

Most plasmas are characterized by a glow. The specific color depends on the type of gas that is involved. This glow can be used as a diagnostic tool. However, to do this, we need to understand how the glow occurs.

The light emitted from a plasma comes from a variety of sources. The most common is the de-excitation of electronic states in atoms and molecules. The light from this process typically ranges from the deep Ultra Violet (~ 200 nm) or even x-ray (< 100 nm) to the mid-infrared ($\sim 5 \mu\text{m}$). Other sources of light are from de-excitation of atomic bonds in molecules. These bonds are subdivided into rotational and vibrational bonds. The light from this process typically runs from the near infrared ($\sim 1 \mu\text{m}$) to the microwave (~ 1 cm) range. This will be discussed below.

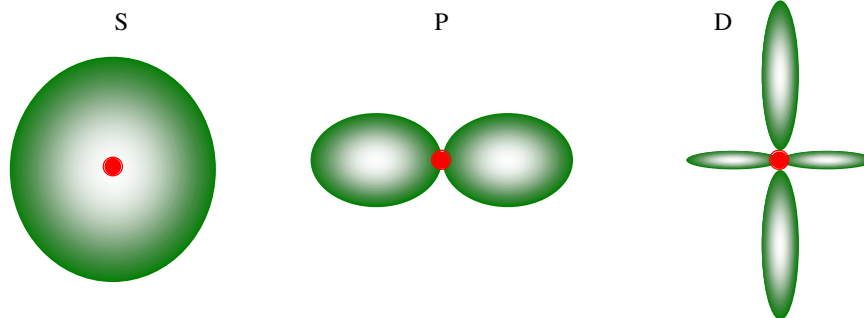
To start, we will consider the simplest, and most obvious source of light from plasma. It is the most obvious because it is in the region that we see. For the purposes of this discussion, we will only consider transitions in atoms.

Electronic Transitions

By Quantum Mechanics, atoms consist of the nucleus, which contains the proton and neutron, and a cloud of electrons that orbit the nucleus.

The internal working of the nucleus is unimportant for our purposes. (If perhaps we were in the regime in which the internal workings of the nucleus were important, the energies of the plasma would be too high to do any reasonable processing, as the plasma system would be ripped to shreds. Such high energies are needed in plasma fusion and the chief problem that is encountered is the destruction of the vacuum system walls.)

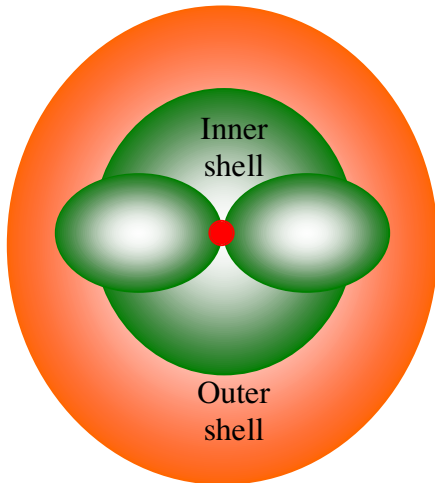
The orbits of the electrons, on the other hand, are important to our process. In general the orbits of the electrons has a series of basic shape, some of which look like:



Various electrons in the orbit of the nucleus have one of these – or a few other – orbital patterns.

In addition, variations in radial distances at which the electrons orbit, known as shells are also very important to our process. The different shells are labeled 1, 2, 3, etc., with the shell with the smallest radius being labeled '1', the next '2' and so on. For atoms with multiple electrons, all of the orbitals might look like the following:

(It should be understood that the electrons do not follow well described paths but rather act as if they are all over the place – like a wave which does not have a specific location. This is part of the particle – wave duality found in quantum mechanics. All things can be described as either a wave or as a particle. Each description can be used to help understand some aspects of the process. For the most part, we will use only the particle aspect of the process.)



Each of the S orbitals can contain up to two electrons in each shell, each of the P orbitals can contain up to 4 and each of the D orbitals can contain up to 8 electrons.

In general atoms, like all items in the universe, like to be at the lowest possible energy state. This is known as the 'ground state'. Each of these orbits also has a specific energy associated with it. In general – BUT NOT ALWAYS! – the S orbit is at a lower energy than the P, which is lower than the D. However, these energy differences are typically – but again not always! – smaller than the energy differences between shells. One of the exceptions for reaching the ground state is when an atom reaches a 'metastable' state. Such states are typically near the ground state but there is no allowed transition between the state and the ground state. Metastable atoms might survive in that state for several seconds, whereas the typical transition time for most states to lower states might be on the order of 10 ns.

