

Critical thin-film processes such as deposition and etching take place in a vacuum chamber in the presence of a plasma. A plasma is an electrically neutral, highly ionized (consisting of unstable atoms) gas. It is by definition an unstable load, and it exhibits the characteristics of many common electrical devices.

Power supplies are used to "ignite" and maintain plasmas that vary continuously. These power supplies must be capable of reacting appropriately to the plasma's changing characteristics so that power remains stable during system operation. Stable power is extremely important to system performance and production.

Depending on the thin-film application, either direct current (dc) power supplies or alternating current (ac) power supplies can be used. This paper examines the many interacting variables involved when ac power supplies (in particular, high frequency power supplies) are used. The following is an introduction to the basic electronic terms and components as they relate to plasma processes.

#### **COMMON ELECTRONIC TERMS**

**Energy** is the work done by electric power, expressed in joules (J).

**Power** is the rate at which energy is produced or transmitted, expressed in watts (W). Mathematically, power is the product of current and voltage; it is also equal to joules per second.

**Charge** is a quantity of electrical energy. An excess or deficiency of electrons in a body results in a negative or positive charge, respectively. Expressed in coulombs (C).

**Voltage (potential)** is the difference between two charges (that is, two points in a circuit). This difference in charge has the potential to do the work of moving another charge by attraction or repulsion, thus producing or transmitting energy. The volt (V) is the measure of the work needed to move an electric charge.

**Current** is charge in motion, a continuous flow of electrons. The potential difference across two differently charged ends of a conductor causes free electrons (a third charge) to move through the conductor to produce electric current. The ampere (amp, A) is the measurement for expressing the rate of flow of the charge. The symbol for current is I.

**Impedance** is the total opposition to current flow through a circuit. It consists of two elements: resistance and reactance, and is expressed in ohms  $(\Omega)$ . The symbol for impedance is Z. Mathematically, impedance is expressed as Z = R + jX.

**Resistance** is the "real" part of impedance. It represents current that is dissipated as heat and is "lost." Resistance is expressed in ohms  $(\Omega)$ . The symbol for resistance is R.

**Reactance** is the "imaginary" part of impedance. It represents electric energy that is stored. No power is actually

dissipated, but the relationships between the voltage and current waveforms are transformed, giving the appearance of an opposition to current flow. Reactance is expressed in ohms  $(\Omega)$ . The symbol for reactance is X.

Admittance describes the ease with which electric current can flow; mathematically, it is the reciprocal of impedance and is expressed as Y = 1/Z. Admittance is the opposite in effect to the total opposition to current flow and is expressed in siemens (S). Like impedance, admittance has two elements: the real part (conductance) and the imaginary part (susceptance). Mathematically, admittance is expressed as Y = G + jB.

**Conductance** is the "real" part of admittance. It represents electric energy that is allowed to flow. The symbol for conductance is G. Conductance is the opposite in effect to resistance and is expressed in siemens (S).

**Susceptance** is the "imaginary" part of admittance. That is, it represents electric energy that is stored. The symbol for susceptance is B. Susceptance is the opposite in effect to reactance and is expressed in siemens (S).

**Imaginary** is the term used to denote characteristics of components that store rather than dissipate energy. In electronics, this is represented by the letter "j" and is mathematically equivalent to  $\sqrt{-1}$ .



#### **PUTTING IT ALL TOGETHER**

The correct form for expressing impedance is R+jX (resistance plus reactance). Since this form has a "j" (imaginary) term in it, it is referred to mathematically as a complex number. Another way of expressing impedance is the polar representation: Z,  $\theta$  where Z is the magnitude (square root of  $R^2+X^2$ ) and  $\theta$  is the phase angle (arctangent [X/R]).

If you use "shorthand" to refer to impedance, you can unknowingly confuse people. For example, if you say that you have a 50  $\Omega$  load, both you and your audience need to be aware that you are implying that the real part of the impedance is 50  $\Omega$  and that the imaginary part is 0  $\Omega$ . Or, if you say that an inductor (which is a reactive device) has an impedance of 72  $\Omega$ , you are implying that the real part of its impedance is 0  $\Omega$  and its imaginary component is 72  $\Omega$ . You might just say that it has a reactance of 72  $\Omega$ , again implying that the resistance is 0. Or you might refer to a load as being reactiveæmeaning to imply that the load has both resistive *and* reactive characteristics.

