How To Improve Energy Efficiency and Reduce CO_2 Emissions With Next-generation N_2 Purge Systems

Using piezo-based valve technology in the design of nitrogen purge systems reaps many benefits — including reducing carbon emissions by up to 4 percent, as demonstrated in a large semiconductor fab.

As the demand for smaller, more sophisticated electronics continues to explode, semiconductor manufacturers must now operate in inert, or nonreactive, environments. Typically, they can achieve these environments by flushing the wafer pods, or front opening unified pods (FOUP), and other production equipment with ultra-high purity (UHP), particle-free nitrogen gas. This protective measure has been an industry standard for decades due to the ability to separate nitrogen from air in large amounts. Once used sparingly on oxidation sensitive layers, nitrogen purging is now widely used across the manufacturing process, owing to the extremely small lithographic features and atomic layer material thicknesses on wafers. However, the compression and cooling processes involved in producing UHP nitrogen consume a lot of energy in order to separate the nitrogen from oxygen and other trace gasses.

All semiconductor manufacturers are facing mounting pressures to reduce their energy consumption and carbon dioxide (CO_2) emissions. The push to become carbon neutral and reduce the effects of CO_2 on the climate is a gargantuan international effort that involves all manufacturing segments, and this effort is considered one of the most important endeavors humankind has ever undertaken. However, achieving the goals set out by climate scientists and the United Nations is no easy task for any industry — let alone the semiconductor manufacturers.

Due to the highly precise, complex nature of the manufacturing process, hundreds of gasses and chemicals play a role across several hundred process steps, such as thin film deposition, coating, chemical mechanical polish (CMP), lithography, metrology, baking and etching and many more. Compounding these challenges, manufacturers must keep up with demand in a global market that is projected to hit over $1,380 billion USD by 2029. In addition to the explosive consumption of consumer electronics around the world, this growth is tied to the development of advanced computing applications, including artificial intelligence, the Internet of Things and machine learning technologies.

For the average manufacturer, keeping up with such massive demand — all while implanting more transistors on shrinking chips, maintaining production yields and developing more advanced semiconductor manufacturing technologies — can make reducing energy and carbon emissions seem like an afterthought.

Fortunately, there is an easy-to-address area within the fab that can unlock tremendous energy savings, and it involves nitrogen (N_2) — the most widely used medium in the semiconductor manufacturing process.

Analyzing the N_2 Purge Carbon Footprint

Among its many roles in semiconductor manufacturing, nitrogen is used to purge FOUPs to create a controlled, contaminant-free environment for wafers as they are held and transported from one machine to another for processing. In large semiconductor fabs, nitrogen consumption can reach 50,000 cubic meters per hour. In addition:

- A study by the European Industrial Gas Institute revealed that nitrogen production at a typical air separation plant requires 549 kilowatt-hours (kWh) per tonne of liquid N_2. Purity Gas nitrogen generation technology can produce the same volume of nitrogen gas with roughly half the input electricity, or 275 kWh.
- In the United States, the electric power industry generated 4.01 trillion kWh from all energy sources, resulting in CO_2 emissions of 1.55 billion metric tonnes — an amount that translates to roughly 0.85 pounds of CO_2 emissions per kWh. When extrapolated to large semiconductor fabs with air separation systems in place, these emissions per kWh amount to roughly 5.8 x 104 metric tonnes of CO_2 per year.

These numbers make the case for energy, cost-effective onsite nitrogen generators (Air Separation Units (ASU)) supporting semiconductor fabs. These systems provide ultra-pure gaseous and liquid nitrogen onsite with less than one part per billion (ppb) impurities. The major industrial gas suppliers continue to improve the ASU's efficiency, but the Laws of Thermodynamics dictate this will never be a "low energy" process.

