Donald M. Mattox, Technical Director • Society of Vacuum Coaters
71 Pinon Hill Place N.E. • Albuquerque, NM 87122
505/856-7188 • FAX: 505/856-6716 • www.svc.org

Plasma Technology: Arcs, Microarcs & Flashovers

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A broad definition of an arc is that it is a sudden increase in current flow through or over an electrical insulator such as a "vacuum" (really a vapor of the electrode material), a gas, a liquid or a solid. Arcs have been around for millions of years in the form of lightning, where charge separation in the clouds generates a voltage (potential difference) large enough to create an electrical breakdown between clouds or from a cloud to ground. Opening a switch in a current-carrying electrical circuit can cause an arc between the contacts. This has been a major concern in power transmission for years. The high dielectric strength of a vacuum and the rapid condensation of metal vapor made vacuum circuit breakers the first commercial use of vacuum arcs.[1] In PVD processing, we are mainly interested in arcs through low-pressure gases, as well as arcs across electrically insulating surfaces and through thin dielectric coatings.

More specific definitions of an arc are used. One for a vacuum arc is: "—a discharge of electricity between two electrodes in a gas or vapor that has a voltage drop at the cathode of the order of the minimum ionizing or minimum exciting potential of the gas or vapor."[2] Using this definition, an electrical arc would be a low-voltage electrical discharge that would necessarily have a high current density in order to sustain the arc. The development of an arc in a high-voltage circuit is generally sensed by a power supply as a rapid increase in current or a rapid decrease in voltage. To quench the arc, the power supply generally responds by cutting off the power to the circuit and shunting the arc to ground. Often, the power supply counts the number of events. The definition of what an arc is, therefore, often depends on the settings of the power supply.

Arcs can occur between surfaces (cathode and anode) separated by a low-pressure gas, such as used in sputtering and arc vaporization for PVD. They may be intentional, as in arc vaporization, or unintentional, as in sputtering. An arc can be initiated in a number of ways. Intentional arcs are commonly formed by having a high-voltage pulse between closely separated electrodes that create gaseous ions, which then provide the conductive path for the low-voltage, high-current arc. A pulsed laser can also provide the ionization path in a gaseous environment.

Unintentional arcs can occur when a hot, thermoelectron-emitting source (such as an oxide particle) on the cathode ejects electrons into an electric-field gradient, where they are accelerated and create ions. Unintentional arcs can also be formed when a "flake" or protrusion of metallic contamination provides a high field point or a bridge that allows voltage breakdown of the gas. These arcs are sometimes called "hard arcs" because they can carry a lot of current for a long time.

Once initiated, an arc can be sustained, such as in arc vaporization, or it may be quenched. Sustaining an arc requires a power supply designed for the job. In arc vaporization for PVD, the evaporation can be from a small spot on a solid cathode ("cathodic arc") or from a large area on a molten anode ("anodic arc"). The cathodic arc is the most commonly used vaporization source, and the arc can move randomly over a surface ("random arc") or its movement can be controlled using a magnetic field ("steered arc"). The small spot gives a very high local temperature and high electric-field gradients. The above figure shows the path of an arc moving over a cathode surface. Arc vaporization has the advantage that most of the vaporized atoms are ionized, particularly in the cathodic arc. The cathodic arc has the disadvantage that some molten globules of the cathode material are ejected ("macros") that may be detrimental to film properties.

An arc may be quenched in a number of ways. These include:

1. The source of the potential difference may be removed,
2. The energy to sustain the discharge may be decreased, or
3. The discharge path may be interrupted.

If the duration of the arc is short and the total current carried is small, the arc is sometimes called a "microarc."

Arcs may be pulsed in several ways. An early method was to repeatedly mechanically "tap" the electrodes in vacuum, thereby drawing an arc on each breaking of the contact. The power supply can also be used to

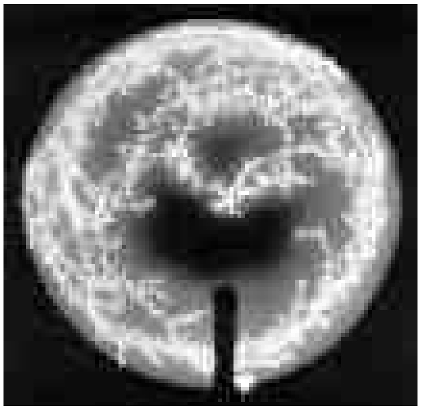

Fig. 1—Arc path on a cathode during arc vaporization. The dark shadow is the high-voltage, high-frequency igniter. Reproduced with permission from Multi-Arc Scientific Coatings.

create a pulsing arc. For example, Hoenig pulsed high-energy power at a frequency of 5 kHz (every 200 microsec) using a vacuum-arc switch, and quenched the arc on each cycle using a "counterpulse" of opposite voltage polarity during each "off" part of the voltage cycle.[3] The counterpulse not only stopped the current flow through the arc, it discharged the energy stored in capacitance and inductance of the power supply and the circuit that can "feed" the arc. Such a wave form is also called a "bipolar pulse."

