

By Randy Heckman, Gregory Roche, James R. Usher of Advanced Energy Industries, Inc.

**THE EVOLUTION OF
RF POWER DELIVERY IN
PLASMA PROCESSING**

Radio frequency (RF) technology has been around since the beginnings of early broadcast communication. In fact, the use of RF in the first half of this century centered around radio communication, as the very name implies. Electronic engineers and physicists began using RF power in semiconductor and thin-film processes in the early 1970s.

RF has assumed a dominant role in the plasma market in the 1990s with elaborate component configurations used in critical high-density CVD and PECVD deposition, etch, and PVD processes for applications including semiconductor manufacture, IC fabrication, thin-film heads for disks, CDs, hard disk coatings, and other industrial uses. Process engineers now commonly use RF in the development of IC devices at geometries from 0.5 to 0.25 microns for DRAMs, logic, ASICs, and other such devices.

THE ROLE OF GENERATORS IN PLASMA

These critical processes all take place in a vacuum chamber in the presence of a plasma—an electrically neutral, highly ionized gas. Generators are used to “ignite” and maintain plasmas that vary continuously and may or may not be stable. RF generators must be capable of reacting to the plasma’s changing characteristics, ensuring that power remains stable during operation.

Typical plasma processing applications involve either a direct (dc) or an alternating (ac) current source provided by a generator. Plasma systems which sputter insulative materials typically use ac or RF generators, which require the designer to use different frequencies. RF is a term generally used to describe frequencies of 10,000 Hz to 1000 MHz. However, in the thin-film process applications mentioned above, the usual operating frequencies range from 40 kHz to 40 MHz, with the most common frequencies at 450 kHz, 2 MHz, 4 MHz, 13.56 MHz, and 27.12 MHz.

RF DESIGN TECHNOLOGIES

Usually, one of two types of RF design technologies are used to generate power for plasma systems: linear or switching.

RF LINEAR TECHNOLOGY

In the evolution of RF power delivery, linear technology was the first effective technology used to provide RF power for plasma manufacturing process. These supplies were readily available, being primarily used in broadcasting.

The linear power supply provides power directly from the transformer to the load through two linear sections: dc and RF. The linear dc supply section comprises large capacitors and large amounts of stored energy. The linear RF amplifier section is a complex assembly, including a significant number of expensive bipolar FETS. Direct current to RF power conversion using linear technology typically results in between 30% to 50% power loss in these solid-state devices. While effective, these large and relatively expensive systems cannot be installed on the chamber. See Figure 1.

Prior-generation RF generators were comprised of a linear dc supply with 1 large 60 Hz iron-core transformer and a complex linear solid-state RF amplifier.

BEYOND LINEAR: SWITCHMODE TECHNOLOGY

The next step in RF generator technology incorporated a high-frequency (100 kHz) dc-to-dc inverter to drive a driver/exciter and 13.56 MHz power amplifier. Advantages of this technology include lower power dissipation, reduced stored

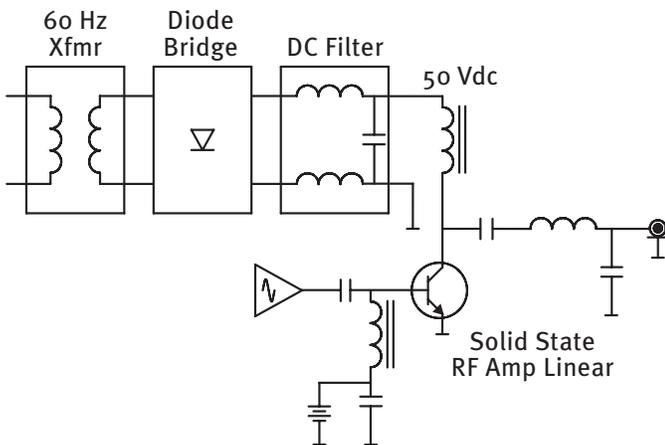


Figure 1. Linear Solid-State Technology. Prior-generation RF generators were comprised of a linear dc supply with 1 large 60 Hz iron-core transformer and a complex linear solid-state RF amplifier.



