# SPUTTER DEPOSITION

Sputtering is one of the most commonly used methods for the deposition of thin films. The sputter process is considered a physical vapor deposition (PVD) process, since the deposited material originates from a solid phase and there are no chemical reactions. Sputtering is the ejection of a material due to the transfer of energy from an energetic particle to a surface. The energetic particles, in the form of ions, neutral atoms, molecules, electrons, neutrons, or energetic photons, impact the surface at an energy greater than the material's bonding energy. The energy transfer creates a collision cascade in the target material causing atoms, ions, molecules, secondary

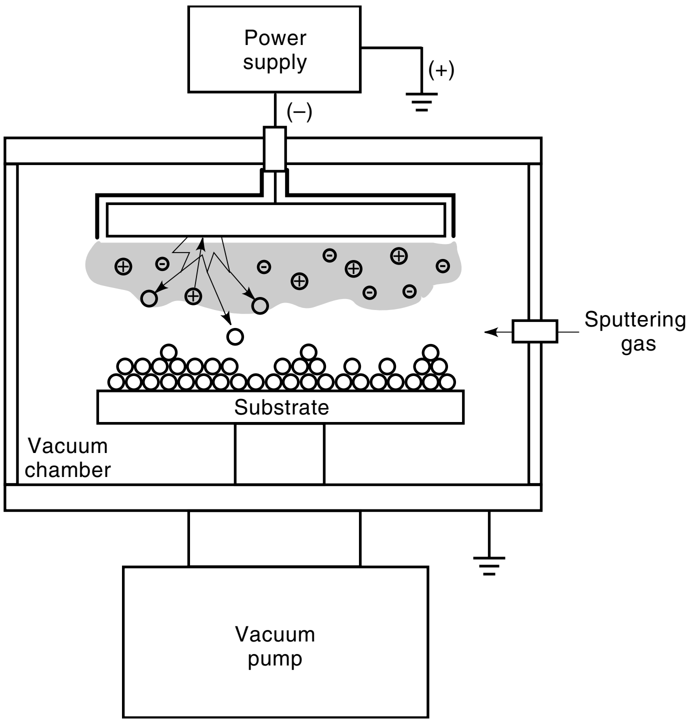


**Figure 1.** Schematic of typical sputter deposition vacuum chamber.

electrons, and photons to be ejected. A typical sputtering system can be seen in Fig. 1.

Sputtering was first viewed as an inconvenience in a gas discharge since it destroyed the cathode. Sputtering is used in many applications include surface cleaning and etching, deposition of thin films, surface analysis, and surface treatment. One of the most common applications of sputtering is thin-film deposition. The sputtering process has many advantages over other deposition methods due to its versatility and flexibility. This process can deposit a wide range of materials since the momentum exchange is a physical process as opposed to a chemical or thermal process. Films of almost every element in the periodic table have been deposited by sputtering. Sputtering is also chemically cleaner than many coating or plating processes and is able to deposit thin films with reproducible characteristics.

Sputter-deposited films have been used, for example, as metallization layers for semiconductor devices (1,2) hard and wear resistant coatings for razor blades and machine tools (3,4), amorphous bubble memory devices (5), insulators, superconductors, piezoelectric transducers (6), low friction coatings for lubricants, decorative coatings for jewelry (7,8), and wear-resistant coatings (9,10).

## STEPS IN SPUTTER DEPOSITION

There are four basic steps in the sputter deposition process: (1) plasma generation, (2) ion bombardment, (3) sputtered atom transport, and (4) film growth. Each of these topics will be discussed individually.

### Plasma Generation

A glow discharge is formed when an inert gas becomes ionized by an electric field applied between two electrodes. An electron, generated by a cosmic ray, UV photon, or field emitted from the cathode surface, is accelerated toward a positively charged anode. The accelerated electron will gain sufficient energy to ionize gas atoms upon collision. This, in turn, generates more electrons and, through an avalanche effect, the background gas between the electrodes becomes ionized. This ionized gas, known as a plasma, is an electrically neutral medium composed of ions, electrons, and neutral species. The plasma can only be sustained if every electron creates another electron upon ionization. The ionization of the background gas can be enhanced with the addition of magnetic fields, electric potential, or secondary thermionic sources (11). The positively charged ions generated within the plasma are then accelerated toward a target and, upon impact, sputter the material.

