Exhibit 15

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POWER SUPPLIES FOR PULSED PLASMA TECHNOLOGIES: STATE-OF-THE-ART AND OUTLOOK

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The power supply is important in the practice of plasma processing because of the intimate connection between it and the plasma. That the output circuits of even simple dc power supplies could affect the results of plasma deposition has been known and investigated for over 30 years. As a better understanding of the nature of the interaction between the power supply and the plasma developed, the power supply design evolved from a simple powering element to a key element in the system. This resulted ultimately in the development of pulsed plasma systems.

This paper reviews the development of the plasma power supply and its interaction with the plasma with particular emphasis on pulsed systems. Nonlinear effects and the effect of source impedance on plasma properties are discussed. The current state-of-the-art of pulsed power supplies is presented, including system control issues and a brief discussion of intellectual property status in both the United States and Europe. Indications of the directions of future developments in processing and pulsed power supplies are given, including the effect of availability of semiconducting switching devices for RF power generators as well as for dc and low-frequency ac power supplies.

INTRODUCTION

Pulsed power is very much in vogue these days. Whenever conventional techniques fail to produce acceptable results, process engineers think of pulsing to give them a new dimension and increased possibility for success. This paper is intended to present the state-of-the-art in power supplies for plasma processing with particular emphasis on pulsed power equipment.

PULSING BENEFITS

Nonlinearities

In cases where there is a nonlinear effect (with greater power providing some benefit X faster than linearly), if the system is limited to some average power, pulsing will provide a higher average value for X. As an example, pulsing the bias on a substrate permits enhancement of bombarding ion energy without undue heating of the substrate. Also, properties often depend upon the rate of deposition, so pulsing at a high rate can provide desirable film properties without overheating of the target or other parts of a system.

Time Dependencies

If an effect happens primarily at the beginning (or end) of a process, pulsing can provide many beginnings (or endings) and, thereby, enhance the effect. For example, it has been reported that the energy distribution of the electrons in a plasma is quite broad at the beginning of a powering pulse, but redistributes to a Maxwellian distribution within a few tens of microseconds. Continued pulsing with pulses shorter than this increases the average energy of the electrons as well as of the population of species created from the higher energy electrons.

Clearing Charges

Periodic reversal of the voltage of an electrode can clear a buildup of charges by attracting the opposite charge during the pulse. This technique has been widely used to reduce or prevent arcing due to charge buildup, especially in reactive sputtering.

So, for the most part, pulsing is done to:

- Avoid arcing—or at least to reduce arc defects
- Achieve better film properties: denser, tougher, brighter, more transparent
- Achieve higher yields
- Increase throughput and productivity

WHAT IS PULSED POWER?

Pulsing has been shown to do all of the above, but not all at the same time. There is a growing body of literature on the subject showing sometimes conflicting results and indicating that the field is still too new to have settled into a clear body of knowledge.

A glossary of terms is given at the end of this paper, but here it will be useful to separately define pulsing. If a system is pulsed, the power may either contain a periodic transient followed by a return to steady state, or it may consist of a periodic variation between two states. In the former case, the transient may be self-generated or may occur in response to a plasma event, such as an arc. In either case, the pulse may be represented by a change in the level of a dc voltage or current, or by a change in the amplitude of a carrier wave. The former has been extensively used in the processes of plasma diffusion, cleaning and etching, substrate biasing, and reactive and nonreactive sputtering. The latter has been used, for example, in semiconductor etching. In principle, a pulse may also be represented by a shift in the frequency or phase of a carrier wave, but this has not been explored in plasma processing to my knowledge.

PULSED DC

This paper is principally directed to pulsed dc (wherein the pulse is represented by a shift in voltage or current and, thus, power). The shift may be from one power level to another, may come from a power level to zero power (interruption), or may be a shift in voltage from one polarity to the opposite. The pulse may be intended to be square (in that only two levels are expected), or it may be a half sinusoid (which is a special case of amplitude modulation of a carrier wave). In practice, the waveforms are virtually never as intended due to nonlinearities of either the plasma or the power supply circuitry. So, the shapes of the resulting power waveforms are complex. One may not be able to control the power waveform, but by controlling the power supply output impedance, one can gain a measure of control over either the voltage or the current.

A high-output impedance gives the power source the characteristics of a current source (in that the current will tend to remain as programmed regardless of the impedance of—and, therefore, the voltage across—the plasma). A true current source has an infinite output impedance and (within its limits to produce adequate voltage) will be unaffected by the plasma impedance. In this case, the voltage will be completely determined by the plasma impedance characteristics. The power supply's limit in producing voltage is called *voltage compliance* or just compliance and can often cause problems in plasma applications.