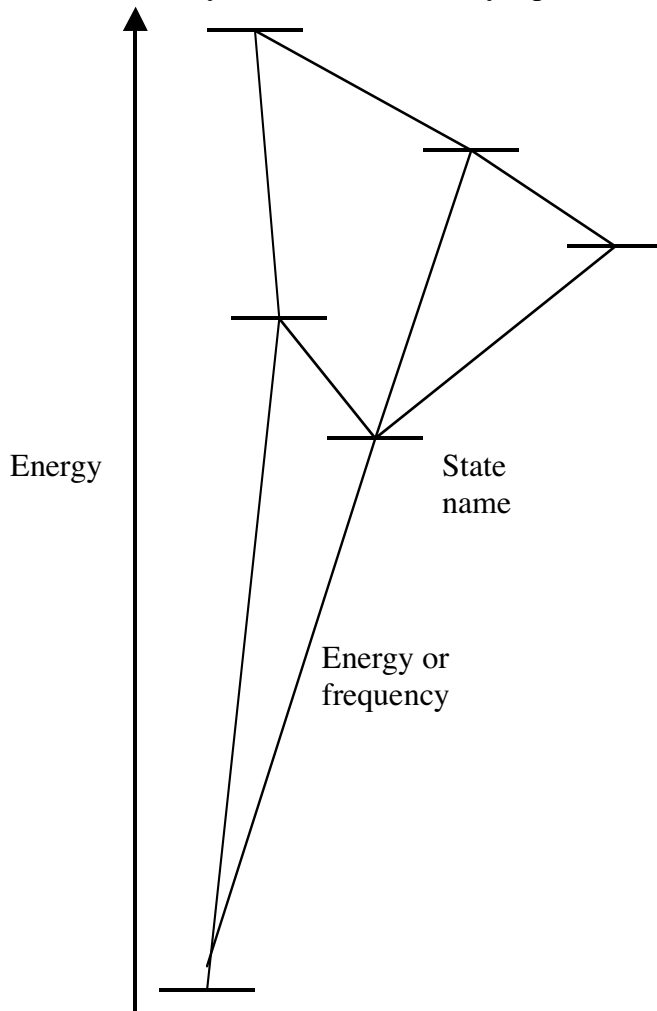
When the electrons in an orbit drop to a lower energy state they do so by giving up energy, through the creation of a photon. This process is known as going through a 'transition'. It is these photons that we see as the glow in our glow discharge. There are very specific rules governing which transitions are acceptable. In general only transitions that go from one shell to another are allowed. In addition, there are limits on transitions between various shaped orbitals. Finally, the higher the shell, in general the less the separation in energy between shells.

The energy drop that an electron might have can be anywhere between fairly small (< 0.001 eV) for transitions between very high shells and the ionization energy, the highest to lowest orbitals, which is typically 10 to 20 eV. Because these orbitals are at very specific energy levels, this gives us a very discrete set of photon energies (or frequencies)

or wavelengths) that can be produced by an atom. Further, because of our energy range, we have in general a range of possible photons that runs from \sim x-ray (100 nm) to \sim mid IR ($5 \mu\text{m}$). The exact range is of course species dependent.

Cascading transitions

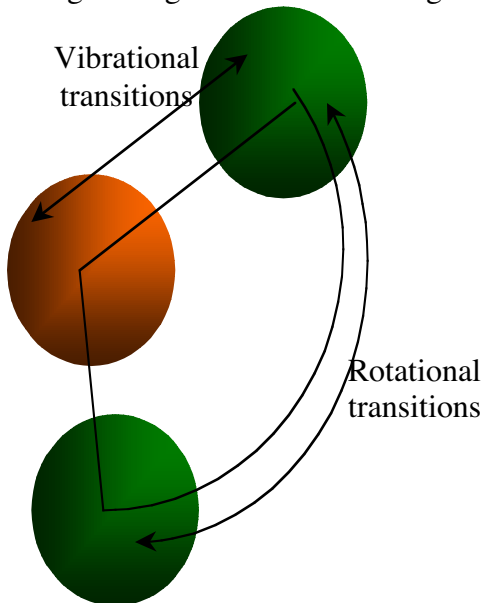
If we have an atom in an excited state, the transition to ground typically involves a multi-step process. Sometimes this is because the transition directly to ground is not allowed, sometimes because, by chance, the atom has decayed to a different state. Most of the lower energy allowed transitions, and certainly all of the common transitions for atoms have been cataloged in what are called Grotrian diagrams. (Perhaps the best set is in a series of books by Bashkin and Stanley (sp?).) These diagram will look like:



As can be seen, it is both possible and likely that an excited state will decay through several channels. In additions, it is possible and likely that an excited state may be populated through decay from several higher states.

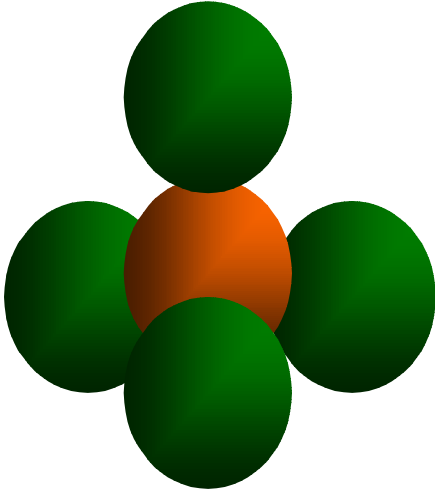
Vibrational/Rotational Transitions

Vibrational and rotational transitions only occur in molecular species. These transitions are due to changes in the binding energy between two – or more – atoms in the molecule. While it is the change in the binding energy that is truly important, this binding energy can come in many forms. Any individual atom in a molecule is interacting with all other atoms in the molecule. It has been shown that there is a limit on the number of way in which all of the individual atoms can interact with all of their neighbors. This limit is set by ‘the degrees of freedom’. In essence a degree of freedom is obtained is there is a change in the molecule (internal or external) that can be arrived at by some movement of part of the molecule. However, if there is a second way to get to the same change in the molecule, this is not a new degree of freedom. Perhaps a better definition is what is the minimum number of coordinates does one need to describe all of the possible positions of the molecule. This is not unlike having the coordinate system X,Y,Z. I can move in the X direction without changing anything in the Y or Z directions. If I where to now study a top (or a ball) I would have to add rotational coordinates to describe all of the possible changes. A general molecule might look like:



This is a picture of a water molecule. It has two degrees of freedom, the angle between the H atoms and the distance between an H atom and the O atom. (Any movement by the second H atom is going to be identical to what the first H atom does.)

More complex atoms have more degrees of freedom. A common shape seen in nature is shown below.



Notice that this molecule has a certain amount of symmetry to it. (This is the shape of Ammonia, NH_3 , and CF_4 , what used to be a common process gas.) However, there are more ways in which we can adjust the shape, than that observed for the H_2O molecule.

Now the typical binding energy between atoms is ~ 0.5 to ~ 3 eV. These changes in shape account for a very small part of that energy. Thus we find that these transitions produce photons with energy on the order of 0.001 or less. This means that the wavelength of the photons is ~ 1 μm or longer – up into the microwave region, ~ 1 cm.

Producing the glow

To create the glow we need some process in which we create excited atoms and electrons. How these excited particles are created depends significantly on the amount of energy required to produce the transition. For example, electronic excited states are typically several eV higher than the ground state of an atom or molecule. To raise the electron to a higher energy state we typically need to have an outside particle collide with the atom/molecule and give up translational (kinetic) energy to internal energy. There are not that many particles in the plasma with sufficient energy to provide to such a process. Typically only the electrons have enough kinetic energy. On the other hand, excited rotational or vibrational states are $\ll 1$ eV above the ground state. Most particles have sufficient kinetic energy to produce such a change. Thus most particles can cause the production of excited states in our atom/molecule.

Electron collision excitation collisions with atoms/molecules occur on a time scale associated with the electrons motion. We know from before that a given electron will collide, on average, with an atom every mean-free path. Thus we have for a given electron,

$$\lambda_{\text{mfp}} = \frac{1}{\sigma n_n}$$

where σ is the cross section for exciting the atom into a given energy state and n_n is the neutral density. We can rewrite this to look at an average rate at which our test electron will collide with our atoms. This time between collisions is

$$\tau = \frac{\lambda_{\text{mfp}}}{\langle |v| \rangle}$$

$$= \frac{1}{\sigma n_n \langle |v| \rangle},$$

We know that the average speed is given by

$$\langle |v| \rangle = \left(\frac{8kT}{\pi m} \right)^{1/2}$$

so that

$$\tau = \frac{1}{\sigma n_n} \left(\frac{\pi m}{8kT_e} \right)^{1/2}.$$

We see that the time is dependent on the temperature of the electrons. Now when we are looking at our plasma we have a lot of electrons that at causing excitation events. The rate-density, e.g. the number per time per volume, is given by

$$f = \frac{1}{\tau n_e}$$

$$= \sigma n_n n_e \left(\frac{8kT_e}{\pi m} \right)^{1/2}$$

This means that our plasma is going to produce glow at this rate per unit time per unit volume.

At this point we can begin to develop some simple theory for how a dc glow works. While this is truly an electron by electron process, we can model the growth in the electron density as we cross the discharge as

$$\frac{dn_e}{dx} = \alpha n_e$$

or

$$n_e = n_{ec} e^{\alpha x}$$

All that this says is that the electron density growth is proportional to the number of electrons that pass through an area. This is fairly reasonable. Here, the proportionality constant, α , is known as the first Townsend coefficient, while n_{ec} is the electron density at the cathode edge. What do we know about α ? Not much. However, through other means, we can show that α can be determined from:

$$\alpha = \frac{1}{\lambda_{\text{mfp}}} e^{-V_i/E\lambda_{\text{mfp}}}$$

where eV_i is the energy required to produce an ionization event, E is the electric field strength and λ_{mfp} is of course the mean-free path. Motivationally one can understand this in the following manner. New electrons can only be produced in a mean-free path so that the spatial rate-of-change must be as such

$$\frac{dn_e}{dx} \propto \frac{n_e}{\lambda_{\text{mfp}}}$$

Further, only those electrons which gain energy in excess of the ionization energy can produce new electrons. This is simply

$$n_e|_{\mathcal{E} > eV_i} = n_e e^{-V_i/E\lambda_{\text{mfp}}}$$

Recalling that the mean-free path is

$$\lambda_{\text{mfp}} = \frac{1}{\sigma n_n}$$

and the ideal gas law states

$$p = n_n k T_n$$

so that

$$\alpha = \sigma \frac{p}{k T_n} e^{-V_i \sigma p / k E T_n}$$

For the most part T_n is roughly a constant (room temperature or there about), σ is roughly a constant (assuming small variations in electron energies), and V_i and k are constants. Combining all of these ‘constants’ we get

$$\alpha = A p e^{-B p / E}$$

These ‘constants,’ A and B , as well as V_i and γ , have been determined for a large number of gasses, some of which are given below [von Engel, *ibid*] and [J.D. Cobine, *Gaseous Conductors*, (Dover, New York, 1958).]

