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Understanding Arc Energy: Methods to Measure, Compare and Control Arc Energy

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Understanding Arc Energy: Methods to Measure, Compare and Control Arc Energy

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As quality and performance metrics of thin films increase in stringency, modern plasma thin film deposition processes must account for the inevitability of arcs and utilize all the available tools to mitigate any damage caused by arc events. For many plasma processes, the ability to identify, measure and limit the energy delivered to a plasma during an arc event remains one of the most important factors to consider.

This paper outlines the electrical characteristics of the common arc event, describes a method to repeatably measure arc energy and provides some techniques using common features available on modern plasma power supplies which can be used to mitigate the energy delivered to a process during an arc. Experimental data, which back up these techniques, will also be presented.

INTRODUCTION

The modern thin film process engineer faces constant pressure to improve the throughput of their plasma process without sacrificing quality, performance or yield. Higher throughput often leads to higher process power, either due to the need for increased deposition rate or a larger deposition area. As process power increases, both the number of arcs and the energy delivered into each arc can also increase. As shown by Christie [1], defect particle size increases as a function of arc energy, which can lead to uncontrollable defects and reduce quality, performance, and yield. The ability to understand, measure and minimize arc energy pays dividends to those facing challenges with arc prone plasma processes. This paper outlines the electrical characteristics of the common arc event, describes a method to repeatably measure arc energy and outlines techniques to mitigate energy delivered during arc using common features available on modern plasma power supplies. Finally, experimental data gathered from a magnetron-sputtered dual-rotatable cathode chamber will be presented.

Anatomy of an Arc

There are many mechanisms from which arcs can form in a plasma process. Defects in targets, dielectric breakdowns in insulating materials and unintended paths to ground through the

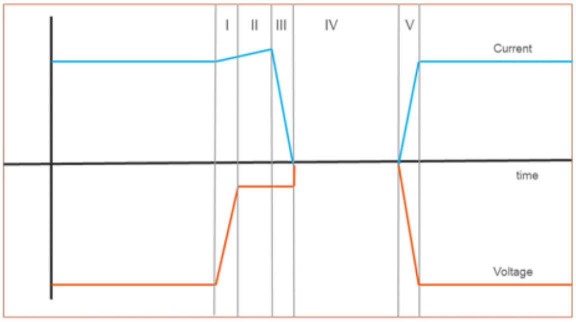

Fig. 1 – Phases of an arc and power supply response

cathode, anode, substrates, or shielding are just some of the many causes. When an arc event occurs, the localized impedance of the arc origination site collapses and the process current, seeking the path of least resistance, begins to flow to the arc location. Left alone, this loop can continue until the local impedance/current density relationship reaches a steady state. Arcs left in this state actively divert energy from the process, leading to damage of targets, substrates, and other process components. To extinguish the arc, the power supply needs to take action. A common and effective method is to reduce the arc current to zero amps and allow the arc site to cool. A typical arc can be broken down into five different phases shown in Fig. 1. Each phase of the arc has distinct characteristics. The following section briefly describes each of the phases.

Phase I: *Initial arc formation and impedance change*

At the start of Phase I, the localized impedance collapses at the site of the arc, decreasing the output impedance measured by the power supply. Depending on the output impedance of the power supply, typically the voltage will drop to the arc burn voltage, and the current will rise throughout the entirety of this phase.

Phase II: *Arc steady-state condition*

By Phase II, the arc has approached a steady-state impedance and will "burn" at these voltage and current levels indefinitely. If left unhandled, the energy entering the arc during this period can damage the target and substrate.

Phase III: *Arc reaction*

By Phase III, the power supply has begun to respond to the arc. Power supplies with modern arc-handling technology shutoff power and actively divert energy from the process by applying a high reverse voltage. This voltage drives the arc currents to zero faster, diverting any additional energy stored in the circuit, typically in the cable. Phase III continues until the arc current has been reduced below the level capable of sustaining the arc event.

