ENABLING THE 'BIG ENABLER' – VACUUM

Chemical or molecular contaminants are harmful in vacuum applications because they disturb the operation, which can lead to lower production yield or faulty measurements, for example. Molecular contamination can be prevented by using suitable materials and clean gases, and by ensuring that parts are properly cleaned, manufactured, assembled and inspected. These issues were the focus of the DSPE Knowledge Day Molecular Contamination Control, hosted by TNO in early November. The event featured presentations from the semicon, space and analytical industries, as well as a tour of TNO research facilities, including the advanced EBL2 (EUV Beam Line 2).

Since 2019, DSPE has been organising knowledge days on precision engineering for vacuum and the related issue of contamination control. Molecular contamination control was the topic of a DSPE Knowledge Day hosted by TNO in Delft (NL) in early November. DSPE board member Kasper van den Broek, contamination control architect at VDL ETG, kicked off the day by welcoming the over 40, mostly young, participants and briefly introducing DSPE and its Knowledge Day format.

Rising star

The host of this event was TNO, the Dutch organisation for applied research that aims to act as a catalyst for open innovation in public-private partnerships and supports many high-tech companies in confidential projects. It was introduced to the participants by Rogier Verberk, director of TNO Semicon & Quantum, and Medical Photonics. He described how contamination control is critical for two of TNO's high-tech industry roadmaps: Semicon & Quantum and Space & Scientific Equipment.

Verberk underscored the relevance of contamination control by presenting TNO's track record in these areas, including instrumentation for atmospheric chemistry, astronomy and gravitational-wave detection, as well as extreme-ultraviolet (EUV) lithography equipment and particle-detection technologies. EUV lithography (EUVL) for realising the smallest semiconductor features requires an ultra-clean vacuum because of the high absorption of EUV in non-vacuum. Another important focus of TNO is quantum technology, which is the rising star in Delft. It involves the quantum computer and networked communication, centred around QuTech, the joint research centre established by Delft University of Technology and TNO in 2014.

No perfect vacuum

Freek Molkenboer, senior systems engineer at TNO in the department of Nano-instrumentation and vice president of NEVAC (see the text box on the next page), described vacuum as the 'big enabler' of big science, particularly in areas such as nuclear fusion and research into elementary particles, gravitational waves and space. However, there is no such thing as a perfect vacuum. Even the best man-made vacuum, an extremely high vacuum of 10^{-12} mbar (= 10^{-10} Pa) pressure, contains some 10^5 molecules per cubic centimeter. Thus contamination, i.e. unwanted matter at an unwanted location, can never be fully eliminated, and each application has its own level of allowed contamination and requires its own specific contamination control measures.

Forbidden elements

After a tour of TNO's research facilities (see the text box on page 23), Paul de Heij, cleanliness specialist at VDL ETG, was the first presenter from industry. He talked about molecular contamination control during the manufacturing of the frames for ASML's EUVL machines, focusing on the prevention of 'forbidden' elements on the surface of grade-1 EUVL parts, in particular the contamination-sensitive EUVL optics, and demonstrated the urgency with a few numbers. Under atmospheric pressure it takes only 3 nanoseconds for a monolayer of contamination to build up, while under high vacuum (10^{-6} mbar) this increases to a mere 3 seconds. It requires extremely high vacuum (10^{-12} mbar) to achieve an acceptable period of about a month.

Even this, however, may be not enough. When highly reactive hydrogen plasma is used to remove hydrocarbons from sensitive surfaces, hydrogen radicals can form molecular acids with phosphorus or sulphur, for example, or form volatile metal hydrides which can redeposit onto

EDITORIAL NOTE

This report was based on the presentations given at the DSPE Knowledge Day on 3 November 2022 at TNO in Delft.

