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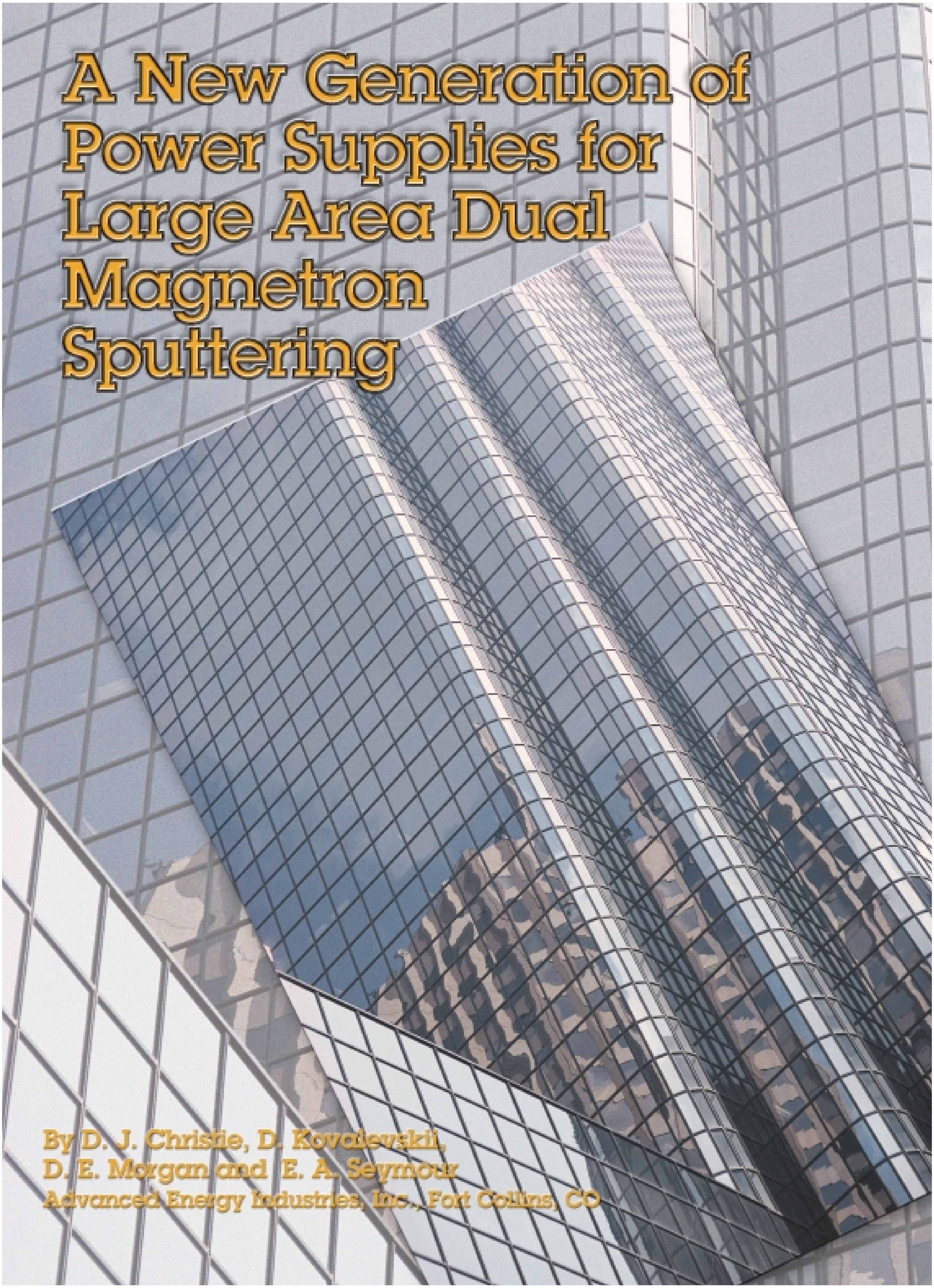

A New Generation of Power Supplies for Large Area Dual Magnetron Sputtering

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Large area coaters are commonly used to deposit thin film layer systems on glass or polymer substrates. Implementation of an optical filter is typically the objective. A combination of interference effects and the transmission and reflection spectra of the discrete metal and dielectric layers are used to arrive at their composite spectral transmission and absorption characteristics. Magnetrons operating in the metallic mode in an argon gas environment and powered by a DC supply are typically used to sputter the metallic layers, commonly titanium, silver, nichrome, aluminum or stainless steel [1].

