Thermal Evaporation

Theory

1. Introduction

Procedures for depositing films are a very important set of processes since all of the layers above the surface of the wafer must be deposited. We can classify thin films into five groups: thermal oxides, dielectric layers, epitaxial layer, polycrystalline silicon, and metal films. Generally, the techniques used to deposit metals are physical, that is, they do not involve a chemical reaction. Processes used to deposit semiconducting and insulating layers often involve chemical reactions. This distinction, however, is changing. One of the areas currently being developed is the chemical deposition of metals [1] [2].

This module will cover techniques to generate metal films. Metal films such as aluminum and silicides are used to form low-resistance interconnections, Ohmic contacts, and rectifying metal-semiconductor barriers [1]. The procedure to generate such films is called physical vapor deposition (PVD).

2. Theory

The most common methods of physical vapor deposition (PVD) of metal are thermal evaporation, e-beam evaporation, plasma spray deposition, and sputtering. Metals and metal compounds such as Ti, Al, Cu, TiN, and TaN can be deposited by PVD. Evaporation occurs when a source material is heated above its melting point in a vacuum chamber. The evaporated atoms then travel in straight lines due to a long mean free-path created by the vacuum and deposit on the wafers. The metal source can be melted by resistance heating, RF heating, or by a focused electron beam. The metal evaporation done by resistive heating is usually called thermal evaporation. The thermal evaporation and e-beam evaporation were used extensively in earlier generations of integrated circuits, but they have been replaced by sputtering in silicon-based ultra large scale integration (ULSI) circuits [1].

A simple evaporator diagram is shown in Figure 1. The wafers are loaded into a high-vacuum chamber that is commonly pumped with either a diffusion pump, a cryo-pump, or a turbo-pump. Diffusion-pumped systems commonly have a cold trap to prevent the back streaming of pump oil vapors into the chamber. The charge, or material to be deposited, is loaded into a heated container called the crucible (boat). It can be heated very simply by means of an embedded resistance heater and an external power supply. As the material in the crucible becomes hot, the charge gives off its vapor. Since the pressure in the chamber is much less than 1 mtorr, the atoms of the vapor travel across the chamber in a straight line without hitting any gas molecule left in the vacuum chamber until they strike a surface where they accumulate as a film. Evaporation systems may contain up to 24 wafers suspended in frame above the crucibles. Furthermore, if an alloy is desired, multiple crucibles can be operated simultaneously. To help start and stop the deposition abruptly, mechanical shutters are used in front of the crucibles to control the metal deposition thickness [2].

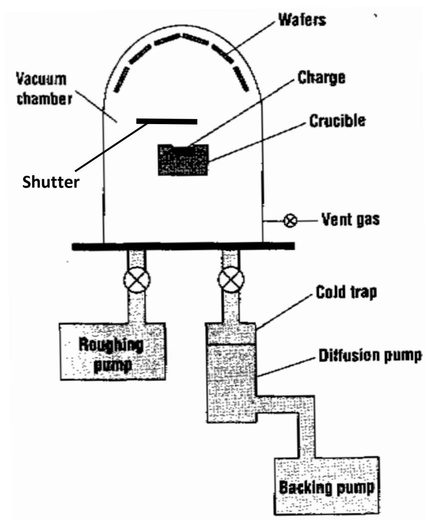

Figure 1. Schematic of an evaporator equipped with a diffusion pump [2].

2.1. Phase Diagrams: Sublimation and Evaporation

Vaporization from molten and solid materials is called evaporation and sublimation, respectively. Thermal evaporation of a metal is performed at pressures below 10^{-2} torr. The evaporation process typically involves molten samples, because the region of operating temperatures offers high-vapor pressures and produces reasonable deposition rates.

At every temperature T, there exists an equilibrium vapor pressure, P^{vap}, over the specific material. Dependence of P^{vap} on T is usually determined experimentally; $P^{vap}(T)$ for several elements is shown in Figure 2. It is evident that a wide range of vapor pressures is accessible simply by changing the temperature of the sample.

