

# Reactive Sputtering Using a Dual-Anode Magnetron System

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## ABSTRACT

Reactive sputtering of dielectrics using a single magnetron is accompanied by slowly covering all inside surfaces of a vacuum chamber with a nonconductive coating. When the chamber walls function as the system's anode, this coating causes variation in circuit impedance and consequential voltage redistribution. Ultimately, the final result of this behavior can be circuit interruption (or the "disappearing anode" problem). A solution for the anode problem is to use a self-cleaning anode system consisting, for example, of two anodes and a single magnetron, powered by an ac supply. Such a novel configuration is called dual-anode or redundant anode sputtering. The dual anode system is described in detail and results of its implementation for high-rate reactive sputtering of dielectrics are described.

## INTRODUCTION

Reactive sputtering of dielectrics is accompanied by a gradual coating of all inside surfaces of the deposition system including anode. As the anode gets coated over with the insulating film, its electrical resistance in the main cathode-anode-power-supply circuitry increases creating a substantial additional voltage drop at the anode surface [1]. When the insulating layer on the anode gets very thick, the discharge is extinguished. We have called this the "disappearing anode" problem [2]. Typically, in this case, periodic maintenance is required for anode cleaning to avoid unscheduled process interruption.

One way to solve the anode problem is to enhance the discharge at the anode so that it runs in the "self-cleaning" regime. In this regime, the dielectric layer deposited on the anode is repeatedly or continuously sputtered off. A self-cleaning anode system consists, for example, of two anodes and a single magnetron, powered by an ac supply (Figure 1). Such a novel configuration is called dual-anode or redundant anode sputtering [2-4].

In Figure 1 two anodes are provided, each connected to one side of a center tapped AC power source. The center point, or "tap," of the power supply is connected to a single magnetron source of the ordinary variety. The system works so that each of the anode elements act alternatively as true anodes (elec-

tron collectors) and as sputtered cathodes (ion collectors or "resting" anodes), depending upon the polarity of the ac power supply. The continuous reversal of voltage and current will also keep any insulating regions of an anode from charging, and therefore inhibit anode arcing. The magnetron is always a cathode, relative to a different anode on each half cycle. Further, charged areas of the target are discharged twice each cycle, as the voltage across the transformer passes through zero. Thus the target discharge rate is twice the driving frequency.

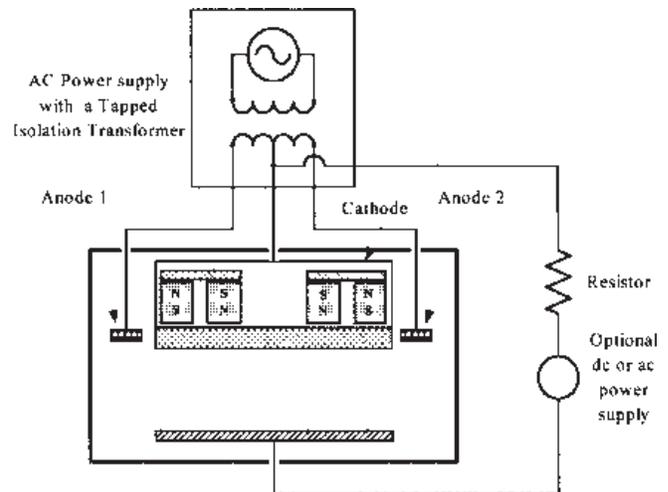


Figure 1: Schematic of dual-anode sputtering system with substrate connection to the cathode.

A dual-anode system (DAS) can provide sustainable anodes and periodically discharging anode and cathode (target) surfaces avoiding arcing. The DAS configuration does not result in high anode falls, and does not exhibit substantial plasma decay on every half cycle and resulting voltage spikes. A DAS can be easily retrofitted into existing DC single target systems and does not experience difficulty of source matching and uneven source erosion typical for dual magnetron systems. Film contamination with anode material, if a problem, may be avoided by using the same material for the anode as for the cathode and/or by placing a shield so as to prevent deposition of material sputtered from an anode from reaching the substrate.

