Digital | Semicon & Quantum

Added value beyond Moore

innovation
for life

Digital | Semicon & Quantum

Added value beyond Moore

Every day, Semicon device manufacturers strive to make chips smaller and more powerful. And every day, they face challenges related to creating those chips in the cleanest and most cost-efficient way. TNO works for leading equipment and device manufacturers to create the best semiconductor tools of today, and explore all the possibilities for tomorrow.

TNO has the experience and expertise to devise concrete solutions. We are the R&D partner that equipment manufacturers turn to when the answer seems out of reach. We are strong in experimental validation and demonstration, to help companies produce tangible equipment that creates better devices with higher yields. In both public-private partnerships and one-on-one (confidential) collaborations, we quickly and efficiently develop the equipment that companies need tomorrow.

For more than 25 years, TNO has been leading the industry in cutting-edge developments in optics, opto-mechatronics, contamination control and other technologies for nano-manufacturing and equipment. More than 500 dedicated researchers create equipment that can keep up with both Moore’s Law and consumer demand. Our sizeable portfolio and numerous patents show that we are leading in the field of state-of-the-art semiconductor equipment.

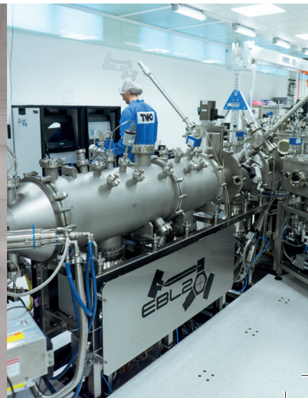
Rogier Verberk
Director Semicon & Quantum
TNO

Optics lifetime for EUV lithography

TNO has been researching the interaction between EUV and different materials since 2000. To keep up with requests from industry, a second facility was developed for EUV exposure and in-situ surface analysis, also known as EBL2. This system helps industrial partners to evaluate their materials and components for EUV radiation and environmental factors to increase the lifespan and prevent contamination.

The EBL2 consists of a high-intensity tin discharge EUV source, a vacuum chamber in which to carry out the EUV exposures in a controlled environment, and an XPS for surface analysis. In this system, samples can be transported between the test environment and the XPS without disturbing the vacuum.

In the vacuum system of the EBL2, samples are exposed to EUV radiation for extended periods of time in a controlled, representative environment. An in-situ ellipsometer with imaging is available for real-time monitoring of exposure progress. The system can handle full-size reticles and has industry-standard interfaces.



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Ultra-clean vacuum for Semicon

Vacuum technology is one of the enabling technologies within the semiconductor industry. Even before the start of EUV lithography, TNO was involved in vacuum-related research for space applications. This background knowledge was the starting point of applied research into the vacuum requirements for EUV lithography.

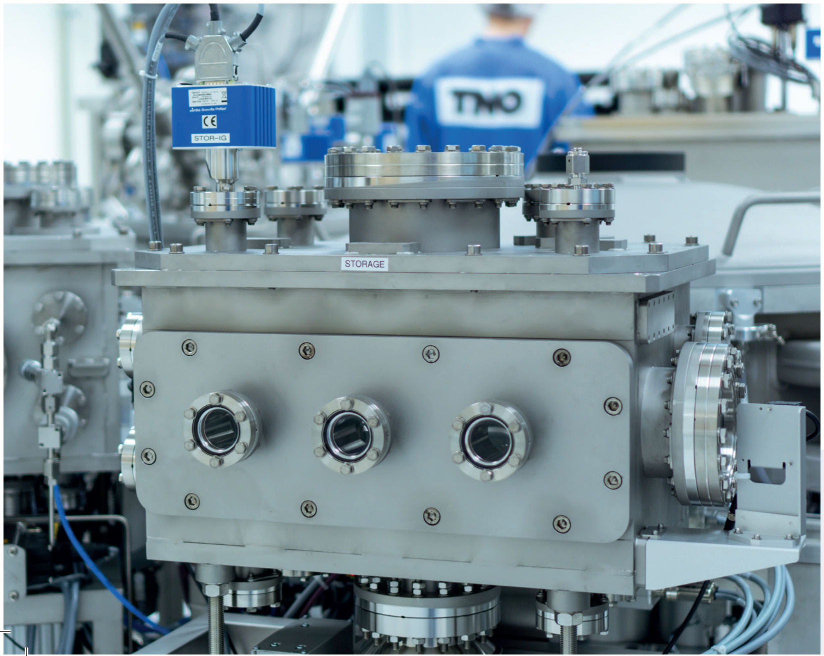
Vacuum technology within the semiconductor domain is not straight forward. All kinds of gasses are introduced to enable the semiconductor process, while other molecules are absolutely prohibited.