Reducing CO_2 Emissions With Efficient N_2 Purge Systems

Given the fact that nitrogen consumption in a large fab reaches 50,000 cubic meters (m^3) per hour, and roughly 0.85 pounds of CO_2 are emitted per kilowatt (kWh), we can calculate how many metric tonnes of CO_2 are produced each year by fabs with typical air separation systems in place:

50,000 m^3/hour x 8,760 hours/year
= 438 x 10^6 m^3/year N_2
= 547,773 metric tonnes/year N_2

x 275 kWh/metric tonne N_2 (air separation system)
= 1.50637 x 10^8 kWh/year

Using the following equations, we can calculate how much it costs a fab to make nitrogen each year (in USD):

Cost at $0.06/kWh:
$0.06 x 1.506 x 10^8 = 9.038 x 10^6 USD, or $9 million

Cost at $0.10/kWh:
$0.10 x 1.506 x 10^8 = 1.506 x 10^7 USD, or $15 million

x 0.85 pounds CO_2/kW
= 1.2804 x 10^8 pounds CO_2/year
= 5.808 x 10^4 metric tonnes CO_2/year

Now, using these values, we can calculate the savings provided by piezo-based N_2 FOUP purge systems. If you use controlled flow, you can reduce from 20 nl/min to 5 nl/min, per FOUP:

15 liters/min x 60 min/hour x 24 hours/day x 365 days/year
= 7,884 m^3/year N_2
= 9.86 tonnes/year N_2

x 275 kWh/tonne
= 2,711 kW/year

Not only do these N_2 purge systems decrease CO_2 emissions significantly, but they also reduce the cost required to make nitrogen at an annual savings between 6 and 10 cents per kW:

Cost savings per FOUP at $0.06/kWh:
$0.06 x 2,711 = 163 USD/FOUP/year

Cost savings per FOUP at $0.10/kWh:
$0.10 x 2,711 = 271 USD/FOUP/year

x 0.85 pounds CO_2/kWh (based on the U.S. average for 2020)
= 2,304 pounds CO_2/FOUP/year

So, CO_2 savings = 1.045 metric tonnes CO_2/FOUP/year

Knowing this, we must use the produced nitrogen wisely, being careful to minimize waste. Careful analysis of the areas utilizing nitrogen in the fab and minimizing usage can yield large savings over a short time. One such area is the FOUP purge, which is shown to have many possible opportunities to use the nitrogen wisely via actively metering with closed loop control. Piezoelectric purge valves can satisfy some of this need, and they run at extremely low power, making them a portable solution within the manufacturing line. In fact, simply deploying such a system has been shown to reduce a large fab's nitrogen consumption, related energy use and CO_2 emissions by 4 percent each year (see sidebar).

The Benefits of Piezo-Based Flow Control

N_2 purge systems that use piezo technology offer greater precision, consume less power and are more energy efficient compared to flow control systems that incorporate solenoid valves. They also increase the energy efficiency of front-end manufacturing processes, improve overall sustainability and contribute to corporate sustainability goals.

N_2 purge systems unlock these benefits because the design of the piezo valve limits the size of abrasion-causing particles to about 0.1 micrometer (µm). This value, which is the N_2 purge system's peak particle size per switching cycle, is about five times smaller than that of conventional N_2 purge systems. By preventing wear due to friction, the piezo technology also lengthens the valve's service life, unlocking significant operational and maintenance savings.

In addition to incorporating piezo valve technology, the most effective N_2 purge systems include the following features and characteristics:

- **Closed-loop control.** This feature ensures an accurate, stable and linear flow rate without hysteresis. The Festo N_2 Purge System, for example, repetition accuracy is rated at +/- 0.25 percent of setpoint.
- **Leak-proof.** The flow controller should be compact and minimize the number of connections. Systems that have just two pneumatic connections, for example, will significantly reduce the risk of leakages. The power requirement of such a system — which is less than one watt — also lowers energy consumption by about 80 percent compared to proportional flow regulators.
- **Space savings.** Look for pre-assembled flow controllers, which accommodate the space-limited nature of many semiconductor production areas. Receiving a pre-assembled functional unit, rather than several individual components, means you will also save on assembly and tubing costs, minimize test times and eliminate extra expenses for stainless steel tubing and fittings.

