

Control of RF Sputtered Film Properties Through Substrate Tuning

Abstract: A means has been found to control the rf potential of the substrate during rf sputtering. The application of this technique to the deposition of silica films has been investigated in detail. The technique can be described as the use of an adjustable rf impedance between the substrate holder and ground electrodes, which generates an rf potential by virtue of the flow of rf current through it. Adjustment of the rf potential of the substrate results in a controlled dc bias potential developed at the film surface, which correlates directly with the physical properties of the deposited films. In general, the most desirable film properties are obtained when the dc substrate bias (obtained by adjusting the substrate-holder rf impedance) is at a high negative potential. The effect of substrate bias on etch rate, pinhole breakup thickness, and argon content has been measured.

Introduction

In dc sputtering of metals, it has been shown¹ that a negative dc bias on the film can influence the resistivity of the film. It is reasonable, then, to assume that such bombardment might have some influence on the properties of insulating films. However, one cannot bias the surface of an insulator with a dc source, because the film is not a conductor. Instead, one must cause the surface of the insulator to be at some rf potential relative to the plasma, which can then result in a "self-bias" by rectification. This "self-biasing" action is identical to that which takes place at the cathode surface and which in fact is responsible for the buildup of the dark space or sheath that creates the conditions for sputtering there.²

In the application of rf sputtering to deposition of SiO_2 films, it has been found that the potential of the substrate has a strong influence on the properties of the films.³ In this paper, experiments are described which show how the potential can be conveniently varied and how the film properties depend on the potential.

Obtaining a bias

One technique for creating the desired rf (and dc) potential difference between film and plasma is called substrate tuning. This technique requires no other power source, but utilizes the rf current flow in the system. A schematic drawing of the system used for these experiments is shown in Fig. 1. An electrical model for this system is shown in Fig. 2. The three capacitors C_T , C_W and C_S , with associated loss resistances, are the approximate

representations of the plasma boundaries at the target, wall and substrate holder respectively.⁴ The diodes represent the rectifying action of the plasma boundary, which occurs due to the higher mobility of electrons compared with the mobility of ions. As the inductance L is varied from zero, the rf impedance between substrate holder and ground decreases to a minimum at series resonance between L and C , and then rises to a maximum when a parallel resonance is reached. Therefore, the impedance between substrate holder and ground can be varied over a wide range. Losses in the substrate impedance will naturally limit the maximum and minimum values of impedance that can be obtained.

A detailed analysis of the circuit of Fig. 2 is rather difficult because the boundary or sheath impedances are not constant, but vary with the rf current flow through them. However, a qualitative description of the rf current variation is necessary to understand the experimental data. Consider the case for which L is adjusted to be resonant with C (minimum rf impedance). This is approximately the case for a conventional untuned system, except for the presence of a dc blocking capacitor. In this case most of the rf current will flow to the wall, which normally has the largest area and, hence, the lowest impedance. If the inductance L is increased, its reactance will partially cancel the capacitive reactance C_S of the substrate sheath, resulting in a lower net impedance between plasma and ground through the substrate holder. The rf current I_S will increase while rf current I_W will decrease. The target rf current I_T is nearly constant, since the impedance between target and plasma is normally quite large. As

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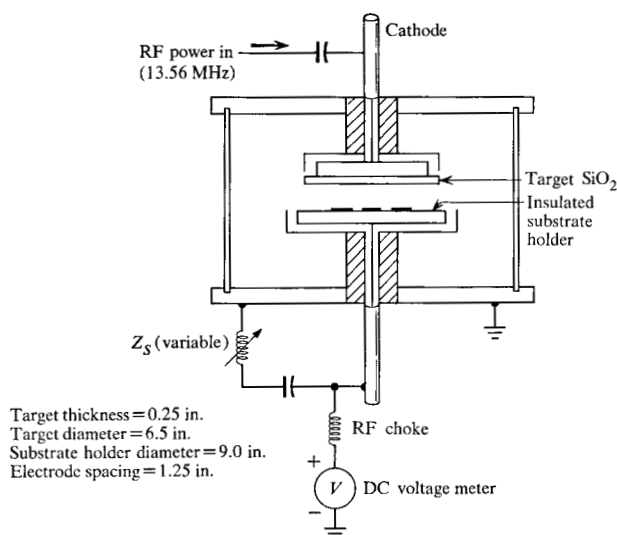


Figure 1 Experimental system for rf sputtering with substrate tuning.