Species	V_i (V)	A ($\text{m}^{-1} \text{mTorr}^{-1}$)	B ($\text{V m}^{-1} \text{mTorr}^{-1}$)	γ (Major ion on Fe)
H ₂	15.4	0.54	14	
He	24.6	0.28	3.4	0.015
N ₂	15.8	1.2	34	
Ne	21.6			0.022
Ar	15.8	1.2	18	0.058
Air	~13	1.5	36	0.02

To understand when the plasma might turn on we need to consider the total current through the system. This is simply the sum of the ion current and the electron current. For simplicity we will first consider the current at the cathode – noting that the current must be constant across the system if we are not building up charge in a location.

$$\begin{aligned} J_c &= J_{ic} + J_{ec} \\ &= J_{ic} + J_{e0} + J_{es} \end{aligned}$$

Here J_c is the total current at the cathode, J_{ic} is the ion current at the cathode, J_{ec} is the electron current at the cathode. We can further break down the electron current into

electrons arising from secondary emission, J_{es} and ‘others’, J_{e0} . Before the plasma is turned on, this ‘other’ electron current might be fairly large, while after it is on, it is meaningless. Now the secondary electron current is proportional to the ion current, with γ being the proportionality constant. Thus

$$\begin{aligned} J_c &= J_{ic} + J_{e0} + \gamma J_{ic} \\ &= (1 + \gamma)J_{ic} + J_{e0} \\ &= (1 + \gamma^{-1})J_{es} + J_{e0} \end{aligned}$$

Now let us consider the current at the other end, J_a . By conservation of charge this must be the same as the current at the anode. In addition, because of the bias, not very many ions will reach the anode. Thus

$$J_c = J_a \approx J_{ea}$$

We now make use of our density variation, and assume that the average velocity of the electrons does not change across the system. This implies that

$$\begin{aligned} J_{ex} &= -e \langle v_e \rangle n_e \\ &= -e \langle v_e \rangle n_{ec} e^{\alpha x} \\ &= J_{ec} e^{\alpha x} \\ &= (J_{es} + J_{e0}) e^{\alpha x} \end{aligned}$$

so that at the anode edge we find

$$J_{ea} = (J_{es} + J_{e0}) e^{\alpha d}$$

Comparing this with the current to cathode, remember

$$J_{ea} \approx J_c,$$

we find that

$$\begin{aligned} (J_{es} + J_{e0}) e^{\alpha d} &\approx (1 + \gamma^{-1}) J_{es} + J_{e0} \\ &\Downarrow \\ J_{es} (e^{\alpha d} - 1 - \gamma^{-1}) &\approx (1 - e^{\alpha d}) J_{e0} \\ &\Downarrow \end{aligned}$$

$$J_{es} \approx \gamma \frac{(e^{\alpha d} - 1)}{(1 + \gamma(1 - e^{\alpha d}))} J_{e0}$$

Plugging this back into the equation for the anode current we find

$$\begin{aligned}
J_{ea} &= \left(\frac{-\gamma(1-e^{\alpha d})}{(1+\gamma(1-e^{\alpha d}))} + 1 \right) e^{\alpha d} J_{e0} \\
&= \left(\frac{-\gamma(1-e^{\alpha d})}{(1+\gamma(1-e^{\alpha d}))} + \frac{(1+\gamma(1-e^{\alpha d}))}{(1+\gamma(1-e^{\alpha d}))} \right) e^{\alpha d} J_{e0} \\
&= \left(\frac{1}{(1+\gamma(1-e^{\alpha d}))} \right) e^{\alpha d} J_{e0}
\end{aligned}$$

This says that the current to the anode (or for that matter to the cathode) is dependent on γ , α and d . Further, this model assumes that there is a current flowing from the region of the cathode that spontaneously appears. This is what one might expect through the random existence of free electrons – e.g. BEFORE THE PLASMA IS IGNITED! (If the plasma were ignited, then the random free electrons that do occur would be small in number in comparison to the secondary electrons. In that case we could ignore J_{e0} . Further our electric field is no longer uniform and thus our model fails!) Under certain conditions, J_{ea} will suddenly spike – we have ignited the plasma. Mathematically this is when J_{ea} goes to infinity. (The model is really only good for very small currents!) This happens when the denominator of the above equation goes to zero,

$$1 = \gamma(e^{\alpha d} - 1) \text{ or}$$

$$\frac{1+\gamma}{\gamma} = e^{\alpha d}$$

At this point we know that the secondary emission coefficient is a number dependent on the surface material, ion type and ion energy, while α is given above as

