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DC Glow Discharge for Sputtering & Biasing

The non-magnetically confined, cold-cathode DC (and low-frequency AC) glow discharge (also called a gas discharge) is probably the most simple plasma generation technique used in vacuum coating.[1] The plasma thus generated is used as a source of high-energy ions for sputtering and ion plating ("atomic peening"). The primary glow discharge properties of concern in these applications are the particle species, charged particle density in the plasma region, cathode fall voltage and the gas pressure. A low gas pressure allows ions and electrons to be accelerated to a high energy in an electric field. This requirement confines the pressure range of interest to the low end of the gas-pressure range for which a self-sustained discharge can be maintained (*e.g.*, ≈ 10–50 mTorr for argon).

If a cathode and an anode electrode are placed in a gaseous environment (DC diode), with a pressure higher than that necessary to establish a self-sustained glow discharge, and DC power is slowly increased across the tube, the current-voltage relationship will be as shown in Fig. 1. At low voltages, the electrodes will collect naturally occurring ions and electrons and the current will be very small (ohmic region). As the voltage gets higher, the electrons will be accelerated and ionization by electron-atom impact will increase the current. In this region (Townsend Discharge region) the electrical field gradient between the electrodes will be uniform, as shown in the upper-left inset of Fig. 1.

If the gas particle density is high enough, at some voltage there will be a "breakdown" and the electric field distribution will change—the discharge will become a "normal glow discharge." This occurs when the secondary electron emission from the ion-bombarded cathode becomes high. In this region, glowing spot(s) will appear on the cathode. As the power is increased, the spot(s) will expand, keeping a constant current density. When the spot covers the whole cathode surface ("cathode glow"), increasing the power will cause the current density on the cathode to increase, and the discharge will become an "abnormal glow discharge." It is in this region that sputtering is normally performed. In the abnormal glow discharge the electrical field gradient becomes high near the cathode ("cathode fall region"), with no field gradient through the plasma region to near the anode, as shown in the upper-right inset in Fig. 1. The anode can be a separate electrode (electrically floating), or may be the grounded portion of a metal vacuum chamber. A typical cathode current density for non-magnetic DC diode sputtering is 1 ma/cm^2 at an applied voltage of several thousand volts.

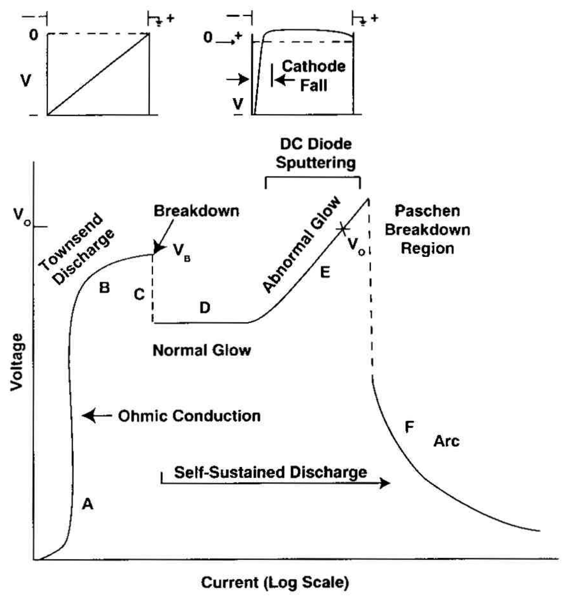

Fig. 1—Current and voltage as a function of increasing power in a DC gas discharge tube (generalized).

At some higher voltage, there will be another electrical breakdown and an arc will form between the cathode and the anode. This type of arc is influenced by cathode properties such as oxide inclusions, gas release and sharp points. Arcing will cause a substantial increase in current and decrease in voltage. Arcs are normally detrimental in sputter deposition and ion plating since they can be destructive to the power supplies and the deposited coatings.

In the abnormal glow discharge region, ions are accelerated to the cathode through the cathode dark-space region from the edge of the plasma region. As they gain energy in the electrical field, they can sustain "charge-exchange collisions" where the ion loses its electron to an atom, thus becoming a high-energy neutral and a low-energy ion. These charge-exchange collisions thus create a spectrum of energetic ions and atoms that strike the cathode. For example, if the applied voltage is 1500 volts, the average ion energy may be 400 eV. The lower the gas pressure, the fewer the charge-exchange collisions and the higher the average energy of the ions striking the cathode. The cross-section (probability) for charge-exchange collisions is much greater than that for physical (momentum-exchange) collisions.

