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WHITEPAPER

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EFFECTS OF THE ANODE CONFIGURATION ON SUBSTRATE HEATING IN DUAL MAGNETRON SPUTTERING

Perhaps one of the most significant advances in the field of PVD has been reactive sputtering, which opened up a field once exclusive to RF techniques. With their lower costs and higher throughputs, reactive processes employing either pulsed dc or mid-frequency ac power have become common in the industry. The process instabilities due to arcing can be overcome with either method of power delivery by discharging the target surface at sufficiently high rates. When coupled with two magnetrons, mid-frequency ac further resolves the disappearing anode issue that can compromise stable long-term operation. Several commercial products such as the TwinMag™, C-Mag™, and others have adopted this approach and are commonly known as dual magnetron sputtering (DMS) tools. Since DMS tools are almost always associated with ac power delivery the terms will be used interchangeably throughout this paper.

Several years ago, reports emerged indicating higher levels of substrate heating and bombardment with the DMS tools as compared to dc methods[1,2]. For a large number of processes this was inconsequential and the small heating loads could be tolerated by the substrate. However, many plastic and polycarbonate substrates experienced damage from the increased heating load because of their low thermal capacitance and temperature susceptibility. As certain manufacturers of optical coatings began to move from glass to polycarbonate substrates (presumably in efforts to reduce costs), the problem became even more acute. This potential barrier to an emerging market was recognized in early 1998 and led to investigations into the nature and origin of the increased heating loads. Presented here are the findings of that investigation along with views on possible solutions.

ORIGINS OF SUBSTRATE HEATING

What is different between the ac and dc processes that causes the additional heating loads? We can start by listing all of the factors we know to contribute towards substrate heating [3]:

- Condensation of sputtered flux
- Kinetic energy of sputtered flux and reflected neutrals
- Radiative heating
- Charged particle bombardment

Now we can begin going through the list imagining ac and dc cases operating under identical conditions of power, pressure, geometry, and other process parameters. We then ask if the factor in question changes the heat load incident on the substrate between the two cases? With some thought we can begin eliminating the individual factors as minimal in change between the ac and dc case[1] until we come upon the last.

[1] *As an example, the heat of condensation for the sputtered flux will be dependent on both the material and deposition rate, which remains nearly identical between the two cases.*

Charged particle bombardment in the form of electrons and ions has been shown to markedly increase the substrate heating load[1]. Such increases in ion and electron bombardment between ac and dc processes have already been illustrated in previous reports, and can be on the order of 50 eV in ion energy and up to a tenfold increase in ion density near the substrate[2]. Such observations make ion and electron bombardment of the substrate the most likely and significant candidate for the increased heating during the ac process.

WHY THE INCREASED SUBSTRATE BOMBARDMENT?

With the likely cause of the heating in hand, the question of why it occurs in ac and not dc configurations becomes the focus of this investigation. The answer as to why the ac process has such a high degree of bombardment is best arrived at by asking the other side of the question: "Why is the level of bombardment so low in dc sputtering?"

It is sometimes taken for granted that dc configurations have low levels of substrate bombardment, but this wasn't always the case. In early diode and triode systems substrate heating was an issue whose solution came with the advent of the magnetron sputter source[4]. In diode and triode systems the plasma was not well confined and significant numbers of ions and electrons were present near the substrate creating the heating effect previously mentioned. The design of magnetron sources resolved this problem by confining the working plasma to the immediate vicinity of the cathode