$$\alpha = Ape^{-Bp/E}$$

Plugging this in we find that

$$\ln\left(\frac{1+\gamma}{\gamma}\right) = \alpha d$$

$$= pdAe^{-Bp/E}$$

↓

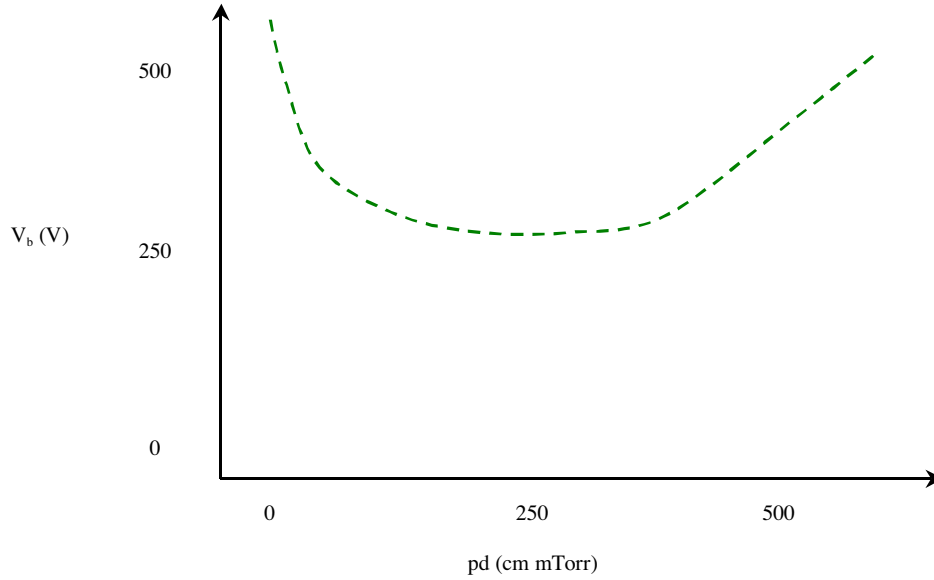
$$Bp/E = -\ln\left(\frac{1}{pdA} \ln\left(\frac{1+\gamma}{\gamma}\right)\right) \text{ but } E = V_b/d$$

↓

$$V_b = Bpd \left(-\ln\left(\frac{1}{pdA} \ln\left(\frac{1+\gamma}{\gamma}\right)\right) \right)^{-1}$$

where V_b is voltage applied between the cathode and anode at which breakdown occurs. This says that the breakdown voltage depends primarily on the pressure times the

distance. If one were to do an experiment, measuring V_b vs. pd , one would find a curve such as



The minimum in the curve is found at

$$\frac{dV_b}{d(pd)} = 0 = B \left(-\ln \left(\frac{1}{pdA} \ln \left(\frac{1+\gamma}{\gamma} \right) \right) \right)^{-1} - B \left(-\ln \left(\frac{1}{pdA} \ln \left(\frac{1+\gamma}{\gamma} \right) \right) \right)^{-2}$$

⇓

$$1 = \left(-\ln \left(\frac{1}{pdA} \ln \left(\frac{1+\gamma}{\gamma} \right) \right) \right)$$

⇓

$$e^{-1} = \frac{1}{pdA} \ln \left(\frac{1+\gamma}{\gamma} \right)$$

⇓

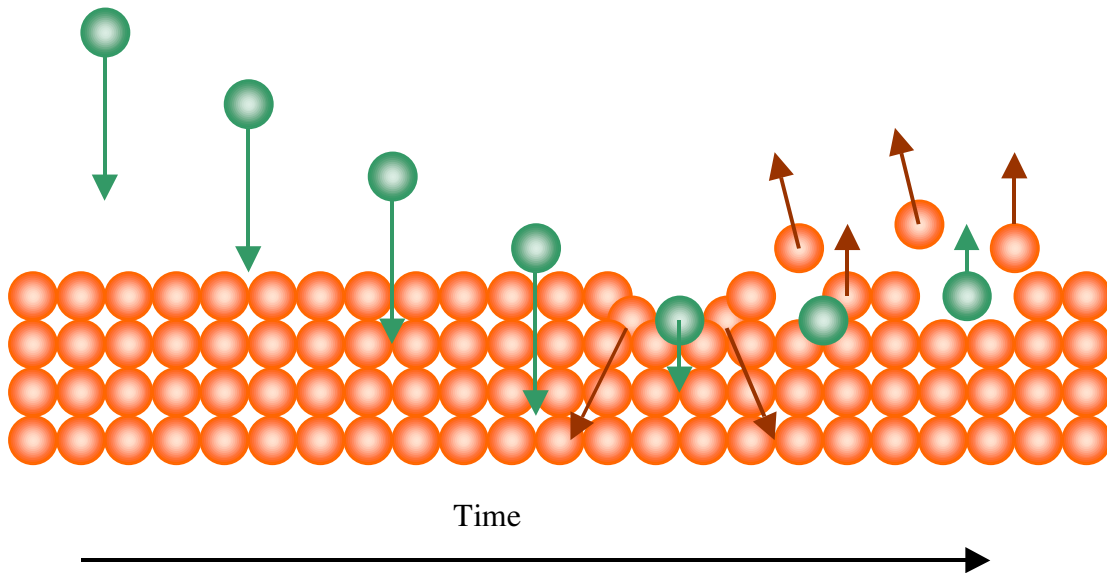
$$pd|_{\min} = \frac{e^1}{A} \ln \left(\frac{1+\gamma}{\gamma} \right)$$