A technique known as reactive sputtering, where a metal or semiconductor is sputtered in the presence of a reactive gas, typically oxygen or nitrogen, is used to deposit the dielectric. The dielectric is formed when the gas combines with the conductive sputtered material. Unfortunately, the dielectric can end up on the sputtering target and anode as well as the work piece. Therefore, an insulating coating may be deposited on both the target and the anode. This will eventually degrade and maybe even terminate the process if it is driven by a DC supply. This effect is referred to as a "disappearing anode." The eventual coating of the anode with an insulator, the same dielectric compound deposited on the work piece, causes it to "disappear" from the electrons needing it as a return path.

A dual magnetron sputtering arrangement, as shown in **Figure 1**, is one solution to this problem. An AC supply, isolated from the plasma chamber, is used to drive the pair of magnetrons. Consequently, the magnetrons alternate roles between cathode and anode. First, the magnetron target is the anode. In that phase, it receives a tiny deposition of dielectric. Then, it is the cathode, sputtering conductive material and the small amount of dielectric deposited on it when it was the anode. Therefore, a clean anode is maintained for completion of the current path.

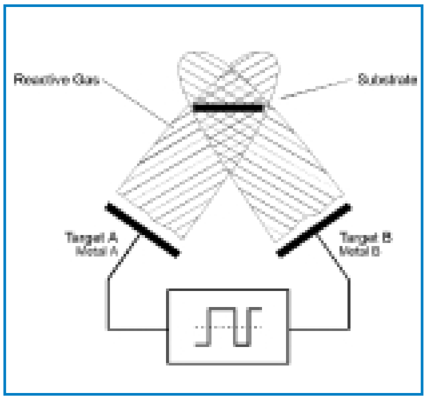

Figure 1. Dual magnetron sputtering arrangement.

This technique was first reported in 1988 [2]. It is commonly referred to as dual magnetron sputtering (DMS) or dual cathode sputtering. It is widely used in the industrial production of low-emissivity ("low-E") coatings on architectural glass in large scale in-line coaters. Mirrors, flat panel displays, and antireflection (AR) coated glass are among the additional applications of the technique. DMS is also applied in roll coaters to deposit coatings on plastic films for adhesively attached glare reduction filters and oxygen barriers for films used in food packaging laminates. It also results in smoother films, owing to a much higher flux of energetic ions at the substrate. Silver layers deposited on these smoother films exhibit lower sheet resistance, with a concomitant reduction in emissivity, while maintaining the same optical transmission characteristics [3].

The importance of DMS has motivated several workers to develop power supplies specifically for the application. Both pulsed and resonant supplies have been developed. High power resonant supplies are now offered commercially. They have been described at conferences and in the technical literature over the past few years [4–6]. Resonant supplies on the market today control and measure the total power delivered to the process. Measurement and control of the power, current and voltage specific to each magnetron is not yet commercially available in resonant supplies.

Greater flexibility in process control is available from pulsed supplies. They are capable of independent power regulation for each magnetron. This has advantages for existing processes, and enables new

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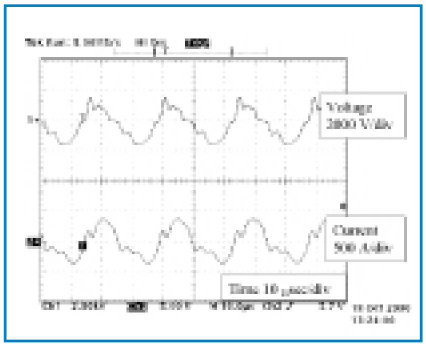

Figure 2. Resonant supply operation at 175 kW into the Al_2O_3 test process.

