Load-lock Pressure Control in the Semiconductor Industry

How to optimize load-lock designs

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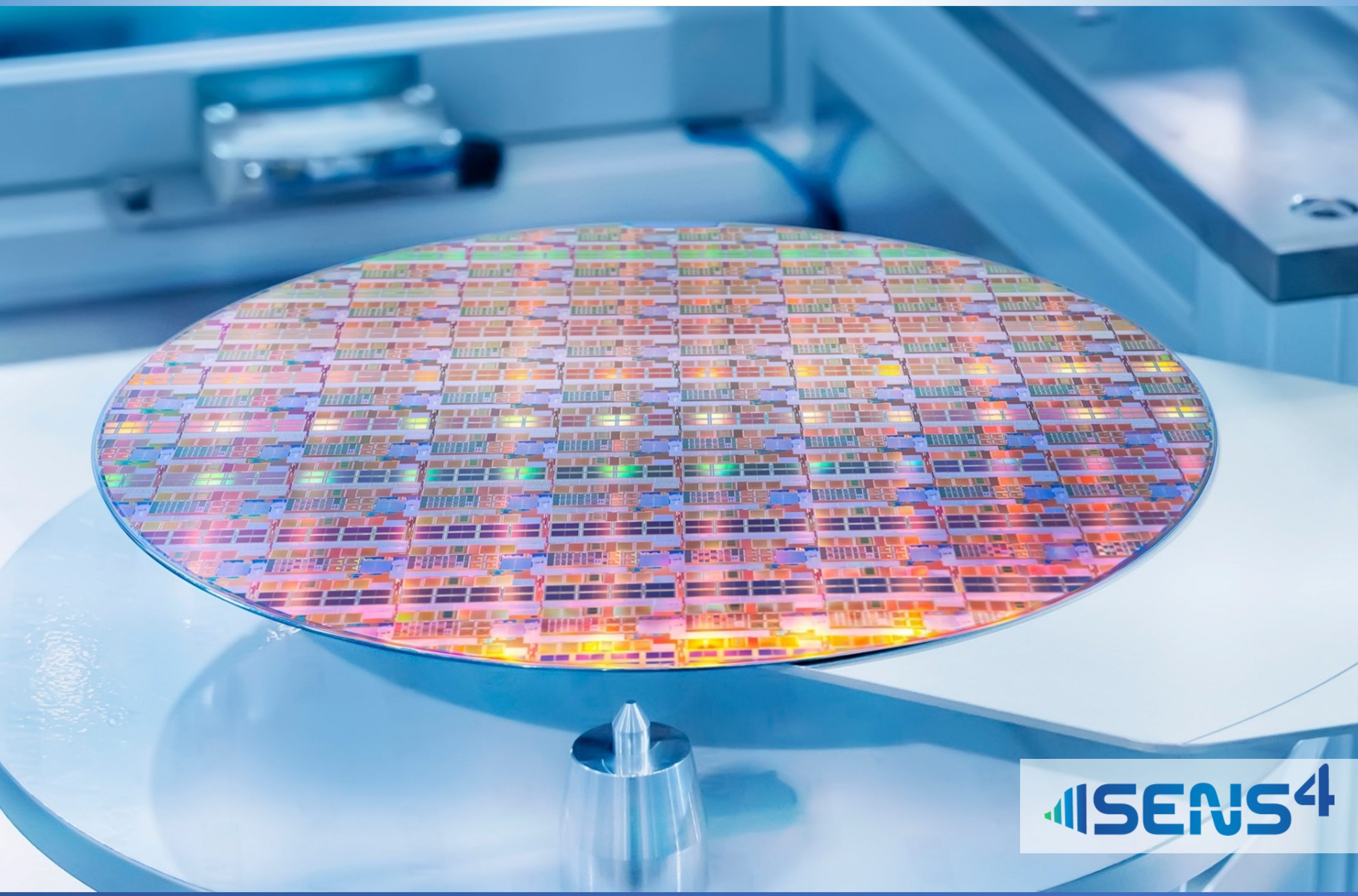
Abstract

Load-lock systems play a critical role in semiconductor manufacturing by enabling wafer transfer between atmospheric and vacuum environments without venting the main process chamber. Accurate and reliable pressure control during each phase of the load-lock cycle — venting, evacuation, stabilization, and transfer — is essential to maintain process yield, minimize contamination risk, and reduce cycle time. This white paper examines the evolution of pressure measurement and control technologies used in load-lock systems. It presents a detailed technical overview of multi-sensor architectures that combine MEMS Pirani, absolute piezoresistive, and capacitance diaphragm sensors to cover the full vacuum range and enable precise gauge pressure control relative to ambient barometric conditions. Advanced features such as autonomous solid-state switching, programmable setpoints, and robust analog and digital I/O interfaces are also discussed. These advancements enable engineers to design reliable, and efficient load-lock systems for demanding semiconductor and industrial vacuum applications.



Background

A load-lock (or loadlock) is an auxiliary vacuum chamber connected to the main processing chambers used in semiconductor manufacturing and other vacuum-based processes. The purpose of the load-lock is to transfer wafers or devices between atmospheric pressure environments and the vacuum chamber without the need to vent the main chamber.

Controlling the pressure inside the load-lock system is critically important to ensure equipment performance and processing yield. This includes enabling fast cycle times, preventing wafer contamination, and avoiding the introduction of water vapor into the vacuum system.

History

Load-locks were introduced in the 1970s[1], but it was in the 1980s that they became common with the introduction of cluster semiconductor processing tools by Applied Materials[2], where multiple processes could be performed on the same tool.