TNO has been working in this domain for over 50 years and still sees an increasing interest as well as a need for this specific knowledge. It resulted in a new, and now commonly used vacuum domain; ultra-clean vacuum.

In the nano-instrumentation department we have over 20 dedicated vacuum systems, ranging from small setups for outgassing measurements (what kind of contamination is coming from a part), to full EUV exposure setups (EBL2).

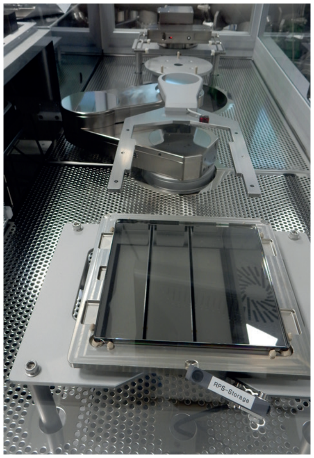
We have the knowledge on how clean the vacuum should be, how to design for this cleanliness level, and how to measure the vacuum conditions.

We expect that the knowledge from semi-conductor vacuum technology will be used in other domains in the near future. We apply it already for quantum-, space-, and plasma technologies.



Contamination control for Semicon manufacturing

At TNO, we use our knowledge of molecular and particle contamination in research on processes and the development of systems for the Semicon industry. In addition, we advise suppliers of the Semicon industry on clean production and how to achieve it.



We apply our expertise in surface physics and physical chemistry in everything we do. That is why we have been able to accelerate developments in all aspects of EUV lithography.
Below are some examples of our capabilities:

- Metrology sensors for molecular contamination (MFIG).
- Several experimental setups, including vacuum vessels.
- Hydrogen-radical sensor based on heat-flux sensors developed in-house.
- Rapid-Nano (RN3) for fast inspection of EUV blanks. This setup is capable of detecting a single particle of some tens of nano-meters on a 142x142mm-area.
- Equipment to test molecular, chemical outgassing and resistance against hydrogen radicals and plasma.
- Plasma metrology equipment (RFEA, Langmuir probe).
- Cleaning technology (wet cleaning, dry cleaning with or without plasma).
- Particle-sensor metrology (PMC card; FastMicro and Part sense – both now also commercially available.
- EUV Beam Lines (EBL1 and EBL2) for optics lifespan research and research on EUV-radiation effects on materials.
- Analysis instrumentation such as optical micro-scopy (OM), Scanning Electron Microscope (SEM), plus material analysis with energy-resolved X-ray spectro-scopy (SEM-EDX), X-ray Photoelectron Spectro-scopy (XPS), ellipsometry, and Atomic Force Microscopy (AFM).

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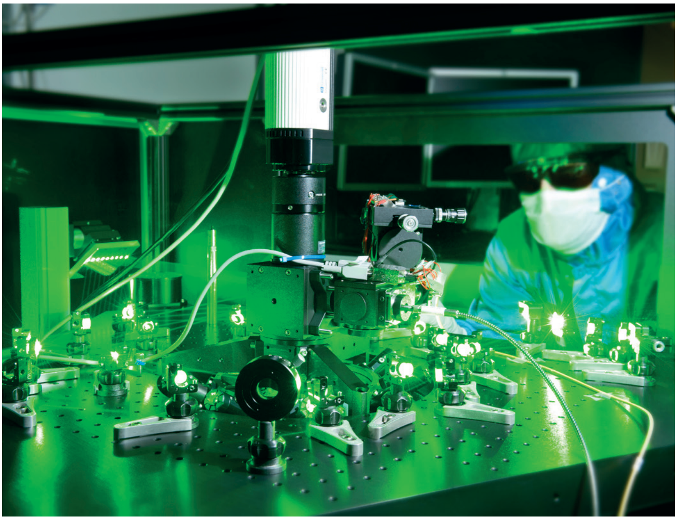
Metrology and inspection concepts



