Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

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Lecture - 27

Hello and welcome to today's class. We will be discussing a very important technique called photolithography. The term "photolithography" is derived from the Greek words photos (light) and lithos (stone), meaning "carving from a single stone." In this lecture, we will focus specifically on ultraviolet (UV) photolithography.

There are various types of lithography techniques, such as X-ray lithography, electron beam lithography, and UV lithography. However, for this class, our attention will be on UV lithography. Before diving into lithography itself, it's important to understand some key concepts. The first term is photoresist. There are two types of photoresists: positive and negative.

Another important concept to understand is masks, which come in two types: bright field masks and dark field masks. So, to summarize: we have two types of photoresist (positive and negative) and two types of masks (bright field and dark field). It's that simple!

Now, let's dive into the properties of photoresist. If we use a positive photoresist, here's what happens: imagine this is the mask, and let's say it has a pattern like a plus sign. If we apply positive photoresist, the pattern on the mask will transfer exactly onto the wafer. However, if we use negative photoresist, the pattern will be reversed on the wafer. So, to clarify: with positive photoresist, the pattern on the mask stays the same on the wafer, and with negative photoresist, the pattern on the mask is reversed on the wafer. Simple! Same pattern with positive photoresist, opposite pattern with negative photoresist.

Different books may explain this concept in various ways, but the essence is the same. For positive photoresist, the area exposed to ultraviolet (UV) light through the mask becomes weaker. So, when we have a wafer coated with photoresist and expose it to UV light through the mask, the exposed area becomes weaker, making it easier to remove during development. The unexposed areas remain stronger. This is the case for positive photoresist, as shown in the example.

In contrast, with negative photoresist, the area exposed to UV light becomes stronger, and the unexposed area becomes weaker and easier to remove during development. This is how negative photoresist works.

Now, let’s move on to the masks. I'll show you how they look. First, I’ll put on gloves to handle the mask properly. The material we use for these masks is chrome, so they are often referred to as chrome masks. Let’s take a look at both bright field and dark field masks, which are essential in this process.

Let me first show you the bright field mask. Can you see it here in my hand? This is what we call a bright field mask. The field is bright, and the pattern is dark. You can see some specific patterns in this field, and if you look closely, you can even see my face through the transparent areas. This is because the field is bright, and the pattern is dark—hence the name bright field mask.

This particular mask is a 5-inch mask. You might be wondering how I know it’s a 5-inch mask—well, I’ll show you by comparing it to the wafer. Here, I’m holding a 4-inch wafer. This is not the correct way to handle it, but just to give you an idea, I’ll show you how the mask fits with the wafer. Once you load the wafer into the system, you’ll see how it fits. The wafer is placed onto the mask aligner, which is a part of the lithography system, and this is how it looks when loaded.

As you can see, there’s a wafer now loaded beneath the 5-inch mask. The wafer gets exposed through the mask as light passes through it. In the areas that are transparent, light will pass through and expose the wafer. The non-transparent areas will block the light. Remember, this is a 4-inch wafer with a 5-inch mask, and the wafer is double-sided silicon. To hold the wafer properly, we use tweezers, which ensure we don’t damage the surface.

Now that you’ve seen the bright field mask, let’s take a look at the dark field mask. Here it is. Notice how most of the field is dark, and only certain areas are transparent. Just like the bright field mask, this is also a 5-inch chrome mask. In this case, the majority of the area is dark, and only a few regions are transparent. This is what we call a dark field mask.

So far, you've seen the bright field mask, dark field mask, and silicon wafer. You’ve also learned about thermal oxidation. Now, we’re ready to move on to the next step, which is the photolithography process. I’ll guide you through how we pattern different materials in order to create devices.

Here, you can see the tweezers we use to hold the wafer. There are different kinds of tweezers, and I’ll show you a few examples. Tweezers are essential for carefully handling the wafer without contamination or damage. Now, let's take a look at the screen and go through the steps of photolithography

Let's begin by understanding the purpose of photolithography. It is used to print features onto a wafer, either directly or by using a photoresist. Typically, the top surface of a sample is patterned with photoresist by exposing it to UV light, followed by development and etching of the target layer.

The first step in this process is wafer cleaning, which is crucial to ensure the surface is free from contaminants. This cleaning process is known as RCA1 and RCA2 cleaning. "RCA" stands for Radio Corporation of America. After cleaning the wafer, we proceed to the next steps: pre-bake and primer coating.