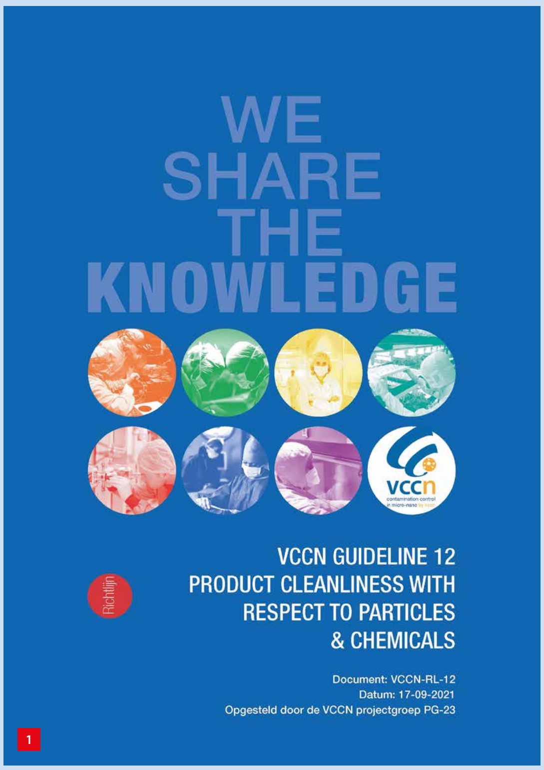
NEVAC, VCCN and Guideline 12

There are two Dutch organisations dedicated to vacuum technology and contamination control in this field. One is NEVAC, the Dutch Vacuum Society, founded in 1962 to promote the exchange of knowledge in the field of vacuum technology and areas in which vacuum plays a major role. The society does this by organising scientific meetings (NEVAC Days), excursions, an extensive course programme and publishing a magazine. The next NEVAC Day will take place on 12 May 2023 at ASML in Veldhoven (NL).

Under the auspices of NEVAC, three vacuum books were written, which can be considered as 'must-haves' for everyone working in vacuum-based research, development, instrumentation, production or business; see the NEVAC website.

The other organisation is VCCN (Dutch Association for Contamination Control), a professional platform for knowledge sharing and knowledge transfer in the field of contamination control, optimising expertise and contributing to the development of this field. It publishes the quarterly C2MGZN magazine, offers a wide range of training courses, and organises various congresses as well as the National Contamination Symposium and the Cleanroom Day. A new VCCN initiative is the Cleanliness & Contamination Control Circle for knowledge sharing; the first meeting will be held in January 2023.

VCCN also recently developed an important contribution to this field: the VCCN Guideline 12: Product Cleanliness (Figure 1). Rather than prescribing solutions for achieving product cleanliness in manufacturing with respect to particles and chemicals, for example through contamination control or cleaning, the guideline describes what should be considered when dealing with product cleanliness. This information should, among other things, enable and align the communication (about specification and qualification) between suppliers and customers, in order to help industries to realise and improve product cleanliness.



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VCCN Guideline 12: Product Cleanliness, published in 2021.

WWW.NEVAC.NL
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the surfaces. Minimising this hydrogen-induced outgassing requires both an ultra-clean vacuum (for which a low hydrogen flow is used to continuously clean critical surfaces) and the reduction of the presence of forbidden materials, following the philosophy that what is not on a surface does not have to be cleaned off, and what is not in a material does not have to be baked out. These forbidden materials range from Zn and Sn to Mg and Ca, and further to N and Si; they are the 'byproducts' of the materials (alloy elements) and processes such as soldering, greasing and cleaning with water and other solvents, as well as the general environment (human beings, buildings, etc.).

Large frames

With the increasing frame size of EUVL machines, the challenges are only getting bigger. Firstly, this has to do with the quality of available materials. For example, cast materials applied in large structures have a higher porosity than wrought materials, and their corrosion resistance is lower, leading to increased outgassing and surface contamination. Naturally, processing times – for manufacturing, cleaning (the large thermal mass complicating matters) and assembly – increase with frame size, and hence the risk and the degree of contamination (for example, due to the exposure to coolants). In addition, options such as ultrasonic cleaning are not feasible at these length scales. De Heij's conclusion was, "Size matters! Scaling up affects cleanliness and contamination control in many ways, and many of the associated problems compound each other."

