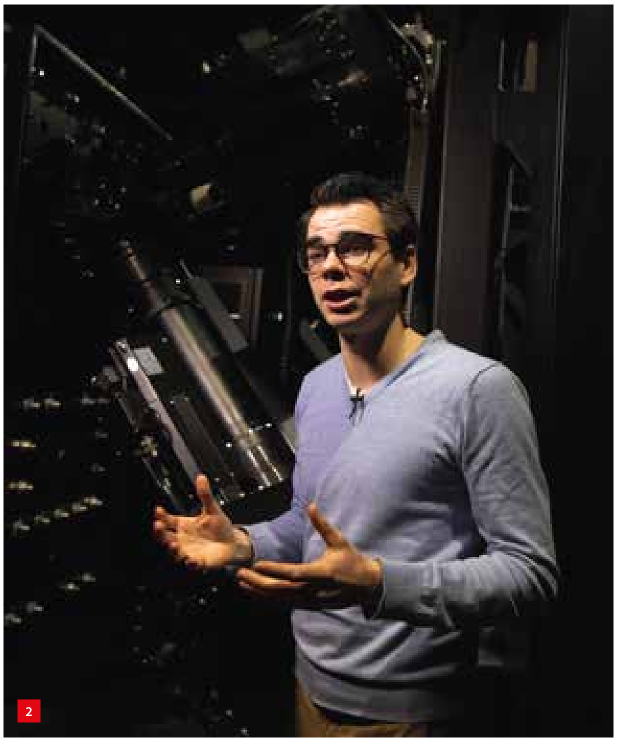
Dynamics

A completely new training course in the Inventas portfolio is Machine Dynamics, which was first offered in 2021. It is taught by a new (part-time) lecturer at Inventas; Dr Jurnan Schilder, assistant professor in Structural & Multibody Dynamics at the University of Twente (NL). In 2022, he will also teach the new Engineering Dynamics training course for the first time, which serves as an introduction to the domain of dynamics.

Schilder's research interests are in the field of flexible multibody dynamics, while his passion also lies in education (Figure 2, next page); in 2014, he was the winner of the University of Twente's Best Teacher Award. He prefers to work with a blackboard and chalk (or tablet and tablet pen), to create the flow of calculations and explain the subject matter step by step, in order to keep every student's attention – always without slides, like every teacher at Inventas working without PowerPoint.

Because of the tightening dynamic requirements in high-tech system design, and facilitated by the ever-increasing computer power, nonlinear calculations and 3D simulations are becoming ever more important for accurately predicting the impact of deformations and vibrations on machine behaviour. Ultimately, this leads to a convergence/combination of finite-element models and multibody models.

Here, multibody refers to the connection of individual (deformable) bodies through joints and other links, such as elastic elements. In principle, every object is multibody, Schilder admits. "But in the 1970s, finite-element modelling (FEM) and multibody modelling, for computational efficiency, have become separate branches of the computational engineering tree. On the one hand, FEM has become very popular with mechanical engineers to analyse individual bodies and derive mechanical and dynamic properties from their CAD models, given a particular load



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Jurnan Schilder presenting for the YouTube channel 'Theme Park Science', showing the motion simulator of 'This is Holland', the 'ultimate flight experience' in Amsterdam. (Photo: Dekate Mousa)

case and the associated boundary conditions. While on the other hand, systems engineers and control engineers, for example, use to reason in terms of multibody models with lumped masses and stiffnesses allocated to joints."

FEM can now be used to calculate properties for each body that is incorporated in a multibody model, Schilder explains. "This model is then built up in an absolute coordinate frame, in which the movements of the various bodies are described, while each body has a local coordinate frame in which its deformations are calculated. From the various FEM models, the elements of the overall mass-stiffness matrix of the multibody model can be calculated. The dynamic simulation of the multi-body model, covering a wide workspace (without linearisation), is then performed and the stresses and strains of the local bodies can be calculated in post-processing."

When system elements are getting lighter and more high-frequent vibrations are being introduced, while strokes are becoming bigger, this combined approach is required to model system dynamics in sufficient detail, in order to enable even faster movements without compromising accuracy. Application examples include extremely fast accelerating stages, robots with rotating arms, hexapods that can control a platform with six independent legs, the unfolding of solar panels for satellites in space, and roller coaster dynamics (Schilder's 'guilty pleasure' specialism).

The new Machine Dynamics training course covers the basic skills that mechanical designers must master to communicate well with a multibody model expert. Think of the principles of dynamics calculations and the distinction and connection between kinematics and dynamics: when can calculations be restricted to the kinematics and when have the dynamics to be incorporated? In the end, the students will be able to understand what happens when dynamics calculations are performed using one of the available commercial software packages.

Ultimately, the two training courses that Schilder now teaches, Engineering Dynamics and Machine Dynamics, are to become part of a series of four courses, which together cover the field of dynamics in increasing order of complexity. The last two training courses have already been developed and are now awaiting their debut in 2022: Vibrations, and Flexible Multibody Dynamics, in which Machine Dynamics and Vibrations come together to produce the state-of-the-art in dynamic systems modelling.