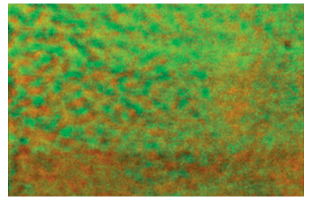
The increasingly complex structures, 3D geometries, and new material combinations in state-of-the-art chips gives rise to a huge demand for new metrology tools. Traditional methods do not suffice, for example because materials are optically opaque.

That is way TNO works on new metrology concepts: sometimes a new approach within an existing field, sometimes we even combine multiple approaches into one concept.

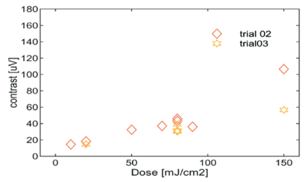
Notes

IR AFM
AFM-based methods are popular techniques to measure and check a broad range of material properties at the smallest length scales, especially in labs and universities Similar to other scanning probe techniques, AFM traditionally relies heavily on operator experience to achieve good results. This can be attributed to poorly characterized tip shapes and complex resonant operating schemes in addition to strongly non-linear tip-sample interactions. TNO is developing unique operating modes, calibration methods, and data analysis algorithms. These all contribute to making AFM reach its high resolution material properties characterization.

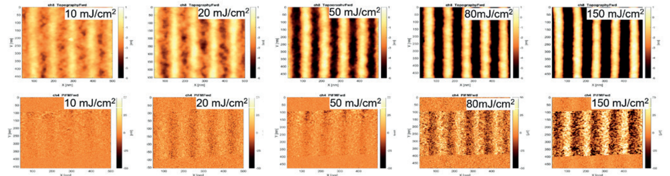
As a showcase, TNO is developing IR-AFM applications on imaging of resist-quality metrics such as chemical heterogeneity from blank resist or latent images. IR-AFM is a chemically specific imaging modality with nanometer resolution through IR spectroscopy applied with an AFM tip. Examples of observations showing the potential are below in the images.



Chemical heterogeneity imaged in a blank MOx resist layer at two different wavelengths, highlighting two different chemical components.

