WHITE PAPER

Vacuum Pumps

Optimizing Semiconductor
Fabrication Equipment
Performance

Semiconductor fabrication consists of highly complex processes that require precise and reliable machinery. This white paper explores the critical role of vacuum pumps in maintaining the high-quality output and seamless operation of semiconductor fabrication equipment. Original equipment manufacturers (OEMs) will gain valuable insights into how selecting the right components for their vacuum pump systems can enhance their products and stand out among the competition.

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Semiconductor fabrication
Increasing momentum in the U.S. Market

Driven by unprecedented technological advancements and growing demand across multiple industries, the semiconductor market is positioned to be a crucial engine of economic growth and innovation. Semiconductors are the heart of consumer electronics and the brains behind advanced driver assistance systems (ADAS) and data centers. Still, they serve a significant role in unassuming industries such as public safety and agriculture.

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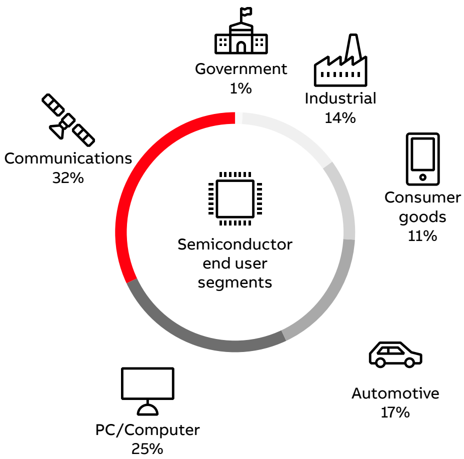
Figure 1: Percentage breakdown of semiconductor end users



The demand for semiconductor chips is projected to increase over the next decade, estimating a trillion dollar global industry valuation by 2030. At the forefront of this exponential growth are emerging technologies such as artificial intelligence and the Internet of Things (IoT), and in the United States specifically, federal incentives.

Assembled in 2021, the Supply Chain Disruptions Task Force was formed to assess and strengthen supply chain vulnerabilities, a critical step to addressing the global semiconductor chip shortage that began in the same year. In 2022, the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act was developed to further alleviate supply chain shortages post-pandemic and increase domestic manufacturing in the U.S., which currently only accounts for 12% of global production. Through monetary investments and tax credits, these incentives seek to improve semiconductor research and development, production, and domestic workforce opportunities, boosting economic resiliency.

Currently, the bulk of semiconductor manufacturing, fabrication, and equipment manufacturing, is conducted in Asia. However, while manufacturing hubs like South Korea and China experienced significant capacity increases between 2021-2022, the United States is projected to experience the highest increase in equipment manufacturing capacity by 2032, at a 203% increase, as shown in the figure below. Additionally, the compound annual growth rate for semiconductor manufacturing equipment between 2024–2032 is estimated at 10.5%, with most growth opportunities anticipated within front-end equipment[4].

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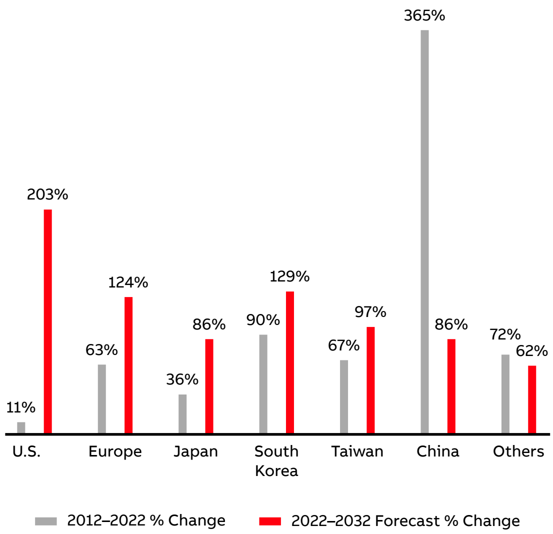
Figure 2.Global Semiconductor Manufacturing Capacity Increase by Geography, 2022-2032



Understanding the essentials of fabrication

The front-end

Numerous steps need to take place to create semiconductor chips. These steps fall into two processes: the front-end and the back-end. In the front-end, wafers are prepared and then developed into semiconductors through fabrication. Wafer preparation involves selecting material, typically silicon, to be formed and polished into a flat wafer ready to enter fabrication. Semiconductor fabrication is a loop-process grouped into four primary categories: deposition, patterning, removal, and modification of electrical properties.

