

Silicon Processing

for the VLSI Era
Volume 1 - Process Technology
Second Edition

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11.2 SPUTTER DEPOSITION FOR ULSI

Sputtering is a term used to describe the mechanism in which atoms are ejected from the surface of a material when that surface is struck by sufficiently energetic particles. It has become the dominant technique for depositing a variety of metallic films in VLSI and ULSI fabrication, including aluminum alloys, titanium, titanium:tungsten, titanium nitride, tantalum, and cobalt.

Sputtering displaced the original PVD technique for depositing metal films (evaporation) for the following reasons:

1. Sputtering can be accomplished from large-area targets, which simplifies the problem of depositing films with uniform thickness over large wafers.
2. Film thickness control is relatively easily achieved by selecting a constant set of operating conditions, and then adjusting the deposition time to reach it.
3. The alloy composition of sputter-deposited films can be more tightly (and easily) controlled than that of evaporated films.
4. Many important film properties, such as step coverage and grain structure can be controlled by varying the negative bias and heat applied to the wafers. Other film properties (including stress and adhesion), can be controlled by altering such process parameters as power & pressure.
5. The surface of the substrates can be sputter-cleaned in vacuum prior to initiating film deposition (and the surface is not exposed again to ambient after such cleaning).
6. There is sufficient material in most sputter targets to allow many deposition runs before target replacement is necessary.
7. Device damage from x-rays generated during electron-beam evaporation is eliminated (although some other radiation damage may still occur).

As is true with other processes, however, sputtering also has its drawbacks. They include:

1. Sputtering processes involve high capital equipment costs;
2. Since the process is carried out in low-medium vacuum ranges (compared to the high vacuum conditions under which evaporation is conducted), there is greater possibility of incorporating impurities into the deposited film.
3. Better step coverage can generally be achieved using CVD.

In general, the sputtering process consists of four steps:

1. Ions are generated and directed at a target.
2. The ions sputter target atoms;
3. The ejected (sputtered) atoms are transported to the substrate.
4. Upon reaching the substrate they condense and form a thin film.

Although it is of interest to note that sputtering can be conducted by generating the energetic incident ions by other means (e.g., ion beams), in virtually all VLSI and ULSI sputtering processes their source is a glow-discharge. The discussion of sputtering in this section will be limited to *glow-discharge sputtering*.^{4,5,6}

11.2.1 Introduction to Glow Discharge Physics

The energetic particles used to strike target materials to be sputtered in ULSI sputter deposition systems are generated by glow-discharges.^{4,5} A *glow-discharge* is a self-sustaining type of plasma (a *plasma* is defined as a partially ionized gas containing an equal number of positive and negative charges as well as some number of neutral gas particles). In Fig. 11-3 a simple *dc-diode type* system that can be employed to study properties of glow discharges used in

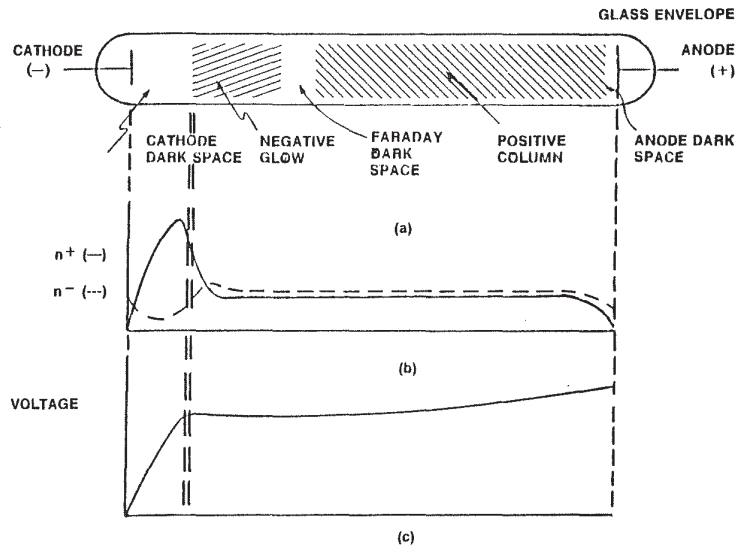


Fig. 11-3 (a) Structure of a glow discharge in a dc diode system. (b) Charged particle concentration in a glow discharge. (c) Voltage variation in a dc diode glow discharge.

sputtering is shown. It consists of a glass tube that is evacuated and then re-filled with a gas at low pressure. Within the tube there are two electrodes (a positively charged *anode* and a negatively charged *cathode*) and a dc potential difference is applied between them.

11.2.2 The Creation of Glow Discharges

Consider the system shown in Fig. 11-3 to examine the case when a tube is filled with Ar at an initial pressure of 1 torr, the distance between the electrodes is 15 cm, and a 1.5 kV potential difference is applied between them. At the outset no current flows in the circuit, as all the Ar gas atoms are neutral and there are no charged particles in the gas. The full 1.5 kV is thus dropped between the two electrodes. If a free electron enters the tube (most likely created from the ionization of an Ar atom by a passing cosmic ray), it will be accelerated by the electric field existing between the electrodes (whose magnitude is: $E = V/d = 1.5 \text{ kV}/15 \text{ cm} = 100 \text{ V/cm}$).

