CHAPTER 14

PLASMAS USED IN SEMICONDUCTOR-MANUFACTURING

Matter can exist in three states: solid, liquid, or gas. However, if enough energy is added to a gas, it will assume a so-called *fourth-state of matter*, that of a *plasma*. Plasmas are important in IC-fabrication, being an integral aspect of many processes, including: sputtering; dry-etch; and plasma-enhanced-CVD. They are also used to create ions for ion implantation and to produce the radiant-energy emitted by mercury-arc lamps used in lithography. Since plasmas are encountered in so many ULSI processes, it is useful to provide background-information about the basics of plasmas. This will help readers gain a deeper grasp of the processes that rely on their use. More details about them can be found in Refs. 1 - 5.

To begin, it is assumed that all of the atoms or molecules in an (ideal)

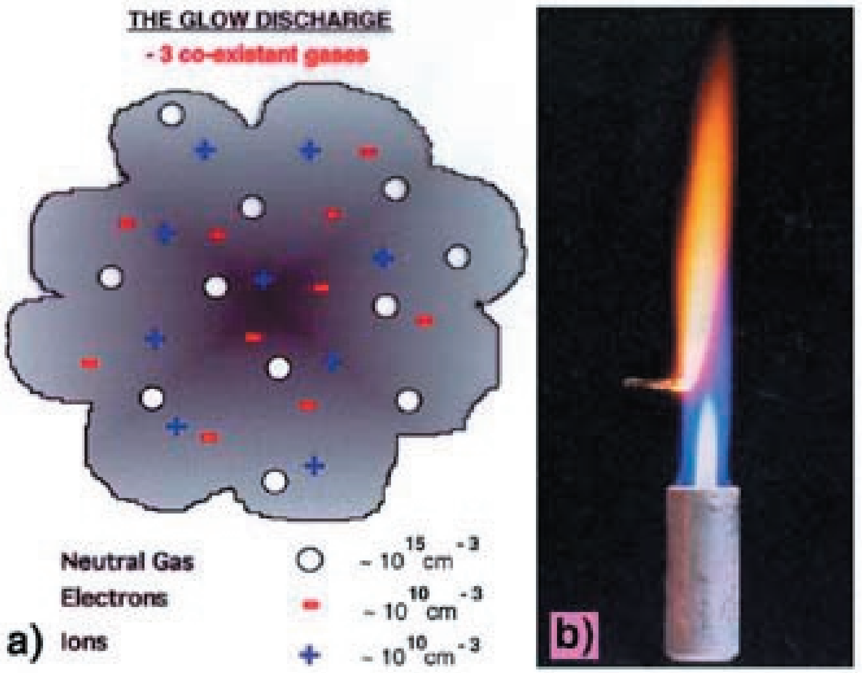

Fig. 14-1 (a) Schematic-diagram of a plasma. (b) A flame is an example of a glowing plasma.

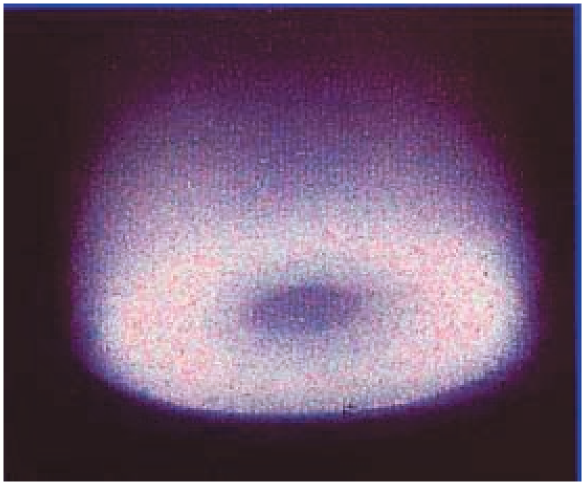

Fig. 14-2 Photograph of a glow-discharge that is excited in a sputtering-tool.

gas are *electrically-neutral*. On the other hand, charged-particles exist in a plasma together with neutral gas-atoms. That is, a *plasma* is a gaseous state of matter containing *an equal number of positively and negatively charged particles per unit volume* (electrons and ions) – usually in addition to neutral gas-atoms (Fig. 14-1a). The energy that must be added to gas to turn it into a plasma can be provided in various ways, but the simplest way is by *heating* the gas.

