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System Improvements and Discussion to Minimize Lightning Arcs or Crazing

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System Improvements and Discussion to Minimize Lightning Arcs or Crazing

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The technology exists to advance film properties and improve throughput in large area systems. However, defects caused by system limitations prevent implementation of new process capabilities. Using the electrical models that show the causes of the lightning arc events, system design recommendations have been identified, implemented, and proven to be effective. Several system design recommendations are proposed to minimize the unintended current paths in large area systems and the reason they are effective.

INTRODUCTION

Lightning arcs (crazing) can be caused by unintended currents on the substrate. When these currents exceed the thermal and current capability of the deposited films, the lightning arc defect begins. These sheet currents can be modeled using electrical models and exist due to the system configuration and coupling from the plasma bias and impedances to ground. A large coater system is electrically complex and interactions between multiple deposition zones must be considered. By modeling the system, it is possible to identify and design mitigations to minimize the current on the sheet by providing alternate current paths and managing the electrons in the system. These system design concepts have been proven to minimize the occurrence of lightning arcs. This paper will state several mitigations that have been shown to be effective in eliminating lightning arcs and the electrical models are the reason the mitigations are effective.

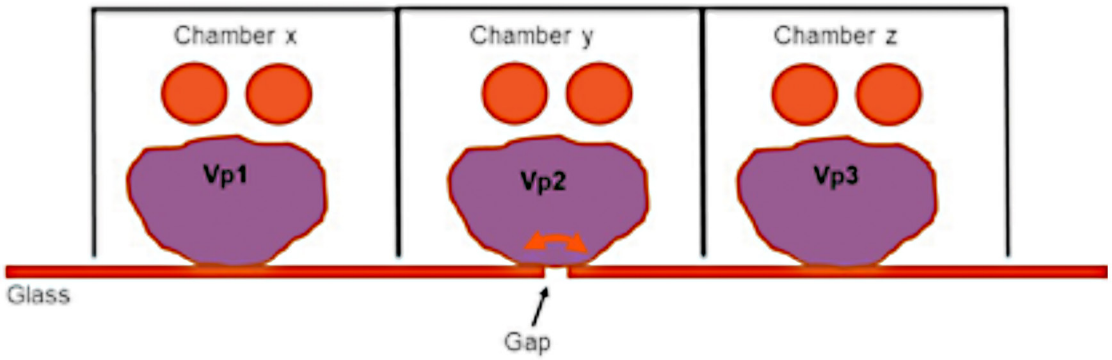


Fig. 1 – Sketch of three adjacent chambers.

MODELING AND DISCUSSION

System Modeling

It is important to consider the effects of the entire system when simplifying a model for easy comprehension. A large system where the substrates are placed close to each other, is shown in Fig. 1. If the gap is small and both substrates are at potential Vp2, the gap is electrically shorted. This allows the length of the substrate to be virtually increased. Thus, a condition in Chamber X can affect conditions in Chamber Z. While it may not be necessary to create complex system models for the purposes of understanding, it is necessary to realize interactions between chambers, substrates, and plasmas of the larger system.

A simplified one chamber electrical model is shown in Fig. 2. This electrical model applies for both DC and AC, where in the AC models' resistors to ground are replaced with impedances to ground. In the case of AC processes, the "anode" is physically moving between magnetrons A and B. The plasma bias, represented by Vp1, induces a current in the sheet. The magnitude of the current in the sheet is dependent on the plasma bias, the impedance of the layers, and the impedance to the chamber.

A more complex AC model can be created by adding inductances and capacitances in circuit. Of note, it is widely recognized that capacitances exist in the layer stacks created by alternating layers of varying impedance and conductivity. Also, there are inherent capacitors created in parallel with the chamber impedance to ground. These create multiple unintended current paths coupling the plasma bias, the sheet impedances, and the impedance to ground. The interactions and current paths are always present in a system and by modeling the system it is possible to design intended current paths to minimize current in the sheet.