The average distance that a free electron will travel at $P = 1$ torr before colliding with an Ar atom (i.e., the mean free path λ) is 0.0122 cm (Chap. 3). Most electron-atom collisions are *elastic*, in which virtually no energy is transferred between the electron and gas atom. Such elastic collisions occur because the mass of the electron is much smaller than that of the atom. Thus, the minimum distance an electron must travel before it can undergo an *inelastic* collision (in which significant energy is transferred to the atom, either by the excitation of an atomic electron to a higher energy level, or to cause its escape from the atom) is about ten times λ , or 0.122 cm. If this is the minimum distance that must be traveled by electrons between inelastic collisions, there must be a significant number of electron path lengths in the range of 0.5–1.0 cm. If a free electron travels 1 cm in the 100 V/cm electric field, it will have picked up 100 eV of kinetic energy. With this amount of energy, the free electron can transfer enough energy to an Ar electron to cause it to be excited or ionized. If this transferred energy E is less than the ionization potential (e.g., $11.5 \text{ eV} < E < 15.7 \text{ eV}$ for Ar), the orbital electron will be excited to a

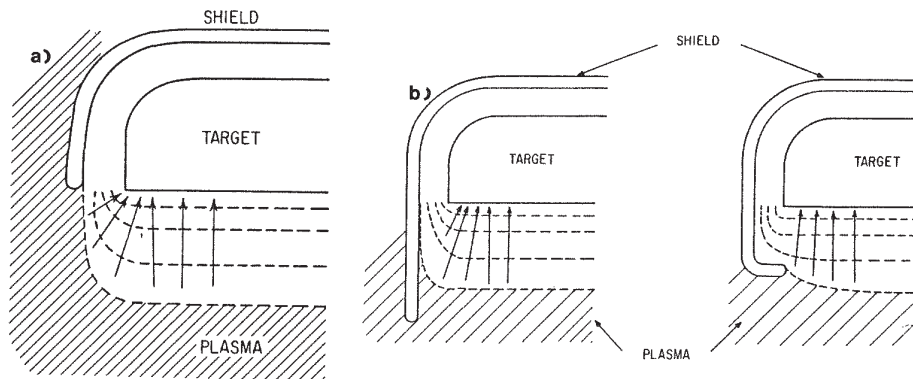


Fig. 11-7 (a) Potential distribution in vicinity of cathode shield (b) Reducing rim effect by extending cathode shield. (c) Reducing rim effect by wrapping shield around the cathode.⁸ From L. Maissel and R. Glang, Eds., *Handbook of Thin Film Technology* 1970. Reprinted by permission of McGraw-Hill Book Co.

dark space however, the ion production rate becomes reduced, and the voltage across the electrodes must rise to increase the secondary electron emission. Such a glow is known as an *obstructed glow*. In most practical sputter deposition systems the glow is obstructed. That is, in order to most effectively collect the sputtered material onto the substrate, the anode (on which the wafers are sometimes mounted) is placed as close to the cathode as possible (typically just far enough away to avoid extinguishing the negative glow).

It is typically necessary to insure that sputtering is allowed to occur only at the front side of the target, as the backside contains cooling coils and attachment fixtures which are definitely not to be sputtered. To guarantee that no sputtering takes place except from desired surfaces, a shield of metal (at a potential equal to that of the anode) is placed at a distance less than the Crookes dark space at all other cathode surfaces (Fig. 11-7). Since no discharge will occur between two electrode surfaces separated by less than this distance, such shielding (termed *dark-space shielding*) is effective in preventing sputtering from unwanted cathode surfaces.

11.3 THE PHYSICS OF SPUTTERING

When a solid surface is bombarded by atoms, ions, or molecules, many phenomena occur. The kinetic energy of the impinging particles largely dictates which are the most probable events. For low energy particles (<10 eV), most interactions occur only at the surface of the target material. At very low energies (<5 eV) such events are limited to reflection or physisorption of the bombarding species. For low energies which exceed the binding energy of the target material (5–10 eV), surface migration and surface damage effects can take place. At much higher energies (>10 keV), the impinging particles travel well into the bulk of the sample before slowing down and depositing their energy. Thus, such particles are most likely to be embedded in the target, and this mechanism is the basis of ion-implantation. At energies between the two extremes, two other effects also arise: 1) some fraction of the energy of the impinging ions is transferred to the solid in the form of heat, and lattice damage; and 2) another fraction of such energy causes atoms from the surface to be dislodged and ejected into the gas phase (*sputtering*).

