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ARCING PROBLEMS ENCOUNTERED DURING SPUTTER DEPOSITION OF ALUMINUM

The physics of plasmas and particularly the physics of plasma arcs and their genesis has received new attention in the last five years. Researchers working on high-power lasers, fusion, charge particle accelerators and others have required high energy pulsed power. Many of these applications use switching technology based upon devices such as thyratron tubes and spark gaps. These devices cause a gas to undergo a transition from normally insulating to a conducting state, a purposeful use of plasma arcs. As demands for increased switching speed at higher and higher current densities grew, greater understanding of arc formation became necessary. While no single, complete theory covers all aspects of arc formation, much working knowledge has been gained. The physical problem of interest is primarily the growth of the ionization of a gas in an electric field and the subsequent breakdown of the insulating qualities of the gas (a very good, current reference on this is in[1]). Although a plasma or glow discharge is already a conducting gas (i.e., it has broken down the insulating properties of a neutral gas), it has not reached current saturation and can be caused to conduct even more current. This research has significant implications for the lower energy uses of plasma commonly found in thin film processes such as etching and sputter deposition where arcs are sometimes troublesome.

Arcs, as used here, are local events within the sputtering chamber that are detrimental to the process. Arcs are high power density short circuits which have the effect of miniature explosions. When they occur on or near the surfaces of the target material or chamber fixtures they can cause local melting. This material is ejected and can damage the material being processed and accumulates on other surfaces. This erosion can contaminate the source as well as degrade the structure.

This article is meant to provide an introduction to the causes, mechanisms, and some cures for arcing in the sputtering environment. Since the application and distribution of power is central to the sputtering process, the new understanding of arcing phenomena will be related to advances in power supply design. In the following sections we will look at sputtering, simplified arc formation, some common causes of arcing and how to minimize them, and how power supply design is important to arc minimization.

THE SPUTTERING ENVIRONMENT

Figure 1 is a diagram of a simple sputtering chamber. A power supply is connected so that a low pressure gas is ionized by the voltage supplied. The ions of gas produced are accelerated toward the target surface by the voltage where they collide with the atoms of the target. The kinetic energy of the ions is transferred to these atoms, some of which are ejected and drift across the chamber where they are deposited as a thin film on the substrate material. Other impacted target atoms are simply heated. This is removed as waste energy. Still other impacts on the target surface produce secondary electrons. It is these electrons which maintain the electron supply and sustain the glow discharge[2].

A schematic drawing of a planar magnetron is shown in Figure 2. The magnetron type source is commonly used to deposit aluminum and is noted for its sputtering efficiency. It also has a greater propensity to arc[4]. The source is designed such that as uniform an electric field gradient as possible is maintained across the active sputtering region of the target material. This determines the local power density which in turn has an impact on arc formation[3,5,6].

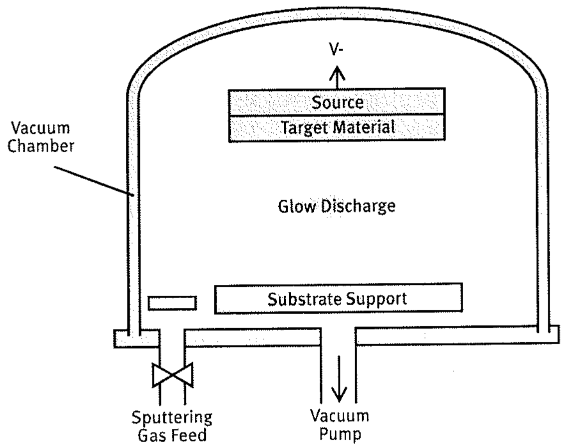

Figure 1. The sputtering environment

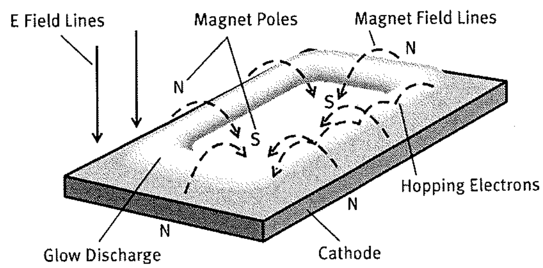

Figure 2. Magnetron

The magnets are placed so that the magnetic field lines are normal to the target material surface at the point of entry. The field is usually parallel to the surface in the sputtering regions. It is common for the shield surrounding the target to be at anode potential.

