SEMICONDUCTOR MANUFACTURING TECHNOLOGY

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CHAPTER 12

METALLIZATION

Metallization in wafer fabrication is the process of depositing metal film over a dielectric film and later patterning it to form the interconnecting metal lines and plugs of integrated circuits. This is similar to using insulated copper wire in an automobile to interconnect all the electrical components to make a fully-functional electrical system. The metal lines are sandwiched between dielectric layers for electrical integrity. High-performance microprocessors use metal lines to interconnect tens of millions of devices on one chip. Transistor densities are projected to reach 1 billion transistors per chip by the year 2010, with a corresponding increase in interconnect complexity.

Microchip interconnect technology has become a critical challenge for future IC performance due to the need to decrease signal propagation delay. Because the density of ULSI circuit elements is increasing, interconnect resistance and parasitic capacitance increase, thereby slowing the signal propagation.

A significant change currently underway in wafer fabrication technology is the reduction in interconnect metal resistivity, ρ. This reduction is achieved by the replacement of aluminum alloy with copper as the primary conducting metal. With deep submicron linewidths, there is also a need for a low-k interlayer dielectric (ILD). Lowering the dielectric constant will reduce parasitic capacitance, which contributes to signal delay.

Traditionally, the methods used to deposit metals on a wafer have been physical processes. On the other hand, processes used to deposit insulating and semiconducting layers usually involved the CVD chemical reactions studied in Chapter 11. This separation into physical and chemical processes is less defined with the introduction of new IC metallization technology.

OBJECTIVES

After studying the material in this chapter, you will be able to:

1. Explain the terminology for metallization.
2. List and describe the six categories of metals used in wafer fabrication. Discuss the performance requirements and give applications for each metal category.
3. Explain the benefits for using copper metallization in wafer fabrication. Describe the challenges for implementing copper.
4. State the advantages and disadvantages to sputtering.
5. Describe the physics of sputtering and discuss different sputtering tools and applications.
6. Describe the benefits and applications for metal CVD.
7. Explain the fundamentals of copper electroplating.
8. Describe a process flow for dual-damascene processing.

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INTRODUCTION

Wafer metallization is the deposition of a thin film of conductive metal onto a wafer by use of a chemical or physical process. This process is closely linked to dielectric deposition. Metal lines conduct the signal through the IC circuit while the dielectric layers ensure signals are not influenced by adjacent lines. Both metal and dielectrics are thin film processes. In some cases, metal and dielectrics are deposited by the same type of equipment.

Metallization has unique terminology for the different metal connections. The term *interconnect* describes the conductor materials, such as aluminum, polysilicon, or copper, that create the metal wiring that carries electrical signals to different parts of the chip. Interconnect is also used as a general term for the wiring between devices on a die and the overall package. A *contact* is the electrical connection at the silicon surface between the devices in the silicon wafer and the first metal layer. *Vias* are openings that pass through the various dielectric layers to form an electrical pathway from one metal layer to the adjacent metal layer. A metal *plug* fills the vias to form the electrical connection (interconnect) between the two metal layers. These connections are illustrated in Figure 12.1.

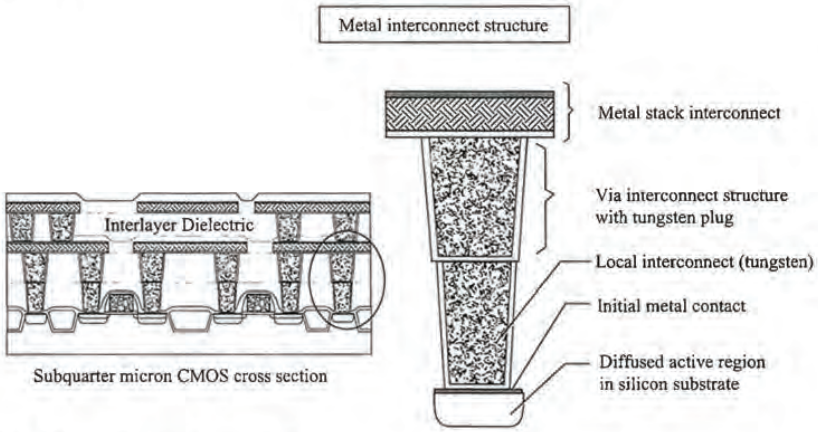

FIGURE 12.1 Multilevel Metallization

The interlayer dielectric (ILD) is an insulating material that electrically separates the metal levels. Once deposited, the ILD is patterned and etched to form via pathways for the various metal layers and the silicon. The vias are filled with a metal, traditionally tungsten (W), to form the via plug. Appreciate that there are many vias on a wafer, up to 10^{11} vias on each individual layer of a 300-mm product wafer.[1] This process of creating vias in the ILD is repeated for every ILD layer on the die. In traditional metallization, a blanket layer of aluminum alloy metal is deposited on the dielectric layer and then patterned and etched to form metal lines. Metal etch is an important technology for traditional metallization.

Metallization is in a transition period and is undergoing rapid change with the introduction of copper metallurgy to replace aluminum alloy. This change is due to the difficulty of etching copper. To overcome this problem, copper metallurgy uses the dual damascene process to form vias and copper interconnects (explained later in this chapter). This metallization process is literally the opposite approach of traditional metallization (see Figure 12.2). Damascene starts with deposition of a blanket dielectric, planarizes the dielectric, patterns and etches holes or trenches in the dielectric for vias and connecting metal lines, deposits blanket metal into the trenches, and then planarizes the metal down to the dielectric to define the metal interconnects.

Metallization technology is critical for increasing performance in advanced ICs, as explained in Chapter 11. Reducing chip performance signal delay caused by interconnect lines was not a significant concern for older IC technologies. The dominant signal delay has traditionally been caused by the device. However, for newer ULSI products manufactured with denser wiring, signal delay

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due to interconnect has become a larger portion of the clock cycle time and has more effect on limiting the IC performance.[2]

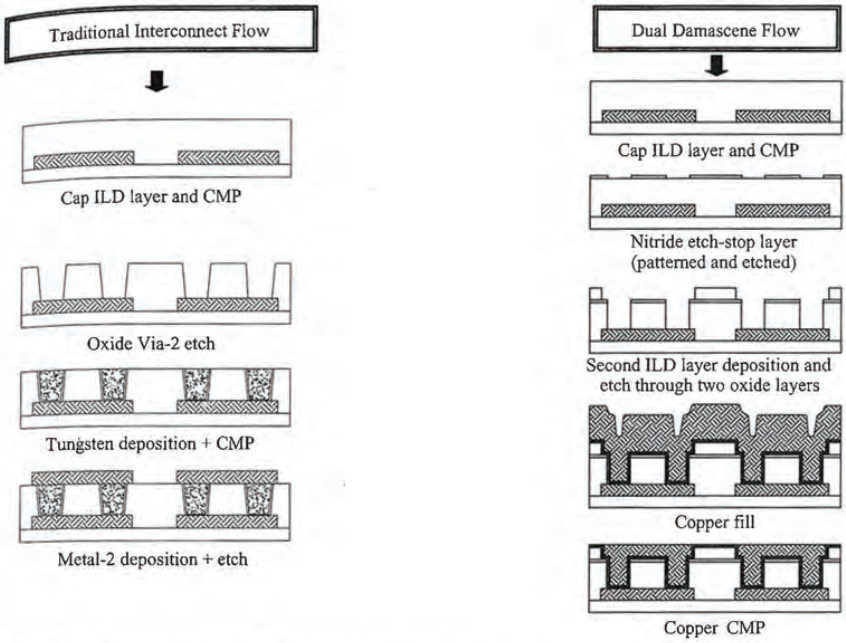
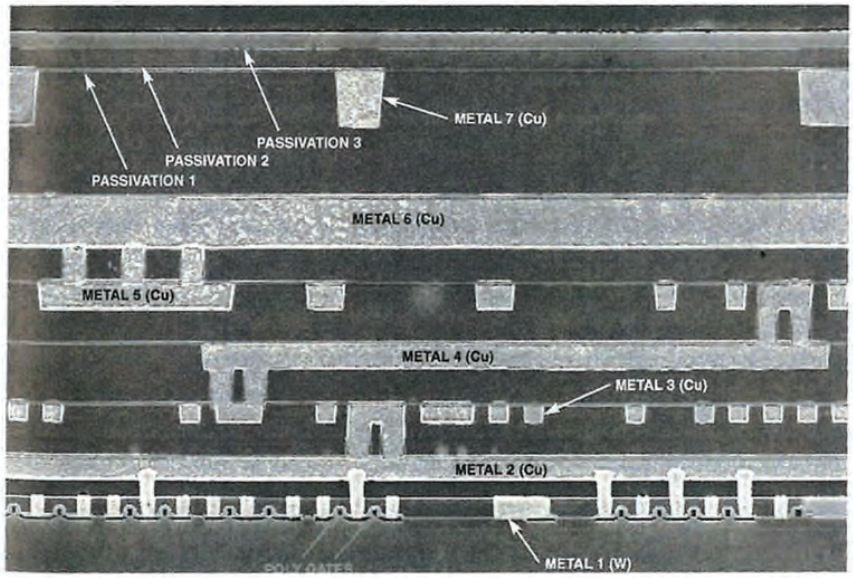


FIGURE 12.2 Traditional Versus Damascene Metallization



Copper Metallization
(Micrograph courtesy of Integrated Circuit Engineering)

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TYPES OF METALS

The types of metals and metal alloys used for chip interconnects are evolving based on the performance requirements. Requirements for a successful metal material are:[3, 4]

1. **Conductivity:** Must be highly conductive and capable of handling high current densities while maintaining electrical integrity.
2. **Adhesion:** Ability to adhere to the underlying substrate and easily connect to external connections. Low contact resistance to semiconductor and metal interfaces.
3. **Deposition:** Readily deposited with a uniform structure and composition (for alloys) by a relatively low-temperature process. Deposition into high-aspect ratio gaps for damascene metallization technique.
4. **Patterning/Planarization:** High-resolution patterning for traditional Al-based metallization without etching the underlying dielectric. Ease of planarization for damascene metallization.
5. **Reliability:** The metal is relatively soft and ductile in order to withstand cyclic temperature variations during processing and service.
6. **Corrosion:** High resistance to corrosion with minimal chemical interactions with the adjacent layers and underlying device regions.
7. **Stress:** Resistance to mechanical stress to reduce wafer distortion and material failures for reasons such as cracking, void formation, and stressed-induced corrosion.

The melting temperature and resistivities of different metals found in wafer fabrication and silicon are shown in Table 12.1.[5]

TABLE 12.1 Silicon and Select Wafer Fab Metals (at 20°C)

Material	Melting Temperature (°C)	Resistivity (μΩ-cm)
Silicon (Si)	1412	$\approx 10^9$
Doped Polysilicon (Doped Poly)	1412	≈ 500 to 525
Aluminum (Al)	660	2.65
Copper (Cu)	1083	1.678
Tungsten (W)	3417	8
Titanium (Ti)	1670	60
Tantalum (Ta)	2996	13 to 16
Molybdenum (Mo)	2620	5
Platinum (Pt)	1772	10

The various metals and metal alloys used in wafer fabrication can be grouped into the following categories:

- Aluminum
- Aluminum-copper alloys
- Copper
- Barrier metals
- Silicides
- Metal plugs

Aluminum

The earliest interconnect metal in semiconductor fabrication was aluminum, and it is still the most common interconnect metal in wafer fabrication. Aluminum is projected to continue as the dominant fab interconnect metal for several more years.[6] Copper interconnect metal is expected to replace aluminum for high-performance IC fabrication during the early 2000s. Nevertheless, it is beneficial to review the background into the selection of aluminum for metallization because many of the same basic technical challenges exist today.

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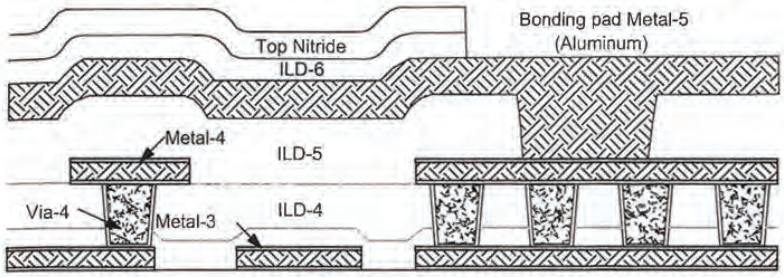
Selection of Aluminum ■ Aluminum has been one of the major materials used in wafer fabrication, along with silicon and silicon dioxide. It is used during wafer fabrication in thin film form to interconnect the different devices in the silicon wafer (see Figure 12.3). At the same time, aluminum is one of the thickest films deposited on the wafer, with the first metal layer deposition about 5,000 Å thick. The upper noncritical layers on a wafer (e.g., metal layer with bonding pads) can range up to 20,000 Å thick.



Metal-4 is preceded by other vias, interlayer dielectric, and metal layers.

FIGURE 12.3 Aluminum Interconnect

Aluminum's low resistivity of 2.65 μΩ-cm at 20°C has similar but slightly higher resistivity than copper, gold, and silver. However, silver and copper are both prone to corrosion and have high diffusivity in Si and SiO_2, a fact that keeps them from being used for semiconductor fabrication. Gold and silver are much more expensive than aluminum and do not adhere well to oxide films. Gold was sparingly used in the beginning of wafer fabrication, but its high contact resistance with silicon required a platinum barrier metal. On the other hand, aluminum reacts readily with silicon dioxide (SiO_2) when heated to form a thin layer of aluminum oxide (Al_2O_3), which promotes adhesion between the silicon dioxide and aluminum. Aluminum is easily deposited on the wafer and etches in solutions that do not attack underlying films. For these reasons, aluminum was selected as the preferred metal for metallization.