RF Grounding

Adding a good RF ground between the chassis of the power supply and the chamber ground creates low impedance return path for high frequency signals back to the power supplies. RF noise can be created by several sources including the plasma PVD process, high frequency switching of the power supply, and the AC switching between magnetrons. At high frequencies, the output cable can be modeled as a transmission line. The transmission line will add impedance in the "anode" and create a high impedance for high frequency signals back to the power supply. Fig. 3 shows the model of a single chamber with the

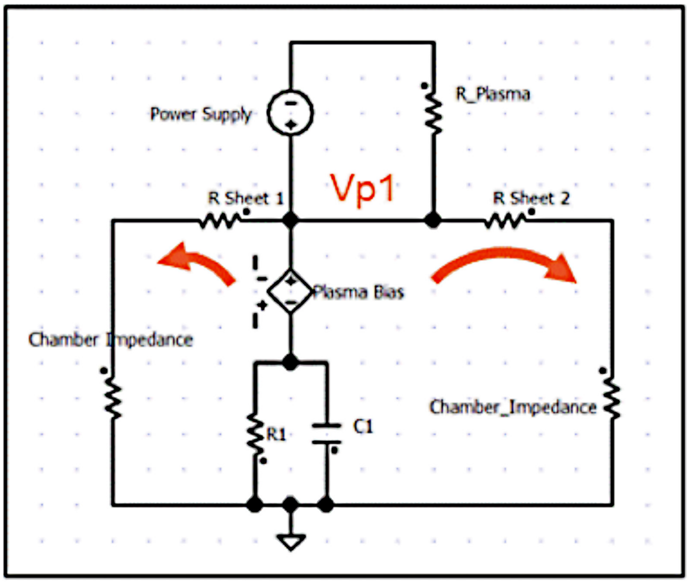


Fig. 2 – Electrical model for single chamber.

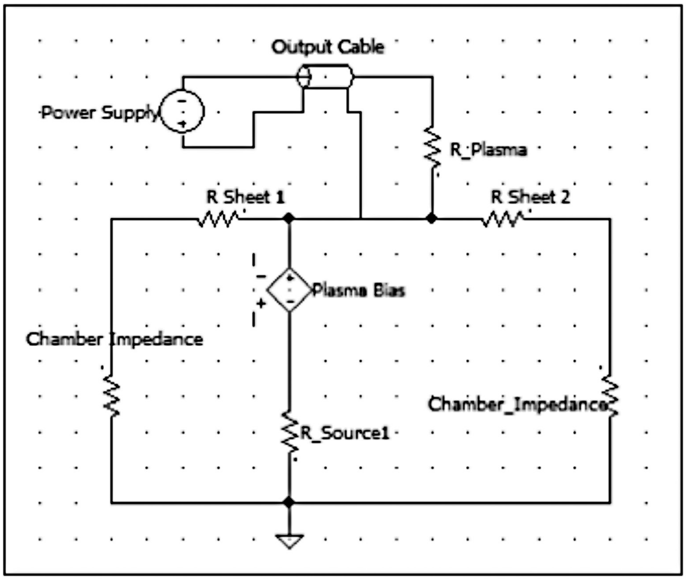


Fig. 3 – Model of system with output cable as transmission line.

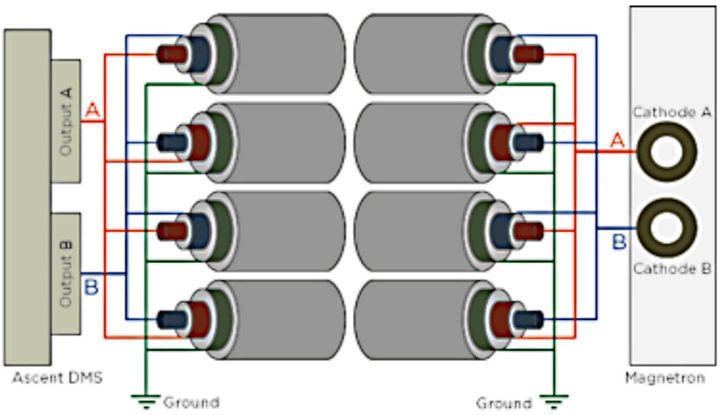


Fig. 4 – Balance triax connections.

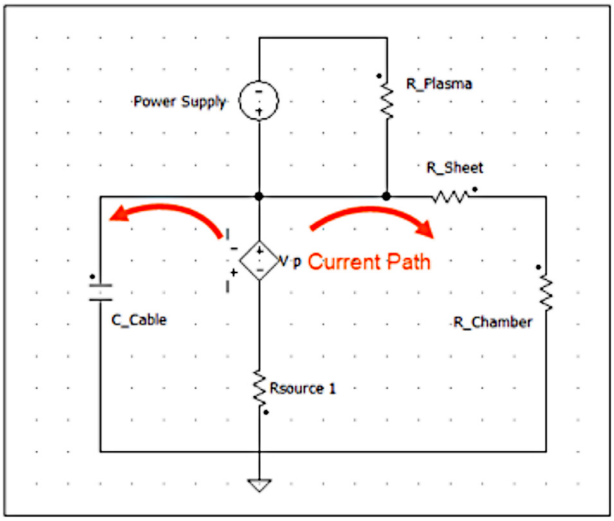


Fig. 5 – Electrical model with cable capacitance.

output cable as a transmission line. Since current will naturally follow the lowest impedance path, providing a low impedance path back to the power supplies establishes an intended current path for these currents to follow. If a sufficiently low impedance ground path is not provided, the current will find is own way to the power supply usually through other chambers, control signals, AC (50/60 HZ) power lines, and the surface of the substrate. Good high frequency grounds are wide, thin conductors. 50 mm to 100 m wide copper strap works well.

