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Glo[redacted] Discharge Processes

SPUTTERI[redacted]G AND PLASMA ETCHING

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Chapter 4. DC Glow Discharges

So far we have been dealing with a rather idealized homogeneous plasma with a well-defined potential and density, and with constituent particles in equilibrium motion characterized by relevant temperatures. The glow discharges which we're using only approximate this condition, for various reasons which we shall be discussing. Nevertheless, many of the plasma concepts are of great utility in helping us to derive some understanding and control of glow discharge processes, even on a semi-quantitative basis. Amongst sputtering and plasma etching folks, the words 'plasma' and 'glow discharge' tend to be used synonymously – to the horror of plasma physicists, I'm sure! One can get into semantic discussions and argue that some discharges are plasmas with two or three different groups of electrons each with a well-defined temperature. That argument could probably be extended indefinitely. So let's accept that our glow discharges are certainly not ideal plasmas, and keep this in mind when we lapse into glow discharge – plasma synonyms.

One of the complicating factors in trying to understand glow discharges is that most of the literature, particularly the 'classical' literature of the 1920's and 30's, deals with dc discharges; whereas practical plasma processes are more usually rf excited. And, as we said above, none of our practical glow discharges are truly plasmas. This gives then, in a sense, a choice: we can either pursue some plasma physics rather exactly, and then find that it does not entirely apply to our systems; or we can follow some simpler, if not always entirely accurate, models which convey the physical ideas rather well and, in the event, are probably just as accurate. In the present book I have opted for the latter.

Before commencing battle, I would recommend reading a delightful history of gaseous electronics by Brown (1974). Prof. Brown tells, for example, the story of the unfortunate pioneer Hittorf who laboured week after week, gradually extending the length of a thin glass discharge tube to try to discover the length of the positive column. Eventually the tube ran back and forth across Hittorf's laboratory. At this stage, a frightened cat pursued by a pack of dogs came flying through the window . . . "Until an unfortunate accident terminated my experiment", Hittorf wrote, "the positive column appeared to extend without limit."

ARCHITECTURE OF THE DISCHARGE

We could make a dc glow discharge by applying a potential between two electrodes in a gas; Figure 4-1 shows the resulting current density j flowing due to the application of a dc voltage V between a chromium cathode and a stainless steel anode, in argon gas at two different pressures. Each electrode was 12.5 cm diameter, and the electrodes were 6.4 cm apart. Most of the space between the two electrodes is filled by a bright glow known as the *negative glow*, the result of the excitation and subsequent recombination processes we discussed in Chapter 2. Adjacent to the cathode is a comparatively dark region known as the *dark space*. This corresponds to the sheath formed in front of the cathode; there is a similar sheath at the anode, but it is too thin to clearly see.

In this chapter, we shall be looking at dc discharges. These are somewhat easier to begin to analyze than rf discharges, although they are still extremely complex and we certainly don't understand all the details. Fortunately, much of what we learn can also be applied to rf systems.

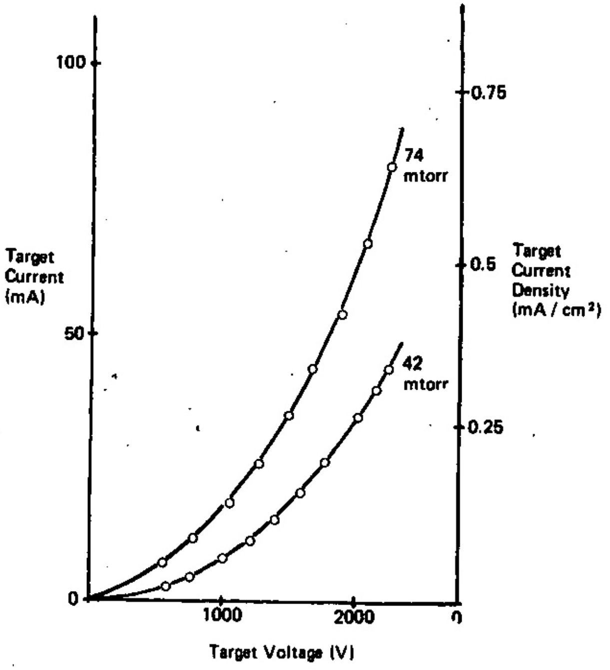

Figure 4-1. I-V characteristics for chromium sputtering in argon (Chapman 1975)

Many textbooks show a whole series of glowing and dark spaces in dc discharges. Figure 4-2 is from Nasser (1971); virtually the same figure appears in Cobine (1958), von Engel (1965) and doubtless many other texts. The *positive column* is the region of the discharge which most nearly resembles a plasma, and most of the classic probe studies have been made on positive columns. It is found that, when the two electrodes are brought together, the cathode dark space and negative glow are unaffected whilst the positive column shrinks. This process continues so that eventually the positive column, and then the Faraday dark space, are 'consumed', leaving only the negative glow and dark spaces adjacent to each electrode. This last situation is the usual case in glow discharge processes (Figure 4-3), where the inter-electrode separation is just a few times the cathode dark space thickness. The minimum separation is about twice the dark space thickness; at less than this, the dark space is distorted and then the discharge is extinguished.