INFORMATION
WWW.INVENTAS.NL


FRENCKEN IS
'EMBEDDED' IN
TOP 10
HIGH-TECH COMPANIES
WORLDWIDE

RETIREMENT OF **FRANS ZUURVEEN**

After thirty years of collaboration, our valued freelance Mikroniek contributor Frans Zuurveen is saying goodbye. "He has written more than one hundred articles for Mikroniek, always interesting technically and at the same time very readable," Hans Krikhaar, president of DSPE, comments. "Besides the articles by academics and officials of high-tech companies, Frans' stories added an independent, practical touch to Mikroniek. See his final contribution on page 20 ff. Frans, on behalf of DSPE, I thank you for your numerous contributions and I hope you will enjoy – at the age of 85 – a well-deserved retirement."

Frans' farewell message

"Thirty years? Yes, for thirty years I've had the pleasure of contributing to the fine professional magazine Mikroniek. How did that come about? In September 1991, I had to leave Philips as part of the Centurion operation (a company-wide reorganisation led by CEO Jan Timmer, ed.). Fortunately, I had just reached the age of 55, which meant that I could take advantage of a fairly favourable financial arrangement. Nevertheless, the forced departure from my workplace at Philips External Relations was tough.

Then I got a phone call from – the sadly prematurely deceased – Jaap Verkerk, chief editor of Mikroniek at the time: did I want to collaborate on his magazine by looking for innovative topics for articles on precision technology? This marked the start of a new working life, changing over from an interesting job as a ghost writer for the Philips top management to an existence as a freelance writing entrepreneur. I started writing articles, not only for Mikroniek but also on travelling with our caravan and – later – campervan, with my wife as a talented photographer, and on many other subjects that challenged me to learn more about. So, I searched for the essence of a topic and tried to put that insight into words as clearly as possible for potentially interested readers. From my graduation in the year 1964, Philips offered me ample opportunity to enjoy technical challenges. I researched the cutting process in shavers, supervised the construction of precision parts for scientific instruments, especially electron microscopes, and worked in corporate mechanisation for professional tubes, including night-vision tubes and X-ray image amplifiers. In 1981, I retired from these management positions and chose a more creative job. I became writing editor of Philips Technical Review. Explaining physical inventions and research results to a worldwide audience led to knowledge and experience that would serve me optimally in my working life after September 1991.

Frans Zuurveen wrote about precision engineering for Mikroniek for thirty years. He also wrote about travelling, camping, water sports as well as history, for example in 2008 the chronicle of the church in Oost-Souburg in 'his' province of Zeeland (NL). (Photo: Ruben Oreel)

Back to my work for Mikroniek. I became increasingly connected with individuals and companies that specialised in precision machining, measurement techniques, and materials. I drew inspiration from various websites and later from conversations with specialists at the annual precision fairs. All of this has resulted in an estimated one hundred plus contributions. Have all those articles been read? I don't know, because actually I only remember a single response. At a precision fair a few years ago, someone addressed me with the question: "So are you the writer whose articles I see so often in Mikroniek?"

One grateful reader, however, is a very poor result. But in any case, since taking office more than 16 years ago, editor-in-chief Hans van Eerden has seen and read all my stories and often provided valuable comments. And what's certain is that many companies were grateful for the 'free publicity' for their business. And yes, I will never know how many techies ever drew inspiration from my writings.

Anyway, after thirty years of writing for Mikroniek, I have reached the age of 85 in reasonable health. A good time to put a stop to that work for Mikroniek. I enjoyed doing it and hope that readers did enjoy my efforts a tiny bit. I sincerely wish you as a reader and Mikroniek as a magazine the very best."

ECP2 BRONZE FOR **THERMAL & FLOW TECHNOLOGIST**

Joris Oosterhuis, senior technologist Thermal & Flow at Philips Engineering Solutions in Eindhoven (NL), has been awarded the Bronze certificate from the ECP2 programme, a European certified precision engineering course programme, which is a collaboration between euspen and DSPE. He is the seventh person to receive this certificate since the first one was presented in 2015. Jan Willem Martens, the founding father of the precursor DSPE certification programme, paid a surprise visit to Oosterhuis' home, to present him with the certificate and flowers.

Euspen's ECP2 programme grew out of DSPE's Certified Precision Engineer (CPE) programme, which was developed in the Netherlands in 2008 as a commercially available series of training courses. In 2015, euspen, DSPE's European counterpart, decided to take certification to a European level. The resulting ECP2 programme reflects industry demand for multidisciplinary system thinking and in-depth knowledge of the relevant disciplines. To promote participation, a certificate scheme was instigated. The Bronze certificate requires 25 points (one point roughly equals one course day); Silver requires 35 points and Gold 45 points, which qualify a participant for the title 'Certified Precision Engineer'.

Joris Oosterhuis studied Mechanical Engineering at the University of Twente (NL). "As a child I was already fascinated by things that work and move." In Twente he also obtained his Ph.D. degree in the field of thermal engineering. "The combination of energy and heat transfer with flow I find particularly interesting." The topic of his thesis: "Oscillatory flows in jet pumps: towards design guidelines for thermoacoustic applications". In 2016, he joined Philips Engineering Solutions as a technologist Thermal & Flow.

