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ADVANCES IN ARC HANDLING IN REACTIVE AND OTHER DIFFICULT PROCESSES

Past approaches to arc control in difficult processes have focused upon reduction of the energy dumped by a dc power supply into an arc, or have used high-frequency or medium-frequency power, either by itself or in conjunction with dc power to reduce or eliminate the onset of arcing. This paper describes an approach that uses dc power together with an accessory element. The accessory can work proactively to greatly reduce arcing or prevent it altogether, especially in processes which form insulating films on the target. It also reduces the energy delivered to any arc which does occur down to the millijoule level, virtually eliminating particulate generation or damage to the target and substrate. This approach makes dc sputtering of highly insulating materials by reactive sputtering (such as Al_2O_3 , Ta_2O_5 , SiO_2 , and the like) practical and greatly improves the optical properties of such films due to the great reduction of particulates as scattering sites.

INTRODUCTION

Modern power supplies that store very little energy in turn deliver very little energy to an arc. Such a power supply can act automatically, through passive circuitry, to extinguish arcs as they occur without disturbing the power supply's regulation or logic circuits. In the past, these "micro arcs" were often ignored as not important; sometimes their very existence was unsuspected, since the power supply did not indicate their presence directly.

Process engineers are becoming increasingly aware that these "micro arcs," while not creating obvious damage to target or substrate, can nevertheless dislodge material from the target. This material can subsequently become embedded in the growing film. Process people have increasingly focused on this source of particulates because demands for ultra-smooth, particulate-free films have become commonplace. For example, glide heights of the heads on computer hard discs have steadily dropped over the years to values well under 100 nm, where even the tiniest particulate creates a glide defect.

ARCS

Types of Arcs

"Arc" is a general term used for any low-impedance condition created by the process that appears at the output of the power supply. This can be created in at least three ways:

Plasma-target arcs. The cathode dark space is bridged by a strong electron flow. This could be started by the breakdown of an insulating region on the target, by the release of trapped gas from the target, or by the presence of a field emission point on the target or another source of electrons originating on the target surface. Reversal of target voltage will immediately quench these arcs.

Shield-substrate arcs. If voltage builds up between a shield or mask and the substrate, an arc can form between them. This can cause film damage. In CD production, such damaged spots

are sometimes called "mousebites."

Target-shield arcs. A low-impedance path is formed from the target to ground (usually a dark space shield). It is generally formed by the direct breakdown of the gas in the intervening space, or by the presence of a conducting bridge such as a flake from deposited material. These arcs or shorts can conduct in both directions and reversal of target voltage will not reliably quench them.

While the last two are interesting in their own right, this paper focuses on plasma-target arcs.

Causes of Plasma-Target Arcs

Arcs would not occur in a well-designed system with clean elements and a smooth target surface running a nonreactive process. Observed arcs of this type in a sputtering system can be caused by particulate contamination of the target surface (or nearby elements); insulating contamination on the target; microscopic irregularities or inclusions in the target surface, surrounding clamps, or other source components which might be capable of field emission; or reactive components in the residual gas which form insulating compounds with the target material, either inadvertently or intentionally introduced (as in the case of reactive sputtering).

How a Plasma-Target Arc Forms

Normally, the atoms in the vicinity of the cathode are in one of two physical states: gaseous or plasma. The plasma state is created by ionization of the gas, and is the source of the

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sputtering ions. A plasma is a roughly neutral cloud of ions and electrons. The ions are created by collisions with energetic electrons; the electrons come from prior gas ionization or from secondary emission of the target. The first ion is formed by a cosmic ray, or by collision with an electron created by a field emission from the target. Once the first few ions are formed, a cascade occurs if the electromagnetic field (and pressure) are within well-defined ranges. This cascade forms as electrons are trapped by the crossed fields above the target; each electron can ionize many neutral gas atoms before being lost through some loss mechanism.

Normally, the plasma density is determined by the electron density, which in turn is a function of the magnetic field. If for any reason a small region of the target feeds electrons at a high rate into the plasma, ions are immediately attracted to create a sheath around the incoming electrons, and a small thread of ions and electrons bridges the cathode gap. This is what we call an “arc.” The condition can be caused by a field emission from the target, by heating of a target spot to thermionic emission, by a release of gas trapped in a gas pocket, or by catastrophic breakdown of the target due to electric forces. This last is the focus of this paper; the condition occurs if an insulating area exists on the target surface. Charging the insulator by bombarding ions can create incredible forces on the atoms.