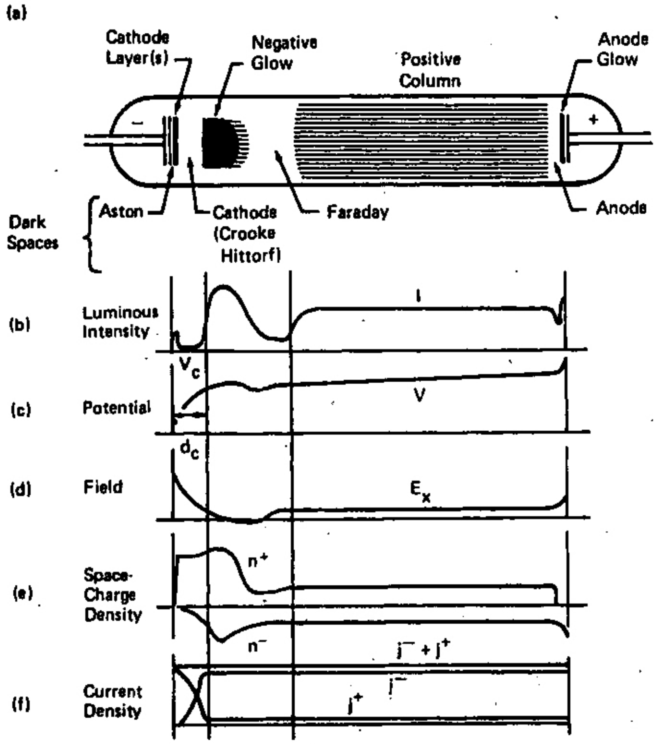

Figure 4-2. The normal glow discharge in neon in a 50 cm tube at p = 1 torr. The luminous regions are shown shaded (Nasser 1971). The abnormal glow would be somewhat different, although the glowing and dark regions would look the same

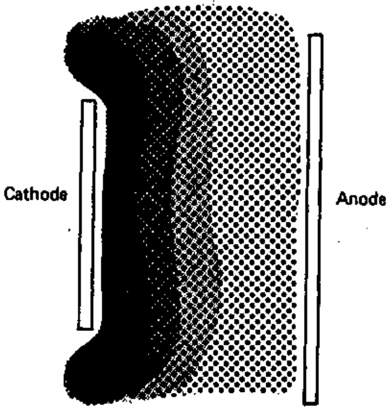

Figure 4-3. DC glow discharge process

Since current must be continuous in a system, it is clear that the currents at the two electrodes must be equal. In this particular system, the only other grounded electrode was remote from the discharge and had a small surface area; thus, the current densities at the chromium cathode and stainless steel anode were approximately equal. Take a typical datum point, which might be 2000V and 0.3 mA/cm^2 at 50 mtorr. This represents an electron current density to the anode that is much smaller than the random current density $\frac{1}{4}en\bar{c}_e$ and so there must be a net decelerating field for electrons approaching the anode, i.e. the plasma is more positive than the anode. But there is still some electron current flowing, so apparently the anode is more positive than floating potential. We earlier calculated a 'reasonable' floating potential 15V less than the plasma potential, and this is consistent with commonly found values of $V_p \sim +10V$ (with respect to a grounded anode) in dc sputtering systems.

The plasma is virtually field-free, as we saw earlier, so the plasma has the same potential V_p adjacent to the sheath at the cathode. But the cathode has a potential of -2000V, so the sheath voltage is $-(2000 + V_p)$, i.e. -2010V in our example (Figure 4-4).

Notice some peculiarities about this voltage distribution:

1. The plasma does *not* take a potential intermediate between those of the electrodes, as might first be expected. This is consistent with our earlier contention that the plasma is the most positive body in the discharge.
2. The electric fields in the system are restricted to sheaths at each of the electrodes.
3. The sheath fields are such as to repel electrons trying to reach either electrode.

All of these peculiarities follow from the mass of the electron being so much less than that of an ion. The third, in particular, is illustrative of the role played by electrons in a discharge.