In deposition, layers of conducting and/or insulating materials are deposited onto the wafer. There are various types of deposition, including molecular beam epitaxy and atomic layer deposition, although the most common methods are physical and chemical vapor deposition. Following deposition, patterning involves photolithography, a process in which light and a chemical called photoresist cause a chemical reaction on the wafer, projecting a pattern to be integrated in the following steps.

In fabrication, various removal methods can be used to ingrain patterns into the wafers; the most common are etching, stripping, and chemical-mechanical planarization (CMP). Etching and stripping focus on removing previously deposited materials, while CMP flattens the wafer surface. In modification of electrical properties, the wafers' electrical, optical, and structural properties are altered to enable electrical conductivity. This process is known as doping, and the most common techniques are ion implantation and diffusion. Ion implantation charges ions and directly inserts them into the semiconductor material, while diffusion moves atoms through the semiconductor material using temperature. The end of this step marks the change from wafer to semiconductor.

The back-end

The back-end of fabrication involves testing, assembly, and packaging. Testing ensures that the semiconductors function properly and meet the required specifications. The two main types of testing are wafer testing, in which the chips are stimulated to confirm proper electrical parameters and effective response time, and package testing, where the chips' packaging is assessed for physical and thermal damage. Assembly and packaging go hand-in-hand as the semiconductors are enclosed in protective packaging, ready to connect to additional chips or an electronic circuit board.

