Biomedical Ultrasound, Fundamentals of Imaging, and Micro Machine Transducers

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Lecture - 51

Welcome to this lecture. In this lecture, we will talk about reactive ion etching (RIE) and deep reactive ion etching (DRIE). If you recall a bit, we have already seen how wet etching can be used. What is the purpose of etching? The purpose of etching is to remove materials from unwanted regions. We can use chemicals for this purpose. If you use chemicals, it is called chemical etching or wet etching.

If we use a different kind of gas, then it is called dry etching. So, reactive ion etching and deep reactive ion etching are both dry etching processes. In RIE, you use a chlorine-based etcher or fluorine-based etcher, while DRIE is generally used to create high aspect ratio features, meaning you etch the silicon wafer all the way through or create a diaphragm as thin as 1 micron. We will see how these techniques are used. For example, let’s look at the slide.

We will talk about RIE and DRIE. I will give an example to clarify what we are discussing. If you take a silicon wafer and perform a photolithography technique, you will know that you cannot directly start using the silicon wafer to deposit material because silicon is a semiconductor. So, first, you must either grow or deposit silicon dioxide or an insulating material.

Let’s say that we have SiO2. This is a silicon wafer, and this is also a silicon wafer. If we say 4-inch silicon wafer about 450 microns thick, we can use a single-sided silicon wafer (single-side polished) or a double-sided polished silicon wafer, what we call SSP or DSP. Now, suppose I want to create a diaphragm. I will spin coat photoresist. After spin coating the photoresist, I can proceed with soft baking. Let’s assume that we are using positive photoresist. I go for soft bake. After soft bake, I load the mask.

Now I am showing the backside of the wafer. You can always flip the wafer to understand what exactly is going on. If I use positive photoresist and a dark field mask, a dark field mask means the field is dark, and the pattern is bright. If you are using a 4-inch wafer, you have to go for a 5-inch mask. So, this is our 5-inch mask, and we are using a dark field. We will expose the photoresist after the soft bake is done. Soft bake is generally performed at 90°C for 1 minute on a hot plate, but it also depends on the data sheet and the type of photoresist you are using. You can always refer to the data sheet before you optimize your photoresist.

An important point while utilizing the laboratory is that the relative humidity and the temperature of the lab are crucial. If the humidity is a bit high, you can always heat the wafer before processing it to remove any moisture that may be present on the wafer. Now, we have the mask. What kind of mask? Dark field mask. Once you perform the soft bake, you can expose this using ultraviolet light. UV light exposure. After you expose the photoresist to UV light, what we learned in lithography is that the pattern on the mask will transfer to the wafer if we use positive photoresist.

The exposed area becomes weaker, and the unexposed area becomes stronger, or vice versa. So, whatever the feature size or features are on the mask, the same features will transfer to the wafer when using positive photoresist. After this you develop it, So, I develop the wafer. What are we developing? The photoresist. After developing the photoresist, we will have a wafer that looks like this: silicon dioxide.

When we develop the photoresist, you will see that photoresist remains in these two places. Because the same features on the mask are transferred to the wafer. So, we have silicon, and the silicon dioxide is thermally grown, about 1 micron thick. For biosensors or MEMS-based devices, we generally use wet oxidation, which is faster than dry oxidation. This is our photoresist.

After this, we need to perform a hard bake. Before the hard bake, I will protect the other side of the wafer with a photoresist. I will spin coat photoresist on the other side and then perform the hard bake. The reason for spin coating the other side and protecting it was to protect the silicon dioxide. Now, after this technique, hard bake is done at 120°C for 1 minute on a hot plate. Once that is done, if I dip the wafer in BHF (buffered hydrofluoric acid). Silicon dioxide will be etched from the area that was not protected by the photoresist. The area protected by the photoresist will not be etched.

Here we have positive photoresist, silicon dioxide, and positive photoresist again. This is silicon dioxide. You can see that we have now exposed the silicon. The first step is done, the second step is done, the third step is done, and this one is our fourth step. After this, if I dip the wafer in acetone, I will have a wafer that looks like this. This is the fifth step. I have silicon dioxide on the front and back of the wafer, and here the silicon is exposed. If I want to create a diaphragm and etch silicon, I can use either wet etching or dry etching. Today, we are learning dry etching.

When we use dry etching, the result will be this: The etching will stop because silicon dioxide acts as an etch stop for any silicon etchant. Silicon etchant cannot etch silicon dioxide, which is why the etching stops here. This is what we get using the dry etching process. If we used wet etching instead of dry etching, the wafer would look like this.

Now, I am not etching all the way. Here we have silicon dioxide. You can see an angle created, which is 54.7 degrees. We have also created a diaphragm, meaning we have etched silicon but using chemicals. What chemicals are used for etching silicon? We can use tetramethylammonium hydroxide or potassium hydroxide to etch silicon and create a diaphragm.