He immediately kicked off by following a training course on thermal effects in mechatronics, combining his own specialty with one of Philips Engineering Solutions' strongholds; mechatronic system design. "There I learned about high-precision applications of thermal & flow engineering, for example how to measure temperatures at mK precision and how to position and mount temperature sensors optimally." In the subsequent years he undertook the 'standard training package' of Mechatronics system design – part 1 and 2. "This allowed me to broaden my scope and to learn from the classical examples, such as the CD player and the wafer scanner."

In recent years, he widened his engineering perspective even further, with the Applied Optics – "more physics depth and more insight through the practicals" – and the Motion Control Tuning training courses. "Jointly with a few colleagues we refreshed our control knowledge. In a subsequent, internal training, we will translate this knowledge to the thermal domain."

Altogether, the five ECP2 training courses that Oosterhuis has followed thus far, all at The High Institute, earned him the Bronze certificate. "I was really surprised that such a big fuss was made about it. I would reckon every high-precision engineer in this region will over the years have followed this number of courses." This partly comes from his own motivation, and partly is due to the stimulus from his managers, who devote ample attention to training and coaching.

In any case, his extensive training has helped him in the wide variety of projects that he has worked on during the nearly six years he has now been with Philips. This ranges from the thermal design of a baby bottle warmer for Philips to the cooling of a Philips CT-scanner or the high-precision design of a thermally balanced module for an ASML lithography machine. For the latter, he has also followed an intensive (non-ECP2) vacuum engineering course. He is now aspiring to immerse himself in system architecture, adding even more to his post-academic curriculum.

WWW.ECP2.EU
WWW.ENGINEERINGSOLUTIONS.PHILIPS.COM

Jan Willem Martens handing over the ECP2 Bronze certificate.

ECP^2 COURSE CALENDAR

COURSE (content partner)	ECP^2 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	7 November 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	22 November 2022
Manufacturability	5	LiS	to be planned
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	to be planned
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	16 September 2022
Modern Optics for Optical Designers (T2Prof) - part 2	7.5	HTI	to be planned (Q1 2023)
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	29 November 2022
Finite Element Method	2	MC	3 March 2022
Design for Manufacturing (Schout DfM)	3	HTI	10 March 2022

ECP^2 program powered by euspen

The European Certified Precision Engineering Course Program (ECP^2) 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 ECP^2 certificate is an industrial standard for professional recognition and acknowledgement of precision engineering-related knowledge and skills, and allows the use of the ECP^2 title.

WWW.ECP2.EU

Course providers

- High Tech Institute (HTI)
  WWW.HIGHTECHINSTITUTE.NL
- Mikrocentrum (MC)
  WWW.MIKROCENTRUM.NL
- LiS Academy (LiS)
  WWW.LIS.NL/LISACADEMY
- Holland Innovative (HI)
  WWW.HOLLANDINNOVATIVE.NL
- Cranfield University (CRANF)
  WWW.CRANFIELD.AC.UK
- Univ. of Huddersfield (HUD)
  WWW.HUD.AC.UK
- National Physical Lab. (NPL)
  WWW.NPL.CO.UK

Content partners

- DSPE
  WWW.DSPE.NL
- Mechatronics Academy (MA)
  WWW.MECHATRONICS-ACADEMY.NL
- Technical Training for Prof. (T2Prof)
  WWW.T2PROF.NL
- Schout DfM
  WWW.SCHOUT.EU
- Systems & Software Academy (S&SA)

Additive Industries launches second generation

Last November, at Formnext, the world's largest international trade fair for additive technologies in Frankfurt, Germany, Additive Industries launched its portfolio of large-frame AM (additive manufacturing) systems and services. Additive Industries, a global player in large-volume metal printing systems, headquartered in Eindhoven (NL), develops and manufactures 3D metal printers for high-quality metal parts for aerospace, automotive, energy and high-tech equipment.

Innovations included the MetalFABG2 and the MF Calibrate tool for automated multi-beam qualification. The new MetalFABG2 offers double productivity, compared to previous models, with over 150 updates implemented, including optimised gas flow and heat management, updated process parameters and automated beam quality measurements. The MetalFABG2 is available in three versions: Core, Automation and Continuous Production.

In addition, Additive Industries presented several partnerships, such as with quality assurance expert Sigma Labs to realise PrintRite3D® integration of melt-pool monitoring; a real-time melt-pool analytics and monitoring solution that reduces waste, improves throughput and enables faster product development and part qualification. This integration is especially interesting for large and massive parts, giving indications of potential errors during production. It may become part of future qualified production processes, automating the quality control per part.

With AM software specialist Materialise, Additive Industries developed workflow improvements, including slicing of bigger data sets, faster processing and optimisation of dynamic laser assignment. Also, a partnership was set up with machinery equipment manufacturer and digital innovation specialist Makino for developing end-to-end AM solutions, aimed at rethinking production beyond printing, from part design to printing, all the way to final-part machining.

The new MetalFABG2 Continuous Production.