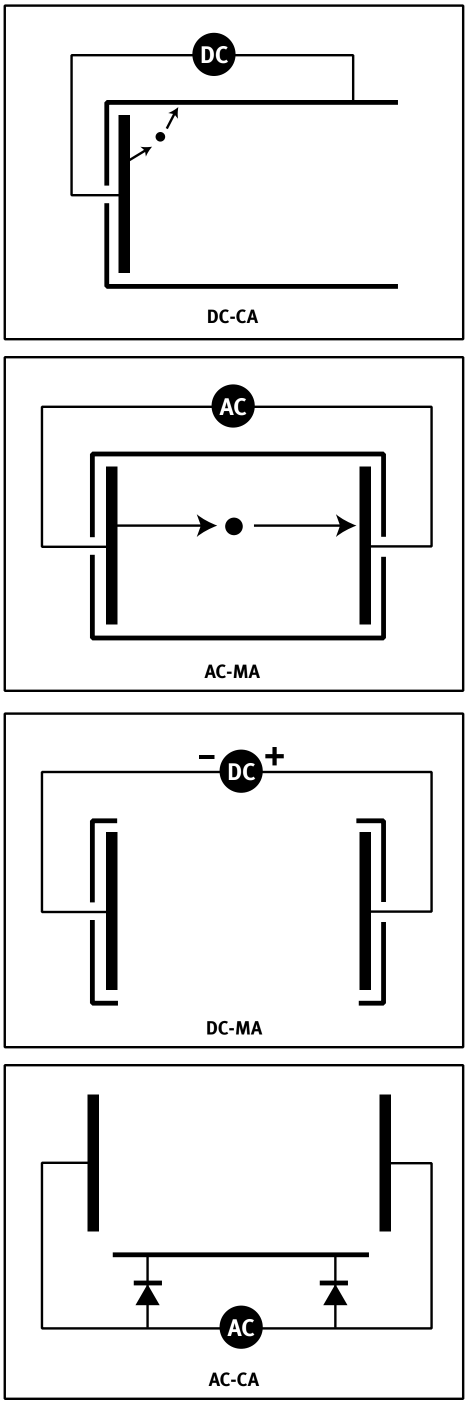

Figure 1. Tested configurations, first two letters indicate method of power delivery while the last specify the system anode:

DC-CA: standard dc using chamber anode

AC-MA: standard ac using magnetron anode

DC-MA: modified dc using magnetron anode

AC-CA: modified ac using chamber anode

using a magnetic trap. Also critical was the placement of an anode structure adjacent to the cathode to collect the low energy electrons and prevent ionization away from the working plasma (Figure 1, DC-CA). Both of these factors act to bring substrate bombardment and hence heating to a minimum in the dc case. Are both factors present in the ac process?

While DMS tools using ac do employ magnetrons to confine the plasma, many observers may note that the plasma appears to visually bloom away from the source indicating poor confinement. Is the magnetic trap not working effectively to contain the plasma or is something else amiss? Remember that the magnetron itself is only half the solution, and the adjacent anode structure is also critical. Where is the anode in an ac system?

Unlike a dc configuration that typically employs the entire chamber as the anode, the ac system relies on the second magnetron of the pair to serve this purpose. Therefore, instead of traversing the short path to the adjacent chamber wall, the electron return current must travel to the surface of the paired magnetron (Figure 1, AC-MA)[2] . Along such a path the electrons could be expected to ionize the process gas and bombard the substrate. Such an effect is purposely created in sources called unbalanced magnetrons where the magnetic fields are oriented in a way that funnels the return current towards the substrate. The primary purpose of these unbalanced sources is to create high degrees of substrate bombardment. Although often unintentional, employing a discreet anode such as a magnetron can create such an effect in the ac process.

While the anode location is of critical importance, the effective size of the anode also plays a role. As anode size decreases, both the plasma and anode potentials can rise significantly. At sufficiently small sizes the anode potential can exceed that of the plasma by an amount greater than the ionization potential of the process gas[5]. When such a state has been reached, a visible anode glow will form. Early thoughts suggested that the change in anode size and location might explain both the increased levels of substrate bombardment and the apparent cathode bloom in the ac process[3]. In order to ascertain whether this view was correct, it became necessary to isolate the anode effects in the ac system from other possible contributions.

[2] *The actual path will be determined by the geometry of the system and structure of electric and magnetic fields.*

[3] *It was speculated that the bloom could actually be a diffuse anode glow that appears superimposed on the confined cathode glow due to the high switching rate of the power supply (40 kHz).*

TESTING THE ANODE EFFECT

Two methods can be used to isolate the anode effect present in the ac system. The first is to modify the standard dc configuration such that the anode is confined to another magnetron (Figure 1, DC-MA). Alternately, the entire chamber can be included in the anode circuit for the ac process (Figure 1, AC-CA). In the first case described, we are adding the anode effect to the dc process, and in the second we are taking it away from the ac process. If the anode structure plays a significant role we would expect to see large increases in substrate bombardment and heating when the anode is restricted in the dc process, and correspondingly there should be a significant decrease in these levels when the chamber is included into the anode circuit of the ac process.