DC SPUTTERING OF INSULATORS

Contrary to conventional wisdom, insulators can be sputtered with a dc potential. The problem is that it cannot be sustained for any length of time.

In dc sputtering of metals, the target is conductive. A negative potential is applied to the target and this attracts positive ions from the plasma (generally argon ions). As the ions arrive at the target they knock loose a target atom (this is, of course, the sputtering process) and also capture an electron from the target because there are many in the metal's conduction band. The ion then becomes a neutral atom and drifts away from the target surface to join the other background gas atoms. The electron is replaced by the power supply through the conductive leads to the target and this becomes the power supply current.

If the ion arrives in a region of a metal target covered by an insulating film, it cannot capture an electron, because there are no electrons in the conduction band of the film. Nevertheless, since sputtering is purely a momentum transfer process, sputtering of the insulating layer does take place, the same as with the metal surface. A positive charge on the surface of the insulating region, however, attracts a “mirror” electron on the conductive target surface or backing plate, and this mirror charge in turn attracts the positive ion, holding it firmly in place. One can think of the insulating layer as a capacitor, with one plate being the metal target and the other the surface of the insulating layer.

Ions continue to arrive at the surface in this way, continually sputtering away the insulator, but also continually “charging up” the capacitor. This charging process increases the voltage across the insulating layer. Because the total voltage from backing plate to ground is fixed by the power source, any voltage building up across the insulating layer must be subtracted from the voltage across the cathode dark space. Put another way, as the ions charge up the surface, they force the surface potential closer and closer to the plasma potential. Eventually there will be no electric field left between the plasma and the target surface to attract more ions; the charging of the target “capacitor” will have used up all of the power supply potential. At this point, sputtering of the insulating region must stop (see Figure 1).

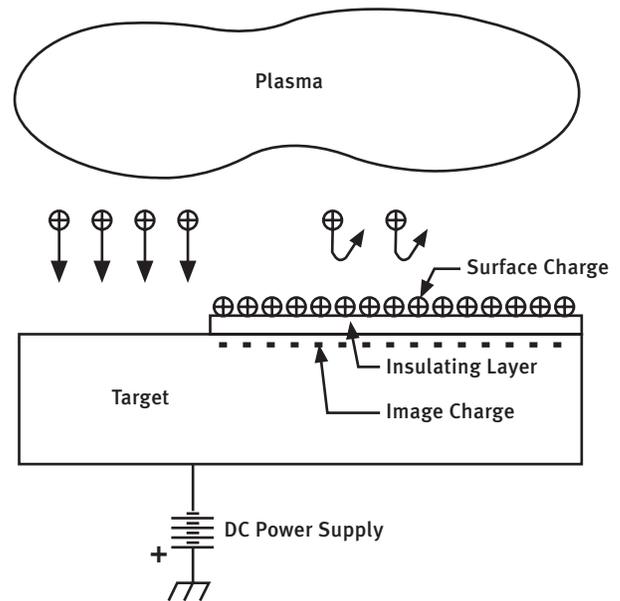


Figure 1. Charge buildup on insulating layers.

The events explained above take place as described provided that the insulating film is able to withstand the electric field created by the charging on its surface. In practice this is frequently not the case, and the film breaks down when the electric field reaches the dielectric strength of the material. This electrical breakdown is often the initiator for an arc. In addition, as the film is torn asunder, particulates are formed. These particulates are often charged and can defy gravity as they are moved long distances by electric fields in the chamber. These projectiles can be included in the film growing on the substrate or can remain on the target or adjacent parts to become the source of further arcing. Our goal is to prevent the electrical breakdown, thus preventing arcing and particulates. Before I describe how this can be done, however, I'd like to discuss the case of nonuniform films briefly.