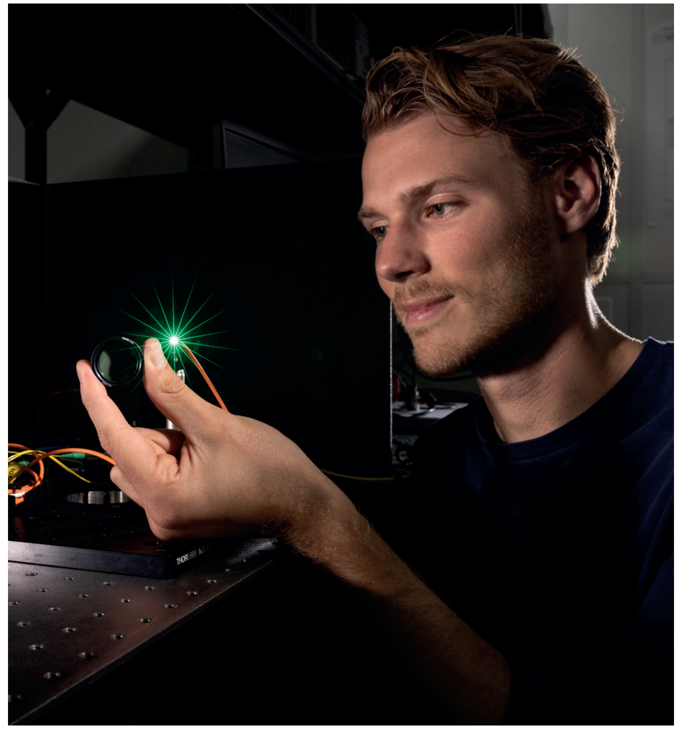


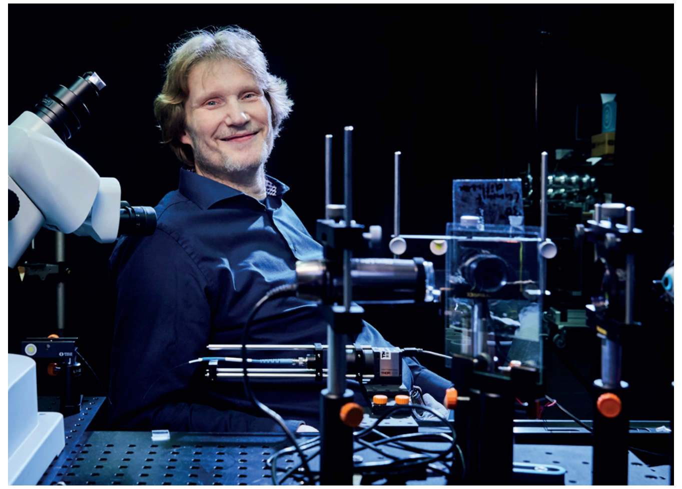
IR-AFM reproducibly captures sensitivity of a particular chemical compound in MOx resist to EUV exposure. The pattern here is difined through interference lithography. Different doses result in reproducible contrast in IR-AFM measurements.



Quantum-Sensing
TNO wants to use its technology and know-how to accelerate the industrialization of quantum sensors. To that end, we set up a testbed where our partners and customers can test state-of-the-art quantum sensors.

The instruments in this testbed are based on Nitrogen Vacancy (NV) centers on diamond. These centers are defects on the diamond lattice, sensitive to magnetic fields, currents, rotation and temperatures.





Optics
TNO develops knowledge within 5 technology lines:

- Spectroscopy identifies samples and characterizes matter using the wavelength of light.
- Fiber Optic Sensors measure chemical, biological, and industrial processes in demanding environments. This enables process control and optimization.
- Nano-Photonics develops integrated sensor systems for chemical, bio-chemical, and physical parameters. We also study the possibilities offered by promising metamaterials.
- Both high-end industrial production, such as lithography, and advanced scientific experiments, for example in astronomy, depend greatly on the availability of precise and robust monitoring systems. Metrology experts imagine, design, and develop such systems, including the technology needed to produce them.
- We offer complete calibration concepts for optical instruments that are unique in their application, such as satellite components.

Acoustic metrology
TNO created a novel acoustic metrology method using GHz ultrasound waves to measure deeply buried subsurface features (>5µm). The concept consisted of a GHz acoustic transducer integrated above the tip of a custom-designed probe, which is then scanned across a sample. The method uses non-damaging solid-solid contact without the need for liquid coupling layers – in contrast to conventional acoustic microscopy. This allows for the use of much higher acoustic frequencies, hence higher on-axis resolutions. An experi-mental setup was built with a 4 GHz transducer and tested successfully on 1.5-2µm-size features buried below a 5µm PMMA or 10µm SiO2 layer, respectively. These results demonstrated the feasibility of the new method, opening new opportunities for metrology and inspection applications.

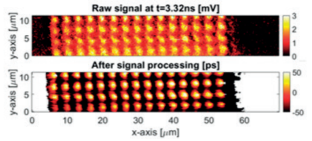


Figure 1 HaWaCAM scan results for 2x2 square silicon features under 5 µm of PMMA

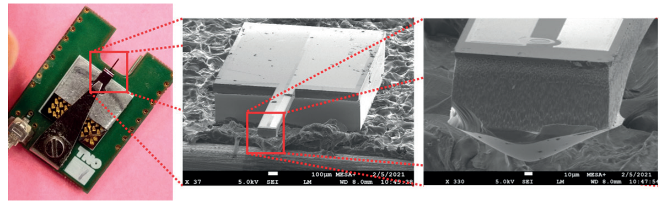


Figure 2 transducer integrated HaWaCAM probe

Our heritage

25 years of innovation for the Semicon Industry. Many of the tools used in Semiconductor manufacturing contain TNO innovations. TNO played a major role in research and development of technologies, design and even realization of (alpha system) modules.