Pressure measurement and control is an essential part of operating a load-lock system. The load-lock must be vented to atmospheric pressure to open the load-lock door and evacuated to medium vacuum to transfer wafers to the process chamber.

In early load-lock designs, legacy convection-type wire Pirani gauges were used to monitor and control pressure. However, the ventilation and gas backfilling systems were typically configured to reach a fixed pressure setpoint, without accounting for variations in actual atmospheric pressure outside the load-lock. As a result, weather-related changes in atmospheric pressure could lead to over-pressurization when opening the door or vacuum pressure, making it difficult to open.

To overcome this issue, a separate differential pressure sensor — measuring relative to atmospheric pressure — was added to the load-lock control system. This provided a switch function to ensure that the internal pressure of the load-lock was properly equalized with ambient atmospheric pressure before opening the door.

MKS Releases New Pressure/Vacuum Transducer

A compact, combination transducer that measures pressure from 10^{-5} Torr to atmosphere.

October 4, 2002 - Boulder, Colorado, MKS Instruments, Inc. - HPS® Products has introduced an enhanced model **HPS® Series 901 Loadlock Transducer (LLT)**. The improved features include three setpoints, a choice of digital communications, a wider set point range and a lower price. The CE marked Series 901 is a combination Piezo and Pirani sensor with an integrated electronic control circuit, digital communications, analog output and three setpoints as standard features for process control.

Semiconductor tools often use a loadlock as an interface to the continuously pumped main chamber. These loadlocks are often pumped to high vacuum levels very rapidly, which can overwhelm the traditional Pirani gauges due to their slower response time. When the loadlock is brought up to atmosphere, a separate switch is used to indicate when the door can be opened. The HPS Series 901 Loadlock Transducer (LLT) combines a vacuum gauge (MicroPirani™) and an atmosphere switch (Piezo) into an integrated, compact package. The Piezo is a differential pressure sensor, which will operate properly under varying outside environmental pressures like weather and elevation, ensuring that the loadlock door will opening at the optimal time.

Unlike traditional Pirani gauges, the element in the MicroPirani™ portion of the Series 901 is made of a one millimeter square silicon chip, allowing the measurements to be made in a very small volume. A traditional Pirani sensor has a measuring range from 10^{-3} to about 100 Torr, rapidly losing sensitivity above 10 Torr. Because the size of the sensing portion of the MicroPirani™ is so small, it has a range from atmosphere down to 10^{-5} Torr. Since the MicroPirani™ is gas-type sensitive, it can be used to find medium to fine leaks in a vacuum system.

Figure 1 Load-lock news release[4]

Using a separate vacuum transducer and atmospheric pressure switch addressed the ventilation challenges but added cost and increased system complexity due to additional cabling and control logic. This created an opportunity to invent a more streamlined, integrated, and compact solution.

In 2002, the first integrated load-lock pressure measurement and control transducer was developed through a joint effort between the Danish startup Wenzel Instruments ApS and MKS Instruments Inc. (now MKS Inc.). This innovation combined MEMS piezo-based differential pressure sensing — relative to ambient pressure — with MEMS Pirani vacuum measurement, and was disclosed by the parties in a joint U.S. patent[3].

The multi-sensor load-lock transducer proved to be a game-changing product for the semiconductor industry for many years.

Load-lock Pressure Cycle

The typical load-lock pressure cycle, as illustrated in *Figure 2*, consists of the following steps:

1. Loading at Atmospheric Pressure

The cycle begins with the load-lock chamber at ambient pressure. The load-lock door opens to allow loading of wafers from the external environment.

2. Pump-Down Phase

After closing the door, the chamber is evacuated. This phase typically involves a roughing pump for the initial pressure reduction, followed by a high-vacuum pump for achieving lower pressures, depending on process requirements.

3. Stabilization and Transfer to Process Chamber

Once the desired vacuum level is reached and stabilized, usually matched to the pressure of the transfer or process chamber, the internal valve opens to transfer the wafer. This step ensures minimal contamination and pressure turbulence.

4. Return and Venting Phase

After processing, the wafers are returned to the load-lock. The internal valve closes, and the chamber is vented with clean, dry gas (typically nitrogen or clean dry air) to bring the pressure back to atmospheric levels.

5. Unloading at Atmospheric Pressure

The door is reopened for unloading, completing the cycle. The load-lock is now ready for the next operation.