THE EVOLUTION OF RF POWER DELIVERY IN PLASMA PROCESSING

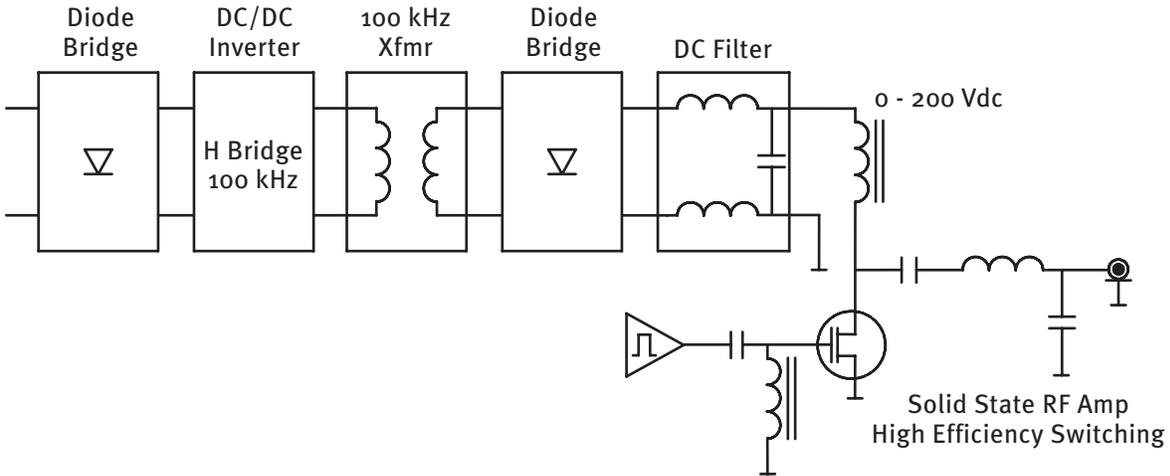


Figure 2. dc-dc Input with Switching Output. High-efficiency dc and RF switching topologies significantly reduce the size of the large input transformer and simplify the RF amplifier modules.

energy, and reduction in system size, since the generators are small enough to be installed on plasma vacuum process tools for thin-film applications including semiconductor manufacture and industrial coating. See Figure 2.

Since switchmode technology operates at higher frequencies, it allows the process engineer to design in smaller and lighter magnetic components than those used in linear technologies. This technology also utilizes advanced thick-film hybrid technology that allows for less variation in component design, reduction in mechanical packaging, and less weight. The combination of these design enhancements has resulted in more efficient generators and has paved the way for the evolution from linear to switchmode power supplies.

Figure 3 illustrates improvements in RF power density realized through this evolution. Table 1 compares the major characteristics of these two technologies.

RF MATCHING TECHNOLOGY

The development of significant breakthroughs in RF technology has stemmed primarily from the need to maximize process repeatability, minimize power loss to the load, and

	Linear	Switchmode
Complexity	Very high	Low
Cost of Ownership	Expensive	Inexpensive
Size	Large—cannot be mounted on the chamber	Shoebox-size
Reliability	Low	High
Dissipation of input power	Up to 50% dissipation	Less than 10%

Table 1. Comparison of linear and switching considerations. For process engineers, the evolution from linear to switchmode technology provided significant benefits.

improve load stability. These technology advances have resulted in more repeatable processes and increased yields for the process engineer.

In theory, all capacitors and inductors store energy, with no dissipation of power. In reality, however, all devices are less than perfect. The challenge, therefore, becomes one of maximizing power delivery and minimizing energy loss to the

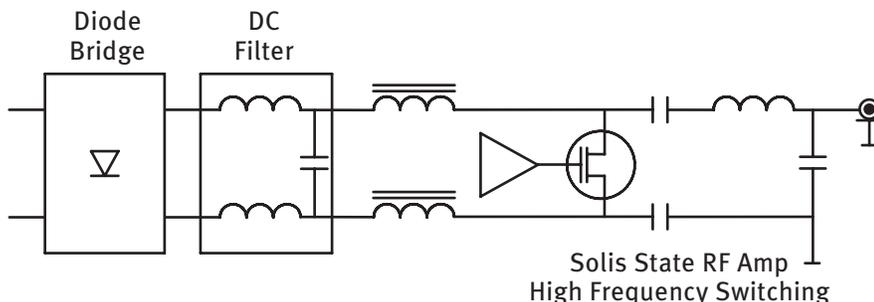


Figure 3. RF Generator Power Density. The greatly simplified Apex™ technology allows for a significant increase in power density as compared with prior technologies.

THE EVOLUTION OF RF POWER DELIVERY IN PLASMA PROCESSING

load. Tuners, or impedance-matching networks, work to shift the voltage and current waveforms so that the power to the load is maximized, while also transforming the load impedance to 50Ω —matching the load impedance to the generator’s output impedance.