Electrons are charged particles. They also have a magnetic field because of their internal spin momentum. When they are ejected from the target surface, the electron's charge and magnetic field interact with the electric field and source magnetic field which causes the electron to remain near the surface[7]. Furthermore, their path near the surface is somewhat lengthened due to electric field gradients in the dark space. This path has two beneficial effects, 1) it provides a greater probability of producing more ions near the surface thereby increasing the sputtering efficiency and 2) the electron current is trapped near the cathode[2]. The latter minimizes electron heating and other damage to the substrate.

Magnetrons require careful attention to cooling because of this more concentrated electron current and higher ionization efficiency[7]. The sputtering area is more confined and controlled which in turn greatly increases the power density. Magnetrons also erode faster in the confinement area. This erosion causes impedance changes because the plasma to source magnet distance changes[2]. Erosion also changes surface texture and electric field gradients. All of these factors can contribute to arcing as we shall see later.

Other chamber factors cannot be ignored. The flow of the sputtering gas through the chamber, the chamber pressure, the power supplied and the source temperature must be carefully controlled as they too can contribute to arc production.

GLOW DISCHARGE POTENTIALS

We will now look more closely at the glow discharge space and the types of energies, potentials and particle species involved. The drawing of Figure 3 gives a relational view of charge versus potential in a typical negative glow discharge configuration.

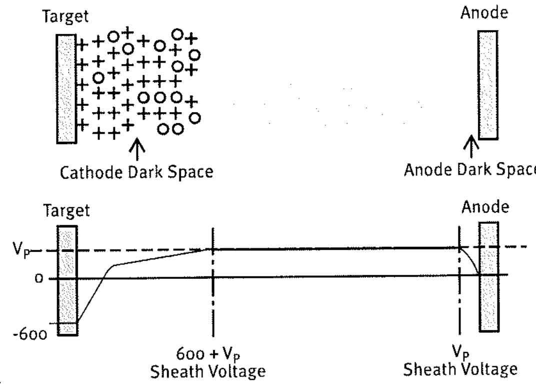

Figure 3. Glow discharge potentials

Through various mechanisms, the areas near both electrodes are striped of electrons and a surface charge is built up. As distance increases away from the electrode the charge balance returns to a more neutral value. This region is depicted by the + and 0 symbols in drawing 3. The potential across the glow region is nearly constant: almost all of the electric field potential occurs in the sheath. The cathode sheath region is of particular interest because it supplies the basic energy for sputtering. Most ions are produced in the negative glow region. These ions are accelerated by the sheath potential and bombard the target surface. This bombardment is what ejects the target material. It also produces a host of other particles and energies which contribute to sustaining the glow discharge.

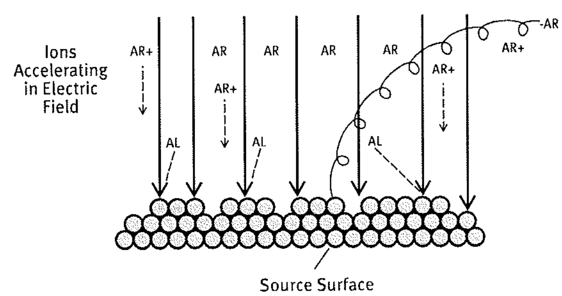

Figure 4. No arc

The surface/near-surface area is a busy place. We have a significant potential voltage supplied by the power supply, high voltage RF transients produced by magnetron oscillations in the plasma, a confining magnetic field, electrons colliding with the surface and gas atoms, photons exciting atoms to become ions, ions hitting atoms which produce more ions and thermal energy exciting atoms at local hot spots. All this with high average power density! At any given time these activities are in balance with degenerative phenomena and normal operation of the sputtering process is observed. This condition is depicted in Figure 4. The electric field lines are uniformly distributed across the surface and no major anomalies are present at the surface or in the dark space immediately above.