Plugging this back in to our expression for the breakdown voltage we find

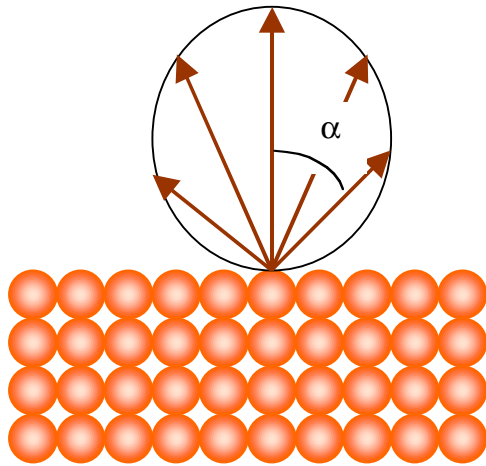
$$\begin{aligned} V_b|_{\min} &= B \frac{e^1}{A} \ln \left(\frac{1+\gamma}{\gamma} \right) \left(-\ln \left(\frac{1}{\frac{e^1}{A} \ln \left(\frac{1+\gamma}{\gamma} \right) A} \ln \left(\frac{1+\gamma}{\gamma} \right) \right) \right)^{-1} \\ &= B \frac{e^1}{A} \ln \left(\frac{1+\gamma}{\gamma} \right) \end{aligned}$$

Sputtering Magnetrons

Now, we can begin to discuss Magnetrons. The primary use of sputtering magnetrons is of course, to sputter material from the target to the deposition surface. Sputtering works not unlike hitting billiard balls with a cue ball. (These are also known as pool balls.) Physically this looks like:

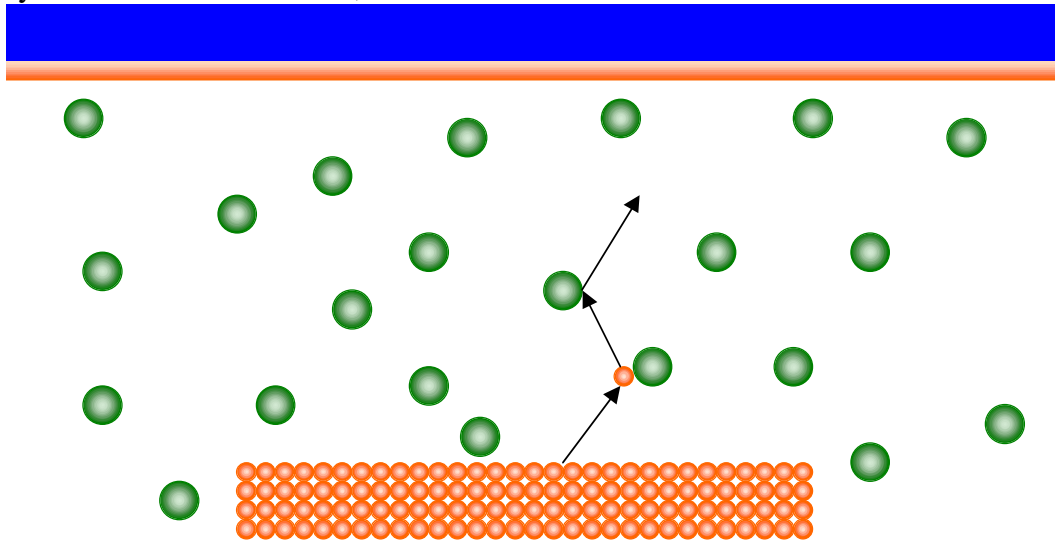


In general the sputtered atoms come off in a 'cos' distribution, where the 'angle' is that measured from the normal. (This is not exact but it provides a useful approximation.)