### Ion Bombardment

Positively charged ions created in the plasma impact the target with high energies and transfer their momentum to the target material. These collisions disrupt the atomic surface causing target atoms, ions, and electrons to be ejected and ions to be reflected or implanted. Only the predominant ion–atom interactions will be discussed here due to the large number of interactions that occur during sputtering. The incident ion may strike either one atom head-on or two atoms simultaneously. When two atoms are struck simultaneously, most of the energy is transferred to a primary knock-on atom, while a small fraction of the energy is transferred to the secondary atom. The primary knock-on atom is embedded into the target lattice upon impact, creating a collision cascade in the surrounding atoms. This collision cascade will eventually cause some surface atoms to be sputtered. The secondary, low-energy knock-on atom transfers its energy to neighboring surface atoms, causing them to be ejected. Head-on ion–atom collisions implant atoms from the surface of the target further into the material lattice. These implanted atoms would require a 90° change in their direction of travel to cause sputtering. The collision cascade may occur between 50 Å and 100 Å below the target surface (12), but most sputtered atoms come from about 10 Å below the surface (12,13). Figure 2 shows a schematic of the bombardment processes occurring at the target surface. The bombardment process is similar on a microscopic scale to the break event in billiards when the cue ball hits the racked balls and the energy imparted by the cue ball disperses the balls in multiple directions.

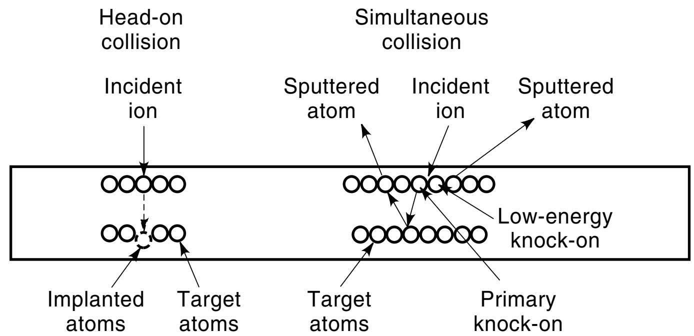


**Figure 2.** Collisional events that occur at the target during sputtering.

Ion bombardment of the target surface can also result in the reflection of incident ions. An incident ion may be reflected back from the target when its effective mass is lower than that of the target atoms (14). The reflected ions may retain most of their initial kinetic energy, enabling them to reach the substrate and to become incorporated into the growing film (15–18).

Ion bombardment of the target surface causes not only the removal of atoms, but also secondary electron emission, trapping and reemission of incident particles, desorption of surface layers, emission of photons, and changes in surface structure and topography. Secondary electrons ejected from the target contribute to the ionization process by providing increased ionization. These electrons are required to maintain the glow discharge in sputtering.

### Sputtered Atom Transport

Sputtered atoms, ions, and molecules can be influenced by collisions they undergo during transport to the growing film. There are three modes of sputtered atom transport in the sputter deposition process. These modes of transport are determined by the background gas pressure.

The low-pressure regime of sputtered atom transport occurs at pressures below 0.1 mTorr. In this regime, the mean free path (distance between collisions) of the sputtered atoms is large. The sputtered particles travel in a line-of-sight mode and retain most of their initial kinetic energy in this regime since they will not undergo many collisions (19). Ion beam sputtering processes, enhanced magnetron, and ECR plasma techniques operate in this low-pressure transport mode.

In an intermediate pressure regime, between 0.5 mTorr and 30 mTorr, the sputtered particles undergo more gas-phase collisions. Increased scattering at this pressure will cause the flux to deposit at higher angles of incidence. The particles will lose their initial energy as the number of collisions is increased. Therefore, the average kinetic energy of the sputtered particles is dependent on the sputtering pressure. Most magnetron and a few RF diode sputter systems operate in this mode of particle transport.

A high-pressure transport regime occurs at pressures between 50 mTorr and 5 Torr. At these pressures, the mean free path is very short and particle motion is governed by diffusion (20). An increased number of collisions in this regime cause the particles to lose most of their initial energy (21). In this regime the sputtered particles become fully thermalized with the background gas (21,22). This mode of transport is common in most RF diode and all dc diode sputtering processes.

### Film Growth and Properties

The sputtered species are ejected from the target in all directions and deposit on surrounding surfaces. Most of the flux arrives at the substrate in atomic form with energies ranging from 5 eV to 40 eV, with an average of 8 eV. The sputtered atoms arrive and condense on the substrate as loosely bonded adatoms (23,24). The rate of adatom diffusion is dependent upon the substrate material, its temperature, and whether or not the substrate is bombarded with energetic particles during growth. Adatoms with high energies may be evaporated or sputtered from the substrate surface. Adatoms with low mobilities are absorbed onto the surface at low-energy sites, such as defects or crystallographic variations. Growth proceeds by adatom diffusion and coalescence into nuclei. The nuclei grow and eventually form islands. These islands grow together until a continuous film is formed. Various nucleation and growth processes can be seen in Fig. 3.

The film growth environment has a significant influence on the structure and properties of the growing film. Sputtering parameters such as ion bombardment, substrate temperature, sputter rate, sputter pressure, and others may determine whether the resulting film will be amorphous, polycrystalline or single crystalline.