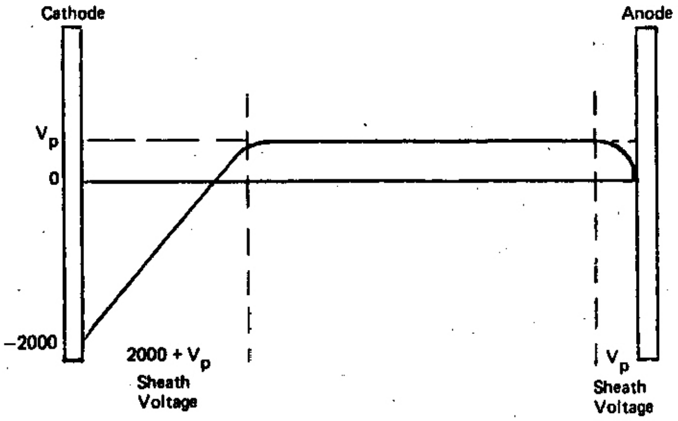

Figure 4-4. Voltage distribution in a dc glow discharge process

MAINTENANCE OF THE DISCHARGE

How is this glow discharge sustained? Electrons and ions are lost to each of the electrodes and to all other surfaces within the chamber. The loss processes include electron-ion recombination (which takes place primarily on the walls and anode due to energy and momentum conservation requirements, as we saw in Chapter 2), ion neutralization by Auger emission at the target, and an equivalent electron loss into the external circuit at the anode. To maintain a steady state discharge, there must be a numerically equal ion-electron pair generation rate; i.e. there must be a good deal of ionization going on in the discharge.

There is also a considerable energy loss from the discharge. Energetic particles impinge on the electrodes and walls of the system, resulting in heating there; this energy loss is then conducted away to the environment. So another requirement for maintaining the discharge is that there is a balancing energy input to the discharge.

THE CATHODE REGION

The type of dc discharge used in glow discharge processes is known as an *abnormal glow discharge*. At lower applied voltages and consequent lower currents, a discharge can result which is characterized by constant voltage and constant current density. This is a *normal glow discharge*. More power applied to the system is manifested by an increase in the size of the region of the cathode carrying current (j and V remaining constant) until the whole cathode is utilised, at which stage the discharge becomes abnormal. We shall not consider normal discharges further in this book.

The cathode plays an important part in dc sputtering systems because the sputtering target actually becomes the cathode of the sputtering discharge. The cathode is also the source of secondary electrons, as we have seen, and these secondary electrons have a significant role both in maintaining the discharge and in influencing the growth of sputtered films.

When the formation of sheaths was being considered in Chapter 3, we made the assumption that there were no collisions in the sheath. Many books and papers on plasma physics are concerned specifically with *collisionless plasmas*, but this is because most current interest is in plasmas which have very high temperatures of many keV, and these are essentially collisionless; such plasmas are of interest in fusion. 'Our' plasmas are very different and do have lots of collisions, both in the sheaths and in the glow. In a moment we shall look at some of these collision processes.

As already pointed out, in trying to understand the mechanisms by which a discharge is sustained, it is clearly necessary to account for all the recombination and energy loss processes which occur (Figure 4-18). We could simplify the situation for analysis purposes by considering a discharge between very large electrodes close together, which is usually the case in high pressure planar diode plasma etchers (see Chapter 7) and some sputter deposition systems (see Chapter 6). Unfortunately I don't have any quantitative data for this dc situation, but the data in Figure 4-1 should be reasonably representative.

To return to our example in "Architecture of the Discharge", a current density of 0.3 mA/cm^2 means that net currents of 1.9 10^{15} ions/cm^2 and 1.9 10^{15} electrons/cm^2 are flowing each second to the cathode and anode respectively. The ion flux at the anode should also be about 1.9 10^{15}/cm^2 sec, as we discussed in Chapter 3. So if we ignore the small electron current at the cathode due to secondary electron emission, and ion-electron recombination at the walls and in the gas volume, then we need an ion-electron pair production rate of at least 3.8 10^{15} ions per second for each cylinder of discharge emanating perpendicularly from the cathode and having 1 cm^2 cross-sectional area.

