From model to best-performing prototype

Elevating the performance of ionization gauges with simulations

Alan Petrillo

alle Bilder: INFICON

Semiconductor manufacturing, particle physics research, and other valuable processes need high-vacuum or ultra-high-vacuum conditions (HV/UHV). To develop a better ionization gauge for measuring pressure in HV/UHV environments, Liechtenstein-based instrument manufacturer INFICON used multiphysics modeling to test and refine their impressive new design.

Innovation is often similar to a competition. It can be thought of as a race among creative people who strive towards the same goal. But even intense competitors share some consensus about how they pursue success. Just as every runner is timed by the same watch, competitors rely on standardized tools to measure progress.

In technological innovation, one such essential tool is the vacuum gauge. HV/UHV environments are used for researching, refining, and producing many manufactured goods. But are the pressure levels in one facility's vacuum chamber truly aligned with those in other facilities? Without shared standards and reliable tools for meeting them, key performance metrics – for both the vacuum chambers and the products being tested – may not be comparable. These potential discrepancies make one device very important (**Fig. 1**): the Ion Reference Gauge 080 (IRG080), produced by INFICON, is the result of a multinational project to develop a better tool for quantifying pressure in HV/UHV environments.

Fig. 1 The Ion Reference Gauge 080

This sensor is more precise, robust, and reproducible than existing ionization gauges. Its development was coordinated by the European Metrology Programme for Innovation and Research (EMPIR) [1]. EMPIR is a collaborative effort by private companies and government research organizations to make Europe's "research and innovation system more competitive on a global scale" [2]. The project participants considered multiple options but INFICON's design fulfilled the performance goals most suitably.

A number of organizations participated in the ionization gauge project [3]: Physikalisch-Technische Bundesanstalt (PTB, Germany), Cesky Metrologicky Institut Brno (CMI, Czech Republic), Institut za Kovinske Materiale in Tehnologije (IMT, Slovenia), Laboratoire national de métrologie et d'essais (LNE, France), Research Institutes of Sweden AB (RISE, Sweden), European Organization for Nuclear Research (CERN), Faculdade de Ciências e Tecnologia Universidade Nova de Lisboa (FCT-UNL, Portugal), VACOM Vakuum Komponenten & Messtechnik GmbH (Germany), and INFICON Aktiengesellschaft (Liechtenstein).

VACOM and INFICON are the two instrument manufacturers who designed and built the gauge prototypes.

© 2024 Wiley-VCH GmbH

Fig. 2 An example of a Bayard-Alpert hot-filament ionization gauge

Gas density through ionization

"Nothing happens in a vacuum" is a familiar expression, but many useful things actually stem from nearly-empty spaces. "There are almost no high-tech products that do not involve a vacuum process," says Martin Wüest, head of sensor technology at INFICON. The term "vacuum" describes a theoretical absolute of absence. In practice, the emptiness of an actual space is usually a matter of degree as indicated by HV/UHV terminology. Measuring different degrees of vacuum depends on various methods for determining pressure levels. Depending on the conditions, certain methods work better than others: For example, near atmospheric pressure, a capacitive diaphragm gauge can be used. In a medium vacuum, heat transfer works by convection. Neither of these approaches is effective at HV (defined as pressure below 0.1 pascals, or Pa) or UHV (below 10^{-6} Pa) pressure levels: "At HV/UHV pressures, there are not enough particles to force a diaphragm to move, nor are we able to reliably measure heat transfer. This is where we use ionization to determine gas density and corresponding pressure," Wüest explains.

The most commonly used tool at HV/UHV pressure is a Bayard-Alpert hot-filament ionization gauge (**Fig. 2**) placed inside the vacuum chamber. This instrument consists of three components: the filament (or hot cathode), the grid, and the ion collector. Its operation starts with supplying low-voltage electric current to the filament to heat it up. The filament becomes hotter and emits electrons. They are accelerated by the grid being supplied with higher voltage. Some of the electrons will collide with any free-floating gas molecules that are circulating in the vacuum chamber and might form ions flowing towards the collector: The measured current is proportional to the density of the gas molecules in the chamber. The application of the ideal gas law provides the pressure which is proportional to the ion current divided by the electron current and by a sensitivity factor depending on the gas in the chamber.