A low-output impedance gives the power source the characteristics of a voltage source (in that the voltage will tend to remain as programmed regardless of the impedance of—and, therefore, the current through—the plasma). A true voltage source has a zero output impedance and (within its limits to produce adequate current) will be unaffected by the plasma impedance. In this case, the current will be completely determined by the plasma impedance characteristics. The power supply's compliance for current is called its *current limit*, and it can also cause problems in plasma applications.

A power supply may be current regulated (which causes the output impedance to be infinite), voltage regulated (which causes the output impedance to be zero), or power regulated (in which case the impedance is not constant, but is controlled to be always equal to the load [plasma] impedance). The circuits that control the power supply have a response time, however, and for times short compared to this regulation response time, the output impedance is determined by passive elements in the system. Generally, the pulse times in a pulsed system are short compared to the regulation response time. If the output circuit is dominated by a large parallel capacitor, the supply will tend to be a constant voltage source for short periods; if the output is a large series inductor, the supply will tend to look like a current source for the pulsing interval.

TYPES OF PULSING DC POWER SUPPLIES

Square-Wave Voltage-Fed Systems

In this approach, semiconductor switches place a large charged capacitor across the plasma periodically. The switches may disconnect during the pulse, may reverse the polarity of the capacitor, or may switch a different capacitor across the plasma. The capacitor appears as a constant voltage for short periods, so the system appears to have near-zero output impedance. Such a system is commonly used for substrate biasing (in which case the capacitor is applied for a short time and then disconnected for a longer time). A simple circuit is shown in Figure 1. The result is a pulse of voltage on the substrate, which attracts ions from the vapor stream. If the stream is largely ionized, the ions will be strongly attracted to the substrate and arrive with high energy. This can greatly enhance film adhesion and affect stress and other film properties. During the interpulse period, there is no ion bombardment. The power dissipated in the substrate is equal to the ion current times the pulse voltage times the duty factor; if the last is kept small, the power may be small even with high voltages and currents, avoiding excessive substrate heating.

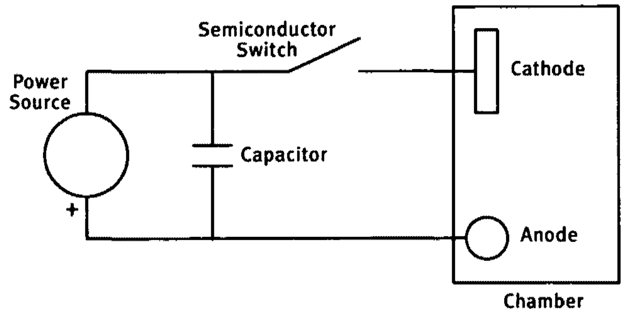

Figure 1.

Voltage-fed systems are used in substrate biasing and plasma diffusion, but are not so effective when applied to sputtering applications because of difficulties with ignition, the delay time in building the plasma density, and, therefore, the sputtering rate. When the voltage source is disconnected, the plasma decays with a two-fold time constant—fast at first ($\tau \approx 5$ µs) as the hot electrons leave the plasma, and more slowly later ($\tau \approx 50$ µs) as particles with slower velocity are lost to the chamber walls. To rebuild the current after this decay requires time, unless excess voltage is available to accelerate ionization. The buildup of current in such a system is shown in Figure 2.

Arc-handling is more difficult in such a system because the arc must be detected by an increase in current, and this takes time to detect. During the detect time, energy is delivered to the arc from the primary power source.

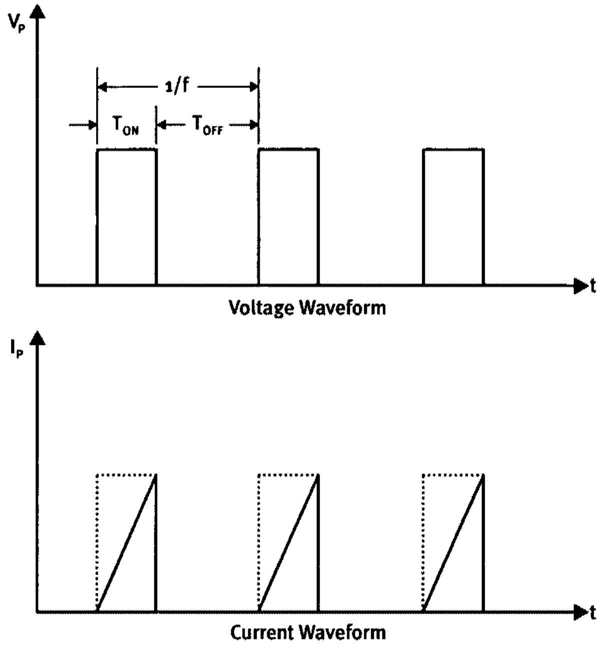

Figure 2.