A large fab has around 20,000 FOUP storage spaces with N_2 purge. If we assume a minimum occupancy of 50 percent, then we need to calculate 10,000 spaces. The cost for 1 year is then:

Cost savings per fab at $0.06/kWh:
10,000 x $163 = 1.63 million USD/year

Cost savings per fab at $0.10/kWh:
10,000 x $271 = 2.71 million USD/year

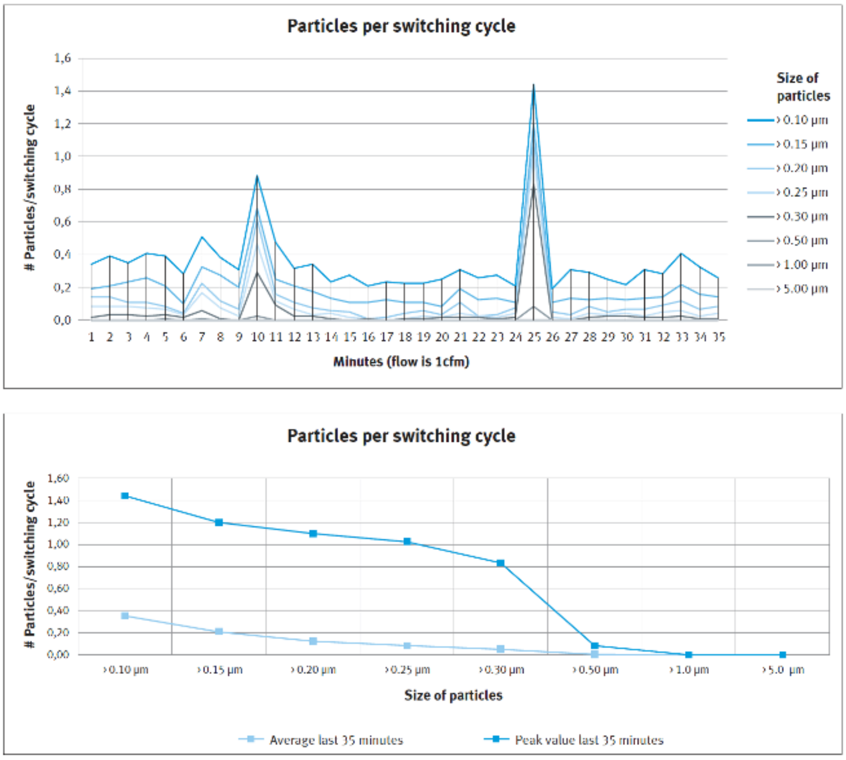
CO_2 savings per fab = 10,000 x 1.045 = 1.045 x 10^4 metric tonnes CO_2/year

Considering large fabs produce 5.8 x 10^4 metric tonnes of CO_2 per year, while piezo-based N_2 purge systems save 1.05 x 10^4 metric tonnes CO_2 per year, we can now calculate the total reduction in emissions associated with these advanced purge systems:

(5.8 x 10^4 - 1.05 x 10^4) / (5.8 x 10^4) = 82%, **or a 18% reduction in CO_2 emissions per year.**

The cost savings is in the same range: 18% cost reduction on nitrogen use.

An overview of the Festo N_2 Purge System.



Particles per switching cycle for the Festo N_2 Purge System.

The N_2 Purge System in Action

One example of a flow control system that leverages energy-efficient piezo valve technology is the Festo N_2 Purge System (see Figure 1). Ideal for individual FOUP storage and buffer spaces, this flow controller consists of a two-way proportional valve and integrated flow sensor, while its integrated electronics include the following:

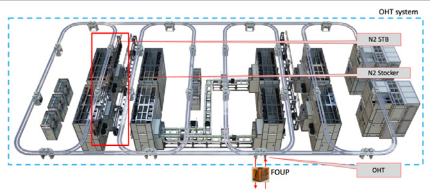
- A power supply.
- High-voltage technology for the piezo bender.
- Stable, precise control loop for the sensor.
- Piezo proportional control valve — e.g., the Festo VEMR.

During the nitrogen purging process, the electronic system continuously controls the flow rate inline with the setpoint value. The piezo valve ensures a repeat, accurate flow rate of up to 25 normal liters per minute (nl/min) over the valve's entire service life, with up to 30 nl/min possible in the short term. Users can monitor the pressure at the outlet of the FOUP using an additional pressure sensor. The SPAN from Festo, for example, works in the 10 kilopascal (kPa) range and features excellent repeatability, remote zero set function and IO-Link compatibility for easy integration into production lines. Improving nitrogen distribution and wafer protection, some FOUPs even incorporate several outlet ports in addition to one inlet port.

An Example of a Front-Line FOUP Setup

Between process steps, the risk of unwanted wafer reactions due to harmful particles, volatile organic compounds, oxygen and humidity is higher, and these conditions can lead to defects on the surface. Using an N_2 purge system reduces these risks and eliminates harmful, submicron-sized contaminants. The nitrogen gas, which is dry and non-combustible, also displaces any oxygen, preventing unwanted oxidation reactions and protecting yields.