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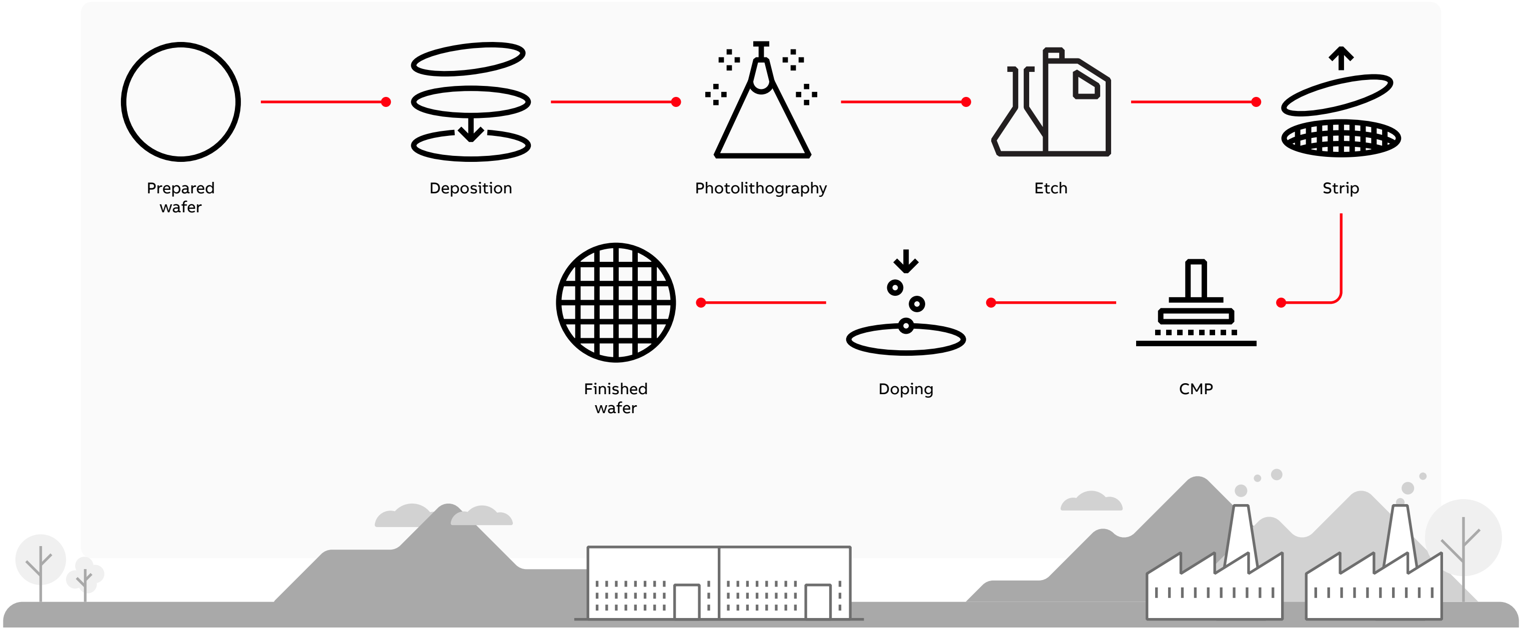
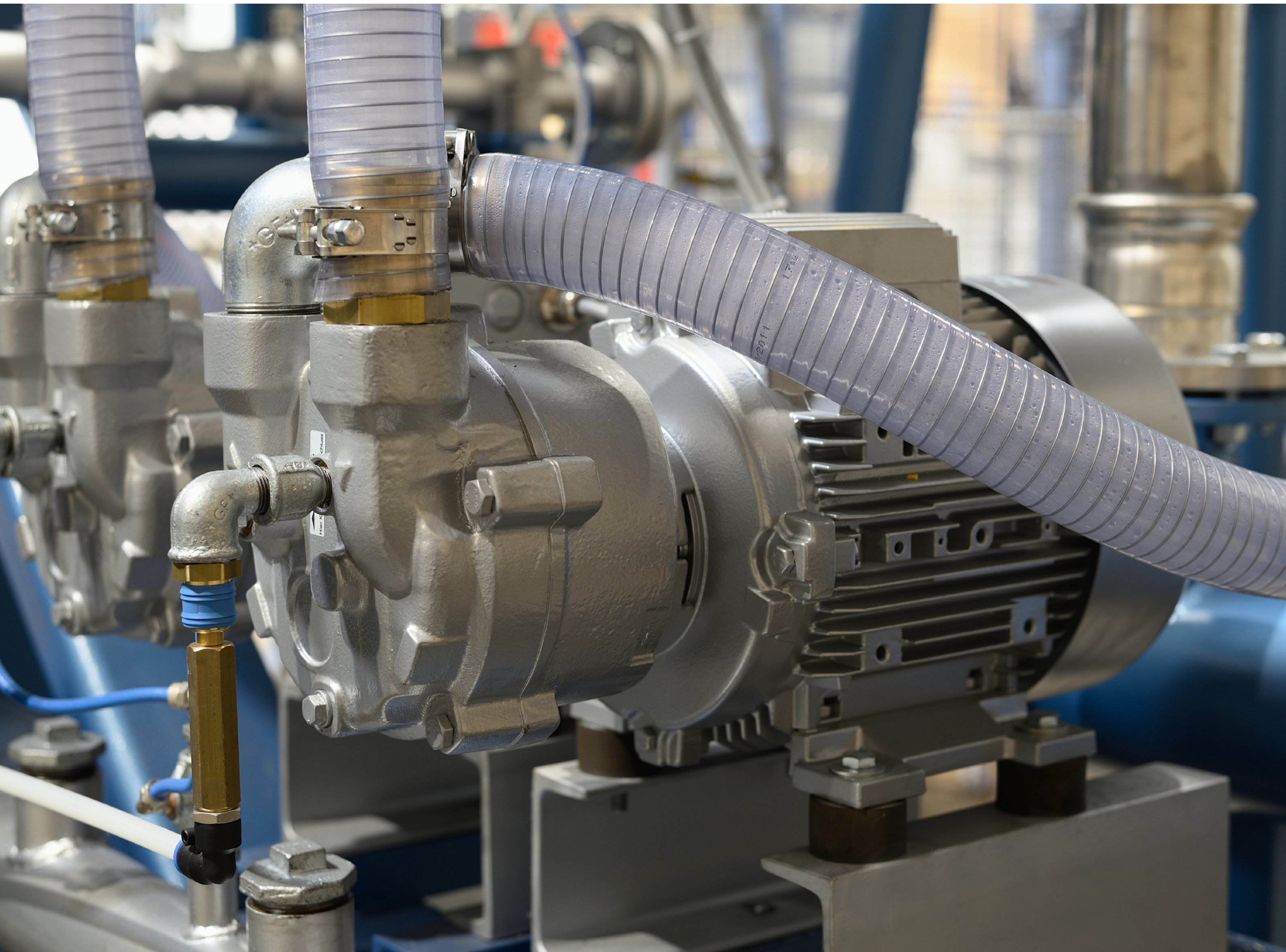
Figure 3: Semiconductor fabrication front-end process



