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By Richard A. Scholl of Advanced Energy Industries, Inc.

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

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.

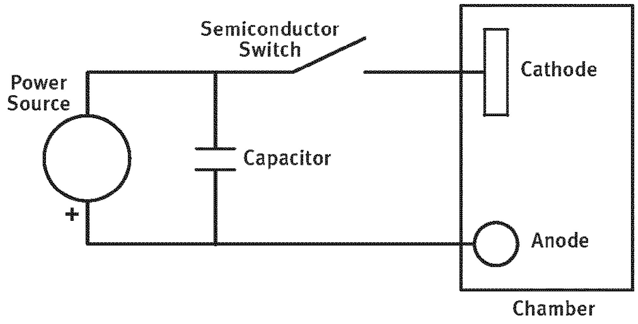

Figure 1.

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.

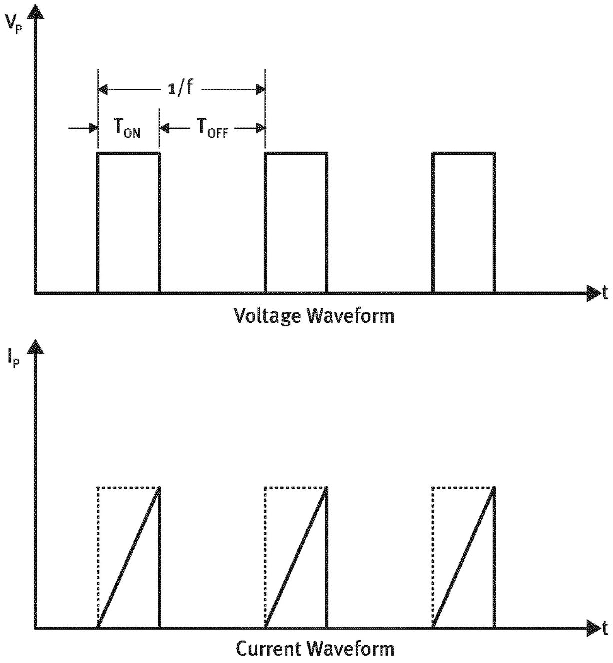

Figure 2.

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.

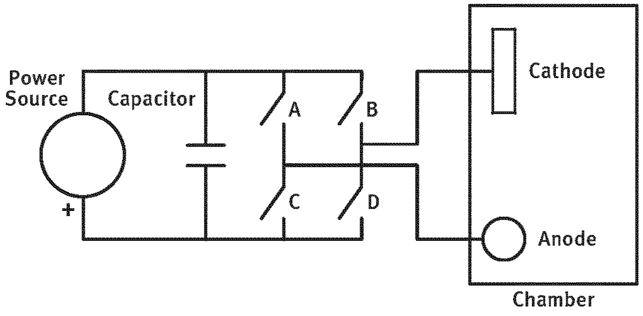

Figure 3.

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].

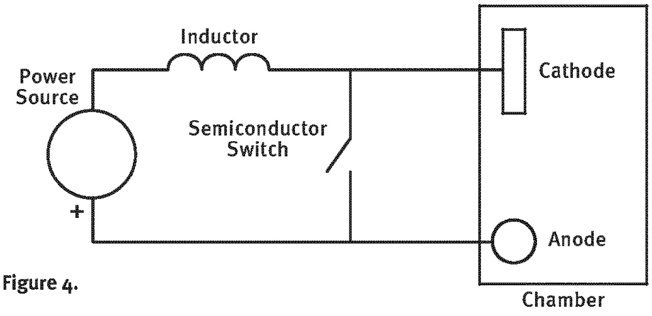

Figure 4.