Within a typical semiconductor fab (see figure below), the FOUP holds and transports the silicon wafers through hundreds of process steps. An automatic material handling system, such as an overhead hoist transport (OHT) system, lifts and lowers the FOUP to access the machines. Between steps, FOUPs are stored in special cleanroom shelves, such as stockers and buffers, which are installed on OHT rails to minimize the equipment footprint.



Front-line system overview. In addition to the FOUP, the front line system includes an OHT vehicle for transferring FOUPs, as well as side track buffers (STB) and stockers for storage.

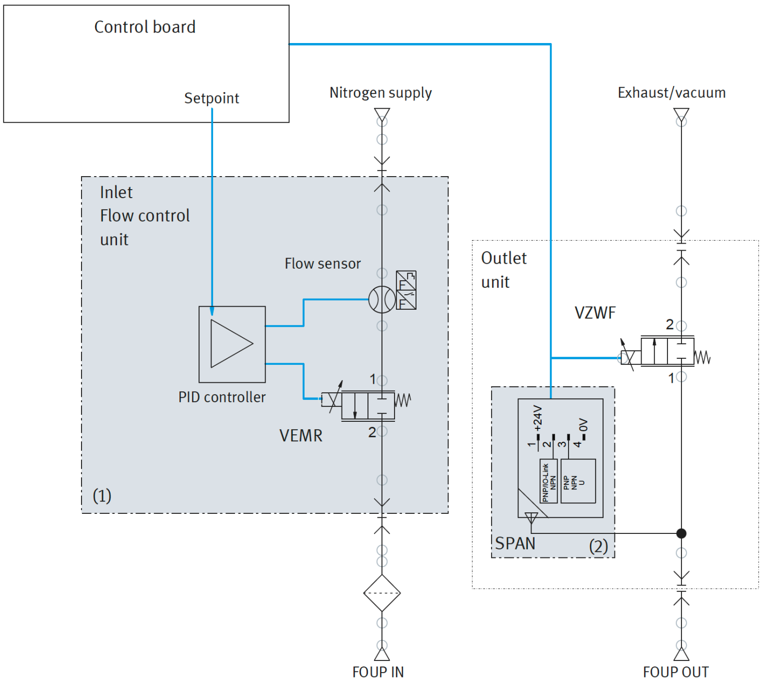


Figure 1: Functional diagram of the Festo N_2 Purge System, with (1) the N_2 flow controller and (2) an outlet solution using the SPAN sensor.

Start Cutting Emissions Today

N_2 purge systems play a critical role in semiconductor manufacturing, storing and transporting wafers while preventing unwanted reactions and surface defects. The best, most effective systems will feature innovative piezo valve technology, unlocking the following benefits:

- Low cost of ownership.
- Reliability, simplicity and precision — no hysteresis.
- Minimal energy consumption.
- Compact construction.
- Minimal risk of leakages.
- Long service life.

Most notably, however, these valve solutions contribute to a more energy efficient, sustainable manufacturing operation — cutting emissions by as much as 4 percent every year. These systems present a very easy way to meet the many challenges of today's market while creating a greener, more sustainable future.

To learn more, please visit: www.festo.com/semiconductor.

What Is Piezo Technology?

Piezo valves incorporate a piezo element, which is an electromechanical transducer that converts mechanical forces like pressure, tensile stress or acceleration into a measurable voltage. These elements also deform when a voltage is applied, generating mechanical motion or oscillations. Depending on the application, you can exploit this effect using various transducer types, such as bender actuators, disc transducers or stack transducers.

Pneumatic valves typically integrate bender actuators. In this case, the performance of the valve depends on the strength of the electric field: the greater the strength, the better the performance and vice versa. Thanks to their capacitive principle, piezo valves require virtually no energy to maintain an active state, eliminating harmful heat generation.

Compared to solenoid valves, these valves offer several benefits. They don't ignite in the event of a fault and are suitable for hazardous environments. They can also hit switching speeds of less than one microsecond, making them perfect for closed-loop control systems. Piezo valves are lightweight and typically come in a plastic housing, avoiding heavy materials like iron or copper. And, they consist of a single solid-state working component, minimizing the number of parts that are subjected to friction and wear.

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