In the case of a DAS, the substrate can be connected to the cathode to provide a bias potential, through a resistor alone, and/or with an additional bias power supply (Figure 1). If there is no resistor or additional power supply in the substrate circuit (i.e., the substrate is connected directly to the cathode), the substrate works as an additional cathode, and the plasma density near the substrate determines the current through the substrate. A resistor in the substrate circuitry lowers the ion currents through it (and the voltage and so the energy of the arriving ions), while a positive potential applied to the substrate can cause the substrate to attract electrons for heating (i.e., to work as an anode).

An investigation of DAS is reported in this work. Results are given for reactive sputtering of  $\text{Al}_2\text{O}_3$  thin film.

## EXPERIMENTAL TECHNIQUE

Experiments were done in a box-coater pumped down by a diffusion pump with a base pressure of about  $2 \times 10^{-6}$  Torr. An HRC-873 planar magnetron (BOC Coating Technology) was modified to have an unbalanced magnetic field. Two U-shape  $3/4" \times 3/4" \times 18"$  aluminum bars placed along the magnetron sides were used as anodes (Figure 2).

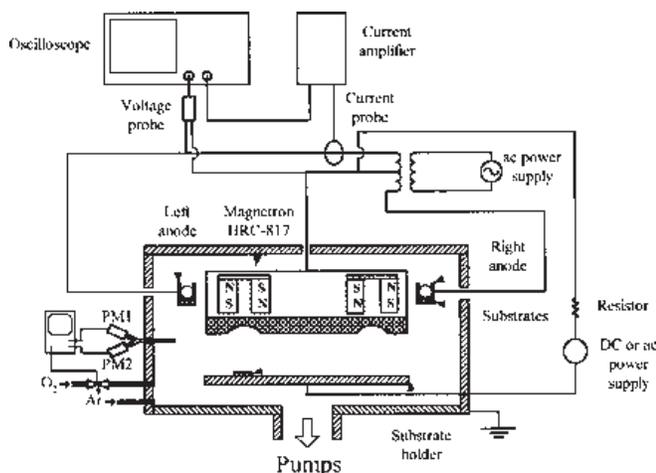


Figure 2: Experimental set-up.

AC power is applied to the cathode and anodes using an AC power supply, model PE II (by Advance Energy) connected to an isolating transformer with a center tap in the secondary coil. The AC power supply is used mainly in the constant power mode. The substrate holder is floating or connected to the magnetron through a resistor and/or a floating DC power supply (MDX-1k) for substrate biasing. In order to study the influence of substrate conductivity on biasing, glass, non-conductive and conductive Si wafers were chosen, which were put on the unheated substrate holder.

A closed-loop control system, made by Corona Vacuum Coaters, Inc., is used to achieve high deposition rates. The

system is based on measuring the ratio of optical emission of metal (Al) and Ar lines and controlling the oxygen gas flow using a fast responding piezo-valve. Measuring the ratio of optical lines removes the uncertainty encountered when one must manipulate power to maintain the plasma.

The  $\text{Al}_2\text{O}_3$  thin films were prepared with 99.999% Al target in a mixture of Ar and  $\text{O}_2$  at total pressure of a several mTorr and at various Ar and  $\text{O}_2$  flow rates. Refractive indices and thickness of the films were characterized by using AutoEL II ellipsometer at the wavelength of 632 nm. Thickness was determined using a stylus profilometer Tencor. Deposition rates were calculated from the film thickness and deposition time.

## GENERAL PROPERTIES

### How the System Works

In Figure 1 two anodes are provided, each connected to one side of a center tapped secondary coil of an insulating transformer. The primary coil is connected to an ac power supply. The center point, or "tap," of the secondary coil is connected to a single magnetron source of the ordinary variety. The system works in the following way.

Let us consider the first half cycle. Assuming that plasma has already been established, when the left anode (#1) starts positive with respect to the right one (#2), anode #1 will collect electrons. If it is of sufficient area and without magnetic field, it will assume a potential close to potential of the plasma. Meanwhile, the magnetron will be negative with respect to the plasma by half the secondary voltage (Figure 3). A regular AC magnetron discharge is generated between anode #1 and the magnetron. The current through anode #1 is approximately equal to the current through the magnetron (Figure 3).