Power and precision: Industrial vacuum pumps
Functions and types

Industrial vacuum pumps are paramount to the fabrication process as they are key to creating and maintaining the clean environments needed for producing high-quality semiconductor chips. During various stages of the fabrication process, such as deposition, etching, and ion implantation, a vacuum environment is necessary to prevent contamination and ensure precision. The vacuum pumps remove gases, vapors, and particles from the chamber that could otherwise corrupt the wafer. For instance, in chemical vapor deposition, a vacuum is needed to ensure that the reactive gases do not react prematurely with unintended substances, while in etching, a clean environment helps to achieve accurate patterning on the semiconductor wafer. By maintaining a controlled negative pressure, vacuum pumps help stabilize the chemical reactions and physical interactions critical to forming the intricate structures and patterns on semiconductor chips.



Moreover, the absence of contaminants and impurities prevents defects and ensures that the final semiconductor products exhibit the desired electrical characteristics and performance. Any deviation in the cleanliness of the fabrication environment could lead to defects, reduced device reliability, or compromised performance, impacting not only the quality of individual components but also the overall yield and efficiency of the manufacturing process. Therefore, vacuum pumps are fundamental to producing reliable, high-performance semiconductor devices that meet the industry's rigorous standards.

Industrial vacuum pumps create a negative pressure differential between the inside of a sealed chamber and the surrounding atmosphere. This pressure difference allows the pump to effectively move gas molecules within and outside the system. Besides the vacuum pump itself, additional components that make up the system are vacuum chambers, a control system (vacuum valves and gauges), fittings and filters, and safety accessories. The vacuum chamber is an enclosed space capable of withstanding variable pressure where the vacuum process occurs. Pressure is monitored, adjusted, and maintained in the control system, usually through gauges and valves. Fittings consist of sealing components such as gaskets and flanges that prevent leaks and maintain the integrity of the vacuum, while filters remove contaminants from the system. Finally, safety components such as emergency stops and alarms are typically included in the system to signal malfunctions and compromised pressure.

