**Microsensors, Implantable Devices and Rodent Surgeries for Biomedical Applications**
**Course Instructor: Dr. Hardik J. Pandya**
**Department of Electronic Systems Engineering**
**Indian Institute of Science, Bangalore**
**Week - 04**
**Lecture - 12**

Welcome to this lecture, where we will continue discussing the hard bake process. The purpose of hard bake is to strengthen the photoresist, making it more resilient. This involves placing the photoresist on a hot plate for about one minute. Once the hard bake is complete, we have a patterned photoresist ready for inspection.

Now, you might wonder why we go through the effort of patterning the photoresist. To illustrate this, let's consider an example. Imagine we have a silicon dioxide wafer, which is silicon with a layer of thermally oxidized silicon dioxide. This oxide layer is created using thermal oxidation or chemical vapor deposition (CVD) techniques. On this silicon dioxide layer, we apply a positive photoresist. Then, using a mask, we expose the photoresist to UV light and develop it, resulting in a pattern. After a final hard bake, we achieve the desired pattern on the photoresist.

Now, let's discuss why we are interested in patterning this photoresist. If we were to immerse this wafer in a silicon dioxide etchant such as buffered hydrofluoric acid (BHF), something interesting happens. The BHF reacts with the silicon dioxide but does not affect the photoresist. As a result, the patterned photoresist acts as a mask, protecting certain areas of the silicon dioxide while allowing others to be etched away. This selective etching process is crucial for creating intricate structures and patterns on semiconductor wafers.

When we dip wafer A, which is coated with positive photoresist, into buffered hydrofluoric acid (BHF), the silicon dioxide protected by the photoresist remains intact while the unprotected areas of silicon dioxide get etched away. This selective etching process creates a pattern on the silicon dioxide layer.

On the other hand, if we dip wafer B into acetone, which is a known photoresist stripper, the photoresist layer gets stripped off. This results in a patterned silicon dioxide layer on the silicon substrate, which we'll refer to as wafer C. To recap, initially, we had a wafer (let's call it step 1) where the entire silicon substrate was covered with silicon dioxide. Through photolithography, we were able to pattern the silicon dioxide layer as shown in the slide. This demonstrates the capability of lithography in creating precise patterns. Following this step, further processes such as heating can be carried out on the patterned silicon dioxide layer.

The main point here is that through photoresist patterning, we can protect certain areas of a material while exposing others to an etchant. This selective protection and exposure process allows us to create patterns in different materials. Hopefully, this explanation clarifies the lithography technique, which involves several steps such as wafer cleaning, pre-baking, photoresist application, alignment and exposure, development, hard bake, and pattern inspection. Let's revisit the slides to understand the process better. The wafer cleaning and pre-bake steps include methods like scrubbing with a bubble jet containing N2 and H2O, high-pressure rinsing, sonication, dehydration through pre-baking, and priming. Priming involves high-temperature baking to remove moisture and improve the adhesion of the photoresist onto the wafer. This is followed by applying HMDS and heating the wafer at temperatures ranging from 200 to 250 degrees Celsius for about 60 seconds.

So, in terms of wafer cleaning and lithography, once the photoresist is coated, it undergoes exposure using a bright field or dark field mask. In the case of positive photoresist, the unexposed areas become stronger, as depicted in this image. Now, let's delve into what a photoresist is. It's a solid organic material utilized to transfer a design pattern onto a surface by altering its photo solubility through a photochemical reaction upon exposure to light. For instance, in negative photoresist, the unexposed regions weaken, whereas in positive photoresist, the unexposed regions strengthen. The parameters of a good photoresist include high edge resistance and good adhesion. What does high edge resistance mean? Let's refer back to the slide for clarification.

Now, looking at the photoresist when it's immersed in buffer hydrofluoric acid, you can observe that the photoresist remains unaffected while only the silicon dioxide is etched away. This demonstrates the photoresist's high edge resistance, which means it can withstand such chemical treatments without deteriorating. Additionally, the photoresist must exhibit good adhesion to the wafer. How is this achieved? The wafer is secured onto a vacuum chuck, and approximately 3 to 5 ml of photoresist is dispensed onto it. Initially, a slow spin is applied to ensure a uniform coating, followed by increasing the spin speed based on the desired thickness of the photoresist. The centrifugal force spreads the photoresist evenly across the surface, and key quality metrics include time, thickness, speed, and uniformity. Defects such as particles on the wafer can occur, affecting both negative and positive photoresists.