In most sputtering processes the substrate is immersed in the plasma, where it is bombarded by ions, energetic neutrals, photons, and energetic electrons ejected from the cathode (25). These electrons can cause substrate heating, which may damage delicate substrates and influence the properties of the growing film (26,27). Ion bombardment of the substrate during growth enhances the mobility of adatoms and produces a more crystalline structure (28,29). Bombardment can also increase nucleation and decrease void formation by inducing surface damage and resputtering (30–32).

At low substrate temperatures the adatoms have a low mobility. A high sticking coefficient at low substrate temperatures limits adatom diffusion. Therefore, they become trapped on the surface at or near the point of first impact, so the resulting films are amorphous or polycrystalline. Films deposited at low temperatures have a low-density, fibrous structure with many voids and defects. At high substrate temperatures, growth proceeds by bulk diffusion. Under these conditions, adatoms have sufficiently high mobility for growth of single crystal films (19,21,33). Thin films with properties similar to that of the bulk material can be obtained at high temperatures.

The sputtering pressure can also affect the energy of the sputtered particles. At low pressures the sputtered particles retain most of their kinetic energy since there are few gas-phase collisions. The adatoms will therefore have a high mobility, improving the chance of forming a crystalline film. At high pressures the sputtered particles undergo many collisions and equilibrate with the background gas (20). The resulting films will be amorphous or polycrystalline, since the adatoms will have a high sticking coefficient and low mobility.

In summary, at low pressures and high substrate temperatures sputtered films will tend to be more crystalline, while films deposited at high pressures and low substrate temperatures will tend to be amorphous. This is the basis for the structure zone models described by Movchan and Demchishin, and later by Thornton and Messier (34,35).

The nature of the sputtering process induces some amount of stress in the deposited films. This stress usually contains thermal and intrinsic components (36). Thermal stress occurs

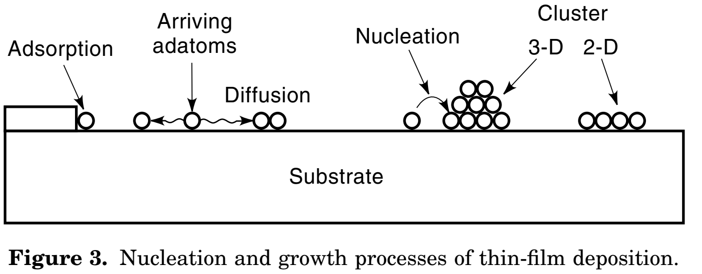


**Figure 3.** Nucleation and growth processes of thin-film deposition.

due to a difference in thermal expansion coefficients of the film and substrate materials. Intrinsic stresses can arise from defects such as dislocations, interstitials, and voids, in the growing film. The intrinsic stress in sputtered films can usually be reduced by tailoring the temperature of the substrate during growth of the material being deposited. The intrinsic stress varies with the sputter conditions. Usually high stress will occur under energetic bombardment conditions. Low stress will occur under low energetic conditions and with high substrate temperatures. Stress may also occur when there is a large mismatch between the lattice parameters of the substrate and film material.

## ASPECTS OF SPUTTERING

### Sputter Yield

The sputter yield of the target material is one of the most important parameters in the sputtering process. The sputter yield is defined as the number of target atoms ejected per incident particle. It is dependent on many parameters, including the atomic mass of, and the bond strength between, the target atoms; the crystallinity of the target, and the energy, mass, and angle of incidence of the bombarding species. In an elastic collision, momentum transfer between two particles is most efficient if the particles have equal mass, and the transfer becomes less efficient as the masses become more unlike. The bombarding ion is therefore most effective in sputtering, when its atomic mass is equal to that of the target atoms. Argon is the most commonly used gas for nonreactive sputtering, since its mass is somewhat close to that of many desirable elements and it is inexpensive, compared with other inert gases. The sputter yield also increases as the kinetic energy of the incident particle increases. No sputtering occurs below a threshold energy of about 20 eV to 40 eV for normally incident ions. However, at very high energies, greater than 1000 eV, the ions begin to penetrate the surface and become trapped or implanted (37–39). Since the momentum of the primary particles is deposited further into the bulk of the target, the collision cascade itself occurs deeper in the solid. Because of this, fewer surface atoms are involved in collisions and the overall probability of sputtering is reduced. The resulting structure is instead a highly damaged target with implanted primary ions.

Neither the charge state of the incident particle nor the substrate temperature has a significant effect on the sputter yield (40). The angle of ion incidence to the target surface does, however, significantly influence the sputter yield (41). At very small incident angles the yield is low. The sputter yield is highest at intermediate incident angles before decreasing again at normal incident angles. Some sputter yields of various materials with varying ion energy can be seen in Fig. 4 (42).