Phase IV: *Shutdown period*

During the shutdown period, no additional energy is applied to the process. The shutdown period needs to extend long enough for two processes to occur. First, the thermal energy at the arc site needs to dissipate. Additionally, in reactive processes, the arc site may need to reaccumulate the insulating poison layer. Without extending the shutdown for a proper time, the probability of an arc immediately reforming when process power is reapplied increases substantially [2]. An optimal shutdown time is long enough that arcs typically will not re-ignite immediately upon reapplication of process power, but not so long that process stability or film properties are affected.

Phase V: *Process recovery*

After the shutdown period, the power supply begins to reapply power. Depending on process conditions, the arc recovery is automatically handled by the power supply. If the process undergoes high arc rates or plasma instability during arc recovery, the power supply can be adjusted to reapply power more effectively.

Measuring Arc Energy

Arc energy is typically measured by capturing the process current and voltage waveforms using an oscilloscope, multiplying the values to calculate instantaneous power and integrating over the span of the first four arc phases to calculate arc energy in Joules. While the same general method applies to most plasma processes, variations in the experimental design can result in large measurement variation. For instance, the authors practiced a conservative approach by measuring voltage and current at the chamber rather than at the power supply. Energy measurements at the output of the power supply could be affected by the reactive impedance of the cable. Additionally, a reverse voltage applied by the power supply could distort Phase III measurements taken at the output terminals of the power supply. Other factors, like test equipment, can also introduce variations in arc energy measurements. To reliably compare arc energy data, care must be taken to ensure the experimental design minimizes variation in measurement technique.

Consistency of the setup, measurement location and process are critical to repeatable results. Since the output cable stores energy, the type, length and even layout effect the arc energy. Measuring the arc energy at the chamber (Fig. 2, Terminal 1) will give a result different than measuring at the output of the power supply.

Fig. 3 shows how the voltage and current waveforms differ across a 7.5-meter triax power cable. In this example, the chamber voltage (channel 1) and the chamber current (channel 2) are used to calculate the instantaneous power delivered into the chamber (F2), while the power supply voltage (channel 3) and current (channel 4) measurements are used to calculate the in-

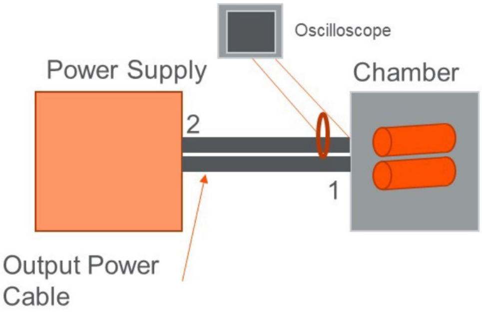

Fig. 2 – Arc energy measurement setup

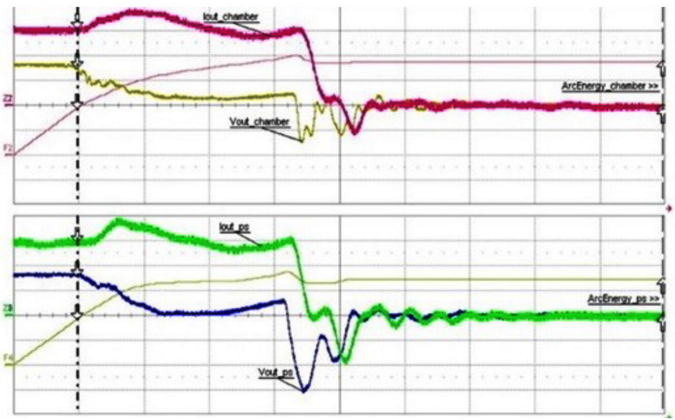

Fig. 3 – V/I waveforms at chamber vs. V/I waveforms at power supply

stantaneous power delivered into the cable (F4). The measured arc energy, calculated by integrating the power waveform between the oscilloscope cursors, is higher at the power supply by 1.25mJ (0.065mJ/kW), caused primarily by the slower voltage decay at the power supply terminals (100ns) due to the output cable. The reverse voltage and current are used to pull energy back out of the cable and chamber to minimize arc energy.