Impedance-matching networks, integrated into high-frequency power delivery systems, have been key in this RF technology evolution. Specifically, fixed match technology brings advances to process repeatability and RF system reliability. A fixed match is a nonmovable match network which operates with a generator regulated on load power. The generator delivers its rated power into the load through the fixed match, thereby accommodating mismatch conditions with higher VA power delivery capability.

Since some vacuum processes require wider impedance ranges, more than one match position may be required. Advanced Energy Industries, Inc. (AE), has developed a selectable fixed match system using pin diodes and SwitchMatch™ technology that allows for multiple impedance matching within a specified range. AE also has taken discrete selectable fixed match technology one step further by integrating the SwitchMatch technology internally in the RF system.

FULLY INTEGRATED RF POWER DELIVERY

The most recent RF power technology breakthrough incorporates switching technology and eliminates the dc-to-dc inverter stage completely. The effect is further simplification of design and significant performance improvement in plasma applications.

The single-package Apex system that AE recently introduced is a fully integrated RF power delivery system.

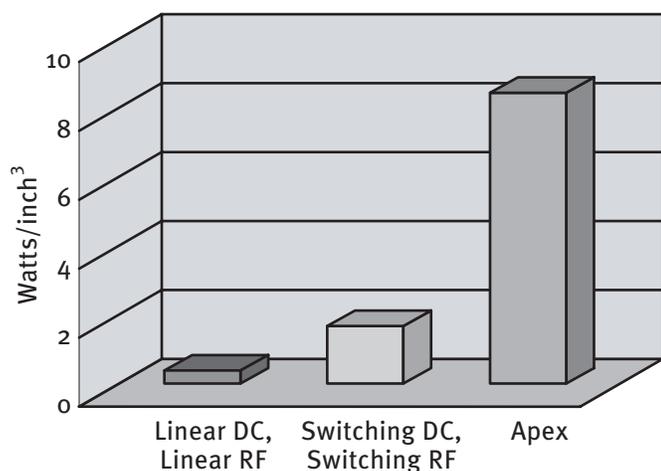


Figure 4. Apex Technology. The Apex technology requires only an output switching RF amplifier that is positioned directly across the rectified line voltage, thereby eliminating the need for any input transformer or dc supply.

For process engineers dealing in critical RF power applications, that means technology that delivers power repeatability, increased reliability, and lower cost. See Figure 4.

In the semiconductor industry, where an RF product failure in the etch process results in total loss of the wafer, that failure can be a costly mistake exceeding \$500,000. In industrial processes where RF is used in deposition and surface treatment, it is critical that the substrate is cleaned to allow for adhesion of coatings such as titanium nitride or zirconium nitride. Process engineers working in these applications must improve yields by reducing variation and increasing throughput. Reducing—or eliminating—risk of failure in the RF system therefore goes directly to a company’s bottom line.

By integrating the RF power amplifier, SwitchMatch technology, and RF sensor in the Apex system, AE has produced a smaller, more compact power source that delivers power more accurately and repeatably at the load or substrate. Installing the RF power delivery system directly at the load is the most accurate way of delivering setpoint power, and the optional use of internal SwitchMatch technology with RF sensor provides the most accurate power delivery available today.

Getting the RF power delivery system as close as possible to the chamber electrode of the PVD/CVD/etch process tools—direct coupling to the source—eliminates the 10% to 25% power loss inherent in typical system component configurations (comprised of a generator, coaxial cable, match network, and RF sensor). Apex technology also supports an MTBF exceeding 200,000 hours—a 300% improvement over existing RF power system configurations by reduction in component content, system complexity, and advanced engineering techniques.

Unlike conventional RF power component configuration systems, some Apex configurations use an integrated RF sensor to collect and measure power, voltage, current, and impedance within the system. The process engineer is then able to better measure and regulate power delivery into plasma impedance changes. One clear advantage of using Apex technology with internal SwitchMatch technology is that it provides for closed-loop control with the system, allowing for better system integration and power management.

The Apex RF topology and internal measurement design include high bandwidth control loops to improve plasma mode-change stability. Optional high repetition rate and internally generated pulse operation can be incorporated to support future process development—enabling the process engineer to develop higher-performance processes in short-lived etch applications, but with high directionality or sensitivity.

The Apex single-package design also reduces the number of parts over existing RF component configurations by 40%,

THE EVOLUTION OF RF POWER DELIVERY IN PLASMA PROCESSING

eliminating cabling and associated hardware that often cause RF measurement errors. When configured with SwitchMatch technology, Apex technology eliminates all moving parts associated with conventional impedance matching networks, thereby dramatically increasing RF product reliability and tool up-time related to RF power. With the ability to close the loop at the RF electrode, this technology provides consistent RF power delivery at the setpoint. A single control interface can be used for both generator and match center impedance selection.