ARCS

Theory deals with two stages of arc formation. The first stage is the primary transition from normal gas state to that of a glow discharge. Let us suppose a dc electric field is applied between two electrodes (a spark gap) in a gas. It we then illuminate the cathode with light, a photoelectric current will be generated at the cathode. We may then move the electrodes together and at some distance the current will become self-sustaining without the light. This first level of current flow is known as a Townsend discharge[6]. Townsend proposed that the advancing primary electrons produced by photon excitation generated some multiple of electrons by electron/neutral atom collisions[9]. Later researchers[8,10] have shown that secondary events such as ion impact on the cathode and the photoelectric effect of the photons generated in the discharge were large contributors. At some point the secondary events happen in numbers sufficient to insure the regeneration of the primary electrons thus continuing current flow.

A second theory, labeled Streamer Theory, was proposed independently by Meek[13], Raether[14] and Loeb[15]. They argue that as the primary photoelectrons avalanche toward the anode they reach a critical size such that their combined charge starts to generate secondary electrons just ahead of the avalanche by photoionization. The avalanche space charge produces electrons efficiently which in turn generates a space charge cloud in front of the avalanche. This process repeats until the anode boundary is reached. This progression is called a streamer. Once the anode is reached a similar process begins at the cathode end of the parent avalanche. There the electrons are accelerated towards the avalanche which extends the ion sheath of the avalanche to the cathode. Breakdown occurs immediately upon the space charge cloud reaching the cathode[17].

If the resistance is low enough, the current will increase indefinitely (limited only by the power supply and the positive column impedance), which brings us to the second stage of arc formation. The current flowing in the gas will produce photons, heat and other reactions as we have seen which enhance the current flow until a visible glow discharge is produced. Depending upon the power available and the energy losses due to the chamber design, the process may stabilize at this point. In our sputtering chambers the cathode resembles an assembly of an infinite number of spark gaps which operate in this stable condition; however, if the current continues to increase an arc is formed. The avalanche path of electrons and associated ion sheath operate at a certain sustaining voltage determined by the gas, gas pressure and voltage potential. The increasing current flow and subsequent secondary activity continue to increase the local space charge. This causes a concentration of the electric field in the vicinity of the current flow. When the local potential reaches a value approximately 20% greater than the sustaining voltage a second breakdown occurs which lowers the gas discharge impedance to its lowest possible level...essentially a short circuit in which all energy transfer takes place. In a typical aluminum sputtering application using argon as the sputtering gas and a planar magnetron, this may happen with an incremental voltage change of as little as 72 volts.

Based upon the foregoing, it appears that a glow discharge process is never more than 20% away from an arc condition somewhere in the chamber. This is certainly true in the surface/near-surface area of the magnetron. This margin can become very much smaller as the design power density of the magnetron source is approached.

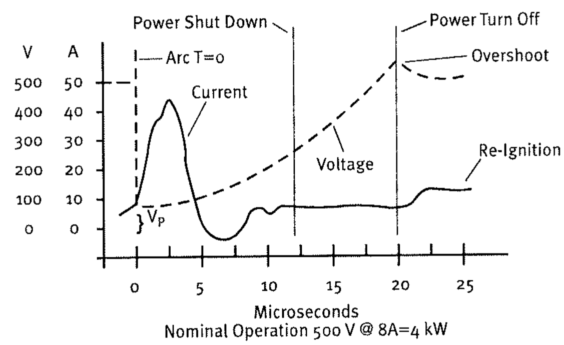

Figure 5. Typical arc profile

Figure 5 presents a profile of an arc in an operating sputtering system. The voltage drops in approximately 5 nanoseconds to an initial value. The load impedance at this point is limited by the power supply output, cable, chamber, etc. This voltage is maintained while the surface charge energy and power supply output capacitor discharge. In some older constant current supplies this current will continue to be supplied until outside factors cause the impedance to increase and extinguish the arc. If this doesn't happen, severe arcing called racetrack arcing can result. As soon as the current goes negative, the arc is turned off. The discharge and charge times and the current values are dependent upon the energy supplied by the surface charge surrounding the arc location and the stored energy in the output stage of the power supply.

ARC SOURCES

In general we may say that all arcs are the result of electric field anomalies, however, for convenience we will look at three classes of arc sources. These classes are mechanical, electric field anomalies and disruptions of surface equilibrium.