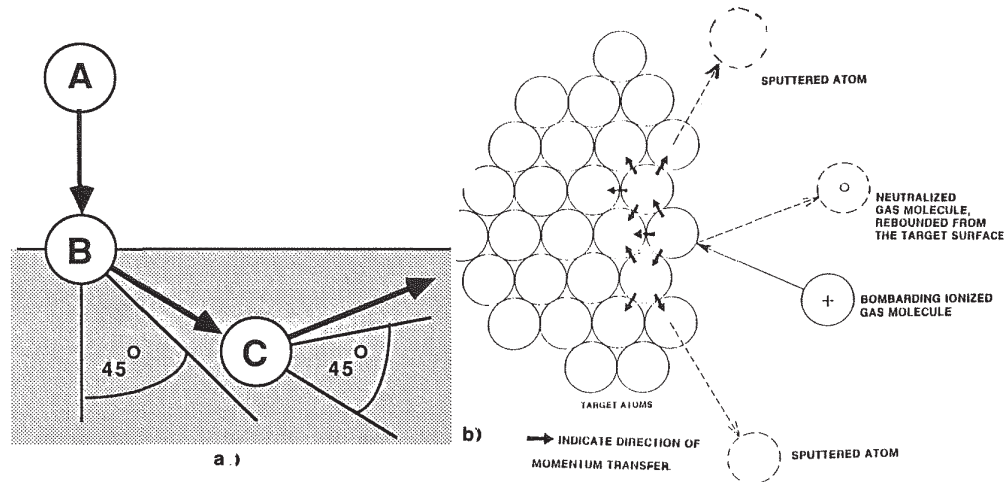


Fig. 11-8 (a) Binary collision between atom A and B, followed by a binary collision between atom B and C. (b) Collision process responsible for sputtering and fast neutral generation.

11.3.1 The Billiard Ball Model of Sputtering

The exact mechanisms which lead to the ejection of atoms under ion bombardment are not known, and a comprehensive theory of sputtering is not likely to be developed in the near future since many parameters are involved. These include the kinetic energy of the ions, lattice structure, and binding energy of lattice atoms. Some of the details, however, are reasonably well understood and can be aptly described with a relatively simple momentum-transfer model. G.K. Wehner, whose theoretical work first established a solid scientific basis for sputtering, often described sputtering as a game of three-dimensional billiards, played with atoms.⁹ Using this analogy, it is possible to visualize how atoms may be ejected from a surface as the result of two binary collisions (Figs. 11-8b and 11-8c) when a surface is struck by a particle with a velocity normal to the surface (e.g., atom A in Fig. 11-8b). Note that a *binary collision* is one in which the primary incoming particle (e.g., atom A) strikes a single object (e.g., atom B in Fig. 11-8b), and gives up a significant fraction of its energy to the struck atom, while retaining the remaining fraction. As a consequence of the collision, atom B may leave the point of impact at an angle greater than 45° . If atom B then undergoes a secondary collision with atom C, the angle at which atom C leaves the secondary impact point may again be greater than 45° . Thus, it is possible that atom C can have a velocity component greater than 90° (and thus be directed toward the surface). As a result, there is a finite probability that atom C will be ejected from the surface as a result of the surface being struck by atom A.

When the directions of sputtered atoms from the surface of polycrystalline materials (and most cathode materials in sputter applications are polycrystalline) are measured for the case of *normal incidence*, it is found that the ejected atoms leave the surface in essentially a cosine distribution. A cosine distribution, however, does not describe the sort of small-angle ejections that would be expected from the simple collision processes described above. Evidently in actual sputtering events, more than two collisions are involved, and the energy delivered by impinging ions *during normal incidence* is so randomly distributed that the effect of the incident momentum vector is lost. Note that the energy range of sputtered atoms leaving the target is

typically 3–10 eV, and the bombarding species also recoil from the cathode face with some energy. Thus, the target surface is a source of sputtered atoms and energetic backscattered species.

For the case when the surface is bombarded by ions at an oblique angle (i.e., 45° – 90°), there is a higher probability that the primary collision between incident ions and surface atoms will lead to sputtering events. Furthermore, oblique incidence confines the action closer to the surface, and thus sputtering is enhanced. In cases of oblique bombardment, the incident momentum vector becomes important, and sputtered atoms are ejected strongly in the forward direction. In addition, the *sputter yield* (defined as the number of atoms ejected per incident ion), may be as much as an order of magnitude larger than that resulting from normal incidence by bombarding ions (Fig. 11-9). This effect also leads to *faceting*, which is covered in Sect. 11.7.4.

11.3.2 Sputter Yield

The sputter yield is important because it largely (but not completely) determines the rate of sputter deposition. Sputter yield depends on a number of factors besides the direction of incidence of the ions, and these include: a) the target material; b) the mass of bombarding ions; and c) the energy of the bombarding ions. There is a minimum energy threshold for sputtering that is approximately equal to the heat of sublimation (e.g., 13.5 eV for Si). In the energy range of sputtering (10–5000 eV), the yield increases with ion energy and mass. Figure 11-10 shows the sputter yield of copper as a function of energy for various noble gas ions. The sputter yields of various materials in argon at different energies is given in Table 11-2.⁹

Several matters related to sputter yield should be noted. First, although the sputtering yields of various materials are different, as a group they are much closer in value to one another than, for example, the vapor pressure of comparable materials. This makes the deposition of multilayer or multi-component films much more controllable by sputtering. The details of sputtering from multi-component targets are discussed in the section on *Process Considerations in Sputter Deposition*. Second, since the bombarding ions are by no means monoenergetic in glow-discharge sputtering, it is not necessarily valid to use the sputter yield values for pure metals if alloys, compounds, or mixtures are being sputtered. Tabulations of sputtering yields, however, are useful for obtaining rough indications of deposition or etch rates of various materials.