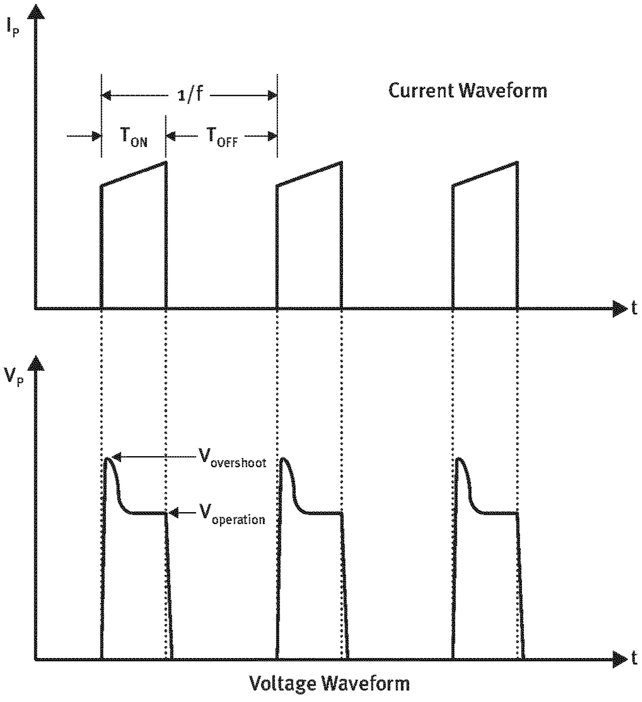

Figure 5. Waveforms for the Current-Fed

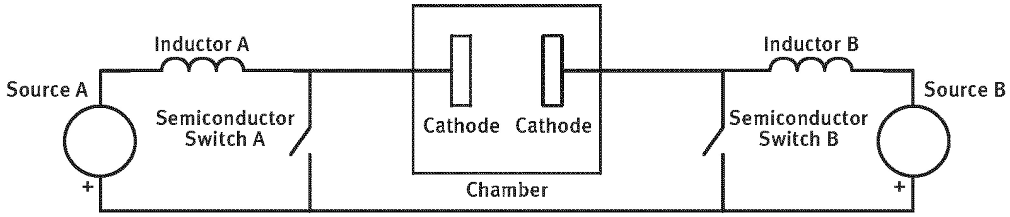

Figure 6.

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.

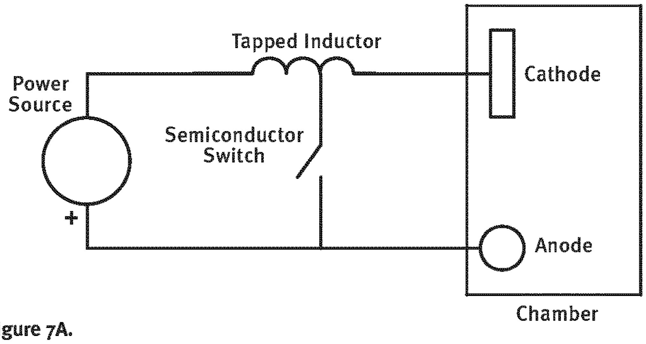

Figure 7A.

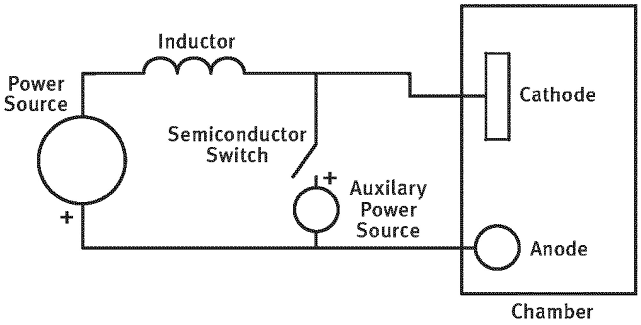

Figure 7B.

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 this effect. The circuit is shown in Figure 8, and typical waveforms are shown in Figure 9. Since the output is a quasi-sinusoidal current, the output impedance is high.

