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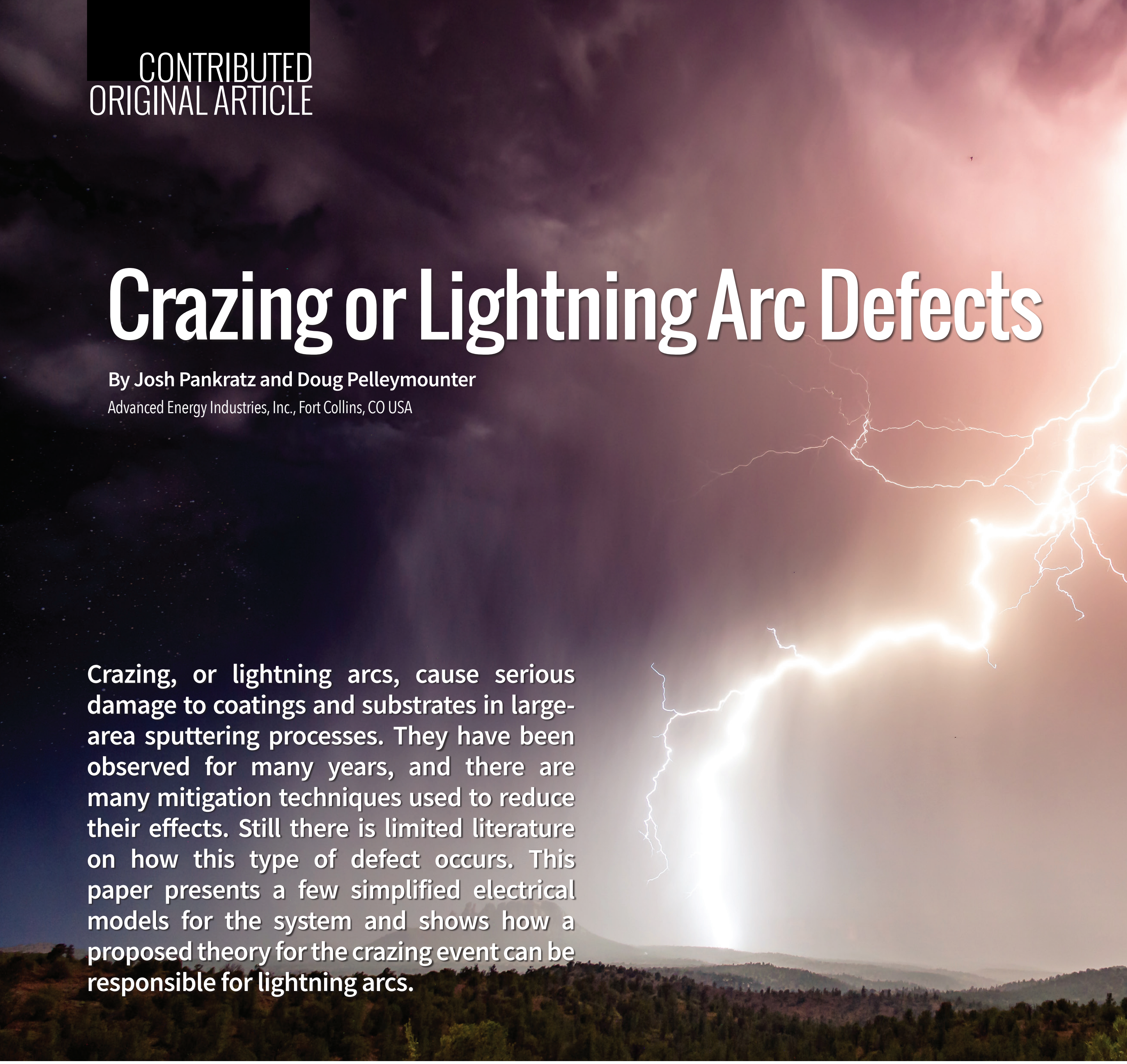

Crazing or Lightning Arc Defects

By Josh Pankratz and Doug Pelleymounter
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Crazing, or lightning arcs, cause serious damage to coatings and substrates in large-area sputtering processes. They have been observed for many years, and there are many mitigation techniques used to reduce their effects. Still there is limited literature on how this type of defect occurs. This paper presents a few simplified electrical models for the system and shows how a proposed theory for the crazing event can be responsible for lightning arcs.