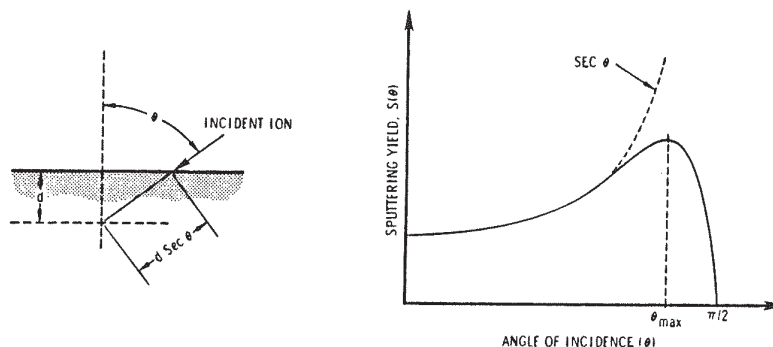


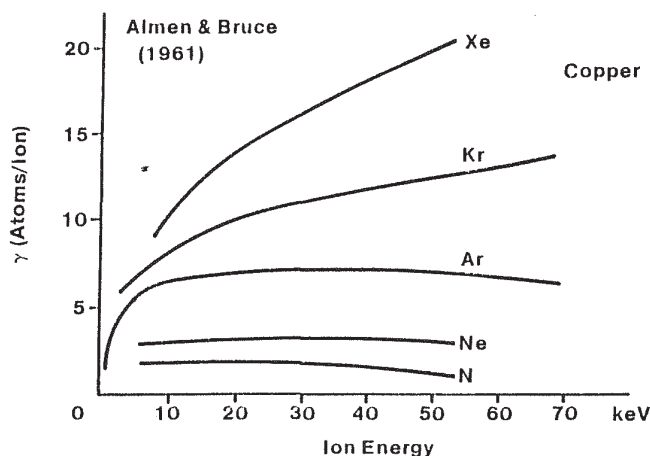
Fig. 11-9 Schematic diagram showing variation of sputtering yield with ion angle of incidence.

Table 11-2 SPUTTER YIELDS FOR METALS IN ARGON (ATOMS/ION)

Target	At.Wt./Dens.	100 eV	300 eV	600 eV	1000 eV	2000 eV
Al	10.0	0.11	0.65	1.2	1.9	2.0
Au	10.2	0.32	1.65	2.8	3.6	5.6
Cu	7.09	0.5	1.6	2.3	3.2	4.3
Ni	6.6	0.28	0.95	1.5	2.1	
Pt	9.12	0.2	0.75	1.6		
Si	12.05	0.07	0.31	0.5	0.6	0.9
Ta	10.9	0.1	0.4	0.6	0.9	
Ti	10.62	0.08	0.33	0.41	0.7	
W	14.06	0.12	0.41	0.75		

11.3.3 Selection Criteria for Process Conditions and Sputter Gas

The information gleaned from sputter yields and the physics of sputtering can also be applied toward an understanding of how process conditions and materials are selected for sputtering including: a) type of sputtering gas; b) pressure range of operation; and c) electrical conditions for the glow discharge.^{4,8} That is, in purely physical sputtering (as opposed to reactive sputtering) it is important that the ions or atoms of the sputtering gas not react with the growing film. This limits the selection of sputtering species to the noble gases. Furthermore, argon is generally the gas of choice, since it is easily available (hence low in cost), and its mass is a good match to those of the elements most frequently sputtered (Al, Cu, Si, and Ti), giving adequate sputtering yields for these elements. The *pressure range of operation* is set by the requirements of the glow discharge (lower limit ~2–3 mtorr for magnetron sputtering) and the scattering of sputtered atoms by the sputter gas (upper limit 100 mtorr). In addition, a desired goal of sputter deposition is to obtain maximum deposition rates. As a result, *electrical conditions* are selected

Fig. 11-10 Sputtering yields of the noble gases on copper, as a function of energy.¹⁰

to give a maximum sputter yield per unit energy. That is, as energy is increased, each energy increment gives a progressively smaller increase in sputter yield. This occurs because higher energy ions implant themselves, and thus end up dissipating a greater proportion of their energy via non-sputtering processes. The most efficient ion energies for sputtering are typically obtained for electrode voltages of several hundred volts.

