1
Introduction to Plasmas

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1.1
Plasmas

In physics and engineering, the word ''plasma'' means electrically conductive ionized gas media composed of neutral gases, ions, and electrons. Words like solid-state plasmas can be used instead of plasmas, because they show certain semiconductor phenomena analogous to known gaseous plasma phenomena, such as current-driven instabilities, a traveling-wave amplification, plasmon excitations, and so on.

It will not be exaggerating to say that the space in the universe is filled mostly with plasmas. An impressive example of plasmas in our daily life is lightning, which discharges a current from 30 kA up to 100 MA emitting light and radio waves. In such lightning plasmas, the electron temperature can approach as high as 28 000 K (2.4 eV) and electron densities may exceed 10^{24} $m^{-3}(10^{18}$ $cm^{-3})$. One can also estimate that lightning plasmas are almost fully ionized by considering that there are 3.3×10^{22} $m^{-3}(3.3 \times 10^{16}$ $cm^{-3})$ neutral atoms in the atmosphere at room temperature.

1.1.1
Plasma Characteristics

Plasmas can be loosely described as an electrically neutral medium of electrons, positive ions, and neutrals in the gas phase which have the Maxwellian velocity distribution for the electron as follows [1]:

$$f_e(\vec{v}) = n_e A_e \exp\left(\frac{-m_e v^2}{2\kappa T_e}\right) \tag{1.1}$$

where $f_e(\vec{v})\, d\vec{v}$ is the electron number density, κ is Boltzmann constant, and T_e is the electron temperature. Each of the plasma components, the electrons, ions, and neutrals, has different density, mass and temperature, but $n_e = n_i = n_0$ which is the plasma density.

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There are two important parameters that characterize plasmas: one is the electron plasma frequency and the other is the Debye length. For simplicity, consider a one-dimensional electron slab on a uniform ion background. If the electron slab is displaced from its neutral position by an infinitesimal distance δx, the electric field generated along the slab is $E_x = -\, e n_0 \delta x / \varepsilon_0$, where ε_0 is the permittivity of the free space, and from the equation of motion,

$$m_e \mathrm{d}^2 \delta x / \mathrm{d}t^2 = -eE_x = -e^2 n_0 \delta x / \varepsilon_0 \tag{1.2}$$

and the electron plasma frequency is given by

$$\omega_p^2 = n_0 e^2 / \varepsilon_0 m_e \tag{1.3}$$
$$f_p = 9 \times 10^3 n_0^{1/2} \ \mathrm{Hz} \quad \text{for } n_0 \text{ in cm}^{-3}$$

The electron plasma frequency implies that electric potential fluctuations in plasmas with their frequencies below the electron plasma frequency must be suppressed. For fluctuations with higher frequencies, the electrons cannot respond and waves are generated in the plasma.

Now let us consider the potential distribution around ions in the plasma. If the electrons have no thermal energy, a cloud of electrons would be trapped around each ion, and there would be no electric field present in the body of the plasma outside the cloud.

However, if the electrons have thermal energies, the electron cloud stays at the radius where the potential energy is approximately equal to the thermal energy, and the shielding is not complete anymore.

For simplicity, the Poisson's equation in one-dimension is given as

$$\varepsilon_0 \mathrm{d}^2 \phi / \mathrm{d}x^2 = e (n_e - n_i) \tag{1.4}$$
$$= e n_0 \left\{ [\exp (e\phi / \kappa T_e)] - 1 \right\} \tag{1.5}$$
$$= n_0 e^2 \phi / \kappa T_e \quad \text{for } e\phi / \kappa T_e \ll 1 \tag{1.6}$$

The Debye length λ_D is thus given by

$$\lambda_D = \left(\varepsilon_0 \kappa T_e / n_0 e^2 \right)^{1/2} \tag{1.7}$$
$$\lambda_D = 743 \times T_e^{1/2} n_0^{1/2} \ \mathrm{cm} \ \left(\text{for } T_e \text{ in eV and } n_0 \text{ in cm}^{-3} \right)$$

and the solution of Eq. (1.6) is given by

$$\phi = \phi_0 \exp (-|x| / \lambda_D) \tag{1.8}$$

For the plasma to be quasineutral, charged particles must be close enough so that each particle influences many nearby charged particles, rather than just interacting with the closest particle, which is a distinguishing feature of plasmas. The quasineutral plasma approximation is valid when the number of charged particles within the Debye sphere is much higher than unity, $n_0 \lambda_D^3 \gg 1$.

From Eqs. (1.8) and (1.3), one also finds that the Debye length is the distance that the thermal electron can travel during one period of the plasma frequency. Obviously, the Debye length must be short compared to the physical size of the plasma.