It is less confusing to refer to an impedance in its entirety, such as "50 + j0 ohms" or "0 + j72 ohms." Then no one has to make assumptions about what you are implying. You will find, however, that not everyone bothers to do this.

Similarly, the least confusing way to refer to admittance is with its full mathematical form:

Y = G + jB. Since admittance is the reciprocal of impedance, it can also be expressed as Y = 1/(R+jX).

Note, however, that impedance and admittance are vector quantities rather than simple scalar quantities (that is, they have two dimensions—magnitude and direction—rather than one dimension). This means that you cannot simply remove the real part of the admittance from the equation and assume that it is equal to the reciprocal of the real part of the impedance. Similarly, you cannot remove the imaginary part of the admittance and assume that it is equal to the reciprocal of the imaginary part of the impedance.

### **OHM'S LAW**

 $V = I \times R$ 

Ohm's Law says that voltage equals current multiplied by resistance (and assumes that the reactance is 0). That is, the amount of potential difference (voltage) between two points in a circuit equals the rate of flow of a charge (current) multiplied by the total opposition to that rate of flow, through a given circuit. Although the opposition is represented here as resistance (R), total impedance (Z) can also be substituted if the reactive portion of the impedance is not 0.

For example, Figure 1 shows a simple circuit with 10 V across 5  $\Omega$  of resistance. The current is:

$$I = \frac{V}{R} = \frac{10}{5} = 2 A$$

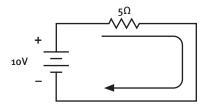


Figure 1. Ohm's law illustrated

Electricity can be compared to water. For example, reducing the resistance in a circuit is like opening a valve: more current flows through the circuit.

To calculate the power dissipated in the resistor in Figure 1, apply the formula:

$$P = V \times I$$
  
 $P = 10 \times 2 = 20 \text{ W}$ 

or, we can substitute Ohm's Law for V, and solve for P to get:

$$P = V \times I$$

$$P = I \times R \times I$$

$$P = I^{2} \times R$$

For Figure 1, that means:

$$P = 2^2 \times 5 = 20 \text{ W}$$

# **BASIC ELECTRONIC COMPONENTS**

This section describes the typical components associated with plasma processes.

Resistor: Provides opposition to current flow. Resistance is measured in ohms ( $\Omega$ ). Ideally, resistance is independent of frequency (however, most resistors change characteristics when operated at high frequencies). Resistors have no energy storage capability—this means that a pure resistor has a real component (R) of a specified value, and an imaginary component (X) of 0.

Diode: Allows current to flow in one direction, but not the other. Current is allowed to flow only after a certain voltage threshold has been reached, and this may result in sudden large current flows. Plasmas exhibit diode characteristics.

by storing energy in an electrostatic field. A plasma chamber has capacitive properties. The reactance of a capacitor increases as frequency decreases.



Capacitance is measured in farads (F). A capacitor is a reactive device. The formula for calculating the reactance of a capacitor is:

$$X_{C} = \frac{1}{(2\pi fC)}$$

 $\pi$  = a constant which equals 3.14159...

f = the source frequency

C = the size of the capacitor, in farads

Inductor: Provides an opposition to change in current flow by storing energy in its electromagnetic field. The reactance of an inductor increases as frequency increases. Inductance is measured in henrys (H). An inductor is a reactive device. The formula for calculating the reactance of an inductor is:

$$X_L = 2\pi f L$$

L =the size of the inductor, in henrys

In electronic circuits, capacitors and inductors present an "imaginary" impedance (represented by a "j,"  $j = \sqrt{-1}$ ). This is because they alter the voltage and current relationships without actually dissipating any energy. For components with no resistance, capacitive impedance is a negative value (-jX), while inductive impedance is a positive value (+jX).

Capacitors and inductors are basically complements of each other; the current through a capacitor leads the voltage, while the current through an inductor lags the voltage. In both cases, the voltage and current are "out of phase" with each other (see the discussion of maximum power delivery on page 9). A capacitive impedance can be canceled out by an inductive impedance (and vice versa). (See Figure 2.)

When an inductor and a capacitor are used together, there is a certain frequency at which the inductive reactance and the capacitive reactance are equal in magnitude, but opposite in sign. This frequency is called the *resonant frequency*. A resonant circuit can be used to select a specific band of frequencies and, at the same time, reject all others. Resonance occurs at

$$f_{R} = \frac{1}{(2\pi\sqrt{LC})}$$

# **ELECTRONIC REALITY**

The basic models used to represent electronic components are just that: models. They are not perfect representations. In reality, when a component is manufactured, because of its physical characteristics, it has some of all of the properties previously discussed.