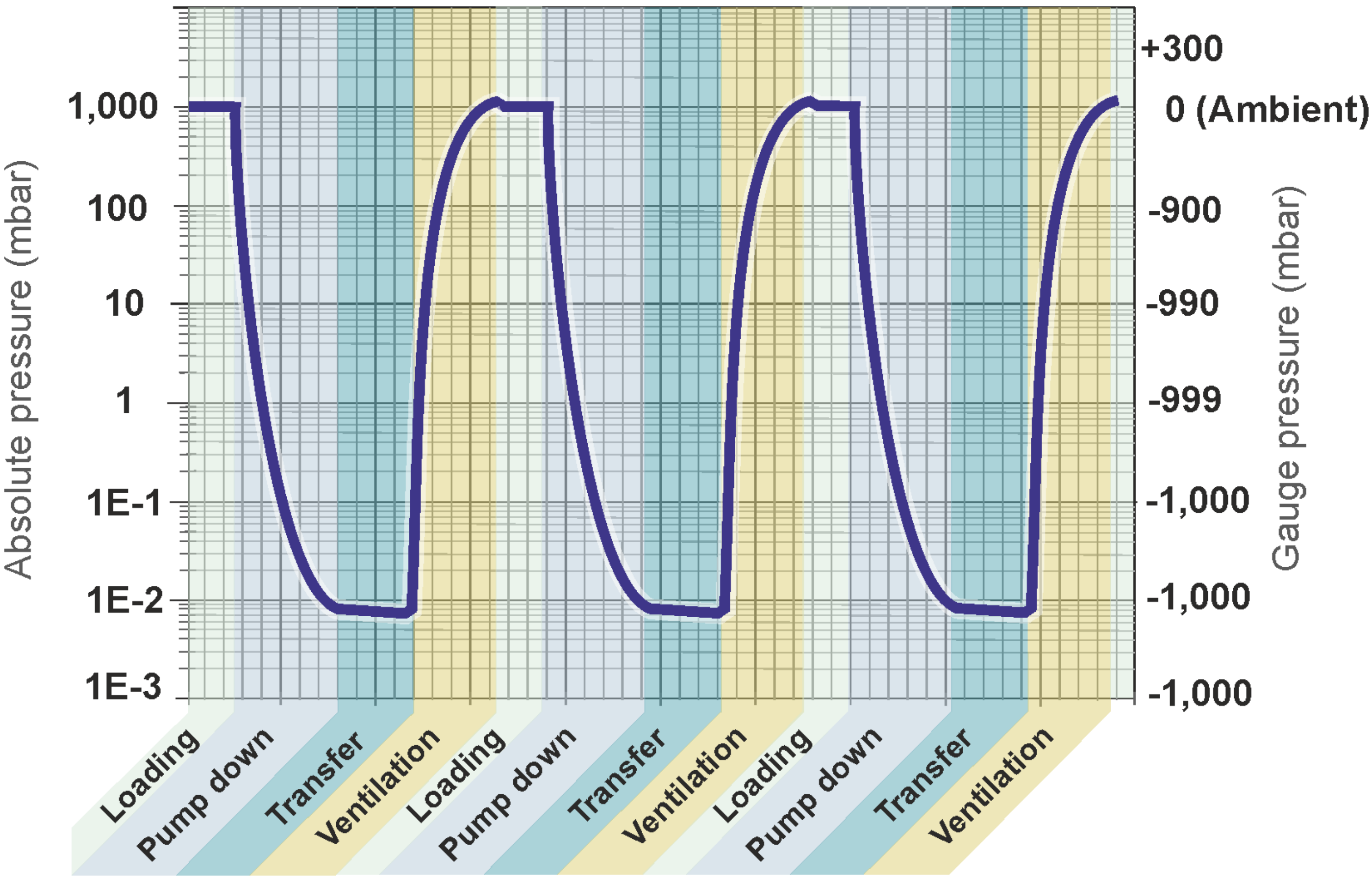


Figure 2 Load-lock steps and pressure cycle

Pressure Measurement

Precision control of the pressure cycle is critical to reduce cycle time, avoid pressure shocks, protect wafers, prevent system contamination, and minimize turbulence.
In a load-lock system, pressure must be measured and controlled in two distinct ways during the load-lock pressure cycle:

1. Absolute Vacuum Pressure Measurement

The absolute pressure in the load-lock can be measured using indirect vacuum sensors, such as Pirani heat-loss sensors, or with absolute diaphragm vacuum sensors, such as piezoresistive or capacitive diaphragm gauges. Modern load-lock transducers often integrate both Pirani and diaphragm sensors to deliver optimal performance across a wide dynamic pressure range.

2. Gauge Pressure Measurement

Gauge pressure refers to pressure measured relative to the surrounding ambient (atmospheric) pressure. This type of measurement is crucial for accurate venting and safe door operation in the load-lock system.

If the barometric pressure around the semiconductor equipment is 1030 mbar, the load-lock should be vented to 1030 mbar or slightly above. Once the pressure inside the load-lock equals the ambient pressure, the door can be safely opened. However, if barometric pressure drops — due to changing weather conditions or a passing low-pressure system — to, for example, 984 mbar, the load-lock should only be vented to 984 mbar to prevent an over-pressurization shock when opening the door. Conversely, if the load-lock is vented to a pressure lower than the surrounding atmosphere, the resulting pressure differential may create enough force to make it difficult — or even impossible — to open the door. Because barometric pressure fluctuates, the pressure in the load-lock during the ventilation cycle must be measured and controlled relative to the changing ambient pressure to ensure safe and reliable operation.