Arc energy is the integral of the power delivered into the chamber over the arc event.

$$Arc\ Energy = \int_{t1}^{t2} P(t)\,dt = \int_{t1}^{t2} v(t)i(t)\,dt$$

To ensure repeatability of measurements, the authors chose to begin the integration at Phase 1, when the chamber voltage falls below 90% of the process voltage (t1), and at the end, when the shutdown time has finished (t2). Integrating power through the end of Phase IV accounts for the stored energy dissipation through the end of the arc, providing a more consistent standard for comparison between chambers and processes. Because some processes produce high variation from arc to arc, multiple arc events should be recorded and averaged.

The most important tool in measuring arc energy is the oscilloscope. Many digital oscilloscopes available today can perform multiplication functions and integrate the power between time cursors. Care should be taken when setting up all test equipment. Ensure the voltage and current probes have been properly configured, zeroed, and degaussed according to the manufacturer's specifications when applicable. Even small scope and probe offsets can introduce large errors in arc energy measurements.

Arc energy is typically normalized as a function of power (mJ/kW) for comparison and specification purposes. However, it should be noted that higher process powers and, more importantly, currents can increase the absolute energy delivered into an arc (J) while decreasing the normalized arc energy (mJ/kW).

EXPERIMENTAL SETUP

Reactive magnetron sputtering experiments were conducted with 1.5-meter dual-rotatable cathodes and implemented both aluminum (Al) and aluminum-doped silicon (SiAl) targets in an oxygen/argon atmosphere. The Advanced Energy Ascent AP30 DMS and Ascent DMS 60kW power supplies were used to power the magnetrons. The output cable connecting the power supply to the chamber was a 7.5-meter triax cable. A LeCroy oscilloscope, high voltage differential voltage probe and 500-amp AC/DC current probe were configured to measure current and voltage waveforms at the chamber connection (labeled Terminal 1 in Fig. 2). Testing was preceded by a 1.5-hour conditioning step using pure argon at full power, 20kW.

Arc energies were recorded while independently varying three different arc handling parameters to determine their respective effects on arc energy. The three parameters can all be readily adjusted in the power supply. The first parameter, voltage arc threshold, is the voltage at which the power supply recognizes an arc has occurred and is typically set to a value between the process voltage and the arc voltage. The second parameter, reverse voltage, is the voltage applied at the output of the power supply during the arc reaction time. The polarity of the reverse voltage is set opposite of the process voltage at the time of the arc to force the process current to zero amps and extinguish the arc. The programmable reverse voltage was varied between 118% and 165% of the process voltage. The final parameter, persistence, is the time the arc condition must exist before the power supply begins to react. Persistence time, also known as detect time, was varied between 4ns and 2000ns. Other parameters, such as power setpoint and frequency, were set such that a sufficient arc density was induced to capture events. To capture the baseline data, the following parameters were used:

Output Power:	20kW
Frequency:	18kHz
Reverse Voltage:	150% of process voltage
Persistence Time:	4ns
Arc Voltage Threshold:	150V

RESULTS

For aluminum and silicon magnetrons, a baseline set of arc energy measurements was plotted in Fig. 4 and Fig. 5 to show the arc energy distributions. As noted by Carter and Walde [3], target materials influence arc energy distributions. For aluminum, the

