Vacuum Equipment

1. Vacuum Pumps

Vacuum is useful in a variety of processes and devices. High to ultra-high vacuum removes obstruction of air, allowing particle beam to deposit materials without contamination. This is the principle behind material deposition and plasma etching which is essential in semiconductor fabrication. In a thermal evaporation process, vacuum condition is used to maintain a constant deposition rate, avoid particle collisions, and prevent heat transfer from the crucible to the wafer.

Most of the vapor deposition equipment used in semiconductor fabrication operates in the rough or medium vacuum regime. For the metal evaporation, we often need to pump the chamber into the high or ultrahigh vacuum regime before starting the metal deposition. For that reason, we will also discuss the production of a high vacuum. The production of an ultra-high vacuum is a difficult task that requires considerable artistry. In microelectronics, it is used primarily for molecular beam epitaxy.

Type of vacuum	**Vacuum Range (Torr)**
Rough vacuum	0.1 – 760
Medium vacuum	10^{-4} – 10^{-1}
High vacuum	10^{-8} – 10^{-4}
Ultrahigh vacuum	< 10^{-8}

1.1 Mechanical Pumps

Rough vacuum pumps all involve the positive displacement of gas through the mechanical movement of a piston, vane, plunger, or diaphragm. These pumps involve three steps: capture of a volume of gas, compression of the captured volume, and gas expulsion. The gas to be pumped is drawn into the cylinder through a valve as the piston is drawn back into the cylinder. During the next part of the cycle, built valves are closed and the gas is compressed. Near the end of the stroke the second valve is opened, and the gas is expelled to the higher-pressure region. Often these valves open automatically in response to a pressure difference [2].

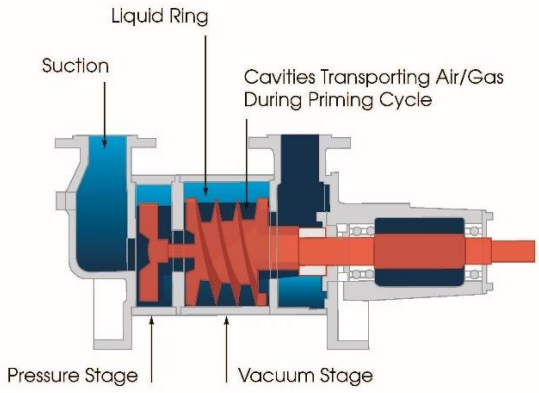

Figure 1. Schematic of a Mechanical Pump [1].

1.2 High Vacuum Pumps

High vacuum pumps for microelectronic fabrication fall into two categories: those that pump gas by transferring momentum to gas molecules and those that trap gas molecules. Of these, the former are preferred when pumping corrosive and toxic gases or when pumping high flows of gases. The latter are preferred when pumping small flows of inert gases or when only using the high vacuum pump for pumping down the chamber before processing. Valves are almost always used to isolate high vacuum trapping pumps; this allows the chamber to be pumped by medium and rough vacuum pumps when the system is pumping down from atmospheric pressure

Two most popular types of momentum transfer pumps are diffusion pumps and turbo molecular pumps.