Introduction

There appears to be many causes to crazing and multiple mitigation techniques have been shown to be effective in the industry. The many interactions in a glass coater cause a complex series of models and multiple – sometimes conflicting – mitigations.

Traditionally, the crazing event has been assumed to be initiated by an electrostatic discharge. Crazing is believed to start at the edge of the glass and then burn inward, toward the center of the glass. Fig. 1 shows an example of crazing on a glass substrate.

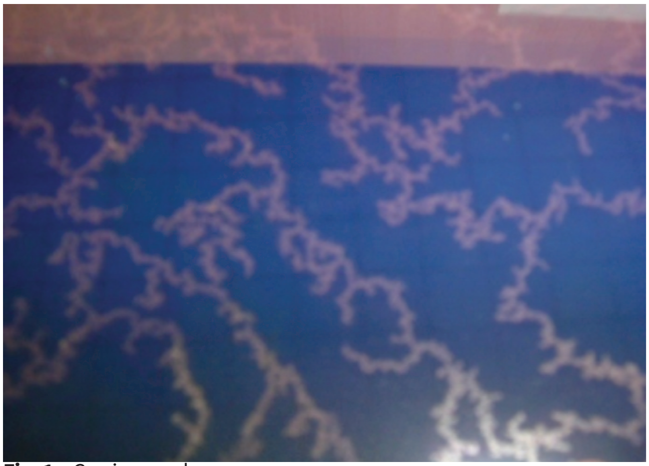

Fig. 1 – Crazing on glass.

Fig. 2 – Example of sudden electrical discharge.

Fig. 2 shows a common example of a sudden electrical breakdown: a lightning strike during a thunderstorm.

This paper proposes several individual models and a new theory for the start of crazing events that do not necessarily begin due to an electrostatic breakdown. The electrical models are intended to show electrical current paths and expand knowledge beyond what cannot be sufficiently explained by existing theories. The models are interdependent and use circuit analysis concepts to break down the comprehensive, complicated model into smaller sub-circuits in order to demonstrate the current flows through the system. The intent of the paper is to create a common foundation of the electrical system and introduce the fundamental catalyst causing the defect to begin.

Modeling and Discussion

Phenomenon of Lightning Arc

Lightning arcs occur when the parasitic current flowing in the substrate exceeds the thermal capacity of the film, causing it to melt and evaporate. Substrate film currents are unintended and occur due to potential differences between separate areas on the glass, unintended impedances to system ground, and film impedance. These currents are always present to some degree and occur in multiple sputtering zones, and even can occur in a single zone.

The parasitic or unintended current paths are not in the generator power delivery loop. Fig. 3 shows current flow in a plasma that is influenced by an unpowered magnetron. This illustrates the system elements affecting current (charged particles) flow outside the intended power delivery system.

Assumptions and Approximations

Several assumptions and approximations have been made to generate the model. First, each plasma has a potential that is referenced to ground, and transients can be approximated by the anode-to-ground voltage. Fig. 4 shows the output of a traditional AC power supply (Advanced Energy's Crystal®), with each terminal measured to ground. When the end block voltage is measured to be positive with respect to ground, the magnetron

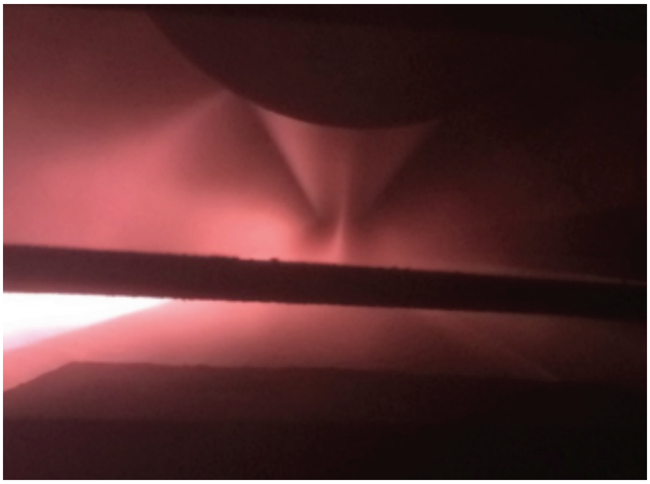

Fig. 3 – Unpowered magnetron affecting current flow.

