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Application of RF Discharges to Sputtering

Abstract: The operation of rf discharges is described and the internal distribution of voltages is considered. The significance of this with respect to sputtering, particularly of insulators, is then discussed. An equivalent circuit for the discharge is presented and the influence of such parameters as pressure and magnetic field on the components of this circuit is described. Finally, energy distributions for positive ions, electrons, and negative ions incident at the substrate during deposition are given.

Introduction

The first recorded observation that material is removed from the walls of a glass tube if it is subjected to a high frequency discharge excited through external electrodes appears to have been made by Robertson and Clapp in 1933.[1] In a follow-up investigation of their work, Hay[2] recognized that the removal of material was due to sputtering and that this occurred only if the frequency used was sufficiently high, although the reason for this was not understood. Some ten years later, Lodge and Stewart[3] provided further evidence that the material was removed through sputtering and associated the latter with the appearance of a negative charge on the surface of the insulator underneath the high frequency electrode. In 1957 Levitskii[4] made probe and ion energy measurements as well as limited sputtering studies in a high frequency discharge containing internal metal electrodes. In 1962 Anderson et al.,[5] pursuing an earlier suggestion by Wehner,[6] showed how the application of an rf voltage to the outside glass wall of a thermionically supported sputtering system could be used to effect cleaning of the inside of the tube and suggested that the method could be used for the deposition of insulating films. This general approach was subsequently developed by Davidse and Maissel[7,8] into a practical method for the deposition of insulating films at reasonable rates over substantial areas. They also showed that a triode system was not necessary and that apparatus resembling a dc sputtering system could be used.

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The radio frequency discharge

Consider a glass tube having two electrodes of equal area facing one another a reasonable distance apart. With the application of sufficient dc voltage, a discharge strikes and a dark space is seen at the cathode. The voltage difference between cathode and anode is dropped almost entirely across the dark space, leaving the glow space nearly field free. If, instead of dc, a low frequency alternating voltage is applied to this tube it is observed that the system behaves as though it had two cathodes, since a dark space is seen at both electrodes. In fact this system is really a succession of short-lived dc discharges of alternating polarity since, at these low frequencies, there is ample time for a discharge to become fully established within each cycle.

If the frequency of the applied voltage is increased, it is observed that the minimum pressure at which the discharge will operate is gradually reduced, the effect being detectable from about 50 kHz and leveling off for frequencies in excess of a few MHz. This indicates that there is an additional source of ionization other than the secondary electrons ejected from the electrodes. This source is electrons in the glow space that are heated as a consequence of the fact that electrons oscillating in a radio frequency field and making elastic collisions with gas atoms can acquire sufficient energy to cause ionization. The high voltage electrode that is essential in a dc glow discharge for the generation of secondary electrons is no longer needed to maintain the rf glow.

Since the applied rf field appears mainly between the two electrodes, an electron that escapes an appreciable distance from the inter-electrode space as a result of a random collision will no longer oscillate in the rf field and will therefore not acquire sufficient energy to cause ionization. Hence it will be lost to the glow. Because of this, a magnetic field parallel to the rf field can perform a valuable function in that it constrains the electrons and reduces their chance of being lost, particularly at lower pressures. While this increases the efficiency, per se, it also has other consequences which we will discuss presently.

Since the rf discharge is not dependent on secondary electrons from the electrodes, large electrode voltages are not necessary for maintaining the discharge. In addition, as pointed out by Levitskii,[4] the mechanisms by which electrons absorb energy from an rf field would not apply to the heavier ions, which would be expected to pick up relatively little energy from an rf field. At first glance one would not, therefore, expect an rf discharge to contain ions with sufficient energy to cause sputtering.

In practice, however, it is found that the glow space of an rf discharge (of the type under discussion) develops an appreciable positive potential relative to the two electrodes,[4] this potential difference appearing across the two dark spaces. This arises because the electrons have much higher mobility than the ions and so are very easily collected on an electrode whenever it becomes positive with respect to the glow space. This, in turn, causes depletion of electrons from the dark spaces with a consequent rise in potential of the glow space with respect to the electrodes. The magnitude of the potential acquired by the glow space is such that, through most of each rf cycle, no electrons can leave it. On the other hand, positive ions will be attracted to the electrodes, which they will reach after several rf cycles once they enter a dark space. Sufficient electrons to balance this relatively small ion current will flow from the glow space to the electrodes during the small fraction of the rf cycle when the potential difference between the glow space and the electrodes is a minimum. The *rf current* through the dark spaces is thus principally electron displacement current, only a small fraction being electron or ion conduction current. Thus, to a first approximation, rf coupling across the dark spaces is capacitive. Note, however, that the majority of the ions that do reach the electrodes have sufficient energy to cause sputtering.

The above discussion was for electrodes of equal area. Let us now consider a configuration in which one electrode is appreciably larger than the other. The relative capacitive coupling of the glow space to the two electrodes now changes, with the result that the potential of the glow space changes. However, no dc voltage differences can be maintained in the external rf circuit, so the dc bias voltages across the dark spaces at the two electrodes remain equal. Hence this configuration behaves as before; that is, it behaves as though the two electrodes had equal areas, and material is sputtered at the same rate per unit area from each electrode.