Overall, aluminum is compatible with the major processes in silicon IC fabrication and is relatively inexpensive, making it the choice for metallization since the early days of IC fabrication. However, because of increased circuit density, increased number of metal layers on a wafer, and the reduction in linewidth due to scaling, the metallization technology has evolved from the simple one-level metal layer to a scheme of multiple metal layers. With its lower resistivity, copper is desirable to replace aluminum as the primary interconnect material.

Ohmic Contact ■ Before VLSI circuitry, pure aluminum was used for metallization. Silicon melts at a temperature of 1412°C and pure aluminum melts at 660°C. However, aluminum and silicon alloyed together actually have a lower melting temperature depending on their composition. For an alloy of 88.7% aluminum and 11.3% silicon, the alloy melts at 577°C, which is referred to as the *eutectic temperature.*[7] The eutectic temperature is the lowest temperature that an alloy melts at a particular eutectic composition.

To form a contact between aluminum and silicon, it is necessary to heat the interface, usually in an inert or reducing H_2 atmosphere at a temperature of 450 to 500°C. This thermal bake is also referred to as a low temperature *anneal* or *sinter.* Baking the aluminum on silicon forms a desirable electrical interface referred to as an *ohmic contact.* An ohmic contact has very low resistance (the voltage-current characteristics of the contact interface behave according to Ohm's law). However, there is a small resistance associated with the ohmic contact and it is inversely proportional to the area of the contact. That is, smaller contacts have higher resistance. In modern chip design, ohmic contacts use a special refractory metal (e.g., titanium in the form of a silicide) as a contact at the silicon interface to reduce electrical resistance and improve adhesion (see Figure 12.4 on page 304). Ohmic contacts are fabricated with a salicide (self-aligned silicide) process to achieve optimal positioning above the source/drain and in close proximity to the gate structure. The salicide process is discussed later in this chapter.

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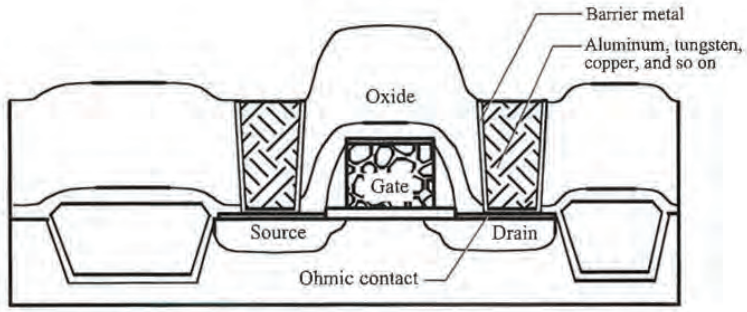

FIGURE 12.4 Ohmic Contact Structure

Given the hundreds of millions of contacts that can exist on a particular die, a reliable contact interface with low resistance and excellent adhesion is extremely important for optimum electrical performance. A failure in any individual contact can cause the entire chip to fail during test or use.

A problem encountered during the earliest work to develop ohmic contacts was undesirable interaction between the aluminum and silicon during the thermal step. This condition led to the microalloying of the contact metal to the silicon, and was referred to as *junction spiking*. Spiking occurs when the interface of pure aluminum and silicon is heated (see Figure 12.5), causing the diffusion of silicon into the aluminum. The amount of silicon dissolved into the aluminum is not uniform and will depend on the time and temperature involved in the heating process. If pure aluminum is heated to 450°C and a source of silicon is present, silicon will begin to dissolve in the aluminum until it reaches a concentration of about 0.5%.[8] The problem is that the source of this silicon is the wafer. As the silicon is dissolved in the aluminum, it leaves behind voids in the wafer, permitting spikes of aluminum to form and penetrate into the silicon contact region. If the aluminum forms an ohmic contact to a shallow junction, the spike may cause a junction short.

The problem of junction spiking was addressed by two methods: the addition of silicon to the aluminum and barrier metallization. The first approach was to use an alloy of aluminum and silicon instead of pure aluminum. If there is already silicon in the aluminum, this will slow down the dissolution of additional silicon from the substrate. However, silicon alloying in aluminum is limited and can lead to silicon nodule formation (small regions of high silicon concentration) in the aluminum due to silicon condensation. Nodule formation can significantly increase the contact resistance and pose a serious reliability concern from local heating at the nodules. The main method to resolve junction spiking was the introduction of barrier metallization to inhibit diffusion (see the following section).

It is important that the oxide at the contact interface be as thin as possible. Wafers with exposed contact regions are often dipped in a dilute hydrofluoric (HF) acid solution immediately before placing the wafers in the deposition chamber. This serves to remove the native oxide layer prior to contact formation.

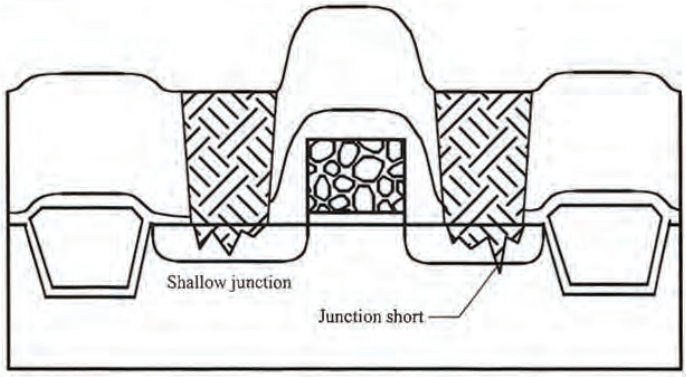

FIGURE 12.5 Junction Spiking

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Aluminum-Copper Alloys

Aluminum metal was selected as the primary interconnect material for ICs because of its low resistivity and its compatibility with silicon and the wafer fabrication process. However, aluminum suffers from a reliability problem known as *electromigration*. This is the movement of aluminum atoms in the conductor due to momentum transfer from the electrons carrying the current.[9] Under high current-density conditions, electrons collide with aluminum atoms, causing the atoms to gradually move. This movement of atoms leads to a depletion of atoms at the negative end of the conductor. In conductor regions where depletion occurs, this action leads to voids, thinning of lines, and a potential open circuit. In other regions of the conductor that have an accumulation of metal atoms, metal atoms pile up and form hillocks (see Figure 12.6).[10] *Hillocks* are protrusions on the surface of metal films due to electromigration. If excessive or large hillocks form, adjacent lines or lines on two levels can short together. With advanced circuitry designs in ULSI technology, there is increased current density and chip temperature, both of which make the aluminum chip metallization more prone to electromigration.

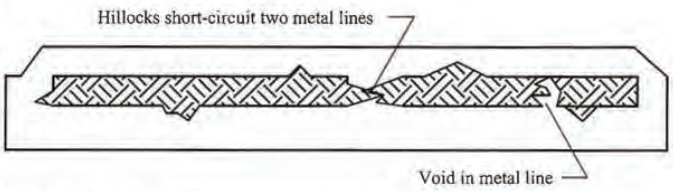

FIGURE 12.6 Hillock on a Metal Line

Electromigration in interconnects is controlled by alloying the aluminum with between 0.5 to 4% copper. This alloying essentially increases the conductor's current-carrying capacity by reducing the grain boundary diffusion effects in the aluminum. At the same time, it has been shown that values of copper in aluminum greater than 8% will actually increase electromigration.[11] The exact reason why the addition of copper reduces the chance of electromigration failure in Al-Cu alloys is not well understood.[12] If copper is alloyed with aluminum, more care must be given to plasma etching this alloyed aluminum (etching is discussed in Chapter 16). Copper is difficult to etch, and any residual copper remaining after etching the aluminum alloy interconnect can promote corrosion.[13] It is also possible to have electromigration in contacts and vias. Electromigration failure in contacts is resolved by the use of barrier metallization.

Electromigration is probably one of the most widely studied failure mechanisms of integrated circuits. Studies of this failure began in the 1950s with the development of the semiconductor and intensified in the late 1960s with the discovery of crack formation in the aluminum conductor leading to failures.[14] The significance of electromigration is that it usually occurs after the chip has been in service for an amount of time, which means that failure occurs catastrophically during customer usage.

Copper

A major transformation is underway in IC design and fabrication by means of the introduction of *copper interconnect* technology. Copper interconnects will replace aluminum metallization with copper to achieve significant benefits in chip performance. A legitimate question that someone may pose is why introduce copper if aluminum has performed so admirably over the years.

Need for Copper ■ The benefits for introducing copper for IC interconnect metallization are:[15]

1. **Reduction in resistivity.** The interconnect wiring resistivity reduces from 2.65 $\mu\Omega$-cm for aluminum to 1.678 $\mu\Omega$-cm at 20°C for copper, reducing RC signal delay and increasing chip speed.
2. **Reduction in power consumption.** Narrower lines consume less power.

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3. **Tighter packing density.** Narrower lines permit tighter circuitry packing, which means that fewer levels of metal are needed.
4. **Superior resistance to electromigration.** Copper does not have a concern for electromigration.
5. **Fewer process steps.** Potential for 20 to 30% fewer processing steps with damascene processing of copper.

As wafer fabrication design rules reduce to 0.15-μm linewidths and below, the increased packing density of devices on the chip permits more electrical signal speed from device to device (the transistors are closer; therefore, the signal has less distance to travel). This density leads to improved chip performance. However, this improved chip performance is only possible if the interconnect system between the devices is optimized. Narrower linewidths lead to increased line resistance. Tightly spaced conductor lines with a dielectric material between them act as capacitors, leading to a degradation in performance from an increase in resistance (R) and capacitance (C). This condition is the signal delay or interconnect delay discussed in Chapter 11. If either or both of these two parameters are reduced, then the signal delay reduces, leading to increased chip performance.

One possible method reducing interconnect resistance is to increase the conductor cross section. However, this contradicts the goal of increased packing density since wider conductors will take substantially more space. Smaller IC feature sizes are not achievable with larger linewidths. This is why the semiconductor industry is placing emphasis on copper—to lower the interconnect resistance, which lowers R and therefore the overall signal delay. The optimum improvement to RC signal delay is gained when resistance (R) is reduced and the capacitance (C) is lowered by using a low-*k* dielectric along with thinner barrier metals (see Table 12.2).[16]

TABLE 12.2 Change in Interconnect Delay Compared to 0.25-μm Device Generation

Technology	0.25 μm	0.18 μm	0.13 μm
Conventional Interconnect Technology:			
• Al/Cu interconnect alloy and TiN barrier metal	0	+21%	+93%
New Technology Introduced by Generation:			
• Reduced barrier thickness	−10%		
• Low-*k* (3.0) dielectric		−27%	
• Dual damascene Cu interconnect and plugs			−16%

Another benefit from the implementation of copper is that smaller linewidths can carry the same amount of current, permitting a tighter packing density on each metal level. This condition produces fewer overall levels of metal on a chip, leading to significantly reduced manufacturing costs.[17]

Copper is a relatively soft metal. It has superior resistance to electromigration, a common reliability problem with aluminum.[18] This means that chips fabricated with copper can handle higher electrical power densities, which permits the development of new product applications. Table 12.3 compares Cu and Al for different properties and processes common in wafer fabrication.[19]

TABLE 12.3 Comparison of Properties/Processes Between Al and Cu

Property/Process	Al	Cu
Resistivity (μΩ-cm)	2.65 (3.2 for Al—0.5% Cu)	1.678
Electromigration resistance	Low	High
Corrosion resistance (in air)	High	Low
Etch processing	Yes	No
CMP (chemical mechanical planarization) processing	Yes	Yes

Copper Challenges ■ There are three major challenges involved with using copper as semiconductor interconnects that distinguish it from traditional aluminum interconnects. These three challenges differ significantly from aluminum technology and must be resolved before the implementation of copper for IC interconnects:[20]

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1. Copper diffuses quickly into oxides and silicon. This is a concern if copper diffuses into the active region of the silicon (i.e., source/drain/gate region of the transistor) because it will damage the device by creating junction or oxide leakage.
2. Copper cannot be easily patterned using regular plasma etching techniques (see Chapter 16 for a discussion of etching). Copper dry etching does not produce a volatile by-product during the chemical reaction that is necessary for economical dry etching.
3. Copper oxidizes quickly in air at low temperatures (<200°C) and does not form a protective layer to stop further oxidation.

These challenges are addressed by converting to dual damascene processing with special barrier metals optimized for copper. Damascene processing eliminates the need to etch copper. Furthermore, tungsten plugs are expected to be used as the first level of metal to contact the source, drain, and gate regions.[21] This use of tungsten overcomes the concern of copper contaminating the silicon (referred to as copper poisoning). The tungsten may even be patterned for wiring of the local interconnect (LI). All other metal lines and vias for the multiple metal layers are expected to be copper.

Another major hindrance to converting to copper in semiconductor manufacturing is the natural reluctance to introducing new materials into production. New materials means there are new sources of contamination, new equipment and procedures, unpredictable results, and so on. Change always brings unforeseen problems that pose increased risks to the semiconductor manufacturer. However, these risks are balanced by the benefits from changing the interconnect material in order to improve IC performance.