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In reactive sputtering, a thin film is created on the surface which is not of uniform thickness (see Figure 1). In reactive sputtering, the metallic target is sputtered away as usual in the erosion zone, but a nonuniform insulating film builds up in the transition region between the erosion zone and the unsputtered region of the target (see Figure 2). This film's thickness builds up from zero to substantial values over a fairly small distance, and one might expect that the first place breakdown might occur would be in the thinnest spot of the film, since thinner films break down at lower voltages. This turns out not to be the case.

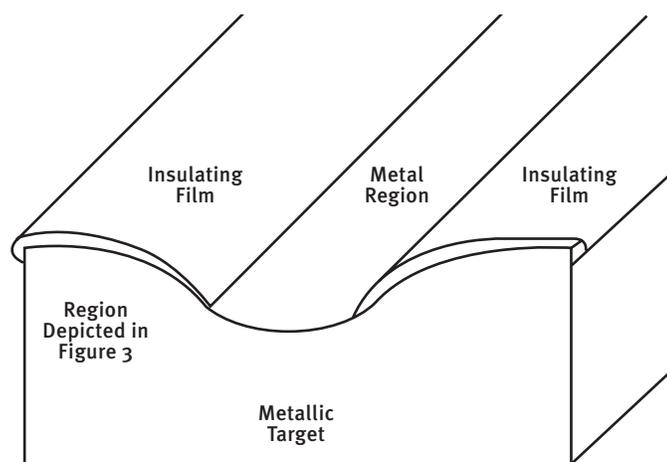


Figure 2. The erosion zone in reactive sputtering.

Figure 3 is an expanded view of the transition region from metal to insulating film. Imagine a small area A of this insulating film being bombarded by a current density J . The area A forms a capacitor with the underlying metal with a capacitance of

$$(1) C = \frac{\epsilon_r \epsilon_0 A}{d}$$

In equation (1), C is the capacitance, ϵ_r is the dielectric constant of the film, ϵ_0 is the permittivity of free space, and d is the film thickness.

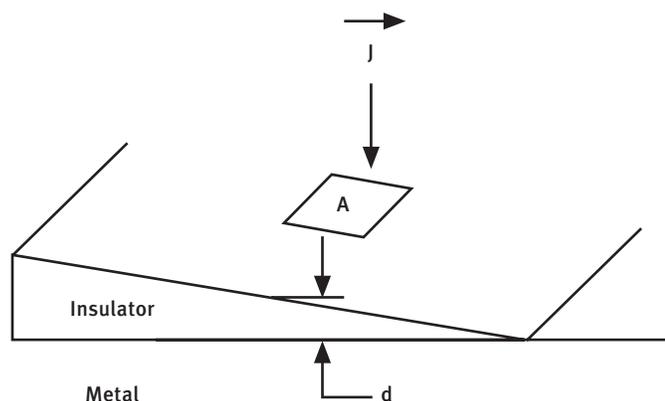


Figure 3. Transition zone from metal to insulator.

The voltage on this capacitor is related to the charge on the area A as follows:

$$(2) Q = JAt = CV$$

where t is the time since the capacitor was last discharged.

Combining equations (1) and (2) yields

$$(3) E = V/d = \frac{Jt}{\epsilon_r \epsilon_0}$$

where E is the electric field in the film.

Thus the electric field in the insulator is not dependent upon the thickness d . Rewriting equation (3), substituting E_b for the value of the breakdown field for the insulating material (i.e., its dielectric strength) and solving for the time to reach this breakdown yields

$$(4) t_b = \frac{\epsilon_r \epsilon_0 E_b}{J}$$

Equation (4) gives the time to breakdown, again independent of d , the film thickness. The reason for this independence is that, while the breakdown voltage is lower at the thinner cross-sections, the capacitance to the target is larger as well, and so the voltage builds up more slowly there. The two effects cancel and all regions of the film break down at the same moment, the time of which is given by equation (4).

This assumes that the current density J is constant, which of course it is not; the current density is higher near the thinner regions, which would cause these regions to break down first. The point of the derivation is to show that there is a compensating effect which holds out hope that if the film can be discharged periodically (with a period less than t_b), breakdown can be avoided.

