Module 13 Sputtering

Class Notes

1. Introduction
   Sputtering is the primary alternative to evaporation for metal film deposition in microelectronics fabrication. First discovered in 1852, sputtering was developed as a thin-film deposition technique by Langmuir in the 1920s. It provides better step coverage than evaporation and can produce layers of compound materials and alloys. These advantages have made sputtering the metal deposition technique of choice for most silicon-based technologies [1].

2. Theory
   A simple sputtering system, as shown in Figure 1, is very similar to a simple reactive ion etch system: a parallel-plate plasma reactor in vacuum chamber. For sputtering deposition, however, the plasma chamber must be arranged so that high-energy ions strike a target containing the material to be deposited. The target material, not the wafers, must be placed on the electrode exposed with the maximum ion flux. To collect as many of these atoms ejected through the ion bombardments as possible, the cathode and anode in the sputtering system are closely spaced, often less than 10 cm. An inert gas is normally ionized and used to bombard the target materials. The gas pressure in the chamber is held at about 0.1 torr. This results in a mean free path in the order of hundreds of micrometers.

   ![Figure 1: Sputtering Vacuum Deposition Process](image)

   Due to the physical nature of the process, sputtering can be used for depositing a wide variety of materials. In the case of elemental metals, simple dc sputtering is usually favored due to its large sputter rates. While depositing insulating materials such as SiO₂, an RF plasma must be used. If the target material is an alloy or compound, the stoichiometry of the
deposited material may be slightly different than the target material. It has been shown that the material with a lower sputter yield will accumulate on the surface of the target until the composition of the deposited film is approximately that of the bulk of the target. (This is true only if the target temperature is kept sufficiently low to prevent solid-state diffusion.) This makes sputtering very attractive for depositing not only elements, but also a very wide range of materials [1].

2.1. Plasma
Glow discharges or plasma is initiated by applying a large voltage across a gap containing a low-pressure gas. The required breakdown voltage is given by the following Paschen’s law:

\[ V_{bd} \propto \frac{P \times L}{\log P \times L + b} \]  

(1)

where P is the chamber pressure, L is the electrode spacing, and b is a constant. Once a plasma is formed, ions in the plasma are accelerated toward the negatively charged cathode. When they strike the surface, they release secondary electrons, which are accelerated away from the cathode. They may collide with neutral species while crossing from cathode to anode. If the energy transfer is less than the ionization potential of the gaseous species, the atom can be excited to an energetic state. The atom decays from this excited state through an optical transition, providing the characteristic glow. If the energy transfer is high enough, however, the atom will be ionized and accelerate toward the cathode. The bombardment of the cathode in this ion stream gives rise to the process of sputtering [1].

2.2. Sputtering Principle
When an energetic ion strikes the surface of a material, four things can happen. Ions with very low energies may simply bounce off the surface. At energies of less than about 10 eV, the ion may also adsorb to the surface, giving up its energy to phonons\(^1\) (heat). At energies above about 10 keV, the ion penetrates into the material and through many atomic layer spacing, transferring most of its energy deep into the substrate and changing the structure of the target materials. These high energy transfer processes are typical for ion implantation. Between these two extremes, both energy transfer mechanisms occur. Part of the ion energy dissipates in the form of heat. The remainder goes into a physical rearrangement of the substrate. For the low energy ion bombardment, nuclear stopping at the surface of the target materials is quite effective. Most of the energy transfer occurs within several atomic layers.

\(^1\) A Phonon is a collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, such as solids and some liquids. Often referred to as a quasi-particle (Wikipedia).
When this happens, substrate atoms and clusters of atoms will be ejected from the surface of
the substrate. The atoms and atomic clusters ejected from the cathode escape with energies
of 10 to 50 eV. This is about 100 times the energy of evaporated atoms. This additional
energy provides sputtered atoms with additional surface mobility to improve step coverage of
the deposited materials relative to the evaporation process. At typical sputtering energies,
about 95% of the ejected material is atomic and most of the remainder is diatomic molecules.

At high energy ion bombardments, such as those used in implantation, chemical-bonding
processes can be largely ignored and the target can be considered as simply a collection of
atoms. At very low energies, no disruption of the target occurs, and a chemical model can be
readily developed. For sputtering, however, the physics of material removal is quite
complicated, involving the coupled effects of bond breaking and physical displacement.
Figure 2A shows some of the processes that may occur when an ion strikes a surface during
the sputtering process.

This near head-on collision may liberate a target atom that has a large momentum directed at
a significant angle with respect to the surface normal. During this process, many of the bonds
in the top layers of the target will be broken. If several of these large angle collisions occur,
the incident atom or the recoiled target atom may develop a significant velocity component
parallel to the surface of the wafer. A subsequent collision can then eject an atom or small
cluster of atoms as seen in Figure 2B.

Figure 2: A) Possible outcomes for an ion incident on the surface of the wafer [1]. B)
Sputtering Process [3].
All surfaces exposed to RF plasma develop a negative potential with respect to the plasma due to the higher mobility of electrons than ions. In a typical sputtering system, most of the voltage drop is on the target electrode, but the bias on the substrate electrode leads to a bombardment of ions on the wafers as well. The bombardment leads to a removal of material from the surface of the wafer. Adjusting the dc bias on the electrode with respect to the plasma can control this effect. This has two major applications in microelectronics: sputter cleaning and bias sputtering.
2.3. Physical Vapor Deposition Methods
The following chart provides an useful comparison between three of the most common methods for physical vapor depositions, including sputtering.