It's important to note that you don't need to memorize all this information because it's readily available online through data sheets and suppliers. What I've demonstrated here is a simple example of how different masks, such as bright field and dark field masks, can create different patterns depending on the type of photoresist used. For instance, if you use a bright field mask with positive photoresist, you'll get a pattern that matches the mask. This pattern, which we can call P, will be the same as the inverse pattern or P star when using positive photoresist.

So, in summary, when using a bright field mask, the bright areas become dark and vice versa, depending on whether you're using negative or positive photoresist. Understanding how to use photoresist involves considering these factors, and we've already covered the parameters for photoresist usage. The image provided will help you visualize the setup with the spindle, vacuum chuck, and vacuum pump, which are essential components in the process.

The spindle rotates to spread the photoresist evenly, while the vacuum chuck holds the wafer in place to prevent it from flying off. About 3 to 5 ml of photoresist is dispensed, and as the spin speed increases, the thickness of the photoresist decreases. This relationship is such that higher spin speeds result in lower thickness, following the inverse square root relationship. Conversely, higher viscosity photoresist coatings lead to greater thicknesses at higher spin speeds, which is a straightforward concept. For soft baking, the recommended temperature and time for both positive and negative photoresists are typically 90 degrees Celsius for 1 minute on a hot plate. However, if an oven is used instead of a hot plate, the baking time may vary. It's crucial to refer to the photoresist's data sheet for specific instructions tailored to the product being used.

Soft bake serves several purposes for the photoresist. It involves partial evaporation of photoresist solvents, which in turn enhances adhesion, improves uniformity, enhances etch resistance, and optimizes light absorptions and characteristics specific to the photoresist. During the exposure of the photoresist to UV light through the photolithography system, the light passes through the lens, and the ideal light intensity is achieved as depicted. However, the deflected light collected by the lens is also significant, especially after being focused by the lens, resulting in the desired pattern formation on the photoresist.

Understanding the photolithography system, including how to load the mask and wafer, how to spin coat, and how to expose the photoresist, is crucial. A laboratory-recorded video can provide a comprehensive understanding of the entire process. Additionally, the development of the photoresist requires careful timing, known as the photolithography recipe. Adjusting the time in the recipe is essential to ensure the desired patterning outcome, as excessive time can lead to undesired results.

For instance, consider the development time specified for 1 minute. If you reduce it to 50 seconds, you won't achieve complete development in the photoresist, as illustrated here. These are hypothetical numbers used for explanation purposes. The key point is that the time or recipe is crucial. The recipe encompasses the types of chemicals to use and the process time, which significantly impacts the outcome. Decreasing the time can lead to incomplete development, while increasing it can result in overdevelopment. Sometimes, there might also be instances of underdevelopment. Therefore, the development profiles can vary based on these factors.

I have provided ample examples to illustrate the comparison between negative and positive photoresist. When faced with such questions, whether in an NPTEL exam, university, or college course, this summary can serve as a quick reference. It outlines how negative photoresist behaves with different masks compared to positive photoresist, influencing the desired pattern outcome in lithography. For those interested in the chemistry aspect, the slide highlights that photoresist serves two main functions: precise pattern formation and substrate protection. It delves into parameters such as optical properties (resolution, sensitivity, refractive index) and chemical-mechanical properties (viscosity, adhesion, thermal stability, etc.). While we won't delve deeply into these specifics in this course, understanding how materials react to light exposure is crucial, as demonstrated by the materials used in photoresist photolithography processes like g-line materials and eye-line resist.

Let's delve into UV radiation. The energy level of UV sources is typically lower than that of visible light. To compensate for this, chemical amplified photoresists are used to enhance efficiency, which falls under the material parameters of photoresists. During exposure to photons, a photo acid generator (PAG) is converted into an acid. In the subsequent post-exposure bake process, this acid molecule interacts with blocking molecules on a polymer chain, rendering it soluble in developer and regenerating the acid molecule. This process is fundamental to understanding how light exposure affects the hardening or softening of specific areas in photoresists.