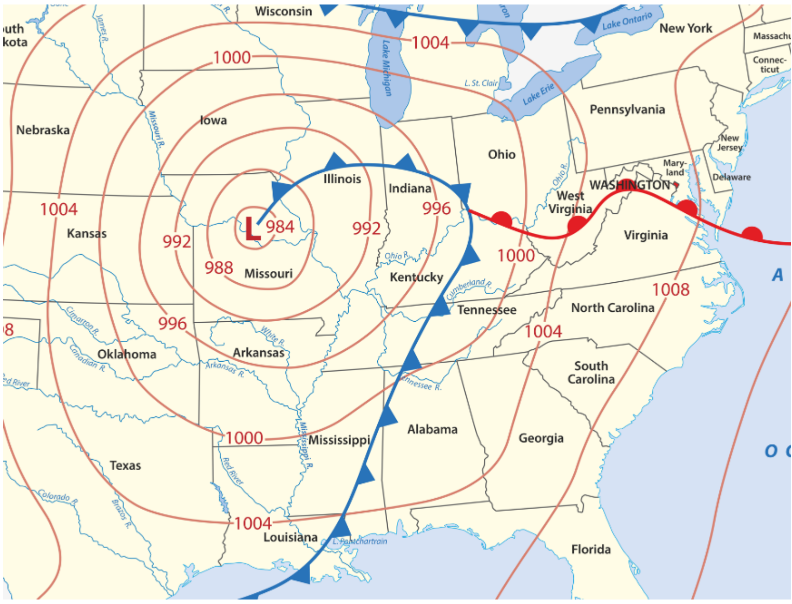


Figure 3 Low pressure isobars on weather map

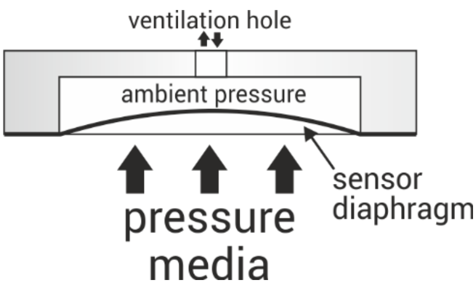


Figure 4 Gauge pressure sensor

Gauge pressure measurement can be achieved using a diaphragm sensor, where one side of the diaphragm is exposed to ambient pressure through a ventilation hole and the other side to the vacuum chamber pressure media as illustrated in *Figure 4*.

This can be implemented with a piezoresistive diaphragm sensor, which features a thin silicon membrane. However, such ultra-thin membrane is permeable to helium, which may lead to false leak indications when using a traditional helium leak detector on the load-lock gauge and load system.

To overcome this, a different approach to gauge pressure is utilized in modern load-lock transducers[5], where two separate absolute pressure sensors are used — one positioned in the vacuum environment and the other exposed to ambient pressure. By subtracting the vacuum reading from the ambient reading, the gauge pressure can be accurately determined.

> “Prevent vacuum system air inrush by accurate atmospheric referenced venting control”

Trible Sensor Architecture

Modern general-purpose load-lock transducers[5] use three pressure sensors to deliver the functionality of four sensors.

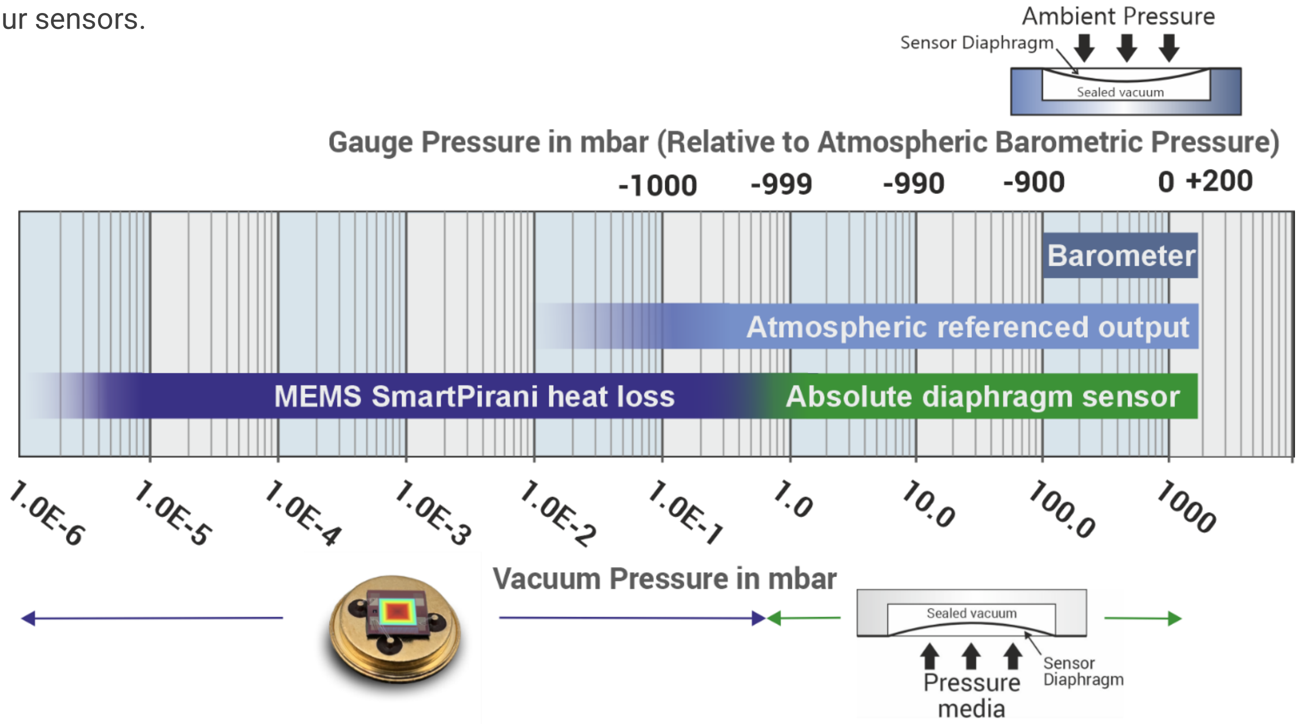


Figure 5 Sensor architecture of a modern Sens4 load-lock transducer

The combination of an absolute diaphragm sensor and a MEMS Pirani heat-loss sensor enables full-range pressure measurement and precise control during the pump-down evacuation phase.

Additionally, by pairing a barometric pressure sensor with the absolute diaphragm sensor, gauge pressure can be determined simply by subtracting the absolute vacuum pressure from the ambient barometric pressure.