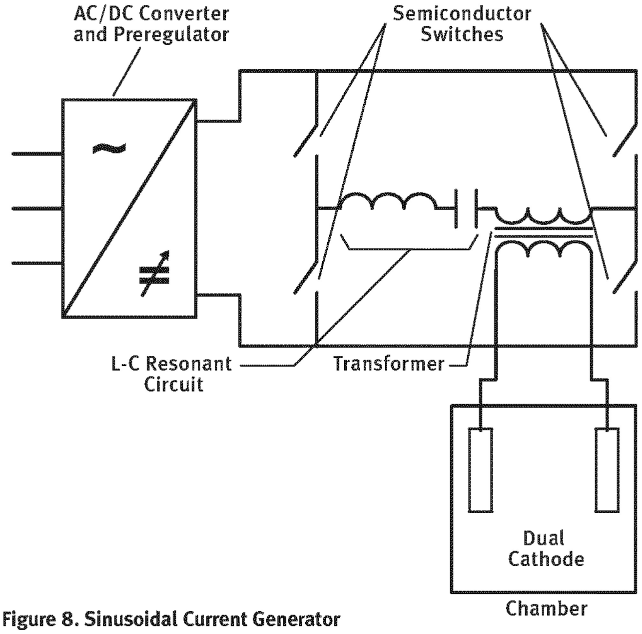

Figure 8. Sinusoidal Current Generator

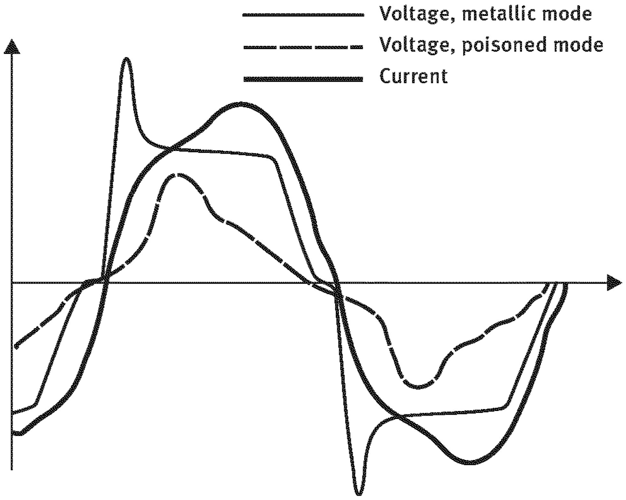

Figure 9.

Arc-handling is more complex in sinusoidal systems. While it might seem that voltage-sensed arc detection would be easy (as in a pulsed current-fed system), the problem is made difficult by the highly nonsinusoidal nature of the voltage waveform.

In the simplest arc-handling approach, arcs are simply ignored on the assumption that they will be extinguished by the reversal of the current on the following half cycle. To prevent damage to the system in the case of a hard arc, a drop in average voltage (i.e., the RMS voltage averaged over several cycles) is used to determine the presence of such an arc—in which case all the switches are opened for a recovery period. The energy stored in the resonant L-C circuit is then discharged into the arc. After enough time has passed for the arc to extinguish, circuit operation is resumed. Since there is an unavoidable delay in arc detection—especially if the circuit Q is high, this arrangement can result in a large energy being delivered to the arc. A more complex system will detect the arc by comparing the integral of a half cycle of the sinusoid with the integral of the prior half cycle; a major disparity indicates an arc. This guarantees the arc will be detected in at most one-half of the period of the sinusoid. By clever arrangement of the switches, the energy stored in the resonant circuit can be partially diverted into the input power supply and if the circuit Q is kept low, the total energy delivered to an arc can be kept to a minimum.

MEASUREMENT IN PULSED SYSTEMS

Pulsed DC Systems

In these systems, the usual setup is to measure the main dc power, and many users assume that this is the power delivered to the plasma. This is not the case, and a correction must be made to the measured dc values of voltage and current.