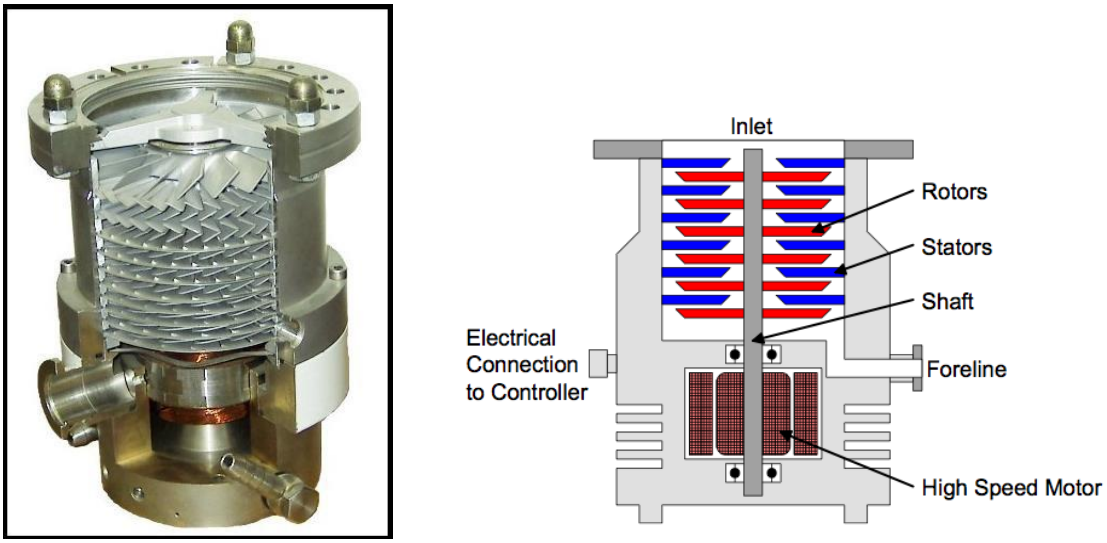

Figure 2. Turbo-molecular pump [2]

1.2.1 Turbo Molecular Pump

A turbo molecular pump (see Figure 2) has a large number of stages in series. Each stage consists of a fan blade (rotor) that rotates at an extremely high speed (>20,000 rpm) and a stationary blade called a stator. The spacing between the stator and rotor is very small (on the order of 1mm). Gas captured by the upper stages is pushed into the lower stages and successively compressed to the level of the fore-vacuum (backing pump) pressure. As the gas molecules enter through the inlet, the rotor, which has several angled blades, hits the molecules. Due to the relative motion of rotor and stator, molecules preferentially hit the lower side of the plates and exit downwards. Thus, the mechanical energy of the blades is transferred to the gas molecules. With this newly acquired momentum, the gas molecules enter the gas transfer holes in the stator. This leads them to the next stage where they again collide with the rotor surface, and this process is continued, leading to small compression and then finally leading them outwards through the exhaust. The high-pressure side of the turbo pump must be attached to a roughing pump since the outlet pressure must be kept relatively low.

Blades of a turbo-molecular pump need to be thick and stable for high pressure operation. For high compression ratio, throat between adjacent rotor blades should be pointing in the forward direction. For high flow rates, the blades are at 45˚ and reach close to the axis.

Each stage may have a modest compression ratio, but because of the large number of stages, the

total pump has compression ratios as large as 10^9. Since the momentum transfer depends on the mass of the gaseous molecule, the compression ratio depends strongly on the gas being pumped. A typical pump that has a compression ratio of 10^9 for N_2 will have a compression ratio of less than 10^3 for H_2. Thus, turbo-pumped chambers can have high concentrations of light gases such as H_2 and He.

When a turbo pump is stopped, oil from the mechanical pump may back stream through the turbo pump and contaminate the chamber. One way to prevent this is to introduce a laminar flow of nitrogen from the top of the pump. The transition from vacuum to nitrogen and from a running to a still turbo pump must be synchronized precisely to avoid mechanical stress to the pump.

1.2.2 Diffusion Pump

The diffusion pump is known as a fluid entrainment pump and works in a completely different manner from a turbo pump. The diffusion pump uses vapor of a boiling fluid to capture air molecules. The fluid is then moved to another location and cooled. The cooling forces the air molecules to be released. The combination of gravity and the downward direction of the vapors move the air molecules toward the bottom of the pump, see Figure 3..