I_s increases, the rf potential across the substrate sheath increases, as does the rf voltage between substrate holder and ground. A maximum should occur in I_s when the whole path between plasma and ground through the substrate holder reaches a minimum net impedance. This condition will yield the maximum rf and dc potential between substrate and plasma.

Figure 3 shows the experimental result of varying the substrate impedance. The data are plotted in terms of the net reactance in ohms of the substrate impedance by assuming no losses but taking into account the stray capacitance of the substrate holder. Positive values indicate inductive reactance and negative values indicate capacitive reactance.

The figure indicates that increasing positive (inductive) values of substrate reactance produce an increasing negative dc potential between substrate holder and ground.* Negative dc potentials are observed because the increasing rf voltage at the substrate sheath is rectified, forcing the substrate to be negative with respect to the plasma. The plasma, on the other hand, is normally at a small positive potential with respect to the wall because of the large value of C_w . The small positive voltage actually decreases as some rf current is diverted into the substrate boundary. Therefore, the dc potential between substrate and wall (ground) is a close approximation to the resputtering potential when the substrate holder has a large negative potential with respect to ground.

* One would expect that the deposited insulator film would make it impossible to measure any dc potential on the substrate holder. However, there is enough dc leakage through film defects and at the edges of the substrate holder (where no film is deposited) so that reliable measurements can be made.

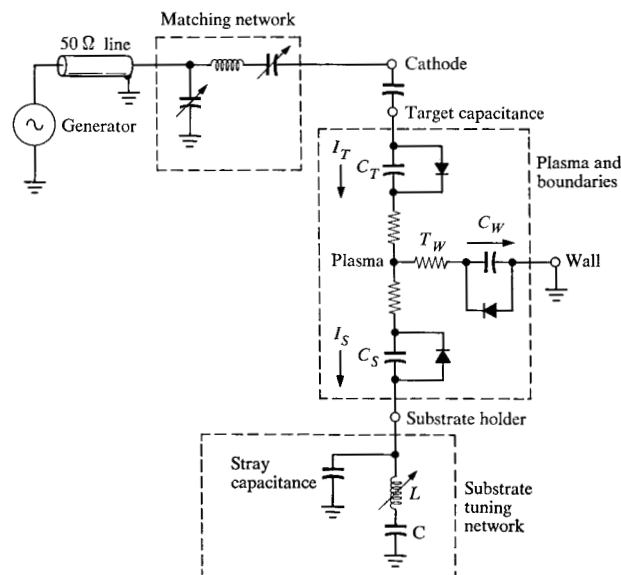


Figure 2 Electrical model for experimental system.

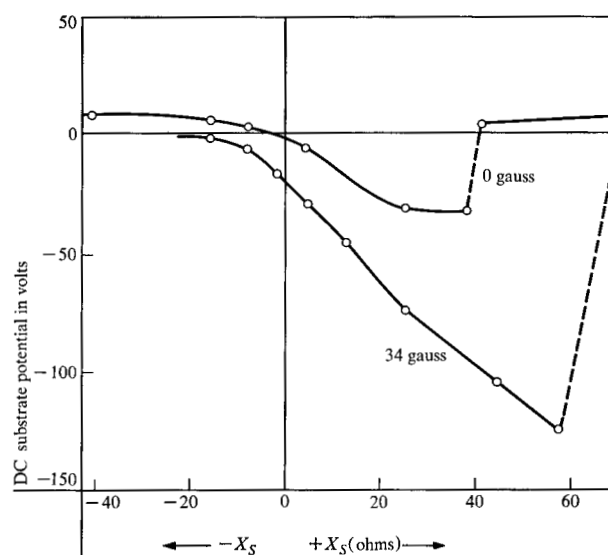


Figure 3 Substrate bias dependence on substrate tuning impedance. (Frequency 13.56 MHz; power density 3.9 W/cm²; argon pressure 15 millitorr.)

