Microsensors, Implantable Devices and Rodent Surgeries for Biomedical Applications

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Hi, and welcome to this class. In the last session, we discussed lithography, and I mentioned that we would explore micromachining, including bulk micromachining, surface micromachining, and etching in particular. When you etch a material, you can either etch the bulk material or the material deposited on the substrate's surface to create a pattern. This process is known as surface or bulk micromachining. However, regardless of the approach, etching is essential for patterning.

Now, there are two types of etching: wet etching and dry etching. In wet etching, let's consider the example of etching silicon. For silicon, we use potassium hydroxide and tetramethylammonium hydroxide (TMAH). KOH is used at 80 degrees Celsius, while TMAH is used at 25 degrees Celsius (room temperature). However, TMAH is neurotoxic, so it's crucial to handle chemicals carefully, especially in a wet bench environment. There are specific procedures for operating and handling chemicals within the bench to ensure safety. For instance, avoid putting your head inside the hood; instead, only your hand should be inside to prevent exposure to gases or VOCs emitted by the chemicals. These gases are filtered and exhausted outside, ensuring a safe working environment.

Before we delve into separate topics, it's important to note that not all devices we discuss in this course require etching processes. We'll touch upon etching later. Now, let's walk through the process steps for designing simple interdigitated electrodes. This exercise will help reinforce our understanding from the lithography lecture and demonstrate how we can apply that knowledge to pattern materials deposited on a substrate. Let's begin with an example of interdigitated electrodes.

Now, let me show you what exactly an interdigitated electrode means. You see, these are digits, right? 1, 2, 3, 4, 5—these are digits, and this is an interdigit. So, now, if you have many fingers like this, it becomes interdigitated electrodes. Now, why do we call it an electrode? Because if these lines are metal and they are not touching, the resistance is infinite; when they are touching, it creates a short circuit.

When you place any material on this interdigitated electrode, you will observe a change in resistance depending on the material's resistance, isn't it? So, the question is, how do we design these interdigitated electrodes? Let's take an example of aluminum, and then I will demonstrate it to you. If you recall our discussion on CVD, we recently explored different types of CVDs, particularly PCVD, which is used at lower temperatures—around 100 to 130 degrees Celsius, compared to other CVD methods. Understanding why PCVD is crucial for certain processes is essential. So, let's examine an example involving aluminum. We will deposit silicon dioxide on aluminum and then explore how we can apply our knowledge from previous classes to design this specific electrode. If you look at the screen, we will discuss interdigitated electrodes further.

So, if I show you the top view, it should look like this, right? We should have some contact pairs; contact pairs are crucial here. This is the structure we want to pattern. Now, when I draw the line, you know, this line, if you zoom in, it has a specific width and spacing. Let's say the width is 10 microns, and the spacing is 5 microns. When dealing with biosensors, closer electrodes enhance sensitivity for certain applications. However, let's not delve into that right now; just understand that the width and spacing between electrodes are crucial for interdigitated electrodes.

Now, if you want to do this, let's start the process, okay? So, we start, and this is the oxidized silicon wafer—assume that the substrate is your oxidized silicon wafer, and this interdigitated electrode is made up of aluminum—aluminum interdigitized electrodes, right? So, let's start.

The first step is to take a silicon wafer; we'll draw the cross-section—this is the top view. So, you have silicon as a substrate, and then, of course, you do pre-cleaning. You dip this wafer into HF. HF stands for hydrofluoric acid. When you dip the wafer in HF for a certain duration, the native oxide—the oxide that is grown onto the silicon due to the presence of oxygen in the atmosphere—that oxide, which is the native oxide, can be etched because hydrofluoric acid is an etchant for oxide. So, when you dip the wafer, the oxide will get etched. Now, you take the wafer out, dip it in DI water, rinse it with DI water, dry it with nitrogen, and then do the pre-bake so that the moisture is gone, and then you start your process. So, the next process is performing thermal oxidation.

Thermal oxidation is a technique by which we grow silicon dioxide on silicon, alright? It involves a furnace where you can load many wafers, close to 25 wafers initially. The temperature is raised to 900 to 200 degrees Celsius in that range. While the temperature is rising, nitrogen flows in the tube because it's a horizontal tube furnace. When the desired temperature is reached, the nitrogen flow is stopped, and oxygen flows through the tube. When oxygen reacts with silicon, it forms silicon dioxide; this is a dry oxidation process: $Si + O_2 \rightarrow SiO_2$. However, if we want to use wet oxidation, water vapor is introduced into the horizontal tube furnace. The reaction becomes: $Si + H_2O \rightarrow SiO_2 + H_2$, but we need to balance the equation. So, it becomes $Si + CH_2O \rightarrow SiO_2 + H_2Si + H_2O$, which simplifies to $2H_2O$ and $2H_2$, giving us $4O_2 + 4SiO_2$ as exhaust. This is known as wet oxidation. In the case of dry oxidation, $Si + O_2 \rightarrow SiO_2$ is the gas. This results in a water vapor of $2H_2O$. This is how silicon dioxide is formed, but the dry process yields better quality. In the dry process, the thickness can be close to 2 microns, while in wet oxidation, the thickness is comparatively less.