WWW.ADDITIVEINDUSTRIES.COM

Nobby Assmann wins a second Zeiss #measuringhero Award

Recently, the Zeiss #measuringhero Award 2021 winners were announced. Nobby Assmann won the award in the Smoothest Surface category, for managing to polish a product of hardened tool steel to a surface roughness of only R_a 540 pm and R_z 3.1 nm. It is the second #measuringhero Award for Assmann. The previous year, he won the award in the Outstanding Application - Smallest measured Component category, for a part of a hearing aid measuring 0.4 mm x 0.4 mm x 0.03 mm. "Both metrology and lapping/polishing are real passions of mine. It's fantastic to receive so much appreciation in both fields of work."

The smoothest surface was ground after wire-EDM'ing, then lapped in two stages as well as polished in two stages. Finally, it was polished with a process called CMP, chemical mechanical planarisation/polishing. Measuring the surface roughness was a challenge in itself. A confocal laser scanning microscope took a stack of pictures of the surface. Software made a 3D map of these pictures and then calculated the R_a and R_z values. In a forthcoming issue of Mikroniek, Assmann will reveal how exactly he achieved this award-winning surface roughness.

WWW.3DMETEN.NL (ASSMANN VERSPANINGSTECHNIEK)
WWW.ZEISS.COM/METROLOGY/CAMPAIGNS/MEASURINGHERO.HTML

Nobby Assmann placing the award-winning product under the Zeiss confocal laser scanning microscope.

Hexagon and Sciaky partner to unlock the potential of e-beam AM

Hexagon's Manufacturing Intelligence division has entered into a partnership with US-based Sciaky, a leading supplier of industrial metal 3D printing solutions and subsidiary of Phillips Service Industries, to enhance the innovative electron beam additive manufacturing (EBAM®) technology with predictive analysis tools. Sciaky's turnkey EBAM metal 3D printers use high-value materials, such as titanium, tantalum, and nickel-based alloys, to produce parts and structures up to 6 m in length. The EBAM process has produced large-scale parts significantly faster, cheaper and with less waste than traditional manufacturing methods, for some of the largest aerospace companies in the world.

Printing large parts composed of high-value metals can be tricky because material behaviours are tougher to predict for large geometries. To address this matter, Sciaky's unique Interlayer Real-time Imaging and Sensing System (IRISS®) enables closed-loop control of the EBAM 3D printing process to eliminate variations and improve its quality and production throughput by sensing and digitally self-adjusting metal deposition in real time, with precision and repeatability.

To further support EBAM's closed-loop control, Hexagon's Simufact solution has been validated to accurately simulate the thermal-mechanical behaviour of the directed energy deposition (DED) process, enabling users to analyse thermal history, stresses, strains, and distortions throughout the process, and optimise build set-up and process parameters virtually before deposition. Not long ago, it took months to complete high-quality simulations for these types of additive processes, but through their collaboration they now have the ability to make the same accurate predictions in days or hours, so the partners claim.

The Sciaky EBAM 110 DED system.

WWW.SCIAKY.COM
WWW.SIMUFACT.COM

Electromagnetic compatibility of electric miniature drives

In many application areas, electric miniature drives belong to the basic equipment required for technical devices. For electronics designers, the challenge is to take the components of the power electronics, μ-controllers and sensor systems that are housed together in the smallest of spaces in the controlled electric drive, into consideration in terms of their electromagnetic compatibility (EMC) and to find compromises that are acceptable to the market. This issue is addressed in the new specialist book on electromagnetic compatibility of electric miniature drives, by Dr.-Ing. Andreas Wagener, head of Systems Engineering Firmware Architecture at Faulhaber.

The new book first provides a fundamental overview of EMC and the currently applicable framework conditions for introducing electric miniature drives to the market. In the next step, the author discusses the effects, coupling paths and test methods for both the emitted interference of the energy conversion as well as for the interference resistance of the sensor systems. The sources for the various types of interference caused by a motor controller are stated and linked to the associated effects. On this basis, the EMC measures typically taken are then discussed step by step, as well as the measurement results used to examine their effectiveness.

The publication is targeted at users to support them in designing their end device in an EMC-compliant manner with a controlled miniature drive as a component. In addition, electronics designers learn about the necessary basic measures for taking EMC into account during the early stages of developing motor controllers for miniature drives. This can help prevent projects from failing due to (un)considered EMC.

"Electromagnetic compatibility of electric miniature drives" (in German) is available through the Vogel Communications Group (vbm-fachbuch.ciando.com).

New investment in photonics packaging and assembly

A new investment by PhotonDelta, an independent Dutch growth accelerator for the integrated photonics industry, and the Smart Industries TTT Fund (managed by Innovation Industries) will help MicroAlign speed up its technology and product development. MicroAlign, a spin-off from Eindhoven University of Technology (TU/e, NL), will use the funds to optimise the quality of optical fibre-to-chip connections at packaging and start exploring the market opportunities. Photonics is a key enabling technology for industries such as aerospace, automotive, foodtech, telecommunications, and high-tech systems & materials (HTSM). The Netherlands globally offers one of the most mature ecosystems in (integrated) photonics.