Balanced Cabling (Triax)

Balanced triax cabling between the power supply and the chamber has proven to be effective in a number of systems. Fig. 4 shows potential connections between an Advanced Energy Ascent DMS power supply and a dual magnetron chamber. This scheme accomplishes multiple things electrically. A triax cable is constructed like a coaxial cable, inner conductor and a shield, but the triax has third conductor, an outer shield. For power systems the outer shield is grounded (on both ends). Power cables can be modeled as transmission lines as a series/parallel combination of resistance, inductance, and capacitance. For triax, capacitance is between the inner conductor and the inner shield, and between the inner shield and the outer shield. This naturally creates an imbalance in capacitance to ground between each cathode. However, with triax, it is possible to balance this circuit element. By using two triax cables per polarity or magnetron, the parasitic capacitance and inductances in each polarity become balanced with respect to ground. Triax puts a physical, distributed, capacitor from each magnetron to ground (outer shield). Since the outer shield is grounded at both ends this creates a low impedance “shunt” path for AC currents in the system. Thus, the power delivery cable can provide an alternate current path away from the surface films on the substrate for AC current to flow. Fig. 5 shows the electrical model including the cable to ground capacitance C cable. This capacitor acts as a current divider and creates an intended low impedance current path to ground around the substrate film. There are other types of power cables that can be used but they may not uniformly control the capacitance to ground as triax does.

Synchronization Between Adjacent Chambers

Synchronizing the phasing of the magnetrons reduced the potential between adjacent chambers. Fig. 6 illustrates adjacent chambers and Fig. 7 shows the synchronization. If the power supplies for Chamber X , Chamber Y and Chamber Z are synchronized such that all magnetrons B are cathodes at the same time, then the voltage potential between Chamber Y magnetron B in Chamber X and magnetron B in Chamber Y will be minimized, as both magnetrons are in phase. Differences in voltage potentials represent areas where unintended current paths can occur.

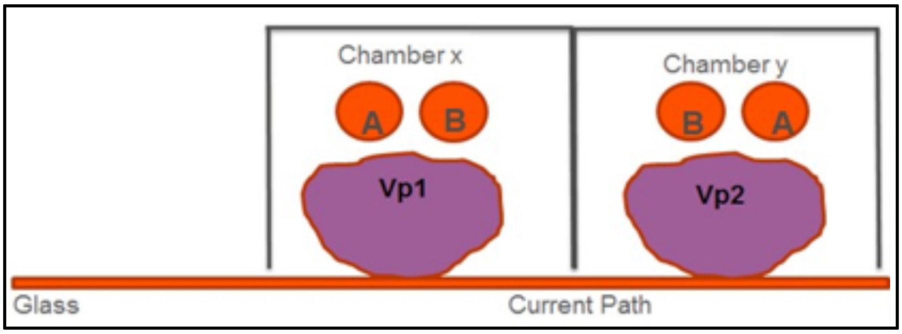


Fig. 6 – Sketch of two adjacent chambers.

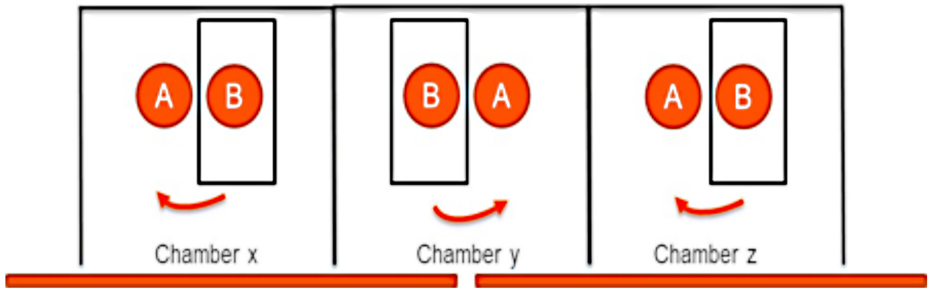


Fig. 7 – Synchronized outputs between Chamber X and Chamber Y.

