An Estimate of the Potentials Developed on Coated Anodes During Pulsed DC Reactive Sputtering

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Key Words: Pulsed and periodic deposition; Sputter deposition; Reactive deposition; Optical coating

ABSTRACT

Pulsed dc power supplies and switching circuits that periodically ground or positively bias cathodes are now widely used to reduce arcing in reactive sputtering. A number of authors have estimated the potentials developed on poisoned targets and the conditions that lead to successful arc suppression. It is also recognized that insulating layers deposited on grounded surfaces play an important role in pulsed reactive sputtering processes as well. However, this “disappearing anode” effect has not received similar analytical treatment. We present a calculation of the potentials that can develop on insulating films, deposited during the coating process, when the currents to ground capacitively couple through them. Each sputter/discharge cycle, typically lasting tens of microseconds, is treated as two separate quasi-dc events. An analytical expression is derived relating the surface potential to the effective anode size and sputtering parameters. Equilibrium values of negative100 volts or more with respect to ground are possible in representative cases. The fields produced by these potentials are sufficient to cause electrical breakdown in the coatings that can be an important source of defects and contamination in some applications.

INTRODUCTION

Pulsed dc reactive sputtering is now often used to avoid arcing, which results when insulating deposits on target surfaces become charged. With pulsed dc power the negative sputtering voltage is periodically reversed so that the cathode is grounded or driven positive. This momentarily attracts electrons, which neutralize the net positive charge that accumulates on poorly conducting regions during sputtering. Because electrons are extremely mobile compared to ions, the duration of the reverse pulse can be quite short. Belkind et. al. have studied the influence of pulse frequency and duration on arcing (1). They found that under the conditions they examined frequencies above 50 kHz and positive pulse durations greater than 1 or 2 µs significantly reduced the number of arcs. Szczyrbowski and Teschner have modeled the frequency dependence of the charge buildup on insulating portions of a target when using two cathodes and ac power and predict similar results (2).

This paper examines the situation at the counter-electrodes during asymmetric bipolar pulsed dc reactive sputtering. The assumption is that an insulating film will be deposited on the conducting surfaces that serve as anodes. During sputtering, the anodes must collect an electron current and if they are coated with an insulator they will acquire a negative charge. An excess positive current discharges them only during the reverse pulse. The plasma dynamics that are favorable for discharging the target are unfavorable for discharging the anodes. We suggest that under some circumstances, because of the low ion mobilities, a steady state condition of zero net current to the anodes can only be reached if they acquire a significant negative charge.

Evidence for anode charging during reactive sputtering is shown in Figure 1. In this experiment the plasma potential was measured as a function of time while dc reactively sputtering AlN at low power using anodes of different surface areas (3). The drift is consistent with a significant reduction in effective anode area and/or a buildup of negative charge on the anode surfaces. During these measurements the plasma could be turned off for several hours and reignited with no change in the plasma potential in the intervening time.

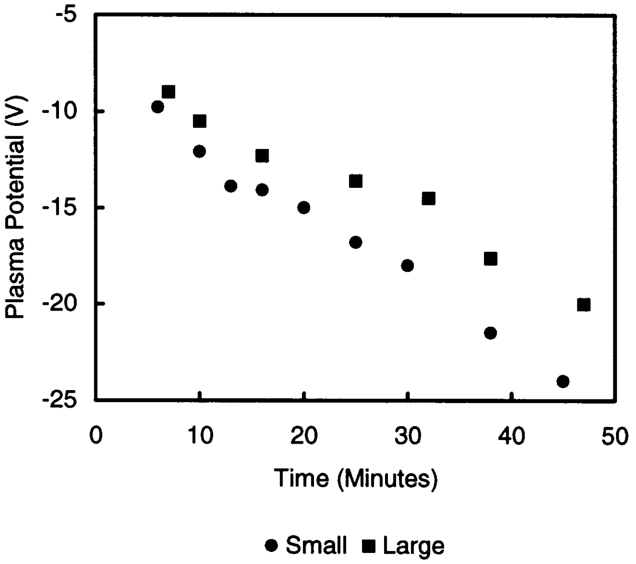

Figure 1. Plasma potential as a function of time while dc reactively sputtering AlN. Anodes with two different areas were used.

