Semiconductor Technology from A to Z

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Plasma, the fourth aggregation state of a material

Plasma state

In many semiconductor manufacturing processes a plasma is used, be it in sputtering, deposition processes, or dry etching. An important point here is that the wafer remains cold in the plasma. This may sound contradictory at first, since the electrons in the plasma are extraordinarily hot, at several tens of thousands of degrees. However, they are so light that upon collision they hardly transfer any energy to the heavy gas particles – the gas itself, and with it the wafer, therefore remain close to room temperature. Such a plasma, in which the electrons and the gas do not have the same temperature, is called a non-equilibrium plasma. Only for this reason can wafers that already carry a metallization be processed in a plasma at all.

Plasma is also referred to as the fourth state of matter. A state of matter is a qualitative condition of substances that depends on temperature and pressure. The three states solid, liquid, and gaseous are also encountered in everyday life. If the temperature is low, every atom in a substance is fixed rigidly at one point. Attractive forces prevent them from moving. At absolute zero (-273.15 °C) substances also do not undergo any reaction. As the temperature increases, the particles begin to oscillate, and the bonds between the atoms become more unstable. Once the melting point is reached, a substance transitions from the first to the second state of matter: ice (solid) turns into water (liquid).

The attractive forces in liquid substances are still present, but the particles can shift position and no longer have fixed places as in the solid state; the particles adapt, for example, to a given shape. If the temperature is increased further, the bonds break apart completely, and the particles move independently of one another. At the boiling point, a substance transitions from the second to the third state of matter: water (liquid) turns into water vapor (gaseous).

While the volume of solids and liquids is constant, gaseous substances completely fill the available space; the particles distribute themselves evenly throughout the entire volume.

Every substance has a very specific melting point and boiling point. Silicon melts at 1414 °C and transitions into the gaseous state at 2900 °C. If even more energy is supplied to a substance, collisions between the particles knock electrons out of the outermost electron shell. Free electrons and positively charged ions are now present in the space: the plasma state has been reached.

Plasma generation

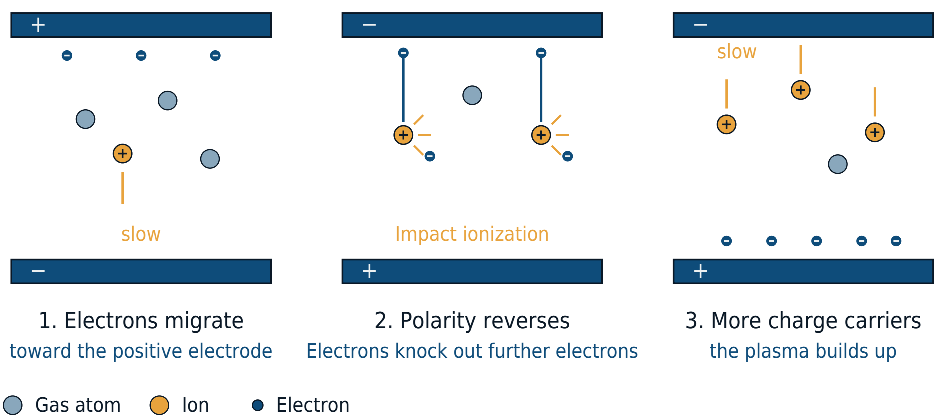
A plasma in semiconductor technology is usually generated by a high-frequency voltage; argon, for example, serves as the gas. The gas is located in a high-frequency field between two oppositely charged plates (electrodes) and is ionized there. This requires electrons that knock further electrons out of the argon atoms. These initial electrons can be generated in different ways:

- electrons are emitted from a thermionic cathode
- electrons are pulled out of the negative electrode by a very high voltage
- in every gas, brief free electrons occur through collisions of the particles

Since the electrons are much lighter than the ions, they are immediately attracted to the positively charged electrode; the heavy ions move slowly toward the negative electrode. However, before they reach it, the polarity of the electrodes is reversed; the electrons are accelerated toward the other electrode and, on their trajectory, knock further electrons out of atoms through collisions. Typical frequencies for plasma generation are 13.56 megahertz and 2.45 gigahertz, meaning the voltage at the electrodes is reversed 13.56 million or 2.45 billion times per second, respectively.

How the Plasma Ignites

The electrodes are reversed millions of times per second

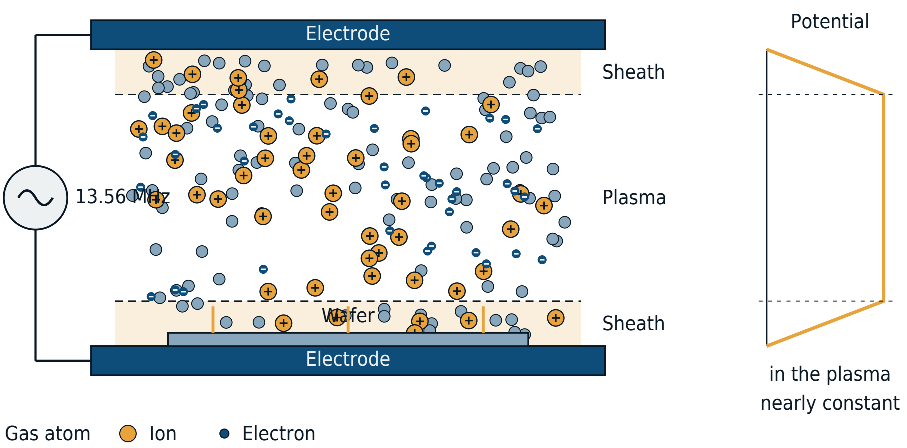


The light electrons follow the alternating field, the heavy ions barely do.
Each polarity reversal creates new charge carriers, until the plasma ignites.

Inside the plasma, electrons and ions are roughly balanced, so it is electrically neutral overall. The situation is different immediately in front of the electrodes: the light, fast electrons reach there much more often than the sluggish ions, which cannot follow the rapid voltage changes. As a result, the electrode charges negatively, and an electron-depleted boundary layer (sheath) forms in front of it. Almost the entire voltage drops across this sheath – it is this voltage that accelerates the ions toward the wafer and thus accounts for the directional component of dry etching.

Plasma Generation Between Two Electrodes

Charges balance out in the bulk, but not in front of the electrodes



The electrons follow the alternating field, the heavy ions do not.
This depletes electrons in front of the electrodes; almost the entire voltage drops across this sheath and accelerates the ions onto the wafer.

Plasma generation takes place under vacuum; the plasma produced is not heated, which is important for many processes. Depending on the gas and the equipment in which the plasma is generated, it can be used in deposition, sputtering, etching, or also in ion implantation. Due to the rapid oscillations of the positive ions in the high-frequency field, they are very energetic. The plasma does not contain only positive ions and free electrons, since other particles are also created through collisions; the state of the plasma changes continuously. Electrons are partially recaptured by the ions and knocked out again; however, these additional particles play no role in the further use of the plasma. Depending on the particle density in the plasma (10^8–10^{12} particles per cm^3), the degree of ionization is 0.001–10 %, meaning the majority of the particles are uncharged.

The simple arrangement with two plates has one drawback: the same voltage determines both how many ions are generated and how hard they strike the wafer. The two cannot be set independently of one another. Equipment for fine structures therefore generates the plasma differently – via a coil that couples in an alternating field from outside, or via microwaves – and applies the voltage at the wafer electrode independently of this. Ion density and ion energy are then two separate, independently adjustable parameters.