Synchronization of the waveforms between adjacent chambers has been shown to be effective in minimizing the lightning arc defect. This is due to the minimization of potentials between plasmas forcing the currents to return on the intended current paths of the electrodes in the same chamber.

If the adjacent magnetrons of Chamber X and Chamber Y are of different polarities, it is possible to create an untended current path to be set up though the film on the substrate. Fig. 8 shows a model of adjacent chambers, where C1 is the parasitic capacitance of the chamber to ground and then to the power supply. If the magnetrons labeled B are of different polarities, an AC current path is created between the two chambers, ground and the power supplies. If the adjacent magnetrons are of the same polarity, the magnitude of the AC current is minimized, and the film current is also minimized.

Isolation

There are several ways to increase the impedance and minimize unintended current paths in the chamber. Any connection to ground represents a current path and increasing the impedance should be considered. The two connections that can be easily identified and designed are the anodes of the DC processes and the transport system.

Referring to Fig. 9 and Fig. 2, if the anode is grounded, this causes Vp1 and Rsource1 to short out, decreasing the impedance to ground seen from other chambers, Vp2, for example in Fig. 9. Equation 1 shows the relationship between the sheet current and the different plasma potentials. In some system designs it is well known that a grounded anode in the DC sections will cause the lightning arc defect. Grounding an anode increases the differences between the chambers' plasma biases and potentials. As the difference in magnitude between Vp1 and Vp2 increase, the sheet current also increases.

$$I\,(R_{Sheet1}) = \frac{(Vp2 - Vp1)}{(R_{Sheet})} \qquad (1)$$

Transport System

A similar effect occurs with the transport system. Fig. 10 shows a simplified electrical model including the bulk resistance to ground for the roller impedance to ground. The impedances the can limit the current are the source impedance Rsource1 and the Roller. From Equation 2, as the roller impedance decreases the current in the sheet films increases.

$$I\,(R_{Sheet2}) = \frac{(Vp1)}{(R_{Sheet2} + Roller)} \qquad (2)$$

Multiple parallel paths to ground the impedances combine to a lower effective impedance at the system level. The lower impedance to ground seen by the substrate will increase the

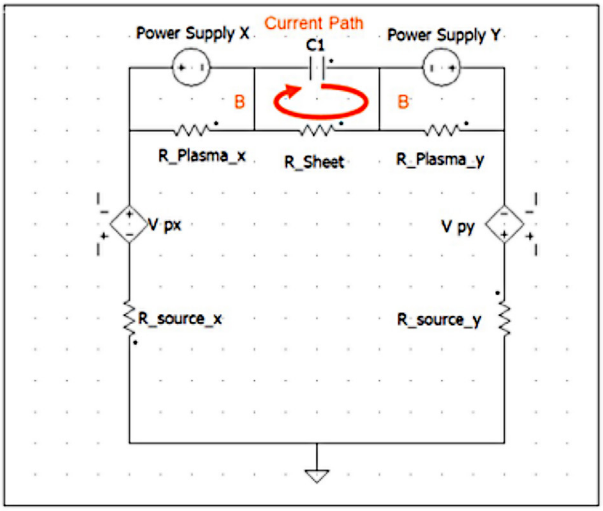


Fig. 8 – Electrical model of synchronized outputs.

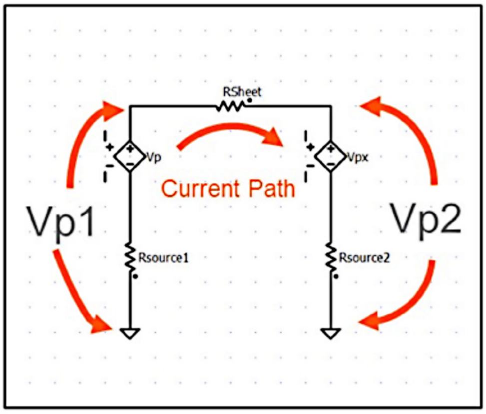


Fig. 9 – Electrical model of two adjacent chambers.