Barrier Metals

A more effective way to make reliable ohmic contacts to shallow junctions without material diffusion or problems such as junction spiking is to use barrier metallization. A *barrier metal* is a thin layer of deposited metal or metals that is designed to prevent intermixing of the materials above and below the barrier (see Figure 12.7). The thickness of barrier metals has typically been around 100 nm for features sizes in the 0.25-μm generation, which is substantially thinner than the 400 to 600 nm thickness required for 0.35-μm generation of devices. Thickness of barrier metals is projected to decrease to 23 nm or less for the 0.18-μm technology node and beyond.[22]

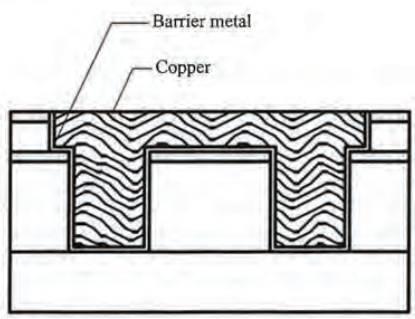

FIGURE 12.7 Barrier Layer for Copper Interconnect Structure

Barrier metals are widely used in semiconductor manufacturing. For contacts between the tungsten (W) plug that connects the aluminum interconnect wiring and the silicon source/drains, the barrier metal prevents the silicon and W from coming into contact with each other. This barrier prevents diffusion between the W and silicon and any junction spiking.

The essential properties of an acceptable barrier layer metal are:

1. Good diffusion barrier properties so that the diffusivity of the two interface materials (e.g., tungsten and silicon) is low at the sintering temperature (*sintering* refers to joining the materials by thermal means).
2. High electrical conductivity with low ohmic contact resistance.
3. Good adhesion between the semiconductor and the metal.

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4. Resistance to electromigration.
5. Stability when thin and at high temperature.
6. Resistance to corrosion and oxidation.

Metals commonly used for barrier metals are a class of high melting point metals known as *refractory metals*. Common refractory metals used in multilevel metallization for wafer fabrication are titanium (Ti), tungsten (W), tantalum (Ta), molybdenum (Mo), cobalt (Co), and platinum (Pt). Refractory metals have been used in wafer fabrication since the 1960s, such as in the formation of Schottky barrier diodes in bipolar processes. The benefits of using titanium as a barrier metal for aluminum alloy wiring are improved adhesion, reduced contact resistance, reduced stress, and controlled electromigration. To achieve good barrier properties, wafers undergo a clean step (referred to as *sputter etch* and explained in a later section) before deposition in the processing chamber to remove native oxides and oxide residues on the wafer.

Titanium tungsten (TiW) and titanium nitride (TiN) are two common barrier metal layers that inhibit diffusion between the silicon substrate and aluminum. TiN is widely used in ULSI manufacturing for its superior barrier performance in aluminum alloy interconnect processing. TiN functions as a barrier metal for both tungsten and aluminum. TiN is also widely used as an antireflective coating on aluminum to improve the photolithography patterning process (see Chapter 14). However, TiN does not produce good contact resistance to silicon. To resolve this problem, a thin layer of titanium (e.g., several hundred angstroms or less) is typically deposited before the TiN so that it can react with the underlying material as a silicide (see the following section for an explanation of silicide) and lower the contact resistance. The Ti and TiN are typically deposited in a cluster tool to keep oxides from forming between the two layers.

Copper Barrier Metals ■ Barrier metals are critical for copper metallurgy. Cu has high diffusivity in silicon and silicon dioxide, which will destroy device performance. Traditional barrier metals are not sufficient barriers for copper. Cu requires complete encapsulation by a thin-film barrier layer that functions as an adhesion promoter and effective diffusion barrier.[23] There is a trade-off between these two requirements since good adhesion requires some reaction with Cu, whereas a good barrier metal should not react with Cu. The special barrier metal requirements for copper are:[24]

1. Prevent copper diffusion.
2. Low film resistivity.
3. Good adhesion to both dielectric material and copper.
4. Compatible with chemical mechanical planarization (CMP).
5. Metal layer is continuous and conformal with good step coverage and deposition in high aspect ratio gaps.
6. Minimal thickness to allow the copper to occupy the maximum cross-sectional area.

For Cu interconnect metallurgy, tantalum (Ta), tantalum nitride (TaN), and tantalum silicon nitride (TaSiN) are candidate materials for barrier metals (see Figure 12.8). The diffusion barrier must remain thin (about 75 Å) so that it does not affect the resistivity of the high-aspect ratio plug while still acting as a barrier metal. This condition is difficult to maintain as geometries continue to shrink and metals are deposited into high-aspect ratio vias. Research has shown Ta has good barrier and adhesion properties for copper, whereas TiN, a traditional barrier metal for Al/SiO_2 interconnects, has good barrier properties but poorer adhesion.[25] If TaN is used, it is obtained by small amounts of nitrogen doping or by deposition with a tantalum nitride compound. Investigations have also shown tungsten nitride (WN) functions as an effective barrier for Cu metal.[26] There is ongoing research in the development of barrier metals for Cu metallurgy.

Copper barrier layers can be deposited by using high-density plasma CVD (HDPCVD) or ionized metal plasma physical vapor deposition. Ionized metal plasma PVD for tantalum achieves good step coverage. For deposition with high aspect ratio gaps, then HDPCVD barrier deposition is often the choice.[27]

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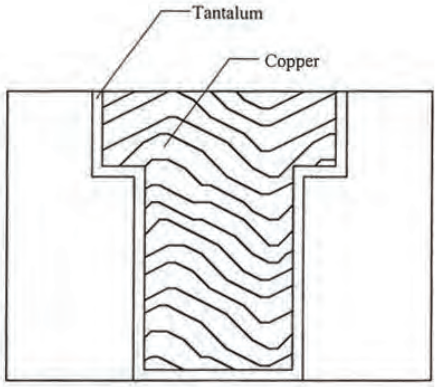

FIGURE 12.8 Ta for Copper Barrier Metal

Silicides

Refractory metals react with silicon when alloyed together to form a silicide. A *silicide* is a metal compound that is thermally stable and provides for low electrical resistivity at the silicon/refractory metal interface (see Figure 12.9). Refractory metal silicides are important in wafer fabrication because of the need to reduce the electrical resistance of the many silicon contacts in the source/drain and gate regions for chip performance. Titanium and cobalt are common refractory metal used for contacts in aluminum interconnect technology.

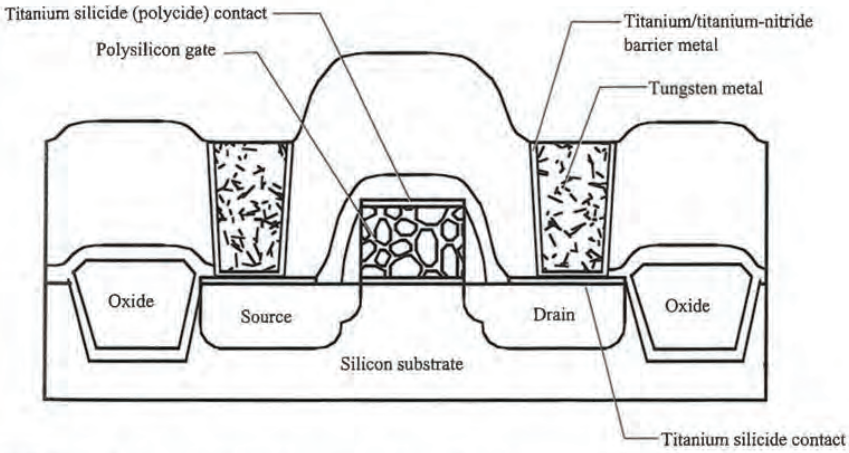

FIGURE 12.9 Refractory Metal Silicide at a Silicon Contact

If the refractory metal is reacted with polysilicon, it is called a *polycide* (see Figure 12.10 on page 310). Doped polysilicon is used as the gate electrode and has a relatively high resistivity (about 500 $\mu\Omega$-cm), which leads to an undesirable RC signal delay. A polycide is beneficial for reducing the series resistance of an interconnection to polysilicon. At the same time, it maintains polysilicon's good interfacial characteristics to oxides.

Silicides improve contact resistance by reducing residual oxides on the silicon surface during silicide formation. Silicides form extremely good metallurgic contact to the silicon, serving as a critical adhesion layer between the contact metal and the silicon junction regions. Many silicides are stable at temperatures exceeding 1000°C with a relatively high eutectic temperature. Table 12.4 on page 310 lists some properties of common silicides used in wafer fabrication.[28] Recall that the eutectic temperature is the lowest temperature where the alloy melts. It is undesirable for the silicide to melt because the liquid alloy can extend into the substrate material and cause junction spiking.

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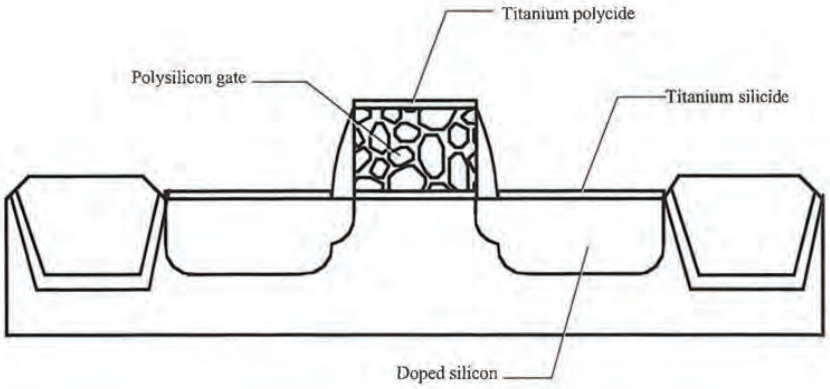

FIGURE 12.10 Polycide on Polysilicon

TABLE 12.4* Some Properties of Select Silicides

Silicide	Lowest Eutectic Temperature (°C)	Typical Forming Temperature* (°C)	Resistivity (μΩ-cm)
Cobalt/silicon ($CoSi_2$)	900	550–700	13–19
Molybdenum/silicon ($MoSi_2$)	1410	900–1100	40–70
Platinum/silicon (PtSi)	830	700–800	28–35
Tantalum/silicon ($TaSi_2$)	1385	900–1100	35–55
Titanium/silicon ($TiSi_2$)	1330	600–800	13–17
Tungsten/silicon (WSi_2)	1440	900–1100	31

* B. El-Kareh, *Fundamentals of Semiconductor Processing Technologies*, (Boston: Kluwer Academic Publishing 1995), p. 537.

Silicide formation typically requires the refractory metal be deposited on the silicon wafer, followed by a high temperature thermal anneal process to produce the silicide material. In areas where there is silicon, the metal reacts to form a silicide. In other areas on the wafer surface, such as where there is SiO_2, there is little or no silicide formation. Often this thermal anneal step uses a rapid thermal anneal (RTA) process in a multichamber cluster tool.

$TiSi_2$ has traditionally been the most common contact silicide for wafer fabrication, serving as the contact between the transistor active regions of silicon and the tungsten plug. It is often referred to as the glue that holds the tungsten to the silicon. Its beneficial properties are high temperature stability, compatibility with self-aligned contact processing (discussed in the following section), low resistivity when compared to other silicides, and its compatibility with TiN barrier metals.[29] $TiSi_2$ forms two different grain phases (a phase is a physically homogeneous material state) as it is annealed, a low-temperature C49 phase and a high-temperature C54 phase (see Figure 12.11). Both of these phases are $TiSi_2$.

The C49 phase of $TiSi_2$ forms at an anneal temperature of 625 to 675°C with a resistivity of 60 to 65 μΩ-cm. The C54 phase is formed in a second anneal following the C49 phase formation and requires a temperature of 800°C or more. It has a much lower resistivity of only 10 to 15 μΩ-cm, which is desirable to lower the overall contact resistance.[30]

However, at the time of this writing, $TiSi_2$ appears limited in its future use as a contact silicide in sub-0.25 μm technologies. Contacts for ultrashallow source/drain junctions are becoming thin. $TiSi_2$ is undesirable for thin contacts because the silicide resistivity increases.[31] It is also difficult to form this contact during the second anneal because of critical time at temperature requirements.

The silicide that appears promising for the 0.18 μm and below technology nodes is cobalt silicide ($CoSi_2$). This silicide maintains a reduced contact resistance of 13 to 19 μΩ-cm after its

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	Sintering Temperature	Resistivity
$TiSi_2$ – C49	625 – 675°C	60 – 65 μΩ-cm
$TiSi_2$ – C54	800°C	10 – 15 μΩ-cm

FIGURE 12.11 Anneal Phases of $TiSi_2$

anneal operation, even with deep submicron geometries of 0.18 μm and less. This reduced resistivity occurs because the grain size of $CoSi_2$ is about ten times smaller than the grain size of $TiSi_2$. Therefore, the low resistance phase is completely nucleated and grown during the thermal anneal operation. A $CoSi_2$ contact is also easier to form because of the smaller grain size.

Note that a silicide is not a barrier metal. In some silicides it is found that silicon diffuses rapidly through them. This diffusion occurs during heat treatment of the metal-silicide-silicon system where silicon diffuses through the silicide to the metal, which then reduces the integrity of the system. The solution to this problem is to place a metal barrier layer between the silicide and the metallization layer (discussed in the preceding section). A common silicide barrier film is titanium nitride (TiN), which is effective for both tungsten and aluminum. A tantalum-based barrier layer is anticipated for copper metallurgy.