The cross-linking of resins plays a crucial role in hardening the photoresist during subsequent hard bake processes. This process is essential for understanding how the mask functions. Before we can apply the mask onto glass, it needs to be designed using software like CleWin. The software assists in creating the mask design, which is then transferred to a glass plate coated with chromium. This is why masks are sometimes referred to as chrome masks due to the use of chromium in their fabrication. Electron beams are used selectively to pattern the mask according to the design generated in the software.

The mask-making process requires high accuracy, and the masks must be meticulously clean. Any defects in the mask can lead to incorrect features in the final devices or chips. Additionally, masks are typically 5 to 10 times larger than the actual features, as the features are scaled down during the lithography process. This scaling down is referred to as a 5x mask or 10x mask. Once the mask is designed and fabricated, it includes alignment marks and test structures for accuracy and calibration. I will now show you examples of multiple masks and how the alignment process works. Let me demonstrate this visually for better understanding.

So, let's take a look at mask 1 and mask 2 in the context of the previous slides. Imagine we have mask 1 and mask 2, and for this example, I'm intentionally drawing smaller alignment marks. Recall that in our earlier pattern, we had two triangles represented by these shapes. Now, let's say we have a wafer that has already been spin-coated with photoresist and undergone a soft bake process. We load mask 1 onto this wafer and perform UV exposure. After the UV exposure process, when we remove mask 1 and develop the photoresist on the wafer, we'll observe the pattern that corresponds to mask 1. This pattern will be visible on the photoresist layer after development. Let's move forward with this sequence.

Let's visualize the process further. Initially, your starting silicon wafer looks like this. However, after going through the mask 1 exposure and development process, your final silicon wafer will look like this due to the presence of the mask's pattern. This wafer has a layer of silicon dioxide on it, so the cross-section appears like this.

Now, after using mask 1 and obtaining this pattern on the wafer, you would dip this wafer in BHF to remove the silicon dioxide layer. The final pattern you get is represented by this diagram. Next, let's consider loading mask 2 onto a new wafer. After spin-coating with photoresist and a soft bake process, you load mask 2 onto the wafer. The alignment of mask 2 should be such that it precisely covers the triangle pattern from mask 1. How can this be achieved? By aligning the marks on mask 2.

The alignment mark on mask 2 (marked as "+") should fit exactly on top of the corresponding mark on mask 1. Why is the alignment mark on mask 2 smaller than on mask 1? This is done so that the alignment mark on mask 2 fits perfectly on the alignment mark on mask 1. This way, instead of aligning the entire pattern directly, we align the alignment marks, ensuring that all patterns align automatically.

Sure, let's delve into the discussion on defects in photo masks and their impact. The first defect we'll consider is a chrome spot, depicted as a highlighted area in this illustration. When we're dealing with devices on a larger scale, such as chips, having defects like chrome spots can lead to significant losses. For instance, within this triangle area affected by the chrome spot, you could potentially lose many devices or components crucial for the chip's functionality. Now, let's imagine a specific device like a micro heater, represented here by a meander-shaped structure. The purpose of this micro heater is to generate heat. How does it work? Well, imagine if we have contact pads connected to this metal structure. By applying voltage across these contact pads, we essentially create a resistance in the metal, causing current to flow through it. This flow of current leads to Joule heating, resulting in a temperature increase.

However, when there's a chrome extension or defect present, it can alter the resistance of this micro heater. This extension can disrupt the intended functionality of the micro heater, affecting its performance in terms of heat generation and temperature regulation.

Therefore, any defect in the photo mask, like a chrome spot, can have adverse effects on the devices and circuits fabricated using that mask.

Let's dive deeper into the impact of defects in photo masks on device functionality. When it comes to a micro heater or any similar device, the resistance calculation depends on factors like length and area. However, if there's a chrome bridging issue, as shown here, it can lead to a short circuit where lines are undesirably connected, disrupting the intended circuitry. On the other hand, if there's a pinhole defect, it can result in either no resistance at all or create gaps in the lines of the micro heater. This kind of inconsistency can affect the device's performance significantly. Moreover, a breakage in the lines, resulting in an open circuit, further impacts the resistance value and functionality of the device. Essentially, these defects like short circuits or open circuits are not acceptable as they deviate from the desired design and functionality of the device.