Mechanical sources are primarily flakes that short circuit various parts of the structure, commonly target to chamber, by bridging the dark space or by contacting the shield. Problems of this nature are cured by cleanliness and reducing actions which produce mechanical bumps and vibrations

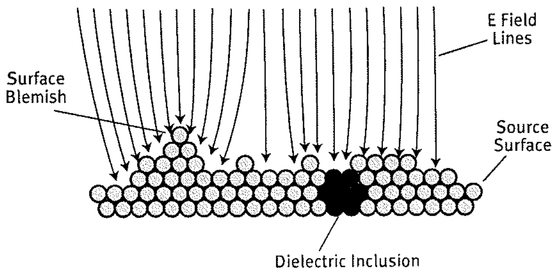

Figure 6. Potential arc source

I am using "electric field anomaly" to designate a small scale local disruption. In this category most of the sources are associated with the target material. The source must be of uniform composition and internal form. Such inclusions as gas pockets, voids, dielectric clumps, grain boundaries and surface blemishes can each cause an arc to form. Obviously the selection of the correct material is important. The material will vary from lot to lot from any vendor, but, a consistent problem may have to do with the material manufacturing process and other forms should be considered. Figure 6 shows the effect of a surface blemish and an oxide inclusion. Both of these defects cause a warp in the electric field in their vicinity which increases the power density. Other surface problems are caused by magnetic dirt attracted by the magnetic field of the source, local thermal hot spots on the target, local pressure fluctuations due to several molecules of water or other contaminants drifting by and the target's previous operating history. Target history is important. An operating target will settle into a certain set of equilibrium conditions including power distribution, heat distribution and re-deposition rate. A step change in power due to power line perturbations or loss of regulation can cause arcing until equilibrium is re-established. Targets that have been exposed to air must be preconditioned by slowly increasing the power level. This burns off accumulated oxides and drives off absorbed water and other contaminants.

Temperature variations can be caused by defects in the target surface which produce higher electric field densities. The surface of the target is always at a higher temperature than the bulk material. Arcs isolated to a specific area may be due to a poor bond between the target material and the source, a blocked cooling channel in the source or the source design itself causing elevated temperatures. These higher temperature areas are one of the principal causes of arcs, either because they are producing thermal electrons or are much closer to doing so. Thermal electrons then contribute to an increase in the secondary ion production cycle and associated power density increase and possible melting and/or sublimation.

Systems that have been modified or are new designs sometimes exhibit significant arcing associated with their structure. Older systems which have significant encrustations of sputtered material and/or severely eroded surfaces may have problems too. These can be cured by cleaning and smoothing surfaces to approximately 600-800 grit. System fixtures should have beveled or rounded edges and interfaces with target, dark space shield, insulators and supports to reduce electric field gradients. Some systems may require auxiliary magnets or secondary electrostatic shielding to eliminate consistent arcing in a specific place.

POWER

It may be said that the power supply feeding the system is the ultimate cause of and cure for arcing. In the discussions above we have covered many of the details of arc formation. In this section we will discuss the management of the power supplied to the process to minimize the occurrence and severity of arcs.

Looking again at Figure 5, we see a large current spike as the arc discharges the chamber and the power supply output filter. Since the chamber normally presents a very small capacitance the majority of the stored energy is due to the power supply output. Anything we can do to reduce this energy directly reduces potential arc damage. One technique which is very effective is to raise the frequency that must be filtered. As an example: for equal levels of voltage and current at the output the amount of energy per cycle which must be supplied at 360 Hz (60 Hz 3 phase) is 100 V x 5 A x 2.8 millisec. = 1.4 Joules while at 100 kHz it is 100 V x 5 A x 5 microsec. = 2.5 millijoules. The smaller energy at higher frequency allows smaller value components to be used. The ripple voltage at the output can be made much smaller which reduces the chance of the power density exceeding the breakdown potential somewhere on the target.