Here we are using the DRIE (deep reactive ion etching) technique to create a diaphragm. In either case, 5 or 6, we will get the diaphragm. Now, let's focus on how DRIE or dry etching works. This is an example before we understand how dry etching can be used. You can see that we can get different types of diaphragms using either wet etching or dry etching.

Etching is used to remove unwanted material, and we can use either surface etching or release etching. Release etching is where we use a sacrificial layer. Let me give an example of a sacrificial layer. You have a silicon substrate, an oxidized silicon substrate, and on this oxidized silicon substrate, you have patterned zinc oxide.

Here is your zinc oxide, SiO2, and silicon. SiO2 and zinc oxide are patterned. Now, we deposit a metal, let's say gold. If I dip this wafer in ZnO etchant, I will have an oxidized silicon substrate with a gold microcantilever. Here, we used ZnO as the release material or sacrificial layer. This is what we call release etching.

Surface etching is simpler: from the surface, whatever you are etching is surface etching. For example, if you take a substrate and have oxide on it, you are etching oxide from the surface. This is surface etching.

Surface etching for microsystems is similar to integrated circuits, where you remove a selected region or one layer of the wafer to create either a structural pattern or expose the underlying material layer. If I etch silicon dioxide, I can now expose silicon. That's what it means. For ICs, the underlying layer is used for conductive interconnects. For mechanical components, the surface layer is patterned into specific shapes, such as cantilevers, mirrors, or probes.

We have taken the example of a cantilever. Release etching is used to release mechanical components; etching is necessary to allow the component to operate according to the design. The component may be required to move up and down, side to side, rotate, vibrate, bend, or flex, and this is one example of a spring that is created, resembling a leaf spring. The image is courtesy of Khalil Najafi from the University of Michigan, who took the SEM image of this leaf spring.

This leaf spring will expand and contract above the substrate. What are the factors that affect etching quality? The etch rate, which is the rate at which material is removed, and second, directionality. Since etching can occur in all directions, it is important to control the direction of etching. Directional control results in achieving the desired shape or etch profile, and the direction depends on whether it is an isotropic etching, anisotropic etching, or a combination of both. Selectivity is also very important, meaning that the material we want to etch should be etched, while the material we do not want to etch should not be. In other words, selectivity is the ratio of the etch rate of the material to be etched to the etch rate of the material not to be etched.

For example, suppose we want to create a silicon diaphragm and etch silicon dioxide. So, you take silicon dioxide here and start etching silicon. If I begin etching silicon, only the silicon should be etched and not the silicon dioxide. Thus, when I etch down to the silicon dioxide, it means that the etching rate of silicon dioxide is much lower than that of silicon. This is what we call selectivity: the etch rate of the material to be etched, which is silicon, should be extremely high compared to the etch rate of the material not to be etched, which is silicon dioxide.

So, these are the factors affecting etching quality: etch rate, directional control, and selectivity. Let us further understand the dry etch process. In dry etching, the wafer is exposed to gases suspended in radio-frequency energized plasma. You can see here that there is an upper electrode and a lower electrode; the wafer is placed on the lower electrode. There are ions, electrons, and free radicals. The collisions between the gas molecules and energized electrons create a mixture of electrons, ions, and radicals, which ultimately etch the substrate or the material on the substrate.

Dry etching, by design, provides much more control over wet etching. Why do we say so? Let me illustrate this for you. If we use wet etching, you will observe this kind of etching. However, if you use dry etching, you will achieve much more directional control compared to wet etching. This is wet etching; this is dry etching. This directional control of the etch, along with process parameters such as pressure, temperature, gas flow, and power, will influence the etching.

Physical etching is similar to a sputtering deposition process; it is entirely physical and no chemical reaction occurs. This means that if I introduce argon gas, for example, and then create plasma, it will dislodge the silicon nitride material from the substrate, which we will consider as silicon. In this case, we are bombarding ions onto the material that we want to etch, causing atoms from the material to be dislodged. Thus, the material is etched. This is similar to the sputtering process, but in this case, we are not depositing anything; we are simply etching.

Physical etching is referred to as ion beam milling or sputtering; ions bombard the surface of the wafer, causing molecules to sputter off the surface. Dry physical etching, dry chemical etching, and the chemical dry etching process are three different things. First, let us focus on dry physical etching. Wafers are placed on a negatively grounded holder in a vacuum chamber. Again, it is essential to have a vacuum chamber. You will see that the substrate holder is tilted at a certain angle to ensure uniform etching of the chemicals across the substrate. A gas is introduced, chamber pressure is reduced, and RF is turned on. A plasma is generated; gas molecules enter the plasma and collide with high-energy electrons, resulting in positive ions. These ions are attracted to the negatively grounded wafer, accelerating as they move toward the wafer, heating the wafer, and sputtering molecules from the surface.