Therefore, during the mask design phase, it's crucial to be meticulous and avoid such defects to ensure the proper functioning of the devices. In the lithography sequence, we follow a systematic approach starting with wafer cleaning, pre-baking to remove moisture, spin coating the wafer with photoresist, and then carrying out soft baking. It's important to note that terms like pre-bake/post-bake and soft bake/hard bake are often used interchangeably, referring to similar steps in the process.

Let's clarify the terminology regarding pre-bake, soft bake, post-bake, post-exposure bake, and hard bake. These terms are often used interchangeably but refer to specific steps in the lithography process. Pre-bake is typically used for moisture removal before applying the photoresist, ensuring a clean surface for the subsequent steps. Soft bake and hard bake, on the other hand, refer to the spin coating of the photoresist onto the wafer and the subsequent baking process to change its properties. The temperature and duration of each bake step can vary based on the type of photoresist being used.

Moving forward in the process, after coating the wafer and applying the mask, we have post-exposure bake (PEB), which is crucial for stabilizing the exposed photoresist. Following PEB, the photoresist is developed to reveal the desired pattern. This sequence of exposure, development, and post-exposure bake is commonly used in lithography processes. It's important to note that these steps may vary slightly depending on the specific material being used for patterning. For instance, when working with materials like SU8, the development typically occurs after exposure and is followed by a post-exposure bake.

In summary, lithography involves projecting the image of the mask onto a photoresist, and the entire process includes designing the optical photolithography system, operating the exposure tool, optimizing the chemical processes during exposure, and managing the post-exposure treatments like development and baking.

We have created a comprehensive video demonstrating the utilization of a photolithography system within a controlled environment like a class 100 or class 1000 clean room. The light source utilized in such systems can vary from visible light to ultraviolet (UV), deep ultraviolet (DUV), or even extreme ultraviolet (EUV), depending on the desired image characteristics. The performance evaluation of a lithography system revolves around three primary criteria. Firstly, resolution, which denotes the minimum feature size achievable. For feature sizes below 2 micrometers, particularly in the nanometer range, e-beam lithography is preferred, while UV lithography is commonly employed for larger feature sizes above 2 micrometers. The choice of lithography method is influenced by the wavelength of light used during material exposure.

Secondly, sensitivity of the photosensitive material is crucial, as it determines the material's response to light and its ability to form accurate patterns during exposure. Proper alignment of the mask with the wafer is equally critical, as any misalignment can lead to inaccuracies in pattern replication on the substrate. For achieving smaller feature sizes, light sources with shorter wavelengths are typically employed. While mercury vapor lamps were traditionally used, modern systems predominantly utilize ultraviolet sources. Standard wavelengths such as the g-line (436 nanometers) and i-line (365 nanometers) are commonly employed for specific pattern dimensions, such as 500 nanometer and 350 nanometer patterns. Additionally, advanced light sources like KRF and ARF lasers cater to different feature requirements. In essence, the exposed system and optics play a paramount role in modern lithography techniques, serving as the cornerstone for precise pattern replication and high-resolution imaging on substrates.

There are three main types of exposure tools used in lithography: contact printing, proximity printing, and projection printing. In contact printing, the mask is directly in contact with the silicon wafer. Proximity printing involves placing the mask close to the silicon wafer coated with photoresist, while projection printing projects the pattern onto the wafer coated with photoresist.

In contact printing, the mask, with its chrome side down, touches the photoresist layer on the wafer directly. Light passing through the mask exposes the resist layer. Contact printing systems offer high-resolution printing due to the direct mask-to-wafer contact, resulting in good resolution and minimal diffraction effects. However, they are not suitable for printing very small features and are not efficient for high-volume manufacturing. Additionally, the hard contact between the mask and the resist layer can potentially damage or contaminate the mask, posing challenges in contact printing processes.

These limitations are specific to contact-based lithography or contact printing. In contrast, proximity printing addresses some of these challenges by significantly reducing the risk of contaminating the mask since it doesn't involve direct contact. In proximity printing, the mask and the wafer are typically separated by 5 to 25 micrometers, hence the term "proximity." However, this separation can lead to degraded resolution due to diffraction patterns. The practical minimum feature size achievable with proximity printing is typically around 20 microns. The resolution of the system can be improved by using shorter exposure wavelengths. For instance, in x-ray lithography where the wavelength is between 1 to 2 nanometers, proximity printing can achieve higher resolution. While proximity printing generally has poorer resolution, utilizing x-ray wavelengths can enhance its performance significantly.