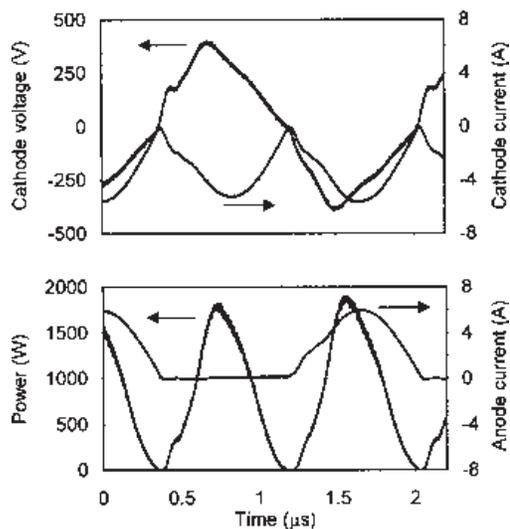


Figure 3: Oscillograms of cathode voltage, cathode and anode currents, and power for a dual-anode system.

Anode #2 is driven still further negative with respect to the plasma by the action of the transformer, to twice the target potential. This electrode collects ions and thus also works as a cathode, causing sputtering of its surface, removing any buildup of insulating materials, which may have formed there previously. The discharge between the anodes is not self-supported but is supported by the magnetron discharge that creates a certain plasma density near anode #2. The current through anode #2 is in the range of mA, much less than the current through the magnetron, and increases with voltage.

The higher the magnetron current, the higher the deposition rate on all surfaces in the chamber, but at the same time, the higher also the ion current through anode #2 and its re-sputtering rate.

Similarly, on the other half-cycle of the AC power, when the voltage is such that the right anode (#2) starts positive with respect to the left, anode #2 will collect electrons, assuming a potential close to the plasma potential. Again the magnetron will be negative with respect to the plasma by half the secondary voltage, and will continue to be sputtered by ions from the plasma. On this part of the cycle, however, anode #1 is driven negative, causing sputtering of its surface, removing any buildup of insulating materials, which might have formed there when it was biased positively.

Thus each of the anode elements act alternatively as a true anode (electron collectors) and as a sputtered cathode (ion collector), depending upon the polarity of the ac power supply. The continuous reversal of voltage and current will also keep any insulating regions of an anode from charging to high potentials against the plasma, and therefore inhibits anode arcing.

The magnetron will be driven negative by the action of the transformer on every half cycle, as previously described. That is, regardless of which anode is being driven positive, the magnetron is driven negative in respect to the plasma and the acting anode. In effect, the plasma acts as a full wave rectifier of the AC supply, and the magnetron current is always in the same direction (Figure 3).

The fact that in DAS there is a single magnetron, and that the magnetron is nearly continuously operating, means that the plasma is never permitted to decay to a point which would require excess voltage to reestablish it, as is the case in DMS. In the case of using a 60-kHz AC power, the plasma decays for about a few tenths of a microsecond. Such off-time is much less than the plasma decay time constant estimated to be about a few tens of a microsecond [5]. As a result of such short off-time, no excess voltage is required to reestablish the plasma. (This is not true for a dual magnetron system, in which the plasma is spatially reorganized every half cycle).

During the off-time, electrons from the plasma are attracted to any positively charged surface region, discharging the surface and, by this way, avoiding arcing.

### Deposition Rates

Deposition rate distribution is an important characteristic of any deposition system. Therefore, introducing any new electrodes in the system requires its reexamination. Distribution of the deposition rate across the target center-line and deposition rate dependence on the distance from the target surface were measured for the DAS and a single magnetron system powered by pulsed DC having the chamber walls and the substrate holder grounded (Figures 4 and 5). In both cases, there were very similar characteristics indicating that introducing dual anodes placed symmetrically along the magnetron long axis does not change deposition rate distribution noticeably.

