Thin film deposition

Many semiconductor processes rely on controlling the atoms and molecules impinging on the surface of the wafer, i.e. controlling the ambient atmosphere.

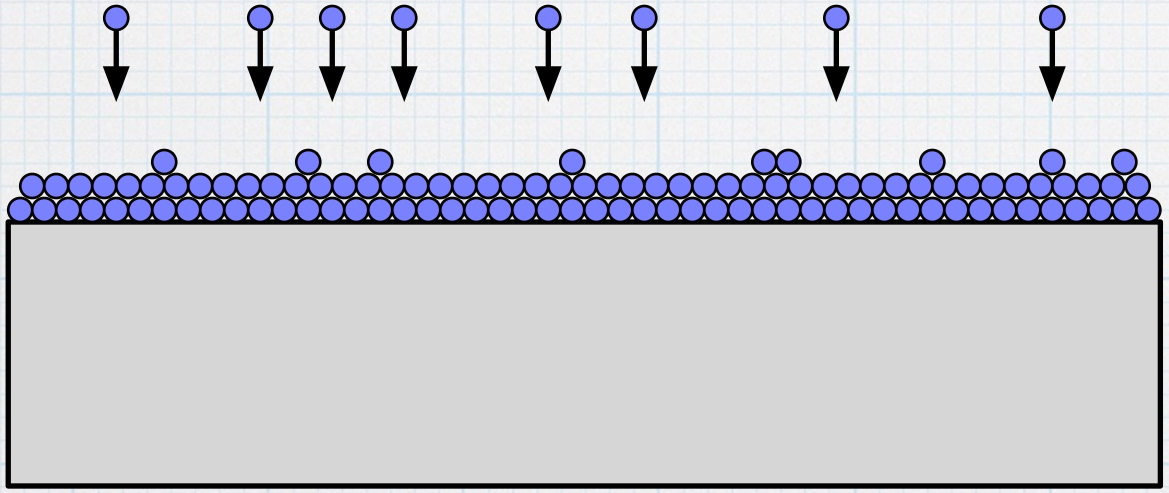
- evaporation
- sputtering
- chemical vapor deposition (including epitaxy)
- plasma etching (deposition in reverse)

Films

- polycrystalline silicon
- SiO_2
- silicon nitride (Si_3N_4, or SiN_x)
- metals (aluminum, tungsten, titanium, etc.)

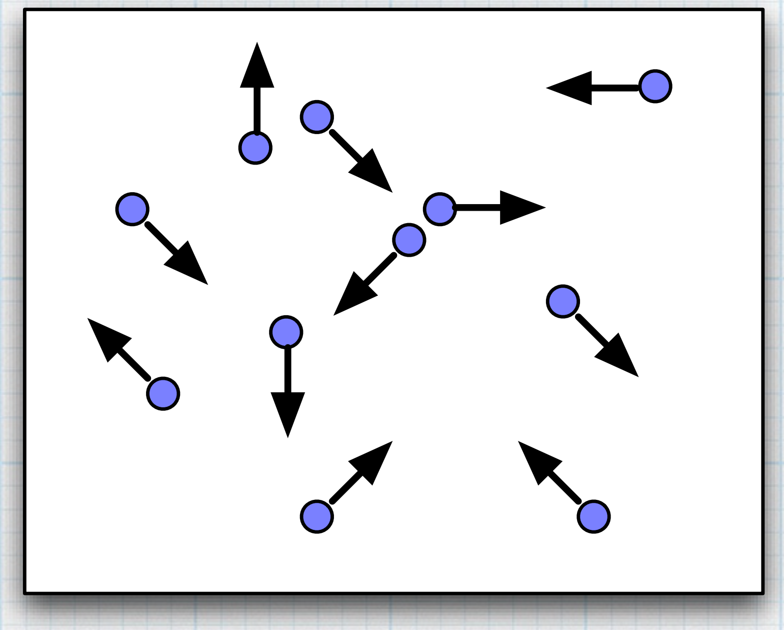
We can grow thin films by causing atoms in the gas phase to hit the surface of the wafer and condense there. The rate at which the films grows is directly proportional to the impingement rate of the gaseous atoms on the surface. We describe this in terms of the incoming flux.

$$\text{growth rate} = \frac{\mathcal{F}}{M}$$



Ideal gases

A fixed volume *V* contains *N* molecules. The temperature is held at constant *T*, and the system is at thermal equilibrium. The situation can be described by the ideal gas law and the tenets of ideal gas theory.