Both contact and proximity printing methods require 1x masks, which can be challenging to produce for reduction systems. However, in projection printing, which you can see illustrated here, there is usually a 4x or 5x reduction. This system provides high resolution while avoiding mask contamination issues. In projection exposure tools, the mask is physically separated from the wafer, and an optical system is utilized to project the image of the mask onto the wafer.

This separation effectively resolves the contamination concerns associated with contact printing. However, the resolution of projection printers is often limited by diffraction effects. Typically, the optical system reduces the mask image by 4 to 5 times, which means that only a small portion of the wafer is exposed during each exposure cycle. To cover the entire wafer, steppers or motors are commonly used to scan across the entire substrate.

E-beam lithography, or electron beam lithography, involves the use of an electron gun that generates a high-energy electron beam. This beam passes through various components such as the alignment coil, blanking plates, secondary condense lens, and limiting aperture before reaching the final lens and coils. The electron beam then scans across a substrate coated with a resist material, with a mechanical stage moving to expose specific areas as needed. One of the key advantages of e-beam lithography is its ability to overcome the size limitations of optical lithography. In optical lithography, resolution is limited by the wavelength of light used, typically in the range of a few hundred nanometers. In contrast, an electron beam has a much smaller wavelength, around 0.62 angstroms, with an energy of 2480 electron volts, allowing for significantly higher resolution.

E-beam lithography utilizes a very narrow beam to directly write patterns onto the wafer, making it a direct writing method. This enables achieving resolutions as fine as 20 nanometers, compared to the micrometer range of UV lithography in photolithography. However, a limitation of e-beam lithography is that wafers need to be written individually, making the process time-consuming.

E-beam lithography presents several limitations, such as being a scanning method unlike conventional lithography, which is a one-shot exposure process. Additionally, this system requires a high vacuum of about 10^-6 torr, making it a costly and slow process. Another factor to consider is the backscatter of electrons, which can impact the resolution of the process. Our central facility, known as the Central for Nano Science Engineering, houses various fabrication techniques like CVD techniques, RIs, DRIs, reactive etching, deep pre-etered etching, and characterization facilities for institute users and others.

The mask aligner is a crucial tool used to align the wafer and expose the photoresist coated onto it. It provides three degrees of freedom: x, y, and theta (rotation axis). This enables the alignment of the wafer to the mask prior to exposure. In a semi-automated system, alignment is performed manually, while in advanced automated systems, automatic pattern recognition is utilized in the alignment process. We have detailed videos of the mask aligner in our lab, which can greatly aid in understanding how it operates.

In the academic setting, semi-automatic systems are commonly used for aligning the mask with the wafer, requiring manual alignment. However, advanced lithography systems like the mask calender utilize image recognition for automatic alignment. Additionally, to view both the plus marks simultaneously, a split-field microscope can be employed. With that, we conclude this section on lithography. While we covered a fair amount of detail, it was balanced to provide a comprehensive understanding without delving too deep into complexities. Laboratory recordings specific to this course are available, showcasing how the photolithography system is utilized in practice.

With this explanation, I trust that you now understand how the photolithography system is utilized. The steps involve cleaning the wafer, pre-baking it, spin-coating the photoresist, soft baking it at 90 degrees for 1 minute on a hot plate (or as per the photoresist type), loading the mask, exposing the wafer with UV light, unloading the mask, developing the wafer to remove the photoresist, performing a hard bake at 120 degrees for 1 minute on a hot plate (or as required), and finally inspecting the wafer. This process encompasses various components such as spin coaters, different types of masks, and exposure systems using UV or E-beam. In the upcoming class, we will delve into designing various etching techniques because once you have the pattern, the next step is to understand how to etch it effectively.

In the next class, we will look into different etching techniques, and shortly after that, we will move on to the fabrication of neural implants. It's essential to grasp the fundamentals of the process and familiarize ourselves with the recipes and techniques that will be employed for creating the neural implants. Until then, take care, and I'll see you in the next class. Goodbye!