Sensitive to heat and handling

Unlike a hammer, saw, and measuring tape which are still usable in case of a few dents and dings, a Bayard-Alpert ionization gauge suffers from routine use and handling: while the operational principles of these devices are sound, their calibration is too easily compromised.

A typical ionization gauge contains fine metal structures that are held in spring-loaded tension. Each time the device is used, the filament heats up to 2000 °C. The high temperature affects the metal in the spring and can distort the shape of the filament. This changes the starting point of the electron flow and its paths.

In addition to their sensitivity to heat, the core components of a Bayard-Alpert gauge can easily be misaligned introducing a measurement uncertainty of 10 to 20 % – an unacceptably wide range of variation. As a result, most vacuum chamber systems are oversized and the need for frequent gauge recalibration wastes time and money.

Building a simulation model

The project team set a measurement uncertainty target of 1 % or less if the gauge is used to detect nitrogen gas. Another important goal was to eliminate the need to recalibrate gas sensitivity factors for each gauge and gas species being detected. The new design's performance needed

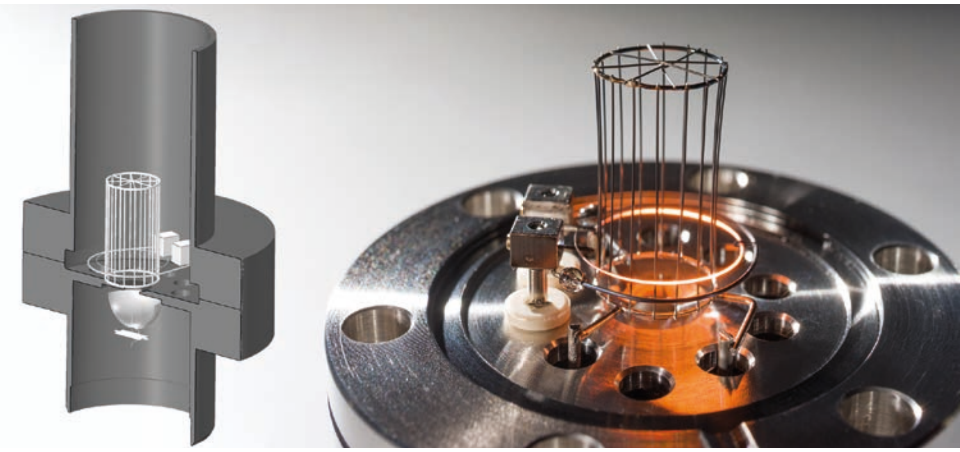

Fig. 3 INFICON's COMSOL model of the IE514 gauge (left) and the physical gauge (right)

© 2024 Wiley-VCH GmbH

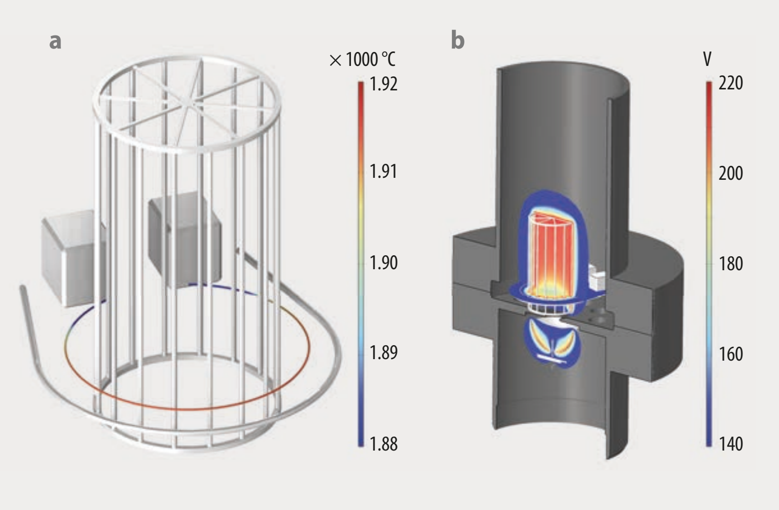

Fig. 4 IE514 simulation of the temperature of the filament (left) and the electric potential surrounding the grid structure (right)

