Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

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Lecture - 16

Hello, welcome to this lecture. In this session, we will continue from where we left off in the last lecture, focusing on silicon and now discussing silicon dioxide. Silicon dioxide is an insulating material, similar to other insulating materials like silicon nitride. In the IC industry, silicon dioxide has various applications, ranging from field oxides, masking oxides, pad oxides, gate oxides, to backend insulators. There are also native oxides.

Let's talk about native oxide and how to remove it. Native oxide is nothing but a very thin layer of oxide that forms on the surface of a silicon wafer due to the presence of oxygen in the atmosphere. This is an unwanted layer that we do not need. To remove this native oxide, we will look into the lithography process. Additionally, we have masking oxides, field oxides, and gate oxides.

As an example, consider gate oxide, a thin layer used in MOSFETs. A thin layer of gate oxide (SiO_2) is used, on which the gate is formed. For a p-type silicon, we can have an n^+ source and drain, and the gate can be of different materials like polysilicon. The thin silicon dioxide, or thin gate oxide, is crucial for gate or tunneling oxides and can also be used for masking.

Now, let's discuss how to remove unwanted silicon dioxide, whether it is native oxide or an oxide that we have grown or deposited. It's important to note the difference between "growing" and "depositing" silicon dioxide. Growing refers to the thermal oxidation process, whereas depositing refers to physical or chemical vapor deposition techniques.

To etch silicon dioxide, we use hydrofluoric acid (HF). When you dip the wafer in buffered hydrofluoric acid (BHF), the SiO_2 is etched away. HF is a general etchant for silicon dioxide.

Now, let's understand the ways to grow silicon dioxide. Before that, let's quickly look at how silicon dioxide can act as a diffusion mask for common dopants and determine the required thickness for silicon dioxide when doping with p-type or n-type materials like boron or phosphorus. Silicon dioxide can also act as a good diffusion mask for other materials like arsenic and gallium.

For example, if we have a silicon wafer and want to dope phosphorus into it, we first pattern the wafer with silicon dioxide. After doping, we should see n^+ regions where the phosphorus has been doped. The silicon dioxide acts as a mask, preventing the dopant from diffusing through it.

Now, the question arises: what should be the thickness of the silicon dioxide? The thickness depends on the diffusion time and temperature during the doping process. For example, if we want to dope phosphorus at 1200°C for 1 hour, the required thickness of the silicon dioxide would be around 1 micron. For boron, under similar conditions, the required thickness would be around 0.1 microns.

To summarize, 1 micron is equivalent to 1000 nanometers, so 0.1 micron would be 100 nanometers. Based on this, you can calculate the required thickness of silicon dioxide to be used as a dopant masking layer.

Now, let’s move to the next topic. There are two types of silicon dioxide growth techniques: thermal oxidation and pyrogenic oxidation. Thermal oxidation is further classified into two types: dry oxidation and wet oxidation.

Thermal oxidation, as the name suggests, involves high temperatures ranging from 900°C to 1200°C. In dry oxidation, silicon reacts with oxygen to form silicon dioxide. In wet oxidation, silicon reacts with water vapor to form silicon dioxide and hydrogen. The equations for these reactions are:

1. Dry Oxidation:

   $Si + O_2 \rightarrow SiO_2$

2. Wet Oxidation:

   $Si + 2H_2O \rightarrow SiO_2 + 2H_2$

Wet oxidation is about 10 times faster than dry oxidation. Dry oxidation produces a thin but excellent insulating film, typically 0.05 to 0.5 microns thick, making it ideal for gate oxides. Wet oxidation can produce thicker films, up to around 2 microns, but the quality of the insulating material is not as high due to the diffusion of hydrogen gas, which creates pathways for electrons.

In practical terms, the room temperature silicon in the air forms a native oxide, which is a thin, poor insulator but can impede surface processing of silicon. The compressive stress of silicon dioxide formed on silicon and the methods to relieve it are topics of interest.

For growing silicon dioxide, there are three techniques: dry oxidation, wet oxidation, and pyrogenic oxidation. Let’s first understand the setup used for these processes, which involves a three-zone modular furnace.

The furnace has three zones: Zone 1, Zone 2, and Zone 3. Zone 2 maintains the high temperature required for oxidation, between 900°C and 1200°C. Zone 1 and Zone 3 are cooler to prevent thermal shock to the wafers when they are introduced into the furnace or removed.

