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PVD Processes: Pulsed DC for Sputtering & Biasing

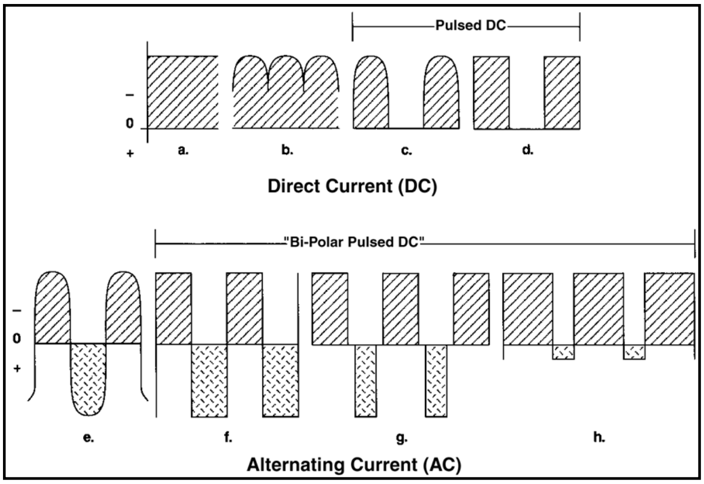
When using a continuous direct current (DC) voltage to sputter material from an electrically insulating (dielectric) target material or to negatively bias a substrate when depositing dielectric films, the insulating surface can attain a surface charge that develops a significant voltage. Under positive ion bombardment, the surface will build up a positive surface charge. This voltage prevents positive ion bombardment for sputtering, or arcing through or over the surface of the depositing dielectric film. In reactive sputter deposition, where the sputtering target is an electrically conductive material, the formation of electrically insulating areas ("poisoning") on the target can cause arcing on the target surface.

Radio frequency (rf) voltages are often used to prevent surface charge buildup on the sputtering target and/or arcing on or through the depositing electrically insulating film. When applying an rf voltage to a metal-backed, electrically insulating sputtering target in contact with a plasma, the dielectric material will be polarized, causing the surface in contact with the plasma to have the same polarity as the metal backing electrode, (*i.e.*, the metal-dielectric-plasma acts as a capacitor). The surface of the insulating material will alternately be charged positively, then negatively on each voltage cycle. This can allow high-energy ion bombardment and sputtering during the negative portion of the voltage cycle.

This rf voltage can be applied alone or in conjunction with a continuous direct current DC voltage. When rf is used in conjunction with a continuous DC voltage, an rf choke must be included in the DC circuit to prevent rf power from entering the DC power supply. The rf frequency range extends from a few kilohertz (~25 kHz) to the high-megahertz (100s MHz) range, with 13.56 MHz and its harmonics being common industrial frequencies used in PVD processing and 400 kHz used for rf heating. For rf high-frequency sputtering in PVD processing, the rf voltage generally has a sinusoidal waveform with a large peak-to-peak (~2000 V) voltage.

At high frequencies, poor impedance matching of the rf electrode to plasma can cause significant power loss (reflected power). The rf electrode acts as an antenna that often radiates power non-uniformly into the plasma-gas, creating non-uniform plasma conditions around a complex-shaped rf electrode (antenna). At high frequencies, some of the radiated power will be coupled to metallic surfaces in the system. If the surfaces are too close to the rf electrode, this coupling can represent a significant power loss.

A major disadvantage of rf sputtering of a dielectric target material is that electrically insulating materials are also generally poor thermal conductors and have poor thermal shock resistance. This means that at a high target power (high sputtering rate), most dielectric target materials will develop thermal stresses and crack. An exception is silicon dioxide (SiO_2), which has high thermal shock resistance because of its low thermal expansion. Except for sputtering SiO_2, rf is generally used, often in combination with a continuous DC bias, to prevent arcing on a conductive sputtering target that has areas that are being "poisoned," or on electrically insulating films that are being



Voltage waveforms.

deposited by reactive deposition.