to be unaffected by minor shocks and reproducible by multiple manufacturers.

To achieve this, the project team dedicated itself to studying HV/UHV measurement at first. Its research encompassed a broad review of 260 relevant studies. After the review, the project partners selected one design that incorporates current best practice for ionization gauge design: INFICON's IE514 extractor-type gauge.

NOVA University Lisbon in Portugal, the European research lab CERN, and INFICON each developed simulation models of the IE514 design. The results of each model were compared to those of a physical prototype of the IE514 gauge to ensure the models' accuracy before proceeding with new designs.

Francesco Scuderi, an INFICON engineer specialized in simulation, used the COMSOL Multiphysics® software to model the IE514 (**Fig. 3**). The model enabled analysis of thermionic electron emissions from the filament and the ionization of gas by those electrons. In addition, it enabled the paths of generated ions towards the collector to be traced. The simulated results were used to calculate an expected sensitivity factor based on how many ions are detected per emitted electron – a useful metric for comparing the overall fidelity of the model with actual test results.

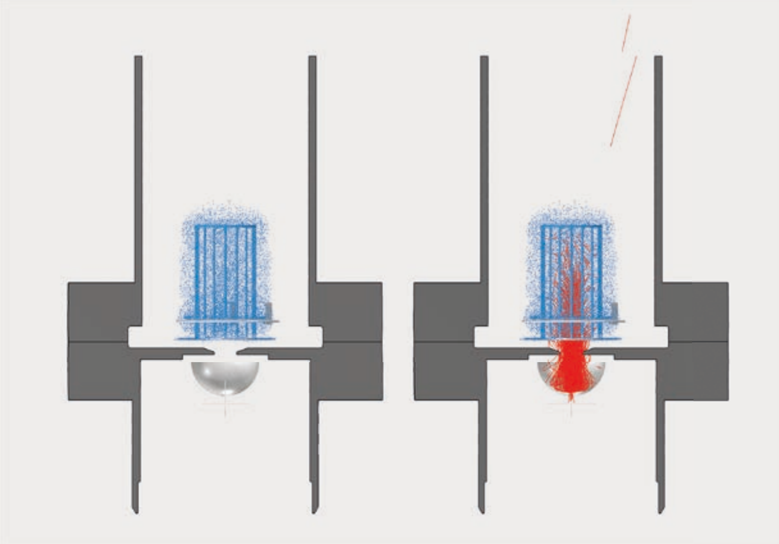

Fig. 5 Ray tracing models showing the simulated paths of electrons (blue) and ions (red) in the IE514

Optimising the design

After constructing the model geometry and a mesh, Scuderi set the boundary conditions for the simulation. He aimed to express the coupled relationship of electron emissions and filament temperature which varies from approximately 1400 to 2000 °C across the length of the filament. This variation thermionically affects the distribution of electrons and their paths (**Fig. 4**).

Using the thermal conditions and the electric field, the ray tracing simulation can start. The software enables the flow of electrons to the grid and the resulting coupled heating effects to be traced. In the next step, the model is used to calculate the percentage of electrons colliding with gas particles. Then, ray tracing of the resulting ions can be performed, tracing their paths toward the collector (**Fig. 5**).

It is then possible to compare the quantity of circulating electrons with the number of ions and their positions. From this, a value for the ion current in the collector can be extrapolated in order to compute the sensitivity factor.