A real resistor has inductance and capacitance.

A real inductor has resistance and capacitance.

A real capacitor has resistance and inductance.

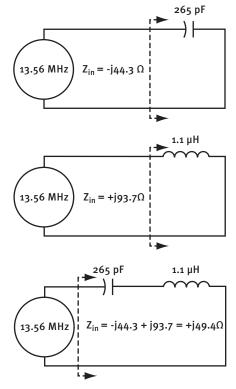


Figure 2. Example of how a capacitor and inductor can cancel each other out

These undesirable, or more specifically, unintentional characteristics are referred to as strays: stray resistance, stray capacitance, and stray inductance (Figure 3). Stray resistance makes a capacitor or inductor "lossy." Due to the stray resistance, power is lost or dissipated in the device as heat.

In many cases, these strays are so small that they do not affect the actual operation of the component. Sometimes they are characterized so well that they can be readily compensated for (such as in many transistors). However, in some cases these stray values are unpredictable or poorly characterized and can cause many problems in a system.

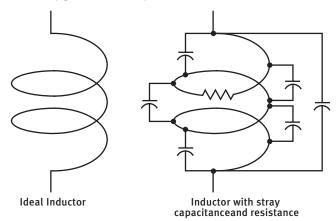


Figure 3. An inductor can have stray capacitance and resistance



#### **Q: THE QUALITY FACTOR**

Sometimes, when dealing with plasmas, the term Q is brought up. Q refers to the quality factor. There are two sets of quality factors (Qs): component Q and circuit Q.

## Component Q

Component Q is the ratio of a device's reactance to its resistance (Figure 4). The higher the Q, the more closely the device resembles the ideal model, which has zero resistance. This factor gives the designer a comparison of stray characteristics a reactive device has in comparison to its expected characteristics. Q is calculated as a ratio of reactance to resistance. Since the units for both of these are in ohms, the units cancel and the Q has no units:

$$Q = \frac{\text{reactance}}{\text{resistance}} = \frac{X}{R}$$

For example, at a specified frequency a capacitor may have  $100~\Omega$  of reactance and  $0.1~\Omega$  of resistance. The Q would be:

$$Q = 100 / 0.1 = 1000$$

This would be a very high quality capacitor. Good capacitors can be found in the high hundreds to low thousands Q range. High quality inductors are in the range of around 100.

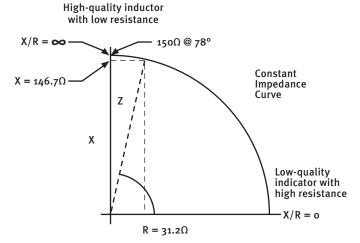
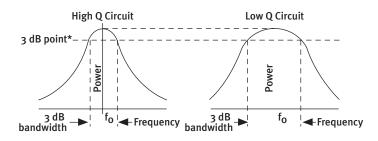


Figure 4. Graph illustrating component Q

# Circuit Q

In a circuit design, Q is typically the ratio of the center frequency ( $f_0$ ) at maximum power output, to the points where the power is one-half the maximum (at the 3 dB bandwidth), as shown in Figure 5.

Sometimes, plasma has a sharp tuning point (high Q), and the matching network of the power system must be able to compensate for this type of load.



<sup>\*</sup> This is where the power is half of that of the peak

Figure 5. Circuit Q illustration

#### **AC AND DC**

Typical plasma processing applications can involve two types of power sources: ac and dc. Dc typically is used in sputtering conductive targets, while ac is used for insulative targets.

Current can also be of two types: direct current (dc) or alternating current (ac).

dc: The power source is constant and does not change with time. This forces the current to maintain the same value and direction at all times. Batteries are the best typical example of a direct current source (Figure 6).

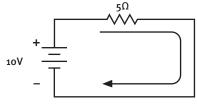


Figure 6. An example of a 10 V dc battery

*ac:* The power source changes with respect to time, actually causing a change in the direction of current flow. The most common example is household current (Figure 7).

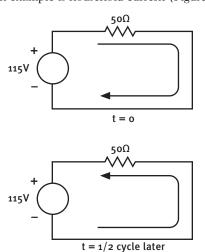


Figure 7. An example of a 115 V ac source



Household ac operates at 60 hertz (Hz) in the United States, which means that the voltage makes 60 complete cycles every second. The time between voltage peaks (one cycle), as shown in Figure 8, is 16.66 ms (t = 1/f).