A maximum negative value is reached in the upper curve in Fig. 3 at a point of instability indicated by the dotted line. This maximum occurs approximately where the net inductive reactance of the tuning network resonates with the substrate sheath capacitance C_s . The absence of a smooth maximum is attributed to the voltage dependence (nonlinearity) of C_s . Beyond the maximum negative voltage, the impedance between plasma and ground

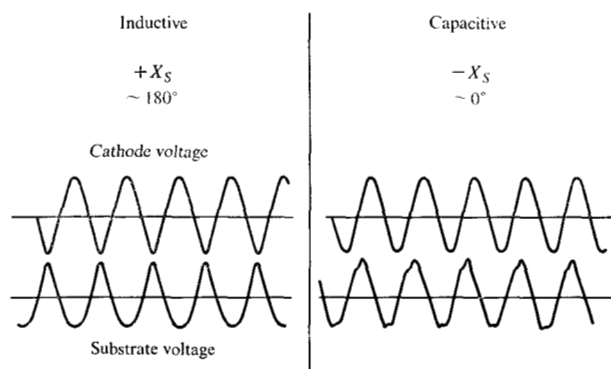


Figure 4 Phase relationships.

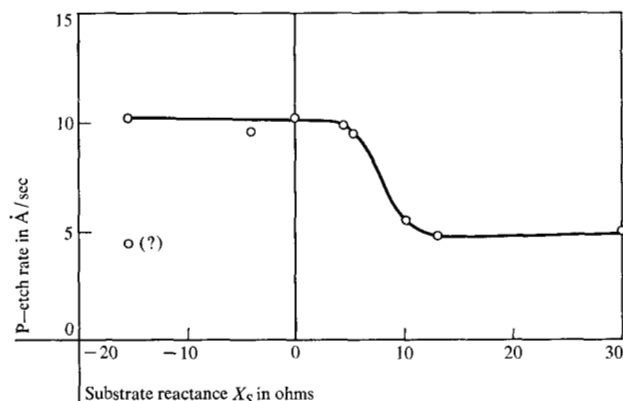


Figure 5 Control of etch rate.

through the substrate holder is large, and the rf current in that path is much smaller. Therefore the substrate holder assumes a potential that is much closer to that of the plasma. Since the plasma is always somewhat positive with respect to the wall (ground), it is not surprising to observe positive dc potentials at the substrate holder.

A second curve in Fig. 3, taken with an axial magnetic field applied, shows that all potentials are depressed to more negative values. The action of a magnetic field is to reduce the radial diffusion rate of electrons, thereby decreasing the plasma density near the wall. The resulting decrease in C_w diverts rf current from the wall into the substrate sheath, producing a larger self-bias between plasma and substrate. Another way to increase the maximum voltage is to reduce the wall area exposed to the plasma. This is equivalent to decreasing C_w in Fig. 2, thus driving more current through C_s .

Figure 4 shows the observed cathode and substrate voltage waveforms for both positive and negative reactances in the system of Fig. 1. The phase relationships here are consistent with the electrical model of Fig. 2.