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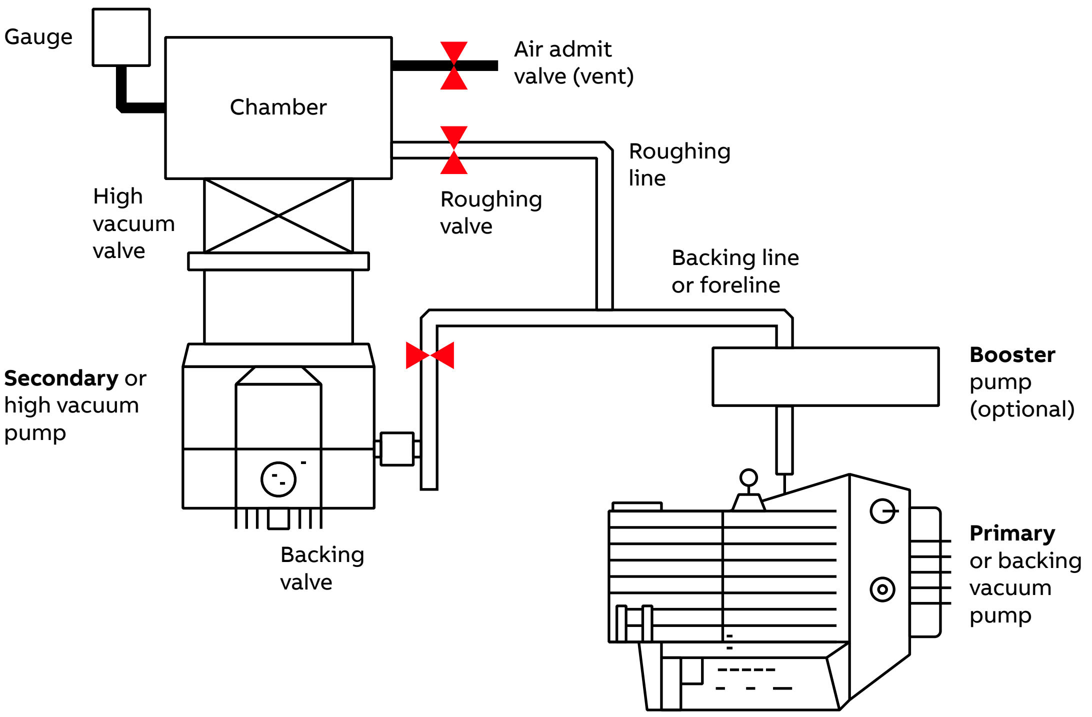
Figure 4: Example of a vacuum pump system



Optimizing vacuum pump selection

Different types of vacuum pumps can be employed in the fabrication process, depending on operational and pressure needs. The most common types found in fabrication are:

- **Rotary vane vacuum pumps** use circling vanes to trap gas and provide a "rough" vacuum. This type of vacuum pump is commonly used for initial air removal in the fabrication process, priming the chamber for additional vacuum processes.
- **Screw vacuum pumps** consist of intermeshing screws that trap and move gas in a continuous flow, requiring minimal maintenance and optimizing energy consumption. This type of vacuum pump provides a higher level of vacuum, making it suitable for various fabrication processes but optimal for chemically reactive processes such as chemical vapor or atomic deposition.
- **Scroll vacuum pumps** use a dual scroll mechanism to trap and displace gas, which is optimal for ion implantation, deposition, and lithography. These vacuum pumps are oil-free, reducing contamination risk and are a great substitution for rotary vane pumps.
- **Turbomolecular vacuum pumps** provide one of the highest levels of vacuum through the use of rapidly spinning blades. As these vacuum pumps can achieve extremely low pressure, turbomolecular pumps are ideal for supporting precision during deposition.
- **Root vacuum pumps** utilize rotors to create a vacuum and are popular in multiple fabrication processes, such as diffusion and ion implantation. Similar to scroll pumps, root vacuum pumps are dry and optimal for preventing contamination.
- **Liquid ring vacuum pumps** are ideal for wet processes such as etching. A rotating liquid ring creates a seal that prevents contamination by corrosive gases.

Given the complex nature of fabrication machinery, multiple or combinations of these vacuum systems are often found in fabrication facilities. Depending on the need and layout of the equipment, the vacuum pumps can be found in an isolated section of the plant, connected to equipment through a series of pipes, or adjacent to the equipment, as can be seen in the figure below. Regardless of vacuum pump type or combination, it is critical to utilize reliable electrical components to ensure a contamination-free environment and continuous operation of the fabrication.