TNO was one of the first partners in the development of EUV lithography. For example by developing and realizing modules for ASML's EU Alpha Demo Tools. Since then, hundreds of projects have been executed, resulting in breakthrough innovations which are now used in the Semicon fabrication plants today.

An extensive program built around the EUV beamline enabled our partner Carl Zeiss and manufacturers of EUV reticles to develop optics that comply with the demanding requirements within the EUV Lithography tools.

Many more examples exist, but in most cases we assure confidentiality to our customers.

Our customers and partners

are mainly based in the Netherlands, Europe, the USA, South-Korea, and Japan.

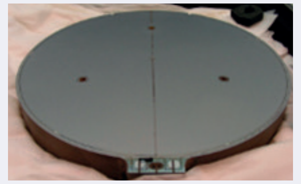
1996

193nm AT Level sensor

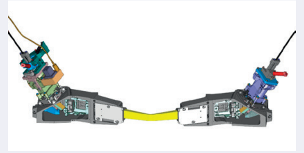
First optics design EUV lithography

1998

Electro static wafer clamp



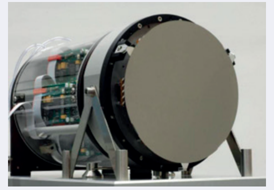
EUV alpha-tool level sensor



2000

Dynamic gaslock EUV

Adaptive optics



Applied vacuumtechnology EUV lithography

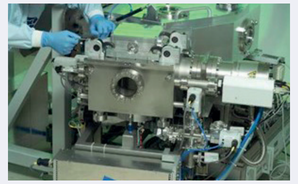
2002

EUV Alignment sensor, Zero sensor, Mirror Contamination Monitoring Sensor

Immersion technology

EUV beamline 1

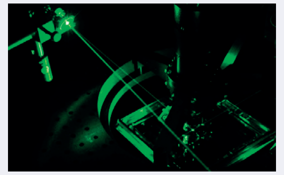
EUV Alpha-demo tool reticle handler



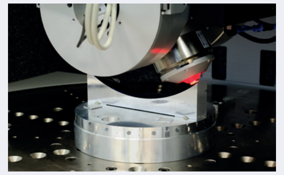
2004

2006

Particle contamination metrology



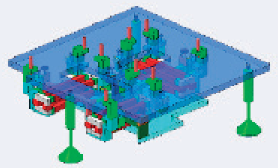
NANOMEFOS Measuring freeform optics



EUV Alpha-demo tool

2008

Planar Maglev Stage



Hummingbird vibration isloIation

Wafer backside cleaning

2010

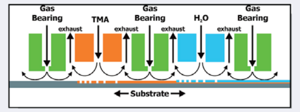
Opening VLL lab

Plasma cleaning strategies EUV optics

UV-Yieldstar

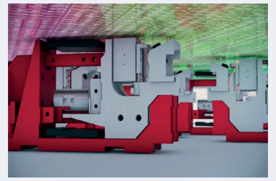
2012

Spatial Atomic Layer Deposition



2014

High throughput AFM

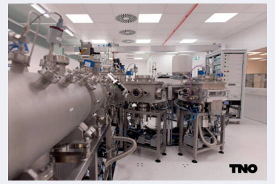


Particle detection; spin off FastMicro

2016

Spinn-off Nearfield Instruments

EUV beamline 2

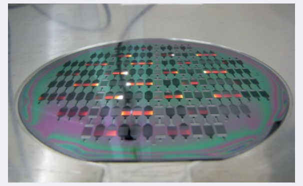


2018

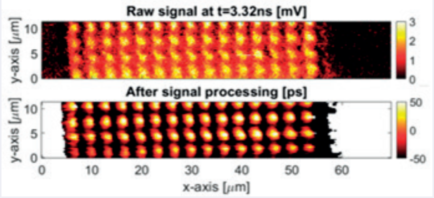
EUV reticle qualification program

2020

Micro Chip Cooling



HAWACAM acoustic metrology

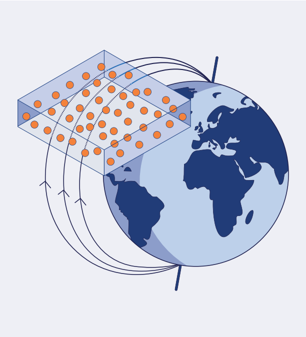


2022

New level sensor concepts

2024

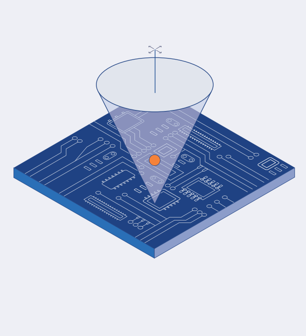
Scanning probe microscope
Equipped with a diamond probe with a single NV centre, this instrument can measure non-destructively and with high-resolution magnetic fields, currents and temperatures.