Plasmas created by adding heat to a gas are found in nature. That is, the matter in stars, sparks, flames, and lightning are all examples of plasmas found in nature (Fig. 14-1b). A gas could be turned into such a *thermal-plasma* if it was heated to a high-enough temperature (dependent on the kind of atoms that constitute the gas). That is, a gas at room-temperature (300 K) contains a negligibly-small concentration of independent charged-particles. To produce a sufficiently-high concentration of charged particles to create a *thermal-plasma*, the temperature of the gas has to be raised to 4,000 K (for such easy-to-ionize gases as cesium) or to 20,000 K (for such hard-to-ionize gases as helium). At these high-temperatures, free-electrons within the gas have high enough kinetic-energies to ionize a sufficient fraction of the gas-atoms to produce a stable plasma-state. However, trying to use such hot gases (plasmas) for wafer-fabrication applications would be impractical, as they would vaporize any thin-films present on the surface of the wafers.

Thus, in order to create plasmas that have gas-temperatures compatible with the thin-films used in IC processing, it must be possible to add energy to a gas in another way to establish a plasma. In arc-welding, an *arc-discharge plasma* is initiated by touching together two electrodes and then separating them while applying a large voltage. This ionizes some of the air molecules (*break down*), causing the air-gas to become conductive. This allows current to flow between the electrodes and to sustain the intensely-heated arc-discharge plasma used for welding.

The plasmas used in semiconductor manufacturing are more *weakly-ionized plasmas* than such highly-ionized arc-discharges, and are produced within process chambers (Fig. 14-2). They are also created by adding energy from electric and magnetic fields, instead of by heating the gas. As will be seen, this allows only the charged-particles in the plasma to gain energy (i.e., the neutral gas-atoms are not directly impacted by the electric and magnetic fields). By gaining sufficient-energy in this way, free-electrons are not only able to ionize the gas-atoms and produce a plasma, but they can also cause other events needed by particular processes (such as the creation of reactive-species in a process-gas used for dry-etching). At the same time, the neutral gas-atoms in such process plasmas do not become heated, but remain very close to the temperature present in the process-chamber. The details of how energy is added to gases using electric (and magnetic) fields is covered in the following sections.

14.1 INTRODUCTION TO GLOW-DISCHARGES

The type of plasma used most commonly in IC-processes is the glow-discharge. A *glow-discharge* is a self-sustaining, weakly-ionized plasma that emits light (i.e., it *glows*). A neon-light is an example of a glow-discharge encountered in daily life (see Fig. 14-3). Similar kinds (excited by dc and rf electric-fields) are created in process-chambers for IC-processing.

Figure 14-4 shows a simple *dc-diode-type* system.

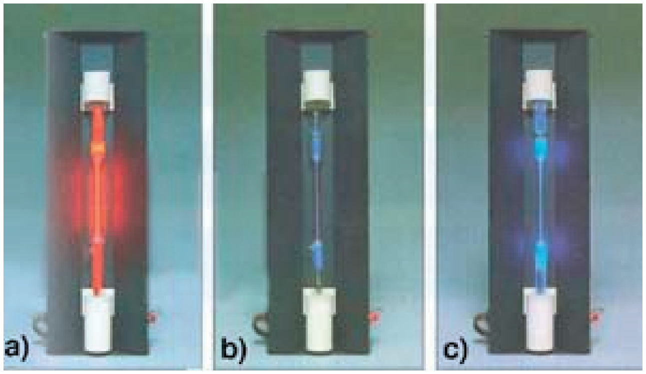

Fig. 14-3 When a gas is excited in a glow-discharge, it glows as it emits light. The colors of the light emitted by three gases – (a) neon, (b) argon, and (c) mercury – are shown. Each emission consist of several-wavelengths of light, and the perceived color depends on which wavelength predominates.

