Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

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Lecture - 23

Hello and welcome to this lecture on physical vapor deposition (PVD), specifically focusing on sputtering. In previous lectures, we explored thermal evaporation and electron beam (e-beam) evaporation. Now, let’s delve into sputtering and how it differs from these other techniques.

In thermal and e-beam evaporation, we apply thermal energy to a source - either a boat or a coil causing the material to melt and subsequently evaporate, depositing onto the substrate. In e-beam evaporation, an electron beam generated by a filament is accelerated and directed onto the crucible holding the material, which melts and evaporates in a similar manner.

Sputtering, however, operates differently. Instead of melting the material, sputtering involves dislodging atoms from a target and depositing them onto the substrate. In the sputtering process, we have several types: DC sputtering, RF sputtering, magnetron sputtering, and reactive sputtering. Here, the targets used are often in the shape of discs, plates, or toroids, and come in various sizes.

In a sputtering chamber, we have a substrate and a target, along with an inert gas like argon. By applying a bias to the anode and cathode, we create a plasma in the chamber. When energetic ions strike the surface of the target, several interactions can occur, leading to the ejection of atoms from the target, which then deposit onto the substrate. Let’s take a closer look at these processes and their implications in sputtering.

When plasma forms in the sputtering chamber, high-energy argon ions strike the target material, dislodging atoms from its surface. These ejected atoms then deposit onto the substrate, forming a thin film. The energy of the ions is crucial for effective sputtering; if the ions have too little energy, they may simply bounce off or be adsorbed onto the surface. At around 10 kiloelectron volts, ions can penetrate the material, leading to ion implantation rather than sputtering.

Ion implantation is commonly used in processes like MOSFET fabrication, where creating the source and drain regions requires precise techniques. If the ions are excessively energetic, they can implant into the substrate instead of just dislodging surface atoms. Thus, for effective sputtering, the ion energy should typically be between 10 to 50 electron volts. This range not only facilitates atom ejection but also provides the sputtered atoms with enhanced surface mobility, leading to better film coverage compared to evaporation methods.

Next, let’s discuss sputtering yield, which is defined as the ratio of sputtered atoms to the number of incident ions. In other words, it measures how many ions strike the target and how many atoms are successfully ejected and deposited on the substrate. The sputtering yield depends on several factors, including the binding energy of the material, the square root of the ion energy, the atomic mass of both the ion and target, the angle of incidence, and the deposition pressure. Understanding these variables is essential for optimizing the sputtering process.

The three images illustrate how various factors influence sputtering yield. The first image demonstrates the effect of ion energy on sputtering yield, showing that higher ion energy typically increases the yield. The second image depicts how the angle of incidence impacts sputtering yield, indicating that an optimal angle can enhance efficiency. The third image illustrates how system pressure affects sputtering yield; as pressure changes, the yield can vary significantly.

Specifically, sputtering yield is inversely proportional to the binding energy of the target material, while it is proportional to the square root of the ion energy. The atomic mass of the ions and target also influences the yield, with the angle of incidence having a direct relationship to the yield as well. These parameters are critical to consider when operating a sputtering system.

Now, let’s discuss DC sputtering. In this setup, we can position the target material (cathode) either above or below the substrate (anode). Typically, the substrate serves as the anode, while the target acts as the cathode. In the provided figure, the substrate is connected to the anode, and the target material is mounted below it.

During the process, argon gas is introduced into the chamber. A high voltage applied between the anode and cathode generates ions from the argon gas. These energetic ions bombard the target, dislodging atoms that then travel to the substrate, forming a film.

At low pressure, the cathode area is wide, and ions are generated far from the target, resulting in a longer mean free path for the ejected atoms. As pressure increases, the mean free path decreases, and more ions are generated. However, if the pressure becomes too high, the sputtered atoms experience increased collisions, leading to scattering that can hinder efficient deposition. Therefore, controlling chamber pressure is crucial for optimizing sputtering yield and deposition rates.

Under typical sputtering conditions, the pressure and current values are critical factors for achieving optimal deposition. As indicated in the graph, the ideal pressure range for DC sputtering is depicted, and this range ensures efficient deposition. In general, the deposition rate is proportional to the power consumed and inversely related to the electrode spacing.

An important aspect to consider is the distance between the target (source) and the substrate. If you increase the spacing, the deposition rate decreases because the atoms have to travel farther, leading to a slower deposition. Conversely, closer proximity results in a faster deposition rate. However, adjusting this spacing can impact the overall film properties, so finding the right balance is key for optimal results.

Now, moving on from DC to RF sputtering, this process typically operates at a frequency of 13.5 MHz. In RF sputtering, the chamber setup remains similar, with a target and substrate. In this example, the target is positioned at the top, while the substrate is at the bottom, which, as previously mentioned, can be interchanged depending on the system design.