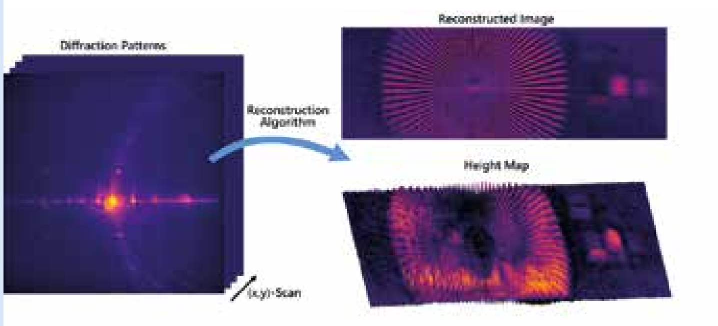
MicroAlign is the next in line of successful TU/e spin-offs, following companies such as photonics designers and producers Smart Photonics and Effect Photonics. With its solutions around packaging and assembly, MicroAlign fills in another important part of the ecosystem, making it more robust and cost-effective for producers as well as customers.

MicroAlign is developing a revolutionary technology capable of manipulating multiple optical fibres individually, by means of a novel microelectromechanical system. The technology aims to improve the quality of each optical fibre-to-chip connection, for tens of optical fibres and with sub-micrometer accuracy. MicroAlign's mission is to provide a solution capable of relaxing the strict alignment tolerances involved in photonic chip testing and optical assembly. The proposed alignment method has potential for a number of applications, ranging from datacom, telecom, sensing, and lidar, up to infrared communication.

WWW.MICROALIGN.NL
WWW.PHOTONDELTA.COM
WWW.TECH-TRANSFER.NL

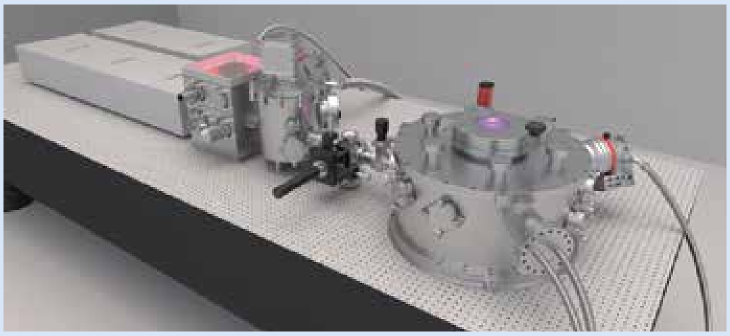
Building a lensless microscope to study next-gen chips

Transistors used in computer chips have reached the nanometer scale, yet manufacturers still lack the optical power to study this new generation of chips. Researchers from Delft University of Technology (NL) have built a lensless microscope to make an image at the scale of 200 nm. With further refining of this technique, they expect to bring images of nanoscale transistors within their grasp in the next two years. The research project is part of the LINX consortium (Lensless Imaging of 3D Nanostructures with soft X-rays), a collaboration between five Dutch universities and industrial partners such as lithography machine builder ASML.



Left: Diffraction patterns, acquired by a camera, contain information about a sample. Right: The computer algorithm is able to reconstruct an image and height map of the sample. (Image: Sven Weerdenburg)

With the success of their first test, the researchers found their baseline to finetune the lensless microscope towards sharper imagery. The end goal: making even the smallest structures on these chips – the 5-nm transistors – visible in the next two years. As images are needed with a resolution beyond the shortest visible-light wavelength of 400 nm, lensless imaging comes into play: it works with extreme utraviolet (EUV), which has a much shorter wavelength of around 13.5 nm. This is the same wavelength as used in today's most advanced machines to produce chips, EUV lithography machines. This helps to detect what might be wrong with the sample that is being measured.



3D rendering with an overview of the complete lensless microscope system. (Image: Sven Weerdenburg)

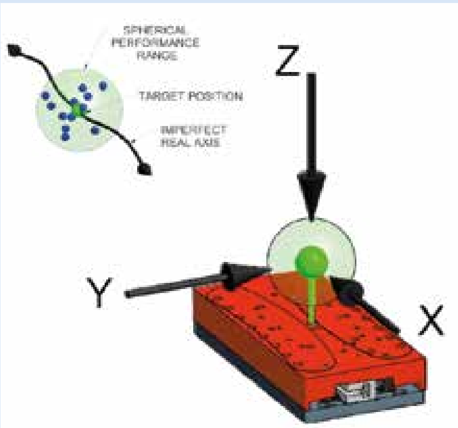
Over a year ago, the researchers started to build the lensless microscope in collaboration with DEMO, the Delft facility for experimental technical and scientific education; this 5-m large set-up contains a powerful infrared laser, a giant box to generate EUV light and an imaging chamber. The infrared laser light is focused, then a noble gas is injected into this beam, which starts to emit much shorter wavelengths. Mirrors are used to shape the EUV beam and focus it on a chip sample that scatters the light; this scattering/diffraction pattern is then captured by a camera in the imaging chamber. Software is needed to translate the scattering patterns into an actual image.