In general, the higher the current at the cathode, the higher is the film deposition rate, since more ions are striking the cathode (and thus cause more sputtering). The product of the cathode current and the electrode voltage gives the input power of the sputtering process. In magnetron sputtering, cathode current densities of 10–100 mA/cm² at a few hundred volts are typical.

From the foregoing discussion on the mechanism of sputtering one can see that sputtering is a highly inefficient process. In fact, ~70% of the energy consumed during the sputtering process is dissipated as heat in the target, and ~25% by emission of secondary electrons and photons from the target. This heating can raise target temperatures to levels capable of damaging the target, associated vacuum components, or the material that bonds the target to the backing electrode. The target must therefore be cooled to avoid these problems. As we will discuss later, this is normally accomplished by bonding the target to a water-cooled Cu backing plate.

11.3.4 Secondary Electron Production for Sustaining the Discharge

Near the outset of the discussion on glow-discharges, it was observed that glow-discharges must be continuously provided with free electrons to keep them sustained. In most dc-sputtering systems, the source of such electrons is secondary-electron emission from the target. An important mechanism that generates such secondary electrons is Auger emission, although other emission mechanisms are also responsible for their production. The *Auger emission* process occurs according to the sequence of events shown in Fig. 11-11. Target electrons require a minimum amount of energy $q\Phi$ to escape into free space (where Φ is the *work function* of the target material, and $q\Phi$ is typically 3–5 eV). However, when a positive ion (such as Ar⁺) comes close to the target surface it appears as a potential well of 15.67 eV to target electrons occupying energy states near the Fermi level. Thus, some of the target electrons can escape by tunneling into these potential wells. The energy difference between 15.67 eV and the minimum free-space escape energy is released in the form of a photon. If this photon (e.g., of energy 10.67 eV = [15.67 eV - 5 eV]) is absorbed by another electron near the target surface, this electron (i.e., the Auger electron) may possess enough energy to be emitted from the target into free space. Since this sequence of events is rather improbable, several ions must strike the cathode in order for a single Auger electron to be emitted. The secondary electron yield per bombarding ion γ_i has been measured to be 0.05–0.1 for metal targets. Thus, each secondary electron needs to generate as much as 20 ion-electron pairs before it reaches the anode to sustain the discharge.

Besides providing a source of electrons to sustain the discharge, electron emission is also important to the sputtering process in other ways. First, ions bombarding the cathode are neutralized. Thus, it is highly probable that each ion that closely approaches the target will extract an electron from the target, and return to the discharge as a neutral atom. Second, the total target current, I , is the sum of the ion flux striking the target, I_i , and the secondary electron current leaving the electrode, I_e . Since γ_i is larger for dielectric materials, their I_e is also larger. This implies that for the same cathode current, I , dielectrics will sputter more slowly than metals. That is, in dielectric sputtering a larger fraction of I is due to electron emission, and thus for equal values of I , a smaller ion flux is striking the dielectric target.

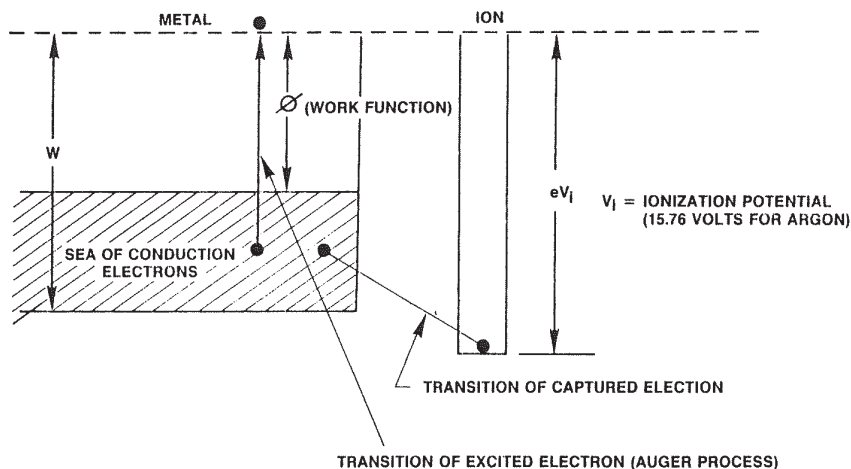


Fig. 11-11 Potential energy diagram for ion approaching a metal target.

11.3.5 Sputter Deposited Film Growth

Upon being ejected from the target surface, sputtered atoms have velocities of $3\text{--}6 \times 10^5 \text{ cm/sec}$ and energies of 10–40 eV. It is desirable that as many of these sputtered atoms as possible be deposited upon the substrates to form the specified thin film. To accomplish this, the target and wafers are closely spaced, with spacings of 5–10 cm being typical. The mean free path, λ , of sputtered atoms at typical sputter pressures is less than 5–10 cm (e.g., at 5 mtorr, $\lambda \approx 1 \text{ cm}$). Thus, it is likely that sputtered atoms will suffer one or more collisions with the sputter-gas atoms before reaching the substrate (Fig. 11-12). The sputtered atoms may therefore: a) arrive at the substrate with reduced energy ($\sim 1\text{--}2 \text{ eV}$); b) be backscattered to the target or the chamber walls; or c) lose enough energy so that thereafter, they move by diffusion in the same manner as neutral sputter gas atoms. These events imply that the sputtering gas pressure can impact various film deposition parameters, such as the deposition rate and composition of the film.