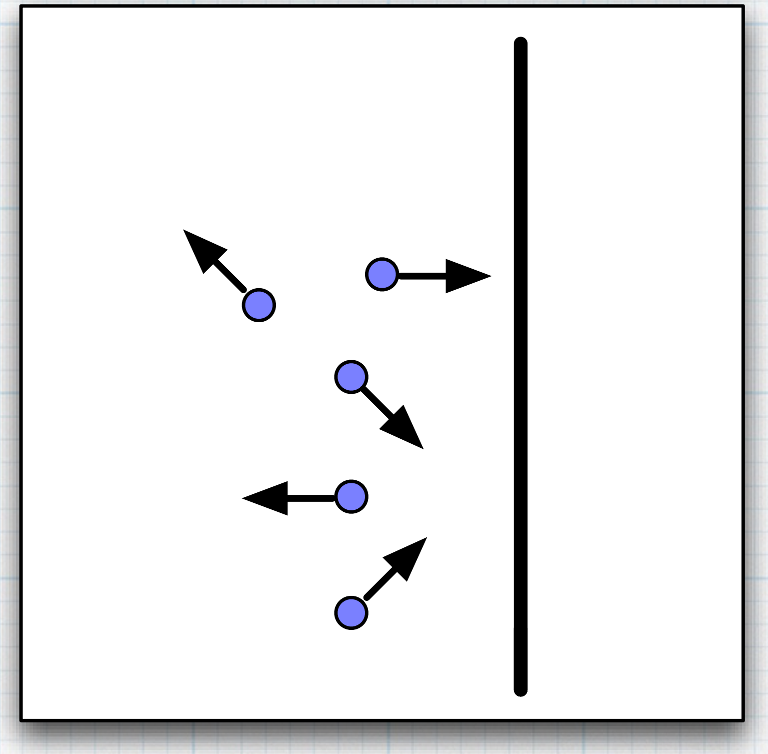


$PV = NkT$

where P is the pressure and k is Boltzmann's constant.

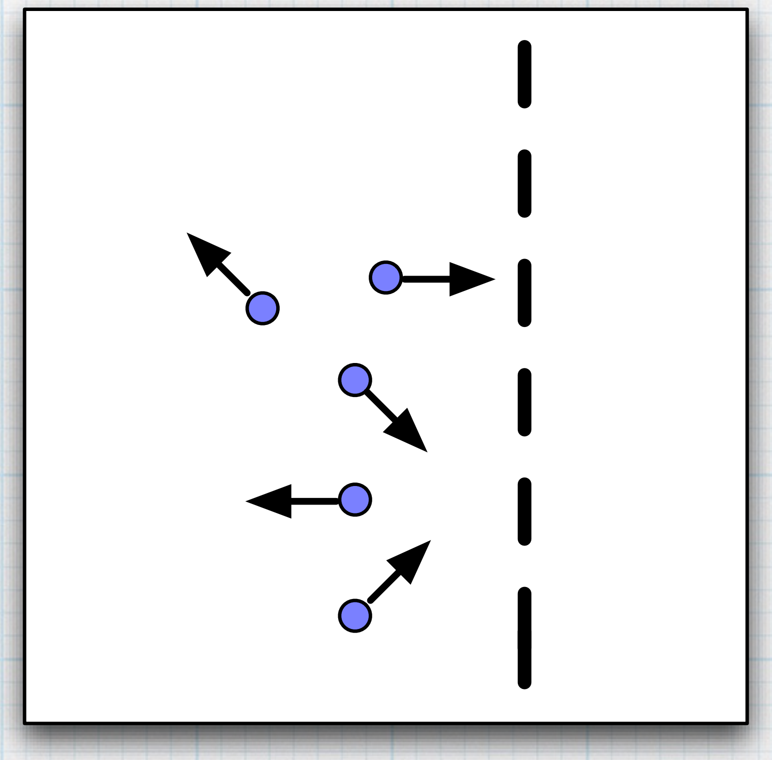
Pressure

An operational definition: Molecules bouncing off the wall of the vessel impart a force on the wall. Pressure is the total force per unit area of the wall.



Clearly the pressure is related to the flux of molecules incident on the wall.

In fact, a wall is not needed in order to define the pressure. Define an arbitrary area within the gas enclosure. Determine the flux moving in <u>one direction</u> through the area. (Of course, the net flux would be zero.)