Additionally, in RF sputtering, a heater is often incorporated into the system to improve the crystalline quality of the deposited film. The heater allows the atoms to rearrange themselves as they deposit, which can enhance the overall structure of the film. This is particularly important because, unlike thermal deposition where the rapid deposition rate gives atoms little time to settle, the controlled heating in RF sputtering enables better atom rearrangement, thereby improving film properties.

For example, if you're aiming to grow a piezoelectric film, heating during deposition can lead to better film orientation. In this image, we see the setup for RF sputtering. The RF power supply is applied between two plates, and there's a pressure control system for the input gas, which is usually argon. We also have vacuum pumps, temperature control, and a vacuum control system. RF sputtering is particularly effective for depositing insulating films with very high resistivity, up to around 10^6 ohm-centimeter.

To clarify, resistivity (ρ) can be understood using the formula $R = \rho \frac{l}{A}$, where R is resistance, l is the length, and A is the cross-sectional area. Rearranging this, $\rho = R\frac{A}{l}$, and with resistance measured in ohms, and length in centimeters, resistivity is expressed in ohm-centimeters. This is the unit used when we refer to high-resistivity insulating films like 10^6 ohm-centimeter.

At an AC signal frequency of about 50 kHz, electrons oscillate in the plasma, gaining enough energy to cause ionizing collisions, reducing the need for secondary electrons. Additionally, RF voltages can couple through any kind of impedance, so the electrodes don’t need to be conductive. This is a key difference from DC sputtering, where both the anode and cathode must be conductive.

In RF sputtering, we don’t have that restriction. This allows us to sputter materials regardless of their resistivity. The typical RF frequency used is 13.56 MHz, as regulated by the Federal Communications Commission. During RF sputtering, the target self-biases to a negative potential, and positive ions bombard the target, dislodging atoms for deposition. Since the target is capacitively coupled to the RF generator, both metals and insulators can be sputtered, making RF sputtering versatile for depositing metals, insulators, and even semiconductors. Now, let’s move on to understand the purpose and functionality of magnetron sputtering.

In magnetron sputtering, the introduction of a magnetic field into the sputtering process whether DC or RF enhances deposition efficiency. The magnetic field B is superimposed on the electric field E between the target (cathode) and substrate (anode), creating a dual-field environment where electrons experience a Lorentz force, expressed as $F = m\frac{dv}{dt} = q(E+v\times B)$, where q is the electron charge, m is its mass, and v is its velocity. Depending on the orientation of the magnetic and electric fields, two key cases arise. In the first case, when the magnetic field is parallel to the electric field, the term $v\times B$ becomes zero, leaving only the electric field EEE to influence the electron motion. In this scenario, the magnetic field has no effect, and the electrons move solely under the influence of the electric field. In the second case, when only a magnetic field is present, an electron emitted from the cathode with velocity v at an angle θ experiences a force $qvB\sin\theta$, causing it to orbit in a circular path. The radius of this orbit is determined by the balance between centrifugal and Lorentz forces. The magnetic field traps electrons near the target, increasing ionization of the sputtering gas (usually argon), which enhances the sputtering process by improving deposition rates and film quality. By optimizing the orientation and strength of both fields, magnetron sputtering offers greater control over deposition efficiency and film properties.

In magnetron sputtering, the motion of electrons becomes helical with a constant velocity component of $V\cos\theta$, influenced by the magnetic field. Without a magnetic field, excess electrons would migrate out of the discharge and be lost at the chamber walls. However, the presence of a magnetic field prolongs the electron residence time in the plasma, enhancing ionization and increasing the rate of deposition. When both electric and magnetic fields are present, the electrons follow a helical path with a constant radius, and as the electrons accelerate in the electric field, the pitch of the helix elongates over time. This time-varying electric field influences the radius of the spiral path, increasing the efficiency of sputtering by allowing more ions to strike the target, dislodging more atoms for deposition onto the substrate.

The magnetic field helps by extending the electron's residence time, thereby enhancing ionization and increasing the number of atoms ejected from the target. As the magnetic field traps electrons near the target, the chances of ion collisions increase, leading to higher deposition rates. Additionally, the magnetic field reduces electron bombardment on the substrate and extends the operating vacuum range. This is a key advantage of magnetron sputtering, as illustrated by the arrangement of magnets near the negatively charged electrode, which influences the helical trajectory of electrons and improves deposition efficiency.

Reactive sputtering is another variation, where thin films of compounds are deposited using metallic targets in the presence of reactive gas molecules like oxygen, nitrogen, or sulfur. This process is particularly useful for depositing oxides, nitrides, carbides, and sulfides. During reactive sputtering, the resulting film may be a solid solution, an alloy of the target metal doped with the reactive element, or a compound formed with the reactive gas. Both magnetron and reactive sputtering provide flexibility in creating thin films with various material compositions and properties.