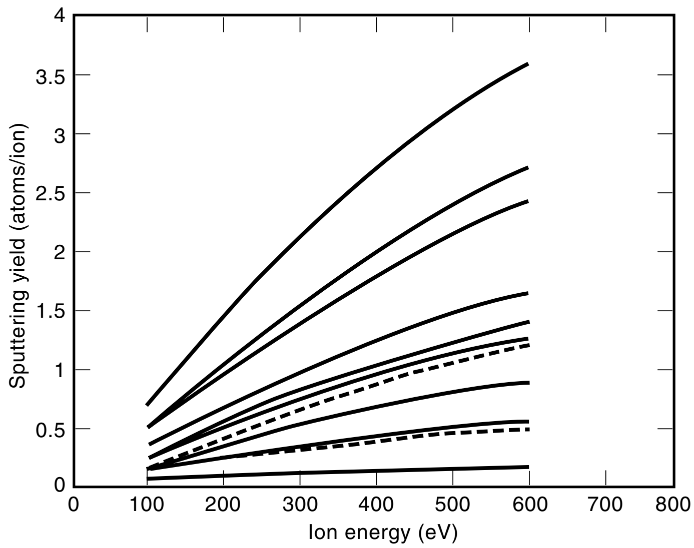


**Figure 4.** Sputter yield of various materials with normal angle of incidence of argon ions.

### Alloys

Sputtering can be used to deposit thin-film alloys with the same composition as the target. Initially, the flux of sputtered particles will not have the same stoichiometry as that of the target. This is due to the preferential sputtering of the atomic component with the higher sputter yield. Eventually, however, the surface composition of the target will be altered in proportion to the difference in sputter yields of the atomic components (43). When this happens, the components with lower sputter yields will be more abundant, and the sputtered flux will have the same stoichiometry as the bulk of the target. To deposit an alloy, a shutter can be used to cover the substrate during sputtering until the flux of sputtered species equilibrates to the stoichiometry of the target bulk.

### Reactive Sputtering

In an inert sputtering environment there is no reaction between the gas and the material being deposited. The sputtering gas is used only for the ejection of target atoms. When a reactive gas is added to the sputtering environment the target material may react with the gas and form an insulating compound on the substrate. Examples of reactive sputtering include the deposition of aluminum nitride or aluminum oxide (44) using an aluminum target and nitrogen or oxygen gas, respectively, and the deposition of titanium nitride (45–47) or titanium oxide using a titanium target and nitrogen or oxygen, respectively.

Reactive sputtering (48–51) can be used to deposit complex compounds with a simple metallic target and a reactive gas species without the need for expensive compound targets to deposit the same material. However, the reactive sputtering process is very complex. A reactive gas introduced into the sputtering gas causes a reaction between it and the depositing metal. At low concentrations all of the gas reacts with the metal, effectively getter-pumping the gas. This is known as the metallic mode of reactive sputter deposition, since the rate of formation of the insulating compound is slower than the sputter rate. The target will remain metallic and the deposited films are usually metal rich. As the concentration of reactive gas in the gas mixture increases, the sputtered films become stoichiometric. This is accompanied by an increase in pressure due to a surplus of reactive gas needed for compound formation. This is known as the nonmetallic or poisoned mode of reactive sputter deposition in which the rate of formation of the compound is greater than the sputter rate. A buildup of an insulating material on the target surface “poisons” the target. This decreases the deposition rate due to the lower sputter yield of the insulating layer compared with the pure metal. A plot of deposition rate versus reactive gas concentration can be seen in Fig. 5. The hysteresis effect of the deposition rate is due to the removal of the insulating compound on the target surface as the concentration of reactive gas is decreased again.

## SPUTTERING TECHNIQUES

Many processes have been developed to utilize the sputtering process for the deposition of thin films. The simplest arrangement is called a diode system. Many additions to the diode process have been made in attempts to increase ion density, deposition rate, and deposition area; and to reduce plasma heating, lower the operating pressure, and coat irregular shapes uniformly. In a triode system a secondary cathode increases the plasma density by adding an auxiliary source of electrons. Magnetic fields may also be used to enhance the diode-sputtering process by taking advantage of electron motion in electric and magnetic fields. The recent advances in magnetron sputtering have made them among the most popular systems for sputter deposition of thin films. Ions generated and focused into an ion beam can also be accelerated toward a target to cause sputtering.

### DC Planar Diode

The planar diode or glow discharge is the simplest type of sputtering device. In this set-up, two electrodes face each other. In the dc arrangement the cathode, or target, is negatively biased and acts as the source of depositing material, while the anode, or substrate, is positively biased or grounded (52). The cathode diameter is typically 5 cm to 30 cm, with a cathode to anode spacing of about 5 cm to 10 cm. Cathode voltages range from 500 V to 5000 V. The cathode is usually water cooled, to remove heat caused by ion bombardment and prevent the target from melting. Before deposition, the vacuum chamber is pumped down to a low base pressure and backfilled with argon or some other inert gas. A typical diode sputtering process is shown in Fig. 6.