- Pre-bake is used to evaporate any moisture left on the wafer. After cleaning, we rinse the wafer with DI water (deionized water). However, there may still be residual moisture on the wafer, so we pre-bake the wafer at approximately 150°C to remove this moisture.
- Following the pre-bake, we apply a primer coating. The purpose of the primer is to improve the adhesion of the photoresist to the wafer. It's important to note that primer coating isn't always required for every lithography step, but it's essential in some cases.

Next, we move on to photoresist spin coating. This process involves applying the photoresist onto the wafer, and the spin coating is done in two stages:

1. Lower RPM (around 500 RPM) is used initially to ensure a uniform deposition.
2. After the initial stage, the RPM is increased to around 2000-3000 RPM to achieve the desired thickness of the photoresist.

The thickness of the photoresist can vary. For example, we can achieve thicknesses from 1 micrometer to 3 micrometers, depending on the process. For thicker photoresists with high viscosity, we can reach up to 5 micrometers. In certain cases, such as with SU-8 photoresist, the thickness can even go up to 200 micrometers.

Once the spin coating is complete, we perform a soft bake (also called a pre-exposure bake). This is done at 90°C for about one minute on a hot plate to prepare the photoresist for exposure.

After the soft bake, we move to the next critical step: alignment and exposure. This step involves aligning the wafer with the mask. You’ve seen how a mask aligner works, and aligning the mask with the wafer is essential for the patterning process.

For example, if this is the mask (hold it up to visualize), imagine aligning it with the wafer below. This alignment step ensures that the pattern from the mask transfers correctly onto the photoresist on the wafer.

In the photolithography process, the first step is wafer cleaning, followed by pre-bake and primer coating. Wafer cleaning is essential to ensure that the surface is free of contaminants, using methods such as bubble jet, high-pressure rinse, or sonication. After cleaning, the wafer undergoes a dehydration bake (or pre-bake) at around 150°C to remove any residual moisture, ensuring the surface is ready for subsequent steps. Next, the wafer is coated with a primer, typically HMDS (hexamethyl disilazane), to enhance the adhesion of the photoresist. After applying the primer, the wafer is heated at 200°C to 250°C for about a minute to ensure proper adhesion.

Following this, the photoresist is applied using a spin-coating technique. Initially, the wafer spins at a lower RPM (around 500 RPM) to allow for uniform deposition, followed by an increase in speed (around 2000-3000 RPM) to achieve the desired photoresist thickness, typically ranging from 1 to 3 micrometers, but thicker layers (up to 200 micrometers) are possible with materials like SU-8. Once the photoresist is applied, a soft bake (or pre-exposure bake) is performed at 90°C for 1 minute on a hot plate, helping to further evaporate any remaining solvents in the resist layer.

The next step is alignment and exposure, where the wafer is aligned with the mask and exposed to UV light. The wafer can be moved in the X and Y directions, or rotated in the theta direction to ensure precise alignment with the mask. After exposure, depending on the type of photoresist used (positive or negative), the exposed areas will either weaken or strengthen. In the case of positive photoresist, the exposed areas will weaken and be washed away during development, transferring the pattern from the mask to the wafer. After development, the wafer undergoes a hard bake at 120°C for 1 minute to ensure that the photoresist adheres well and is ready for further processing. Finally, the patterned wafer is inspected to verify the quality of the transfer.

In summary, photolithography involves wafer cleaning, pre-bake, photoresist application, soft bake, alignment and exposure, development, and hard bake. The photoresist is a crucial organic material used to transfer the mask pattern onto the wafer's surface, playing a key role in defining the features for further etching or device fabrication.

When a photoresist is exposed to UV light, it undergoes a photochemical reaction that changes its photosolubility. This means that its solubility in a developer solution is altered due to the exposure. A key characteristic of a photoresist is its high etch resistance and good adhesion. High etch resistance ensures that the photoresist can withstand the etchant used during the etching process without being removed or damaged. Good adhesion means that the photoresist must stick well to the surface of the wafer, ensuring that the pattern remains intact throughout the process.

Let’s consider an example. Suppose we have a silicon wafer with an oxidized silicon layer on top, and above that, a layer of aluminum. After applying the photoresist on top of the aluminum, we perform photolithography. This process includes spin-coating the photoresist, performing a soft bake, aligning the wafer with the mask, exposing the wafer to UV light, developing the pattern, and finally performing a hard bake. At the end of this process, the photoresist is correctly patterned on the wafer.