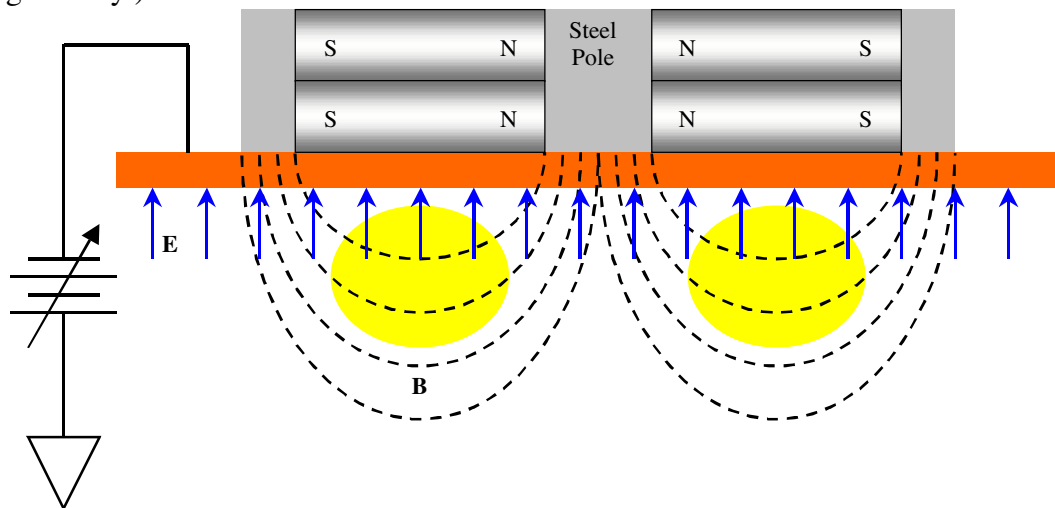


The target atoms that are sputtered off of the cathode target now fly across the plasma chamber, sticking to whichever surface they strike. (It is possible for the sputtered atoms to 'bounce' once or twice when they hit the next surface but this is somewhat usual.) If one assumes hard sphere collisions, one can calculate an approximate uniformity. The one problem that occurs is that the more uniform the deposited layer, the more the sputtered atoms are scattered all over the system. This means that a large fraction of sputtered atoms are wasted in the process and hence the more often the target needs to be

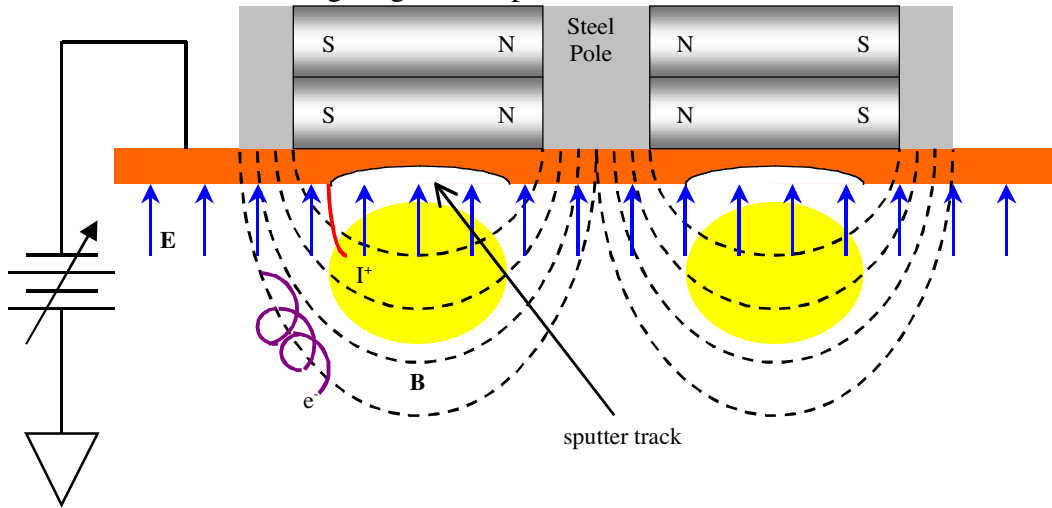
replaced. (THIS IS NON-TRIVIAL!) In addition, this also means the more often the system needs to be cleaned, which is also non-trivial.



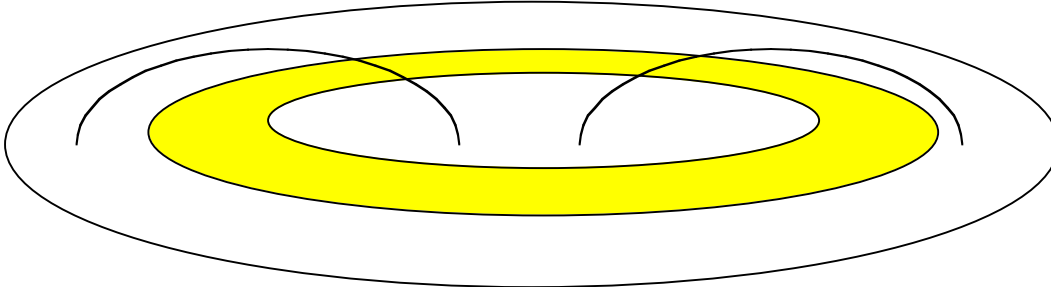
There are a large number of geometries that magnetrons are made in. All of them are characterized by crossed E and B fields. In some magnetrons, the magnetic field is produced by an electromagnetic while in others, permanent magnets are employed. (Permanent magnets are more common.) As can be seen in the picture, the plasma is effectively trapped between the magnetic and electric fields. (This is really only true for the electrons, which are ‘magnetized’ – meaning that the Larmour radius is small compared to the plasma size. The ions on the other hand are unmagnetized as their Larmour radius is large compared to the plasma size. This requires a small range of magnetic fields strengths, usually on the order of 200 to 500 G, as measured at the cathode surface where the B field is tangent to the surface. Smaller field strengths will result in too large of electron Larmour radii while Larger will result in too small of ion Larmour radii. (The exact range of useful magnetic fields depends on the system geometry.)



The motion of the ions and electrons is as follows. The net affect of the location of the plasma, with a large number of ions in one location over the next results in a sputter track that makes only a small part of the cathode useful. To over come this some manufacturers use moving magnets to spread out the track.



The most common is the planar type. It looks like the next figure below.