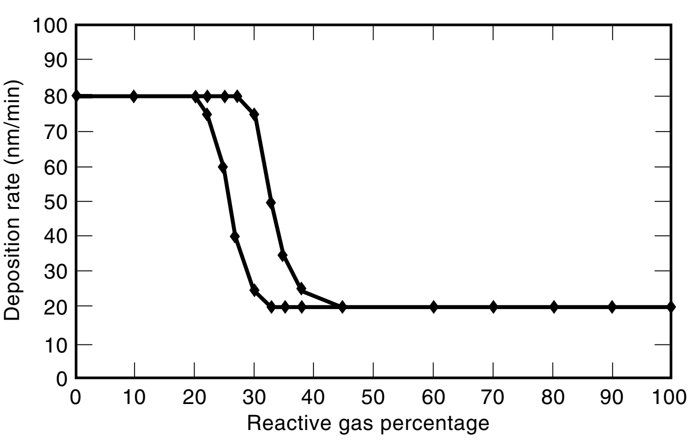


**Figure 5.** Change in deposition rate as a function of reactive gas composition.

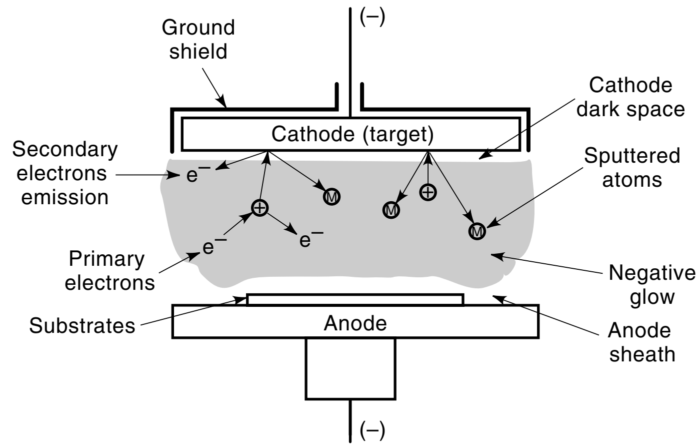


**Figure 6.** Schematic of planar diode sputtering system.

A glow discharge is formed when a negative potential is applied to the target. A free electron generated by a cosmic or ultraviolet (UV) ray, or field emission gains enough energy to ionize a gas atom as it is accelerated toward the positively charged anode. A collision with a gas atom produces primary electrons which collide with other gas atoms producing the volume ionization required to sustain the discharge (53,54). This stage of plasma development is known as a Townsend discharge (52). Positively ionized gas atoms bombarding the cathode create secondary electrons, which provide further ionization of the inert background gas. An avalanche effect, producing many electrons, increases ionization of the background gas atoms in the region between the cathode and anode, creating a plasma. This is the normal glow state (53) in which the number of electrons and ions are equal and the plasma is self-sustaining. The requirement for sustaining a discharge is that each ionizing collision between an electron and a gas atom release at least one electron per incident electron involved in the collision. This type of discharge can therefore only be sustained at relatively high working pressures, where a high density of electron–gas atom collisions occurs. As the number of electrons and ions increases, the plasma glow becomes brighter and the ion density increases. This is the normal sputtering regime, where the plasma is characterized as an abnormal negative glow discharge since the plasma establishes a positive potential due to the more rapid loss of electrons than ions. A grounding shield is used to suppress plasma formation on the sides of the target so that only the face of the target is exposed to the glow discharge. Most of the electrical potential that is applied between the anode and the cathode is consumed in a cathode dark space, or sheath region (53). The sheath thickness is typically 1 cm to 4 cm, depending upon the sputtering pressure (55). Positive ions created in the glow discharge are accelerated toward the target across the sheath. Impact with the cathode sputters the target material. Increasing the discharge voltage, the sputtering pressure, or the target–substrate distance can increase the sputtering rate. Increasing the discharge voltage produces more electrons, thus increasing the plasma density and the number of ions available for sputtering. Increasing the sputtering pressure provides more gas atoms for ionization and, therefore, increases the sputtering rate. However, at very high pressures the sputtering rate is decreased due to the increased number of gas–atom collisions. One limitation of this technique is that nonconducting targets cannot be sputtered using a dc bias due to charge buildup on the target surface.

## RF Sputtering

The application of a radio frequency (RF) potential to the target overcomes the inability to sputter insulators. Radio frequency potentials enhance the plasma by sweeping the electrons back and forth between the cathode and anode, increasing the life of the individual electrons and, therefore, the probability of ionization. In fact, ionization can be enhanced enough so that secondary electron emission from the target is not necessary to sustain the discharge. RF sputtering (14,56–61) can be used to deposit nonconducting, conducting, and semiconducting materials. In a RF planar diode system the target is placed over the driving electrode and the substrate is placed on the counter electrode. An RF diode system is set up similar to the dc diode in Fig. 6, with the exception of the target power supply. The electrodes reverse cathode-anode roles on each half-cycle. Most RF power supplies operate at a frequency of 13.56 MHz, allocated by the FCC for industrial use. At these high operating frequencies there is no charge accumulation on the target due the short cycle time on each electrode (40).