WWW.TUDELFT.NL
WWW.LINX-NWO-TTW.NL

ALIO's Point Precision in ASME standard

It was recently announced that the draft of the ASME B5.64 standard "Methods for the Performance Evaluation of Single Axis Linear Positioning Systems" has been completed and passed to the ASME (American Society of Mechanical Engineers) for balloting. For ALIO, an Allied Motion company, this is a significant milestone, so it claims, as this demonstrates industry recognition of its new method for defining the precision of advanced motion control solutions.

When analysing motion control solutions that provide sub-micron and nanometer-level accuracy, ALIO contended that a new language was necessary, and new standards were required to indicate the real levels of precision that different motion control solutions can achieve. With this in mind, over ten years ago ALIO trademarked the phrases Point Precision® and 6D Point Precision®.



6D Point Precision incorporates all sources of error at any desired work location into a meaningful 3D value

All motion systems operate in 3D space and have errors in six degrees of freedom (6-DoF). However, motion systems are often only characterised by performance data of a single DoF or a subset of the six DoFs. This practice leaves several error sources unaccounted for in performance data and specifications. According to ALIO, repeatability performance for metrology inspection and manufacturing systems must be analysed and specified using a 'point repeatability' method that accounts for 6D spatial errors in order to provide true representation of nanometer-precision performance. This is now an area that the ASME B5.64 standard has highlighted as important.

Many traditional stage and motion systems specify repeatability as a single number representing the variation in linear displacement along an axis of travel, i.e. plane repeatability. Historically, this practice was valid as the repeatability specifications were large enough that other error factors were only a small percentage of the total error and could be ignored. The repeatability of the plane position along the axis is effectively measured over many cycles at a target position. The intersection of this plane with the axis is a point on the axis line and the collection of these points results in 1D repeatability performance.

This test method makes a critical assumption, namely that the plane only moves in one dimension and the axis is perfectly straight. This assumption is no longer realistic, as in nanometer-level precision systems 'other' errors that were previously ignored in less accurate systems often become equal or greater contributors to the 6D repeatability performance. At the nanometer-level, the axis of travel should actually be shown as bending and twisting through 3D space and hence plane visualisation becomes meaningless, because the axis will tip, tilt, and twist as the stage moves along the axis. The stage moves in 6D space, therefore neglecting these additional error sources can result in a misrepresentation of actual stage repeatability performance.

Each linear (or angular) direction the stage moves (or rotates) in, leads to a positional error in that direction. That motion, which must not be neglected when nanometer-precision is desired, will have an associated repeatability of that error motion. Each point on a stage mounting surface will move in 3D space as a result of this 6-DoF error motion. It is the point repeatability of an infinite number of points attached to a stage that must be characterised by testing and specification data. Thus, each point repeatability will result in a spherical repeatability range. To accurately characterise the point repeatability of a stage along the entire axis, X, Y, and Z components must be measured in a systematic process. Additionally, a process must be implemented to test the influence of pitch, yaw, and roll errors of the axis on repeatability.

WWW.ALIOINDUSTRIES.COM
WWW.ASME.ORG

Angstrom Technology acquires Connect 2 Cleanrooms

Last month, US-based Angstrom Technology, an industry leader in modular cleanroom design and production, signed an agreement to acquire UK-based Connect 2 Cleanrooms (C2C). This new deal creates a partnership of two leading cleanroom companies with a presence on both sides of the Atlantic.

Established in 2002, C2C operates internationally from its head office in Lancaster, with additional offices in London and Geldermalsen (NL). C2C is a modular cleanroom platform serving healthcare, pharma, and industrial clients with its range of cleanroom solutions, providing a vertically integrated comprehensive suite of offerings, including engineering services, design & build services, cleanroom training services, and testing & validation services. Additionally, C2C also offers an e-commerce platform for cleanroom consumables and supplies.

Founded in 1989, and headquartered in Grand Rapids, Michigan, Angstrom designs, builds, and services fully customisable modular cleanrooms for regulated industries and adjacent markets, including aerospace, defence, technology, semiconductors, pharmaceutical, automotive, healthcare, and industrial end markets. It completes fully customisable and turnkey projects that give customers a high level of control over airborne and surface particulates to manufacture, test, and assemble products in a safe and clean environment.

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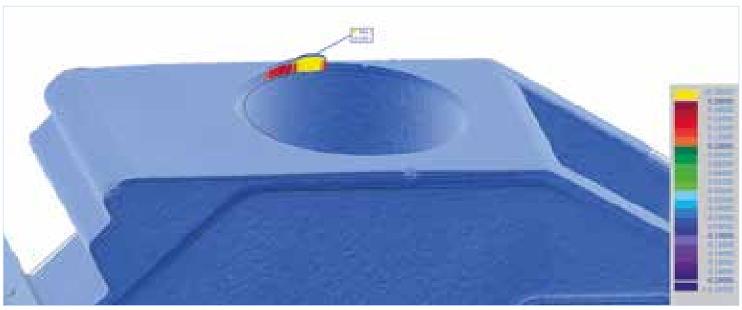
CT-assisted automatic burr detection

In addition to determining geometric properties such as dimensions as well as shape and position tolerances, burr inspection is one of the most important tasks in the quality assurance of plastic workpieces. Computed tomography, in combination with intelligent software, enables fast inspection with high reliability.