There is a direct relationship between pressure and flux. Using the kinetic theory of gases, it can be shown (ICBS)

$$\mathcal{F} = \frac{P}{\sqrt{2\pi m k T}}$$

where m is the mass of the molecule and T is the temperature.

Another useful concept is the "mean free path". This is the average distance that that molecule travels before colliding with another molecule. This must be inversely proportional to pressure.

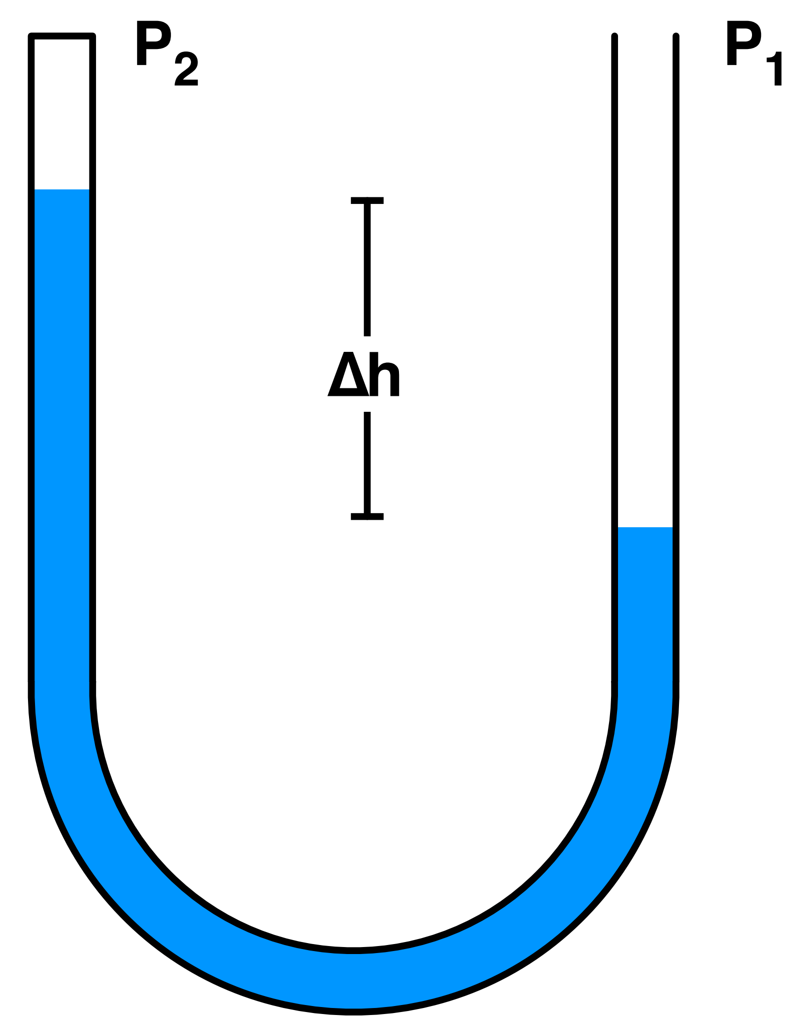
$$\lambda = \frac{kT}{\sqrt{2}\pi d^2 P}$$

where d is the effective diameter of the molecule. (Usually on the order of 1 nm.)

Units

A good starting point is 1 atmosphere, the pressure that we experience living on the surface of the earth. (Of course, it's not a constant, but doesn't change too much.)

SI units: 1 Pascal = 1 N/m^2. 1 atm = 101,325 Pa
old school: 1 atm = 14.7 psi (pound-force per square inch)
os-2: 760 Torr = 1 atm; 1 Torr = 133.3 Pa. (Torr: short for Torricelli.)



Where does that come from? One of the original methods for measuring pressure was the manometer.

$$\Delta h \propto P_1 - P_2$$

If mercury is used as the liquid and $P_2 \approx 0$ (i.e. that side is evacuated), then atmospheric pressure will push the mercury column up to 760 mm (≈ 30 inches.)

Levels of vacuum

(Note: “higher vacuum” means lower pressure.)

It shouldn’t be surprising that there are prices (technological, monetary) to be paid for creating vacuum.

low vacuum	1 atm → 1 Torr	easily achieved at relatively low cost
med vacuum	1 Torr → 10^{-4} Torr	still easy, but need more attention to seals, etc
high vacuum	10^{-4} Torr → 10^{-7} Torr	need better pumps, better materials, special procedures
ultra-high vacuum	10^{-7} Torr → 10^{-10} Torr	high-end pumps, special materials and seals, load locks!