A dc pulsing unit (such as that shown in Figures 7A and 7B) acts as a dc transformer if the switch is operated at a pulse width t_{rev} and frequency f. While the power is unchanged (neglecting losses in the pulsing unit), the voltage and current will be modified by the duty cycle factor $\eta=1-t_{rev}f$, as follows:

$$V_{plasma} = V_{ps} / \eta$$

$$I_{plasma} = \eta I_{ps}$$

$$P_{plasma} = P_{ps}$$

The apparent drop in impedance (drop in voltage and increase in current as read by the power supply's metering) will occur when the pulsing is begun and may be surprising to the new user. It should be pointed out that the current in the plasma is about the same before and after the pulsing is started, while the voltage is transformed (increased) by the factor η^{-1}. Thus, the peak power during the period the switch is off is raised by the factor $1/\eta$, while the average power is the same whether the plasma is pulsed or not, again neglecting losses in the pulsing unit. In the following, we will account for the pulsing losses.

In the passive circuit of Figure 7A, there are losses in the pulsing unit roughly proportional to the power:

$P_{loss} = (1-k)\ P_{in}$

and the above equations become

$V_{plasma} = V_{ps} / \eta$

$I_{plasma} = \eta k I_{ps}$

$P_{plasma} = kP_{ps}$

This latter set of equations hold for a passive pulsing unit like that of Figure 7A, where the plasma power is always less than the input (metered) power. If the equivalent circuit of Figure 7B is implemented directly (with an actual power supply for the voltage source), this auxiliary power supply can also be delivering power to the plasma. The power in this case can be more than that indicated on the meters of the main power supply (by an amount that depends upon the actual voltages, frequency, and duty cycle). This can make such a supply appear to be more efficient in pulsing than a passive unit, since not all of the real power is being accounted for. In either case, a correction must be made to the measured power when making sputtering efficiency calculations.

MEASUREMENT IN SINUSOIDAL SYSTEMS

Some sinusoidal systems originally intended for induction heating do not measure power at the output of the supply (i.e., at the plasma). These units may have an oscillator section that is comprised of one or more semiconductor switches operating into a resonant circuit and transformer (whose secondary is connected to the plasma). The frequency of oscillation usually is controlled so that the circuit is operating in-phase with the resonance, even in the face of changes in the plasma load. This permits the energy losses in the semiconductor switches to be minimized. It is relatively easy to measure power in sinusoidal systems, but in the plasma environment, the waveforms are complex, and some manufacturers have elected to simply measure the dc power coming into the oscillator section. If this is done, the measured power includes not only the power going to the plasma, but also the power lost in the oscillator circuits, the resonant circuit, and the output transformer. Such losses can be substantial and can easily reach 30% to 50% of the delivered power. At the lower frequencies, the most common solution to direct measurement of the plasma power is to accurately measure the voltage and current in real-time and to deliver them to a multiplier circuit. The output of this circuit is the product of V(t) and I(t) (the instantaneous power), which can be averaged or filtered to produce an average power signal. This can be done easily up to a few MHz, but at higher frequencies more complex approaches must be used. It is important to understand the measurement method, as this can affect many characteristics of the power supply. For example, the cost of a supply is dependent upon the power level, and in comparing the cost of equipment, one obviously needs to know if the 120 kW power supply one is contemplating can only deliver 70 kW to 80 kW to a plasma due to unmeasured losses in its oscillator and output sections.

REACTIVE GAS CONTROL

A serious problem with reactive sputtering (a common use of pulsed power supplies) is control of the reactive gas. This is large enough to be the topic of a separate paper, but for now we can say that several means have been used. The well-known hysteresis phenomenon prevents the use of simple mass flow control. Fast valves (with response times ~1 ms) have been used and controlled to regulate the target voltage, the plasma emission, or the partial pressure of the reactive gas. An alternative has been used that varies the power at slow (chemical) rates to inhibit the hysteresis effect.

OUTLOOK

Development of nonsinusoidal pulsed systems (particularly at high powers) has been slow. The first pulse systems designed as voltage sources (see Figure 3) were developed up to the 100 kW level, but reliability problems and high cost prevented general acceptance. Low-power current-fed units for both single-target and dual-target operation (Figures 4 and 6) have been available for about five years, but a high power (120 kW) counterpart to the sinusoidal power systems has only now become available. This unit operates in dual-target mode (Figure 6) up to 35 kHz and in single-target mode (Figure 4) up to 60 kHz and can deliver 250 A into each target, with independent adjustment of the current and the pulse width for each target. A 180 kW version is now under development and higher powers (up to 400 kW) are planned in the future.