Previous analyses of bias voltages in rf glow discharge systems do not apply well to the case of pulsed dc sputtering. In a conventional (megahertz frequency) rf discharge the ions respond only to the dc bias between the plasma and the associated electrode, while the electrons flow in and out of an *abeyant sheath* (4). This situation can be modeled by assuming that the rf electron currents in the sheaths are displacement currents and the plasma couples capacitively through the sheaths (5). This is clearly not the case in pulsed dc, where continuity requires the collection of electrons by the anodes during sputtering. Furthermore, the ion current densities at the two electrodes in a magnetron system are vastly different, so that other models that have been developed for resistive sheaths are also not appropriate (6).

DISCUSSION

The system we will describe is shown in Figure 2. It consists of a magnetron cathode (of arbitrary area) and an anode of area A, which we will assume is covered uniformly with a non-conducting film. There is no current flow to any other surfaces.

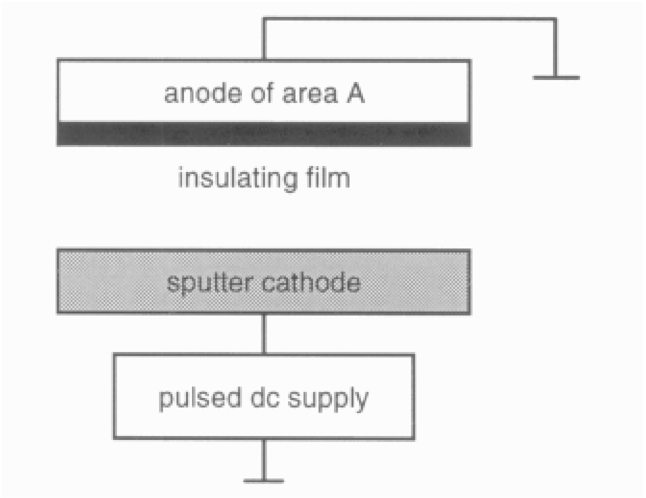

Figure 2. Schematic of the situation described in this analysis.

Figure 3 illustrates the power supply voltage as a function of time and the expected plasma potential and surface potential of the anode. The sputtering current is made up of both ion flow to and secondary electron emission from the target surface. An equal current must be collected by the anode and capacitively coupled to ground through the insulating film. While sputtering, relatively small changes in the difference between the anode and plasma potentials can drive very large electron currents, so the anode sheath voltage will readily adjust to maintain the net negative current to the anode surface. During the reverse pulse, however, the maximum net flow of positive charges to the anode surface will be determined by the space charge limited ion current density J_i. This current will be able to compensate for the flow of electrons to the anode during sputtering if the inequality

$$\frac{I}{A}T \le J_i t \tag{1}$$

is obeyed, where I is the sputtering current, A is the anode area, T is the sputter pulse duration, and t is the reverse pulse duration. If J_i meets this requirement, the integrated current to the anode can be zero with no appreciable increase in the sheath voltage. For systems that do not obey this inequality, we expect the anode potential to become more negative with time until equal numbers of ions and electrons are collected on each cycle. Because the ion current J_iA depends on the plasma parameters and not on the sheath voltage, another mechanism is needed to produce the equilibrium conditions.

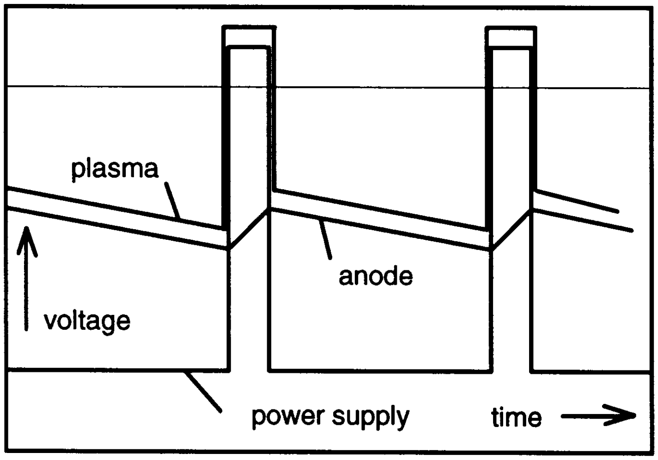

Figure 3. Representations of the power supply voltage, the anode voltage and the plasma potential as functions of time in steady-state operation.