THE SOLUTION

A circuit has been designed which reverses the target voltage periodically to a value about one-tenth of the operating target voltage. The voltage reversal attracts electrons to the target surface, discharging any ions which may reside on any insulating layers. At the same time, the voltage is not so large nor the time so long as to disturb the ion cloud. Once the surface is discharged sputtering can begin again. The voltage reversal is held for $5 \mu s$, and the period between reversals is $50 \mu s$. Using equation (4), and assuming material characteristics of Al_2O_3 ($E_b = 10^8$ v/m, $\epsilon_r = 10$), the discharge period t_b of $50 \mu s$ will suffice to discharge a surface bombarded with a current density of approximately 10^3 A/m² (100 mA/cm²).

The method used to create the voltage reversal is simple: An electronic switch and transformer circuit act to reverse the target voltage to a value approximately equal to one-tenth of the operating target voltage. This is generally slightly more



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positive than the plasma potential. This positive voltage acts to attract electrons from the plasma to the target. While the electrons actually arrive in a few nanoseconds, the positive potential is maintained for about 5 μ s because stray inductances and capacitances can cause potential delays in the appearance of the voltage on the target surface.

While the positive potential is being applied to the target surface, a fairly large inductance, preloaded to be carrying a current just equal to the power supply current, is shunted across the power supply leads. This completely isolates the power supply from the target voltage reversal. Thus the servo loops of the power supply do not see the abrupt change in voltage at the target, and need not slew to attempt a correction. This means that the power supply is ready to resume normal operation within a very short time after the pulse is terminated.

Because the full output voltage of the power supply is applied to the above-mentioned inductance, the current in the inductor, initially equal to the steady-state process current, will ramp up slightly. This represents storage of the energy delivered by the power supply during the pulse. At 10 kW, this amounts to about 50 mJ. A special “snubber” circuit shunts this excess energy to a power resistor during the “off” time.

Arc Handling

The unit will also handle arcs if they do occur. This arc handling action is actually identical to that described above. When an arc begins, there is an abrupt drop in voltage across the cathode dark space. A trigger circuit has been designed to monitor the target voltage and produce a trigger event when the voltage drops below a nominal arc threshold level. This trigger is used to turn on the electronic switch in between “self-triggered” events. Shunting the power supply current and reversing the voltage not only extinguishes the arc but also greatly reduces the energy delivered to it. Typically the energy delivered to an arc is under 1 mJ.

Applications

The system can be applied in a wide variety of processes. In applications where reduction of particulates is of considerable interest, the units can increase yields because of the much lower energy dumped into the arc. In reactive sputtering applications, the units can permit much higher rates than were previously possible with a single cathode system. In addition, the lower energy content of the arc handling in such systems makes the inclusion of particulates in the film (which often destroys its optical properties) a much smaller problem.

This design has been used in processes wherein the final film was highly insulating, including SiO₂ and Al₂O₃. In such cases the problem of the “disappearing anode” must be dealt with. Every system must have an electrode which collects electrons lost from the plasma; the resulting current flow is

actually the return current to the power supply. The anode may be a separate electrode or the chamber walls. If, as is usually the case, the anode is exposed to deposition, and if the deposit is highly insulating, eventually the process must stop for lack of an effective anode. From the power supply’s point of view, the impedance of the plasma appears to increase over time until the supply reaches its voltage limit. It is possible to design anodes which are still effective when exposed to coating; these are usually a reentrant structure of some sort. Users intending to use designs such as this to deposit highly insulating films from a single cathode must carefully consider this problem from the outset when designing such systems.

OTHER METHODS

Several other methods relating to arc control have been described in the literature. These include use of dual sources^[2,3,4], so-called “mixed mode” sputtering^[5], low-frequency ac technique^[6], and use of radio frequencies either alone or in combination with dc power. The principal advantage of the Sparc and Sparc-le technique is that it can be added to existing systems at low installed cost and with a minimum of system changes.

CONCLUSION

It is possible to design active switching circuitry which can greatly reduce the incidence of arcing in reactive sputtering processes, particularly when the resulting film is highly insulating. The same techniques can be used to lower the energy available to an arc, and thereby greatly decrease the detrimental effects of arcing, including particulate generation and target and substrate damage. The technique can generally be applied quickly and inexpensively to existing systems without system redesign.

ACKNOWLEDGMENTS

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