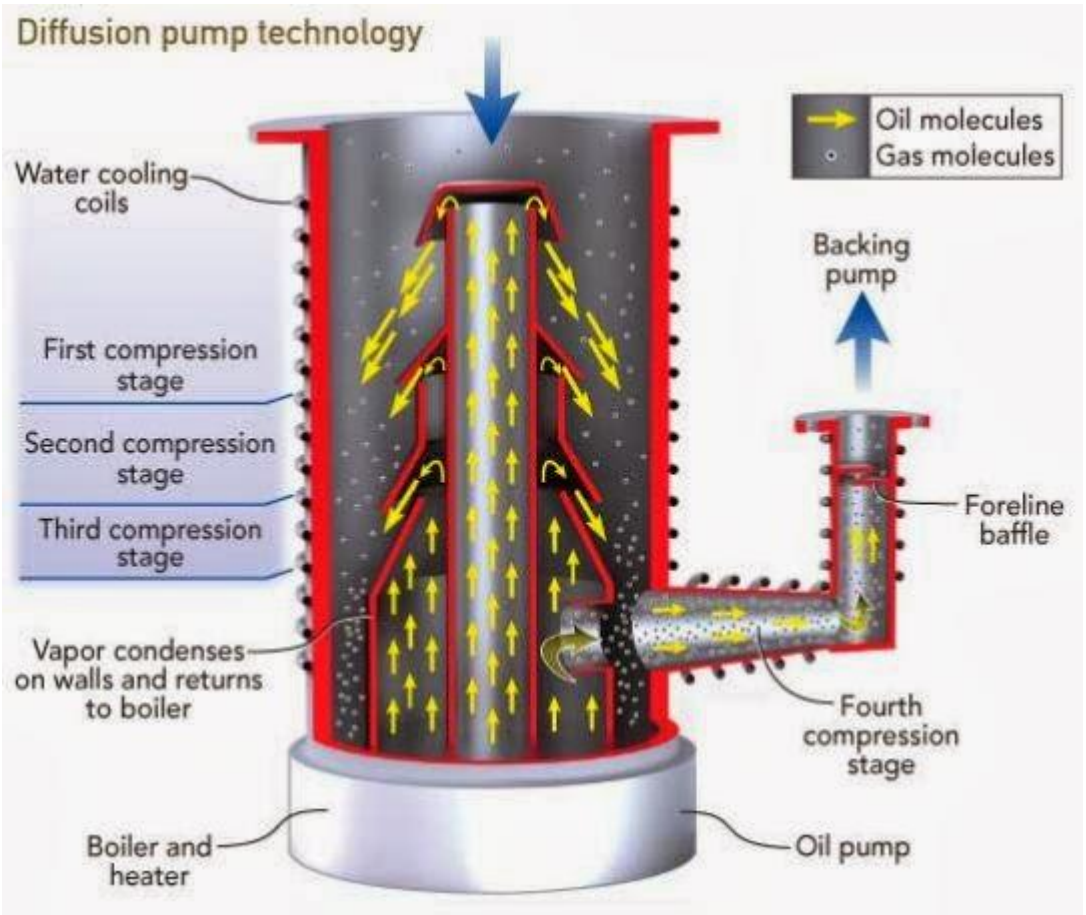

Figure 3. Diffusion Pump [3]

Pump oil is located at the base of the system and the heaters heat the oil until it vaporizes. The oil vapors rise up to the center of the pump and exit the nozzles at a downward angle. These nozzles are in a ring and form a curtain or "skirt" of vapor that extends from the nozzles to the pump wall. As the gas travels towards the walls of pump chamber, it traps air molecules along the way through diffusion. When the oil vapor hits the water-cooled walls of the pump, the oil cools as it runs down the sides of the pump. By the time the oil reaches the reservoir once again, it has given off its trapped gas and is ready to begin the cycle anew. Any gas molecule that tries to wander upward is caught by the vapor "skirt" above it and forced downward again. By continually forcing the air molecules downward, we create an area at the bottom of the pump that is higher in pressure than the top of the pump. In other words, when the pump is in operation the pressure is higher below each oil skirt than it is above that skirt. At the bottom of the pump, the pressure is high enough for the gas to be pumped out by a standard mechanical pump. Although oil vapor is directed downward, it is possible for some of it to wander toward the top of the pump. To avoid having this oil migrate into the chamber, a cold cap can be fitted at the top of the nozzle assembly to condense vapor in that area. A concentric circular chevron baffle at the mouth of the pump allows air molecules to wander in, but traps the heavier oil vapors as they try to escape.

1.2.3 Cryopump

A cryopump or a cryogenic pump is a vacuum pump that traps gases and vapors by condensing them on a cold surface, but are only effective on some gases. The effectiveness depends on the freezing and boiling points of the gas relative to the cryopump temperature.

A typical cryopump is shown in Figure 4. It consists of a cryogenic refrigerator producing refrigeration at two temperature stages. Each stage in turn cools an extended surface cryopanel onto which gases will freeze. The first stage of the refrigerator usually operates in the range of 50-75 K and is used to cool the outer cryopanel and the louvres across the inlet opening of the cryopump. Water vapor will freeze onto these panels. The second or the cold stage as shown usually operates between 10-20 K and is used to cool the inner cryopanels. Gases such as nitrogen and oxygen will freeze onto these panels.