Now, if we dip the wafer into an aluminum etchant, we expect that the aluminum will be etched away from all areas except those protected by the photoresist. However, if the etch resistance of the photoresist is poor, the etchant will also remove the aluminum under the photoresist, ruining the pattern. Therefore, a good photoresist must resist the etching process, ensuring the pattern is properly transferred.

To coat the photoresist, we initially dispense 3-5 ml of the photoresist onto the wafer and perform a slow spin followed by ramping up the spin speed to around 1100-5000 RPM. The photoresist spreads across the wafer due to centrifugal force, and the key parameters to control here are time, thickness, spin speed, and uniformity. The faster the spin speed, the thinner the photoresist layer. Conversely, slower spin speeds result in a thicker layer.

There are two types of photoresist: positive and negative, and two types of masks: bright field and dark field. For example, if you use a bright field mask with a positive photoresist, the pattern on the mask will be replicated on the wafer. However, if you use a negative photoresist, the opposite pattern will appear on the wafer.

In terms of equipment, the wafer is held by a vacuum chuck to prevent it from flying off during spinning. The spindle spins the wafer, while the photoresist is dispensed using a photoresist dispenser. A slow initial spin ensures a uniform coating, and the final thickness is determined by adjusting the spin speed and time. Increasing the spin speed results in a thinner photoresist layer, while longer spin times will further reduce the thickness

If you decrease the time of rotation during spin coating, the thickness of the photoresist increases. The relationship between thickness and spin speed is such that thickness is inversely proportional to the square root of the spin speed. Different photoresists, such as viscous, less viscous, or highly viscous types, require careful consideration of various factors, including the use of HMDS (Hexamethyldisilazane) and the specific data sheet for each photoresist. The data sheet provides important details about soft bake and hard bake temperatures, as well as the process time for each stage of lithography.

The soft bake plays a crucial role in improving adhesion, ensuring uniformity, enhancing etch resistance, and optimizing light absorbance, all of which are important characteristics of the photoresist. After performing the soft bake—typically done at around 90°C for 1 minute—the wafer should be cooled to room temperature before UV light exposure to ensure accurate patterning.

Understanding the optics of lithography is essential, particularly how light passes through the mask. The distance between the mask and the lens, which collects the diffracted light, is critical. While the ideal light intensity should follow a predictable pattern, practical results may deviate slightly. Additionally, the dosage of UV light exposure varies depending on the material being processed, so optimizing process parameters is essential.

After exposure, the next step is developing the photoresist by dipping the wafer into a developer solution. Proper development ensures good feature size, but underdevelopment may leave excess photoresist, and overdevelopment can lead to etching areas that should not be removed. Therefore, following the process time and recipe is vital for success.

For negative photoresist, the exposed areas become stronger, while unexposed areas become weaker. Conversely, with positive photoresist, the exposed areas become weaker, and the unexposed areas remain strong. Understanding this principle is crucial when working with masks.

In terms of mask design, software tools like Clewin and AutoCAD can be used to create the mask pattern. The mask material is typically a glass plate coated with chromium, also known as a chrome mask. The mask is patterned using an electron beam to selectively remove the chrome, forming the desired pattern. It is important that the mask be completely defect-free to ensure accurate lithography results.

Defects in photomasks can significantly affect the performance of devices or chips. In future sessions, we will explore alignment and test structures using a two-step lithography process to fabricate a device. During this process, you will see how alignment marks, such as those shown here, help in aligning the wafer with the second, third, and subsequent masks. Additionally, different materials, such as Fe_2O_3 on soda lime glass, can be used to create masks. There are various types of masks, including chrome masks and bright field masks, where most of the field is transparent, and dark field masks, where most of the field is darker.

Defects in photomasks come in many forms and can degrade device performance. Common defects include chrome spots, chrome extensions, chrome bridging, clear breaks, pinholes, and clear extensions. Each of these defects can cause problems. For example, if there’s a pinhole in the mask while fabricating a resistor, the resistance, calculated by $\rho L/A$ (resistance in ohms), will be altered. A hole or break can change the measured resistance, leading to an open circuit, while a short can cause a short circuit. Defects like chrome extensions and chrome spots can interfere with the design, especially in large-scale devices like chips with millions of transistors. Even minor defects can lead to the failure of many transistors, which is why any defects in the photomask are unacceptable.