# **RADIO FREQUENCY (RF)**

Plasma systems sputtering insulative materials typically use ac power supplies, which requires the designer to use higher frequencies when designing the generator. Radio frequency (RF) is a term generally used to describe frequencies above 10,000 Hz and below 300,000 MHz.

Wavelength represents the actual physical distance between two points of corresponding phase in consecutive cycles.

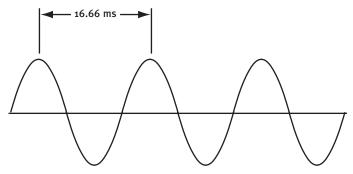


Figure 8. 60 Hz sinusoidal voltage waveform

In free space (such as a vacuum), the wavelength (l) can be calculated by dividing the speed of light (c) by the frequency (f):

$$\lambda = \frac{c}{f}$$

$$c = 3 \times 10^8 \text{ m/s}$$

so, for 60 Hz, the wavelength in free space is 5 million meters (Figure 9).

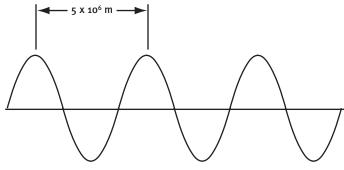


Figure 9. The waveform in free space for 60 Hz

Using the same formula, we can calculate the wavelength for  $13.56\ \mathrm{MHz}$  in free space.

$$\lambda = \frac{(3 \times 10^8 \text{ m per sec})}{(13.56 \times 10^6 \text{ cycles per sec})} = 22.12 \text{ m}$$

If we force the electricity to flow through any medium besides free space, the wavelength is shortened by an amount proportional to the relative permittivity (e) and permeability (m) of the material.

$$\lambda = \frac{\lambda_0}{\sqrt{(\epsilon_R \mu_R)}}$$

 $\lambda_0$  = free space wavelength

 $\varepsilon_{\rm R}$  for Teflon<sup>®</sup> = 2.1

(Teflon® is used as an example because it is a common insulator for coaxial cable.)

μ<sub>R</sub> for RG393 cable is approximately 1.09

So the actual wavelength of 13.56~MHz through RG393 cable is then calculated to be 14.62~m (approximately 48 feet).

It is generally desirable to use cable lengths that are at least one-half wavelength; this assures the same potential at both ends of the cable. However, there may be instances where the effects of a different cable length are desirable.

#### **POWER SUPPLIES**

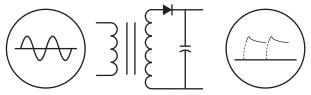
Generally, one of two types of power supplies is used to generate power for plasma systems: a linear power supply or a switching power supply.

## Linear Power Supply

One type of generator used in plasma systems is the linear power supply. This type of supply essentially provides power directly from the transformer to the load.

Additional capacitance does smooth out the output (Figure 10). However, in certain processes, too much capacitance can be detrimental; if an arc or a short circuit occurs, the input power must be switched off and the energy stored within the output capacitors must be removed. Unfortunately, the energy is usually dissipated into the load, which can cause more damage.

A large capacitance is used to smooth out the output waveform  $% \label{eq:capacitance} % \labe$ 



The actual value of capacitance depends on the line frequency, load, operating voltage and the regulation desired. Typically it can range from hundreds of microfarads to tens of thousands of microfarads.

Figure 10. Example of a linear dc power supply



# Switching Power Supply

Another type of generator used in plasma systems is the switching power supply (Figures 11 and 12). This type of supply essentially provides power from the transformer, through a high speed switch, then to the load.

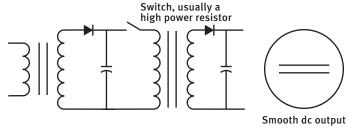


Figure 11. Example of a switching dc power supply

The switch is operated at a high frequency. The higher the switching frequency, the closer are the peaks on the output. The smoothing capacitor on the output can be smaller for higher frequencies (the capacitor does not have to store much energy very long in order to maintain a smooth output).

This feature allows for a fast reaction time. If an arc or a short circuit is detected, the switch is opened, and only a small amount of energy from the smoothing capacitor is dissipated into the load. Typically, this amount of energy is not large, and results in minimal or no damage.

All AE generators are switching supplies.