Salicide ■ Because of the need to scale device sizes in VLSI and ULSI to optimize performance, the cross-sectional area of the source/drain (S/D) contact between the silicon and the first metal layer is small. This small size leads to increased resistance. A technique to decrease contact resistance at the source and drain areas by providing stable contact structures is referred to as a salicide. A *salicide* approach (taken from the expression *self-aligned silicide*) is used to create silicides that are properly aligned with the exposed silicon of the source, drain, and polysilicon gate. There are numerous chip performance issues that depend on salicide formation (see Figure 12.12).

The basic salicide steps are shown in Figure 12.13 on page 312. This process flow corresponds to Step 6 of the CMOS process flow described in Chapter 9. To form a salicide, oxide has been previously deposited and etched back with a dry plasma etch to leave oxide sidewall spacers

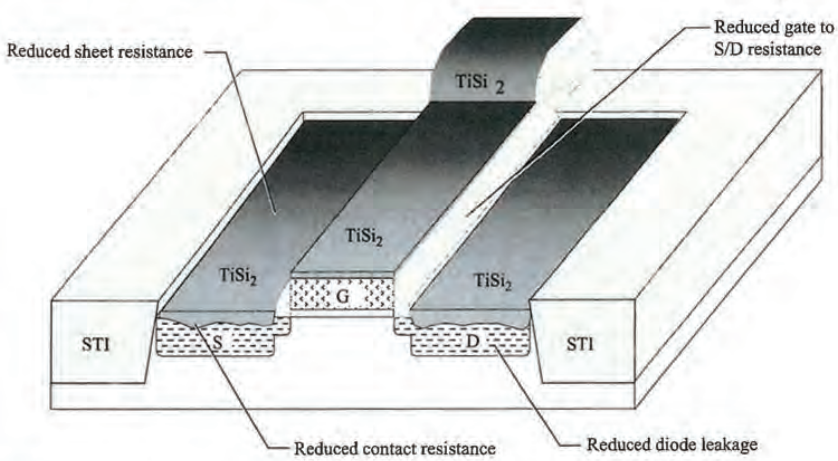

FIGURE 12.12 Chip Performance Issues Related to a Salicide Structure

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on the side of the polysilicon gate (Step 5 of the CMOS process flow described in Chapter 9). With the sidewall spacers, only the top poly surface of the gate is exposed. After an HF-dip clean step to remove native oxides, a 250 to 350 Å thin layer of titanium metal is deposited on the wafer. The refractory metal undergoes an RTP rapid anneal at 600 to 800°C to create the high-resistivity C49 titanium silicide phase wherever the refractory metal contacts silicon. The sidewall spacer keeps the S/D $TiSi_2$ from shorting out to the sides of the gate poly, while the oxide of the shallow trench isolation separates the devices. After the first RTP anneal, all unreacted titanium is removed by a wet chemical etch in ammonium hydroxide (NH_4OH) and hydrogen peroxide (H_2O_2). $TiSi_2$ remains and covers the S/D areas and top surface of the poly gate. A second RTP silicide anneal at 800 to 900°C creates the low-resistivity C54 metallic silicide. A major benefit of the salicide process is the avoidance of alignment tolerances that would occur if patterning were required to align the refractory metal on the silicon contact. Care must be taken during the anneal steps to avoid oxygen contamination in the furnace tube. Titanium reacts easily with oxygen to form undesirable titanium oxides. This oxide contamination can promote silicide formation on top of the oxide spacer regions, leading to a short between the polysilicon gate and source or drain.

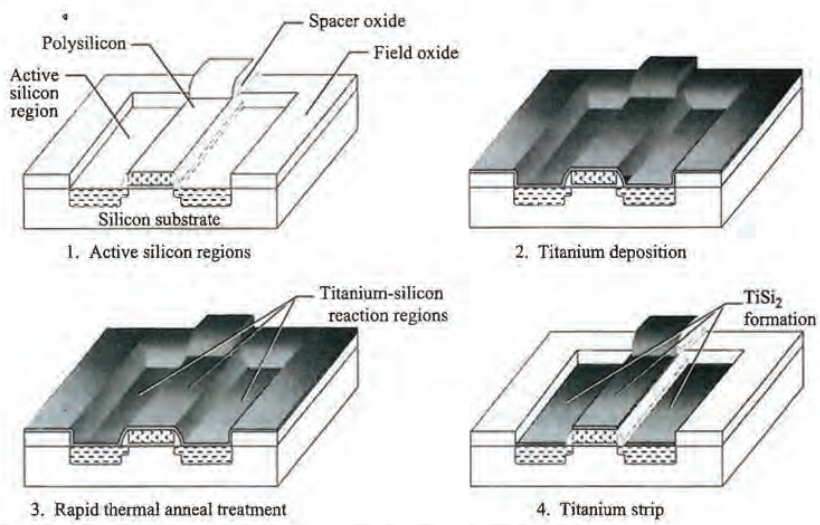

FIGURE 12.13 Formation of Self-Aligned Metal Silicide (Salicide)

Metal Plugs

Multilevel metallization creates the need for billions of vias filled with metal plugs to form electrical pathways between two metal layers. A contact plug is also used to connect the silicon devices in the wafer to the first level of metallization. The most common metal currently used for plugs is tungsten (W), which is why plugs are often referred to as *tungsten plugs* (see Figure 12.14). Tungsten has been traditionally used as a plug material because of its ability to uniformly fill the high-aspect ratio vias when deposited by chemical vapor deposition (CVD) methods. Tungsten is resistant to electromigration failure. It also serves as a barrier to inhibit diffusion and reaction between Si and the first metal layer. Tungsten is a refractory material with a melting point of 3,417°C and a bulk resistivity of 52.8 $\mu\Omega$-cm at 20°C.

Aluminum would be desirable as a plug material because of its lower resistivity (2.65 $\mu\Omega$-cm at 20°C), but sputtered aluminum cannot fill high-aspect ratio vias (see the next section for a description of sputtering). For this reason aluminum is used as the interconnect material and tungsten is limited to the plug. There has been recent interest in reflow aluminum plugs, where aluminum is sputter deposited into the via and then reflowed by a high-temperature anneal with a rapid thermal processor (RTP).[32]

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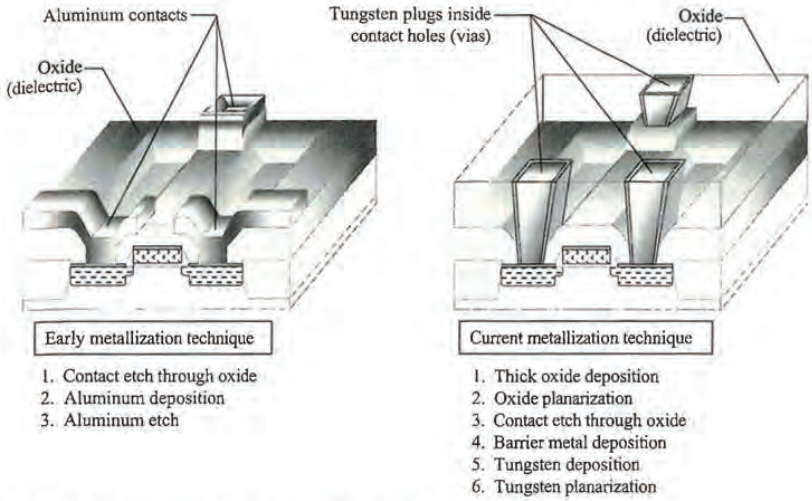

FIGURE 12.14 Tungsten Plug for Multilevel Metal Layers

METAL DEPOSITION SYSTEMS

The traditional metallization techniques used in semiconductor manufacturing fall under a category called *physical vapor deposition* (*PVD*). PVD has been done with filament evaporation, followed by electron beam evaporation and, most recently, sputtering. Chemical vapor deposition (CVD) has recently become a frequently used technique to deposit metal films. Each change in the deposition system has brought improved control of thin film properties and quality.

During the SSI and MSI eras of semiconductor manufacturing, evaporation was the method for metallization. It was replaced by sputtering primarily because evaporation has poor step coverage. Evaporation is still used in research applications and for semiconductors using III–V technologies. It is also used in some specialized areas, such as for C4 bump deposition during packaging (see Chapter 20).

Electroplating technology has been employed in various applications. In recent years it has been used for thin film head metallization in the disk drive industry. However, electroplating is just now being introduced for semiconductor manufacturing as a copper deposition method. It is the early deposition method of choice for creating copper interconnects.

The different metal deposition systems used in traditional and dual damascene metallization are:

- Evaporation
- Sputtering
- Metal CVD
- Copper electroplate

Evaporation

In the early days of semiconductor manufacturing, all metal layers were deposited by the PVD method of *evaporation*. Since the late 1970s, sputtering has replaced evaporation in most silicon wafer technologies in order to gain improved step coverage, gap fill, and yield. It is beneficial to review evaporation to understand how it functions and why the silicon industry changed to sputtering.

The process of evaporation consists of placing the material to be deposited in a crucible and heating it inside a vacuum chamber until it vaporizes (see Figure 12.15 on page 314). The most typical method of heating was the use of an electron beam to heat the metal placed in a crucible. By maintaining a high vacuum in the evaporator, the mean free path of the vapor molecules is increased, and the vapor travels in a straight line in the chamber until it strikes a surface and condenses to form a film.

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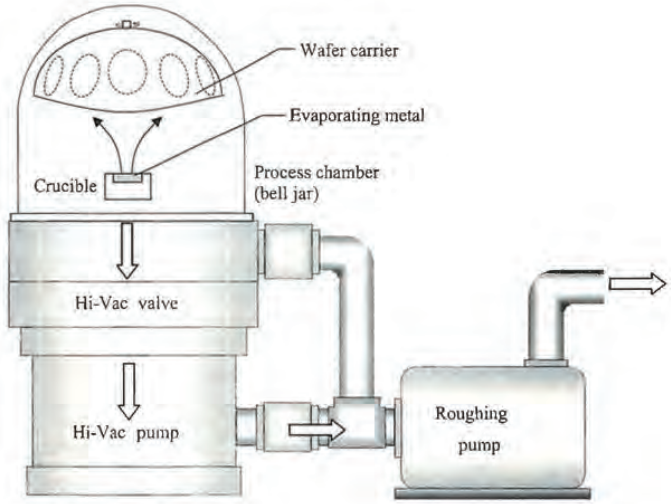

FIGURE 12.15 Simple Evaporator

The biggest drawback to evaporation was the inability to produce uniform step coverage. As the industry progressed to VLSI and ULSI technology, metallization needed to be capable of filling higher aspect ratio holes and producing conformal step coverage. Evaporators made some progress for step coverage by heating the wafers and rotating the wafers in the chamber with a hemispherical cage. However, evaporator technology is not able to form a continuous film over features with an aspect ratio greater than 1.0:1, and is marginal for an aspect ratio of 0.5:1 to 1.0:1. This drawback to evaporation led to its demise in IC production.

Another serious drawback of evaporation is its limitation for depositing alloys. The evaporator requires multiple crucibles for the different materials, which is a problem because of the different vapor pressures of the materials. This limitation makes it difficult to control the ultimate composition of the deposited alloy with any degree of accuracy.

Ultimately, the wafer fabrication industry quickly replaced evaporators with sputtering systems due to their improved step coverage capability. The evaporator is still used in research applications and for some compound semiconductor technologies that can actually use the poor step coverage of evaporators to their advantage during specialized processing. In addition, evaporators are still sometimes used in the chip packaging process to deposit solder bumps on the chip surface (see Chapter 20).

Sputtering

Sputtering, a form of physical vapor deposition (PVD), was discovered in 1852 by Sir William Robert Grove and developed as a thin film deposition technique in the 1920s by Langmuir.[33] As its name implies, sputtering is mainly a physical, rather than chemical, process. In the sputtering process, high-energy particles strike a solid slab of high-purity target material and physically dislodge atoms. These sputtered atoms migrate through a vacuum and eventually deposit on a wafer.

The advantages of sputtering are:[34]

1. Ability to deposit and maintain complex alloys.
2. Capability to deposit high-temperature and refractory metals.
3. Ability to deposit controlled, uniform films on large wafers (200 mm and larger).
4. Capability of multichamber cluster tools to clean the wafer surface for contamination and native oxides before depositing metal (referred to as *in situ sputter etch*).

While sputtering was a big improvement in gap fill over the earlier metallization method of evaporation, its limited capability for step coverage and filling high-aspect ratio gaps makes it insufficient for ULSI applications.[35] Over the years, improvements have been made to the sputtering

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process to obtain better step coverage, including recent advances with ionized metal plasma PVD. For critical applications, such as the step coverage in tungsten plugs, deposition will usually be done with a CVD metal process. Sputtering continues to be used for depositing critical barrier and seed layers, such as tantalum/tantalum nitride used in copper metallization (when the aspect ratio is reasonable).

Basic Sputtering Steps ■ There are six basic steps to sputtering:[36]

1. Positive argon ions are generated in a plasma in a high vacuum chamber and accelerated toward a target material at a negative potential.
2. During acceleration, the ions gain momentum and strike the target.
3. The ions physically dislodge (sputter) atoms from the target, which has the desired material composition.
4. The dislodged (sputtered) atoms migrate to the wafer surface.
5. The sputtered atoms condense and form a thin film on the wafer surface with essentially the same material composition as the target, following the stages for thin film growth outlined in Chapter 11.
6. Excess material is removed from the chamber by vacuum pump.