The Apex RF generator product line is more than 75% smaller in size than competitive systems, and it can accommodate on-board mount at the process tool and/or more RF units per rack for remote installation. Nonrack mount Apex configurations are shoebox-sized, permitting minimal-footprint OEM solutions. The RF power conversion technology of Apex units eliminates the typical front-end dc-to-dc conversion components, increasing power density up to 400% over conventional RF generators at the 5500 W level. At 10 kW, density increases two to three times that found at the 5500 W level.

In eliminating the traditional dc-to-dc conversion stage, Apex technology directly converts the rectified line voltage (208 Vac 3 ϕ or 400 Vac 3 ϕ) into RF power. It uses AE's proprietary RF power amplifier and measurement circuits to accommodate outputs of 50 W and other predefined impedance ranges.

Apex technology utilizes an integrated microprocessor that permits simple addition of digital serial communication interface options, including RS-232, RS-485, Profibus, and DeviceNet™ protocols. The microprocessor also enables self-diagnostics testing and extended functional testing in the field. The Apex platform offers CEX and high repetition rate pulsing capabilities (optional), and will be available in power ranges of 1.5 kW to 10 kW and frequencies of 13.56 MHz and 27.12 MHz.

By providing the process engineer with closed-loop control of the power delivered to the chamber, Apex models foster higher yields through greater repeatability. In addition, this enables the process engineer to achieve chamber-to-chamber matching. The end results in the semiconductor industry are better DRAMs, logic, ASICs, and other such devices, as the geometries continue to shrink and wafer size continues to increase. Many industrial applications are experiencing the same trend, with the growing size of substrates increasing requirements for the uniformity of properties of the deposited films.

RF DIAGNOSTICS

A stand-alone version of the VI probe used in Apex technology, Z-Scan™ RF Probe, provides harmonic content of the voltage, current, and phase with software that allows data

logging. When installed into existing systems, such as commercially available plasma etchers and deposition equipment for semiconductor and industrial applications, the Z-Scan sensor will allow the process engineer to control power delivery on the basis of voltage, current, and phase of the fundamental frequency as well as harmonics of the fundamental.

Figure 5 is a screen capture from a Z-Scan probe during etching of SiO₂ off of an Si wafer. It shows the fundamental V, I, and phase of the fundamental frequency (13.56 MHz) as well as the V, I, and phase of the 4th harmonic (54 MHz). Note the strong change in the 4th harmonic as the etch nears endpoint at 50 seconds. That is, as the SiO₂ begins to clear off of the substrate, the plasma impedance changes, and this shows strongly in the 4th harmonic of both the current and the voltage. (It also shows to a lesser degree in the fundamental and even 2nd harmonic.) In this example, the SiO₂ film is completely removed at about 64 seconds. The process engineer can use this signal to control the process, in other words shut off the RF power at 64 seconds. Further, the rate of change of the signal from 50 seconds to 64 seconds is an indication of the uniformity of the etch process. The process engineer can track this information and correlate to process issues with the etching plasma system or the deposited film.

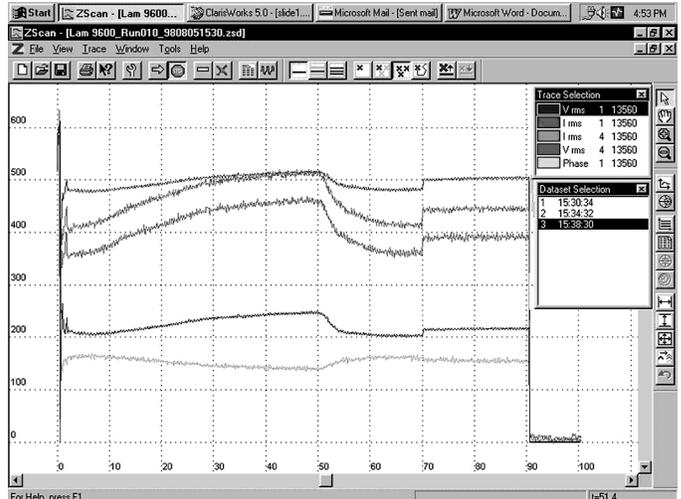


FIGURE 5: Z-Scan™ Data Traces. Data traces from Z-Scan RF sensor, installed in a Lam 9600 Metal etch tool. The tool was configured for oxide etching, and these represent a single wafer's data trace during the etching of contacts. Note the change in the traces, starting at approximately the 50 second mark. The strongest changes are in the 4th harmonic.