Atm. ref. Output = Absolute pressure - Barometric pressure

More than one Solution

In recent years, several new product solutions have emerged to deliver the atmospheric switching function, utilizing either simplified or more sophisticated sensor configurations. These innovations are designed to either enable more accurate absolute pressure measurement throughout the pump-down cycle or a limited measurement range for a more cost-effective solution.

“Tailored performance, delivered by a family of load-lock transducers”

Vacuum measurement transducers with load-lock atmospheric switching functionality are also used in other vacuum applications and industries than the semiconductor industry including analytical instrumentation and industrial PVD coating. To meet the demand in these applications the load-lock product family was extended beyond the traditional load-lock sensor configuration as illustrated in *Figure 6*.

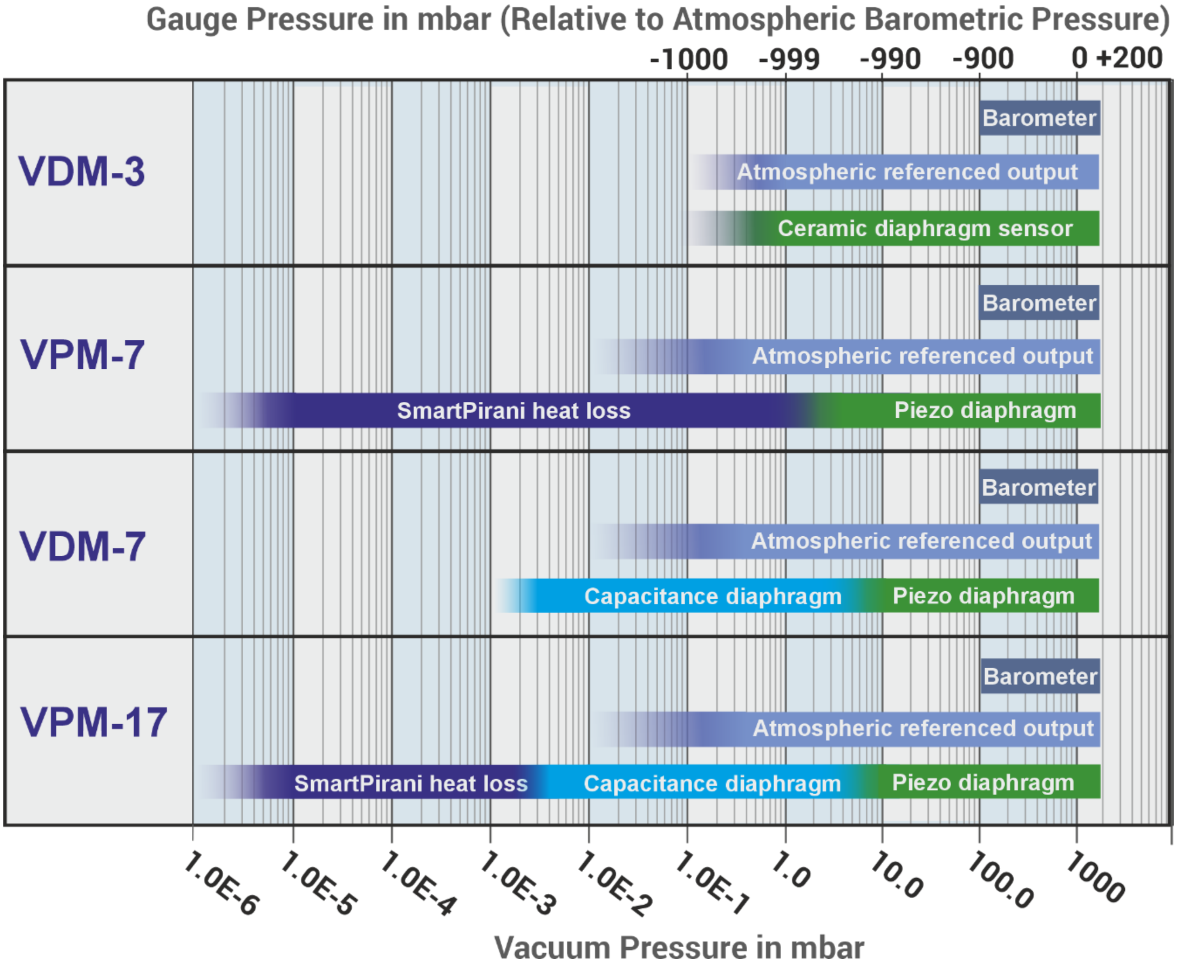


Figure 6 Sens4 transducer series with atmospheric switching function

Capacitance Diaphragm Sensor Technology

The Capacitance Diaphragm Gauge (CDG) — a widely used vacuum sensor — extends gas-independent pressure measurement over a broad range, from atmospheric pressure (1333 mbar) down to 5×10^{-3} mbar. This makes it especially valuable in applications where the gas composition is variable, unknown, or subject to change during the process. Unlike heat-loss Pirani sensors, CDGs rely on mechanical deflection of a diaphragm, which makes their accuracy independent of the gas type. This provides reliable, stable pressure readings in demanding environments such as semiconductor processing, coating systems, or research applications, where gas type or composition is switching.

> “Innovative multi-sensor system with seamless integration delivers precise, gas-independent measurements across a wide range.”