Let us now insert a capacitor somewhere in the external circuit.[9] The dc potential difference between the glow space and the smaller electrode is now no longer required to equal that at the larger electrode and it may, therefore, be significantly greater. A rough relationship for the ratio of the dc potential differences between the glow space and the two electrodes can then be derived as follows:

It is assumed that: (1) the current density of the *positive ions* is uniform and is equal at both electrodes, (2) the positive ions come from the glow space and traverse the dark spaces without making inelastic collisions, and (3) the capacitance across a dark space is proportional to the electrode area and inversely proportional to the dark space thickness. Then, based on assumption (2), the equation for space-charge limited ion current[10] applies:

$$j_i = KV^{\frac{3}{2}}/D^2M_i^{\frac{1}{2}},$$

where j_i and M_i are the current density and mass of ions respectively, K is a constant, V is the voltage across the dark space, and D is the thickness of the dark space. With assumption (1), the above equation gives

$$D_1/D_2 = (V_1/V_2)^{\frac{3}{4}},$$

where D_1 and D_2 are the thicknesses of the dark spaces and V_1 and V_2 are the dc bias voltages across them. Capacitive division of rf voltage between the dark spaces, which is in effect rectified to give dc bias, requires that $V_1/V_2 = C_2/C_1$, where C_1 and C_2 are the respective capacitances across the dark spaces. Assumption (3) requires

$$C_2/C_1 = A_2D_1/A_1D_2,$$

where A_1 and A_2 are the areas of the electrodes. Combining the above equations gives the result

$$V_1/V_2 = (A_2/A_1)^4. \quad (1)$$

If we place a layer of insulation over one of the electrodes, instead of using a capacitor in the external circuit, the situation is electrically unchanged and an appreciable voltage will still be developed between the glow space and the smaller electrode. If the latter is the one with the sheet of insulation placed over it, then ion bombardment, and hence sputtering, of the insulator can take place.

Voltage distribution in real systems

The above discussion has been somewhat idealized since in actual sputtering systems such as the one shown in Fig. 1, the substrates will be mounted on some kind of holder which in turn is connected to the base plate of the vacuum chamber. The latter will (in general) be at ground potential, as is one terminal of the rf generator. Consequently the larger electrode, as defined above, will include the base plate along with all other surfaces that

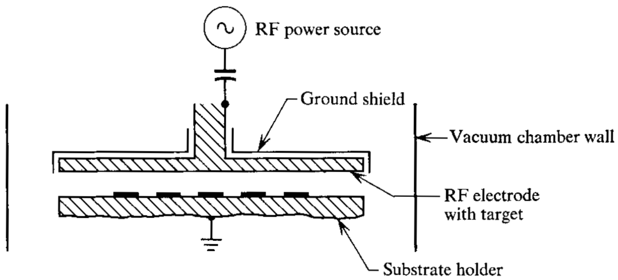

Figure 1 Schematic of rf sputtering system.

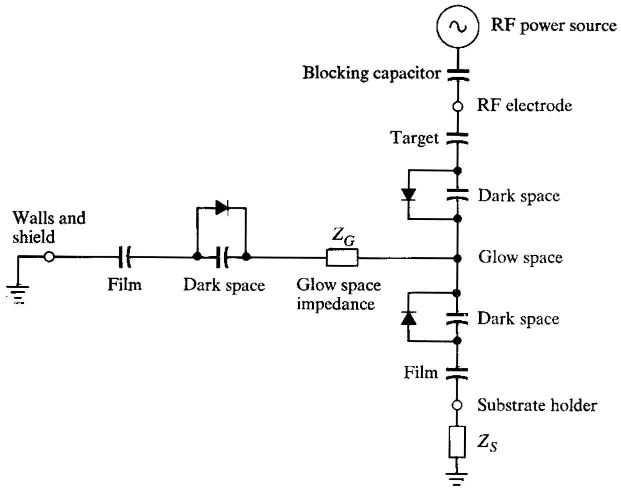

Figure 2 Representative rf impedance network for rf sputtering of insulators.

are at ground potential, such as the vacuum chamber walls (if metal) and the cathode shield. Thus the grounded electrode will be substantially larger than the rf (or target) electrode, so that in terms of Eq. (1) there will be very little dc potential difference between it and the glow space.

Unless special precautions are taken, however, it cannot be assumed that the substrate holder assembly will have zero rf impedance to ground. Bearing this in mind then, we can represent the discharge by the circuit shown in Fig. 2. Detailed analysis of this circuit is beyond the scope of the present paper, but we would draw attention to two elements in it:

(a) Z_G, the effective impedance through the glow space, between the rf electrode and the various grounded surfaces, is controlled by the density of electrons and their mobility in the radial direction. The former increases with pressure and the latter is decreased by the presence of an axial magnetic field. As a result, Z_G increases with magnetic field and decreases with increasing pressure. Increasing Z_G thus tends to isolate all surfaces other than the substrate assembly from the rf circuit, thereby increasing the voltage drop between glow space and substrates. (b) Z_S, the impedance to ground of the substrate assembly, will be a function of the geometry of the system. It is, however, possible to insert a suitable network between this assembly and ground so that both the magnitude of Z_S and the phase change across it can be controlled.[11] The consequences of this are discussed more fully elsewhere, but one effect is to control the voltage drop between the plasma and the substrates.[11]

The significance of being able to control the voltage difference between glow space and substrate will also be discussed more fully elsewhere[12] but, briefly, it is desirable for a significant fraction of the film material to be re-emitted throughout its growth. If this does not happen, a marked deterioration in film quality is likely.