During dry oxidation, nitrogen is used initially to prevent oxygen from reacting with the silicon wafer. Once the wafers reach the desired temperature in Zone 2, nitrogen is turned off and oxygen is turned on, allowing the silicon to react and form silicon dioxide. After the oxidation process is complete, oxygen is turned off, and nitrogen is turned back on to prevent further oxidation.

The second oxidation technique is the wet oxidation technique. In the wet oxidation process, we use a bubbler. The bubbler is filled with water (H_2O) and has a heating mantle that heats the water, forming water vapor. Initially, nitrogen is used. In this setup, valve 1 is on, while valve 2 and valve 3 are off, allowing nitrogen to pass through valve 1. The oxygen is kept off when loading the wafer.

In the second step, nitrogen is turned off, and oxygen is turned on. Now, valve 1 is off, and valves 2 and 3 are on. At this point, silicon reacts with gas, liquid, and solid phases. During the unloading of the wafer, nitrogen is turned on again, oxygen is turned off, and valve 1 is on while valves 2 and 3 are off. When valves 2 and 3 are on, oxygen passes through the bubbler, picking up the water vapor, which then goes inside. This is how the wet oxidation technique works.

Now, let’s see the pyrogenic oxidation technique. In pyrogenic oxidation, we have nitrogen, oxygen, and hydrogen separately. Oxygen is mixed with hydrogen to form H_2O, which reacts with silicon to form silicon dioxide. During wafer loading, oxygen and hydrogen are off, and nitrogen is on. During silicon dioxide formation, both oxygen and hydrogen are on, and nitrogen is off. During wafer unloading, oxygen and hydrogen are off, and nitrogen is on. Using H_2O and N_2O in this technique is much cleaner than using just H_2O. These are three different techniques to grow silicon dioxide on a silicon substrate.

The furnace used looks like a three-tube horizontal furnace with multi-zone temperature control. You can use any of the three tubes or all of them simultaneously. Horizontal furnaces are generally more popular than vertical furnaces. The furnace material or tubular reactor is made of quartz, which is heated by resistance. In a magnified view, you can see how wafers are loaded into the furnace using a silicon rod that pushes the wafers in at approximately 1 centimeter per second.

The growth techniques of oxidation are used for gate oxides in MOSFETs, mask oxide in the fabrication process, and field oxides as an insulating layer in CMOS fabrication. Once the oxide is ready, there are various techniques to measure its thickness.

The first method is called surface profilometry or mechanical thickness measurement. For example, if I have a silicon wafer with silicon dioxide grown on it and want to know the thickness of the silicon dioxide, I will use photolithography to etch and pattern the silicon dioxide. Then, using a stylus, I can measure the step height, which determines the thickness of the silicon dioxide. This is a destructive technique since we etch the silicon dioxide to create patterns for measurement.

Another way to measure silicon dioxide is by observing its color. This is a crude method, but as the thickness increases, the color changes due to constructive interference of light passing through the transparent silicon dioxide film and reflecting off the substrate. This method allows us to distinguish between films differing in thickness by as little as 10 nanometers, especially if we have experience observing silicon dioxide in the fab.

A more accurate measurement can be obtained using an ellipsometer. In this technique, light passes through a polarizer and a quarter-wave plate before hitting the silicon dioxide film. The reflected light is then analyzed to determine the thickness, using the known refractive index of the oxide layer. This method can also measure the thickness of multi-layer stacks, such as silicon dioxide and silicon nitride.

There is also an electrical technique for measuring the oxide thickness using capacitance-voltage (C-V) measurements on a MOSFET structure. By applying a small AC voltage on top of a DC voltage, we can measure capacitance changes corresponding to different conditions like accumulation, depletion, or inversion of charge carriers at the interface.

In summary, we have discussed how silicon dioxide is grown on silicon wafers using two thermal oxidation techniques: dry oxidation and wet oxidation. Wet oxidation can be done using water vapor or by mixing hydrogen and oxygen. Horizontal furnaces are typically used for this process. We also covered the advantages and limitations of both oxidation techniques. In the next lecture, we will discuss physical vapor deposition (PVD) techniques and how to deposit various materials on substrates.