1.2
Discharge Plasmas

When high power is injected into a relatively high-pressure (such as 10^5 Pa) gas, ‘‘thermal plasmas’’ are produced with the temperature as high as 15,000 K ($T_e = T_{ion} = T_{gas}$). ‘‘Although the plasma depends very much on the input power, there is no temperature difference among electrons, ions and neutrals for the pressure above 10^4 Pa, because of heavy collisions; this kind of plasma is called ‘‘*thermal plasma*’’.’’ On the contrary, in the lower pressure range below 10^4 Pa, the temperature difference between the electrons and ions increases ($T_e \gg T_{ion} = T_{gas}$), and the kind of plasma is called ‘‘*glow discharge plasma*’’. According to a rough estimation, in the glow plasma the ion temperature stays at about 300 K, but the electron temperature tends to increase from 5,000 K (0.5 eV) at 10^4 Pa to 20,000 K (2 eV) at 1 Pa.

Plasmas in laboratories for researches and industrial uses are mostly generated by electrical discharges in vacuum chambers of various sizes equipped with a gas feeder and a pumping system. Inside the chamber, various gadgets are implemented around a substrate on a position controllable holder with a heater and monitors.

1.2.1
Glow Plasma

A glow discharge plasma generally operates in the pressure range from 100 to 0.1 Pa and the degree of ionization remains a few percent. Quite often inert gases like argon or helium are used to generate the main plasma into which various seed gases like CCl_4, CF_4, $SiCl_4$, SiH_4, and so on, are introduced depending upon specific subjects of plasma processing.

What is the role of the glow plasma in the system? Firstly, the electrons in the inert gas plasma interacting with the seed gas molecules create useful radicals for synthesizing materials, which may be called ‘‘*plasma chemistry*.’’ Secondly, the electrons can also produce etchant atoms, usually Cl or F, which combine with substrate atoms and fly off as volatile molecules. The processing is known as ‘‘*dry etching*’’ to fabricate nanoscale structures. Thirdly, the electric field across the plasma sheath straightens the orbit of etching ions, and flat etching surfaces can be structured. Fourthly, the potential drop across the plasma sheath can be controlled by controlling the electron temperature of the main plasma facing the substrate.

When it comes to plasma processing, key issues are accumulated at the plasma–substrate boundary, and one will find controlling of the plasma electron temperature is the crucial issue, because it is proportional to the ion bombardment energy.

The plasmas generated by the application of DC or low-frequency-RF (<100 kHz) electric field in the gap between two metal electrodes are probably the most common glow discharge plasmas.

Capacitively coupled plasma (CCP) and inductively coupled plasma (ICP) are both glow discharge plasmas produced with high-frequency (typically 13.56 MHz)

RF sources. These are widely used in the field of plasma processing such as microfabrication and integrated-circuit manufacturing with dry etching and plasma-enhanced chemical vapor deposition. These are not only employed for producing CCP and ICP but are also widely employed to generate glow discharge plasmas with various kinds of electrodes to meet specific requirements. A large ladder-shaped electrode, for example, a kind of self-discharging RF antenna, is devised for fabricating a large-scale solar panel. Many innovative ideas have been proposed to realize low-cost/high-efficiency thin-film silicon solar cells.

Helicon wave plasma (HWP) [2] can also generate glow plasmas with an order of magnitude higher density than CCP and ICP with the same power, but the mechanism is not fully understood yet. HWP typically requires a complicated electrode structure with the coaxial magnetic field for the wave propagation. Concerning the effect of the magnetic field, in most cases the ions have little effect, but the electrons are anisotropic with their properties in the direction parallel to the magnetic field being different from those in the direction perpendicular to it.

1.2.2
Atmospheric Plasmas

It may be interesting to note that in the history of plasma application only a few products carried or used plasmas in their final stage, for example, surface modifier, electrosurgical instrument, arc welder, plasma spray, plasma display (TV), fabric synthesizer, and so on. These are all devised to use atmospheric, or nearly atmospheric, plasmas. On the other hand, glow plasmas are used as a tool for manufacturing.

- **Plasma spray** is the typical thermal plasma generated using high power supplies. The development of the plasma spray processing started with the invention of the DC plasma torch in the 1960s. In the thermal spraying process, raw materials are sprayed in either powder, solution, or vapor form, and metallurgical processes are studied. The fundamental role of the plasma is to provide the extremely high temperature environment and its flow, which are not achievable by any combustion flames [3].
- **Streamer corona** was once extensively studied in relation to electrosurgical instruments [4, 5]. When high RF voltages (300 kHz, 5 kV) are applied to a sharp electrode tip mounted on a narrow piping and at the same time gases like He or Ar are sent into the same piping from a side arm, a long streamer corona plasma of He or Ar extends steadily out of the piping tip. The plasma stream gives rise to coagulation without excessive drying, sterilization, and destruction of the spore's genetic activity.
- **Dielectric barrier discharge** is widely used in the web treatment of fabrics. The application of the discharge plasma to synthetic fabrics and plastics modifies their microstructure, and functionalizes the surface to allow for paints, glues, and similar materials to adhere.

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