processes. First, each magnetron can be forced to receive the same power. This causes the racetracks to erode uniformly on each magnetron. In comparison, an impedance difference between the two magnetrons can result in faster erosion of one target when a resonant supply is used. This may unnecessarily reduce the time between target replacements. Second, the two magnetrons may be intentionally operated at different powers. Occasionally, a target can develop a tendency to arc. In that case, its power can be reduced to a level corresponding to an acceptable arc rate. The power to the other magnetron can be increased to compensate and, sometimes, maintain the same deposition rate from the pair. Third, controlled mixtures of materials in the film may be created when the magnetron targets are dissimilar materials. The result can be films with controlled custom indexes of refraction. For example, SiO_2 films can have an index of refraction of approximately 1.5 and TiO_2 can be deposited with a refractive index of about 2.4. A dual magnetron sputtering arrangement with one Si target and one Ti target allows the ratio of Ti to Si to be controlled by adjusting the power delivered to each magnetron. Therefore, in principle, it is possible to adjust the refractive index anywhere between 1.5 and 2.4. This technique is called co-sputtering [7].

HIGH POWER RESONANT SUPPLIES

Overview

The new high power resonant supplies described here have been specifically designed to drive high power process plasmas. The resonant circuit is the heart of the supply. It enables fast arc response and stable operation into high power plasma processes. These power supplies have only one active power processing stage, in contrast to the two or more stages in other resonant supplies reported in the technical literature. Output power is controlled by modulating the frequency of the inverter section. The resonant circuit is a multi-resonant type. It allows the ability to both increase and decrease voltage, deliver full power over a wide impedance range, and stabilize operation into a plasma.

An oscilloscope waveform of normal operation at 175 kW is shown in **Figure 2**. The asymmetry in the waveform is due to the gas distribution system in the test chamber. A strategy of creating the worst case conditions for the unit under test was adopted, so the asymmetry is just one way of maximizing the test stress on the power supply.

Arc Response

Arc response requirements are determined by the specifics of the coating system. In many cases, it is common for a reactive process to be operated in the poisoned mode, at a relatively stable operating point. In those cases, the conventional wisdom has been that a shutdown due to an arc of 100 ms or less would not result in visible banding in a large area in-line glass coater. In the past few years, there has been a move toward operation in the transition mode, where the operating point of the process is stabilized just past the knee of the hysteresis curve, by use of a partial pressure sensor or optical emission monitor. In those cases, the required arc response time is much shorter. In one paper, it was shown that response times on the order of 1 ms are required, otherwise, even for disturbances of only 10 ms, partial pressure disturbances lasting well beyond the allotted 100 ms may result [8]. This makes closed loop control to maintain operation in the transition mode nearly impossible when more than a few arc responses occur per second.

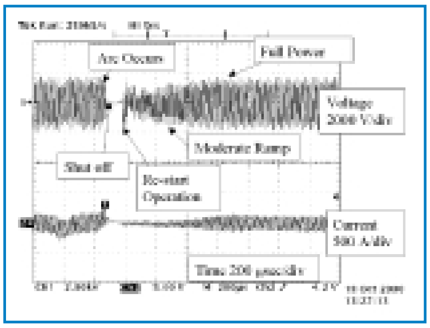

Figure 3. Resonant supply arc response at 175 kW into the Al_2O_3 test process.

There are two main requirements for arc response. One is fast detection. An arc must be detected in order for the power supply to handle it. The second requirement is low arc energy. This may be accomplished by minimizing the energy stored in the resonant circuit, and by providing someplace other than the arc for most of the stored energy to go. Fast arc detection requires that the resonant circuit not be too “stiff,” so the arc can be quickly observable. One paradigm makes use of a filter between the resonant supply and the magnetron pair [9]. These filters are designed to mask small arcs, so the power supply “rides” through them. The new power supplies reported here detect and respond to every arc.

An arc response waveform is shown in **Figure 3**. The time scale is such that the occurrence of the arc, the shutdown, and the recovery to full power are visible. Notable in the return to full power is the recovery ramp. There are three choices for the recovery ramp: instantaneous, moderate and slow. The different recovery ramp speeds are used for different materials. For example, immediate recovery can often be used for TiO_2, while the slow ramp is usually best for low melting point processes, such as SnO_2 and ZnO. A view of the arc response on a much shorter time scale is shown in **Figure 4**. Here, the detection and shut down are visible. What is notable here is the detection within a quarter cycle, and the rapid shut down and ring-out of the resonant circuit. Most of the energy stored in the resonant cir-