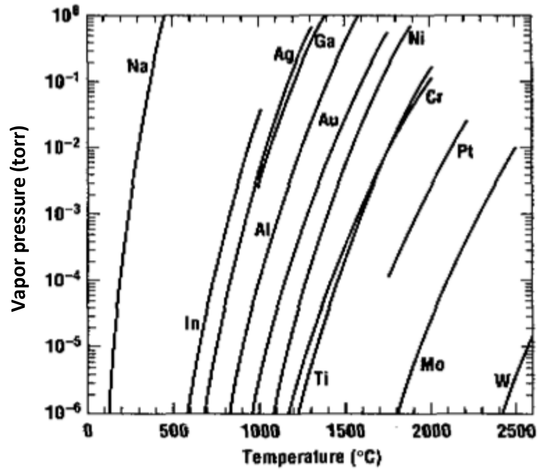

Figure 2: Vapor pressure curves for commonly evaporated materials [2].

To obtain reasonable deposition rates the sample, vapor pressure must be at least 10 mtorr. From Figure 2 it is obvious that some materials must be heated to much higher temperatures than others to obtain the same vapor pressure. The class of materials known as refractory metals, which includes Ta, W, Mo, and Ti, has very high melting temperatures and therefore has low vapor pressures at moderate temperatures. For example, tungsten requires a temperature in excess of 3000°C to obtain a vapor pressure of 10 mtorr.

2.2. Evaporation Systems: Crucible Heating Techniques

To obtain large deposition rates, evaporators are often operated with very high crucible temperatures. To obtain the best uniformity, the evaporation rate should be fairly low (1-3 Å per second). Operation at such low rates requires extremely high vacuums to avoid contamination of the film.

The deposition rate is commonly measured using a quartz crystal rate monitor. This device is a resonator plate that is allowed to oscillate at the resonance frequency, which is then measured. The resonance frequency shifts due to the additional mass as material is deposited on top of the crystal. When enough material has been added, the resonance frequency will shift by several percent and the oscillator will no longer show a sharp resonance. The sensing elements are quite inexpensive and are easily replaced. By linking the output of the frequency measurement system to the mechanical shutters, the thickness of the deposited layers can be well controlled over a wide range of deposition rates. Furthermore, the rate of the deposited thickness changes can be fed back to the crucible temperature to maintain a constant deposition rate, if so desired.

Since the chamber does not contain a perfect vacuum, gases other than the vapor may also be incorporated in the deposited film. This deposition may be a simple physical mixing, or it may involve a chemical reaction. Because of the long mean free path in the chamber, if a chemical reaction occurs, it will probably happen at the surface of the wafer. An example of such a reaction is aluminum deposition in the presence of oxygen, which results in aluminum oxide. Incorporation of gaseous species may be intentional [reactive evaporation], or it may be an unintentional incorporation of gases due to a vacuum leak or incomplete chamber evacuation.

Evaporated materials deposit non-uniformly if the substrate has a rough surface (as integrated circuits often do). Because the evaporated material attacks the substrate mostly from a single direction, protruding features block the evaporated material from some areas. This phenomenon is called "shadowing" or "step coverage."

There are three types of crucible heating systems: resistive, inductive, and electron-beam systems. A **resistively heated system** is the simplest type of evaporation source. Resistive evaporation is accomplished by passing a large current through a resistive wire or foil containing the material to be deposited. Given a high vacuum chamber equipped with power supply to a resistor, it is possible to construct a simple evaporator with only a small coil of wire and a simple variable transformer. The charge in such a system is a small solid bar laid over the heated element (see Figure 3A). The input power is adjusted to prevent the charge from becoming molten and dripping through the coil. Wire type evaporation sources are usually made from tungsten wire and can be formed into filaments, baskets, heaters, or loop-shaped point sources. More practical heating systems use resistively heated boats (crucibles) to hold the charge, as shown in Figure 3B. Boats are usually made from tungsten, tantalum, molybdenum, or ceramic materials capable of withstanding high temperatures.