Isolation of the anode for the DC-MA configuration was accomplished by removing the internal grounding strap of the power supply and connecting the positive lead to the target of a second magnetron in the system. By breaking the internal grounding, the power supply was allowed to float and the full return current was forced through the paired magnetron. Including the chamber in the anode circuit for the AC-CA process required the use of diodes arranged in a manner that allowed electron return current to pass from the chamber to the positive side of the supply, but eliminated the possible charging of the chamber itself.

All the configurations mentioned were run in an industrial box coater with a set of 6" diameter closed field (fully balanced) magnetron sources in an opposed configuration. A 64 cm^2 aluminum substrate was located midway between the sources at a throw distance of 25 cm using a ceramic standoff. Sputtering of the aluminum targets was done at 2.5 kW in a pure argon environment of 6 mtorr. Deposition rates were recorded for individual runs to verify that the deposition rate remained a constant factor.

Measurements of the anode and substrate self-bias were made in an attempt to estimate the ion energy. Although the plasma potential was not directly measured, a previous investigation by Doyle[6] found the plasma potential to be approximately that of the anode for the range of positive biases encountered in our tests. The previously mentioned work of Belkind[5], however, cautions us to use the anode bias only as an indicator of increased plasma potentials and not an actual value.

While measurements of ion current and self-bias are useful indicators of the level of substrate bombardment, true heating loads are determined from substrate temperature rise profiles. Substrate temperatures were recorded from a thermocouple clamped to the substrate during each run. When coupled with an appropriate energy balance (Equation 1), the values of Q (incident heat load) and ε(substrate emissivity) can be empirically fit to the data.

$$Q - A\sigma\varepsilon(T_1^4 - T_2^4) = mc\,{}^{dT}/_{dt}$$

Equation 1. Energy balance on substrate assuming only radiative losses

RESULTS AND DISCUSSION

One of the most significant observations in all the tests was both immediate and visual. When configuration DC-MA was tested, the anode magnetron was surrounded by a very visible and diffuse glow while the cathode discharge displayed the typical well confined racetrack. While in no manner conclusive, this simple visual cue of ionization near the anode is the simplest, most compact representation of the data that follows.

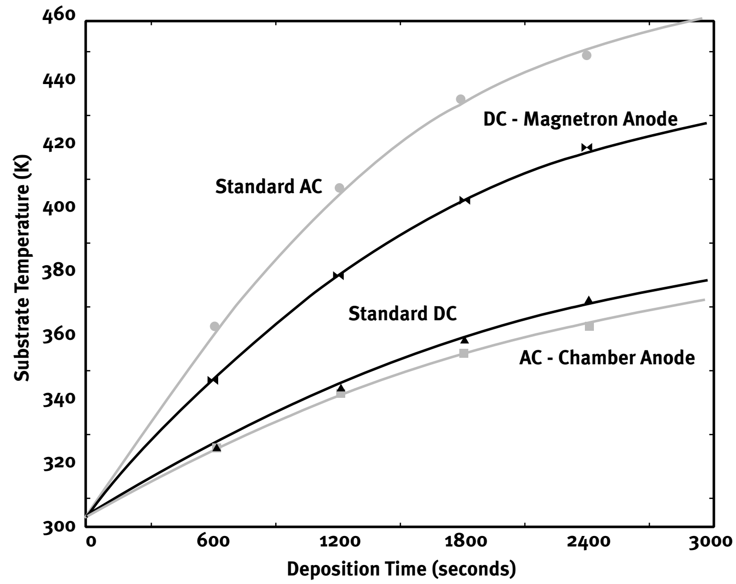

Figure 2. Temperature rise profiles for tested configurations; points indicate actual measurements and lines represent the best empirical fit of the energy balance (see Equation 1) with ε = 0.20

Aside from the visual observation mentioned above, another depiction of the data that illustrates important trends are the temperature rise profiles shown in Figure 2. We immediately see the large difference between the heating rate in the standard AC-MA and DC-CA processes. In terms of the anode effect, it is evident that restriction of the anode in the DC-MA case greatly increased the substrate heat load. Consequently, the addition of the chamber into the anode circuit for the AC-CA process actually lowered the heating rate to a level below that found in the standard DC-CA process. These are the trends expected if the anode structure has a significant role in substrate heating.