Burrs can form during the manufacture of workpieces in injection moulding, die casting, or stretch blow moulding, but also during machining. In plastic injection moulding, a burr occurs when two mould forms do not close completely or only with an offset. One cause is that the moulds can only be manufactured to fit accurately within certain tolerances. In addition, there is wear as well as injection parameters that are not optimally set, such as injection pressure. Burrs can cause visual blemishes or even functional limitations of the workpieces.

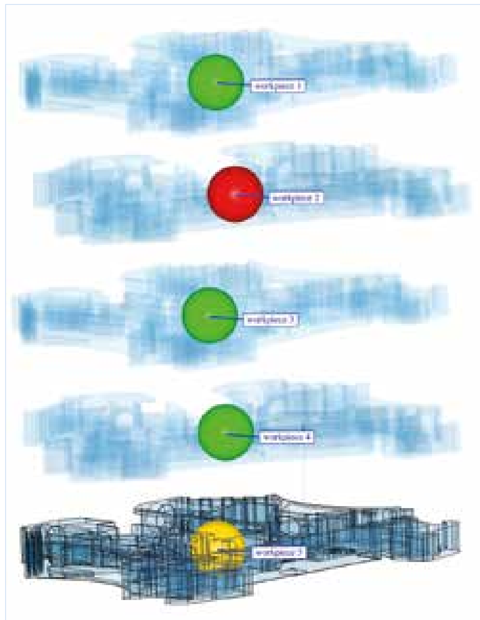
The automatic detection of burrs is a major challenge for metrology. Particularly in the case of plastic injection moulding workpieces; very often, even very small burrs are to be found. For production monitoring, many workpieces have to be evaluated in a short time. Since not every burr is problematic, it should be possible to restrict the automatic search to specific workpiece areas and parameters of the burrs to be detected in an application-specific manner.



Colour-coded deviation display of the burr, with colour-coded and numerical display of the maximum burr length.

Burrs and chips on plastic or metal workpieces can be automatically measured with the WinWerth measuring software, from German metrology firm Werth Messtechnik, in combination with other geometric properties such as distances or form and position deviations in a single measuring sequence. The burr detection can be taught in on one workpiece and subsequently applied to all workpieces of the same type measured with computed tomography (CT).

On the workpiece volume created during the measurement, the areas to be inspected are first marked by applying user-defined 2D or 3D windows, based on the CAD model. The automatic burr detection can be taught offline. After setting the desired windows, the operator enters the minimum and maximum burr thickness of interest and the allowable tolerance for the burr length. The result is a colour-coded deviation representation of the burr and the maximum burr length. Analysis markers allow a quick visual assessment by automatically setting flags with colour-coded and alphanumeric information.



For multi-object measurements, the workpiece elements show the status and allow access to the various measurement results with a mouse click.

WWW.WERTH.DE

Pooling resources for laser microprocessing

The German companies Scanlab and Pulsar Photonics have launched a collaboration for the development and distribution of more highly integrated laser scan systems. Scanlab is an independent OEM manufacturer of scan solutions for deflecting and positioning laser beams in three dimensions. Pulsar Photonics is a high-tech company in the field of laser technology, focused on development, production and distribution of laser machines for material processing with short and ultra-short pulse lasers.

Besides collaborating on the development of a 'photonic drill engine' for laser micro-drilling at a high throughput rate, Scanlab will now be able to supply a range of Pulsar's beam-shaping systems (see below) and other customised solutions. In doing so, the company will expand its product range for micro material processing and offer users new solutions that will help them to improve their productivity and processing quality. The market for ultrashort-pulse (USP) laser applications is continuing to grow; in general, the most significant challenges involve achieving increases in throughput. Parallelisation of laser processes using multi-beam systems can help to overcome this precise challenge.

The Microscan Extension (MSE) could be described as a '1 µm laser blade'. This scan lens easily transforms a scan head into a microspot scan system. The combination of a galvanometer scanner and MSE enables highly precise component processing; the focus diameter is less than 4 µm and even less than 1.5 µm in the UV wavelength range.

No stress with PECM

For over 30 years now, Exakt Fijnmechanika has been manufacturing high-precision metal parts for the medical, defence and high-tech OEM markets. Up until now, only one method was used: mechanical removal of material by cutting. Apart from one EDM machine (for electrical discharge machining), Exakt mainly has been working with Swiss lathes and milling machines to achieve very high precision and surface quality.

As the years passed, the level of accuracy increased, which resulted in more customers, driving business and pushing the boundaries. To keep pace with ever-rising expectations, Exakt decided to invest in the future by acquiring its first PECM machine from PemTech in Germany, thus enhancing its potential to meet future demands. In principle, PECM, or Precision Electro Chemical Machining, does the same as cutting, i.e. removing material to achieve the desired form and accuracy. However, PECM does have advantages that allow customers to go much further in their demands regarding complexity, accuracy and especially surface roughness and integrity.