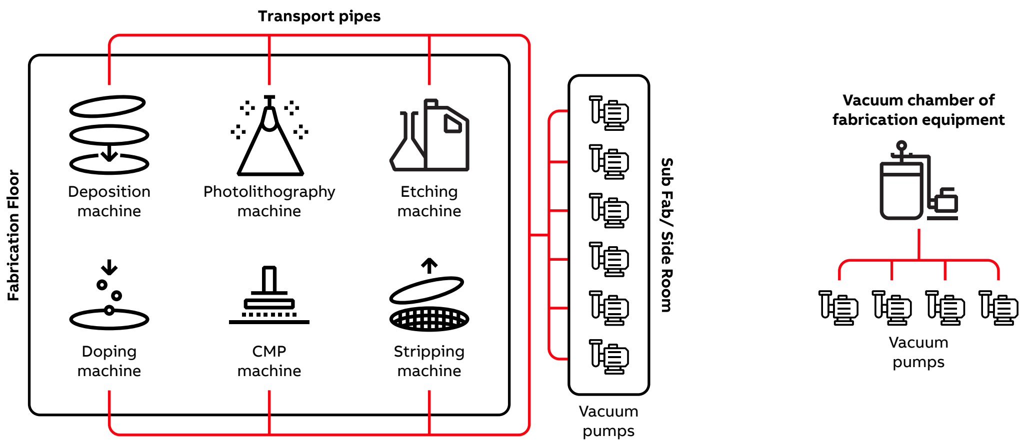


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Figure 5: Model of vacuum pump location and connection to equipment

Mitigating challenges for optimal vacuum pump performance

Key challanges

Contamination
While vacuum pumps create and maintain the necessary low-pressure environments for fabrication, they face significant operational challenges that can impact manufacturing efficiency and wafer quality. In processes such as chemical vapor deposition and plasma etching, highly reactive, corrosive by-products pose a threat to production lines and successful yield as they increase the risk of contamination. Even minor exposure to contamination in a clean environment can lead to defective wafers, resulting in material loss and production delays. Corrosive by-products, if not properly maintained, can also lead to pump degradation that will ultimately affect fabrication. Balancing high throughput with contamination-free operation can be achieved by leveraging advanced electrical components that help optimize pump performance and consistency.

Energy consumption
Another key challenge is energy consumption. Vacuum pumps can consume up to 20% of the total power used by semiconductor fabrications. As manufacturers aim to reduce operational costs and improve sustainable practices, they need vacuum systems that can efficiently adapt to real-time production needs. This challenge is compounded by evolving technology, such as smaller semiconductor nodes that require even stricter environmental controls and precision.

Downtime
Fabrications typically run 24/7, and any unplanned downtime can lead to significant financial loss and material waste. Given the nature and importance of vacuum pumps in fabs, having to reset the pumps and prepare the chambers can take anywhere from hours to days, causing cascading delays, and loss throughout production. Along with production, downtime poses a higher risk for contamination as exposure to ambient air can compromise in-progress wafers.