The formation and growth of the thin film on the substrate proceeds according to the general discussion on thin film formation given in Chap. 4. Therefore, this discussion is restricted to the events that uniquely impact the formation and growth of glow-discharge sputtered films.

The substrate surface (onto which the desired film of the sputtered target material is deposited) is also subjected to impingement by many species. The sputtered atoms arrive and condense onto the substrate. For a typical deposition rate of 20 nm/min, a monolayer of deposited film will form approximately every second (assuming the size of a typical atom is $\sim 0.3 \text{ nm}$). For this case, and even for much higher deposition rates of Al (e.g., 620 nm/min), the heat of condensation is not necessarily the most important source of substrate heating.

11.3.6 Species that Strike the Wafer During Film Deposition

In addition to the sputtered atoms, the substrate is also struck by many other species (Fig. 11-13), the most important being: 1) *fast neutral sputter gas atoms*, which retain significant energy after striking and recoiling from the cathode. As they impinge upon the substrate, some may embed themselves in the growing film; 2) *negative ions*, formed near the cathode surface by

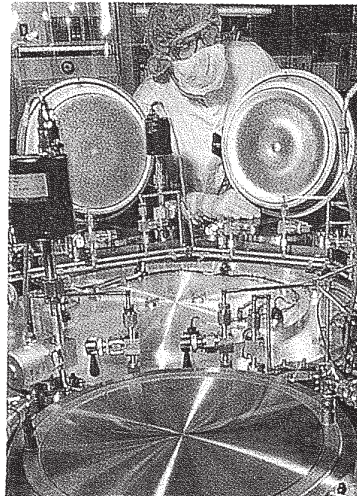


Fig. 11-23 An spent aluminum circular-planar-magnetron target (right) is being changed.

reported that deposition rates of 1200-nm/min can be achieved when depositing Al:(0.5%)Cu films on 200-mm wafers.³⁰ In fact, the maximum sputter deposition rates with such sources are usually not limited by any aspect of the plasma (as in dc and rf diode cases), but rather by the ability to cool the cathode target to keep it from melting.

The fact that the annular shape of the plasma in a circular planar magnetron results in a non-uniform erosion of the target also causes the deposition onto nearby wafers to be non-uniform. In fact the deposition profile mirrors the race track when the wafer is close to the target, but this deposition profile becomes more smeared as the sample is moved further from the target (see Fig. 11-24a). Thus, a tradeoff is often made between deposition rate and thickness uniformity (i.e., uniformity improves as the target-to-wafer spacing is increased, but the deposition rate decreases). Note also from Fig. 11-24 that the target diameter is made larger than the wafer diameter to improve thickness uniformity. As an example, for 200-mm (8 in) wafers, the target diameter is typically 330 mm (14 in). Figure 11-24b shows such a target sputtering onto a smaller wafer. In practice, thickness uniformities of $\pm 5\%$ (3σ) within a wafer can be achieved.

11.6 VLSI AND ULSI SPUTTER DEPOSITION EQUIPMENT

A number of different sputtering systems have been designed for commercial use in IC fabrication. Only the dominant sputtering systems designs that were used in VLSI and ULSI generations will be described (i.e., those used for IC fabrication on 125-mm, 150-mm, and 200-mm wafers). Sputtering systems used for earlier IC technologies are described in the first edition of Vol. 1. In this section the generic components of a sputtering system are discussed first. Then the sputtering systems used in 125-mm and 150-mm wafer processing are briefly examined. The focus of this discussion is on the sputtering systems used for 200-mm wafers (and larger).

11.6.1 The Components of a Generic Sputtering System

The schematic of a basic sputtering system is shown in Fig. 11-25. It consists of the following subsystems: a) the sputter chamber, in which the substrate holder and sputtering source reside (the source also includes the target); b) vacuum pumps; c) power supplies (dc and/or rf); d) sputtering gas supply and flow controllers; e) monitoring equipment (pressure gauges, volt-