To illustrate sputtering, Figure 12.16 shows the basic configuration of a simple, DC diode sputter deposition chamber with parallel plates. It consists of the solid *target* material, a substrate (wafer), and a vacuum enclosure. The target is electrically grounded and referred to as the *cathode*, while the substrate has a positive potential and is termed the *anode*. The anode and cathode are both called *electrodes*. The sputtering target is composed of the necessary material for deposition. Targets are manufactured to achieve a homogeneous composition, fine grain size, and specific crystallographic orientation, all of which contribute to achieving a uniform film deposition rate across the wafer.[37] Target purity levels of 99.999% (5 nines) or better are required for achieving acceptable film purity for sub-0.25 μm geometries.

A high density of positive ions from an argon gas glow discharge is strongly attracted to the negative target material, striking it at high velocity and dislodging the atoms to be deposited. The atoms are sputtered (knocked off) from the target material and scatter in the chamber; eventually some come to rest on the wafer or the chamber walls. This action necessitates cleaning of the chamber in some systems. The atoms on the wafer nucleate and grow a thin film. An important aspect of sputtering is that this process can be used to sputter-deposit alloys, in particular aluminum-silicon

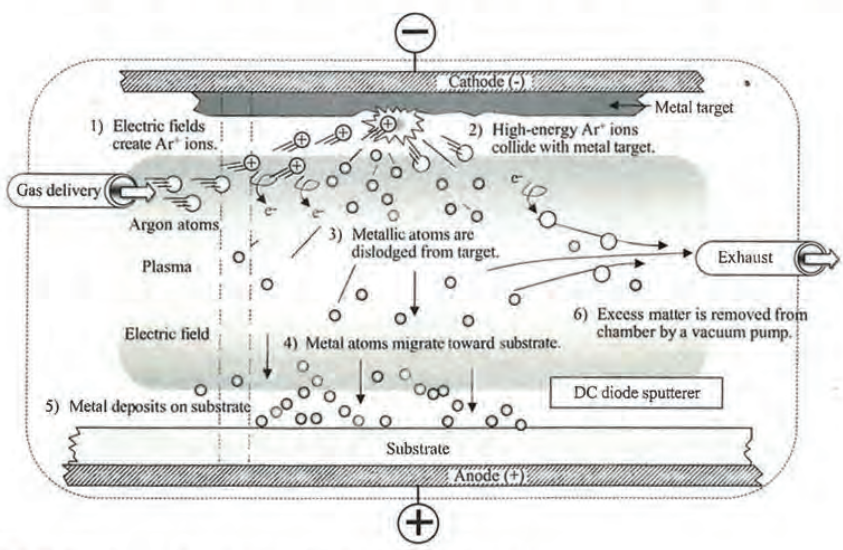

FIGURE 12.16 Simple Parallel Plate DC Diode Sputtering System

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and aluminum-copper alloys. For instance, if the target material is aluminum with 1% copper, then the deposited film will be aluminum with 1% copper (at steady-state conditions).

The latest technology of sputtering equipment systems are multichamber cluster tools. The system has a loadlock that moves single wafers from the wafer cassette to its ultimate base vacuum pressure. The loadlock may consist of dual loadlocks to move the wafer through a staged vacuum sequence from ambient atmosphere to base vacuum pressure. A robot transfer system designed specifically for the cluster tool environment moves wafers from the various process chambers and a buffer chamber. It is important that the robot operate without generating particles and be extremely reliable. Cluster tool robots are often magnetically coupled, which permits the robot drive motor to remain on the outside of the process chambers to reduce particles.

Vacuum conditions are important in the sputtering chamber to create the plasma and maintain purity of the deposited films, with base vacuum typically at 10^{-7} torr during initial pump down. The rate that argon gas enters the process chamber is critical because it causes the pressure to rise in the chamber. With the argon and sputtered material in the chamber, the pressure rises to about 10^{-3} torr. The hot, high-vacuum environment of the process chamber promotes the formation of the sputtered atoms into thin films on the wafer surface.

Physics of Sputtering ■ An essential aspect of sputtering is the formation of the ionized argon gas into a plasma (see Chapter 8). Argon is used as the sputtering ion species because it is relatively heavy and is a chemically inert gas, which keeps it from reacting with the growing film or the target. If a high-energy electron strikes the neutral argon, the collision knocks off outer electrons and creates a positively charged argon ion. This energetic particle is used to strike the negatively charged target material to be sputtered.

Sputtering Mechanism. Positively charged argon ions in the plasma are strongly attracted to the negative potential of the cathode target. The charged ions accelerate and acquire kinetic energy (or energy of motion) as they pass through the voltage drop of the glow-discharge dark space (see Chapter 8 for a description of glow discharge). When the Ar ions strike the target surface, the momentum of the Ar ion transfers to the target material to dislodge one or more atoms. This action is referred to as *momentum transfer.* The ejected neutral atom or atoms move through the plasma (with a small chance of being ionized) and land on the wafer. The incident ion energy must be large enough to dislodge target atoms but not so large that the ion penetrates into the target material. Typical sputtering ion energies range from 500 to 5,000 eV.

An analogy for dislodging metal atoms from the surface of the target material during sputtering is hitting billiard balls in a pool game. Even though the cue ball in pool is travelling in one direction, the billiard balls can be knocked in some other direction. This same effect occurs in sputtering, where the argon ion impacts the target and dislodges one or more atoms from the surface of the target (see Figure 12.17).

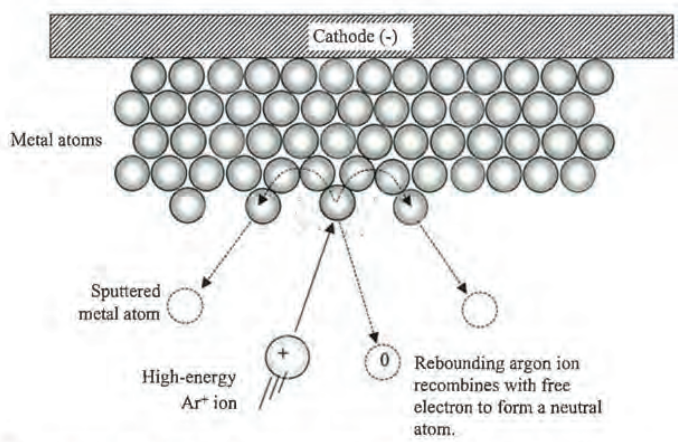

FIGURE 12.17 Dislodging Metal Atoms from Surface of Sputtering Target

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The *sputtering yield* is defined as the number of atoms ejected by the target (cathode) per incident ion that strikes it. The yield largely determines the rate of sputter deposition. It varies from about 0.5 to 1.5. A sputter yield of 0.5 means that, on the average, two ions must strike the target for one atom to be ejected. The sputter yield depends on the following conditions:[38]

1. Incident angle of the bombarding ions.
2. Composition and geometry of the target material.
3. Mass of bombarding ions.
4. Energy of the bombarding ions.

A method of increasing the sputtering deposition rate is to confine the plasma to the region between the target and wafers. Due to the ionization process, there are dark spaces just to the front and the sides of the target. Dark space shields are placed on the sides of the target to prevent target material from being sputtered on the sides, since this material will never deposit on the wafers. Shields require periodic changing because sputtered target material builds up on the surface and causes particulate contamination.

Targets undergo erosion from the ion bombardment and are replaced when about 50% or more of the target material is removed.[39] Much of the energy consumed during the sputtering process is dissipated as heat in the target, or by emission of secondary electrons and photons by the target. For this reason, cooling of the target material is done to maintain a low target temperature.

In addition to being struck by the sputtered atoms, the substrate has other species landing on it (see Figure 12.18). These species cause heating of the substrate (up to 350°C) which leads to uneven film deposition. The high temperature can also create an undesirable aluminum oxide during aluminum deposition, which interferes with the sputtering process. The many species impinging on the wafer surface during diode sputtering also increase the possibility of damage due to radiation to sensitive devices.

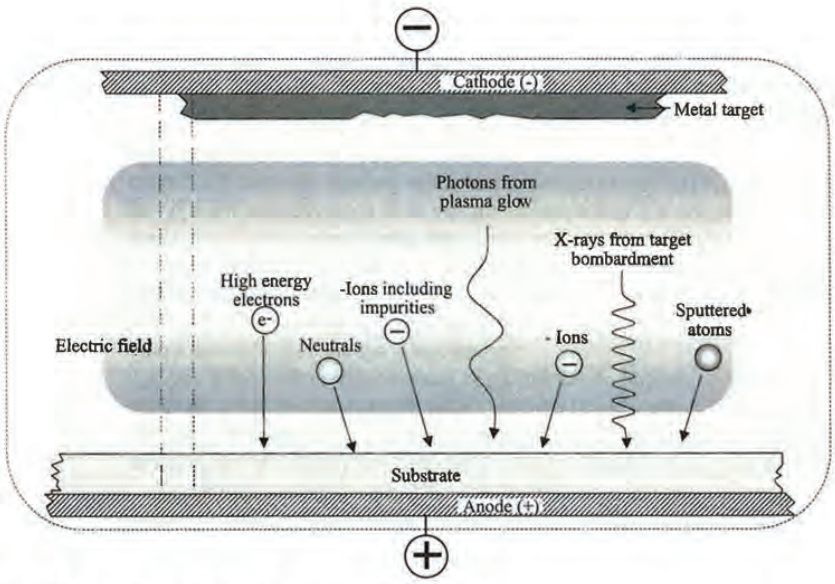

FIGURE 12.18 Different Species Landing on Substrate

Note the presence of the impurity gas atoms during diode sputtering. This is a problem if the impurity atoms are incorporated into the growing film on the substrate. The sources of contaminants are: (1) impure sputtering gas, (2) outgassing from the wafer holder, (3) outgassing from chamber walls, and (4) vacuum leaks.[40] It is necessary to use ultrahigh purity (UHP) sputter gases and to verify there are no chamber leaks.

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The spacing between the cathode and anode must be optimized for each sputtering system. The goal is to have as many sputtered atoms as possible be deposited on the wafers and form the desired film.

The sputtering system described thus far is a simple DC diode system that has a DC voltage applied between two electrodes (cathode and anode). The DC diode sputtering system has serious drawbacks that limit its use in manufacturing. A DC diode type sputtering system cannot be used to sputter dielectrics because the electrodes become coated with the dielectric and the glow discharge cannot be sustained. The target rapidly builds up a positive charge, which repels incoming positive ions. DC diode type sputtering is also not capable of performing a sputter etch. *Sputter etch* (or *reverse sputter*) is a preclean step where the sputter process is reversed and argon atoms are used to remove thin native-oxide layers and remaining etch residues that contaminate contacts and vias. In other words, the wafer is sputtered instead of the target. This sputter etch preclean is important in multichamber cluster tools because of the benefit of cleaning followed by deposition without removing the wafer from the vacuum environment.

Three types of sputtering systems are covered in the following pages:

- RF (radio frequency)
- Magnetron
- IMP (ionized metal plasma)

The simple RF sputter system is not used in wafer fabrication because of its inherent inefficiency. The magnetron has traditionally been the most widely used sputter system, and ionized metal plasma (IMP) is becoming more common for sub-0.25 micron technology.

RF Sputtering ■ In an *RF sputtering* system, an RF field is used to create the plasma instead of the DC field described above. The RF frequency has commonly been 13.56 MHz. It is applied to the back surface of the target electrode and capacitively coupled to its front surface (see Figure 12.19). Both the electrons and ions in the plasma are exposed to the RF field, but due to the high frequency, the electrons respond most strongly. The chamber and electrode behave like a diode, creating a high amount of electron flow and resulting in a negative charge on the target electrode. This negative charge (produced by a self-bias) attracts positive argon ions, which sputter material from the insulator or non-insulator target.[41]

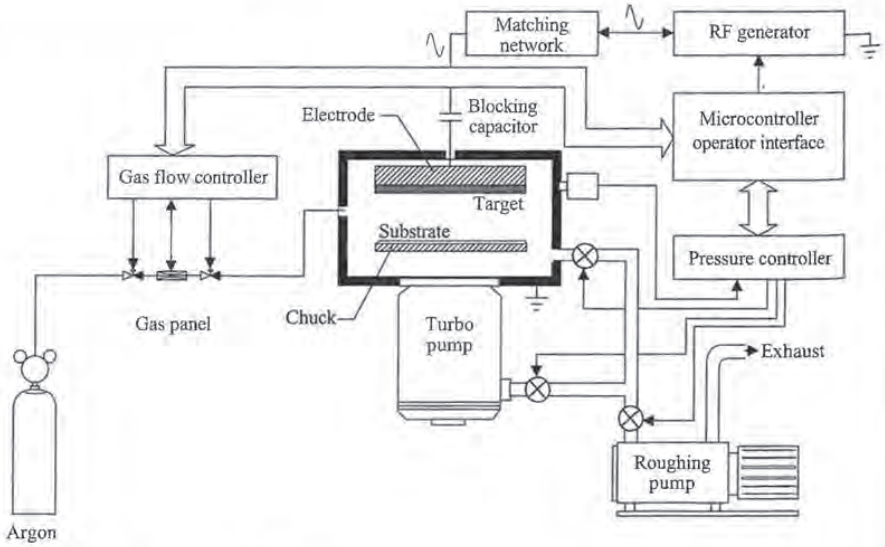

FIGURE 12.19 RF Sputtering System

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The wafer can be electrically biased to put it at a different field potential than the argon. The bias applied to the wafer causes the argon atoms to strike the wafer directly. This RF biasing permits the exposed wafer surface to be sputter etched and cleaned.