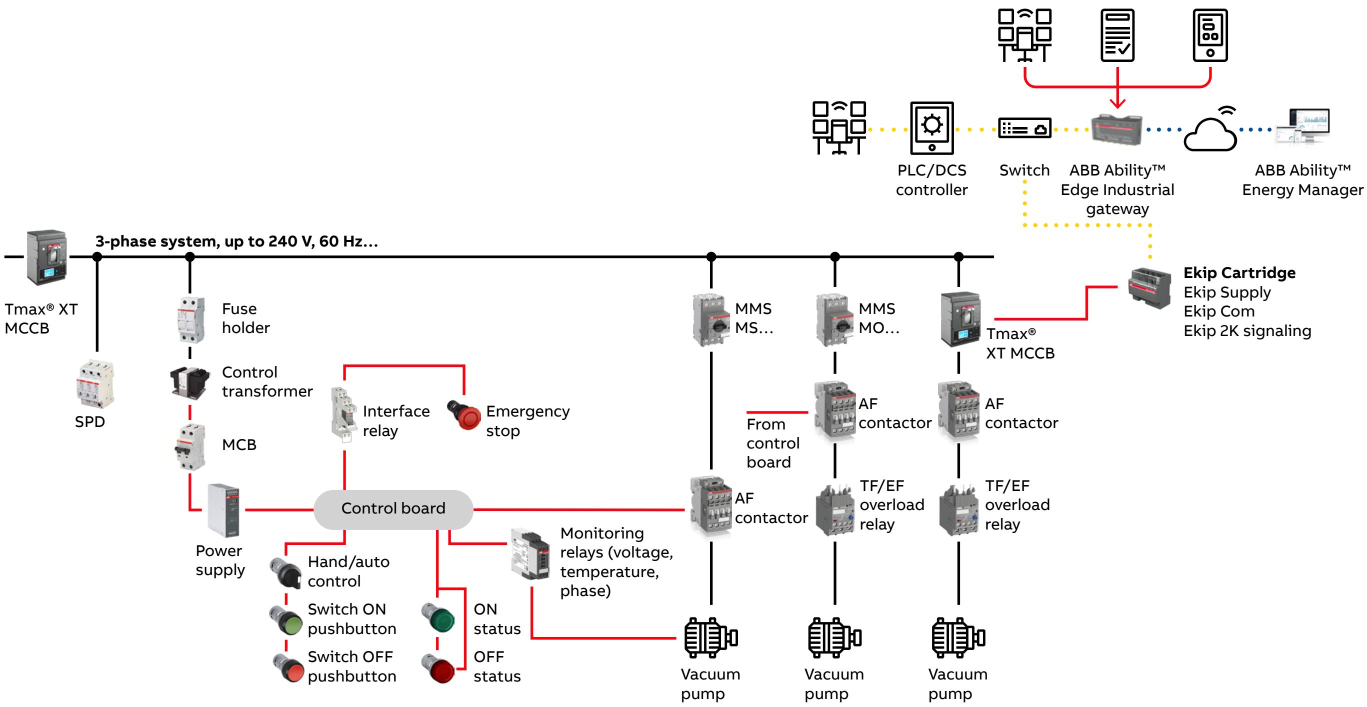
Desired outcomes

The most desirable outcome for vacuum pumps is to provide consistent, contamination-free performance under varying conditions, including high temperatures and reactive gas exposure. For fabrications, the desire is modular and adaptable vacuum pumps that can support various processes while minimizing maintenance needs, cost, and energy consumption. When manufacturing vacuum pumps for fabrication, OEMs can help fabrications achieve these conditions by ensuring pumps operate at optimal performance levels with minimal environmental impact. At the core of achieving this value is selecting the right electrical components and vendor, not only for optimal equipment protection, but also to help drive the productivity and competitiveness of the semiconductor manufacturing process.

Selecting the right electrical components for your vacuum pumps

Vacuum pump systems require power and control solutions to create and maintain the pressures needed for fabrication. The components that help to achieve this status are motor starters and protection devices. These components are not only critical to the precision of fabrication processes but can also enhance equipment lifecycle and energy efficiency.

ABB products can offer a range of solutions dependent on pumping needs, demonstrated in the figure below:



Legend:

- Power circuit
- Control circuitABB
- Ability EAM
- Modbus TCP

MMS Manual motor starter
MO Magnetic protection
MS Magnetic and thermal protection

Main components	Functional description
SACE® Tmax® XT molded-case circuit breaker	Main power distribution
MS… series manual motor starter	Isolation, overload, and short circuit protection
MO…series manual motor starter	Isolation and short circuit protection
AF series contactor	Remote isolation and control
EF/TF overload relay	Overload and phase failure protection

Circuit Breakers

Circuit breakers are crucial for the reliable operation of vacuum pumps in semiconductor fabrication machinery, serving as essential protective devices that enhance both safety and performance. Vacuum pumps are integral to maintaining ultra-low pressure environments. Given the varying electrical loads these pumps encounter, circuit breakers are vital in detecting fluctuations and preventing overloads that could lead to motor burnout or catastrophic equipment failure.