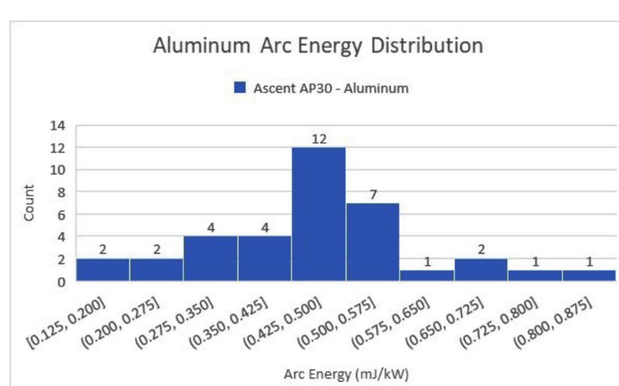

Fig. 4 – Arc Energy Distribution of AlOx

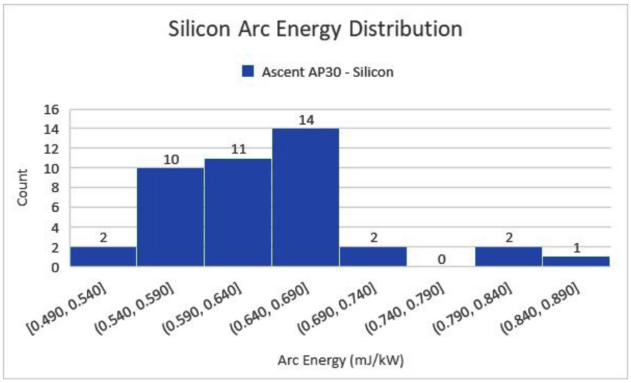

Fig. 5 – Arc Energy Distribution of SiOx

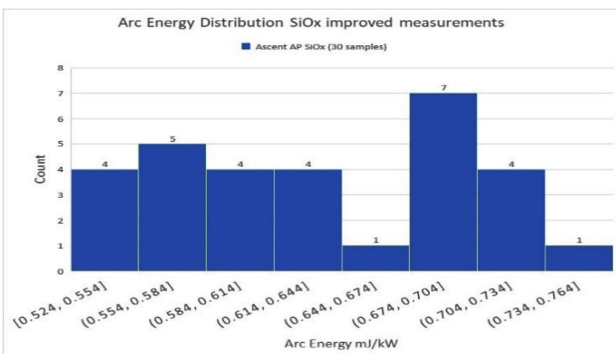

Fig. 6 – Arc Energy Distribution with Improved Measurement Techniques on SiOx

bulk of arc energies is between 0.275 mJ/kW and 0.575 mJ/kW and for silicon 0.540 mJ/kW to 0.690 mJ/kW.

Throughout the course of testing, variability in the distribution was observed and several factors were found to be particularly sensitive to the arc energy measurement. Target conditioning, current probe drift over time and temperature and oscilloscope trigger methods were all found to have noticeable effects on results. Although the targets were kept under vacuum, following a consistent target burn in cycle before taking measurements improved the arc measurement variation, indicating target and material temperatures affect arc energy. Measurement equipment also had an effect. Testing using 150A DC current probes resulted in drift over time due to internal heating. Switching to 500A DC current probes for the 60A process resolved all drift issues. Using a current threshold trigger set just above the process may have skewed early results due to ignoring arcs with lower peak currents, thus increasing the arc energy distribution. To capture better random sampling of events and eliminate measurement bias, the oscilloscope was triggered off the shutdown time instead of voltage or current threshold used. Fig. 6 shows SiOx arc energy distribution after the arc energy measurements were improved. The distribution is narrower and more uniform.

Power supplies with modern arc management capabilities can contain the majority of the total arc energy to Phase I, typically less than 500ns of the arc event. The waveform in Fig. 7 shows about 60% of the total measured energy entering the arc event during Phase I, while the impedance was collapsing. In Fig. 7, Ch1 is the chamber voltage, Ch2 is the chamber current, and F2 is integrated energy delivered to the chamber. Power supplies with longer detect times or a passive response will have much higher arc energy contributions from Phases II and III, resulting in higher total energy.