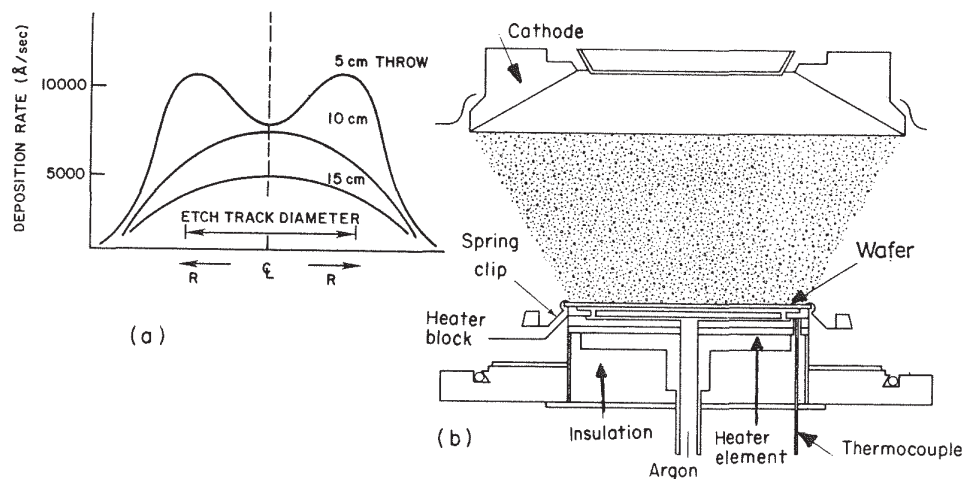


Fig. 11-24 a) The deposition profile and deposition rate on a sample in front of a magnetron cathode as a function of sample distance.²¹ Reprinted with permission of Academic Press. b) Sputter deposition from a planar magnetron target whose diameter is larger than that of the wafer.

(pressure gauges, voltmeters, and residual-gas analyzers); f) wafer holders and handling mechanisms; and g) microcomputer controller.

In modern sputter tools the sputter chambers are isolated from the ambient by a load lock. That is, a cassette of wafers to be sputter deposited is placed into the loadlock. Then the valve connecting the loadlock to the outside ambient is closed. The loadlock is pumped down, and upon reaching the base pressure of the transfer chamber the vacuum valve to the transfer chamber is opened. A robotic arm in the transfer chamber removes a wafer from the cassette and brings it into the transfer chamber. The loadlock/transfer chamber valve is then closed. The sputter chamber awaiting the wafer has also been pumped to the appropriate low base pressure (e.g., 10^{-6} – 10^{-8} torr). The vacuum valve to the sputter chamber is opened, and the wafer is then

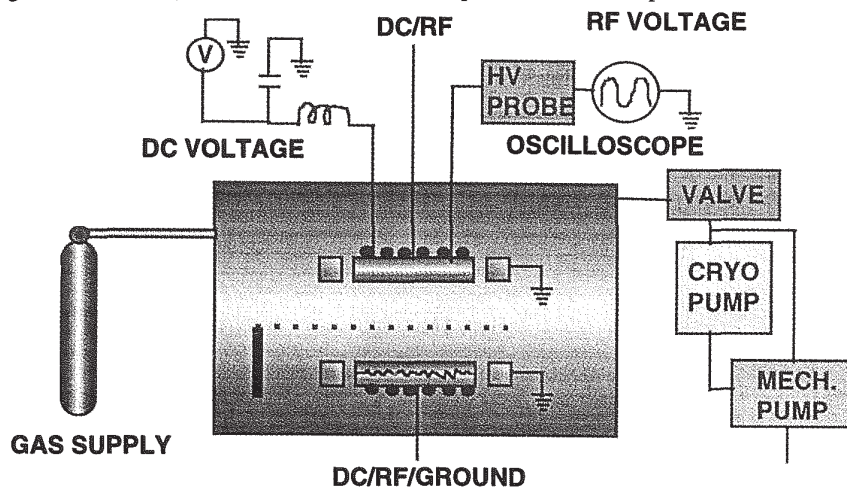


Fig. 11-25 Schematic drawing showing some of the components of a sputtering system.

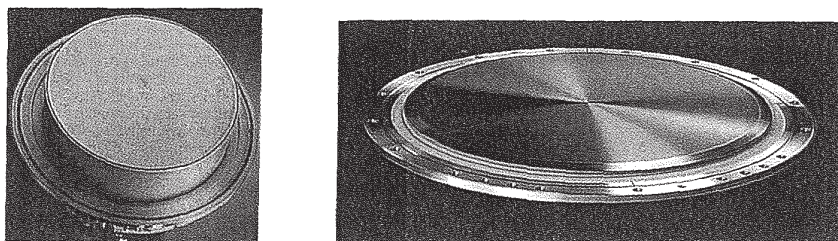


Fig. 11-26 Examples of sputtering targets for planar circular magnetron sources.

inserted into the sputter chamber by the robot arm. After the arm withdraws, the vacuum valve between the sputter chamber and the transfer chamber is closed, and sputter gas is flowed into the chamber to the appropriate pressure (e.g., 5 mtorr) and flow rate. The sputter process can then be started.

11.6.1.1 Sputtering Targets: *Sputtering targets* consist of the material that is to be sputter-deposited onto the wafer. Targets in circular magnetrons are circular discs 3 to 10 mm thick, as shown in Fig. 11-26. These are bonded to a water-cooled Cu backing plate for good thermal contact, usually by soldering with a low-melting-temperature metal (or with a conductive epoxy). Since over 70% of the energy incident onto the target goes into target heating, targets must be adequately cooled to prevent the following problems: warpage; deposition-rate changes due to thermal restructuring of the target material; delamination from the backing plate; or even target melting. De-ionized water is used as the cooling liquid to prevent electrolytic corrosion between the electrically biased backing plate and the grounded water supply. The entire cathode assembly is floated off ground by a ceramic insulator ring.