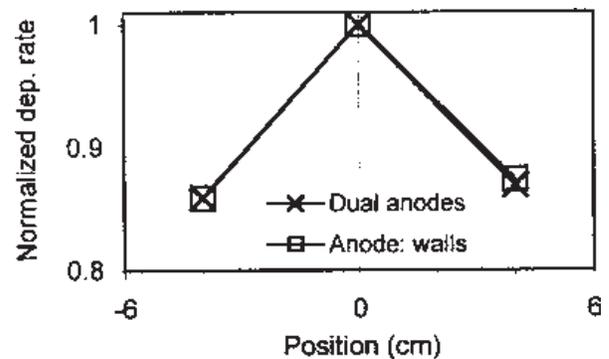


Figure 4: Deposition rate versus substrate position across the magnetron center line for a dual-anode and regular single-anode arrangements. Depositions were done in the oxide mode.

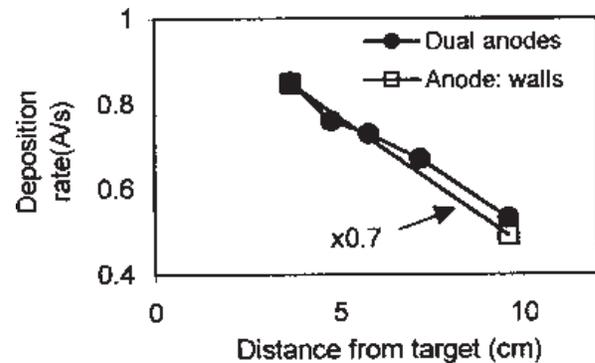


Figure 5: Deposition rate versus target-to-substrate distance for a dual-anode and regular single-anode arrangements. Substrates were placed under the target center. Depositions were done in the oxide mode.

Deposition rate is usually proportional to the power consumed by the magnetron [6]. There is the same proportionality when the DAS is used; increasing magnetron power increases the deposition rate linearly. All these data show that

introducing a dual-anode arrangement in a single-magnetron system does not change the fundamental deposition process characteristics.

The DAS system used in this work was successfully tested using AC frequencies in the range of 40 to 100 kHz. As it can be expected, variation of the AC frequency does not significantly influence system performance.

Implementation of a DAS does not inhibit the use of a closed-loop control system. An example of such an implementation is shown for deposition of  $\text{Al}_2\text{O}_3$  films in Figure 6. Deposition of transparent  $\text{Al}_2\text{O}_3$  films was achieved by relating the argon to aluminum emission ratio to various stages of target condition produced as increasing oxygen levels. Transparent  $\text{Al}_2\text{O}_3$  films were deposited by setting the Al:Ar ratio from 20% to as high as 70%. The refractive index of the films at 638 nm increased with the set-up ratio. At the ratio of 70%, the refractive index was about 1.65, which is typical for dense  $\text{Al}_2\text{O}_3$ . These films, qualitatively were also quite scratch resistant. The deposition rate at the set-up ratio of 70% using 1.4 kW power was about  $5.9 \text{ \AA/s}$ , that is about 6 times higher than the deposition rate of  $\text{Al}_2\text{O}_3$  films made in the oxide mode.

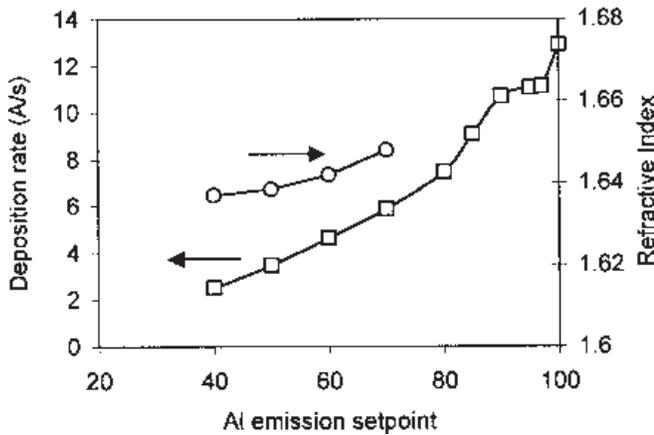


Figure 6: Deposition rate of  $\text{Al}_x\text{O}_y$  and refractive index of  $\text{Al}_2\text{O}_3$  films versus setpoint of the closed-loop control system.