Target performance

- Resolution ~50 nm.
- Sensitivity ~5 µT/√Hz.
- Speed: 100 pixels / s.

Compact Vectorial Magnetometer
Using an ensemble of NV centres on a macroscopic piece of diamond, these compact instruments can measure vectorial magnetic fields with high sensitivity.

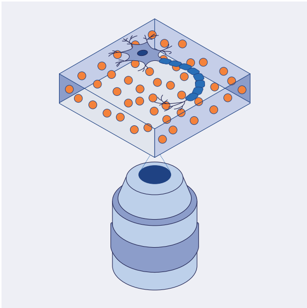


Target performance

- Resolution ~3 mm.
- Sensitivity ~1 nT/√Hz.
- PICs and Fiber based solutions.

Wide Field Magnetometer
Using a piece of diamond as a 'sample holder', this microscope can image magnetic fields and currents in seconds.

Target performance
- Resolution ~400 nm.
- Sensitivity ~500 nT/√Hz.

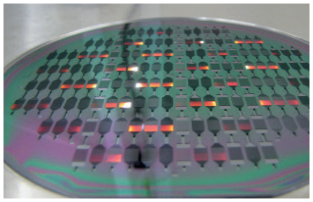


High-performance flow and thermal management

Semiconductor equipment and many other domains require high-performance flow and thermal management solutions for extreme stability. An example of a complex flow problem is keeping gasses and/or fluids apart even when the surfaces that confine the gasses/fluids move fast relative to each other. Examples of applications that involve complex flow problems:

- Immersion hood for lithography or metrology equipment.
- Development of a spatial Atomic Layer Deposition system.
- Pressure and test wafers for ultraprecise (<1mW) determination of wafer heat loads and pressure distributions (1Pa).
- Heating or cooling of semiconductor wafers within a specific time and with a specific homogeneity.
- Micro-Fluidic Cooling of Automotive Electronics such as EV battery packs or 5G telecom driver chips.
- Flow and temperature slip (accommodation) properties of materials at reduced pressures.

We have combined the domain expertise with the thermal and flow expertise to design and validate the above high-performance systems. We use simulation (CFD, FEM) and testing for this purpose. We hold a unique exclusive IP position in Micro-Fluidic cooling or evaporation.



Integrated device cooling

An important way to improve the performance of microelectronics, as well as the packages into which they are integrated, is structure-size reduction, which increases the energy density of the device. Doing so requires the most efficient cooling possible. This can be through upscaling or downscaling, but usually, both go hand in hand: performance is upscaled while weight and size are downscaled, also regarding cooling.