Voltage-fed systems can be used for dual targets. In this configuration, shown in Figure 3, four switches are used in an *H-bridge* configuration to reverse the voltage from the capacitor across a pair of targets. This system suffers from the same ignition, delay time, and arc-handling problems mentioned above.

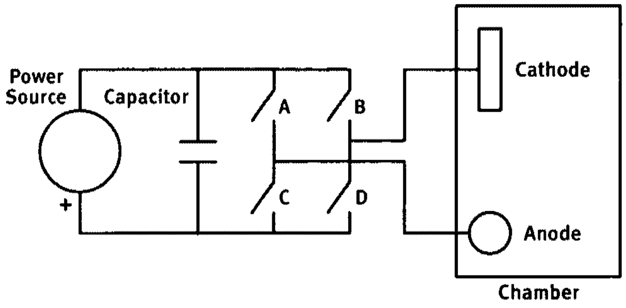

Figure 3.

Square-Wave Current-Fed Systems

In the patented[1] configuration shown in Figure 4, an inductor is charged to a current by a switch in parallel to the plasma. When the switch is opened, the inductor current is diverted to the plasma. Since the inductor appears as a current source for short periods, such a configuration has a high output impedance. The voltage compliance is limited by the voltage rating of the switch and the need to provide snubbing circuits (not shown in Figure 4) that act to limit the voltage excursions to a safe level for the switch. Nevertheless, when the switch is opened into a partially decayed plasma, the voltage rises quickly, which accelerates the buildup of current. This greatly increases the power delivered to the plasma during the pulse. The voltage and current waveforms are shown in Figure 5. Systems using this approach are widely used for reactive sputtering; their use in this regard for depositing insulating films is the subject of an issued US patent[2].

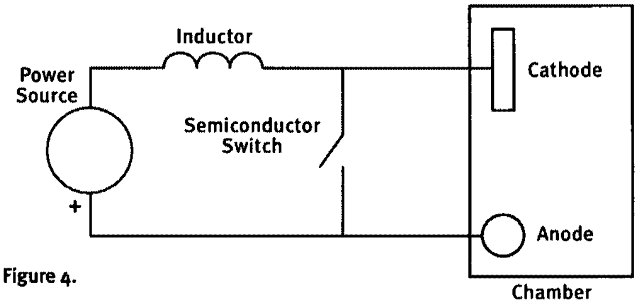

Figure 4.

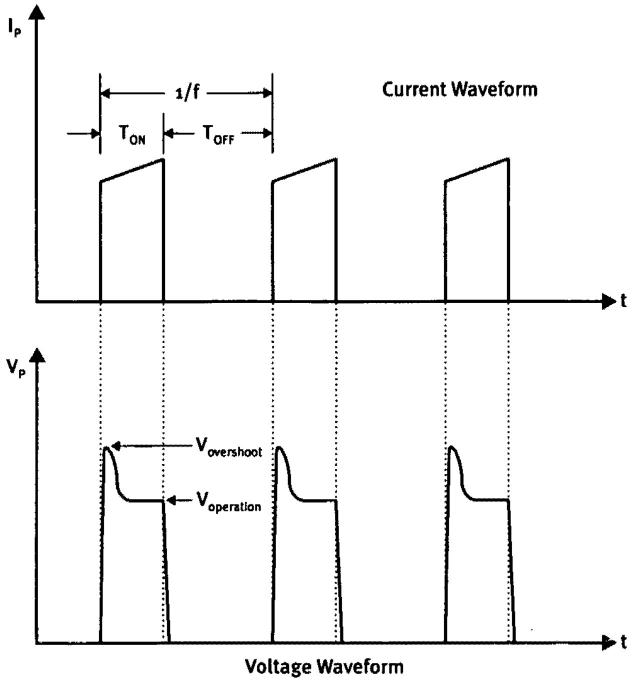

Figure 5. Waveforms for the Current-Fed

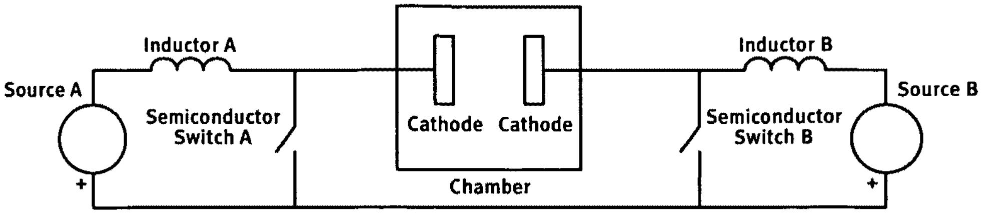

Figure 6.