In practice, an RF sputtering system is limited because it does not have a high sputtering yield, leading to a low deposition rate. Many of the secondary electrons emitted by the target pass through the discharge region without contributing to the creation of plasma. The sputtering rate of the target would be much higher if these secondary electrons were involved in ion collisions, leading to the creation of more ions to bombard the target. To overcome this inefficiency and to achieve high metal deposition rates necessary for wafer fabrication, the concept of magnetron sputtering was developed.

Magnetron Sputtering ■ *Magnetron sputtering* employs magnets configured around and behind the target to capture and restrict the electrons in front of the target (see Figure 12.20). This setup increases the ion bombardment rate on the target in order to produce more secondary electrons, which then increases the ionization rate in the plasma. The end result is that more ions cause more sputtering of the target, which increases the deposition rate of the system. The invention of magnetron sputtering to improve the deposition rate is one of the main reasons why sputtering has become the leading process for single-wafer deposition systems for aluminum and contact alloys used in metallization.

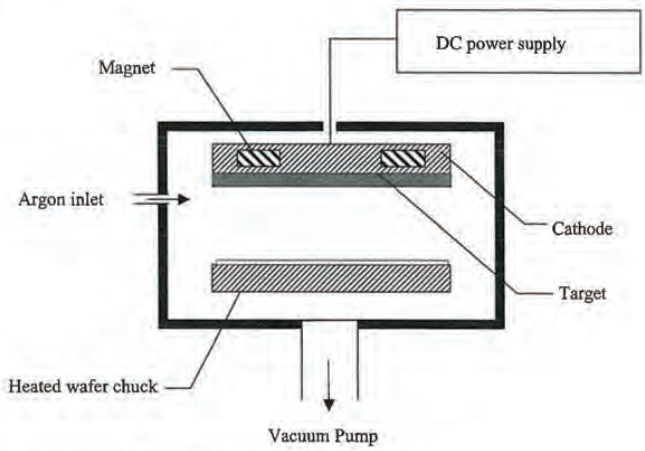

FIGURE 12.20 Magnetron Sputtering

The magnetron sputtering design requires a substantial amount of power supplied to the argon plasma to maximize the sputtering rate (about 3kW to 20 kW of power). Because the sputtering target absorbs most of this power and is in contact with the cathode, cooling of the cathode is required. An important challenge is uniformity of the sputtered deposit on large wafers. To achieve high deposition rates and film uniformity in single-wafer cluster tools, new cathodes have been developed with rotating, rare earth, high-strength permanent magnets.[42]

Step Coverage. Sputtering requires a vacuum environment with high-purity argon to avoid contamination from residual gas. The vacuum during the sputtering process is around 1 mtorr, with a mean free path of several centimeters. This is approximately the distance between the target and wafer. Because of this distance, atoms dislodged from the target essentially pass on to the wafer by following a line-of-sight path.

This line-of-sight path for the ejected atoms exiting at many different angles from the target causes poor coverage on steps and sidewalls in contacts and vias. Due to their geometry, the sidewalls and bottoms of high-aspect ratio contact windows and vias will receive only 10% or less of the metal deposited on the top surface.[43] For this reason PVD is not usually chosen when depositing a material on high aspect ratio steps and trenches.

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Collimated Sputtering. To achieve increased coverage on the bottom and side of a contact or via, directional enhancement can be achieved by the use of *collimated sputtering* (see Figure 12.21). The collimator is configured so that it appears as the electrical ground for the plasma. In this manner, any neutral species sputtered from the target at a high angle is intercepted and deposited on the collimator. Other atoms that are ejected straight back from the target will pass by the collimator and deposit on the bottom of the contact hole. At the same time, a collimator reduces sidewall coverage in the contact or via.

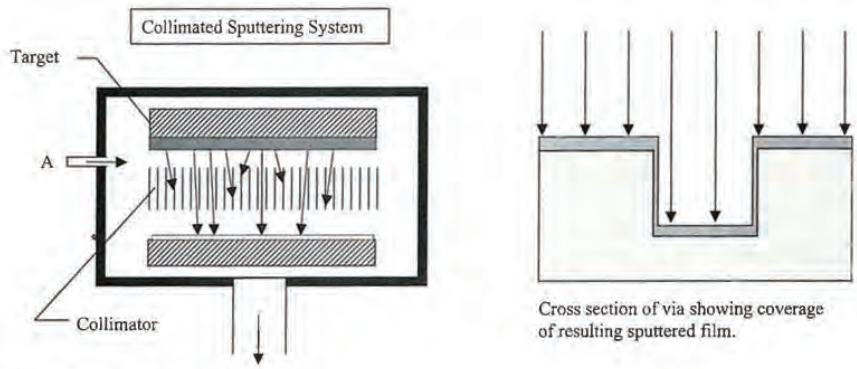

FIGURE 12.21 Collimated Sputtering

The use of a collimator means that a large portion of the sputtered material will not reach the wafer, since most of the sputtered material ends up on the collimator. This result lowers the sputter yield and increases the cost of deposition, since fewer sputtered atoms reach the wafer. At the same time, maintenance costs increase because the target is less efficient. Given these problems, it is more efficient to use ionized metal plasma (IMP) or CVD deposition over magnetron sputtering if step coverage is a critical factor.

Ionized Metal Plasma (IMP) ■ A problem for sputtering technology in wafer fabrication for high performance ICs is that as feature sizes shrink, the capability to sputter into high aspect ratio vias and narrow trenches becomes limited. A recent development in PVD to overcome this problem is *ionized metal plasma PVD (IMP* or *ionized PVD),* which was introduced in the mid-1990s. In this approach, the sputtered metal is ionized in an RF plasma at a pressure of 20 to 40 mtorr (see Figure 12.22). The positive metal ions then travel in a highly directional, vertical path toward a wafer configured with a negative voltage bias. This voltage bias can also be used to control the energy of the incoming metal ions, which helps reduce damage to the surface of the wafer.[44] Biasing the wafer enables a higher degree of film conformality in the bottom and corners of high aspect ratio gaps.

Ionized PVD achieves good hole-fill for Ti and TiN on structures with 0.25-micron contacts and vias and 6:1 aspect ratios, with 70% bottom coverage, 10% sidewall coverage, and excellent sidewall integrity. This coverage is critical in the bottom, bottom corner, and lower sidewall areas of holes with a typical 85° sidewall angle.

Ionized PVD is used in production to deposit titanium and titanium nitride barrier films for devices at the 0.25 μm and below generations with high-aspect ratio contact and via structures.[45] It is also capable of depositing tantalum, tantalum nitride, and copper, which are important metals for copper metallization. The development of ionized PVD has further improved sputtering to extend its usefulness in high-aspect ratio gap fill.

Metal CVD

The use of chemical vapor deposition (CVD) for metal deposition is increasing because of its superior conformal step coverage and void-free filling of high-aspect ratio contacts and vias. These factors are critical for wafer fabrication as feature sizes decrease to the 0.15-μm generation and

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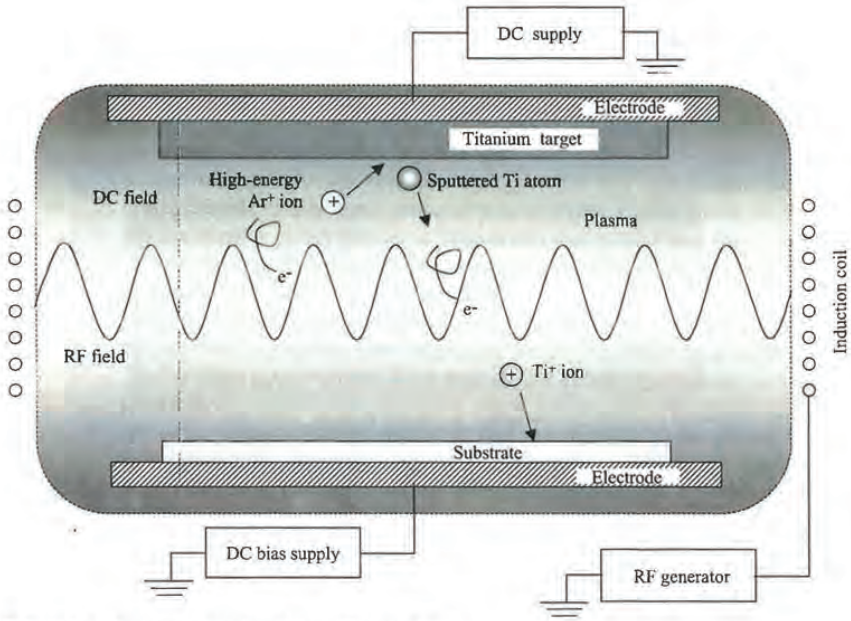

FIGURE 12.22 Concept of Ionized Metal Plasma PVD

beyond. The projected aspect ratio for vias in DRAM memory is projected to be 7:1 for the 0.15-μm generation, and 2.4:1 for logic.[46]

Tungsten CVD ■ *Tungsten (W) CVD* is used in multilevel interconnection technology as the process to deposit the via plug and to act as the contact plug between the first metal layer and the silicide contact. Tungsten CVD is also used as the local interconnect (LI) because of its low resistivity. Tungsten has performed reliably, with billions of W CVD plugs used on one microchip. However, its usefulness as a vertical interconnect may be limited with the introduction of the new damascene copper metallization scheme.

Tungsten CVD is common as a plug material due to:

1. Excellent step coverage and gap-fill, particularly in high-aspect ratio vias.
2. High electromigration resistance.

Low-pressure CVD (LPCVD) is the usual method for depositing W plugs, along with plasma-enhanced CVD (PECVD). Reactors are both hot- and cold-wall and configured as batch or multichamber cluster tools. The most common source gas for W is WF_6.[47] Sputtering costs less to operate than CVD for W deposition but has traditionally poorer directional control. This coverage produces nonuniform tungsten deposition quality in vias, which is why CVD has been the preferred method. This may change with the recent development of ionized PVD.

Tungsten CVD is typically deposited in blanket films. Blanket deposition deposits tungsten nonselectively on the entire wafer surface, including the via pathways, and is the most common approach.

Blanket Tungsten CVD Deposition. Blanket tungsten deposition followed by chemical mechanical planarization (CMP) is the common method used to fill vias to connect between metal layers. As always in CVD, the properties of the film deposited with CVD depend on the chemical reactions that occur at the wafer's surface. For blanket tungsten CVD, the most frequently used reaction is the reduction of tungsten hexafluoride (WF_6) by hydrogen to produce tungsten and hydrogen fluoride:

$$\underset{\textit{tungsten hexafluoride}}{WF_6\,(gas)} + \underset{\textit{hydrogen}}{3H_2\,(gas)} \rightarrow \underset{\textit{tungsten}}{W\,(solid)} + \underset{\textit{hydrogen fluoride}}{6HF\,(gas)}$$

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PVD Cluster Tool
(Photo courtesy of Applied Materials, Inc.)

Typically the first step in blanket tungsten CVD is to deposit a titanium/titanium nitride (Ti/TiN) barrier layer (see Figure 12.23). The Ti is deposited before TiN to react with the underlying material and lower the contact resistance. If this is a contact in the first interlayer dielectric (ILD-1), then Ti reacts with silicon to form $TiSi_2$ silicide. The TiN functions as a barrier metal and adhesion promoter (glue layer) for tungsten. It needs a minimum bottom thickness of about 50 Å with continuous sidewall coverage to be an effective barrier metal and keep the tungsten from attacking underlying layers.[48] The Ti/TiN barrier layer may be deposited by IMP PVD. The TiN barrier metal may also be deposited either by CVD using ammonia and one of a number of precursor molecules, including the tetrakis dimethylamino titanium (TDMAT) or tetrakis diethylamino titanium (TDEAT). CVD has usually been preferred for TiN because of improved step coverage.

It is necessary to remove the excess blanket tungsten above the dielectric layer. This was previously done by a tungsten etchback process to remove the excess tungsten and leave a planarized plug. In 0.25-μm device generations and below, planarization of tungsten by chemical mechanical planarization (CMP) is the preferred process (CMP and etchback are addressed in Chapter 18).[49] Barrier metals such as TiN and Ti are used to prevent diffusion between the tungsten and the silicon.

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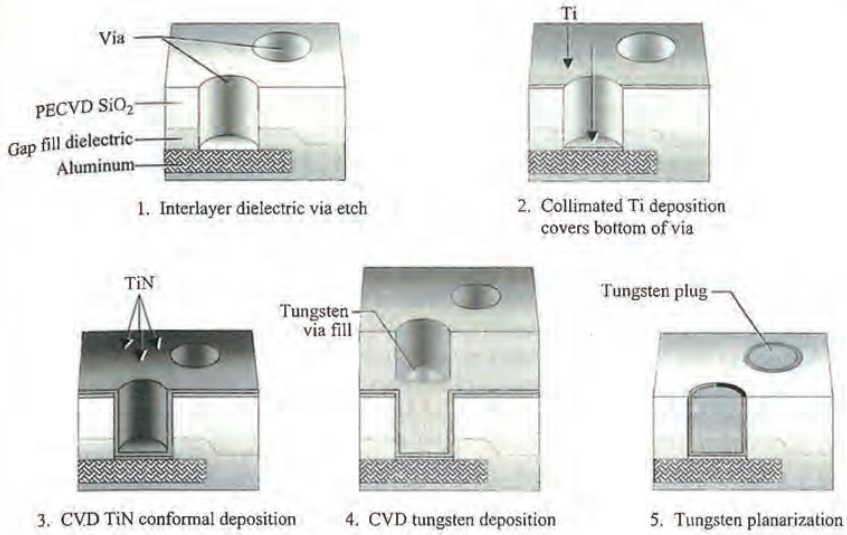

FIGURE 12.23 Blanket Tungsten CVD with Ti/TiN Barrier Metal

Copper CVD ■ *Copper (Cu) CVD* is a potential process for depositing a thin copper seed layer necessary for copper electroplating. The seed layer, or strike layer, is thin (about 500 to 1000 Å) and deposited on top of a diffusion barrier (most likely a Ta-based barrier metal). For successful electroplating, it is critical that this seed layer be continuous and free of pinholes and voids along the feature sidewalls and bottom. If a seed layer is not continuous, this can create a void in the electroplated copper. The excellent conformality of CVD is why this process has been investigated for the seed layer.