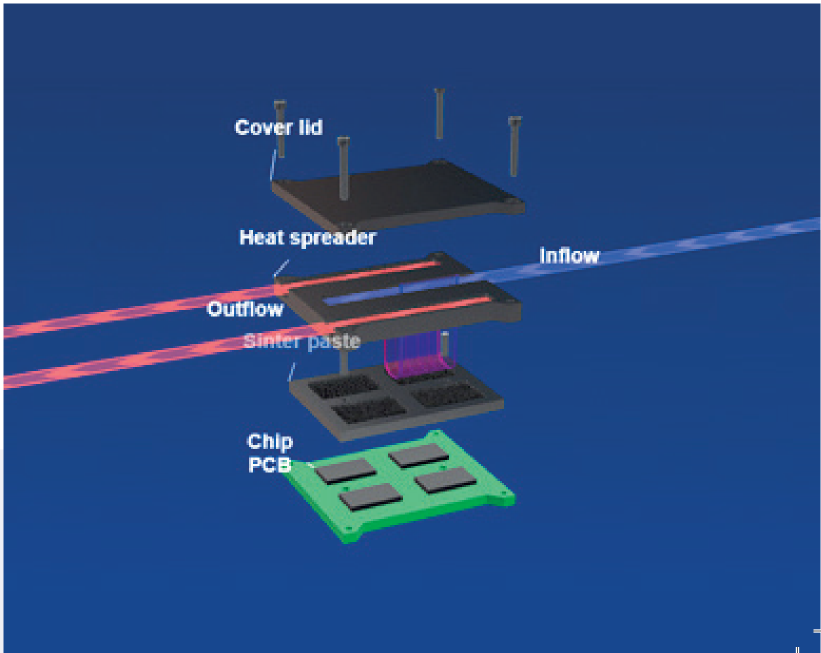
TNO's High Performance Thermal Management Technology is the solution to this twofold challenge. The technology offers hundreds of times more cooling capacity than conventional applications while being integrated, on a small scale, close or into the microelectronics themselves. This results in using much less space and being positioned directly on top of the heat source.

Technology for active thermal management

TNO has developed and patented the disruptive microfluidic, two-phase cooling technology, which features:

- An ultrathin cooling body, wafer level (100µm), PCB level (1 mm+).
- An extremely high (500x higher) heat-transfer coefficient (>>100 watt/cm2).
- An extremely low (500x lower) flow rate.
- A cooling body that can be bonded on (silicon) wafers/chips.
- Manufacturing made possible by a range of cost-efficient techniques.

The liquid cooling technology can be applied in numerous fields – from data centers, electric vehicles and LEDS to active thermal management of Fuel Cells.

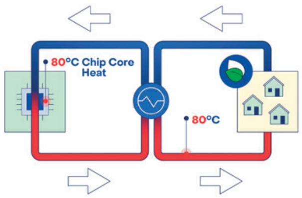


Improving data-center efficiency

One of the application areas of this new technology is in microelectronics integrated into the server boards mounted on data center server racks, contributing to an overall increase in data-center efficiency.

TNO's direct-to-chip or in-chip active two-phase liquid cooling technology enables:

- (Hyperscale) data centers with powerful server cards with GPUs and CPUs reaching thermal design powers (TDP) in excess of 400 watts/cm2 and higher.
- Supercomputers/high-performance computing (HPC) not limited by excessive GPU/CPU temperatures.
- Efficient artificial-intelligence (AI) infrastructures.
- Up to ten times less cooling-fluid consumption as compared to current data-center cooling technologies.
- High-quality waste energy, for example waste cooling fluid at 80 degrees Celsius that can be applied to heat nearby offices and/or homes, reducing global energy consumption and possibly increase the acceptance of new data center buildings by local governments and residents.



Another application area is that of high-density, high-complexity, and, in some applications, high-power microelectronics on interconnected printed circuit boards (high density PCBs). TNO's microfluidic, two-phase cooling technology enables:

- In-package (PCB-level) microfluidic cooling.
- Double-sided microfluidic device cooling within packages.
- Hotspot prevention of devices at high temperatures.

High-End Optics Manufacturing

System optimization and state-of-the-art manufacturing. Complex optical components can be manufactured using TNO's expertise in Optics Manufacturing. TNO provides solutions for advanced optical systems in demanding environments. TNO's manufacturing facilities support manufacturing and metrology of optical components with high shape accuracy, low roughness and application-specific coatings.

TNO is specialized in the manufacturing and qualification of single units up till small batches of optical components. TNO also advises customers on manufacturability to optimize instrument performance during the design phase of an instrument.

At TNO, optics manufacturing aspects are considered early in the instrument design process, resulting in optimized system performance for example in:

- System layout - optimizing designs and avoiding high angles of incidence on mirrors where layout changes can result in a better system with less complex coatings.
- Mirror body material - matching mirror materials to the structure of an instrument resulting in more accurate and reliable mounting.

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