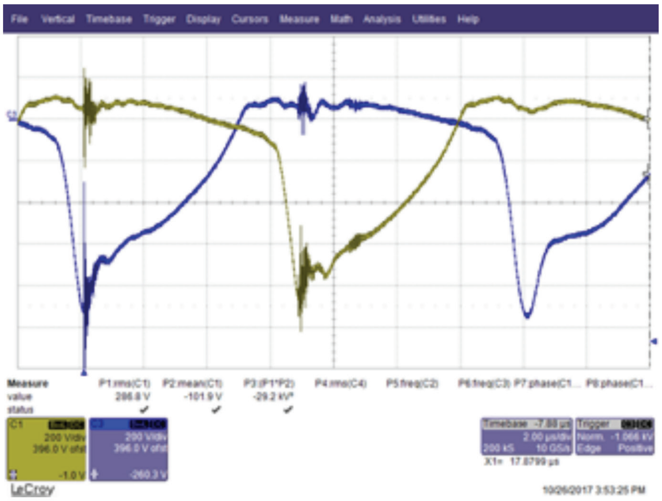

Fig. 4 – Crystal output magnetron to ground.
Ch. 1: Magnetron A
Ch. 2: Magnetron B

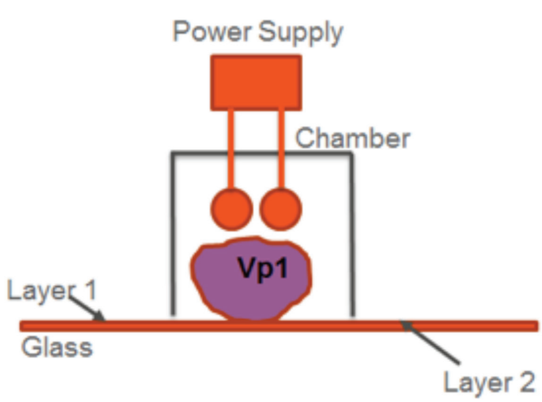

Fig. 5 – Model of a single sputtering zone.

is acting as the anode, and differences or changes in the anode voltage affect the plasma bias.

The second assumption is when the substrate is in the coating zone, the plasma is in contact with the substrate and the surface becomes self-biased to the local plasma potential.

Model Creation

Fig. 5 is a sketch of a single coating zone with plasma Vp1 referenced to ground.

The plasma bias is modeled as a dependent voltage source with source impedance, as shown in Fig. 6.

The dependent source is used because the plasma bias is dependent on the material, pressure, gas, and power density. The plasma bias in relationship to the intended power delivery system, or power supply and plasma, is shown in Fig. 7.

This also shows the substrate surface in the model, the node connection between the cathode of the independent power supply, and the anode of the plasma bias. The sign of the plasma bias is chosen arbitrarily and for modeling purposes; either a positive or negative bias can be used.

Expanding the model further, the deposited film is conductive and modeled as a resistance R_Sheet1 and R_Sheet2. Due to the size of the substrates, the resistances R_Sheet1 and R_Sheet2 extend out of the modeled chamber. R_sheet1 can be assumed to be the sheet resistance of the previous layer and R_Sheet2 is the combined resistance of the new layer stack.

All material has a conductivity; this is intended to be generic and can be used for any material. Along the substrate surface and edges, there exists impedance to the rest of the system or ground. This is modeled in Fig. 8 as a bulk impedance, R_Chamber_Impedance.

This impedance is distributed and extends outside the coating chamber. The impedance is designed to be large, but accounts for most of the unintended return paths. The model shows a closed electrical path in which current can flow in the deposited film and return to the plasma bias source via the chamber impedance and system ground. The magnitude of the current is defined by the Equation 1:

Equation 1

$$I\,(R\_Sheet2) = Vp1 / (R\_Source1 + R\_Sheet2 + R\_Chamber\_Impedance)$$

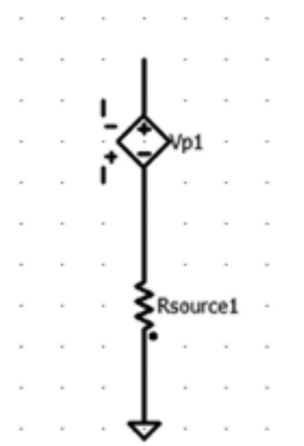

Fig. 6 – Model of plasma bias.