The secondary electrons that are emitted under ion bombardment of the cathode are accelerated away from the cathode, causing electron-atom ionizing collisions. The process is then repeated. High-energy secondary

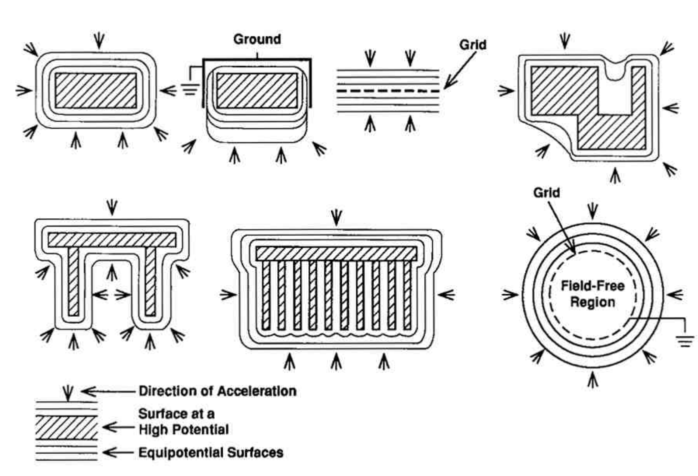

Fig. 2—Equipotential surfaces around various shapes.

electrons can be a source of heating of surfaces facing the cathode. Ions (and high-energy neutrals) striking the cathode are neutralized and may be incorporated into the surface or reflected from the surface as high-energy neutrals.

The glow discharge thus formed consists of two parts. One is the plasma-generation region near the cathode where the electric field gradient is concentrated and charged particles are accelerated. The other is the field-free, volumetrically neutral, plasma region that extends from the edge of the cathode dark space to near the anode. This electrically conductive region acts to extend the anode electrode toward the cathode. This region is also called the "positive column" because it has a positive potential with respect to ground. The luminosity of the discharge will vary with position, with the principal regions being the "cathode glow" on the cathode, the "cathode dark space" near the cathode, a relatively bright "negative glow" region at the edge of the dark space, and a positive column (plasma region) that extends nearly to the anode. Optical emission from the plasma region gives the glow discharge its name. The plasma region can occupy a large volume or extend for a long distance between electrodes.*

At low pressures, charged particles are mainly lost from the plasma region by recombining at surfaces in contact with the plasma. In a self-sustained glow discharge, the plasma-generation region must continually replenish the plasma with charged particles.

If the anode (or ground) electrode is brought nearer to the edge of the cathode dark space, a point is reached where the conditions for "self-sustaining" the discharge are not met and the discharge is extinguished. The separation of the cathode and the anode where the discharge is extinguished follows Pachen's Rule, which states that the pressure (p) times the separation distance (d) equals a constant value ($p \times d$ = constant). The value of the constant depends on the gas(es) involved. This means that at lower pressures the critical separation is greater than at higher pressures. For argon at 15 mTorr, the separation is about 1 cm. A ground shield closer than that distance, at that pressure, will extinguish the discharge between the two surfaces.

It should be noted that in the glow discharges being discussed only a small fraction (10^{-4}) of the gas atoms in the plasma region are ionized ("weakly ionized" plasma). In a large chamber, the plasma densities can vary significantly depending on the location of the plasma-generation region, the position of the anode and whether the anode is floating or grounded.

If the electric field that sustains the discharge is turned off, the electric field gradient will disappear immediately and only the plasma ("afterglow") will remain. The charged particle density in the plasma will exponentially decay as the charged particles reach surfaces and become neutralized. In this weakly ionized plasma ("cold plasma") the ion temperature is about 0.1 eV (or lower), and the ion speed is less than 0.1 km/sec (0.1 meter/millisecond). Thus, it will take about 1 msec (or longer) for the majority of the ions in the plasma to reach a surface and be neutralized.

If the discharge is periodically turned off and restarted, as when using a pulsed DC or an alternating current (AC) voltage between the electrodes, the frequency can be a factor in the plasma behavior. If the "off-time" is greater than about 1 msec, most of the plasma ions will have been lost and the discharge will have to be reinitiated (reignited) using naturally occurring charged particles ("cold start"). If the off-time is significantly shorter than 1 msec, residual charged particles from the plasma aid in reinitiating the glow discharge. In the "mid-frequency" range of 25 kHz to 250 kHz, which is used, for example, in "mid-frequency dual-cathode AC magnetron sputtering," the plasma does not completely decay over a cathode before the glow discharge is reestablished.

DC glow discharges are often established by applying voltages much higher than needed for breakdown, then controlling the power using a current-regulated power supply. This gives an initial "spike" of high voltage followed by a steady-state condition of current at a lower voltage. Using this procedure, initiating an abnormal glow discharge requires less than a microsecond. If a voltage-regulated power supply is used, and the voltage is not much above the breakdown voltage, a significantly longer time may be needed to reestablish the glow discharge or a separate ignition source (high-voltage pulse, laser, etc.) can be used to establish the glow discharge.