NOTES

1 US Patent 5,576,939

2 US Patent 5,718,814

3 DE patent 4,438,463

4 US Patent 5,427,669

LEXICON

There is a lot of confusion in the literature about the use of pulsed technology terms, and it would be worthwhile here to define a few of the more widely used terms. Such definitions are to some extent arbitrary, and I do not claim to have done more than to indulge my own preferences, but as there exists at present no well defined lexicon, I offer my own here.

Arc	An arc is a transition from the high-voltage (abnormal glow) region (wherein the voltage rises with increasing current) to a low-voltage region (wherein the voltage falls with increasing current). A *bipolar arc* is an arc that can conduct current in either direction (generally from a metal surface to another metal surface) sustained by metal-ion formation at the cathode. A *hard arc* is an arc that persists after brief arc-control measures have been taken (e.g., reversal of voltage or removal of power for a few microseconds). A *micro arc* is an arc that is extinguished by brief arc-control measures; also used to mean an arc that has extinguished itself without outside measures.
Duty Cycle	Given a period of on-time (during which power is applied) and a period of off-time (during which power is either off or applied at a different level), the duty cycle is the ratio of the on-time to the sum of the on- and off-times.
Off- and On-Times	*See duty cycle.*
Overshoot	A transient response wherein the desired quantity (voltage, current, or power) exceeds the desired value before settling to its (desired) steady-state level.
Power, Average	In a repetitive cycle, the total energy delivered by the power supply divided by the cycle time or period of the repetitive waveform.
Power, Measured	The power indicated by the measurement circuits of a power supply. Depending upon the placement of the measurement circuits and the architecture of the supply, this may be different from the actual power delivered to the plasma.
Power, Peak	The maximum rate of energy flow in a repetitive cycle.
Power, Plasma	The rate of energy flow into a system (i.e., through the chamber wall). Generally, losses in the leads to—and inside of—the chamber are ignored as they are often small compared to the total power. The plasma power may be dissipated in the target, shields, chamber walls and other parts, and substrate, but it is all considered plasma power.
Power, Pulsed	This term is ill-defined and should not be used. Some consider this the same as *peak power*, others the same as *average power*, and some use this for *RMS power*.
Power, RMS	The heating value of the power. Obtained by integrating the product of the voltage and the current over the period of a repetitive waveform and dividing by the period.
Pulsing	• Power containing a periodic transient followed by a return to steady state • Power consisting of a periodic variation between two states
Pulsing, Asymmetrical	In general, a power delivery waveform that has no point of symmetry. That is, there is no time (ts) such that $P(t_s - t) = \pm P(t_s + t)$. In a dual-magnetron system, this is a power delivery method that permits independent adjustment of the peak power to the two targets.
Pulsing, Bipolar	• A power delivery waveform that reverses the sign of the voltage and current • A floating power delivery system that supplies power to two sputtering targets such that each is the anode for the other
Pulsing, Unipolar	A power delivery system in which the voltage and current do not reverse sign.
Source, Current	A power supply that tends to have a constant current output (i.e., whose output voltage is proportional to the plasma [load] impedance).
Source, Voltage	A power supply that tends to have a constant voltage output (i.e., whose output current is inversely proportional to the plasma [load] impedance).

ADVANCED ENERGY®

Advanced Energy Industries, Inc.
1625 Sharp Point Drive
Fort Collins, Colorado 80525
800.446.9167
970.221.4670
970.221.5583 (fax)
support@aei.com
www.advanced-energy.com

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F: 408.263.8992	F: 856.627.6159	F: 44.1869.325004	F: 49.711.7778700	F: 82.31.705.2766	F: 81.3.32353580	F: 886.2.82215050	F: 86.755.3867984