Cu Precursors. There are two precursors for CVD Cu, Cu(I), and Cu(II). Note that Cu(I) indicates a copper ion with a +1 positive charge and Cu(II) indicates a +2 positive charge. The most widely used Cu(I) precursor is Cu(hfac)(TMVS), chemical name trimethylvinylsilylhexafluoroacetylacetonate copper (I), chemical formula $C_{10}H_{13}CuF_6O_2Si$, and referred to by its trade name of CurpraSelect.[50] This molecule combines copper in a +1 oxidation state with TMVS and hfac ligands to make a clear yellow, liquid precursor (a ligand is a molecule or ion surrounding a central metal cation). TMVS is flammable, but the compound Cu(hfac)(TMVS) does not ignite easily. Cu(hfac)(TMVS) is compatible with industrial stainless steel delivery vessels. The CVD deposition proceeds by reducing a copper atom to metal while oxidizing another atom to $Cu(hfac)_2$ and releasing free TMVS as by-products. The chemical reaction is:

$$2Cu^{+1}(hfac)TMVS\ (gas) \rightarrow Cu^0\ (solid) + Cu^{+2}(hfac)_2\ (gas) + 2TMVS\ (gas)$$

The most common Cu(II) precursor is $Cu(hfac)_2$. For example, the Cu(II) reaction can proceed by reduction in H_2:

$$Cu(hfac)_2\ (gas) + H_2\ (gas) \rightarrow Cu^0\ (solid) + 2H(hfac)\ (gas)$$

Copper Electroplate

The transformation of IC fabrication to copper metallization is underway for all chip manufacturers. Initially, high-performance microprocessors and fast, static RAMs are being converted to copper technology. *Copper electroplate,* also known as *electroplating, electrochemical deposition (ECD),* or *electrofill,* is the first-generation deposition method to be used for copper metallization. Cost and performance will be important issues that affect when copper will replace aluminum as the mainstream interconnect metallization. Electroplating has not traditionally been used in semiconductor manufacturing. However, it has been an important metallization process in other areas of electronic manufacturing, such as thin film heads used in disk storage devices and copper wiring for printed circuit boards. Therefore, its process and equipment requirements are well understood.

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Copper Electroplating Tool (Photo courtesy of Novellus)

Electroplating Fundamentals ■ The basic principle of electroplating copper metal is to immerse a wafer with a conductive surface into a solution of copper sulfate ($Cu(SO_4)$) which contains copper ions to be deposited (see Figure 12.24). The wafer and its seed layer are connected electrically to an external power supply as a negatively charged plate, or cathode. A solid piece of copper is immersed in the solution and configured as the positively charged anode. Electrical current passes through the wafer, into the solution, and through the copper anode.[51] When current flows, the following reduction reaction occurs at the wafer surface to deposit copper metal:

$$Cu^{2+} + 2e^- \rightarrow Cu^0$$

Copper ions *Electrons* *Copper metal*

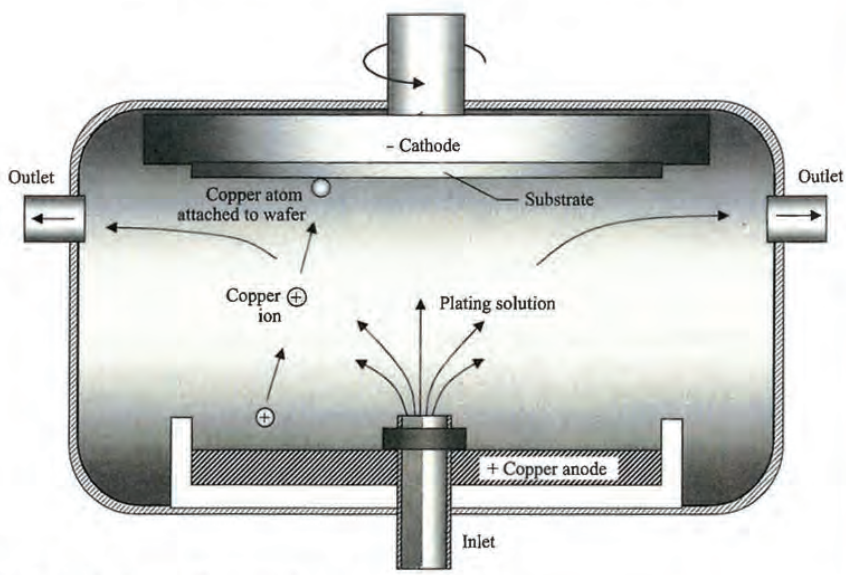

FIGURE 12.24 Copper Electroplating

Metal copper ions on the cathode wafer surface are reduced to metal copper atoms during electroplating. At the same time, an oxidation reaction occurs at the copper anode that balances the current flow in the cathode. This reaction maintains electrical neutrality in the solution.

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The quantity of copper deposited is directly proportional to the current delivered to the conductive wafer surface (Faraday's law of electrolysis).[52] With this relationship, the basic parameters to control in electroplating are current and time. With no current flow, there is an equilibrium potential among the anode, cathode, and solution. When an external power source applies a voltage, a current flows between the anode and cathode and metal is deposited on the cathode proportional to the amount of current.

In practice, electroplating is complicated to control, especially the electroplating solution and how the current is applied. Given the high-aspect ratio holes and trenches that must be filled on high-performance ICs, electroplating is challenged to maintain a uniform current density in the holes. This condition is important because the plating rate is a direct function of current density. If there is a high current density at the top of the hole and a lower current density at the bottom of the hole, then copper will plate faster at the top.

Different types of voltage waveforms applied to the cathode/anode system can assist in plating high-aspect ratio holes. For instance, by applying an oscillating electric field and controlling the amplitude of the waveform, a deposit/etch (referred to as dep/etch) sequence is obtained. In this manner, the copper can be slightly removed (etched) in the high-density current regions to balance the copper gap-fill capability.

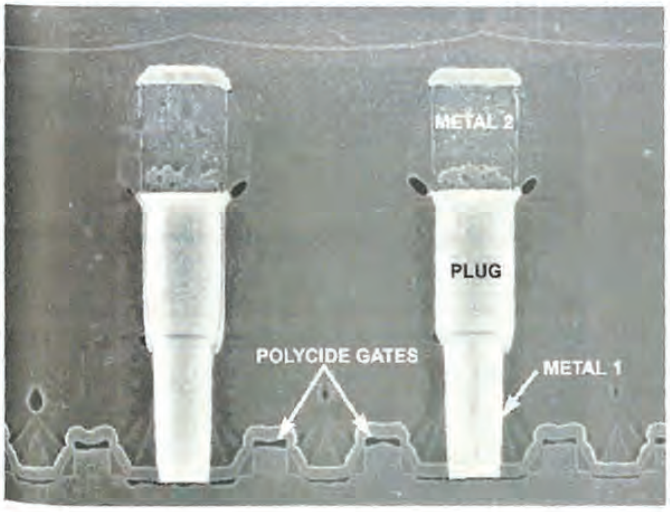
Because the copper electroplating metallization is a new process for semiconductor manufacturing, there are a host of other issues to address. For instance, it is important that no copper plate on the backside of the wafer. Electroplating also poses concerns for chemical control and disposal. It does simplify the metallization process somewhat by avoiding a high vacuum or complex heating of the wafer.

METALLIZATION SCHEMES

The strategy for metal interconnects for IC fabrication is undergoing dramatic change. After many years of development activities, copper is being implemented as the main chip interconnect conductor for a wide range of ICs.[53] Either aluminum or copper metallization is expected to be used for chip applications during a transition period until copper is fully implemented. The type of metallization scheme used depends on how the chip design is optimized for performance and price.

Traditional Aluminum Structure

The traditional interconnect metal has been an aluminum-copper alloy with an interlayer dielectric of SiO_2 to insulate between the metal layers. The process steps for the traditional aluminum



Blanket Aluminum Etch (Micrograph courtesy of Integrated Circuit Engineering)

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interconnect technology for an ILD-2 and metal-2 (one complete level) are described in Steps 11 and 12 of the process flow described in Chapter 9. This traditional process can be viewed as an *aluminum subtractive process* because the aluminum is deposited as a blanket film and then etched away (subtracted) to form the circuitry. The critical step that defines the width and spacing of the aluminum interconnect lines is metal etch, while SiO_2 is deposited into the narrow gaps between the lines.

New materials and processes are being rapidly introduced into advanced wafer fabs to support the 0.18-μm technology node with traditional aluminum alloy metallization. This is a transitional period until copper metallization is eventually implemented. As a rule, most fabs will change only one major microchip material at a time (e.g., metal or insulator) to minimize the inherent risk to production. With these new fabrication materials and their stringent processing requirements, the general trend is for increased use of high-density plasma CVD (HDPCVD) for dielectrics, a shift from sputtered metals to metal CVD, and increased use of chemical mechanical planarization (CMP). The goals are to increase product performance and manufacturing productivity.

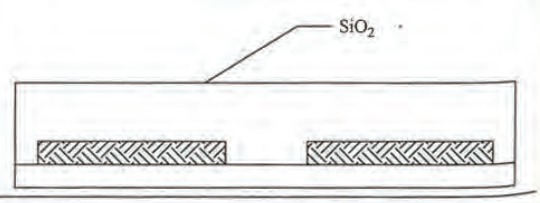
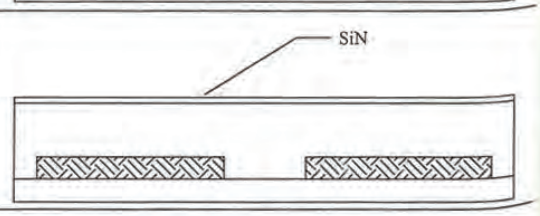
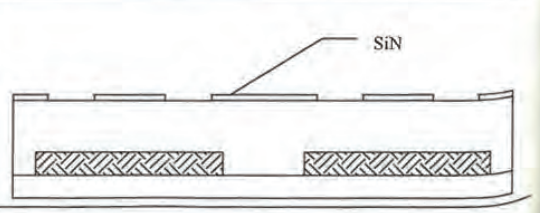
Copper Damascene Structure

The semiconductor industry is implementing copper as the interconnect material for microchip fabrication. The traditional process flow will not be used for copper metallurgy because copper is not suitable for dry-etching. Copper also has special requirements to minimize its diffusion into silicon. To form copper interconnect wiring, a dual-damascene process is used to avoid copper etching. In the damascene process, it is no longer metal etch that defines the critical line width and spacing, but rather dielectric etch.

Dual Damascene Process ■ Since copper is difficult to etch, early developers of copper technology were forced to consider alternative approaches to creating metal lines. The *dual-damascene process* became the consensus process for copper metallurgy. It creates both the vias and lines for each metal layer by etching holes and trenches in the ILD, depositing copper in the etched features and using chemical mechanical planarization to remove the excess copper (referred to as *copper overburden*).

There are many possible scenarios for a dual-damascene process flow. Table 12.5 explains a basic process flow with the essential technologies that may or may not include all the steps performed by a particular manufacturer.

TABLE 12.5* Copper Metallization using Dual Damascene

Process Step	Description	Structure
1. SiO_2 deposition	ILD oxide deposition with PECVD to desired thickness for via. There is no critical gap fill; therefore, PECVD is acceptable.	
2. SiN etch stop deposition	Thin (250 Å) SiN etch stop is deposited on ILD oxide. The SiN needs to be dense and pinhole-free; therefore, HDPCVD is used.	
3. Via patterning and etch	Photolithography to pattern and dry etch via openings into SiN. Strip photoresist after completion of etch.	