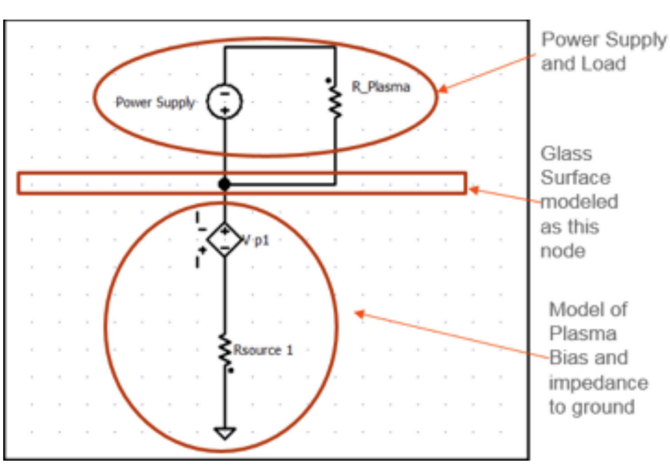

Fig. 7 – Coating zone electrical model.

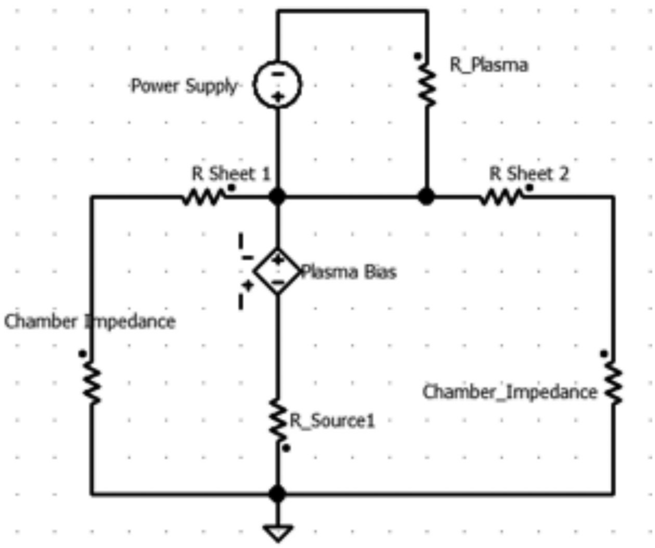

Fig. 8 – Single zone electrical model

As an example, assume the resistor Chamber_Impedance in Fig. 8 is a roller in the transport system. If the roller impedance drops, loop series resistance also decreases. This increases the magnitude of the current in the loop and film.

In large-area systems, it is common to have coating zones adjacent to each other and a substrate large enough to be in multiple zones at the same time. Fig. 9 shows adjacent chambers with plasma bias Vp1 and Vp2, with a glass substrate between them.

Fig. 10 shows the electrical model between two zones with the generators and chamber impedance removed. There is a current path between the chambers that always exists and the magnitude of the current flowing in the films is defined by Equation 2:

Equation 2

I (R_Sheet1) = (Vp2 – Vp1) / (R_Sheet + R_Source1 + R_Source2)

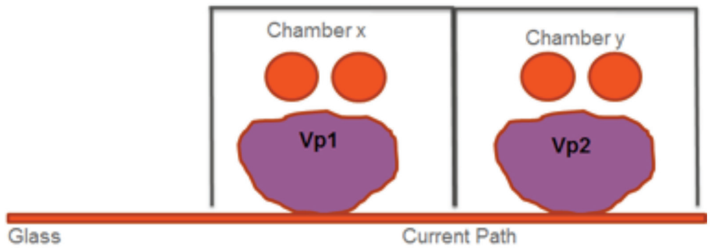

Fig. 9 – Sketch of two sputter zones.

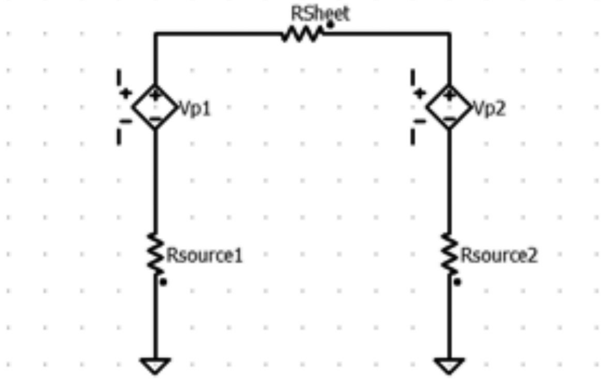

Fig. 10 – Two-zone electrical model.