Mean free path:

room atmosphere: ≈ 10 nm; 10^{-3} Torr (0.133 Pa): ≈ 7 mm

10^{-5} Torr (1.33×10^{-3} Pa): ≈ 70 cm; 10^{-9} Torr (1.33×10^{-7} Pa): ≈ 70 km

Vacuum pumps

There are many types of vacuum pumps, but the primary methods for moving gas are mechanical and cryogenic.

Mechanical pumps use rotating paddles or blades to push gas from one side of the pump to the other (from vacuum to exhaust). This is the same principle that your vacuum cleaner at home uses.

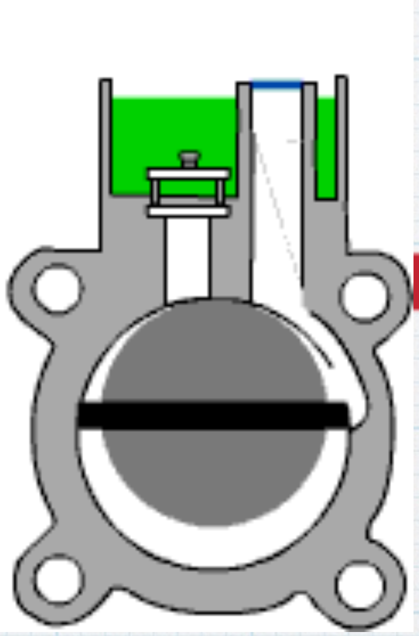
Cryogenic pumps create cold surfaces that give gases a place to condense, thus lowering the gas pressure. You've probably noticed that the inside of your refrigerator or freezer is much drier than the air in the kitchen - the cold temperature cause much of the water vapor to condense out. Another way of stating this is to say that the vapor pressure of the gas has been reduced by the colder temperatures.

There are versions of mechanical and cyro pumps for working at low vacuum (known as roughing pumps) and high vacuum.

Mechanical pumps

Uses rotating vanes and time valving to move gas from one region (the vacuum chamber) to another (exhaust).

Can pump a volume from atmosphere down to 1 mTorr or somewhat less.



Relatively inexpensive.

Limited to pressures above 1 mTorr. Potential for oil contamination.

Turbomolecular pump (turbo pump)

Same basic idea as the simple mechanical pump, but uses a series of blades spinning at very high speed to achieve high vacuum – can be better than 10^{-9} Torr.

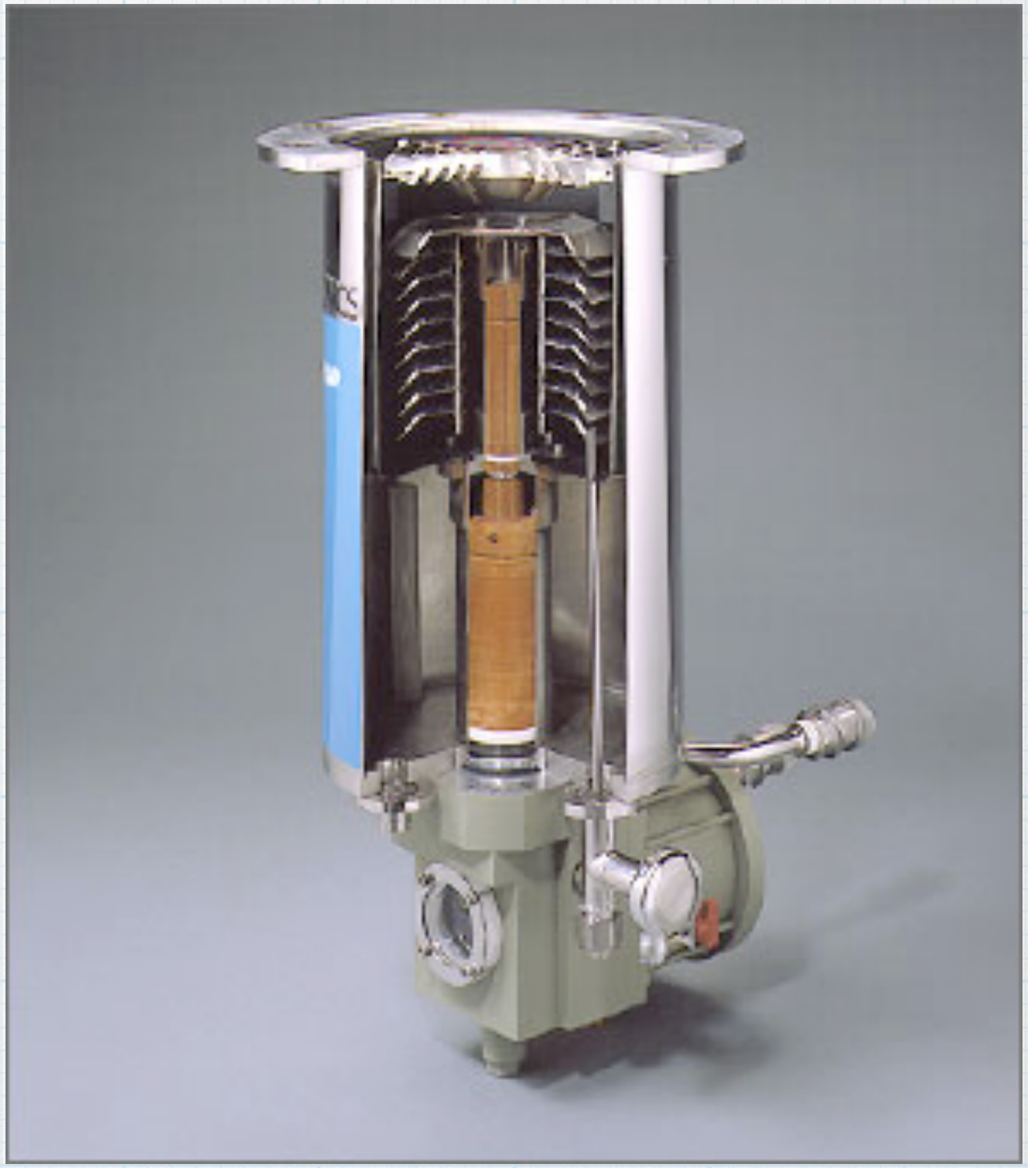
The blades spin at > 30,000 rpm.