The process continues until the pattern is etched, exposing the underlying layer, and we can control the etching accordingly. When you talk about dry chemical etching, it is a little different from dry physical etching. In dry chemical etching, the chemical etching requires the presence of plasma energy and a select gas to etch the wafer's surface layer. The process begins similarly to physical etching, but here a plasma is struck, and collisions occur between high-energy electrons and gas molecules.

However, in dry chemical etching, the radicals formed by collisions perform the etching rather than the positive ions. When you introduce the gas, the radicals that are generated will etch the material on the wafer itself. In physical etching, the gas introduced will convert into ions, and these ions will be used for etching the material. When we discuss the chemical dry etching process, it is slightly different because here the radicals generate faster and survive longer than ions. More radicals are available in the plasma; they transfer toward the wafer and are adsorbed on the surface, which etches the material that needs to be removed, again taking silicon nitride as an example. A chemical reaction occurs between the atoms of the materials and the radicals, and the byproducts of this reaction dissolve from the surface and diffuse into the gas present in the chamber. The reaction desorption in this case is a chemical etch.

There are two critical parameters in the dry chemical etching process: first, pressure; second, how much power you apply (this is radio frequency). Chemical etching requires high-pressure ranges and low RF power levels, while physical etching requires low-pressure ranges and high RF power levels. So, you need to understand that if there is a question regarding what etching requires compared to physical etching, you can easily identify the difference: in chemical etching, you need high-pressure ranges, while in physical etching, you need lower pressure ranges. In chemical etching, you require low RF power levels, while in physical etching, you require high RF power levels.

Reactive ion etching (RIE) uses mid-level RF power and mid-range pressure to combine both physical and chemical etching. The positive ions of the plasma bombard the surface while the radicals are adsorbed onto the surface. This combination etches the material. The RIE process provides a high selectivity ratio. It also offers anisotropic etching for features less than three microns wide. Its ability to leverage the advantages of both physical and chemical processes makes RIE an invaluable tool in manufacturing microsystems. We can use RIE with chlorine and with fluorine. This is our homework: to identify when we use chlorine and when we use fluorine for reactive ion etching.

Now, we go one step further to achieve features such as those seen in a leaf spring or cavities created in silicon. We use a process called deep reactive ion etching (DRIE), also known as the Bosch process. In addition to creating cavities, DRIE can be used to create tall components of microsystem devices, which can be released through other etching methods. The SEM on this particular slide shows the leaf spring created using DRIE. This is another example where we create a cavity in silicon; you can see that the sidewalls are much smoother compared to wet etching.

Most systems use the Bosch process, which is why it is also called Bosch etching, where a fluoropolymer is used to passivate the etching of sidewalls. The passivation protects the sidewalls from being etched but not the horizontal surfaces. During the entire etching process, gas mixtures are alternated between etchant gases and passivation. Initially, when you take the silicon wafer that you want to etch, let us say this is the silicon wafer, the etchant will begin etching. It will etch like this, and once it has etched, you stop the etchant and start the passivation layer.

Thus, you start the passivation layer, which will form a layer like this. Then, you start etching again, stop the passivation, and then start etching once more. This cycle allows you to control the etching process according to your desired parameters or the cavity you want to create for the final diaphragm. The role of passivation is to protect the sidewalls, which is why you have the features shown in this slide. If you simply Google DRI techniques and SEM images, you will find many more features similar to what is displayed on this slide.

Deep reactive ion etching, a special subclass of RIE, is also used to create deep cavities in substrates. It has a relatively high aspect ratio, such as 50:1. These cavities can be hundreds of microns deep while being only a few microns wide. In this case, the depth is about 20, 40, or 80 microns, but the width is only about 2 or 3 microns. The SEM image here shows a series of cavities that can be created in one go. You will notice that the deeper cavities have wider openings. This means that, similarly, a number of different etch openings will achieve different depths: a larger width will yield more depth, while a smaller width will yield less depth. As I mentioned, this process is also called the Bosch process.

In summary, we have seen microfabrication techniques or sensor fabrication techniques where we miniaturize components and utilize microtechnology. Therefore, we have to employ several techniques: first, deposition; second, lithography; and then etching. When we talk about etching, it can either be wet etching (which can be isotropic or anisotropic) or dry etching (which can be physical, chemical, or both). Finally, we can have RIE and DRI.

With this, we conclude this particular lecture on dry etching techniques. I hope you understand what we have discussed. We are nearing the end of this course, as we are in the 9th to 11th module. If you have any questions, please feel free to ask us through the NPTEL forum, and we will respond to your query as soon as we can. Until then, take care, enjoy the remaining lab videos, lecture videos, and I look forward to receiving any feedback or questions. Until next time, take care, and I will see you in the next class. Bye for now.