Removing material electrochemically takes place under aqueous electrolyte, and no contact with tooling occurs. Consequently, no stress is applied and no thermal effect on the product is induced. This results in surfaces that exhibit 100% integrity and are crack-free, down to R_a 0.03 µm. As PECM is a single-axis process, it is extremely stable and precise. The process is not hindered by material hardness, which implies that any conductive material from stainless steel, tooling steel or titanium can be processed, leaving no burrs, no chips and no contamination.

"Shapes and quality can be achieved beyond imagination and with extreme repetition accuracy," says sales manager Michael Stegeman. As tool wear is non-existent, repetition accuracy is an intrinsic aspect of PECM. Multiple tools can be placed in array, offering high throughput. These tools can be produced with PECM using the same 'mother' tool, thus guaranteeing that all tools are exact copies of each other. "We are proud to have been able to make this investment. Currently, we are in the training phase and first tooling has proven the concept in house. We look forward to customers demanding complex products with special surfaces in high quantities. It is our mission to partner with OEMs in an early design stage. Our creativity, know-how and capacity to design and produce the needed electrodes in house at Exakt should help our OEM customers to raise their bar."

The PECM machine in Exakt's production facility.

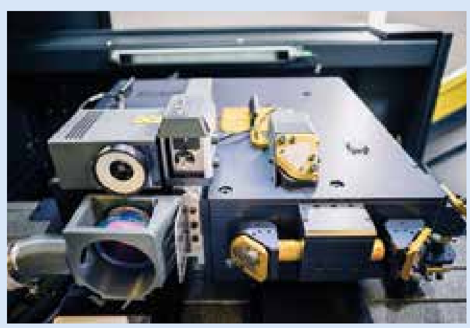
WWW.EXAKT.NL

The MultiBeamScanner (MBS) is a scan solution that enables laser cutting, drilling and removal processes to be performed simultaneously. The use of diffractive optical elements divides the incident laser beam into a configuration made up of multiple partial beams, enabling multiple laser spots to be worked on at the same time in a single image field. This means that multiple components can be processed at the same time or that structures can be produced more quickly. Combining this technology with the XL SCAN solution further improves the precision and speed of parallel laser processing.

The most complex system is the FlexibleBeamShaper (FBS), a beam-shaping system that can be integrated into a machine and can generate user-defined beam distributions as required. Thanks to the optical phase modulator, which can be controlled electronically, the FBS is, so to speak, a 'photonic toolbox' containing a range of predefined beam shapes. The system, featuring an integrated galvo-scan head, opens up new possibilities for process developers when it comes to flexible, efficient microprocessing.

The Beam Alignment Module (BAM) is used to actively stabilise the beam position. Alignment errors, thermal effects caused by laser sources, variations in the ambient temperature, and all their resulting effects on the beam position can be measured and corrected. As a result, the BAM ensures that process results remain consistent, even when the environmental conditions change.

The collaboration between USP expert Pulsar Photonics and Scanlab goes above and beyond a typical joint distribution project for the specified products. Over the course of their 'photonics drill engine' development project, the two companies will jointly develop an extremely dynamic, versatile multi-beam tool for laser material processing. This technology is particularly suitable for use in the electronics industry, for instance for laser drilling circuit boards in order to increase drilling rates for high-density applications.



Pulsar Photonics' FlexibleBeamShaper.

WWW.SCANLAB.DE

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

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

30 March 2022, Den Bosch (NL)
Machine Learning Conference
The fourth edition of this event brings together industrial and scientific specialists who are applying ML techniques in high-tech domains, or are interested in doing so.

WWW.BITS-CHIPS.NL/MACHINE-LEARNING-CONFERENCE

13-14 April 2022, Den Bosch (NL)
Food Technology 2022
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/CLEAN

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.

The conference keynotes are presented by Thomas Sesselmann of Heidenhain, on Geneva's special contribution to precision manufacturing and metrology, and Begoňa Vila of NASA about on-orbit commissioning of the James Webb Space Telescope.

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

22-23 June 2022, Eindhoven (NL)
3D Production Days
New event organised by Mikrocentrum, as the merger of four events: RapidPro (22-23 June), Smart Maintenance Congress (22 June), Virtual (R)evolution (22 June), and MBD Solutions Event (23 June). Together they cover all aspects of 3D production: the 3D drawing with product and manufacturing information (PMI), 3D scanning, prototyping, 3D simulation, 3D printing / additive manufacturing, postprocessing, and 3D visualisation.

WWW.3DPRODUCTIONDAYS.NL

30 August - 2 September 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.MAAKINDUSTRIE.NL/ESEF

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

28-30 September 2022, Huddersfield (UK)
SIG Meeting Structured & Freeform Surfaces
Special Interest Group Meeting, hosted by euspen and dedicated to replication techniques, structured surfaces to affect function, precision freeform surfaces, large-scale surface structuring, surfaces for nanomanufacturing, and metrology.

WWW.EUSPEN.EU

16-17 November 2022, Den Bosch (NL)
Precision Fair 2022
The 21th edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum.

WWW.PRECISIEBEURS.NL

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