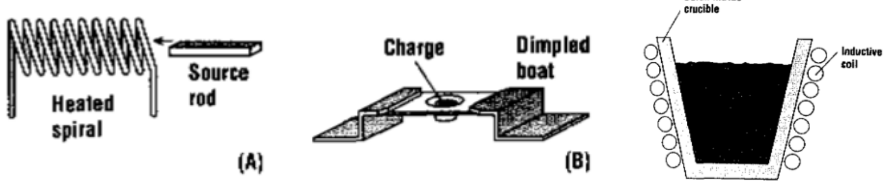

Figure 3: Examples of evaporator systems: (A) Resistive - Simple sources include heating the charge itself and using a coil of refractory metal heater and a charge (source) rod. (B)

Resistive - More standard thermal sources including a dimpled boat in a resistive media. (C) Inductively heated crucible for refractory metal evaporation [2].

Another way to achieve at least moderate charge temperatures is to use **inductively heated crucibles**. As shown in Figure 3C, a solid charge is placed in a crucible, typically made of boron nitride (BN). A metal element is wound around the crucible and RF power is run through the coil. The RF induces eddy currents in the charge causing it to heat up. The coil itself can be water cooled to keep its temperature below 100°C, effectively eliminating any loss of material from the coil.

While inductive heating can be used to raise the crucible temperature high enough to evaporate refractory materials, contamination of the charge from the crucible itself remains a serious problem. Heating only the charge and cooling the crucible can avoid this effect.

Another commonly used evaporator is **an e-beam evaporator**. Here, an electron gun placed under the crucible ejects an intense, high-energy beam. The location of the filament minimizes deposition of the filament material, typically W, on the surface of the wafer. A strong magnetic field bends the beam through 270° causing it to be incident on the surface of the charge (Figure 4). The beam can be led across the charge to melt a significant fraction of the surface. The hot portion of the charge is then effectively self-contained by the cooler portion of the charge [2].

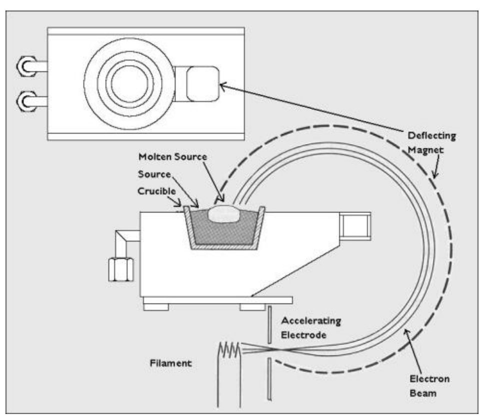

Figure 4: Electron beam evaporation source with a 270° arc in which the beam can be led across the surface of the charge. The magnet must be much larger than shown to achieve the full 270° of arc [3].

Because of their ability to easily deposit a wide range of materials, e-beam evaporators are commonly used in GaAs technologies.

3. Optimization

- Purity of the deposited film depends on the quality of the vacuum, and on the purity of the source material.
- At a given vacuum pressure, the film purity will be higher at higher deposition rates as this minimizes the relative rate of gaseous impurity inclusion.
- The film thickness is affected by geometry of the evaporation chamber. Collisions with residual gases aggravate non-uniformity of thickness.
- Wire filaments for evaporation cannot deposit thick films, because the size of the filament limits the amount of material that can be deposited. Evaporation boats and crucibles offer higher volumes for thicker coatings. Thermal evaporation offers faster evaporation rates than sputtering. Flash evaporation and other methods that use crucibles can deposit thick films.
- In order to deposit a material, the evaporation system must be able to vaporize it. This makes refractory materials such as tungsten hard to deposit by methods that do not use electron- beam heating.

4. References

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