Targets consisting of metals with relatively low melting points (e.g., Al, Cu, and Ti) are fabricated by melting and casting the metals in either vacuum or protective ambients. The starting materials to fabricate the targets must be very pure (e.g., up to 99.9999 pure [or six nines] for aluminum targets). In the case of cast alloy targets, fine grain size is preferred to minimize segregation of constituent elements into nodules during ion bombardment (since such nodules are a source of large particle ejection from the target during sputtering). Targets of high-melting-point refractory metals (e.g., W:Ti) and compound materials are generally formed from powders by hot-pressing. Although there may be no alternative, this fabrication method is less desirable than the vacuum-melting process. Less-than-theoretical densities are achieved with powder processing. As a result, such targets release trapped gases, particulates, and exhibit occlusions as their surfaces are eroded. The latter can give rise to non-uniform target erosion, arcing, and deposited films of inferior quality. Some device applications (e.g., memory circuits) also demand material very low in alpha-particle emitting elements (i.e., less than 0.01 ppb U and Th content).³⁷

Pre-sputtering of targets is done to clean their surfaces prior to film deposition. Once the target surface is clean, sputter deposition onto product wafers can take place. Arcing may occur at the target surface in dc sputtering until the surface is cleaned. Thus, it is common practice to

condition freshly installed targets by slowly increasing the applied power, until all the material that could give rise to the arcing has been sputtered away.

11.6.1.2 Vacuum Pumps for Sputtering Systems: *Vacuum pumps* are also an important part of the sputtering system (as will be described in more detail in Sect. 11.6.3). Modern sputtering systems use cryopumps to keep the sputter chambers under high (or ultra-high) vacuum between times of sputtering.¹⁹ Cryopumps offer higher water pumping speeds than turbo pumps (see Chap. 3) and clean operation. State-of-the art sputtering chambers typically operate with base pressures of 1×10^{-8} torr, or less. Prior to beginning the sputter process, the chamber is backfilled with Ar gas. Since an open-flow process configuration is used, once the sputter process is initiated, the cryopump is used to continually pump the sputter gas (Ar) out of the chamber. That is, during sputtering Ar is metered into the chamber at a controlled flow rate, and the pump simultaneously evacuates it while maintaining the pressure in the chamber at the desired process pressure (e.g., 2–5 mtorr). Such continuous renewal of the Ar gas is another measure taken to ensure that the partial pressures of contaminant gases in the chamber are kept to adequately low levels.

11.6.1.3 Power Supplies for Sputtering Systems: Sputtering systems are typically provided with both a *dc* and an *rf power supply*. Dc power supplies can be built to supply up to 20 kW of power, whereas rf power supplies are limited to ~3 kW. As a result, dc magnetron sputtering can provide higher deposition rates than rf magnetron sputtering. Consequently dc-magnetron sputtering is the operational mode of choice for high-deposition-rate processes. Dc power supplies for sputtering must be designed to be capable of withstanding arcs without damage.¹² Such arcs are thought to arise from the local dielectric breakdown of native oxides on freshly installed targets, or from other surface regions on which contaminant insulator layers have formed. Conversely, rf sputtering removes such regions as a matter of course, and rf supplies are not subjected to arcing. The dc supplies, however, must be designed to handle such local arcing without shutting down or damage, as the regions responsible for such arcing are normally cleaned within minutes after the power is supplied to the system, and arcing then ceases. On the other hand, the supply must be able to sense large arcs caused by such events as metal flaking between the target and ground, and to be able to switch off soon enough to prevent damage to the target.

11.6.1.4 The Gas Supply for Sputtering Systems: As noted earlier, Ar is used as the process gas for almost all sputtering applications (with one exception being the reactive sputtering of Ti, where a mixture of Ar and nitrogen is used to deposit TiN films). The gas is metered into the chamber by a mass-flow controller. The purity of the Ar gas is its most important characteristic. As will be discussed in Sect. 11.7, if contaminant gases (especially H₂O, O₂, and N₂) enter the sputter chamber in even low parts-per-million amounts, the characteristics of the films being deposited can be significantly altered. Thus, ultra-high-purity Ar must be used, and the gas lines that deliver the Ar to the chamber must be kept leak tight. Note that at the times when a wafer is not loaded into the process chamber, the Ar flow is typically shut off, allowing the chamber to return to an ultra-high vacuum base pressure.

11.6.2 Commercial Sputtering Systems for 125-mm and 150-mm Wafers

The most widely used sputtering systems for 125-mm and 150-mm wafers were the Varian 3180 models (for wafers up to 125-mm in diameter) and the Varian 3290 models (for wafers up to 150-mm in diameter). They employed a *static* sputtering mode, insofar as the wafer and target