The simulated values of INFICON's model aligned closely with test results from the benchmark prototype. Now, the team could observe how changes to the modeled design affected key metrics, including ionization energy, the paths of electrons and ions,

© 2024 Wiley-VCH GmbH

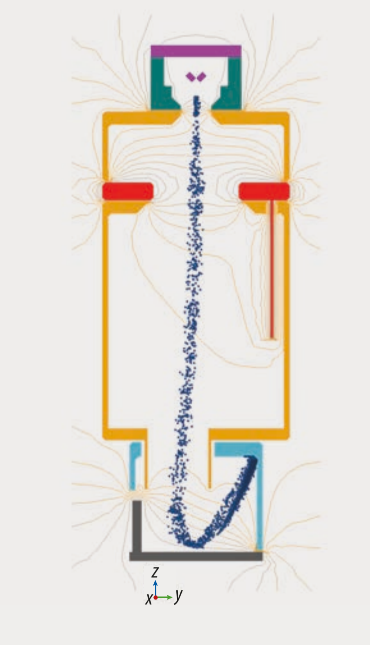

Fig. 6 Image from a COMSOL model of the IRG080 gauge

emission and transmission current, and sensitivity.

More precise and robust

The final product of INFICON's design process, the IRG080, incorporates many components similar to the ones of existing Bayard-Alpert gauges but key parts look quite different. For example, the new design's filament is a solid suspended disc not a thin wire. The grid is no longer a delicate wire cage but is instead made from metal parts with stronger structure. The collector now consists of two components: a single pin or rod that attracts ions and a solid metal ring that actually helps to directing electron flow away from the collector and towards a Faraday cup. This arrangement was refined using a ray tracing simulation with the COMSOL Multiphysics® software (**Fig. 6**) and improves the accuracy by better separating the paths of ions and electrons.

INFICON built 13 prototypes for the evaluation by the project consortium. Testing showed that the IRG080 achieved the objective of a measurement uncertainty below 1 %. Regarding sensitivity, the IRG080 performed eight times better than the benchmark. In addition, the INFICON prototype yielded consistent results during multiple testing sessions, delivering a sensitivity repeatability performance that was 13 times better than the benchmark gauge. Twenty-three identical gauges were built and tested during the project, confirming that INFICON has created a more precise, robust, and reproducible tool for measuring HV/UHV conditions.

With the completion of the ion gauge project, the INFICON team hoisted an impressive trophy: the IRG080 itself. Of course, this success was not based on the team alone. INFICON benefited from its partners' insights and support; in turn, the broader scientific and manufacturing community will benefit from more consistent measurements of HV/UHV conditions. The entire project is an excellent example of a contest where, in the end, everyone wins.

[1] Euramet, "Towards a Documentary Standard for an Ionisation Vacuum Gauge," Feb. 2021; https://www.euramet.org/project-16NRM05
[2] Euramet, "About EMPIR," 2023; https://www.euramet.org/research-innovation/research-empir/about-empir
[3] EMPIR, "Ion Gauge: Members of the Project," May 2019; https://www.ptb.de/empir/16nrm05-consortium.html

Author

Alan Petrillo, Content Writer,
Comsol Multiphysics GmbH,
Robert-Gernhardt-Platz 1,
37073 Göttingen, www.comsol.de

© 2024 Wiley-VCH GmbH


THE **FUTURE** DEPENDS ON OPTICS

Edmund Optics®
Your One-Stop Shop for Optics

- Extensive inventory of over 34.000 different components
- Over 2 million optics in stock and ready to ship
- New products & services added continually
- 24/7 product & application support chat – an industry first!
- Global company with over 80 years of experience in optics

Browse our extensive online shop today!

www.edmundoptics.eu/marketplace

EU/UK: +44 (0) 1904 788600
GERMANY: +49 (0) 6131 5700 0
FRANCE: +33 (0) 820 207 555
sales@edmundoptics.eu

Edmund optics | worldwide