Requires a backing pump, since it cannot pump from atmosphere.

Reliability of bearings is always a concern.

Cryogenic pump

Cryo type pumps remove gas by freezing. By making a surface extremely cold, gas will condense on it, thereby lowering the pressure.

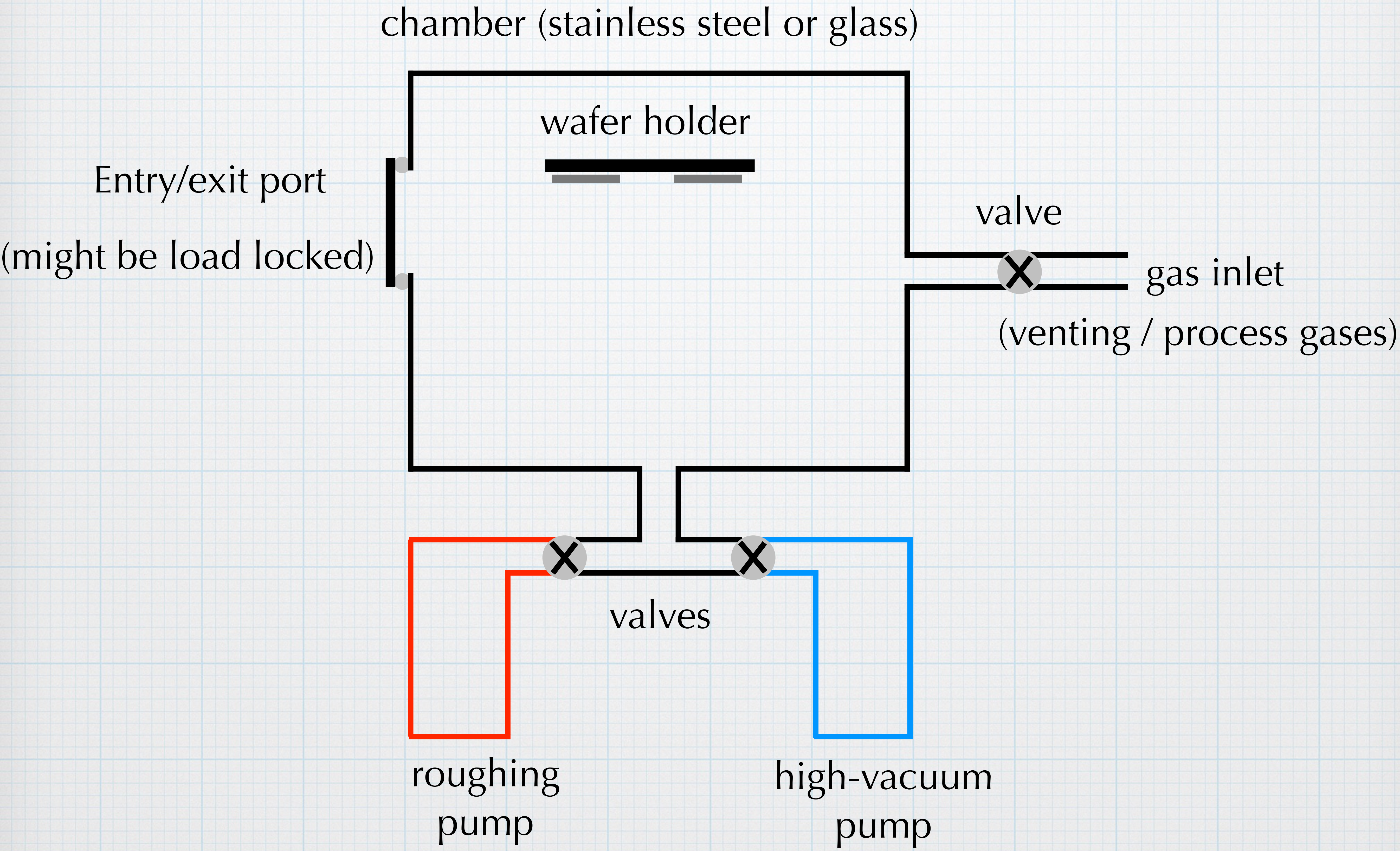


A cryopump is essentially an extremely high-end refrigerator. It uses He as the working gas. The interior surfaces can be cooled to about 10K, which will condense out all gases except H and He.

Ultimate pressure is about 10^{-9} Torr.