<table>
<thead>
<tr>
<th>Method</th>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Beam Evaporation</td>
<td>1. High temperature materials</td>
<td>1. Some CMOS processes sensitive to radiation</td>
</tr>
<tr>
<td></td>
<td>2. Good for lift off</td>
<td>2. Alloys difficult</td>
</tr>
<tr>
<td></td>
<td>3. Highest purity</td>
<td>3. Poor step coverage</td>
</tr>
<tr>
<td>Filament Evaporation</td>
<td>1. Simple to implement</td>
<td>1. Limited source material (no high temperature)</td>
</tr>
<tr>
<td></td>
<td>2. Good for lift off</td>
<td>2. Alloys difficult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Poor step coverage</td>
</tr>
<tr>
<td>Sputter Deposition</td>
<td>1. Better step coverage</td>
<td>1. Possible grainy films</td>
</tr>
<tr>
<td></td>
<td>2. Alloys</td>
<td>2. Porous films</td>
</tr>
<tr>
<td></td>
<td>3. High temperature materials</td>
<td>3. Plasma damage/contamination</td>
</tr>
<tr>
<td></td>
<td>4. Less radiation damage</td>
<td></td>
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2.3. Vacuum pumps
According to the different physical principles, which are exploited to create, improve or maintain vacuum, there are different types of vacuum pumps:

- **Positive displacement or mechanical pumps**, which provide empty volume to be filled with the gas being pumped. The empty volume is cyclically isolated from the inlet; the gas is then transferred to the outlet. In most types of positive displacement vacuum pumps the gas is compressed to atmosphere before the discharge at the outlet. Positive displacement pumps work independently of the gas species to be pumped.

- **Kinetic pumps**, which impart momentum to the gas being pumped in such a way that the gas is transferred continuously from the pump inlet to the outlet.

- **Entrapment or capture vacuum pumps**, which retain gas molecules by chemical or physical interaction on their internal surfaces.

- **Diffusion pump**, The two most popular types of kinetic pumps (momentum transfer pumps) are diffusion pumps and turbomolecular pumps. Diffusion pumps (Figure 4) are extremely simple and robust. They operate by heating oil at the bottom of the pump. The pump oil vapors rise through the center stack and are ejected through vents at very
high speeds. These high-speed oil molecules transfer their momentum to the gas molecules and push them downward to be expelled by the mechanical pump. Then, the oil molecules strike the cooled-walls of the pump, condense, run down the wall of the pump, and then are heated again. Gas molecules may also be transported by dissolving in the vapor droplets. As the oil is heated again at the bottom of the pump, the gas is given off and removed through a roughing pump (also known as fore-line pump), which is connected to the fitting on one side of the diffusion pump (bottom right on Figure 4). It is possible to obtain compression ratios of $10^8$ torr in these pumps.

![Figure 4: Diffusion Pump][5].

Most diffusion pumps can not be exposed to an atmosphere, or a chemical reaction called cracking may occur between the hot pump oil and the oxygen in the air. Even more serious are concerns that some of the pump oil vapor will not condense in the pump and will back-stream into the vacuum system leading to contamination. Diffusion pumped systems may use baffles or cooled traps to remove most of the back-streamed pump oil. Because of this concern, diffusion pumps are generally not desirable when extremely high purity is required. [6]

- **Cryo pump**, Together with the getter² and the sputter ion pump, the cryo pump is the most prominent representative of the latter group. A cryo pump is defined as a vacuum pump, which captures the gas, and cool it to temperatures below 120 K (cooling the surface). To achieve a vacuum in a closed volume, it is necessary to remove all molecules in the gaseous phase within this volume. Usually, the cooled surface is at least partly covered with a porous sorbent material. Besides straightforward

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² A getter is a deposit of reactive material that is placed inside a vacuum system, for the purpose of completing and maintaining the vacuum (Wikipedia).
parameters, such as pressure and temperature, the performance of the cryo pump is very much governed by the complex interaction between gas particles and cooled sorbent surface. These interactions can be produced by charcoal kept at these cryogenic temperatures. The cryo pump is the pump type that provides the highest pumping speeds, especially when operated in situ of the vacuum recipient [4].

![Figure 3: Schematic view of a typical cryopump](image)

As for all high vacuum pumps (i.e., pumps working below the 1x10^{-6} torr range) an appropriate way to establish the final pressure is to start the vacuum with a mechanical rough-pump (also known as fore-line pump), before the cryo pump can be started. The rough-pump is also needed to exhaust the gas to the atmosphere. Whereas this gas transfer is done continuously in the case of kinetic and positive displacement pumps, entrapment pumps do this in a batch-wise manner as they accumulate the gas during pumping and must be regenerated from time to time. During the actual pumping, the gases within the entrapment pump systems are instantaneously immobilized and no outlet is required at all [4].

The cryopumping effect is produced by the intimate interaction between the gas particles to be pumped and a cold surface provided to them in the cryo pump. The forces involved are relatively weak (primarily van der Waals dispersion type) and do not include chemical bonds, as is the case for chemisorption with the chemically active alloys in getter pumps. Consequently, cryo pumps do not require such high temperatures for regeneration. Cryo pumps can pump all gases including noble gases, if the temperature is sufficiently low. The amount of molecules that can be accumulated depends on a number of physical factors.
such as temperature of gas and surface, physicochemical properties of gas and chamber surface (surface energy distribution), microscopic roughness of the surface, etc.

Thus, the relevant saturation curve becomes identical with the sublimation curve, i.e., during pumping, the gas particles undergo direct phase transition from the gaseous to the solid phase without any liquid phase. As is customary in cryo pumping, the term ‘condensation’ is used for both types of transition out of the gaseous phase; it combines re-sublimation (gaseous $\rightarrow$ solid) and condensation (gaseous $\rightarrow$ liquid) [4].

### 3. References