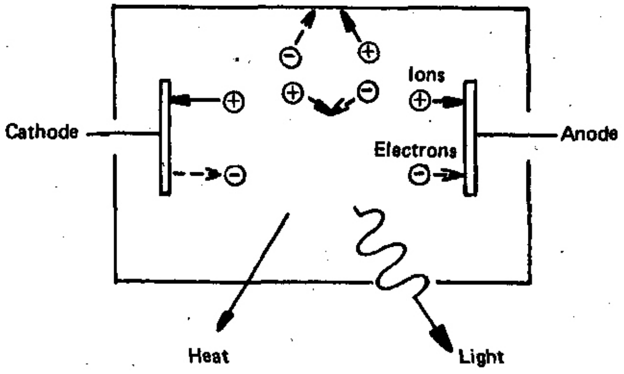

Figure 4-18. Discharge loss processes

Ionization In The Sheath

Electron Impact Ionization

Some descriptions of the glow discharge process rely on ionization caused by secondary electrons from the target as they are accelerated across the dark space (Figure 4-19). This can be modelled by considering the amount of ionization caused by a flux $N_e(x)$ electrons passing through a thin slab of thickness Δx located x from the cathode (Figure 4-20). The density of neutrals is n and the ionization cross-section (assumed energy-independent for simplicity) is q.

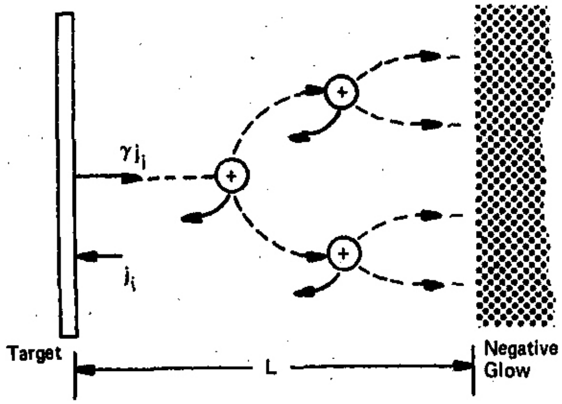

Figure 4-19. Ion pair production in the dark space

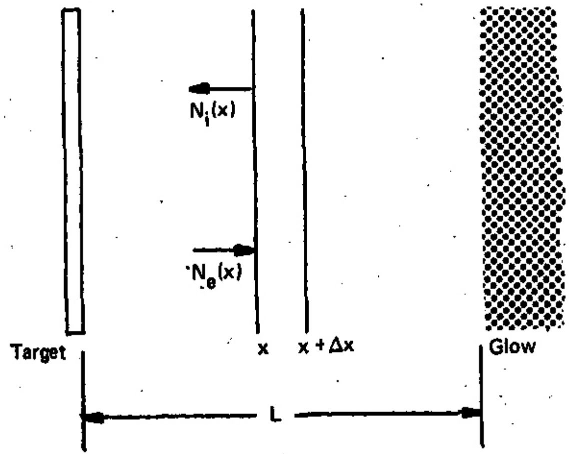

Figure 4-20. Analysis of ion pair production in the dark space

Structure of the Anode Sheath

In Chapter 3, we saw how a small sheath must be set up in front of the anode, of sufficient magnitude to repel some of the random flux $\frac{1}{4} n_e \overline{c_e}$ of electrons and reduce the current density at the anode to a more practical value. Our model of the sheath was essentially the same as that in front of a floating substrate (Chapter 3, "Sheath Formation at a Floating Substrate") except that the sheath voltage isn't as large at the anode. Later in Chapter 3, we needed to involve a pre-sheath or transition region to satisfy the Bohm criterion, and we expect this to apply to the anode too. The anode sheath is found to be so thin, usually about an order of magnitude less than the cathode sheath, that it should be essentially collisionless – and in particular not a source of ionization, which was tenuous even in the much thicker cathode sheath.

The anode sheath won't be very different from that in our derivation of Debye shielding. The Bohm criterion requires the ions to enter the sheath with an energy of about kT_e/e, and they then accelerate through the anode sheath to reach energies of 10 - 15 eV. The energy increase of a factor of 3 - 10 is equivalent to a velocity increase of $\sqrt{3} - \sqrt{10}$, and an inverse change in ion density. The main point is that the ion density is not far from the uniform density assumed in the Debye sheath derivation, and does not vary anywhere near as much as in the cathode sheath. At the same time, the sheath voltage is small enough that the electron density does not go to zero as in the cathode sheath. The net result is that the anode sheath consists primarily of a pre-sheath and a Debye-like region.

Energy Dissipation in the Discharge

In order to clarify a couple of terms that I shall use, consider one of the 'water splash' rides that one sees at fairgrounds (Figure 4-30a). Having been mechanically raised, the boat accelerates rapidly down a ramp so that it acquires kinetic energy as it loses potential energy; let's say that a lot of kinetic energy is *generated* in the ramp. The boat then hits the water and is quickly slowed down as its energy is *dissipated* by transfer to the water. Note that no energy is generated in the water trough since it is level.