So, again, we will use this process called thermal oxidation, okay. We will look into the thermal oxidation process; erase this because we need this space for our process flow. So, the next step, step 1, is to take a silicon wafer, then clean it or pre-clean it, remove the native oxide, then pre-bake it, followed by thermal oxidation. So, step 1, step 2 is we have grown thermal oxide. Now, when you take the wafer and place it into the chamber or into the horizontal furnace, the oxide will grow on both sides because oxygen will react with silicon on the front and back sides of the silicon.

So, you can grow silicon dioxide on the front and back. Now, let's take an example of wet thermal oxidation, so that we have about 1 micron thick silicon dioxide. The next step is to deposit aluminum. Now, how do you deposit aluminum? Can you recall from our previous lectures? You can use physical vapor deposition, okay. This is SiO_2 over silicon, physical vaporization.

So, SiO_2 over silicon is oxidized silicon vapor, okay, do not get confused. PVD, we can use thermal evaporation. With thermal evaporation, you can deposit aluminum onto the oxidized silicon substrate, that is, aluminum SiO_2 silicon SiO_2, using thermal evaporation, okay, nice. This is our step number 3. Next, we go to the next slide, alright? The next slide is where we will draw the oxide layer. Once you understand this process, it becomes very easy to fabricate a lot of devices and pattern a lot of materials, okay.

So, that is why I am drawing each step again and taking enough time so that I hope you understand this aluminum layer on aluminum. Now, you have to pattern the aluminum, right? If you go back and look at this cross-section, how it will look like, okay. This will look like this: aluminum interdigitated electrodes, silicon, and these layers are SiO_2, okay. So, we want this particular pattern starting with the silicon.

So, silicon oxide, aluminum deposition, or aluminum which is deposited as a thin film. We will spin-coat positive photoresist, this is our fourth step. After spin-coating photoresist, what is the next step? Do you remember? Soft bake, right? Next step after soft bake is mask, no. So, we require a bright-filled mask. Why am I saying bright-filled? I will show it to you. This is our oxide, you do not need to write down every time like this. If you correctly give different patterns, for example, on the side you say, "Okay, this is my silicon, then this is my silicon dioxide, then this is aluminum, then this is photoresist," then we do not have to mention every time, okay? If you draw the process correctly. So, SiO_2, on that, we have our aluminum. What happens here is aluminum on aluminum; we have photoresist which is already soft-baked. On photoresist, we will load the mask, okay? And I said, what, bright-filled mask.

So, filled is bright, pattern is opaque or dark. Filled is bright, pattern is dark, okay? By filled mask. Now, once you load the mask and align the wafer, the next step is exposure using UV light, ultraviolet light. Once you expose the photoresist, which is a positive photoresist here, with UV light, the unexposed region will become stronger. After exposing with UV light, you unload the mask. The next step is, write down here or draw here, you dip the wafer in a photoresist developer. Correct, we dip the wafer in photoresist developer. When you dip the wafer in photoresist developer, what will happen? The photoresist will get patterned similar to your mask because the unexposed region becomes stronger.

The next step is hard bake, hard bake at 120 degrees for 1 minute on a hot plate. After hard bake, you dip the wafer in an aluminum agent. When you dip the wafer in the aluminum agent, what will happen? Okay, the area which was not protected by photoresist, you see this area which is not protected by photoresist. The area which is not protected by photoresist will get etched in the aluminum agent, meaning the aluminum, which is not protected, on this particular oxidized silicon substrate. So, the aluminum, which is not protected by the photoresist, will get etched, and aluminum, which is protected by the photoresist, will not get etched. So, after this, the next step is the role of photoresist is to act as a mask, to act as a mask, okay.

Now, the next step, we are at step 6 and 7, right? Step 7. So, the next step is that we need to strip the photoresist. If you want to strip the photoresist, we will dip that wafer in acetone. Okay, we will dip this one as the next step in acetone, okay. If we dip the wafer in acetone, what will happen? Acetone is the stripper for photoresist, okay. Acetone is the stripper for photoresist. So, what we will have is aluminum interdigitated electrodes, you see. Now let us say this is step 8. Now, you see this, and remember, okay, this pattern you remember. Let us go back one step, two steps back, see this one is similar to our step 8, isn't it? We have an oxidized silicon substrate on which there are aluminum interdigitated electrodes.

So, that is what we have got here also. So, this is the beauty of lithography that you can pattern the aluminum material or any other material, per se, and get different structures. Now let us take an example of this P CVD and its advantage, okay. I want to now deposit silicon dioxide, a grown silicon dioxide, on this particular wafer. So, if I go for any other CVD techniques, right, then you know that the temperature is greater than 700 degrees Celsius. But if I heat the wafer, so that I can have... So, what I want is I will show it here, this is what I want, okay. I want my aluminum interdigitated electrodes to be covered by silicon dioxide to join two points, okay, good. Now this is our silicon dioxide, okay, the dotted region is silicon dioxide. So, this is the silicon dioxide that I want on this particular aluminum interdigitated electrodes. But as you know, silicon dioxide, this thermal oxidation, this one, this silicon dioxide is using thermal oxidation, and in thermal oxidation, the temperature is 900 to 1200 degrees Celsius.