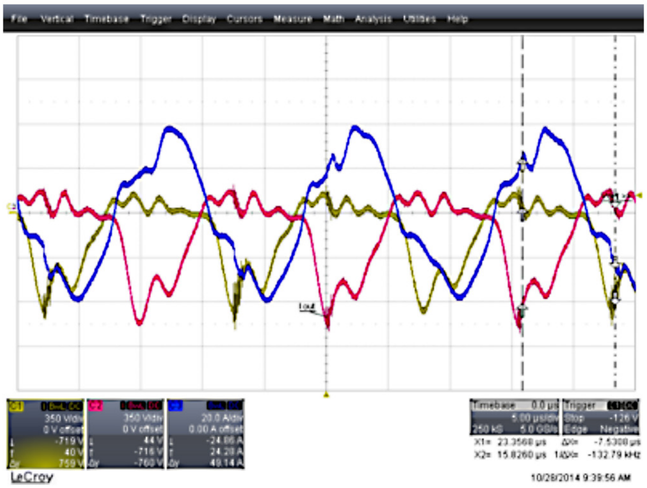
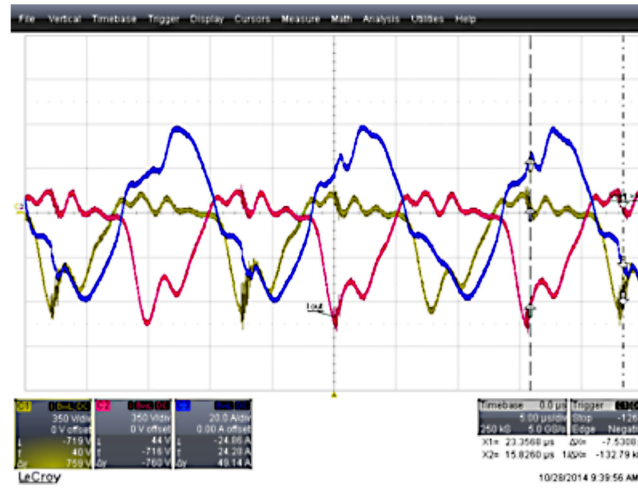


Fig. 10 – Electrical model of single chamber and transport system.



Ch1 = Va to ground (350V/div)
Ch2 = Vb to ground (350V/div)
Ch4 = Current (20A/div)

Fig. 11 – Output of an AC supply without anode clamping.

current on the sheet. Maximizing these impedances to ground becomes a system design concern.

Anode Clamping

Systems without the previous design recommendations, anode clamping can be an effective mitigation. In a dual magnetron system, the power supply periodically switches the voltage polarity on each magnetron between cathode and anode. If the voltage on the anode is assumed to be the plasma bias, variations of the anode voltage drive the plasma bias Vp1. The oscilloscope capture of the output of an AC supply shows these anode variations can be significant. Simply the difference in magnitude between adjacent chambers, Fig. 9 and Equation 1, Vp1 and Vp2 drives the current in Rsheet. In Fig. 11, these anode magnitudes are greater than 150 V.

If lightning arcs occur and the anode voltage is high; clamping the anode voltage to ground with an Anode Fall Box, modeled by D1 in Fig. 12, has been effective to clamp the voltage Vp1 and eliminate the defect in systems that have not implemented the other system design guidelines. D1 provides the system two benefits. The first the diode will clamp the maximum voltage the plasma bias can be above ground. The second it provides a secondary path for current to flow that is not in the sheet, giving an intended current path.

There have been cases where adding the Anode Fall Box has increased the lightning arc defect rate. This can be explained by the clamp D1 lowers anode voltage too much and effectively shorts out Vp1 and, as illustrated previously, the sheet and film currents increase to the point where the lightning arc defect occurs.

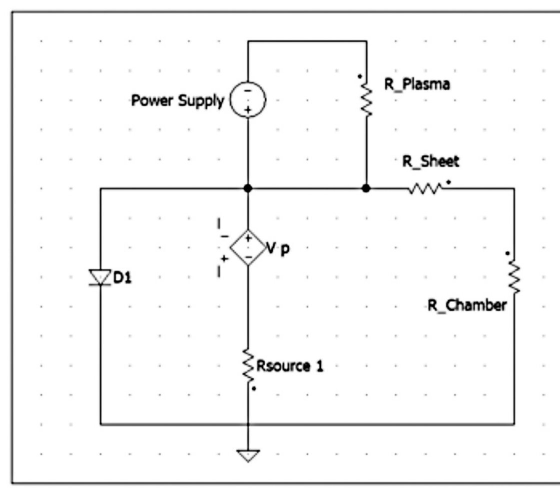


Fig. 12 – Electrical model with anode clamping.

CONCLUSION

Several mitigations that are known to be effective were presented with the electrical models showing the potential current paths away from the film. Modeling of large area systems can show unintended current paths and impedance interactions. From these models, it is obvious that current flowing in the substrate film is unavoidable, and the goal of the system is to provide low impedance paths currents enabling dedicated current return paths to the source that are not in the film. Electrical models can be used to explain the changes in the substrate film current that leads to lightning arc defects. Minimizing the current flowing in the substrate films becomes manageable once an understanding of the system is known.

About the Author: Josh Pankratz

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.