The lithography process involves several steps. Starting with a clean wafer, the photoresist is coated, pre-baked, aligned with the mask, and exposed to UV light. Following this, a post-exposure bake is done, the photoresist is developed, and the patterns can be inspected. Lithography can be understood as a process in which the image of the mask is projected onto the surface coated with photoresist. A typical optical photolithography system includes the mask aligner, which handles the design and operation of the exposure tool. Additionally, optimizing the chemical processes during the exposure of the photoresist is crucial.

The light source used in lithography can range from visible to ultraviolet (UV), deep UV, or extreme UV light. There are three primary measures of lithography system performance: resolution, sensitivity, and alignment. Resolution refers to the minimum feature size that can be achieved, and it depends on the ability of the photoresist to reconstruct the pattern from the aerial image. Sensitivity refers to how responsive the photoresist is to the exposure process. Lastly, the alignment system's precision determines how accurately the mask is aligned with the wafer, which directly impacts the yield and accuracy of the fabricated devices, reducing failure rates and improving overall device quality.

To achieve smaller feature sizes, a shorter wavelength light source can be used. In UV lithography, a typical feature size is around 2 microns, but using electron beam lithography, much smaller features can be achieved due to the shorter wavelength. There are various light sources available, such as g-line, i-line, KrF laser, and ArF laser. Lithography or exposure systems can utilize three main types of printing techniques: contact printing, proximity printing, and projection printing.

In contact printing, the mask is placed in direct contact with the photoresist layer on the wafer, with the chrome side facing down. As shown in the illustration, the physical contact between the mask and wafer allows for high-resolution printing. However, this method is inefficient for producing very small feature sizes and is not suitable for high-volume manufacturing because the mask and wafer must be aligned and physically contacted for each exposure. Additionally, the hard contact may damage or contaminate the mask. The advantage of contact printing is its higher resolution, but its limitations include contamination risks and unsuitability for large-scale production.

Proximity printing addresses the contamination issue by avoiding direct contact between the mask and wafer. In this method, there is a small gap between the mask and the wafer, which helps prevent contamination. However, this separation can degrade the resolution, and the minimum achievable feature size is typically around 20 microns. The system's resolution improves as the wavelength decreases. For example, using x-rays with wavelengths between 1-2 nanometers offers better resolution. Both contact and proximity printing require 1X masks, which are challenging to produce for reduction systems.

The third method, projection printing, is the most commonly used in lithography. It provides high resolution while avoiding mask contamination since there is no physical contact between the mask and the wafer. In projection printing, the mask and wafer are physically separated, preventing contamination. Optical systems in projection printing often reduce the image size by 4X or 5X, meaning that only a small portion of the wafer is printed with each exposure. Steppers are then used to expose the entire wafer gradually.

For further resolution improvements, electron beam lithography can be used. In this system, an electron gun emits electrons that pass through various optical components such as alignment coils, conditioning lenses, blanking plates, and apertures before reaching the photoresist substrate. The electron beam scans the substrate and exposes it simultaneously. In optical lithography, the size limitations arise from the fact that resolution depends on the wavelength of light. Therefore, shorter wavelengths, such as those in electron beam lithography, offer a path to smaller feature sizes.

As the electron beam has a much smaller wavelength, electron beam lithography (e-beam lithography) can achieve significantly higher resolution compared to optical methods. This technique uses a very narrow electron beam to directly scan and write patterns on the wafer, a process known as direct writing. The system includes an electron source, lenses, and a reflector. With e-beam lithography, a resolution of around 20 nanometers is possible. However, this method has its drawbacks: because each pattern must be written individually, it is a slow process. Moreover, it requires a high vacuum environment, typically around 10^{-6} torr, making the process both time-consuming and expensive.

In terms of mask aligner systems, which we'll see in recorded videos, there are examples from our facility, such as the EVG 620 and the MJB4. In the EVG 620, the wafer is loaded here, and the mask is loaded there. This system features split-field microscopy, allowing you to simultaneously view the alignment marks on both the mask and the wafer. The MJB4 also provides a stage for aligning the wafer and mask, crucial for transferring the desired features from the mask onto the wafer.

In future classes, we will explore an example using a pressure sensor to demonstrate the role of alignment marks in achieving precise features. Although this section on lithography has been a bit fast-paced, I hope you now have a better understanding of how lithography enables the patterning of various materials. In the upcoming classes, we'll delve deeper into how lithography works in combination with physical vapor deposition techniques to fabricate devices. In the meantime, feel free to review these slides and lecture notes, and don't hesitate to ask any questions on the NPTEL forum. Take care, and see you next time.