Quantitative values of the heating rates are given in Table 1. By simply restricting the anode of the standard dc process in the case of DC-MA, we see an 82% increase in the substrate heating load. This represents 56% of the total increase in substrate heating between the standard AC-MA and DC-CA processes. Alternately, testing of the AC-CA process shows a 7% drop in the heating load relative to DC-CA. This represents somewhat of a paradox as one would expect the result of subtracting the effect from the ac process (a decrease of 3.6 W) to be the equivalent of adding it to the dc process (an increase of 1.9 W) assuming that the effect is independent of other variables.

Configuration	Load (W)	% Increase
AC-MA	5.7	147%
DC-MA	4.2	82%
DC-CA	2.3	0%
AC-CA	2.1	-7%

Table 1. Substrate heating loads calculated from Figure 6; percent increase is relative to standard dc configuration

Some amount of the paradox can be resolved by an observed decrease in the deposition rate for the AC-CA configuration relative to the other three scenarios (Figure 3). This 23% reduction in deposition rate will lower the heat of condensation and can explain to a degree the lower heating rate observed. Whether this effect alone can account for the full discrepancy is open to challenge, and there may be a heating factor present in the ac process that is the combined effect of the anode configuration and the time variant nature of the process.

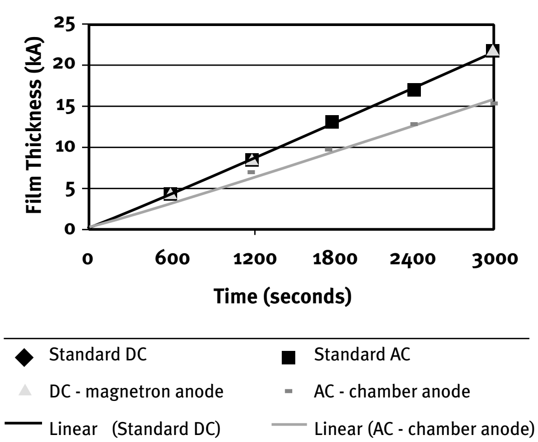

Figure 3. Substrate deposition rates at 2.5 kW; values of 7.2 and 5.3 A/sec calculated for DC-CA and AC-CA, respectively

Measurements of grounded ion current, substrate floating potential, and anode bias (Figure 4 and Table 2) all support the trends illustrated by the temperature profiles. Higher ion currents and biases are present in those configurations with higher heating loads indicating higher levels of bombardment as expected.

A final observation in support of the anode effect was the disappearance of the cathode bloom when the chamber was included into the anode circuit of the ac process (AC-CA). In this configuration both magnetrons displayed the well-confined racetrack typical of standard dc processes with no visible ionization witnessed outside the working plasma.

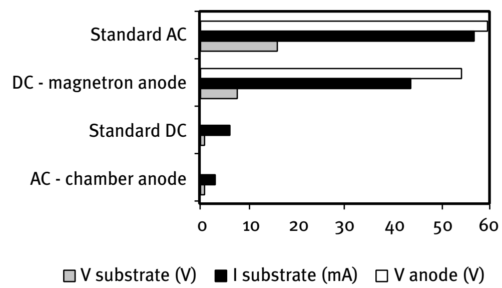

Figure 4. Self-bias voltages and ion currents on the substrate and anode

SEARCHING FOR SOLUTIONS

With the restriction of the anode appearing to account for a majority of the substrate heating load, anything that can be done to provide for an anode structure that is either more local to the cathode or in other ways more efficient at collecting the electron return current will be of benefit.