SACE® Tmax® XT molded case circuit breakers (MCCBs)
Designed to be easy to use, integrate, and connect, ABB's family of SACE® Tmax® XT molded case circuit breakers (MCCBs) can help ensure optimal performance and protection features from 15 up to 1200 A. Built to deliver safety, reliability, and quality, everything you need is self-contained within the breaker, requiring no external relays or other devices to purchase, install, or wire.

Reliability can be further increased, and installation speed reduced thanks to Bluetooth connectivity through the EPiC app for mobile devices. The SACE® Tmax® XT family can can use multiple communication protocols with the ABB Ability™ cloud platform to provide real-time data analysis. Access to accurate information anywhere and anytime makes it easier to monitor resources and identify savings opportunities.

Manual Motor Starters

In environments where precise control over equipment is required, such as semiconductor fabs, manual motor starters (MMS) help ensure that pumps can be safely started and stopped without risk to the motor or production process. They protect against overloads and phase failures while also offering a simple way to manage pump systems during maintenance. Manual motor starters allow the pump(s) to be isolated from the power source for repairs without compromising safety or operational resiliency, ultimately helping to extend the vacuum pump lifespan. Combining fuse-less motor control and protection into one device, MMS is a compact and cost-effective solution that, when paired with a contactor, can protect, and help ensure the longevity of your vacuum pump system.

MS132/MO132 Manual Motor Starters
ABB's MS132 manual motor starter provides motor protection up to 600 V AC/ 32 A with a rated short-circuit breaking capacity of 65 kA. The MS132 model is available as thermal and magnetic while the M0132 model is magnetic only. Additional features include a built-in disconnect function, temperature compensation, a lockable handle, and a trip-free mechanism.

Contactors

Contactors permit control over power flow within the vacuum pump system. This helps to reduce unnecessary energy consumption and mechanical wear. In tandem with a circuit breaker and overload relay, contactors can rapidly disconnect motors from the power supply if a fault occurs, minimizing, if not preventing, damage.

AF Contactors
ABB's AF contactor stands out over conventional contactors with its integrated, electronically-controlled coil. AF contactors can be used for 25 to 2,850 A, up to 600 VAC, and have a wide range of control voltage options covering 24 V to 500 VAC 50/60 Hz and 20 V to 500 VDC. It is offered in the screw, push-in spring, and ring tongue connection types. ABB's AF contactors, along with manual motor starters and overload relays, have connection bars that allow for easier installation and maintenance. It also has built-in surge suppression and easy-to-use accessories through a snap-to-connect function.

Overload Relays

Overload relays monitor motor currents and shut down the vacuum pump if the currents exceed the safe operating threshold. This protects the pump from overheating or burning out. Integrated with additional components such as circuit breakers and contactors, overload relays help create a compact starting solution in which overcurrent conditions can be mitigated without manual intervention, ensuring optimal pump performance in the fabrication process.

EF/TF Overload Relays
ABB offers both electronic and thermal overload relays that help protect the motor from overload and phase failure. Thermal overload relays cover a current range from 0.1 A to 200 A, while electronic overload relays can cover an even larger range from 0.1 A to 1250 A. Both relays combine high accuracy with an energy-efficient design that does not need an extra external supply. ABB's overload relays are designed to withstand harsh conditions, making them optimal for hazardous processes in semiconductor fabrication.

Conclusion

As the semiconductor industry continues to evolve through emerging technologies and process enhancements, the dependence on reliable vacuum pumps will only increase. Understanding and enhancing the performance of these pumps is critical to achieving the desired outcomes in fabrication, ensuring that manufacturers can meet the growing demand for faster, more powerful semiconductor chips. Proper electrical configuration ensures not only consistent pump performance but also maximized uptime and optimal production yield.

ABB can provide manufacturers with reliable and efficient motor control and power solutions, optimizing semiconductor fabrication. By incorporating these solutions, consumers can enhance equipment lifecycle and efficiency, reduce operating costs, and achieve operational excellence through sustainable electrification.

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