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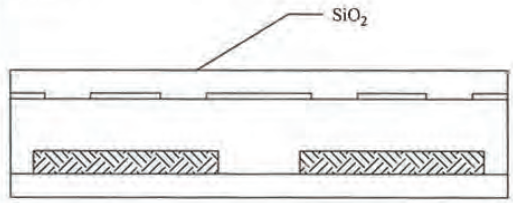
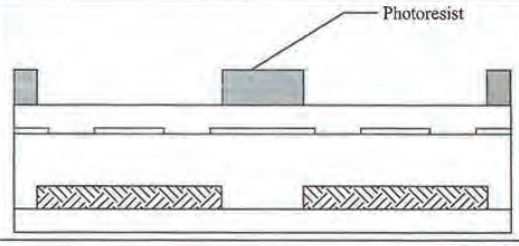
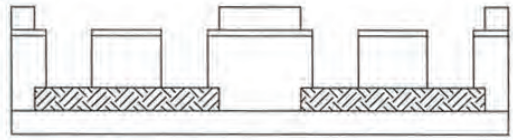
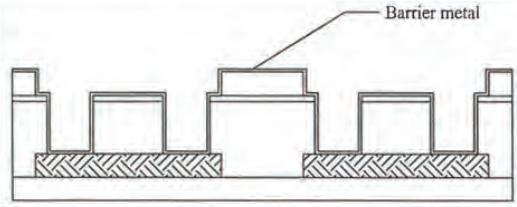
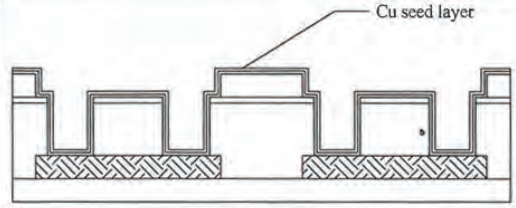
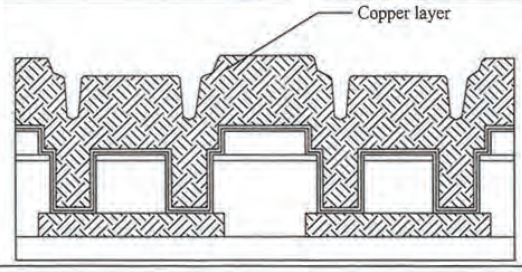
Process Step	Description	Structure
4. Deposit remaining SiO_2	PECVD oxide deposition for remaining ILD oxide.	
5. Interconnect patterning	Photolithography to pattern SiO_2 trench with resist. Previously patterned via openings are located in trench.	
6. Etch trench for interconnect and hole for via	Dry etch trench in ILD oxide, stopping on the SiN layer. Etch continues to form via opening by passing through opening in SiN.	
7. Deposit barrier metal	Deposit Ta or TaN diffusion layer with ionized PVD on bottom and sidewalls of trench and via.	
8. Deposit Cu seed layer	Deposit continuous Cu seed layer with CVD. The layer must be uniform and free of pinholes.	
9. Deposit Cu fill	Deposit Cu fill with electrochemical deposition (ECD). Fill both via opening and trench.	

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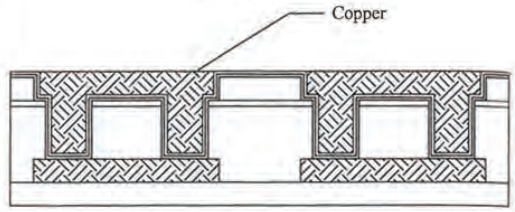
Process Step	Description	Structure
10. Remove excess Cu with CMP	Remove excess Cu using chemical mechanical planarization (CMP). This planarizes the surface and prepares for the next level. The resulting surface is a planar structure with metal inlays in the dielectric to form the circuitry.	

* P. Singer, "Making the Move to Dual Damascene Processing," *Semiconductor International* (August 1997): p. 79.

For dual-damascene processing, a two-tiered metal inlay is created that includes a series of holes (for contacts or vias) in addition to the interconnect trench for metal lines. The vias and metal line levels undergo copper fill concurrently, which saves a process step and eliminates the interface between the via and metal line.

There are different approaches to performing dual-damascene processing, each with their own set of challenges. Most of the manufacturing methods integrate the use of etch-stop materials to control how deep etching occurs for the via and trench. Etch stop is typically done by using a barrier metal such as silicon nitride (Si_3N_4 or Si_xN_y) as a hard mask at the bottom of the via or trench. Si_3N_4 etches at a much slower rate than the dielectric material, thus effectively stopping the etch process. Some approaches may even have two separate Si_3N_4 layers, which adds process complexity. In addition, Si_3N_4 has a high-*k* and increases the interlayer capacitance of the interconnect stack, which is why the Si_3N_4 layer needs to be thin.

The dual-damascene flow shown above has the via etch done in the same etch step as the trench, with the SiN etch stop to define the bottom of the trench. In other variations of dual-damascene, the via is etched first, then the trench is patterned and then etched. Trench structures created over topography from a previous via etch pose a significant challenge for photolithography.

The most important reason for using a damascene approach to copper metallization is to avoid metal etch. A second advantage to damascene processing is that there is no further need for dielectric gap fill between etched metal lines, since the dielectric is applied as a blanket and then etched.

The dual-damascene process in wafer fabrication potentially uses 20 to 30% fewer steps than traditional aluminum metal interconnect. Not only are there fewer manufacturing steps, but dual damascene also eliminates or reduces some of the most difficult steps of traditional aluminum metallization, including aluminum etch and many of the tungsten and dielectric chemical-mechanical polish steps.[54] Reducing process steps in wafer fabrication is important for improving the yield of the process, since fewer process steps translate to fewer sources of error that reduce assembly yield.

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METALLIZATION QUALITY MEASURES

Wafer fabrication quality measures for metallization are provided in Table 12.6.

TABLE 12.6 Quality Measures for Metallization

Quality Parameter	Types of Defects	Remarks
1. Sputtered metal adhesion.	A. Metal layer does not adhere to substrate.	Parameters affecting film adhesion are: • Wafer contamination • Stress • Types of materials • Temperature of substrate • Argon pressure
2. Sputtered film stress.	A. Excessive stress leads to: • Cracks in the film surface. • Loss of film adhesion. • Increased resistivity in some materials.	Film stress can be caused by excessive temperature of the wafer substrate. Ways to reduce wafer temperature are: • Lower deposition rate • Increased backside cooling Cracks can cause: • Peeling of the film layer • Contaminant migration • Electrical opens or short. Measure film stress (bow of wafer surface) before and after deposition. Units for stress are dynes.
3. Sputtered film thickness.	A. Metal layer does not meet film thickness specifications (e.g., sheet resistance out of specification).	Parameters that affect film thickners are: • Incorrect recipe • Improper flow rates • Improper substrate temperature • Improper chamber pressure • Improper power supply energy • Wrong time setting
4. Uniformity of electroplated (electrochemical deposition, or ECD) metal film.	A. Nonuniform film thickness indicated by: • Inadequate gap fill and step coverage for high aspect ratio openings (nonuniform metal thickness at top and bottom of high aspect ratio holes). • Nonuniform deposition thickness across the wafer and from wafer to wafer. • Voids in film.	Critical parameters for electroplating film uniformity are: • Depositing a uniform CVD seed layer without voids. • Maintaining proper electroplating bath chemistry (composition and concentration) for organic additives, primarily brighteners and suppressors, to attain void-free deposition that fills bottom and sidewalls of gaps.

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METALLIZATION TROUBLESHOOTING

Common troubleshooting problems for metallization are provided in Table 12.7.

TABLE 12.7 Common Metallization Troubleshooting Problems

Problem	Probable Cause	Corrective Actions
1. Degradation in step coverage of metal film.	A. Decrease in substrate temperature. For Al alloy sputter deposition, step coverage is dependent on the wafer temperature during deposition.	Heating the substrate to improve step coverage because surface mobility of deposited metal atoms improves.
	B. Increase in deposition rate.	Decrease deposition rate. Increase in sputter deposition rate may degrade step coverage due to reduced surface mobility because of arrival of more atoms at surface.
2. Vacuum chamber integrity.	A. Chamber cleanliness or moisture in chamber.	• Check for vacuum leaks or chamber outgassing. Residual gas in chamber that can change film reflectivity. • Check for O_2 or N_2 in metal films that can change resistivity and film stress. • Clean chamber and do H_2O bake-out.
	B. Outgassing or system leaks.	• Use helium leak detection to inspect for system leaks. • Assess the chamber conditions before deposition with residual gas analyzer.
3. Contamination of metal film.	A. Particles on surface of film.	Check the following common particle sources: • Dirty input wafers. • Problems in hand-off between robot and chamber mechanism. • Incomplete chamber cleaning between runs. • Dirty cassettes. • Contaminated nitrogen backfill.
4. Voids in copper trench fill after dual-damascene electroplating.	A. Excessive seed layer thickness on the wafer surface (field) that pinches off the via or trench, creating a center void in the film.*	Optimize the CVD Cu seed layer deposition by evaluating the electroplating current from the field to the bottom of vias and trenches. The goal is to deposit adequate seed layer at the bottom of a high-aspect ratio feature without increasing field thickness.
5. Excessive copper dishing after dual-damascene CMP.	A. Cu dishing for Cu CMP is often caused by tantalum diffusion barrier, which must be polished back in the presence of Cu.**	After Cu is polished, the Ta layer must be removed from the level. The Cu pad/slurry field does not effectively remove Ta. Options are: • Optimize the pad/slurry for Ta. • Minimize the Ta field level thickness.

* R. Jackson et al., "Processing and Integration of Copper Interconnects," *Solid State Technology* (March 1998): p. 56.
** Ibid.

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SUMMARY

Metallization deposits a thin metal film to form the interconnect wiring and contact or via connections on the chip. There are six metal categories used in wafer fabrication, with specific requirements for optimum performance. Aluminum has been the traditional metal for interconnect lines. An ohmic contact is the low-resistance contact between silicon and the interconnect metal. Aluminum is sometimes alloyed with silicon to reduce junction spiking at the ohmic contact. Aluminum is often alloyed at 0.5 to 4% copper to minimize electromigration reliability problems. New interconnect metallization is based on copper metallurgy to decrease the metal resistivity. Copper combined with low-k dielectric will decrease the chip interconnect delay, but copper does require a new processing approach since it does not etch well. Barrier metals are used when joining metals. Different barrier metals have optimum properties depending on the application. A silicide is a refractory metal alloyed with silicon to improve contact resistance and adhesion. A salicide is a particular silicide that is aligned to the source, drain, and gate structure. Metal layers are connected with vias filled with tungsten plugs. The most widely used metal deposition system is sputtering. Sputtering physically bombards a target to dislodge atoms and deposit the atoms as a thin film on the wafer surface. The three most common types of sputtering are RF, magnetron, and ionized metal plasma. RF sputtering is inefficient, while magnetron has a higher deposition rate but limited gap-fill capability. Ionized metal plasma has improved directionality for high-aspect ratio deposition. CVD metal has the best conformality and is used for tungsten plug fill and copper seed layer. Copper electroplate is the process chosen by major semiconductor manufacturers for copper wiring deposition. Traditional aluminum metallization deposits a blanket aluminum film and then etches line patterns to form interconnect wiring. Copper metallurgy will use a dual-damascene process that etches vias and trenches in dielectric, deposits copper fill, and then removes excess copper through chemical mechanical planarization.

KEY TERMS

interconnect
wiring
contact
vias
plug
eutectic temperature
anneal or sinter
ohmic contact
junction spiking
electromigration
hillocks
copper interconnect
barrier metal
refractory metals
silicide
polycide
salicide
tungsten plugs
evaporation
physical vapor deposition (PVD)
target
momentum transfer
sputtering yield
sputter etch (reverse sputter)
RF sputtering
magnetron sputtering
collimated sputtering
sputtered aluminum
ionized metal plasma PVD (IMP or ionized PVD)
tungsten (W) CVD
copper CVD
electroplate (electroplating, electrochemical deposition (ECD), or electrofill)
evaporation
aluminum subtractive process
dual-damascene process

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REVIEW QUESTIONS

1. Define the following terms: interconnect, contact, via, and plug.
2. What metal has traditionally been used for interconnect wiring, and what is its replacement?
3. List and describe the seven performance requirements for metals used in wafer fabrication.
4. List the categories of metals and metal alloys used in semiconductor manufacturing.
5. Explain why aluminum has been the interconnect metal of choice for microchips.
6. What is an ohmic contact and what is its advantage?
7. Describe junction spiking and list the two primary ways it was resolved.
8. Discuss electromigration and how it affects reliability. How is electromigration controlled in aluminum wiring?
9. List and discuss the five benefits for introducing copper metallization.
10. What are the three major challenges for converting to copper for interconnects?
11. Explain what a barrier metal is and the essential properties of a barrier material. What metals are commonly used as a barrier metal?
12. List the special requirements for a copper barrier metal.
13. Define silicide and explain why refractory metal silicides are important in wafer fabrication.
14. What are the benefits of titanium silicide? Explain the C49 and C54 phase structures.
15. What silicide is promising for future wafer technology? Why?
16. What is the salicide process?
17. Describe a tungsten plug, and discuss how it is used in multilayer metallization.
18. Why was evaporation replaced as a metal deposition system?
19. Provide a short explanation about sputtering and how it works.
20. Is sputtering suitable for alloy deposition?
21. What are the advantages to sputter deposition?
22. List and explain the six steps to sputtering.
23. Explain the physics of sputtering.
24. Describe sputter yield.
25. What is the purpose of sputter etch?
26. Describe an RF sputter system. What is its major limitation?
27. Discuss how a magnetron sputtering system improves the deposition rate.
28. Explain why sputtering has poor step coverage. How does collimated sputtering improve step coverage?
29. Describe ionized metal plasma. How does this process improve high-aspect ratio gap fill?
30. What is the typical method for creating a tungsten plug in advanced ICs?
31. Why could CVD be used for the copper seed layer?
32. Explain the fundamental process of copper electroplate.
33. Why is traditional aluminum metallization a subtractive process?
34. What is the primary reason for implementing the dual-damascene process for copper?
35. List ten steps for a dual-damascene metallization process.

METALLIZATION EQUIPMENT AND MATERIALS SUPPLIERS' WEB SITES

Angstrom Sciences Inc.	http://www.angstromsciences.com/
Applied Materials	http://www.appliedmaterials.com/products/
Genus Incorporated	http://www.genus.com/
Materials Research Corporation	http://www.materialsresearch.com/
Nordiko USA Inc.	http://www.nordiko.com/
Novellus Systems Inc.	http://www.novellus.com/index.htm
Process Materials Inc	http://www.processmaterials.com/
TEL, Tokyo Electron Ltd.	http://www.teainet.com/
Veeco-CVC	http://www.veeco.com

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