Arcs can occur over electrically insulating surfaces. This is important to electrical feedthroughs and for electrical isolation in the deposition chamber. The design, the materials, and the surface finish of the electrical insulator are important to its "voltage standoff" ability. If the insulator becomes covered with contamination, the voltage standoff may be decreased. Arcing across the insulator surface generally originates at the "triple-point" (insulator-metallic cathode-vacuum interface). Electron emission at the triple-point initiates the arcing event. The arcing is aided by electron emission, electron cascade along the arc path, and outgassing of the insulating material.[1, 4] If the arc is not sustained, it is called a "flashover." Arcing can cause vaporization of the insulating material and deterioration of the insulating properties of the surface.

Charge buildup on an electrically insulating surface can occur due to electron or ion bombardment. If positive ions bombard a dielectric surface, they remove electrons by ion neutralization and secondary electron emission. A positive potential then develops on the surface. When the potential is high enough, positive ion bombardment ceases. If there is a conductive surface near the insulating surface, arcing can occur over the surface to neutralize the charged sites on the surface. The rate at which charge buildup occurs on the dielectric surface depends on a number of factors, such as bombardment flux, current leakage, etc.[5]

In RF (high-frequency AC) sputtering, a target of dielectric material, such as SiO_2, is backed by a metallic electrode, and the surface of the dielectric is in contact with a plasma generated by the RF potential.[5] The metal-dielectric-plasma configuration acts as a capacitor, and when a negative potential is applied to the metal, the dielectric polarizes in such a manner that a negative potential appears on the surface in contact with the plasma. This negative potential attracts positive ions from the plasma to bombard and sputter the dielectric surface. When the voltage polarity reverses, the surface is polarized positive and electrons from the plasma neutralize the positive charge site on the dielectric surface. If the applied potential were DC, the negative charge on the dielectric surface would be neutralized by the positive charge sites generated by the ion bombardment, and the sputtering would soon cease. In RF sputtering, where a self-bias is desired on the target, the frequency can be 13.56 MHz, a commercial RF frequency, where electromagnetic radiation is not a concern.

When "pulsed power" is used for sputtering, the voltage is periodically turned off or the polarity of the voltage is periodically reversed (bipolar pulsed power), allowing electrons from the plasma to periodically neutralize any positive charge buildup so high-energy positive ion bombardment can occur in a periodic manner. To be the most effective, the frequency of the pulsing should be greater than some value that is determined by the charge buildup rate.[5] Typically, this frequency is greater than 25 kHz.

Arcing on a metallic sputtering cathode can occur when it is first turned on due to oxide layers and contamination on the surface. Often a "break-in" (or "run-in") period is used to clean the target surface before the substrates are exposed to sputter deposition. Excessive arcing is undesirable because modern power supplies sense the arc and are turned off to protect the solid-state rectifiers. It is interesting to note that before high-power solid-state rectifiers were available, gaseous rectifiers (mercury-vapor thyratrons) were used, and they could tolerate arcing much better than solid-state rectifiers.

In reactive sputter deposition of electrically insulating materials, particularly when using a metallic planar magnetron sputtering cathode, arcing can occur on the "poisoned" areas of the cathode. The poisoned areas on the cathode are formed where the surface is not being rapidly eroded and can react with the reactive gas to form an insulating surface. The area that is being poisoned can be minimized in some configurations, such as the rotatable cylindrical magnetron[6] and the post magnetron, but the poisoned area is generally large in rectangular ("racetrack") planar magnetron configurations.

Arcing on the sputtering cathode can be minimized by using AC[5] or high-frequency RF (HF-RF),[5] a combination of DC and RF,[7] pulsed DC (single-cathode[8, 9] or dual-cathode[10,11]), or bi-polar ("counterpulse") pulsed power.[12, 13] In each case, the negative potential on the target is reduced, usually to zero, or made positive for a portion of each voltage cycle, thus allowing electrons from the plasma to neutralize part or all of the positive charge buildup on the insulating surface before arcing occurs.

Because the electrons are highly mobile compared to the ions, the "off" portion of the cycle may be significantly less than the "on" (bombardment) portion of the cycle, *i.e.*, the waveform may be asymmetrical in time and/or voltage magnitude. It should be noted that even when using these procedures the power supply should be able to sense arcs (hard arcs), and shut down for a period of time long enough to quench the arc.

In the deposition of electrically insulating films, it is often desirable to subject the depositing material to concurrent energetic ion bombardment (ion plating) to promote chemical reactions and densify the film. When using a DC bias on the substrate, this bombardment can cause arcing over or through the insulating film. Arcing on the depositing film can be minimized by using AC, HF-RF, pulsed DC, or bi-polar pulsed power for biasing.

Arcing, either on the sputtering cathode during reactive sputter deposition or on a depositing dielectric film, can be important to the processing and/or the resulting film properties.[13] Arcing can be minimized by proper choice of the power supply and the waveform used for sputtering or biasing. *P&SF*

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