The advantage of reactive sputtering becomes evident when working with multiple materials. In all types of sputtering, including DC, RF, magnetron, and reactive sputtering, biasing is often used to control film properties. In bias sputtering, the electric field near the substrate is modified to influence the flux and energy of the charged species incident on the substrate. This is achieved by applying either a negative DC or RF bias to the substrate. The target voltage typically ranges between -1000 to -3000 volts, while the bias voltage is usually between -50 to -300 volts. Due to the charge exchange process in the anode dark space, very few discharge ions strike the substrate with full bias. The concept of anode dark space, along with related phenomena such as Crooke's dark space, falls under the realm of thin film physics, which is beyond the scope of this discussion.

However, the key takeaway here is that bias sputtering has been successfully utilized across different sputtering techniques to alter a broad range of properties in deposited films. These properties include resistivity, stress, dielectric characteristics, optical qualities, etch rate, and adhesion of the deposited layers. In a typical sputter deposition setup, the target material and wafers (or substrate) are placed in the chamber. The wafers are positioned on the anode electrode, and a heater is used to enhance crystal orientation during deposition. Plasma is generated in a vacuum chamber filled with argon sputter gas, and a voltage is applied, establishing an anode and cathode configuration in the case of DC sputtering.

Plasma is essential in sputtering to make the gas conductive, allowing ions to be generated and then extracted to strike the target. This method operates at relatively high pressures, typically between 1 to 100 milliTorr, and is particularly effective for depositing alloys and compounds, a process that is more challenging with thermal evaporation or electron beam (E-beam) techniques. As we discussed previously, depositing alloys through thermal or E-beam evaporation is difficult, but sputtering, especially reactive sputtering, makes this task easier.

In the sputtering process, argon ions bombard the target material, dislodging atoms that are then deposited onto the substrate or wafer. The system remains similar to other deposition techniques, with components such as a vacuum system, including pirani and penning gauges for pressure measurement, a substrate heater, and a rotating substrate for uniform deposition. The sputtering chamber setup also includes high and low-pressure regions, and the process is closely monitored and controlled via control electronics.

In summary, the sputtering system consists of a vacuum chamber, viewing window, vacuum pumps, gauges, and a control system. Plasma is generated by applying an RF signal, which produces energetic ions that bombard the target. The target is bombarded by these ions, knocking atoms loose, which then travel to the substrate and deposit as a thin film. A key advantage of sputtering is its ability to deposit a wide variety of materials since the material is transferred into the vapor phase through a mechanical rather than chemical or thermal process. Unlike thermal and E-beam evaporation, where step coverage can be problematic, sputtering offers excellent step coverage and sharp topologies due to the higher chamber pressure.

Film stress during sputtering can be controlled to some extent by adjusting chamber pressure and

RF power. The advantages and disadvantages of sputtering include several key points. Advantages include the ability to deposit films on large-sized targets, with precise control over film thickness through adjusting parameters like pressure, deposition time, and operating conditions. Sputtering is also particularly effective for depositing alloys, offering better step coverage and enabling in-vacuum sputter cleaning of substrates. One notable benefit is the absence of X-ray generation, which is a concern in electron beam (E-beam) operations where the electron beam striking the target can produce secondary X-rays that may damage sensitive devices. Sputtering avoids this risk, making it a safer option in terms of device protection.

However, sputtering also has its limitations. High capital costs are one of the primary disadvantages. Additionally, the deposition rate for certain materials, like insulating SiO2, is relatively low. Organic solids may degrade more easily during the process, and there is a greater likelihood of introducing impurities to the substrate due to the high-pressure operation of the system. Comparing physical vapor deposition (PVD) with chemical vapor deposition (CVD), PVD generally offers a higher deposition rate and avoids harmful exhaust gases, which is a significant environmental and safety advantage. However, the uniformity of the deposited film is often not as good as with CVD, and step coverage is inferior since in CVD, the reactive gases interact uniformly with all parts of the substrate.

When comparing thermal and E-beam evaporation with sputtering, several factors must be considered, including deposition rate, material choice, purity, substrate heating, potential surface damage, in-situ cleaning capability, X-ray damage risk, and the ability to decompose certain materials. Additional considerations include uniformity, capital equipment cost, number of deposition cycles, thickness control, adhesion, shadowing effects, and film properties such as grain size and step coverage.

In conclusion, physical vapor deposition (PVD) is a versatile technique for film deposition, based on the formation of a vapor from a solid material, which is either heated until it evaporates or sputtered by ions. This vapor then condenses to form a thin film on a substrate.

In sputtering, ions are typically generated by plasma discharge using an inert gas, most commonly argon. However, it's also possible to bombard the sample with an ion beam from an external ion source, allowing control over the energy and intensity of ions reaching the target. This flexibility enhances the sputtering process.

That's all for this overview on sputtering. In the next class, we’ll dive into micromachining, exploring how surface and bulk micromachining techniques can be used to create diaphragms. In the meantime, I encourage you to review this lecture to solidify your understanding of sputtering, as well as the differences between thermal evaporation, E-beam evaporation, and vacuum deposition. This is all part of grasping the various methods for depositing thin films.

I’ll see you in the next class with a new topic. Until then, take care and see you soon!