Figure 7 shows how the target voltage changes as a function of time. An RF potential applied to a capacitively coupled electrode generates a negative self-bias voltage on the target (62). This occurs due to the relatively high mobility of the electrons compared with the low mobility of the ions. In the first half-cycle, when the applied target voltage is negative, there is a negligible amount of current flow due to the low mobility of ions. When the voltage alternates positive in the second half-cycle, the target becomes positively charged and draws a large electron current due to high electron mobility. The target, or powered electrode, now behaves like a negatively biased cathode. An ion sheath is formed in front of the target and gas ions are accelerated toward the cathode, resulting in sputtering.

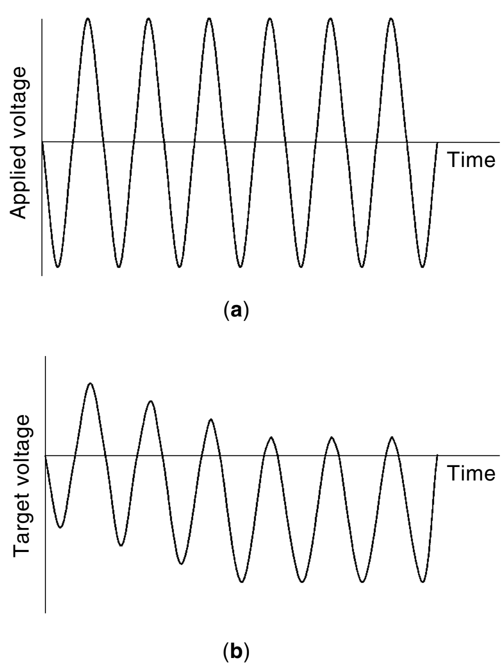


**Figure 7.** (*a*) Applied voltage; and (*b*) target voltage waveform in an RF discharge.

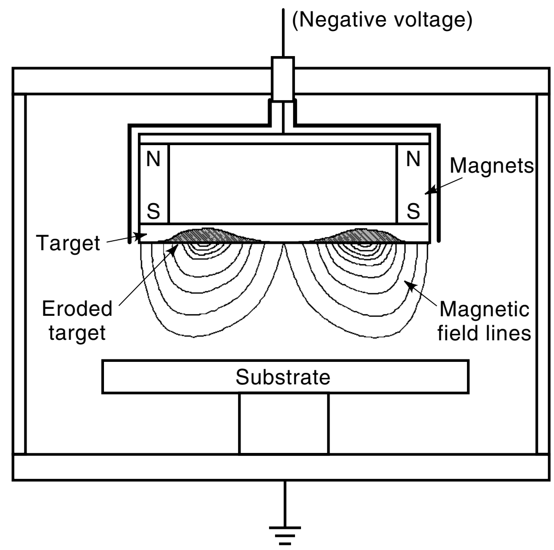


**Figure 8.** Planar magnetron sputtering system.

An RF discharge in a planar diode arrangement can be operated at lower pressures than can dc discharges. This is because fewer electrons are lost and the ionization efficiency of the background gas is increased. Typical operating pressures for RF sputtering are 1 mTorr to 15 mTorr.

RF sputtering has disadvantages as well. The RF power source is much more complicated than a dc power source and requires a matching network. RF sputtering is not limited to planar diode configurations. Magnetron sputtering sources can also be used with an RF power source.

## Magnetron Sputtering

The diode sputtering process is fairly inefficient for the sputter deposition of thin films due to electron loss to the chamber walls. Magnetron sputtering systems have diode type arrangements with the addition of magnetic fields near the cathode to confine electrons near the target surface, enabling them to increase ionization. Magnetrons can vary in design from planar (63–65), cylindrical (66–68), inverted (68,69), or conical (70), with permanent, rotating, or electromagnets. In a planar design, a magnetic field line will emerge from a south pole magnet on the outside of the target, arch over, and be collected by a north pole magnet in the center of the target. The magnetic field created by this arrangement is toroidal, which resembles a race track or doughnut ring on the surface of the target. A typical magnetron sputtering system can be seen in Fig. 8.