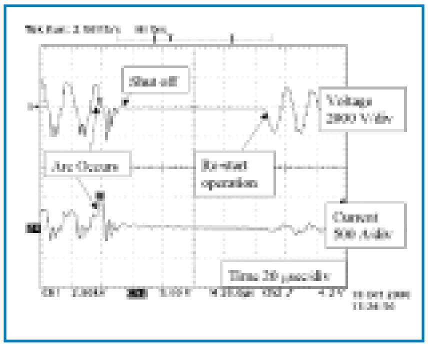

Figure 4. Zoomed-in view of the resonant supply arc response at 175 kW into Al_2O_3 process.

cuit is returned to the DC bus capacitors. Only a fraction of the resonant circuit energy is delivered to the arc.

This new power supply handles every arc. Some previous approaches ignored low level arcs, and only shut down when a large scale arc developed. The approach taken here is to detect and handle every arc, as part of a strategy to achieve a managed low arc density. This prevents hot spots from growing, and eventually developing into low impedance bipolar arcs.

Arcs are detected by looking at output current. When an arc occurs, the output current rises above the normal operating level. The arc threshold is set automatically by an algorithm which adapts to the operating point. Therefore, constant threshold adjustment is not necessary when making changes in operating power.

Load Matching and Plasma Stabilization

The resonant circuit has been designed to deliver full power over a 2 to 1 voltage range. This range is sufficient for all known large area reactive sputtering processes. A transformer with multiple taps is used to center the output voltage range. Some processes, especially high power transition mode, operate at higher voltages, similar to metallic mode operation. The tap can be quickly changed with simple tools.

Natural stabilization is obtained as a result of the resonant circuit characteristics. A plasma impedance variation toward a lower impedance will result in a reduction of the delivered power, which results in an increase of the impedance, and a return to the desired operating conditions.

One approach to process stabilization has been the introduction of a high power filter between the resonant supply and the load [9]. These filters were designed differently for each process. One of their functions was also to mask low level arcs, so the power supply would just ride through them. The new approach described here eliminates the need for these filters, and is therefore more flexible in a production process environment. This is especially important when a single power supply is used to power different processes as the coater is reconfigured to deposit different layer systems for other products. The need to tune the filter for the specific process operating point is also precluded.

HIGH POWER PULSED SUPPLIES

Overview

Pulsed power supplies offer greater flexibility for DMS, and can even enable the industrial deposition of new films. For large area coating applications, they need to be rated at 120 to 200 kW, and regulate on voltage, current, or power [10, 11]. They must be capable of delivering full power over a 2 to 1 voltage range. Sophisticated arc management is required, including arc prevention, recovery, and very low arc energy. Variable frequency is desirable as a degree of freedom in process tuning. A process should be driven at the lowest frequency resulting in an acceptable arc rate. This results in the highest deposition rate. Operation at higher frequencies can be advantageous for the cleaning cycles required by some processes.

Square wave pulsed voltage source supplies have been applied to DMS [12]. They tend to have slow current rise and high peak currents into arcs. As a result, they have had limited commercial acceptance. Further development has focused on pulsed current source supplies [13–15]. Versions at 120 kW were commercially available in 1998, followed by a 200 kW version in 2000. A 20 kW version was reported in 1996 [16].

Co-Sputtering

Co-sputtering of two different materials is typically accomplished with ion sputtering or the use of rf or DC supplies. The advent of pulsed supplies which can reliably regulate the power delivered to each magnetron enables reactive co-sputtering in a conventional DMS arrangement. Co-sputtering has typically been reported on a small scale. A constant concern is scaling to large substrates, with sizes appropriate for architectural glass. Results for large scale in-line coaters were reported in 1991 [7, 17, 18]. Several issues of scaling, such as uniformity and film quality, were addressed.

Characteristics

The high power pulsed supplies discussed here have plasma stabilization characteristics which are qualitatively similar to those of the resonant supplies described previously. The supply acts like a true current source over time frames on the order of a few cycles. Consequently, a perturbation in the plasma causing a reduction in impedance will cause the delivered power to decrease, which causes the impedance to rise again. Similarly, an increase in impedance will cause the delivered power to rise, which causes the impedance to decrease.

