A new generation of power supplies with configurable powers from 30 kW to greater than 200 kW has been developed for large-area dual magnetron sputtering applications. These power supplies have settable frequency, duty cycle, and rise time, and optimizing these parameters can influence film properties such as index of refraction, crystallinity or morphology. Selectable fixed frequency enables operation of the process at the lowest possible frequency with the highest deposition rate. New features, like the ability to control power to each magnetron by changing duty cycle, enable comparatively more power to be delivered to one of the targets in order to compensate for differences in remaining target material. Arc energy is dramatically reduced, which enables lower defect rates in deposited films. This article describes applications of this new technology for increasing flexibility of coating lines and extending process performance.

**Introduction**

There is a need to deposit a wide variety of thin films in industrial applications. Sputtering has been widely applied to deposition of elemental materials and compounds. Many industrially useful compounds are dielectrics. For example, in low-ε layer stacks, dielectric films of various indexes are deposited on architectural glass with a large area coater [1]. These dielectrics can also be deposited on the sputtering anode in a DC process, resulting in a disappearing anode which needs to be cleaned in order to continue the process. Dual magnetron sputtering (DMS), as shown in Figure 1, is one solution to this problem. It can be used to deposit the dielectric layers [2] without explicit anodes. The two magnetrons, driven by an AC or pulsed DC supply, alternate roles as cathode and anode. Reported by Este and Westwood in 1988 [3], it has become a standard approach in industrial applications.

Initially, DMS processes were driven with AC supplies. Then pulsed DC supplies were developed, offering more flexibility in control of the process. They offer, for example, independent regulation of power to each magnetron. This has some advantages for existing processes, and enables the implementation of new processes. It is possible to adjust power to a pair of magnetrons with different inventory levels, so they reach end of life at the same time. Another possibility is to reduce power to a target which has a tendency to arc, to manage its arc rate. Frequency can be adjusted to trade off arc rate with deposition rate. Higher frequency tends to reduce arc rate, but it also reduces deposition rate. Pulsed DC supplies allow the lowest frequency with acceptable arcing to be set, maximizing deposition rate. Finally, independent regulation enables the creation of controlled mixtures of materials in the film by co-sputtering [2].

High power industrial dual magnetron sputtering systems typically require power in the range of 30kW to >200 kW. User selectable regulation of voltage, current, or power covers most applications [4]. It is necessary to deliver full power over a significant voltage range in order to operate reactive sputtering processes transitioning from metallic to poisoned modes, or controlled at a set point on the transition curve. Extended frequency range at reduced power levels should also be possible, for processes requiring high frequency to reduce or prevent arcs. Some processes require periodic cleaning cycles, and, in this case, the ability to run at higher frequencies for cleaning is desirable.

Square wave voltage source supplies were tried early on [5]. Voltage source supplies typically demonstrate rectangular voltage wave shape and a slow rising triangular current waveform, with a high peak current into an arc. Later work focused on development of pulsed current source supplies [6-8], with commercial availability of high power pulsed current source supplies at the 20 kW level in 1996 [9], followed by the products delivering 120kW and up to 200kW. New approaches and refinements have resulted in a new generation of pulsed DC supplies for high power industrial dual magnetron sputtering.

**Architecture**

A first step was defining the desired waveform to deliver power to the DMS system. The preferred waveform for large area sputtering using dual magnetron systems is shown below in Figure 2.

![Figure 1. Dual magnetron sputtering arrangement.](image1)

![Figure 2. Definition of optimized bipolar waveform for dual magnetron sputtering applications.](image2)
Key features of this waveform are the voltage boost period following each polarity transition and fast current rise time due to that boost. Ideally, the boost voltage would be adjustable. It is expected that adjusting the boost voltage will enable some tuning of the film properties, since it will effectively allow tuning of ion energy within the process. Additionally, adjustable duty, the ratio of positive to negative pulse width, would allow more power to be delivered to one of the magnetrons when desired.

For flexibility, the DC power supply function is separated from the pulse function. As will be described later, this allows tremendous flexibility in configuration and power granularity. A block diagram of the simplest pulsed current supply system is shown in Figure 3, depicting the power flow from 3 phase mains power to the plasma load. The system consists of two key components: The AC mains are rectified and output voltage and current regulated to deliver the desired power utilizing a DC power supply that has the ability to communicate with the bipolar accessory. Output of the DC power supply is connected to the input of this bipolar accessory.

Further expansion can be achieved by connecting these accessories in a Master/Slave (M/S) fashion. These multiple accessories are powered by several DC supply units connected in their own M/S set. This way, configurations delivering > 200 kW are possible. An additional feature available is common exciter synchronization (CEX) for multi-cathode web coaters, batch, or in-line tools, where operation of several DMS sets has to be synchronized to prevent cross talk between magnetrons, and to coordinate arc response between multiple adjacent magnetron pairs. An example system with all of these features is shown in Figure 4.

 Ideally, voltage, current, and power measurements can be provided for each of the magnetrons in the pair. These measurements, if fast enough, can be used for external process control loops, for example, transition mode operation of a reactive process. Reactive co-sputtering may require control of each target independently, to maintain the desired

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working point. Power is measured as the true total average power and average power delivered to each magnetron. The polarity of the current indicates which magnetron is sputtering at any instant. This allows an average power to be determined for each magnetron independently.