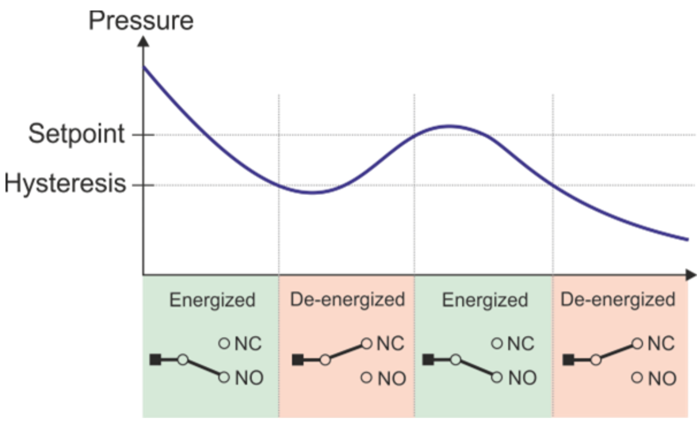
Essential Dual-Sensor Solution for Cost Sensitive Applications

For applications requiring both atmospheric switching and rough vacuum measurement, a streamlined dual-sensor solution is now available in a minimal configuration. This sensor setup combines the functionality of atmospheric pressure switching with accurate vacuum measurement down to 1 mbar — all in a simplified transducer package. Ideal for cost-sensitive, it delivers reliable performance without the complexity of a wide range vacuum measurement capability. Whether used in simple load-lock systems, analytical equipment, or industrial coating, this configuration offers essential functionality with maximum efficiency.

Autonomy Control System and Logic

Setpoints are commonly used to trigger and control the various steps in the load-lock pressure cycle. The setpoint control circuit is typically integrated into the load-lock transducer. A specific target pressure value is programmed as the setpoint, and a switch function is used to activate and trig external equipment when the target pressure is reached.

Today's load-lock transducers include multiple independent setpoint and the autonomy setpoint control system can run independently of other systems enabling use as a safety interlock circuit.

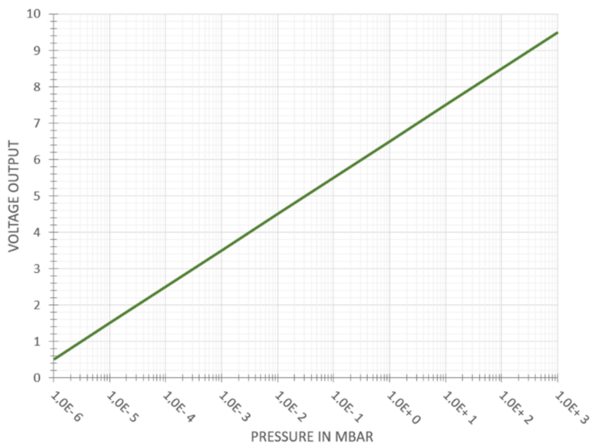


The reliability of load-lock setpoint control circuits is critical. Modern load-lock transducers therefore utilize **solid-state switching relays**, offering a significant improvement over the **mechanical relays** found in older systems. Solid-state relays deliver higher reliability and faster switching performance. They operate with arc-free contacts, produce no electromagnetic interference (EMI) during switching, and have no moving parts — resulting in greater durability and longevity.

Analog Voltage Output

The use of analog voltage signals to transmit measurement data is still widely used in the vacuum industry.
Although analog signals can be sensitive to electromagnetic interference and signal loss over long cable runs, they still have relevance in the semiconductor industry.

Load-lock transducers traditionally provide a measurement signal of 1 VDC per decade in Torr, mbar, or Pascal that enables easy conversion from voltage to pressure value.



Digital Interface and Communication

Digital signals are less susceptible to external interference than analog voltage signals, particularly in electrically noisy environments. Serial interfaces such as RS-232 and RS-485 have been used reliably for many years in load-lock transducer designs, demonstrating robustness and dependability.