Current-fed systems can also be used for dual targets. The configuration shown in Figure 6 (essentially a pair of Figure 4 circuits) is the subject of several patent applications and one issued patent[3] in Germany. Its use for depositing insulating films by reactive sputtering is also covered by a US patent[2].

The dual-cathode configuration shown in Figure 6 has unique features. Because of the lack of a transformer, the user has complete freedom in setting the current levels and the pulse widths of the power delivered to the two cathodes. This permits the use of the dual-cathode approach—which greatly alleviates the disappearing anode problem, while supplying each of the targets with a different material running at different voltages, currents, and powers that can be varied during a deposition to permit continuous variation in film properties. Such a system (using reactive sputtering) can create dielectric films with graded index of refraction, for example.

Arc detection in either the single- or dual-target configuration is particularly easy, because for a constant current, the arc represents a large drop in voltage. Simple voltage-comparing circuits can detect an arc in as little as 50 ns, and the closing of the parallel switch (or both switches in Figure 6) will quench the arc with very little energy delivered to it. Pulsed dc power supplies operating at the 120 kW level are available commercially that deliver as little as 100 millijoules to an arc.

Hybrid Current-Source/Voltage-Source Systems

Several power systems are available that are hybrids, acting as a current source in one period and a voltage source in a second period. Slightly different configurations have been used, but all of them are roughly equivalent to the circuits shown in Figure 7. These have all been designed for use with single targets. The constant current feature of the series inductor is used to produce a rapid current rise for reinitialization of the plasma current after the interruption, and the auxiliary voltage source (to which the switch is connected in Figure 7B) aids in overcoming any inductance of the leads to the target. The transformer action of the tapped inductor in Figure 7A provides the equivalent voltage as the auxiliary source. This configuration is patented[2][4]. Some papers have been written claiming a preferential sputtering effect of the voltage source due to an excess reverse voltage appearing on insulating islands in this configuration, but the existence of such an effect is very doubtful since there does not appear to be a physical mechanism for obtaining the excess reverse voltage on the insulating islands.

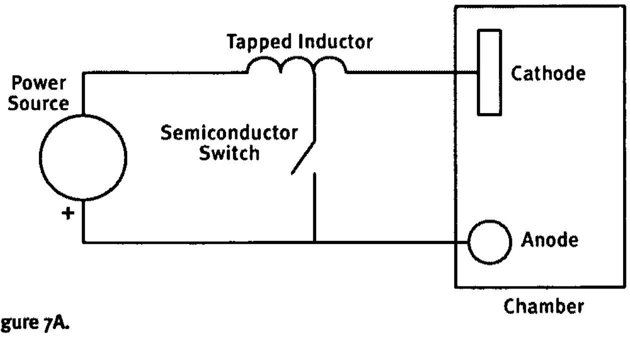

Figure 7A.

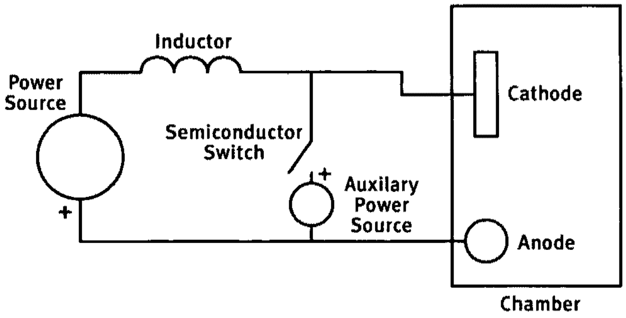

Figure 7B.

Sinusoidal Systems

Sinusoidal currents can be generated by a variety of circuits, but the most efficient (and by far the most used today) is a circuit composed of electronic switches, creating a square wave of voltage, which is then impressed upon a series resonant L-C circuit (some power supplies use a parallel resonant system). This configuration produces a sinusoidal current, which is then delivered to a transformer for impedance matching. The transformer output can be delivered to a single target or to dual targets and may also be used for CVD applications. Power adjustment (regulation) is accomplished either by controlling the pulse width of the switches or by controlling the peak voltage with a preregulator. As the on-time of the switches is shortened to less than 50% of the period, the current waveform will be increasingly distorted; use of a preregulator eliminates

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