A continuous DC voltage can have a smooth waveform, as shown in Fig. 1(a), or significant "ripple," as shown in Fig. 1(b). A "pulsed" DC voltage is a periodically interrupted DC, as shown in Fig. 1(c) and (d). When the pulsed DC has a voltage and cycle time (frequency) similar to an rf voltage, it has many effects similar to the rf voltage. Positive charge buildup on the dielectric surface is neutralized by electrons from the plasma during the off-time of the DC pulse. When the high negative potential is applied to one side of the dielectric, a high negative potential is induced on the other side. This negatively charged surface then attracts positive ions from a plasma to bombard the surface with a high energy. This bombardment causes sputtering of a "poisoned" area on a conductive sputtering target, or sputtering and film growth modification of a dielectric film being deposited on a conductive substrate. When sputtering small, electrically insulating areas on a conductive surface, the polarization of the surface is modified by "current leakage" over the surface and by "shorting" resulting from the proximity of the nearby metal-plasma (no dielectric) contact.

An advantage of the pulsed DC is that the off-time can be made any portion of the cycle time. Because the time needed to discharge any positive charge buildup on the surface is very short (a few microseconds), the high negative voltage can be applied for as much as 80–90 percent of the cycle and still prevent significant positive charge buildup and arcing on the surface. This gives about double the bombardment that is achievable by the application of a sinusoidal rf voltage. Pulsed DC, up to about 200 kHz, can be generated by using voltage-interrupter circuits ("chopped") with a conventional continuous DC power supply input.

Pulsed DC voltage waveforms, such as shown in Fig. 1(c) and (d), can be called "unipolar pulsed DC." It is possible to make the voltage reverse polarity instead of having an off-time, and some authors and equipment suppliers call this a "bipolar pulsed DC" as shown in Fig. 1(f), (g) and (h). In reality, since the polarity is reversed and the current in the circuit is reversed during each cycle, this "bipolar pulsed DC" is really an alternating current (AC) voltage. If the input to the power supply is a DC voltage and the output is an AC voltage, then the power supply is a DC-to-AC voltage converter.

The "bipolar pulse" can be symmetric, where the positive and negative waveforms are the same, or asymmetric, with the relative voltages and duration time being variable and even containing an "off-time." Generally, in asymmetrical "bipolar pulsed DC" sputter deposition, the negative pulse (*e.g.*, -500 V) is greater than the positive pulse (*e.g.*, +100 V), and the negative pulse time is 80–90 percent of the voltage cycle and the positive pulse is 20–10 percent of the voltage cycle.

It should be noted that the output waveform and the magnitude of voltages from the power supply, as measured in the open circuit condition, are not necessarily what will appear on the dielectric surface in contact with the plasma. The plasma is a source of electrons and positive ions. As a surface tries to go to a positive voltage with respect to the plasma, electrons from the plasma will move rapidly from the plasma to prevent any large positive voltage from appearing on the surface. Positive ions, which are much more massive than the electrons, will move much more slowly to the electrode in response to a negative voltage on the surface. It should also be noted that when the gas discharge is extinguished because of the lack of a potential gradient necessary to accelerate electrons to cause ionization, the plasma will still exist for an appreciable time ("afterglow"). The plasma will "decay" in charge particle density by the charged particles in the plasma recombining, and this primarily happens at surfaces. The presence of residual plasma makes it easier to "reignite" the gas discharge when the discharge voltage is reapplied to the discharge electrodes.

The optimal frequency of pulsing, the pulse duration and the relative pulse heights seem to depend on the materials being sputtered and deposited, according to several authors. For example, when reactively sputter depositing a "good" electrically insulating material such as Al_2O_3 from an aluminum target, a frequency of about 50 kHz seems to be best. When reactively sputter depositing a somewhat conductive material, such as TiN or indium-tin-oxide (ITO), however, a higher frequency (150 kHz) seems to be best. Possibly this is because of the more rapid conduction of the surface charge away from the surface. It may, therefore, be desirable to have a pulsed power supply with a variable frequency output.

Pulsed DC and "bipolar pulsed DC" power supplies with pulse powers of up to several hundred kilowatts are commercially available. It should be noted that the power is rated over the whole duty cycle. If the off-time is increased and the power is kept the same, the power density during application of the voltage increases. The pulsed DC power supplies are usually provided with arc detection and suppression circuitry, which further diminish damage from arcing in the system. P&SF