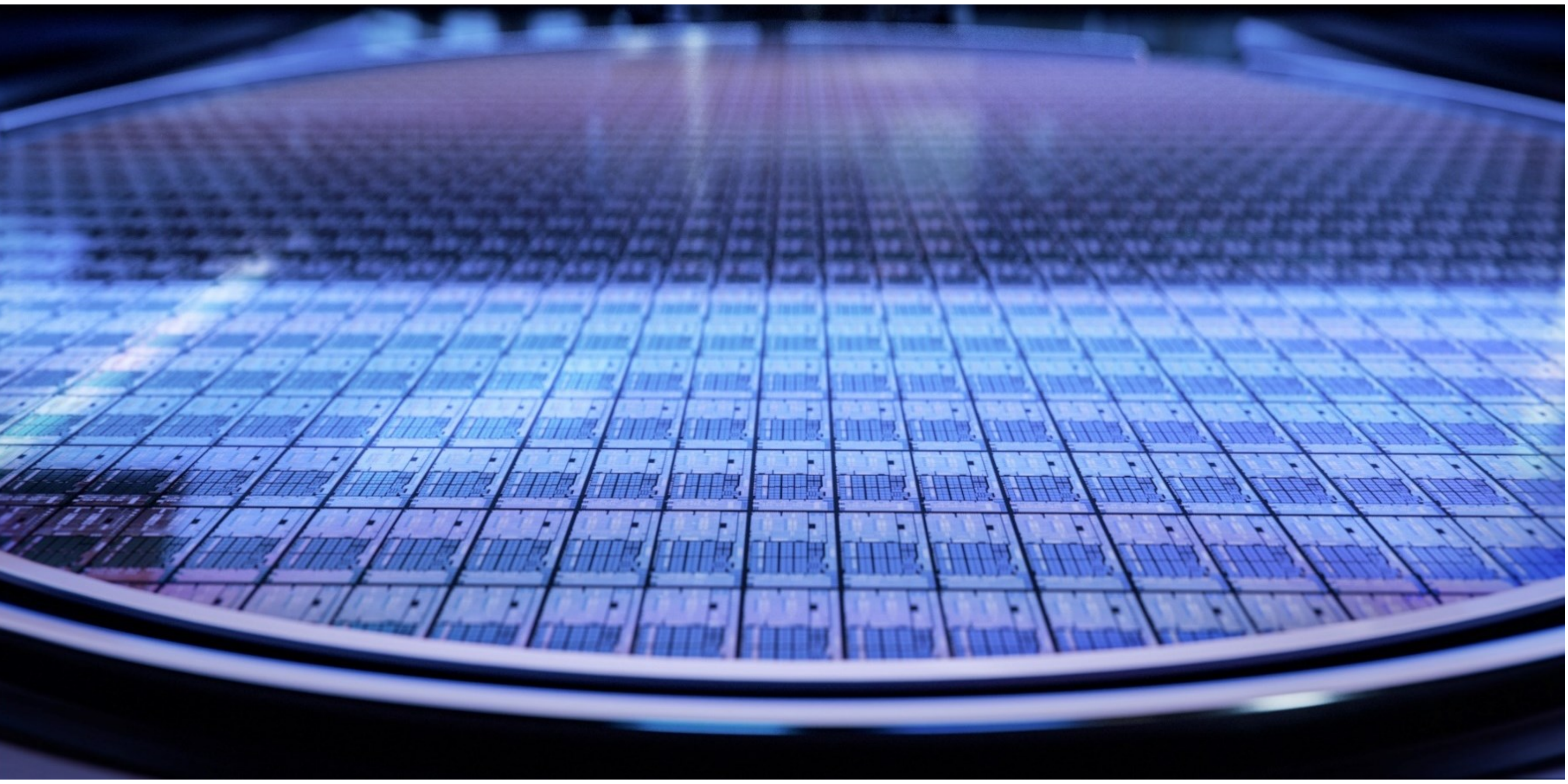
Historically, DeviceNet was the dominant digital communication protocol and architecture for semiconductor equipment instrumentation. However, the added cost of integrating DeviceNet at the product level has led to its declining adoption in load-lock transducers.

DeviceNet has largely been replaced by EtherCAT, which offers significantly better performance. Modern semiconductor tools now incorporate load-lock transducers into the EtherCAT network.

To support interoperability, stakeholders from the vacuum and semiconductor industry have established a formal standard for EtherCAT-based vacuum gauges[6]. This standard ensures consistent performance and protocol compliance across different brands, allowing semiconductor equipment manufacturers to maintain business continuity by qualifying drop-in compatible vacuum transducers from multiple vendors.

Prevent Particulate Contamination

Particulate contamination in load-lock chambers poses a significant risk to wafer and system cleanliness and integrity in semiconductor manufacturing — especially as device geometries continue to shrink. Effective contamination control in load-lock systems requires a well-established balance between throughput performance and clean handling environments.



Precise control of the load-lock ventilation cycle is essential to ensure that the internal pressure is properly equalized with ambient pressure, minimizing the risk of air and particulate ingress. To prevent backflow of ambient air, the pressure setpoint can be configured slightly above atmospheric pressure. This ensures that the venting gas, typically nitrogen or clean dry air (CDA), flows outward from the load-lock, thereby limiting contamination by particulates present in the ambient air.

Another key load-lock design consideration is the prevention of aerodynamic turbulence during vacuum evacuation and venting. Turbulence can disturb settled particles on chamber surfaces, increasing the risk of particle adhesion to wafer surfaces. To mitigate this, a controlled evacuation process using multistage pumping and carefully regulated venting rates is recommended.

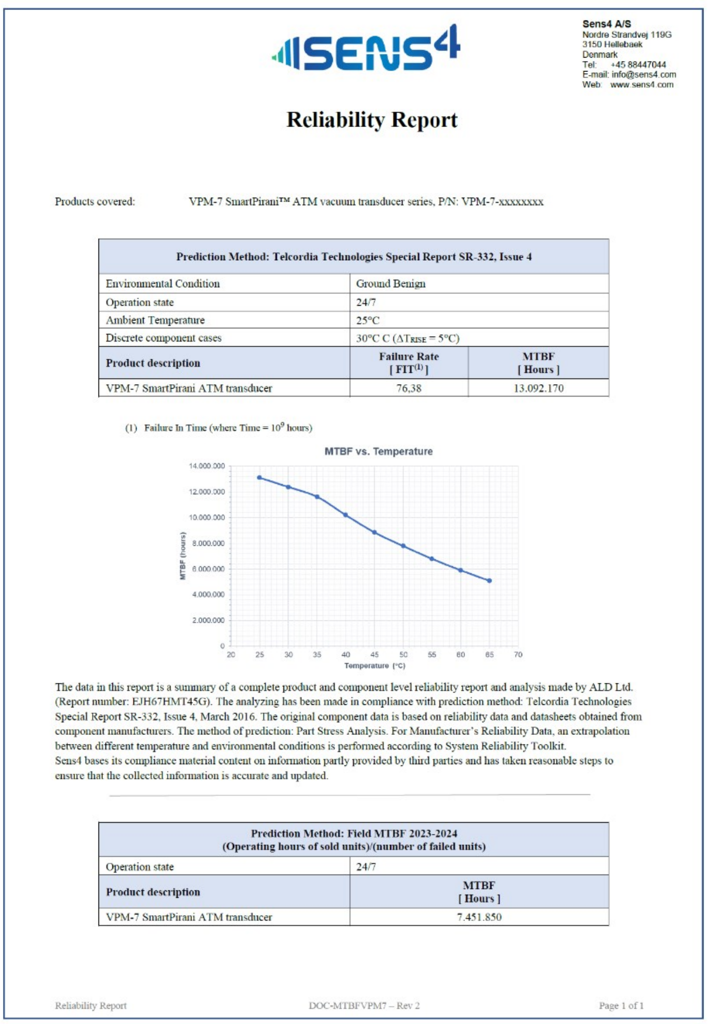
Research demonstrates[7] that effective contamination control in load-lock systems requires careful consideration of multiple design parameters, including evacuation methodology and rate, chamber volume, and structural design.