### SUBSTRATE BIASING

DAS employs a floating power delivery circuit (Figure 1). To include the substrate (holder) in the circuit, the substrate is disconnected from ground and connected in parallel with the magnetron to the center tap of the isolation transformer (Figure 1). With such a connection, during the on-time the substrate holder has the magnetron AC negative potential against the plasma and works as a cathode. The oscillogram of the substrate current confirms this picture but also uncovers a strong electron current when the cathode voltage is so low that it cannot support the magnetron discharge (off-time) (Figure 7). If during the off-time, there is a voltage drop near the

substrate (like at the anode), the electron current can provide substrate heating additional to that caused by ion bombardment. In general, the joint effect of substrate ion bombardment and heating or even just the effect of ion-bombardment could be either too strong or too weak to produce the desired film structure and therefore, should be controlled. In a DAS, this control can be achieved by varying the resistor value and/or by addition of a separate floating power source.

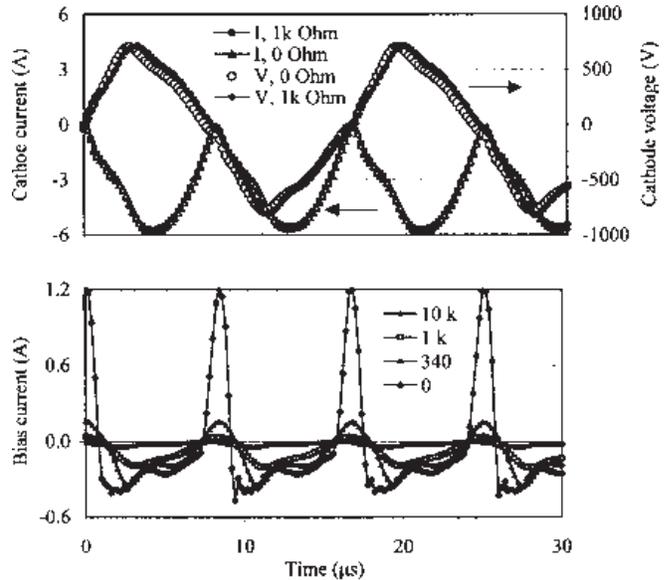


Figure 7: Oscillograms of cathode voltage, cathode current, and bias current at different biasing resistors shown inside the figures.

The resistor lowers both the ion and electron currents through the substrate holder (Figure 7). During the on-time, the voltage drop across the resistor makes the substrate holder potential more positive, i.e. closer to the plasma potential. Both the average ion energy and ion flux that bombards the substrate, go down, decreasing the energy (and momentum) delivered to the substrate by ions. During the off-time, with the substrate potential closer to the plasma potential, the electron current of the decaying plasma also decreases.

An additional floating power supply inserted into the substrate circuit can enhance or diminish substrate ion and electron bombardment. When an additional positive potential is applied to the substrate, the substrate potential goes closer to the anode and plasma potentials decreasing ion bombardment and increasing the electron current (Figure 8). When the potential applied to the substrate is negative, the potential difference between the substrate and plasma increases resulting in higher ion bombardment and lower electron current.

Varying the resistor in the substrate circuit changes the refractive index of the  $\text{Al}_2\text{O}_3$  films deposited on conductive substrates (Figure 9). As the resistor value increases ion bombard-

ment will decrease. This has the effect of increasing the refractive index ultimately reaching a maximum at about 1.65, typical for a dense film. Increasing the resistor value further decreases the refractive index to 1.58 typical for a porous film [7]. When low value resistors are used in this manner the ion bombardment to the substrate is very strong and in the extreme can have a damaging effect on the  $\text{Al}_2\text{O}_3$  film structure. In the other extreme when the resistors values are too high, the ion bombardment is not strong enough for film densification. This example demonstrates how these two phenomena, having opposite effects on the film structure, can be used in a DAS to define optimized conditions for both film density and related refractive index properties (Figure 9).