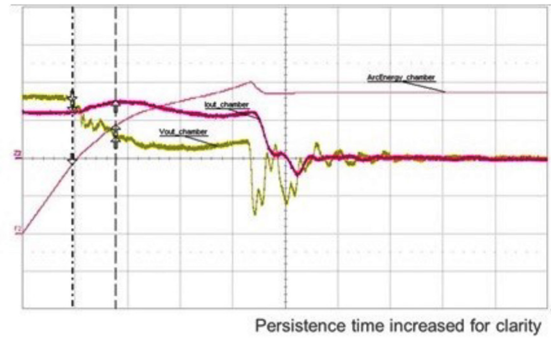

Fig. 7 – Arc Energy Delivered in Phase I

Voltage Arc Detection Threshold

Experimental data shows that increasing the voltage arc detection threshold to a value close to the sputter voltage improves arc reaction time and reduces Phase II arc energy. In these experiments, arc thresholds were incrementally increased from 50V (15% of sputter voltage) to 250V (75% of sputter voltage), as

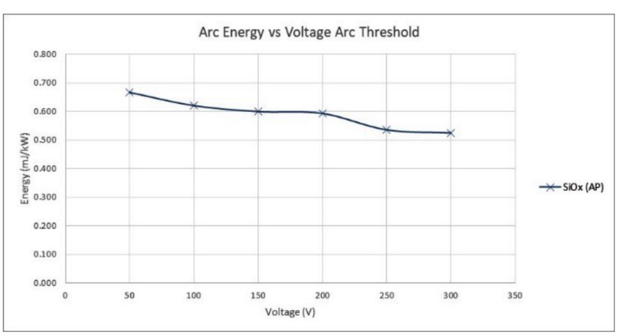

Fig. 8 – Arc energy as function of voltage detection threshold

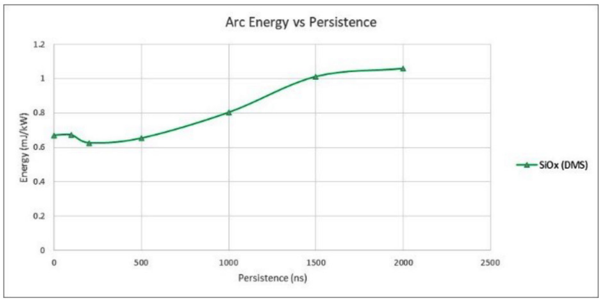

Fig. 9 – Arc energy as function of persistence time

shown in Fig. 8. This fits with expectations, as an increased voltage threshold leads to earlier arc detection in Phase I. The typical time saved when triggering at 75% vs. 15% of sputter voltage is up to 400ns. Phase I typically contributes 60% to 70% of the delivered energy. When considering detection thresholds, 10% to 20% reductions in arc energy can be realized. It is important to balance arc energy delivered vs. process instability due to false arc detection.

Persistence Time

Fig. 9 shows arc energy as a function of arc persistence time. Persistence times below 500ns cause the reaction time to dominate total arc energy. Above 500ns persistence time, the detection delays begin to dominate the arc response, and arc energy increases substantially. During normal process operation, persistence times can be used as a protection against false arcs, especially in processes with high-voltage ringing. Persistence times up to 500ns can typically be used without impacting arc energy. Similar to voltage arc detection threshold, the optimal persistence time setting requires a balance between minimizing false arc responses and minimizing arc energy. Experimental data shows that on SiOx targets, persistence times between 500ns and 1000ns significantly increase the Phase II energy contribution. Depending on process requirements, adjusting the persistence past 500ns can be beneficial in certain instances. For example, a target conditioning step may purposely introduce higher arc energy to burn off impurities on the magnetrons using non-reactive gas flows. The persistence time offers a convenient knob to predictably increase arc energy.