Clean and dry

Rients de Groot, senior system design engineer at Thermo Fisher Scientific, talked about cleanliness for (transmission) electron microscopy, or (T)EM. Vacuum is everywhere in a TEM system, comprising the electron source area (10^{-10} - < 10^{-12} mbar), the column area (10^{-6} - 10^{-8} mbar) and the projection chamber (10^{-5} - 10^{-6} mbar). Hence, optimal performance requires a very high cleanliness level, especially of all the parts and modules in contact with the high- to extremely-high-vacuum environments.

The vacuum is important, besides ensuring a sufficiently long (> 60 mm) 'mean free path' for the electrons, also for minimising oxidation (caused by oxygen from air or water) and contamination (carbon growth) on the sample or the electron source; and preventing particles from 'igniting' electrical discharge, and deflecting or blocking the electron beam. In addition, the trend in EM is towards lower accelerating voltages, making the microscopy even more sensitive to contamination. De Groot's conclusion was, "We need a clean and dry vacuum." Here, 'dry' also refers to reducing the water content in the vacuum to prevent ice growth on cryogenic (biological) samples.

From grades to levels

In Thermo Fisher Scientific's outsourcing relationship with its suppliers, its requirements for the parts involved are specified via Technical Product Documentation, while the required cleanliness is specified via the Quality of Electron Optics (QEO) documents. The cleanliness grades are related to the application in which the parts are used and cover the range from no cleaning, general cleanliness, and pre-cleaning for final cleaning (by Thermo Fisher Scientific), to low- and high-vacuum cleaning (by the suppliers).

De Groot announced that a QEO upgrade is needed for modules and ultra- to extremely-high-vacuum cleaning/treatment, as well as for alignment with ISO standards. In the new QEO standard under construction, the specifications are in terms of particle and chemical cleanliness levels, PCLs and CCLs, respectively. These are defined for the various types of contamination in a more detailed fashion as compared to the current cleanliness grades. This enables Thermo Fisher Scientific to specify higher cleanliness levels and provides suppliers with a more detailed insight into the cleanliness required for their parts.

The weakest link

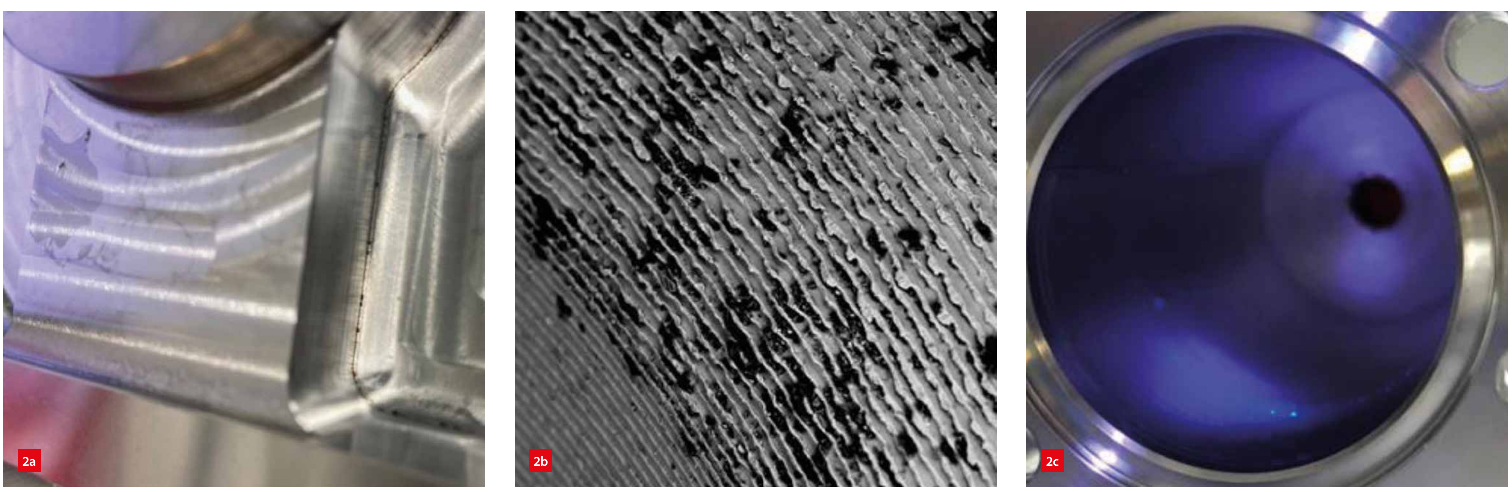
To conclude, De Groot illustrated the broad scope and complexity of the cleanliness and contamination control challenge. After showing the company's clean lab, featuring RGA (residual gas analysis) tools, a scanning electron microscope and a flow cabinet in which an optical microscope is used for inspection, he presented measurement and inspection examples of the various contamination types (Figure 2). These included: particles, dirt and burrs from (threaded) holes, corrosion of and cleaning stains on stainless steel, and powder blasting residues on parts; organic contamination in ploughing tracks on turned titanium surfaces; and many more potential EM error sources. This once again underscored De Groot's motto of "A vacuum is as good as the weakest link".