Let's see if we can apply some of these ideas to the discharge. There are three regions to consider: the sheaths at cathode and anode, and the glow itself. Using the values in our example again, we need at least $3.8\ 10^{15}$ ions produced per second per cm^2. Each ionization step requires a minimum energy of 15.7 eV, whether by one-step or two-step processes. The minimum energy consumption is therefore $3.8\ 10^{15}\ x\ 15.7$ eV/sec cm^2, which is equal to $3.8\ 10^{15}\ x\ 15.7\ x$ $1.6\ 10^{-19}$ joules/sec cm^2, or 9.6 $\mathrm{mW/cm}^2$. In practice, the electron energy loss per ionization is more than 30 eV since the collision products also have some kinetic energy, and there will be many more ionizing collisions than $3.8\ 10^{15}/$ cm^2 sec to account for wall losses. There will also be further energy losses due to the inelastic collisions producing excitation. If, as seems likely, most ionization occurs in the glow, then the power consumption there (requiring an equivalent amount of dissipation) will be at least 9.6 mW/cm^2, and probably several times this value. The glow region is rather like the water trough in the analogy, except that the glow does have some electric field across it. We have already seen that the glow should be equipotential within a few kT_e/e, and this appears to be consistent with measurement; Brewer and Westhaver (1937) found values of just a few volts. Let's assume 10 V across the glow. The current through the glow in our example is 0.3 mA per cm^2 of the target. These values give a power generation in the glow of 3 mW/cm^2, considerably less than even the very minimum value of 9.6 mW/cm^2 which must be dissipated there.

Where does this energy come from? The main power generation in the discharge is in the cathode sheath, and amounts to 2010 x 0.3 mW/cm^2, i.e. 603 mW/cm^2. Most of this goes into kinetic energy of ions and subsequently into heating of the cathode. We won't be far wrong by assuming a collisionless sheath and a secondary electron coefficient of $\gamma = 0{\cdot}1$, so that 10% of the current is carried by electrons. In the absence of collisions, these electrons enter the glow with a kinetic energy equivalent to the cathode sheath voltage, and so inject 60 mW/cm^2 of power into the glow, notably adequate to account for the ionization required with power to spare. The excess power is consistent with the observation that some fast electrons lose very little or no energy in the glow and hit the anode at high velocity. We shall see some evidence of this in Chapter 6, when we look at sputtering. It's as though the water trough in our analogy was not completely efficient in arresting the motion of the boats, so that some boats hit the end wall with considerable velocity even in the presence of a 'braking' hill (Figure 4-30b). I now understand my fear of such amusements! Notice the similarity between Figures 4-29 and 4-30b.

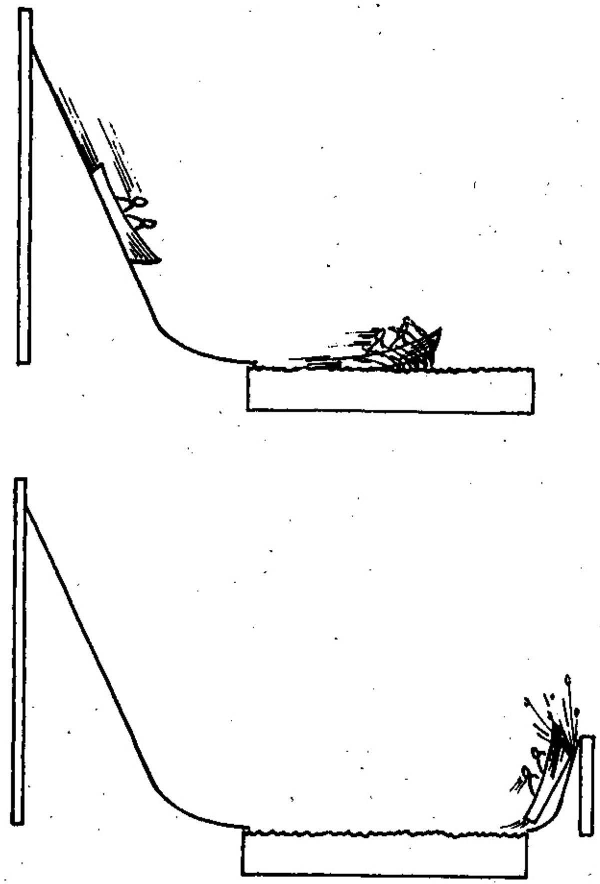

Figure 4-30. The water splash