Higher frequencies allow much faster response to problems on both the input and output of the power supply. Again, a 60 Hz, 3 phase power supply can reduce a 10% input voltage increase to 1% in about 20 milliseconds while a 100 kHz supply can do the same in 30 microseconds. Arc inception times are in the range of 10-6 seconds[21] which puts the 1 00 kHz supplies response in the same decade, certainly an advantage. This same rapid response holds true for load-induced transients such as impedance changes.

Knowledge of arc mechanisms has improved circuitry for suppressing them. It has been found experimentally[22] that an area where an arc has occurred takes approximately 5 milliseconds to return to equilibrium conditions (cool down the surface or gas, disperse particles and fields) after the discharge current has fallen to zero. Building in a short delay of this order before power is re-applied virtually eliminates a second arc at that site[23].

Increasing the accuracy of instrumentation available enables the power supply to detect arc initiation ever closer to the fact. Tighter measurements allow greater repeatability and stability.

We have taken a brief look at arc mechanisms, their causes in the sputtering environment and the improvements in power application made possible by the study of them. As always, research continues.

REFERENCES AND FURTHER READING

1 J. M. Meek and J. D. Craggs, eds., ELECTRICAL BREAKDOWN OF GASES New York: Wiley, 197

2 B. Chapman, GLOW DISCHARGE PROCESSES New York: Wiley, 1980

3 J. S. Chapin, RES,./DEV. 25(l),37(1974)

4 J. L. Vossen, J. VAC. SCI. TECHNOL. 8,512, (1971)

5 L. T. Lamont, Jr., VARIAN VAC. VIEWS 9(3), 2(1975)

6 L. T. Lamont, Jr., J. VAC. SCI. TECHNOL. 14,12 (1977)

7 R. K. Waits in "THIN FILM PROCESSES" (J. L. Vossen, w. Kern, eds) Academic Press, 1976

8 F. Llewellyn Jones, IONIZATION AND BREAKDOWN IN GASES London, England: Methuen, 1966

9 J. S. Townsend, THE THEORY OF IONIZATION OF GASES BY COLLISION London, England: Constable, 191 0

10 F. Llewellyn Jones, "Ionization growth and breakdown," HAND. PHYS., vol. 22, pp 1-92,195

11 E. D. Lozanskii, "Photoionizing radiation in the streamer breakdown of a gas." SOV. PHYS.TECH. PHYS., vol. 13, pp 1269-1272, Mar. 1969

12 L. B. Loeb, "Electrical breakdown of gases with steady of direct current impulse potentials," HAND. PHYS., vol. 22, pp 445-530,1956

13 J. M. Meek, "A theory of spark discharge," PHYS REV., vol. 57, pp. 722-730, Mar. 1940

14 W. Rogowski, "Impulse potential and breakdown in gases," ARCH. ELECTROTECH., vol. 20, pp 1928

15 L. B. Loeb, FUNDAMENTAL PROCESSES OF ELECTRICAL DISCHARGES IN GASES New York: Wiley, 1939

16 G. M. Petropoulos, "Avalanche transformation during breakdown in uniform field," PHYS. REV. vol. 78, pp 250-253, May 1950

17 R. C. Fletcher, "Impulse breakdown in the 1 0 -9 sec range of air atmospheric pressure," PHYS. REV., vol. 76, pp 1501-151 1, Aug. 1945

18 A. Doran and J. Meyer, "Photographic and oscillographic investigations of spark discharge in hydrogen," BRIT. J. APPL. PHYS., vol. 18, pp 793-799, Mar. 1967

19 A. H. Guenther and J. R. Bettis, "The laser triggering of high-voltage switches," J. PHYS. APPL. PHYS., vol. 1, pp 1577-1613, June 196

20 F. R. Dickey, Jr., "Contribution to the theory of impulse breakdown," J. APPL. PHYS., vol. 23, p 1336-1339, Dec. 1952

21 K. McDonald, M. Newton, E. Kunhardt, M. Kristiansen and A. H. Guenther, "An electron beam triggered spark gap," IEEE TRANS. PLASMA SCI., vol. PS-8(3) 181, Sept. 1980

22 D. Schatz, "The MDX as a strategic tool in reducing arcing," APPLICATION NOTES, Advanced Energy Industries, Inc., 1983

23 PHYSICAL VAPOR DEPOSITION (R. J. Hill, ed.)

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