"Reflect before you begin"

Gabby Aitink-Kroes, senior opto-mechanical system engineer at SRON (Netherlands Institute for Space Research), talked about the practical difference between cleanliness and contamination. To clarify matters, she started by defining the two key concepts. Contamination is the process or fact of making a substance or place dirty or no longer pure by adding a substance that is dangerous or carries disease. Cleanliness is the state of being clean or the habit of keeping things clean.

For contamination control, it is customary to define requirements in terms of cleanliness, but ultimately it is about achieving an acceptable level of contamination. So, when a critical system has to be assembled, there are several factors that determine the outcome. It is not only the (input) cleanliness of the parts that have to be assembled and the cleanliness (ISO class) of the cleanroom in which assembly will take place, but the duration of the assembly process also matters, as it determines the available time for build-up of contamination on the system.

Hence, contamination control is not just about cleaning parts and ensuring the appropriate cleanroom class, but also about developing efficient assembly procedures, in order to reduce exposure to the environment, giving things less time to become dirty. Aitink-Kroes illustrated this for the Dutch contribution to the Mid Infrared Instrument for the James Webb Space Telescope, of which the assembly could be carried out so quickly that an ISO-5 flow cabinet inside an ISO-7 cleanroom was sufficient, eliminating the need for a complete ISO-5 cleanroom (with its tighter rules and regulations). And taking efficiency one step further,



Measurement and inspection examples of the various contamination types.
(a) Contamination of a stainless-steel part, including local corrosion (at the inner edge), particles and stains; UV-A-light inspection.
(b) Organic contamination in ploughing tracks on a turned titanium surface (R_a < 0.6 µm); SEM image.
(c) Organic particles (white luminescence) in a vacuum transport container; bare-eye (with protective goggles) UV-A-light inspection.

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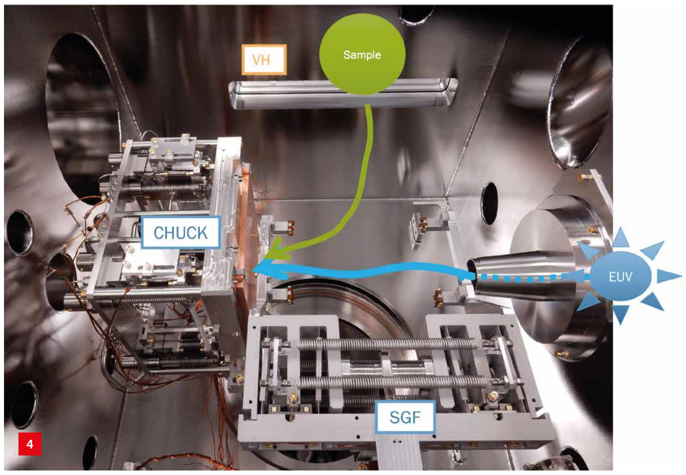
Working in a cleanroom environment is not much fun.