Planar magnetrons also come in ‘racetrack’ type magnetrons. These magnetrons are mostly used for coating large windows for skyscrapers. (The processing systems used for this typically are the size of one of the bays in the clean room.)



In addition, there are magnetrons that have moving magnets, so as to use the target to the maximum amount possible. (We will discuss this in a moment.) There are also magnetrons that are combined with hollow cathodes so as to ionize the atoms sputtered off of the target. This allows better control of the deposition process, particularly the fill of deep trenches. Note that this is known as iPVD, for ionized PVD.

Show pics from PhD Thesis

Discuss exb drift from TES and MJG

Discuss Ion temp from MJG and TES

LAB

This lab will involve measuring the pressure-current-voltage response curves of our dc-planar magnetron. Note that these curves are system dependant, e.g. while 'identical systems' will give very similar values, small changes such as different gas types can result in large changes in the results.

While we have attempted to take every reasonable precaution in the setup of this system, the power supply used in this lab is capable of causing instantaneous death. It puts out up to 5 A of current at 500 V – or 2.5 kW of power. If anything looks amiss or if you do not understand what you are doing – ask a UTD staff member, your TA or your professor. DO NOT OPERATE THE EQUIPMENT BY YOURSELF!

- 1) Turn on the breaker (left-hand back of the MDX).
- 2) Turn on the dc power supply and set it in the program mode. This amounts to turning the key to 'program'.
- 3) Set the right-hand display to 'actual' by depressing the 'actual' button.
- 4) Set 'ramp' to 0 minutes. (Hold down the 'ramp' button and turn the 'modify' knob until the right-hand display reads 0 minutes.)
- 5) Set the regulation mode to 'voltage' by depressing both the 'power' and the 'current' buttons simultaneously. The voltage supplied to the cathode will now be displayed in the right-hand meter. (Make sure that the meter is reading in 'Volts'.) Pressing the buttons individually gives either power or current regulation.
- 6) Set the left-hand display to current by depressing the 'current' button.
- 7) At this point you should change the set point on the voltage to zero. (You do not want to turn on the high voltage with out setting up the rest of the system. If it is massively miss-set, damaging arcs can occur between the cathode and the walls or anode.) This is done by pressing the 'level' button, turning the 'modify' knob and observing the right-hand display. (This can also be done with the set point button for the right-hand display – just be sure to set it back to 'actual'.)
- 8) Set the pressure in the chamber to that desired. For this lab, we will use 2, 5, 10, 20, and 50 mTorr for both Ar and N₂. (All of these pressures, except 50 mTorr, can be obtained with 50 sccm of gas flow. 50 mTorr requires 100 sccm of gas flow.)
- 9) Begin to raise the voltage until breakdown is reached. Record the voltage at which break down occurs. Note that the power supply puts out slightly above the set voltage if there is no plasma (or current to the cathode). As best possible,

- record the voltage just before the plasma turns on. This is known as the breakdown voltage.
- 10) Continue to raise the voltage until you reach 600 V or 2.5 A, whichever is first, recording the current at each bias. Please do not exceed 2.5 A as we wish to continue to use this target for a number of years.
 - 11) Reduce the voltage to the breakdown voltage and begin to drop the voltage until the plasma turns off. Record the currents and voltages.
 - 12) Estimate the size of the plasma and record. Note that this is a Doughnut shape and thus you will need a major diameter and a width. You will need these numbers to calculate the area of the plasma in the lab write-up.
 - A) Plot the P-V-I measurements for both gases.
 - B) Plot the P-V breakdown for both gases.
 - C) Why does the plasma persist at voltages below the breakdown voltage?
 - D) Why does the power supply operate at a voltage above the set point if the plasma is not present? (The power supply is specifically setup in this manner.)
 - E) How does the breakdown voltage depend on the pressure?
 - F) How does the breakdown voltage depend on the gas type?
 - G) Would contamination of the target have any influence on the P-V-I curves? If so why?
 - H) Reactive Physical Vapor Deposition, PVD, makes use of gas and metal combinations that react to form what are often dielectric surface layers. For example O_2 might be added to a system that is sputtering Al to deposit Al_2O_3 . What challenges might this entail for sustaining the discharge?
 - I) Calculate the mean free path, MFP, for the sputtered atoms (Cu for this lab) in each of the gases at each of the pressures. How does the MFP compare to the distance between the substrate and the cathode? What does this mean for uniformity of the deposited layer? What does this mean for the speed at which a layer is deposited?
 - J) Assume that each ion striking produces 0.1 secondary electrons and sputters three target atoms. Further assume that the plasma contacts the cathode uniformly over the region observed during the lab. (This should give you an ion/time/area estimate and a sputtered atom/time/area estimate.) The target starts with a surface thickness of approximately 5 mm. How long will the target last at the highest and lowest recorded currents? Estimate a kilowatt/hours lifetime of the target.

Gas type:	$V_{bd} =$	$V_{bd} =$	$V_{bd} =$	$V_{bd} =$	$V_{bd} =$
Voltage	2 mTorr	5 mTorr	10 mTorr	20 mTorr	50 mTorr
200					
210					
220					
230					
240					
250					
260					
270					
280					
290					
300					
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