Cryopumps are very clean - no risk of oil contamination. Like the turbopump, the cryopump will not pump at atmospheric pressure, so a 1st stage roughing pump (probably a sorption pump) is required to get down to get below 1 Torr. Also, they need to be purged occasionally to remove the accumulated condensate.

Generic vacuum system



Plasma

A plasma is a collection of gas atoms (molecules) in which some appreciable fraction is ionized.

The presence of the ions, and the associated free electrons, provides the possibility for doing some interesting work with the plasma.

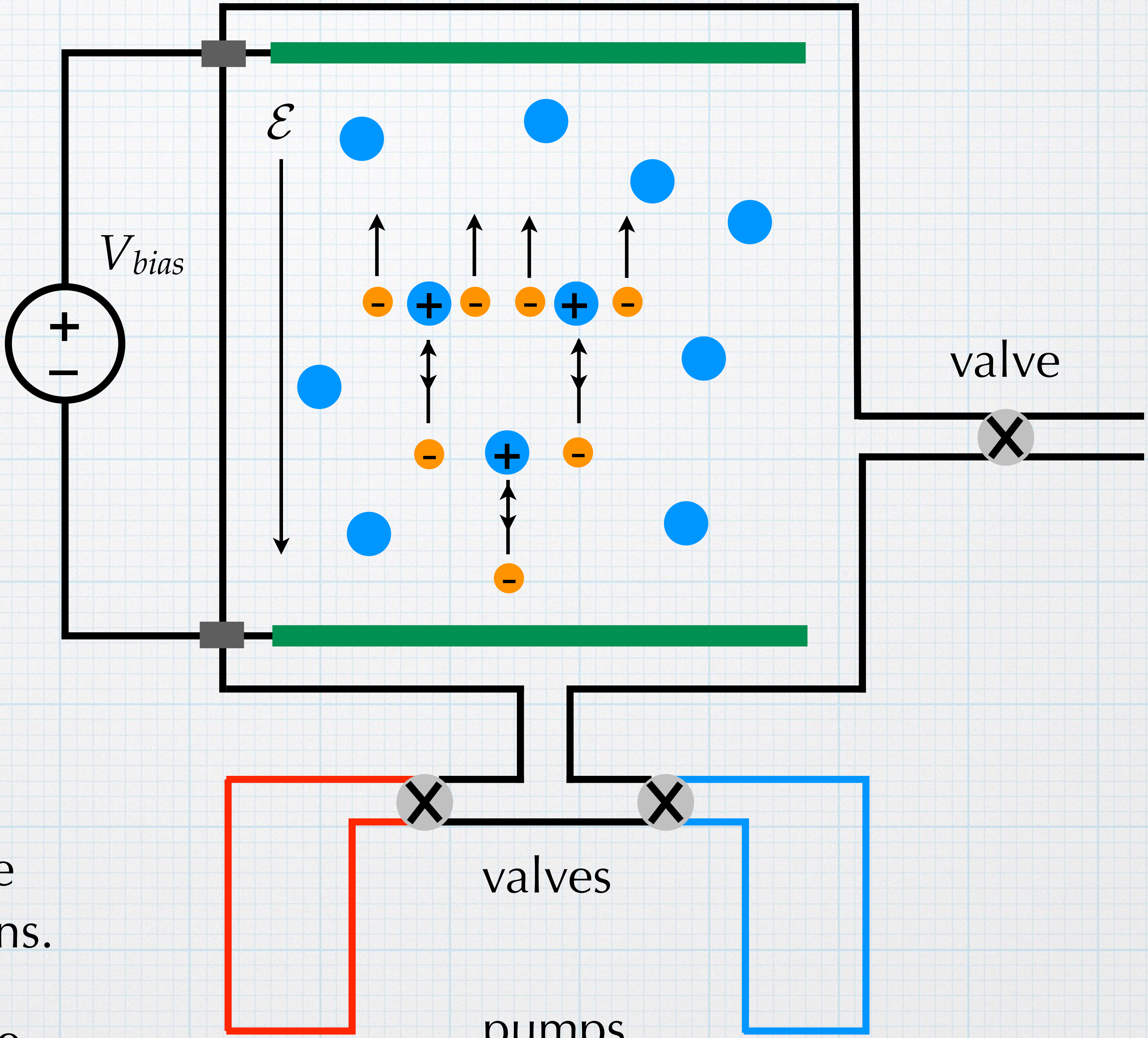
- Sputter deposition
- Plasma enhanced CVD (PECVD)
- Plasma etching and cleaning.