Species bombarding the film during growth

Since it is known that re-emission of material during film growth can occur through mechanisms other than temperature or positive ion bombardment,[13] there was considerable interest in determining the various species arriving at the surface of an SiO_2 film during its deposition through rf sputtering. The determination was done using an arrangement similar to that described by Davis and Vanderslice.[14] A small sputtering system, including walls, etc., was placed inside a larger vacuum chamber. By making the former relatively gas tight and admitting the sputtering gas to it, it was possible to maintain a significantly lower pressure in the latter. Typical figures are 5×10^{-3} torr in the sputtering chamber and 5×10^{-5} torr in the vacuum chamber. A small hole in the substrate assembly or in the target allowed a sample of the various particles bombarding the film or the target to enter the vacuum area where their charge and energy could be analyzed using standard retarding potential techniques.* In Fig. 3 are shown the results for positive ions and electrons. The energy of the majority of the ions centers about the dc bias voltage across the dark space at the substrate, while the maximum energy of the electrons corresponds to the maximum voltage across the dark space at the target. The electrons in question originated at the target surface and traversed the inter-electrode space with very little loss in energy.

Negative ions originating at the SiO_2 target surface were also detected and measured. To make measurements on negative ions, a small permanent magnet was used to give a cross field above the retarding potential instrument, thereby deflecting electrons sufficiently to prevent them from entering, while ions entered with only a small deflection. The negative ion current for the operating conditions of Fig. 3 corresponded to a negative ion yield of the order of one percent of the positive ions incident on the target. The negative ion current decreased with increasing

* It is intended to publish the details of the experimental arrangement separately at a later date.

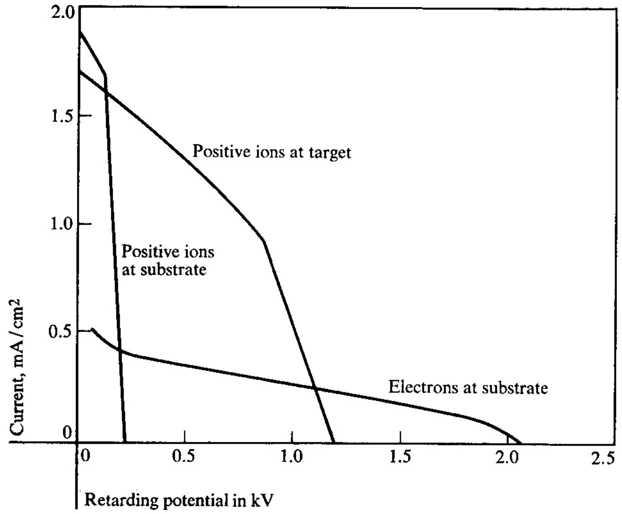

Figure 3 Positive ion and electron currents from retarding potential measurements.

pressure, a dependence attributed to detachment of their electrons by collision with the sputtering gas, the energetic negative ions being assumed to become energetic neutral atoms or molecules.

Thus the growing film is bombarded by negative ions and neutral atoms whose energy may be appreciably higher than that of the positive ions arriving at the film, but whose density at the film surface is of the order of one percent of the density of positive ions on the target. It is also possible that some of the energetic neutral species may have been argon atoms.[13]

Conclusions

RF sputtering systems are operated at frequencies much greater than the plasma ion resonant frequency of the glow space and much lower than the plasma electron resonant frequency. In this circumstance, the glow space is at near-uniform potential and the potential difference between the two electrodes is taken almost entirely across the dark spaces at the electrodes. Due to the large difference in ion and electron mobilities, the glow space potential is always higher than the potential of the electrode surfaces.

The capacitance across the growing film is relatively very high so that the rf voltage across it is negligible. The target also is nominally of high enough capacitance that the rf voltage across it is small compared with the voltage across the dark space adjacent to it. To a first approximation, the rf voltage presented to the discharge at the surface of the target is divided between the dark spaces at the rf electrode and the ground electrodes. The rf voltage across a dark space is in effect rectified to give a dc bias voltage across it. The total dc bias voltage available for division between the two dark spaces is equal to one half the peak-to-peak voltage applied at the target surface. If the target is thin enough, this is equal to one half the peak-to-peak voltage measured on the rf electrode.

The ions incident at the electrodes have energies dependent primarily on the dc bias voltages across their respective dark spaces. Consequently, resputtering of the film during deposition is dependent on the division of the applied rf voltage between the dark spaces. This, in turn, depends on the relative areas of the electrodes and other features of the whole sputtering chamber. For example, when a magnetic field is used, the voltage across the dark space at the ground electrode increases.

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