If I heat this particular wafer, which is wafer number 8, at 1200 degrees Celsius and even at 700 degrees Celsius and above, what will happen? The aluminum interdigitated electrodes will melt because aluminum's melting point is comparatively lower. So, in this case, I cannot use my thermal oxidation technique. So, what are the alternatives? One alternative is you can go for sputtering. And the second alternative is you can use PECVD (plasma-enhanced chemical vapor deposition).

We can use plasma-enhanced chemical vapor deposition because PECVD can be used at 100 degrees Celsius to 200 degrees Celsius, and this temperature will not affect the aluminum interdigitated electrodes. So, if I go for PECVD or if I go for sputtering because with sputtering also you can deposit silicon dioxide, either with plasma-enhanced chemical vapor deposition or sputtering is a physical vapor deposition. If you want to have better step coverage, then PECVD is better, as you know. So, if I go for PECVD and if I perform the chemical reactions in a chamber which is at 100 to 200 degrees Celsius, then what will I have? I have my aluminum interdigitated electrodes covered with PECVD oxide, correct. Now let us understand that suppose there is oxide everywhere, oxide everywhere, but I cannot take the contact outer because the oxide is also on the contact pad.

So, I have to remove the oxide from the contact pads, is it correct? Because the oxide is everywhere, I have to remove the oxide from both the contact pads. So, to do that, what is the process? Let us understand the process. In that case, I will have a silicon substrate with aluminum interdigitated electrodes, and I only want the contact pads to be free of this silicon dioxide, or silicon dioxide should only be etched from the contact pads. This is my SiO_2, which is PECVD oxide. This SiO_2 is thermal oxidation, thermal oxidation silicon, and this one is my aluminum interdigitated electrode. So, what I will do is I will spin coat photoresist again. I will spin coat only positive; you can use positive or negative, but I will spin coat for the positive photoresist.

After that, I load the mask, isn't it? I have to load the mask, and if I have positive photoresist, then I load the mask in this fashion. I will design my mask in this fashion. I will use a dark fill mask. I will tell you what is the reason for using the dark fill mask. This is my dark fill mask. Now I will expose this with UV light. Expose the photoresist which is below the mask, right, with UV light.

Now, when I say that we will spin coat the photoresist and load the mask, it is assumed that we will perform the soft bake at 90 degrees Celsius for 1 minute on a hot plate. Then, when we expose it, what will happen? The unexposed region will become stronger, and the exposed region will become weaker. Why? Because we are using positive photoresist. So, when I dip this wafer in photoresist developer, what will I have? I will have an oxidized silicon wafer with interdigitated electrodes, and we see that dioxide is there, right? The area which is not exposed on the photoresist will become stronger. So, I will have here, and I have here. What is this? This is the area of the photoresist which was not exposed. Since it was a positive photoresist, we will have a similar pattern like our mask, right?

Positive photoresist stays in the area which was not exposed, and the area which was exposed to light, that particular photoresist becomes weaker and it gets developed in the photoresist developer. After this step, you know what to do. You have to perform the hard bake. After hard bake, if I dip this wafer in buffered hydrofluoric acid (BHF), what will happen? I will have my silicon dioxide interdigitated electrodes. And the photoresist, okay, correct, because here the oxide is not protected by the photoresist.

So, when you dip the wafer in BHF, the oxide will get etched. Once you do that, the next step is to dip this wafer in acetone. So, when you dip this wafer in acetone, what will you get? And if you have noticed something, what you have to notice is that the oxide layer which was at the bottom, this one also got etched. You see, because that oxide layer was not protected, so it will get etched in the buffered hydrofluoric acid. What will I have? I will have my contact pads open, right, and the other area is not open. I just wanted to give you an example, okay? I just wanted to have the contact pads. I do understand that this whole design will not be of further use because we have covered the interdigitated electrodes with silicon dioxide, right?

I just wanted to show you the example of how to use a dark-filled mask and how to take the contact pads out. These are contact pad 1 and contact pad 2, correct, from the interdigitated electrodes. But, how to use the bright-filled mask and how to use the dark-filled mask, that was the whole purpose of showing you this particular pattern, alright? Now, I hope that you understood how to deposit a metal, how to use a lithography system or process, and with that, how to pattern it if I want to go for silicon dioxide on metal, which is having a lower melting point than PECVD depositing is better. And if I want to open the contact pad, how to design the mask and how to expose it, and what are the processes. So, with this, I will stop it here. In the next class, we will see an example of microelectrode arrays, high-density microelectrode arrays that can be used for acquiring the neural signals. So, till then, I take your leave. I will see you in the next class.