Common examples

- Lighting – fluorescent, street lights, mask aligner bulb
- “Sparks” – static shocks, arc faults, lightning
- Astrophysics – stars, etc.

DC plasma

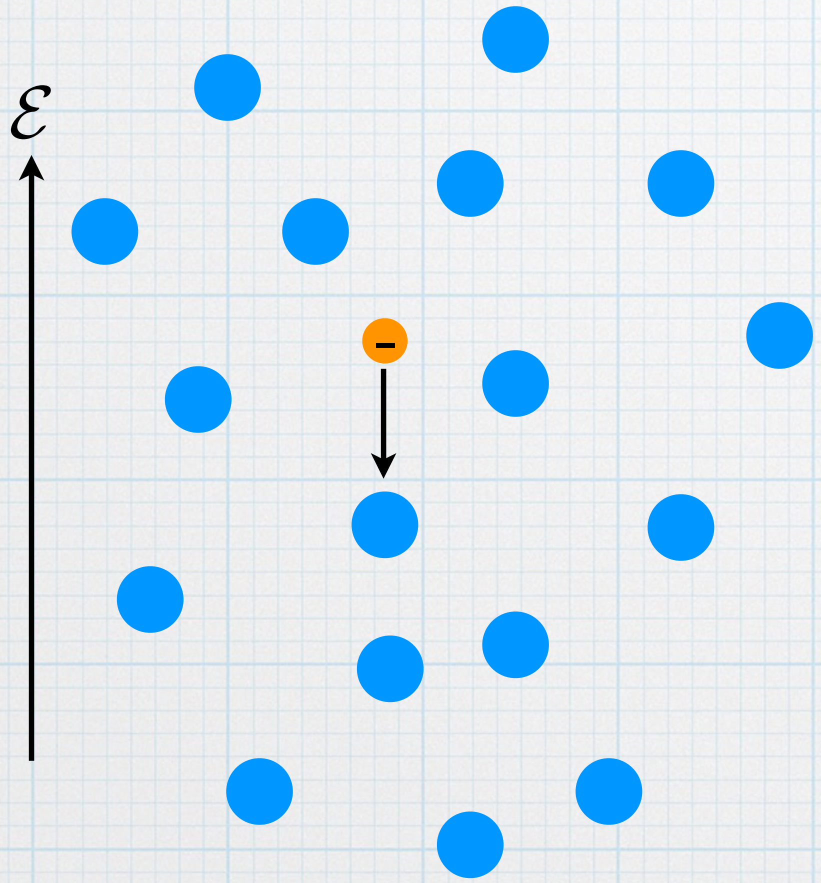
1. vacuum system
2. Electrodes and a DC bias
3. Add process gas adjust pressure
4. free electrons will accelerate and ionize gas atom during collisions
5. The charged particles will accelerate off in opposite directions.
6. The fast electrons create more ions.