Trigger for Lightning Arcs

The film current flow in the center of the sheet will flow with a uniform current density. As the current approaches the edge, this changes. The edge is not uniform and can be modeled as a series of sharp points, as shown in Fig. 11.

Where the edge becomes jagged and sharp, the current density is focused and increased. This increased current density increases the losses in the film and dissipates as heat (I^2R losses).

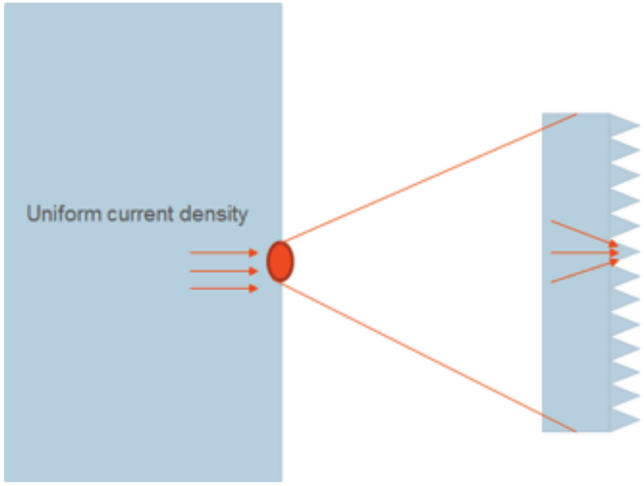

Fig. 11 – Effect of edge on current density.

At some point, the localized film temperature exceeds thermal capacity of the film, causing melting and evaporation, and a lightning arc or crazing event begins.

The melting of the film can be compared to a common electrical protection device – the fuse. The fuse opens when current in the fuse exceeds the design threshold, melting the fuse element. The fuse element opens the circuit and stops the current flow. A simple explanation of the fuse is shown in Fig. 12.

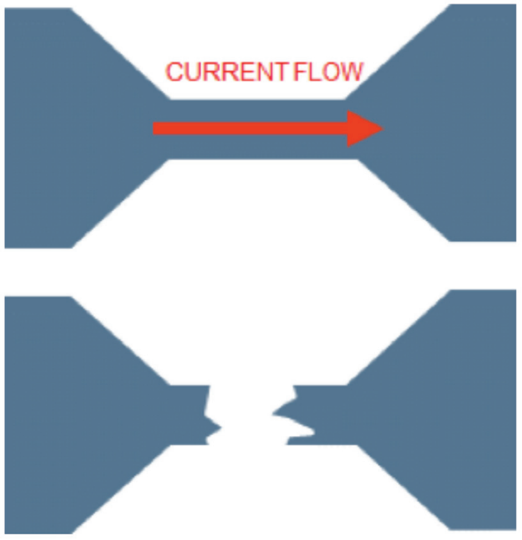

Fig. 12 – Diagram of fuse element.

Conclusion

Simple descriptive electrical models of the chamber system have been presented showing the electrical paths in a large-area sputtering system. These currents always exist but the magnitude is defined mainly by the source impedance of the plasma bias, the sheet resistance, and the magnitude of the plasma biases. These currents are intended and parasitic in nature, as they occur outside the main electrical path of the power generators.

Lightning arcs typically begin when the parasitic current in the arc focused at the edge of the substrate and the losses in the film are increased, generating additional heat in the film. When the film's thermal capacity is reached, the film fails and melts and evaporates. The film can be thought of as an electrical fuse that will open when the current rating is exceeded.

About the Authors: Josh Pankratz and Doug Pelleymounter

With more than 20 years of experience in power supply design, Josh Pankratz currently serves as Engineering Director for Advanced Energy's Thin Film business. In his role, he develops key architecture strategy and oversees project implementation.

Doug Pelleymounter is a Senior Applications Engineer for Advanced Energy Industries and received the SVC's Mentor Award in 2009 for "his outstanding mentorship to sputtering professionals through process design, applications engineering, and problem solving in real world applications". Doug has been trying to control ions and electrons in vacuum systems for 41 years. One day he may succeed. SVC