Figure 5 shows voltage and current waveforms of the 200 kW version oper-

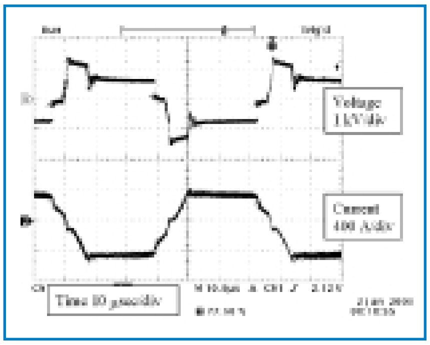

Figure 5. Waveforms at 200 kW into a TiNxOy process.

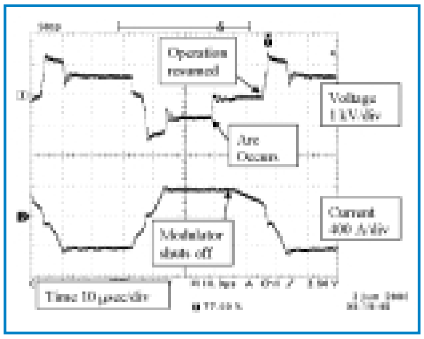

Figure 6. Arc response waveforms at 200 kW for TiNxOy process.

ating at full power, 200 kW. A defined dead time is required when switching between polarities. This allows the sophisticated soft-switching circuitry in the modulator to prepare for the next half cycle. Key features of these waveforms are the fast current rise and fall and the flat top of the current waveform. The output voltage quickly goes to the clamp (or, maximum allowed output) value until the current ramps to the value provided by the internal current regulator. The result is a fast current rise.

Arc Management

Arc management can be seen as having two facets. One is arc handling, including arc detection and arc response and recovery. The other is the strategy for reducing the number of process arcs and minimizing the arc recovery time. These power supplies act as true current sources during a single pulse, so they have a high output impedance. When an arc occurs, the process voltage falls immediately, with no current increase. Arc detection is based on voltage fall, so an arc is detected at the instant it occurs. The modulator is turned off when an arc occurs, so only the energy stored in the inductance of the output cabling and the leakage inductance of the output transformer is delivered to the arc. The modulator shuts off to handle the arc and then resumes operation in the opposite polarity. This will quench most arcs in practical production scale processes. Occasionally arcs occur which require the modulator to shut off for a defined longer time so the hot spot which maintains the arc by emitting electrons can cool. These are considered to be hard arcs. They are arcs which do not go out after a defined number of attempts to shut off and resume operation in the opposite polarity. Arc handling parameters can usually be set and used for all production processes. Relevant parameters include voltage threshold, hard arc count (number of attempts before declaring a hard arc), and delays before looking for an arc and acting on an arc indication.

Low melting point materials such as Sn and Zn benefit from the extremely low arc energy and from handling every arc. Previously used and badly cratered targets, as well as brand new targets, can be operated with a minimum of conditioning. The arc handling features have also been helpful on Si, which can arc uncontrollably above a threshold power. The plasma is very stable as viewed by the human eye. Arcs are difficult to find due to their low energy and optical intensity relative to the glow region above the racetrack. They look like tiny sparks from the cathode surface through the dark space to the bright glow region. Flashing or blinking is rarely observed, except when responding to a hard arc. Detecting and responding to every arc significantly reduces the number of hard arcs. Electron emission sites that could sustain arcs are not allowed to reach high temperatures from energy in undetected microarcs. Consequently, these pulsed current source supplies can deliver up to twice the power into processes that have been power limited due to arcing with conventional resonant supplies.

Waveforms of the 200 kW version responding to an arc are shown in **Figure 6**. Output voltage falls immediately when the arc occurs, but the current stays constant. The modulator shuts off after about seven microseconds, and the output current starts to decrease. Then, only the energy in the transformer leakage inductance and output cabling are delivered into the arc. In this case, arc energy is estimated at only 280 mJ. Operation is restarted in the opposite polarity completing the quenching of the arc. Most often, occasional isolated microarcs are all that is seen.

Summary

A new generation of power supplies for DMS has been developed, including both pulsed and resonant supplies. These developments represent new options for the large area coating system designer and the process engineer. Both types exhibit excellent arc handling, plasma stability, and process flexibility. The pulsed supplies also enable industrial scale reactive co-sputtering.

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