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Overview of the EBL2 exposure chamber with the various components. VH is the central vacuum handling chamber, SGF is the sample gripper flipper.

she said, "Cleaning things is difficult, so don't make them dirty!" This may help to relieve cleanliness requirements further down the contamination chain. "So," she added, "reflect before you begin."

Aitink-Kroes also drew attention to the human factor (Figure 3). People are the most 'burdened' by the required clean way of working and are at the same time the biggest contaminator of a cleanroom. Working in a cleanroom is difficult because of the gowning (including the face mask), the tiring environment (temperature, noise), the strict procedures, the extensive run-up and wrap-up, and the disastrous effects of 'little pleasures' (smoking, make-up, hair gel). So, everything that can help to reduce cleanroom time is welcome.

Sample gripper flipper design

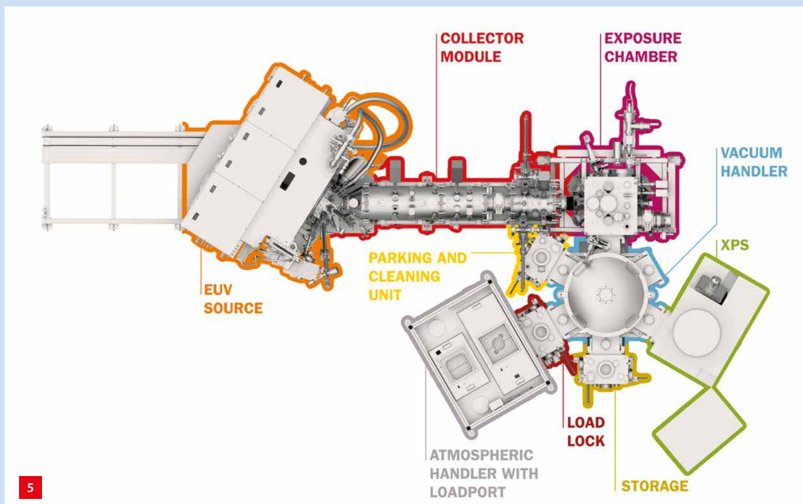
As the final speaker, Peter Kerkhof, optomechatronic design engineer at TNO, presented the design of a sample gripper flipper for TNO's EBL2 research facility (see the text box). The function of this gripper flipper is to change the orientation of the sample that is fed into the exposure chamber horizontally and has to be flipped to a vertical direction for EUV illumination. The sample can be either a bare reticle or a multi-layer mask, quartz plate or wafer contained in a holder (a square aluminium plate, basically).

Design challenges for the sample holder included the integration of different sets of handling interfaces, for EBL2's various vacuum regimes. These range from the ambient handling chamber to the central vacuum handling chamber to the ultra-high-vacuum exposure chamber, which comprises the sample gripper flipper and a chuck onto which the sample holder is mounted. The complete design (Figure 4) was successfully completed and realised, as evidenced by the five years of 'clean' running of the EBL2 facility.

TNO research facilities

At the DSPE Knowledge Day in Delft, three TNO research facilities for semicon (in particular EUVL) applications were included in a tour for the participants:

- ATOM: Advanced Tool for Outgassing Measurement, for measuring the outgassing rates of various molecular constituents from vacuum equipment components.
- DGL: Dynamic Gas Lock, for measuring contamination levels and studying mitigation strategies.
- EBL2: EUV Beam Line 2 (Figure 5), for simulating the environment of, for example, an EUVL machine to determine the effect of high EUV dose on specific samples and the degree of contamination that occurs.



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Overview of the EBL2.

INFORMATION
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