The magnetic fields have a significant effect on the motion of electrons in the glow discharge. An electron subjected to a uniform magnetic field will orbit around a field line with a spiraling motion along the field line. This effectively causes the electron to be trapped by magnetic field lines (71,72). A magnetron source combines a magnetic field, $B$, with an electric field, $E$, to create an $E \times B$ drift in a direction perpendicular to both the electric and magnetic fields (67,68). Therefore, secondary electrons, emitted during ion bombardment of the target, and electrons generated from electron–gas collisions, become trapped in the circular magnetron track near the target surface. This prevents the loss of electrons to the anode and chamber walls and increases the path length of the electrons. The increased path length from a straight line to a spiral increases their probability of colliding with gas atoms. Increased electron collisions enhance ionization in this region, which can be seen as a toroidal glow. These ions are accelerated across the sheath and sputter the target material. The enhanced ionization in the magnetic field ring causes increased sputtering of the target in this area, which creates an erosion track common in magnetron sputter sources (73). Electron trapping and more frequent electron collisions allow the magnetron sputtering process to operate at lower pressures and at higher deposition rates than the normal diode sputtering process. Since electrons are confined to the target region there is also less substrate heating, compared with the diode sputtering process. The magnetic field enhancement effect makes the sputtering process more efficient, which makes it useful in many areas of manufacturing. One drawback to the magnetron sputtering process is the inefficient utilization of the overall target surface area due to increased erosion in the high magnetic field region. Typical magnetron sources utilize up to 35% of the target area (64,74). Rotating magnets behind the target makes it possible to increase target utilization greater than 75% (75–77). Magnetrons operate at voltages of 200 V to 1000 V, with powers of 1 kW to 100 kW, at pressures between 0.5 mTorr and 100 mTorr.

The magnets in a magnetron source can be balanced or unbalanced. In a balanced magnetron configuration, all the magnetic field lines emanating from the outside ring of magnets will be collected by the center magnet (78). In an unbalanced magnetron configuration this is not the case (79). Some of the field lines leak out of the source toward the substrate, resulting in higher ion and electron bombardment of the substrate. These sources can be very useful in the deposition of some thin films.

### Pulsed Sputtering

Pulsed sputtering is a new sputtering technique combining the advantages of dc and RF sputtering into a single power supply. Dc sputtering has commonly been used for sputtering of metals. Dc has also been attractive for many manufacturing processes due to the ease of implementation, scale-up, and controllability. However, dc cannot be used to deposit insulating target materials and is not very useful in reactive sputtering due to target poisoning. New pulsed sputter power supplies operate in a medium frequency range of 10 kHz to 100 kHz (80,81). These power supplies provide higher ionization rates, and can be used for reactive sputter deposition of thin films without target poisoning. Pulsed sputtering has the advantage over RF sputtering in that it has higher deposition rates with less complex, more reliable power supplies. These systems can operate in a single magnetron mode with a unipolar signal, or in a dual magnetron mode with a bipolar signal (82). A unipolar pulse prevents the buildup of an insulating material on the surface of a metal target by periodically interrupting the discharge. The pulse frequency can be used to control the charge buildup on the target due to an insulating layer. In the bipolar pulse mode with dual magnetrons, the sources alternate anode–cathode roles on each half-cycle. This ensures that a conducting anode will always be present during the deposition process. These systems can be used to reactively deposit $Al_2O_3$ (82), $SiO_2$ (82), InSnO (83), $SnO_2$ (84) and $TiO_2$ (82,84). These specialty power supplies have also been used in plasma-enhanced chemical vapor deposition (PECVD) systems for deposition of thin films.

### Triode Sputtering

Another enhancement of the planar diode system is the addition of a second cathode. This cathode is usually a thermionic emission device, which serves as a secondary source of electrons to enhance ionization in the plasma (85–87). The increased rate of ionization provides higher deposition rates at lower pressures (88). In triode sputtering the thermionic emitter can be used to control the ion energy and flux of the sputtered particles. The target bias can also be reduced in triode sputtering, since secondary electron emission from the target is not necessary to sustain the plasma. A schematic of a triode sputtering system is shown in Fig. 9. Hollow cathode electron sources have been added to magnetron sources to provide an additional enhancement to this process (89). Some disadvantages of enhancement include difficulty in scale-up and reaction of the thermionic emitter with reactive gases.

### Ion Beam Sputtering

Ion sources were first developed for space propulsion applications and later applied to thin-film deposition (90,91). Ion beam sputtering can be used to deposit thin films under highly controlled conditions. Ion beam sources are unique in their ability to independently control the energy, flux, and angle of incidence of the ions incident on the target surface (92). In an ion beam assisted deposition (IBAD) system, a second ion beam directed at the substrate, is used to modify the properties of the growing film or to react and synthesize new compounds. This level of independent control over arrival

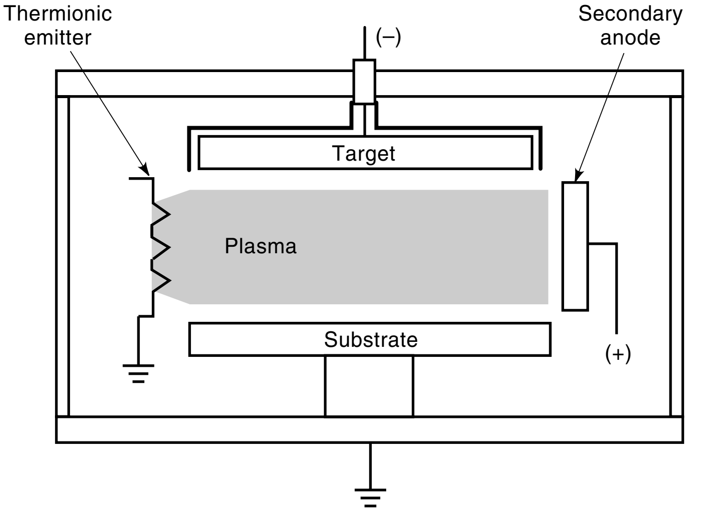


**Figure 9.** Schematic of triode sputtering system.

flux, energy, and direction cannot be achieved by any other process.