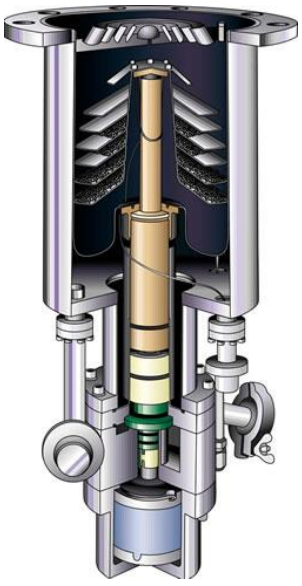

Figure 4. Cryopump [4]

Comparison of different types of vacuum pumps [5]

	Diffusion pump	Cryo-pump	Turbomolecular-pump
Advantages	• High pumping speed and low cost • No moving parts (reliable and durable)	• Fast and clean pumping • High speeds and throughput	Large compression ratios (10^9)
Disadvantages	• Backstream into the sample chambers • Cannot be exposed to atmosphere when hot • Needs mercury diffusion pump to keep chamber clean.	• Condensates easily • Needs to be cold to hold vacuum	• High side pressure of pump must be attached to a roughing pump (outlet must be maintained at low pressures) • Performance depends on mass of gaseous molecules. • Oil from pump may stream back and contaminate the sample

2. Vacuum Gauges

Vacuum gauges are devices which measure pressure after production of vacuum. The two most common types of vacuum gauges are Thermal Conductivity gauges and Ion gauges.

2.1 Thermal conductivity gauges

Thermal conductivity gauges rely on the fact that the ability of a gas to conduct heat decreases with pressure. In this type of gauge, a wire filament is heated by running current through it. A thermocouple or Resistance Temperature Detector (RTD) can then be used to measure the temperature of the filament. This temperature is dependent on the rate at which the filament loses heat to the surrounding gas, and therefore on the thermal conductivity. A common variant is the Pirani gauge which uses a single platinum filament as both the heated element and RTD. These gauges are accurate from 10 torr to 10^{-3} torr, but they are sensitive to the chemical composition of the gases being measured.

2.2 Ion gauges

Ion gauges are used in ultrahigh vacuum. Ion gauge is typically a triode, which is the most widely used as a low-pressure (vacuum) measuring device ranging from 10^{-2} to 10^{-10} torr. It consists of a filament, a helical grid and a collector wire. The filament emits electrons which are attracted to the helical grid by a positive bias (+180V). The electrons collide with gas molecules and ionize some of the gas. The gas ions are attracted to the anode. The ion current is directly proportional to the density of the gas inside the gauge. The current is then amplified and calibrated to get the pressure. Ionization gauge calibration is very sensitive to construction geometry, chemical composition of gases being measured, corrosion and surface deposits. Their calibration can be invalidated by activation at atmospheric pressure or low vacuum.

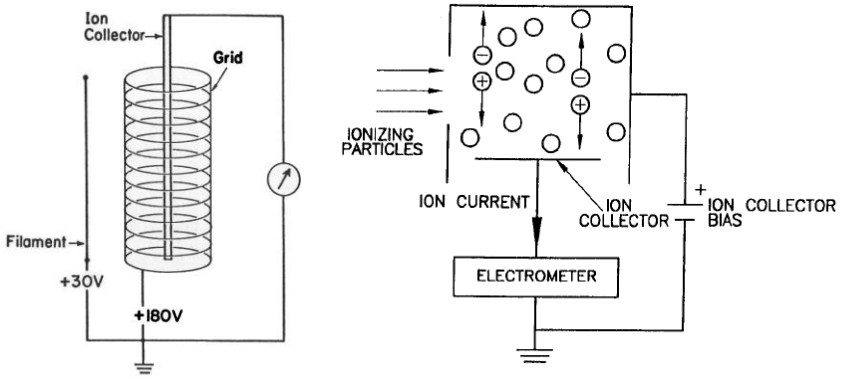

Figure 5. Schematics of an ion gauge (left). The gas molecules are partially ionized and the ions are collected by the collector (right) [6].

There are two types of ion gauges: hot and cold cathode. In the **hot cathodes gauge**, an electron beam is produced by an electrically heated filament. Hot cathode gauges are accurate from 10^{-3} torr to 10^{-10} torr. Hot cathode gauges can be damaged or lose their calibration if they are exposed to atmospheric pressure or even low vacuum while hot. In the **cold cathode gauges**, an electron beam is produced by a high voltage electrical discharge. Cold cathode gauges are accurate from 10^{-2} torr to 10^{-9} torr. The composition of gases at high vacuums will usually be unpredictable, so a mass spectrometer must be used in conjunction with the ionization gauge for accurate measurement.

3. References

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