To obtain an RF output, the switched dc is used to power an amplifier that is made to oscillate at the desired frequency. The RF output is sinusoidal.

## **POWER INTO A "REACTIVE" LOAD**

Ideally, all reactive devices (capacitors and inductors) *store* energy. No energy is dissipated in the device. However, this is true for the theoretical model onlyæin reality, all devices are somewhat lossy and less than perfect.

By applying Ohm's Law to the circuit in Figure 13, we can calculate that the current will be as shown below. Note that since the voltage phase angle is 0° and the current phase angle is 77.3°, voltage and current are 77.3° out of phase.

$$\frac{(10 \text{ V } @ \text{ 0}^{\circ})}{(45.4 \Omega @ -77.3^{\circ})} = 0.22 \text{ A } @ 77.3^{\circ}$$

Ideally, no power is dissipated in the capacitor. The power delivered to the resistor is:

$$(0.22 \text{ A})^2 \times 10 \Omega = 0.484 \text{ W}$$

Remember that the impedance caused by a capacitor can be canceled out by the impedance of an inductor. We will have to reintroduce the "j" representation of imaginary impedances. If we choose an inductance that will exactly cancel out the capacitance in our circuit, more power can be delivered to the load resistance. Figure 14 includes an inductor.

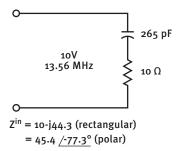


Figure 13. Reactive load

To calculate the value for the inductor, we use the formula:

$$X_I = 2\pi f L$$

by inversion we get:

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{44.3}{(2 \times \pi \times 13.56 \times 10^6)} = 520 \text{ nH}$$

Now we see that the impedance of the circuit is equal to:

$$j44.3 + (-44.3) + 10 = 10 \Omega$$

This gives us a peak current of:

$$\frac{(10 \text{ V})}{(10 \Omega)} = 1 \text{ A}$$

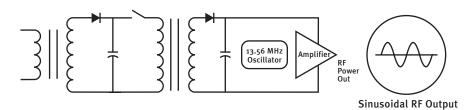


Figure 12. Example of a switching RF power supply



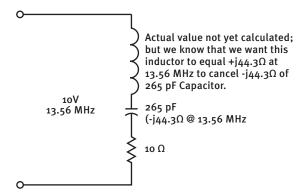


Figure 14. Calculating the value of an inductor

Since the phase angle for both voltage and current is  $0^{\circ}$ , the maximum amount of power is transferred. This is obviously an improvement over the original circuit in the peak power delivered to the resistance:

$$(1 \text{ A})^2 \times 10 \Omega = 10 \text{ W}$$

#### **MAXIMUM POWER DELIVERY**

Remembering that power is the product of voltage and current, consider the waveforms shown in Figure 15. Note that these waveforms are "in phase"—that is to say that both cross the line (zero) at the same time and peak at the same time. If you multiply the instantaneous voltage and current measurements together, you see that power is equal to zero for all of the points where the line is crossed, and to some other positive number at every other point. If you average these values together over time, you will get a positive number.

Now consider the case illustrated in Figure 16, where the voltage and current waveforms are 90° out of phase. There are twice as many points where a waveform crosses the line (zero). This means that when you multiply the instantaneous voltage and current measurements and average them, the result is zero.

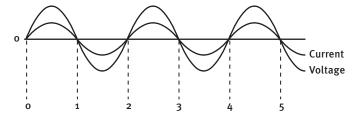


Figure 15. Voltage and current in phase

This is exactly what happens in a capacitor or an inductor—the voltage and current are shifted apart by 90°. Although there is no real power dissipated in the device, shifting the voltage and current waveforms from 0° (in phase) to 90° out of phase results in a shift from maximum to minimum power transfer.

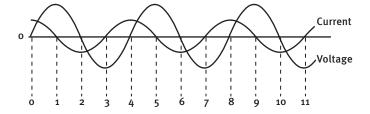


Figure 16. Voltage and current 90° out of phase

AE's tuners work on a similar principle. They shift the voltage and current waveforms so that the power to the load is maximized. They also transform the load impedance to  $50 \Omega$ .

#### **IN CONCLUSION**

This paper discussed a number of electronic variables, components, and relationships that are important to people working with power supplies and plasmas. It also explained in general how to achieve maximum power delivery from a power supply to a plasma. Impedance-matching networks, which are integral to high frequency power delivery systems, are discussed in the AE White Paper entitled Impedance Matching.

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