One of the most common types of ion beam source is the Kaufman source. This source consists of a discharge chamber, extraction grids, and a neutralizer (93). A plasma is generated in the discharge chamber by a thermionic emission device or RF excitation. The ions are then extracted and accelerated from the discharge chamber to the sputter target. The ions are electrostatically focused into a beam by a set of biased extraction grids. With proper grid design, the beam may be parallel with a slight divergence, focused, or divergent. A thermionic emission device such as a hot filament or a hollow cathode electron source is used to neutralize the beam by adding electrons. This is especially important for nonconducting targets to prevent surface charging, which may cause beam spreading by space charge repulsion. Gridded ion beam sources are able to operate at low pressures around $5 \times 10^{-5}$ Torr to $5 \times 10^{-4}$ Torr.

Another type of ion source is known as an End Hall (94,95) or closed drift source. This source generates the plasma in the same way that the Kaufman source does, but the ions are not accelerated into a beam by grids. Instead, the ions follow diverging magnetic field lines out of the source. The beam has a wide divergence and operates at a pressure of $10^{-3}$ Torr to $10^{-5}$ Torr. These sputter sources are used for etching and surface modification, as well as direct beam deposition.

Ion beam systems consist of an ion source inside a vacuum chamber directed at a sputtering target. The incident ions accelerated from the ion source sputter the target material onto an adjacent substrate. The angle of the target with respect to the ion source can be adjusted between 0° and 90° to optimize the sputtering rate. A typical ion beam sputtering system is shown in Fig. 10.

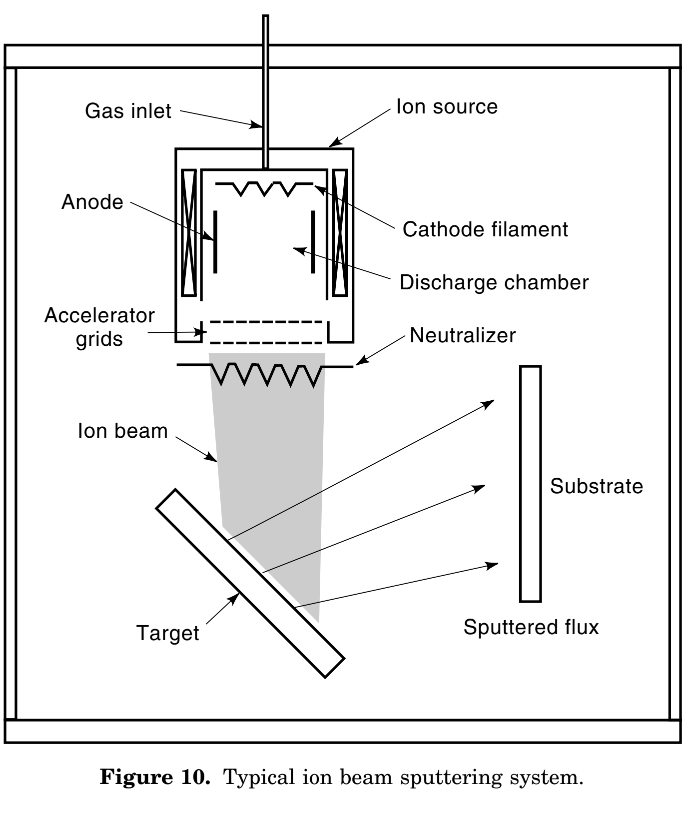


**Figure 10.** Typical ion beam sputtering system.

The drawbacks of ion beam deposition are short filament and grid lifetimes in reactive gas environments, low deposition rates, and the inability to deposit films over large surface areas. Ion beam sources are typically used in ion beam etching and fundamental research applications where highly controlled deposition parameters are required.

## CONCLUSION

The steps to film deposition by sputtering have been discussed along with the methods of sputter deposition. The sputtering process will continue to be a popular thin-film deposition technique for industry in the future. Emerging from the basic field of ion beam sputtering is the development of metal plasma beams for large area deposition and high deposition rates. Processes such as the cathodic arc and postionized enhanced sputter processes produce plasma beams of material where sputter processes play a role in beam generation. These systems will find numerous applications in the microelectronics, optics, magnetics, and tool-coating industries.

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