We propose the following description of the sheath dynamics in front of the anode. While collecting electrons during sputtering, it is covered with a conventional anode sheath with a thickness of only a few Debye lengths, or fractions of a mm. The ion and electron densities and electron temperature adjacent to the sheath are those of the magnetron sputtering plasma. When the power supply reverses, the plasma potential rises to approximately the reverse bias voltage. Therefore, the anode becomes the negative electrode in the system and the *extant sheath* in front of it instantaneously expands (4). This expanding sheath captures the ions within its volume, which can then fall to the anode under the influence of the potential gradient. After the power supply returns to the sputter mode, the sheath again collapses. Evidence suggests that during the reverse pulse the plasma does not extinguish and we will assume that the characteristics are those of the sputtering plasma (1). The sputtering time of ten µs or more is long enough that the ions, having thermal velocities of several hundred m s^{-1}, can diffuse into the region just depleted and be available for the next cycle. In conventional rf sputtering, which is the closest analog to this situation, the period of the sheath oscillations is so short that the relatively massive ions cannot respond to the changing fields and their density profile is essentially constant in time. We believe that this is an important distinction between pulsed dc sputtering and conventional dc or rf sputtering.

If the sheath expands to a thickness d, the ionic charge trapped within the sheath volume is

$$Q_i = n_i edA \qquad (2)$$

where n_i is the plasma ion density and e is the electronic charge. Assuming all of this charge reaches the anode during the reverse pulse, the steady-state requirement that the anode collects equal numbers of electrons and ions per cycle becomes

$$IT = n_i edA + J_i At \qquad (3)$$

We will assume that during the reverse pulse the sheath reaches a quasi-equilibrium condition described by the collisionless Child-Langmuir law. Specifically, the relationship between the ion current density, sheath thickness and sheath voltage V is given by

$$J_i = \frac{4\varepsilon_o}{9}\sqrt{\frac{2e}{m_i}}\frac{V^{\frac{3}{2}}}{d^2} \qquad (4)$$

where m_i is the ion mass. Combining Equations 3 and 4 we get

$$V = \left\{\frac{9J_i}{4\varepsilon_o}\sqrt{\frac{m_i}{2e}}\left(\frac{IT - J_i At}{n_i eA}\right)^2\right\}^{\frac{2}{3}} \qquad (5)$$

Normally J_i is limited by Bohm diffusion into the sheath and is therefore given by

$$J_i = 0.6 n_i e\sqrt{\frac{kT_e}{m_i}} \qquad (6)$$

where kT_e is the electron energy (7). With this substitution we get

$$V = \left\{\frac{0.95 n_i}{\varepsilon_o}\sqrt{kT_e e}\left(\frac{IT}{n_i eA} - 0.6\sqrt{\frac{kT_e}{m_i}}t\right)^2\right\}^{\frac{2}{3}} \qquad (7)$$

When the squared term is negative it means that the space charge limited ion current is able to compensate for the electron current during each cycle and the anode sheath voltage can remain small. The maximum sputtering current for this condition to be met is

$$I_{max} = 0.6 n_i eA\sqrt{\frac{kT_e}{m_i}}\frac{t}{T} \qquad (8)$$

Above this value, V will increase rapidly in order to create the sheath thickness required to capture the additional ions.

To calculate values of V in a typical case, we will use the plasma parameters measured previously while reactively sputtering AlN with two targets and a 40 kHz power supply (8). This is probably more representative of pulsed dc plasmas than either dc or rf data. At a pressure of 10 mTorr and a power of 500 W we found a value for n_i of $6.4\text{x}10^{16}\,\text{m}^{-3}$ and for kT_e of $5.1\text{x}10^{-19}$ J (3.2 eV). Figure 4 shows the calculated values for V as a function of I/A for four different power supply operating parameters.

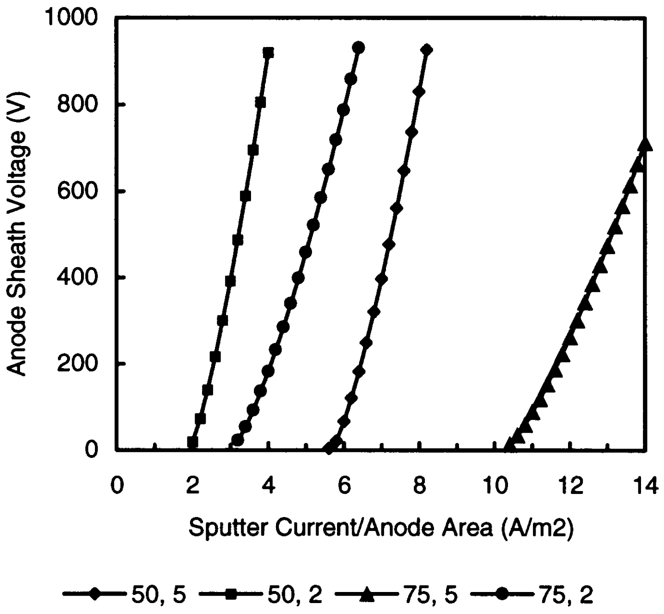

Figure 4. Anode sheath voltages predicted from Equation 7 for four combinations of power supply frequencies in kHz and reverse pulse times in µs.