One of the first questions posed in view of the data was the degree to which the use of a magnetron as an anode restricted the ability to collect the return current. It should be expected that the same magnetic trap that so efficiently confined electrons to the cathode would now tend to exclude them from the anode. To test this influence, the magnetics package was removed from the anode of the DC-MA configuration and identical tests were run. The heating load on the substrate was reduced by 17% from that with magnetics, and correspondingly the values of ion current, substrate floating potential, and anode bias dropped to 24.1 mA, 8.5 V, and 30 V respectively. While the effective anode size restriction created by the magnetics does have an influence, the true size of the anode and its location appear to play more dominant roles in our configuration.

The first true attempt at a solution was the crossed anode approach. In a crossed anode configuration the isolated center anode of each magnetron is connected to the target of the other (Figure 5). In this manner, an anode local to the cathode can aid in collecting a fraction of the electron return current before it creates ionization in the region of the substrate.

Tests run with the crossed anode approach in the ac process showed a reduction in substrate heating and bombardment on the order of those recorded for the DC-MA case. Although these results are promising, questions remain as to the long-term stability of such an approach. The susceptibility of the anode to becoming coated with a dielectric may be quite high depending on the deposition rate on the anode surface.

Ultimately one comes to the realization that the very stability of the ac technique requires that the anode be sputtered to provide a clean and reliable path for the return current. This is performed most practically if the anode is a magnetron source. While a variety of techniques may act to minimize the heating due to the anode effect, its elimination in the ac process is, to a large degree impractical.

Configuration	V_{target} (V)	I_{target} (A)	$V_{substrate}$ (V)	$I_{substrate}$ (mA)	V_{anode} (V)
AC-MA	663	3.9	15.9	56.5	60.0
DC-MA	570	4.4	7.54	43.3	54.1
DC-CA	664	3.8	0.70	6.00	0.00
AC-CA	599	4.4	0.93	2.98	0.00

Table 2. Currents and voltages for target, substrate, and anode for the tested configurations; all voltages are referenced to ground

As is so often true, most solutions require one to rethink the problem. When properly defined, the problem simplifies to one of preventing ionization in the region near the substrate and not in the entire chamber. One of the most promising methods of accomplishing this goal was presented by Ounadjela[7] where a magnetic field applied parallel to the surface of the substrate reduced its temperature from 200°C to near room temperature during deposition. Such a field will be perpendicular to the motion of the electrons and produce a lateral force to deflect electrons around the substrate. This method is easily transferable to the ac process where similar results are to be expected. Unfortunately, this technique was discovered after our experimental runs were made and such benefits have not been confirmed by us.

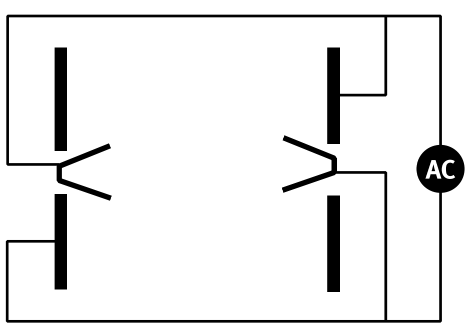

Figure 5. Crossed anode configuration utilizing center anode posts

CONCLUSIONS

Measurements of the substrate heating load indicate that over 50% of the increase witnessed between ac and dc processes can be accounted for by changes in the anode configuration alone. By restricting the anode to a paired magnetron, the ac process produces high degrees of substrate bombardment that have been linked to increased heating loads both here and in other investigations[2,8]. Visual observations of the discharge indicate that the apparent cathode bloom witnessed in the ac process is likely a superimposition of anode and cathode glows. Methods of reducing the heating load have been proposed with the most promising being that of magnetic exclusion offered by Ounadjela[7].

Although the primary focus of this investigation was to discover and eliminate the sources of substrate heating, other applications of the findings are possible. Several processes benefit from substrate bombardment to produce better film qualities and adhesion. The data presented here suggest that high levels of bombardment can be created in standard dc configurations with the proper choice of anode structure. In theory, levels comparable to or exceeding those of highly unbalanced magnetron sources should be achievable with no modifications of the source itself.

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