The different considerations for selecting vacuum pumps and optimizing the evacuation process in load-lock systems are analyzed in a study by Pfeiffer Vacuum and OTB Solar[8].

By combining optimized pressure control, real-time monitoring, and careful mechanical design, particulate contamination in load-lock chambers can be effectively minimized without compromising throughput.

Reliability & Longevity

In the semiconductor industry, uptime is critical. High-value manufacturing processes run 24/7 in highly controlled environments, and any unplanned downtime can result in significant production losses, yield degradation, cost increase and missed delivery deadlines. The reliability of every single component — from vacuum pumps, valves, and vacuum gauges to gas flow controllers and plasma sources — directly impacts the stability and consistency of the manufacturing process. Even minor failures can halt production, contaminate wafers, or compromise product quality and yield.
Therefore, suppliers of components and subsystems to the semiconductor industry must meet stringent reliability standards. Products must be designed and validated to perform flawlessly under prolonged operation cycles.



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Reliability Report

Products covered: VPM-7 SmartPirani™ ATM vacuum transducer series, P/N: VPM-7-xxxxxxx

Prediction Method: Telcordia Technologies Special Report SR-332, Issue 4		
Environmental Condition	Ground Benign	
Operation state	24/7	
Ambient Temperature	25°C	
Discrete component cases	30°C C (ΔT_{RISE} = 5°C)	
Product description	**Failure Rate [FIT(1)]**	**MTBF [Hours]**
VPM-7 SmartPirani ATM transducer	76,38	13.092.170

(1) Failure In Time (where Time = 10^9 hours)

The data in this report is a summary of a complete product and component level reliability report and analysis made by ALD Ltd. (Report number: EJH67HMT45G). The analyzing has been made in compliance with prediction method: Telcordia Technologies Special Report SR-332, Issue 4, March 2016. The original component data is based on reliability data and datasheets obtained from component manufacturers. The method of prediction: Part Stress Analysis. For Manufacturer's Reliability Data, an extrapolation between different temperature and environmental conditions is performed according to System Reliability Toolkit.
Sens4 bases its compliance material content on information partly provided by third parties and has taken reasonable steps to ensure that the collected information is accurate and updated.

Prediction Method: Field MTBF 2023-2024 (Operating hours of sold units)/(number of failed units)	
Operation state	24/7
Product description	**MTBF [Hours]**
VPM-7 SmartPirani ATM transducer	7.451.850

Reliability Report DOC-MTBFVPM7 – Rev 2 Page 1 of 1

Figure 7 VPM-7 SmartPirani ATM reliability report

Predicted MTBF vs. Real-world MTBF

When designing load-lock transducers for the semiconductor industry, careful selection of high-quality components is critical. Reliability must be built in from the start — not added later. Every element, from sensors to electronics to seals, must be chosen to ensure long-term durability and stable performance under demanding vacuum and cycling conditions.

But design assumptions must be validated. That's where field-proven performance plays a key role. Demonstrating real-world reliability under actual operating conditions is the ultimate test of a robust design. While predicted MTBF values provide a theoretical benchmark, only field data from a significant installed base over several years of use can confirm true operational lifetime.

It's this combination — innovative design, engineering excellence, quality components, controlled manufacturing, and real-world application validation — that ensures reliable, long-life performance in even the most critical semiconductor applications.

> "Reliability isn't proven in theory — it's earned in the field."

Conclusion

The performance and reliability of load-lock systems are critical to the efficiency and cleanliness of semiconductor processes. Precise control of the pressure cycle — including accurate measurement of both absolute and gauge pressure — is essential to avoid contamination, minimize cycle time, and prevent stress during wafer transfer. Modern load-lock transducers leverage advanced sensor architectures, including MEMS-based Pirani, piezoresistive, and capacitive diaphragm sensors, to deliver real-time control across the full pressure range. Furthermore, innovations in atmospheric pressure switching, sensor integration, and digital communication interfaces have significantly improved integration and performance. As semiconductor processes continue to evolve with smaller geometries and stricter contamination limits, the role of reliable, intelligent load-lock systems becomes even more vital than ever.

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About the Author

Ole Wenzel has been a pioneer in vacuum measurement technology for over 30 years. His journey began in 1992 with the founding of Wenzel Instruments, where he introduced the industry's first MEMS-based Pirani gauges — a breakthrough in compact and advanced Pirani vacuum gauging. In 2002, Wenzel Instruments was acquired by MKS Instruments, where Ole continued as Managing Director for the next 14 years, driving innovation of the 900 Series vacuum gauge product line. In 2017, he founded Sens4, a company that has since launched a series of groundbreaking vacuum measurement solutions — setting new benchmarks for performance, precision, and integration in the industry.
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About

Sens4 is a Danish technology company that develops, manufactures, markets, and distributes vacuum and pressure measurement solutions for industrial and scientific applications worldwide. Our mission is to provide compelling product solutions that fit our customers' needs and enable them to efficiently measure and control advanced processes around the world.

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