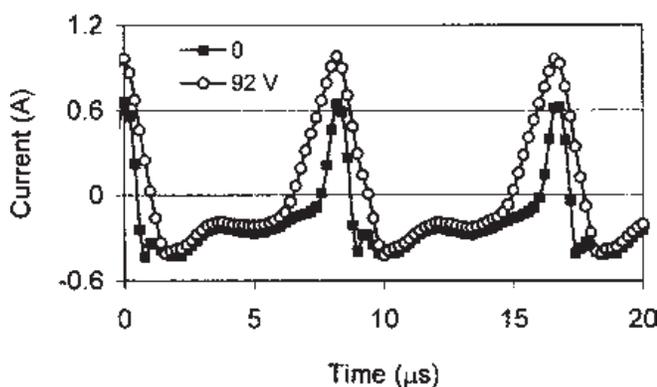


Figure 8: Oscillograms of the bias current (b) measured without and with a biasing voltage of 92 V applied using an additional floating power supply.

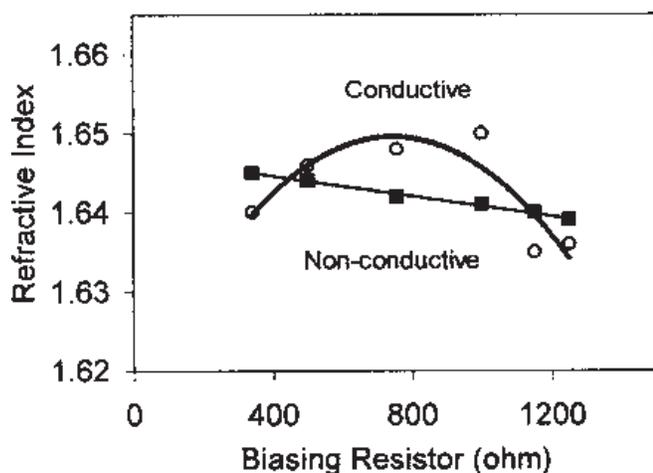


Figure 9: Refractive index of  $\text{Al}_2\text{O}_3$  films deposited on conductive (open circles) and non-conductive (filled squares) substrates versus bias resistor. Depositions were done in the oxide mode.

Variation of the resistor in the substrate (holder) circuit does not change (in the first approximation) the refractive index of  $\text{Al}_2\text{O}_3$  films deposited on non-conductive substrates. Ion bombardment of a floating non-conductive substrate is determined only by the plasma density and electron temperature at its surface. Variation of the resistor in the substrate circuit should not influence ion bombardment of a floating surface unless by some reason it changes the plasma density near it. In our case, a small non-conductive silicon wafer was lying on a big conductive substrate holder. In this case, variation of the resistor may be causing some plasma redistribution near the substrate; this may explain the small decrease of refractive indices seen in Figure 9 for the non-conductive substrate case.

## CONCLUSION

A dual-anode system does not demonstrate the “disappearing” anode problem commonly seen when depositing in other reactive deposition systems. The dual-anode system employs a transformer whose secondary coil has a center tap. The ends of the coil are connected to anodes while the center tap is connected to a magnetron. Using this connection the magnetron works as a cathode full time, having a rectified double frequency current, whereas alternatively one of the anodes every half cycle is an anode and the other an additional cathode. This behavior creates a self-cleaning regime for both anodes. The system was usefully tested in the AC frequency range of 40–100 kHz.

Plasma density near the magnetron slightly changes every half cycle, therefore, dropping the necessity for voltage overshoot for its reestablishment. Such re-establishment is often seen for a dual-magnetron system, where the dense plasma jumps for one magnetron to another every half cycle.

Introducing dual anodes placed symmetrically against the magnetron does not change the deposition rate distribution along the substrate holder surface. It also does not restrict implementation of closed-loop control systems for the production of transparent, scratch resistive  $\text{Al}_2\text{O}_3$  films, deposited with high deposition rates.

To control ion-bombardment of the growing film, the substrate holder is connected to the magnetron through a resistor and/or additional floating power supply. The high refractive indices of the deposited  $\text{Al}_2\text{O}_3$  films indicate the fruitfulness of such a connection especially in combination with an unbalanced magnetron.

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