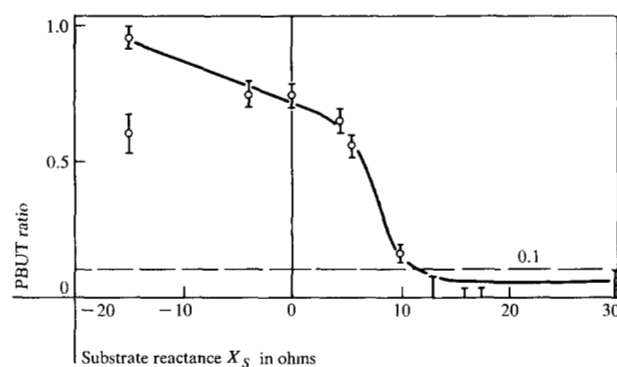


Figure 6 Control of pinhole breakup thickness.

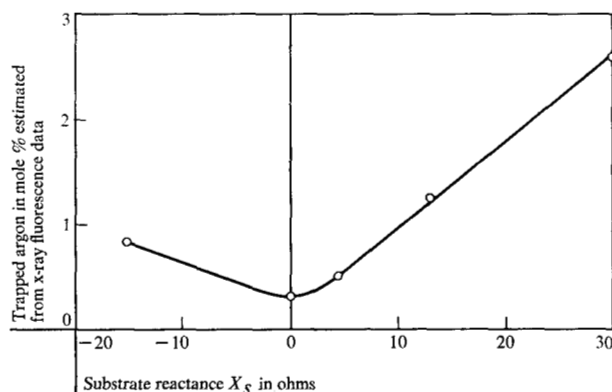


Figure 7 Argon content vs. substrate reactance.

Film properties

One of the more sensitive indicators of insulator film quality is the etch rate. High stress or impurities can make large changes in the etch rate. Pliskin⁵ has found a sensitive etchant that is useful for evaluating glass films. This is called P-etch* and has been used to characterize films deposited at different substrate bias levels in the system of Fig. 1. In these experiments, the substrates were polished silicon and the temperature was held between 160°C and 180°C throughout the 30-minute runs. An rf power density of 3.9 watts/cm² at 13.56 MHz (deposition rate 450 Å/min) was used with an argon pressure of 15 millitorr. No magnetic field was used. Figure 5 shows the variation of P-etch rate with substrate reactance. A drastic drop is observed at a reactance of 5 to 10 ohms, which produces a bias of -30 or -40 volts dc. The P-etch rate of thermally oxidized silicon films is about 2 Å/min,⁴ so the sputtered film properties approach those of thermally grown SiO₂ films when the most negative potentials are used.

* P-etch composition is 300 parts H₂O, 10 parts HNO₃ and 15 parts HF.

Another sensitive indicator of film quality is the pinhole breakup thickness (PBUT), which is discussed in another paper.³ This is the thickness to which an insulator can be etched before massive pinholing or penetration occurs. The results are usually expressed as a fraction of the original film thickness called the PBUT ratio. Figure 6 shows the behavior of the PBUT ratio as a function of the substrate tuning reactance. Again, a rather dramatic decrease in this quantity occurs at 5 to 10 ohms (-30 to -40 volts). A PBUT ratio of 0.1 or less indicates a high quality film.

To obtain direct evidence of the argon ion bombardment, the films were examined by x-ray fluorescence to determine the argon content as a function of substrate reactance or bias.⁷ Figure 7 shows the results of these measurements. Clearly, the argon is at a minimum where the substrate bias is low and increases with negative bias as one might expect. The presence of argon trapped in rf sputtered SiO_2 films has been observed by others and is not known to have any detrimental effect on its properties as an insulator or passivation layer. The form of the curve (a minimum value with large increase at negative bias) is similar to that observed by Winters and Kay⁸ in metal films and is presumably due to the same mechanism.

Conclusions

It has been shown that the properties of rf sputtered SiO_2 can be significantly influenced by the electrical potential of the substrate relative to the plasma. Etch rate and pinhole breakup thickness are both improved by negative potential. Evidence of increased argon ion bombardment

has been obtained by direct measurement of trapped argon in the films and correlation of the amount with increasing negative film bias. A technique for obtaining adjustable film bias has been described. This technique requires no additional power source and uses simple electrical components outside the vacuum chamber.

Acknowledgments

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