Applications of the Z-Scan probe include deposition processes, particularly in systems that handle large substrates such as industrial glass. In these cases, the process engineer may want to develop a process endpoint on a parameter such as "integrated delivered 2nd harmonic power." The exact utilization of the RF diagnostics will be largely dependent on the specifics of the application.

THE EVOLUTION OF RF POWER DELIVERY IN PLASMA PROCESSING

THE FUTURE IN RF POWER DELIVERY SYSTEMS

As the power density in RF generators continues to increase and the dollar/watt decreases, the generators will become more and more cost-effective for applications such as inductively coupled plasma (ICP) sources of ions. These ICP sources can be used for industrial applications, including augmenting reactive sputtering processes with oxygen and nitrogen and removing of organic films (such as kapton) from an in-line plasma processing system. Figure 6 shows etch rates of a kapton film via a remotely mounted ICP source.

Additional applications of ICP sources are in the abatement of perfluorocarbons (PFCs), “greenhouse gases.” These environmentally harmful PFCs are typically inert and defy all but the most extreme methods of elimination industrial effluent. In this method, the PFC can contain exhaust from an industrial process would be run through the ICP source, combined with O and H to convert the PFC into a chemical that is either environmentally benign or at least is able to be scrubbed.

CONCLUSION

Today’s innovative approaches to RF generators used in plasma-enhanced processes draw heavily upon technologies found in microprocessors, FETS, and sensor technology: state-of-the-art devices that were not available in prior years. The products resulting from these technologies—and the products we will see in the years to come—stand as a tribute to the semiconductor and other vacuum process industries. The relentless pursuit to create smaller device geometries for use in commercial and industrial products will continue to affect and improve our daily lives, from PCs and cell phones to automobiles and even the faucets used in household plumbing.

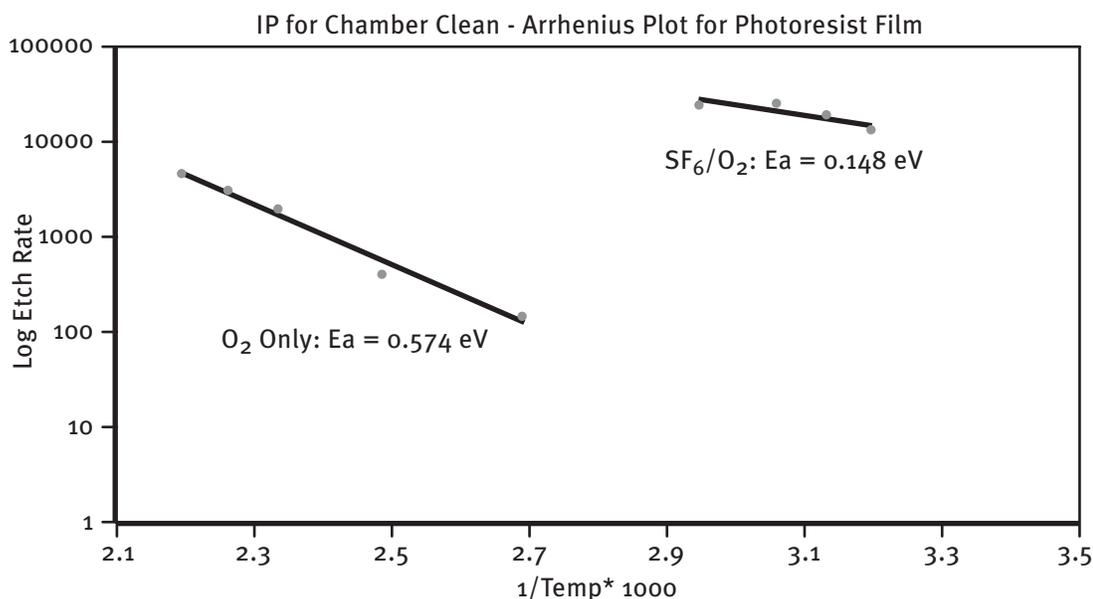


Figure 6. Arrhenius Plot for Polimide Film. Etch rates of a kapton film via a remotely mounted ICP source. This Arrhenius plot representation of experimental data is a technique commonly used by process engineers. This plot shows the activation energy (Ea).



THE EVOLUTION OF RF POWER DELIVERY IN PLASMA PROCESSING



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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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