From a process perspective, the current measurement of interest is the average current delivered to each magnetron when it is sputtering. In some cases, it may be desirable to regulate on average current. However, the current is measured in real time and the information is also used for overload protection, loss of plasma and arc detection. The voltage measurement is also done separately for each magnetron and, just like current, is measured in real time. This measurement is used to determine whether the system exceeded the safe operating voltage limit, to calculate the average process voltage, boost voltage, and detect arcs. This voltage is a good indication of process conditions, particularly for reactive processes.

Arc management is critical to the success of any power supply system driving a dual magnetron sputtering arrangement. There are two facets of arc management. The first is arc handling, encompassing arc detection and the action taken when an arc is detected. The second is arc recovery, which is the strategy used by the power supply to reduce the number of process arcs and to minimize the recovery time when an arc does occur. These power supplies are configured as current sources. As such, they present a high impedance at their output. Consequently, an arc will cause the process voltage to fall immediately, without almost any increase in current. The arc detection circuit is based on voltage drop; therefore an arc can be detected as soon as it occurs. In cases where arc energy has to be absolutely minimized and there is potentially high energy storage in the cabling system, the bipolar accessory unit’s arc management protocol will reverse its output and therefore pull the energy out of the cables, hence further reducing the delivered arc energy. When an arc occurs in one polarity, the accessory can reverse its output to handle the arc and then resume operation in the opposite polarity. This is sufficient to quench most arcs which occur in practical production scale processes. With flexible control algorithms and inter-leaving techniques implemented in this system, it is possible to tolerate and handle very high arc rates, up to thousands of arcs per second.

Occasionally arcs occur which require that the power source shut off and allow the hot spot which is maintaining the arc by emitting electrons to cool down. These arcs are referred to as hard arcs. They are detected as an arc which will not go out after a number of attempts to simply shut off and resume operation in the opposite polarity.

Arc handling parameters can generally be preset and used for many or most production processes. Flexibility in setting arc handling parameters such as voltage threshold, hard arc count (number of attempts before declaring a hard arc), and delays before looking for an arc and considering an arc indication to actually be an arc enable one aspect of process optimization.

The approach taken here addresses the technological requirements of sputtering critical films such as TCOs (transparent conductive oxides, such as AZO, ZNO, ITO, etc.), compound materials and amorphous oxide semiconductors (IGZO) especially for the FPD, PV, and glass industries where defects caused by arcing on the substrate and on the target result in yield loss, target damage and increases in system...
maintenance. Typical arc energies are in line with low arc energy DC power supplies available today, and lower than typical AC or bipolar supply arc energies. In most cases processes are operated at the lowest frequency that results in an acceptable arc rate. Lower frequency operation results in higher deposition rate for a given peak current, because a smaller fraction of the processing time is lost while switching polarities. This means that lower peak current is required to deliver the same power to the process at lower frequencies. Lower current means less resistive heating, hence, lower losses and higher reliability. Some low melting point materials, such as Sn and Zn, require periodic cleaning of the target surfaces by running with pure Ar. In that case, it has been beneficial to clean at higher frequencies and sometimes with swept frequencies. The full featured bipolar accessory system is optimized to operate at maximum power between 10 kHz and 20 kHz. However, the maximum operating frequency is much higher, and is limited to 50 kHz, with possible de-rating of current or power, depending on system specifics.

Experimental Results
High power pulsed current source supplies are required to run in production facilities 24 hours a day, 7 days a week. They can power DMS processes on large inline coaters for architectural glass and other glass products or multiple cathode batch tools where they are all synchronized (CEX). Their operation is characterized by high film quality and high yield. They can be used on planar magnetrons and rotating target magnetrons, on web coaters and inline coaters. These could include processes using materials such as AZO, SiO₂, Si₃N₄, SnO₂, TiO₂, IGZO and ZnO.

Following development and simulation of promising circuit concepts, a prototype was created and tested in hardware. First, operation was verified on resistive loads and an electronic arc simulator. It is important to test at conditions that realistically represent industrial sputter deposition processes.

The test setup used for plasma testing is a dual rotatable magnetron system from Sputtering Components, Inc. (SCI). The magnetron targets are 1.5 m long by 0.16 m diameter. In these experiments the targets rotated at 10 RPM. Cabling was designed to represent the inductance seen in realistic industrial systems. Base pressure is 3.5 x 10⁻⁷ T. Tests were typically conducted between 1 and 5 mT with excursions beyond these limits, in metallic and poisoned modes, where applicable. Target materials used for testing included Al, Si (Al doped), AZO, Ti and Sn. Plasma testing resulted in waveforms substantially similar to the desired waveform shown in Figure 2. Observed arc energy was an order of magnitude lower than for AC supplies of comparable power.

Conclusion
This is the latest generation of pulsed DC power tailored for DMS applications, enabling tuning of the waveform to address application requirements for specific processes. Benefits of this approach are greater process flexibility, lower development costs and faster time to market due its waveform and system configurability.

References

Acknowledgements
The authors would like to acknowledge the contribution of the product development team who turned their ideas into a product.

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David Christie received his PhD from Colorado State University, is currently Director, Engineering with Advanced Energy, and has served on the SVC Board of Directors. His first SVC paper was in 1996, on pulsed dual magnetron sputtering. He has more than 35 thin film related publications, and 6 related patents.

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