The value of I_{max}/A according to Equation 8 is plotted in Figure 5 as a function of power supply frequency and reverse pulse duration. The same plasma conditions have been used as were assumed for Figure 4.

As the voltage on the surface of the anode becomes increasingly negative, the plasma potential will follow it during sputtering, as shown in Figure 3. Since the sputtering voltage is the difference between the plasma potential and the power supply voltage, this will begin to have a significant impact on the power delivered to the target. The observed consequence may be an inability of the supply to deliver the desired power.

Self-consistency for the model requires that the ions be able to traverse the sheath during the reverse pulse. The actual time-dependent sheath potential is not known, so we will make the simplifying assumption that the field is uniform. An ion

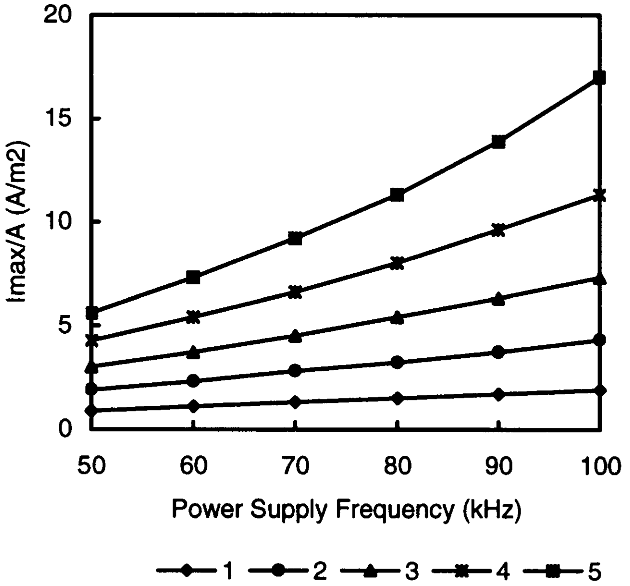

Figure 5. Maximum sputtering current per anode area at which the anode sheath voltage begins to rise, shown as functions of power supply frequency for five reverse pulse times (in μs).

at rest at the sheath edge will cross the distance d in a time τ given by

$$\tau = \sqrt{\frac{2d^2 m_i}{eV}} \tag{9}$$

Equations 4 and 6 can be combined to give

$$\tau = 1.76\left(\frac{m_i \varepsilon_o}{n_i}\sqrt{\frac{V}{kT_e e^3}}\right)^{\frac{1}{2}} \tag{10}$$

For the same conditions used previously, at a voltage of 400 V the transit time will be about 0.1 μs. This is much shorter than the shortest reverse bias times used in pulsed dc sputtering, so the anode should be able to collect all of the ions trapped in the expanding sheath. That is the only limitation placed on the duration of the reverse bias in this model. It is also worth noting that the only predicted impact of the dielectric thickness in this analysis will be the size of the ripple on the anode potential.

The voltages shown in Figure 4 are probably overestimates of the actual anode sheath potentials. There will be secondary electron emission from the anode during the reverse bias pulse and it may be significant. Even at modest ion energies γ is measurable and some dielectrics have relatively high emission coefficients (9). Furthermore, as the current I increases the ion density in the plasma will also increase. This will have the effect of reducing the required sheath thickness and therefore V. On the other hand, we have assumed a collisionless sheath. This is marginal for the numbers we have used and sheath collisions will increase the anode potential.

CONCLUSIONS

We have used a simple model to predict the potentials developed on the surfaces of coated anodes during pulsed dc reactive sputtering. Of course, actual systems are much more complicated than the one described. Portions of anodes that are shielded from appreciable coating flux can provide conducting return paths for the plasma electrons for a considerable period of time. Once these areas become covered with an insulator, however, the model predicts that there is a maximum sputter current to anode area ratio beyond which the “hidden anode” problem will be significant. This critical ratio depends on the space charge limited ion current to the anodes, which is a function of the ion density and electron energy in the sputtering plasma. It is also strongly dependent on the power supply frequency and reverse pulse duration.

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