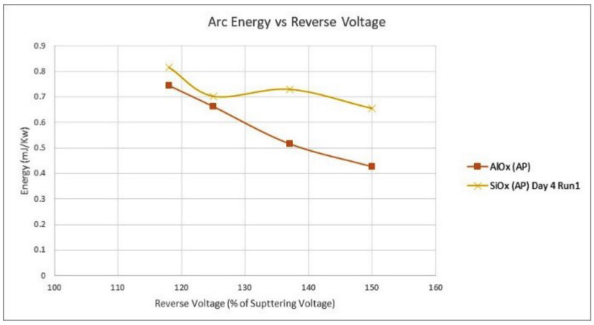

Fig. 10 – Arc energy as function of reverse voltage

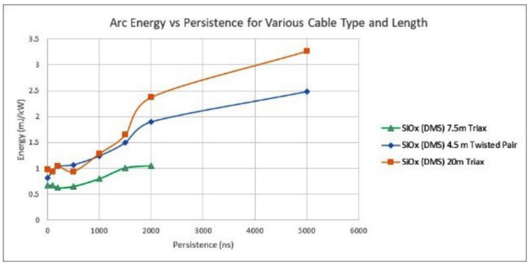

Fig. 11 – Output cable influence on arc energy

Reverse Voltage

For both AlOx and SiOx, increases in reverse voltage led to decreases in arc energy. Fig. 10 shows a trend of decreasing arc energy when reverse voltage increased from 118% to 150% of the process voltage. The reverse voltage is applied during Phase III, and higher magnitude voltage reversals shorten Phase III time. The reverse voltage's effect on reducing Phase III time and total arc energy will be greater at higher process currents due to the following relationship:

$$dt = \frac{(Vrev) * di}{L}$$

where Vrev is the reverse voltage, L is the cable and process inductance, and di is the process current being driven to zero amps.

Effects of Output Cables

The reactive impedance of the cable, determined by its materials, geometry, and length, will also impact arc energy. Even though the output cable is not an adjustable parameter, the effects of power supply parameters can change depending on the cable selection. Cables of various lengths and types were tested to show the impact of cable characteristics on arc energy. A 7.5-meter triax, a 20-meter triax and a 4.5-meter twisted pair cable were compared, with results repeating the persistence variation experiment shown in Fig. 11. The type of cable and its length are extremely sensitive parameters to the arc energy delivered. This is because of the energy storage properties of the cable, specifically the cable self-inductance and cable capacitance. Of all the parameters tested, the cable type and length impacted arc energy the most.

CONCLUSION

The entire arc process, from formation to recovery, can be divided into five distinct phases. The arc formation and arc energy delivery occur in Phases I and II, while reversal, shutdown and recovery occur in III, IV and V. Using power supplies with modern arc management technology and optimized arc settings, most of the arc energy is delivered in Phase I.

When measuring arc energy, it can be difficult to produce repeatable results. Care needs to be given to the location of the measurement, equipment used, system setup, cabling, materials and arc parameters, as they all have effects on the energy delivered into an arc. When comparing arc measurements, it is imperative to keep these considerations in mind and use consistent measuring techniques.

For the three power supply parameters varied during experimentation, all influenced the delivered arc energy. Long persistence times had the greatest effect on energy delivered into the arc event. Voltage arc detection threshold should provide a balance between faster arc detections and avoiding false detections. Increasing the reverse voltage reduces arc energy by diverting energy away from the arc back into the power supply during Phase III and has greater influence in processes with higher currents. Parameters outside of the power supply also affect arc energy. Target materials and the output cable selection have significant influence on the arc energy. Experiments showed al-most a 2:1 increase in arc energy using a 4.5-meter twisted pair vs. a 7.5-meter triax output cable.

The reduction of unwanted arc induced defects on the target and substrate, and other components will continue to play a major role in all plasma processes. The quality and performance metrics along with advancements in plasma power supply technologies will continue to reduce arc energies. Using the techniques outlined in this paper, a process engineer can understand, measure, and reduce the energy delivered to an arc to optimize results.

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