Plasma conditions

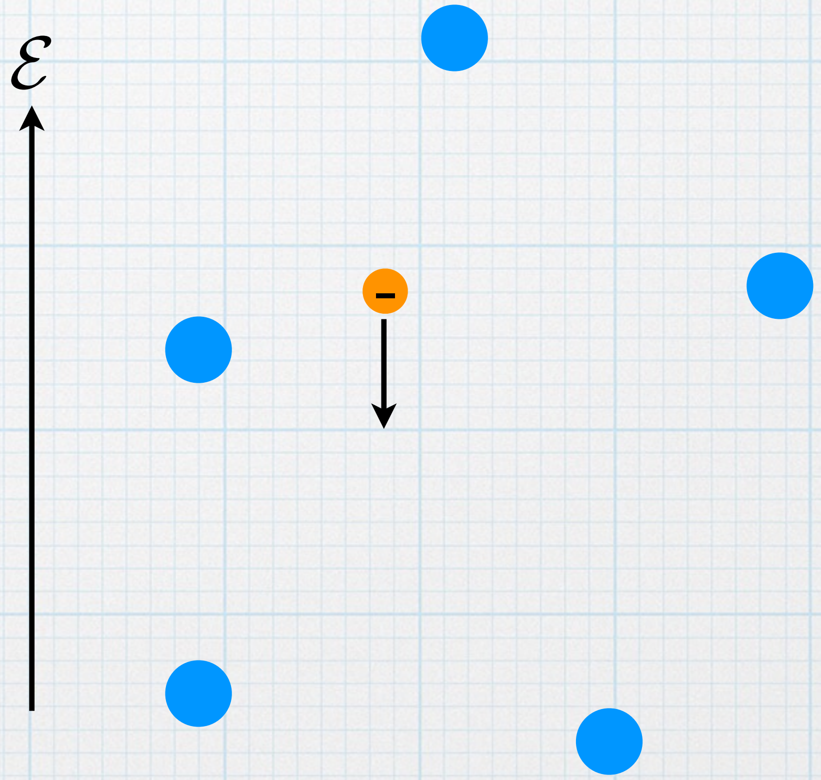
Mobile electrons cause most of the ionization. Heavy ions do most of the “work”.

With proper conditions (pressure, voltage) a plasma can be sustained (1% - 20% ions in the gas).



$$E_{elec} = q\mathcal{E}\lambda > E_{ionization}$$

higher pressure → smaller λ



lower pressure → larger λ
nothing to hit!

Note that the interactions are purely physical, depending only on collisions in the gas. This allows the use of nearly any gas to form the plasma. In fact, the inert gas argon is commonly used in plasma systems. However, the choice of will depend on the application. (More later.)

Plasmas give off lots of light. (They are sometimes known as “glow discharges.) In the collisions (electron-atom, ion-atom) electrons in the atoms are knocked from lower states to higher states. (Of course, ionization is the process of knocking an electron completely free of the atom.) Electrons that are not broken free but are merely pushed to higher energies will relax back down to the ground state energies, giving off photons in the process. The color (photon energy) of the light is dependent on the energy levels of the particular atom. So the color coming from a plasma depends on the gas making up the plasma.

If you take this a step further and examine the light coming out spectroscopically, you can discern many things about the plasma. This is known as optical emission spectroscopy (OES).

Of course, we also use plasmas for light bulbs.

RF plasma (AC plasma)

We can also make plasmas using AC excitation. We might want to do this if we wanted to use non-conducting electrodes.

The key to an AC plasma lies in the fact that the electrons and ions travel with much different speeds in response to the applied fields.

The asymmetry in the response of electrons and holes leads to the build-up of a DC field (self-bias) in the plasma. So even though the applied voltage is swinging back and forth, the self-bias will create a net flow of current through the plasma, creating pretty much the same effect as the DC plasma.

Typical frequencies for AC plasmas are 13.56 MHz and 2.4 GHz. (Frequencies that are not regulated by the FCC.)

Other types of plasmas: electron-cyclotron resonance (ECR), inductively coupled (ICP).