We use it to explain how glow-discharges are established. The dc-diode system consists of a glass-tube from which the air has been evacuated. It is then re-filled with a specific-species of gas at low-pressure. Within the tube are two electrodes (a positively-charged *anode* and a negatively-charged *cathode*) and a dc-potential-difference is applied between them.

14.1.1 The Creation of DC Glow-Discharges

Assume in Fig. 14-4 that the glass-tube is: **1**) filled with argon-gas at a pressure of 1-torr; **2)** the distance between the electrodes is 15-cm; and **3**) a 1.5-kV dc potential-difference is applied between them. At the outset no current flows in this circuit - because all of the Ar gas-atoms are neutral, and thus there are no charged-particles in the gas. The full 1.5-kV is then dropped entirely between the two electrodes. However, if a free-electron enters the tube (most likely created from ionization of an Ar-atom by a passing cosmic-ray), it will be accelerated by the electric-field E existing between the electrodes (and whose magnitude is: E = V/d = 1.5-kV/15-cm = 100-V/cm).

The average-distance that a free-electron travels at a pressure *P* = 1-torr before colliding with an Ar-atom (i.e., the *mean-free-path* □) is 0.0122-cm (see Ch. 6).

Most such electron-atom collisions are *elastic*. This means that virtually no energy is transferred between the electron and gas-atom as a result of the collision

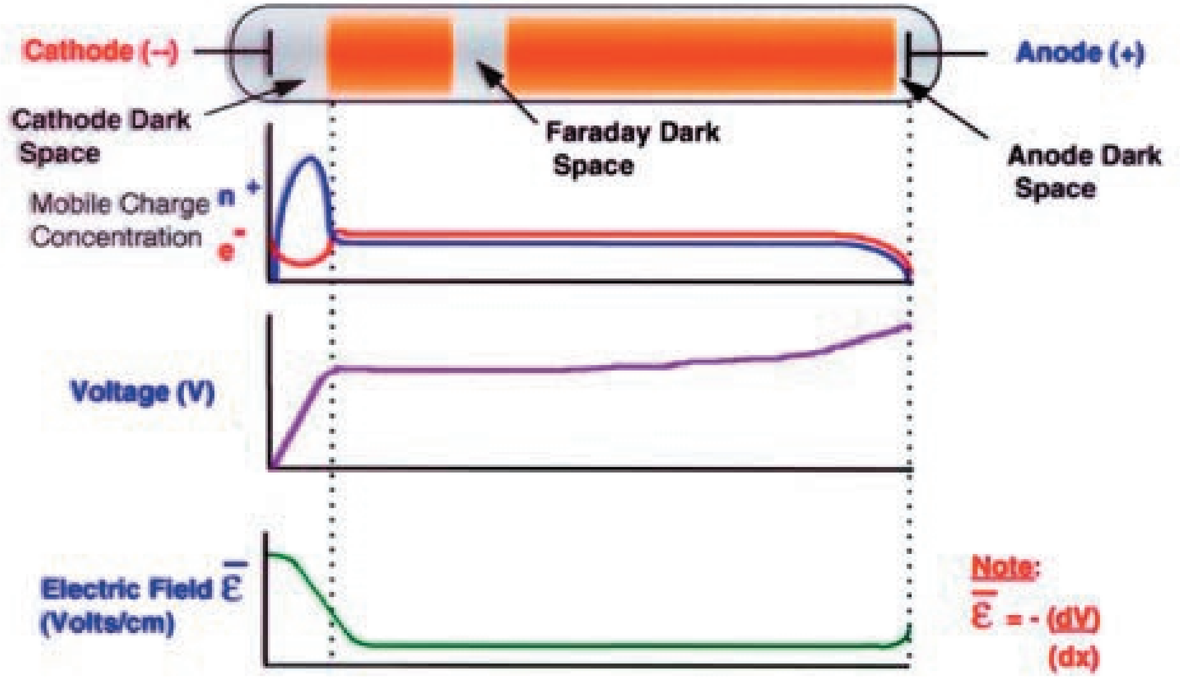

Fig. 14-4 (a) Schematic drawing of a dc glow-discharge established in a glass tube containing a gas under reduced-pressure,