When a glow discharge is initiated with a voltage-regulated power supply, it is often noted that the current decreases with time. This can be due to the fact that oxides on the surface have a higher secondary electron emission under ion bombardment than does the clean metal, and the current decreases as the oxides are cleaned from the surface. One way to monitor the amount of contaminants in the gas is to note the final equilibrium current conditions (everything else held constant). If contaminants are present there will be continual "poisoning" of the cathode surface by the formation of oxides, and the

** In Brian Chapman's book Glow Discharge Processes, he relates the story of Johann Wilhelm Hittorf (1824–1914), one of the early investigators of glow discharges and cathode rays. Hittorf labored week after week extending a glass discharge tube in an attempt to establish the maximum length of the positive column. Eventually the glass tube ran back and forth across Hittorf's laboratory with no end in sight. At this stage, a frightened cat pursued by a pack of dogs came flying through the window…Hittorf reported, "Until an unfortunate accident terminated my experiment, the positive column appeared to extend without limit."*

equilibrium current will remain higher than if there are no contaminants present. In the extreme, poisoning can render the whole cathode surface non-conducting and the discharge will cease.

Arcing can be a problem in a gas discharge and may be due to several conditions. If an oxide particle on the cathode surface is heated to a high temperature, it can emit thermo-electrons. This local electron source can cause an arc from the cathode to the anode/ground. If a portion of the cathode surface has a dielectric layer (such as an oxide) on it, bombardment of the oxide can cause a positive charge buildup on surface sites that causes arcing through the film or across the film to the metallic cathode surface. This can be a problem in the reactive sputter-deposition of dielectric materials. Arcs can also occur if sharp points or flakes of material create high field regions on the surface. Typically, DC-glow-discharge power supplies react to the rapidly decreasing voltage or increasing current associated with an arc by momentarily shutting off the power, diverting the arc to ground, and sometimes applying a voltage with an opposite polarity. Therefore, the power supply circuit defines what is to be called an arc. DC power supplies used in potentially arcing conditions should have as little energy stored in their circuits as possible.

If the surface of the cathode is planar, the equipotential surfaces will be planar and parallel. Ions and electrons are accelerated normal to the equipotential surfaces, so the bombardment will be uniform over the planar surface. Where equipotential lines are curved, the ions will be focused (or defocused), giving higher (or lower) bombardment fluxes in certain areas. This can be a problem when using a DC discharge to bias a substrate fixture for cleaning or film deposition. Figure 2 shows some possible substrate/fixture surface configurations and associated equipotential surfaces. Another problem can be encountered if the surface configuration is such that field-free cavities are formed. These features can create a hollow-cathode effect, where dense plasmas are formed that heat the surrounding material and produce electron beams that are accelerated away from the cavities create plasma density discontinuities and surface heating. The use of "pulsed power" for biasing can minimize some of these effects. If low voltages are desired for substrate biasing it is necessary to generate a plasma from another source, such as a hot-filament glow discharge or an unbalanced magnetron sputtering source.

A disadvantage of the non-magnetically confined glow discharge is that the electrons are accelerated away from the cathode normal to the surface. This means that ions are formed a long way from the cathode and can suffer charge exchange and physical ("thermalizing") collisions before they reach the cathode surface. Magnetic confinement, such as in various "magnetron" sputtering-target configurations, confines the electron path to be near the surface. This means that lower gas pressures can be used and the average ion energy striking the cathode can be higher. The use of magnetic confinement makes the structure of the glow discharge very complicated but allows higher cathode current densities and higher average ion energies at lower applied voltages. It should be noted that Pachen's rule does not apply if magnetic fields (stray or deliberate) are present. This can present a problem with shielding around magnetron sputtering cathodes.

A problem with the planar magnetron sputtering source, when used for reactive sputter deposition, is that a portion of the cathode is not being aggressively sputtered and can easily be poisoned. This makes arcing over the surface more active.

Gas discharges at higher pressures are used for plasma cleaning and etching, polymer surface treatment, and plasma-enhanced chemical vapor deposition (PECVD). **P&SF**

Note: Voltage is the electrical potential difference between two points. The potential is the voltage at a point with respect to ground. In the MKS system of units, a volt represents doing one joule of work in moving one coulomb of electric charge from one point to the other. The voltage polarity indicates which direction an electron will flow between the two points due to the voltage between the points.

Reference

1. *Glow Discharge Processes*, Brian Chapman, John Wiley & Sons, 1980.