Sensors and Actuators
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Lecture – 02
Sensors Part 2

Hi, welcome to this module. In the last module if you remember I said that we will see actuators in the next class, but before moving to actuators let us see what kind of sensors we have and what are the roles of those sensors in real life and in the biomedical space. We will talk about lot of sensors later to healthcare technologies because, that is why I particularly focus in and I feel that it will be very interesting for you to understand how getting knowledge of fabrication of micro sensors and actuators will help you to design a technology that can be used in healthcare domain as well as in different applications.

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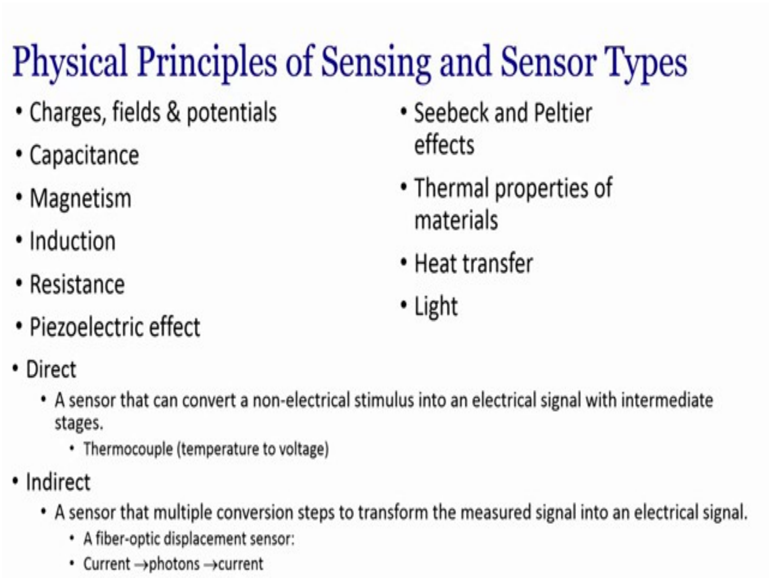

So, having said that this was the last slide in the class that I talked about that how the physical principles of sensing and sensor types are related. Studying from charges and application was from Seebeck to Peltier effects tools, Heat transfer and light and further we discussed about the direct and indirect kind of sensors. Now, sensors when talk about sensors, sensors are fabricated using a material called silicon.

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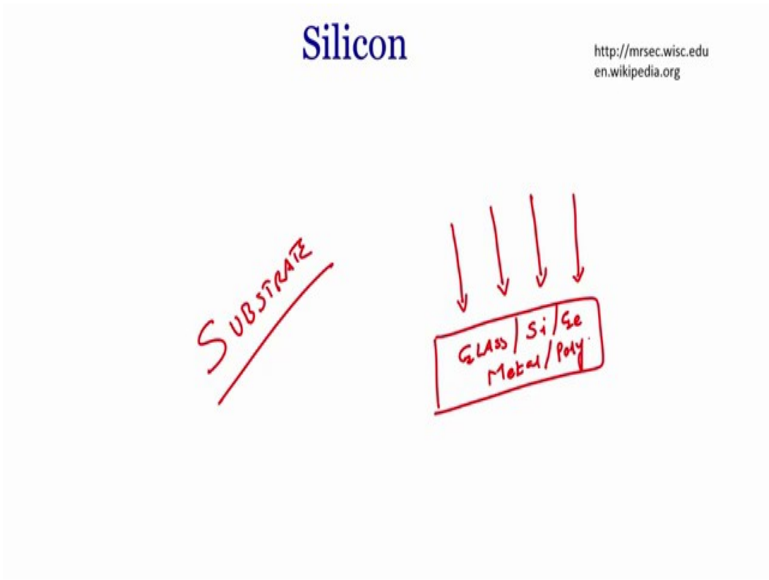

So, any substrate actually what is substrate? If I say substrate what we mean by substrate, alright? So, substrate is any material on which we are going to fabricate a sensor or an actuator, alright. This is very easy definition of a substrate a material on which we are going to fabricate our device that becomes a substrate. Now, this material can be glass.

So, glass can be used as substrate, this can be silicon, this can be germanium, this can be an insulating material. Already we have discussed. This can be a metal as well this can be polymer as well alright. So, substrates when we define it can be a material made up of polymer; semiconductor polymer will be an insulator or a conductor on which we are going to fabricate a sensor alright. Now, in this particular space 90 percent of the sensors are fabricated on silicon on silicon.

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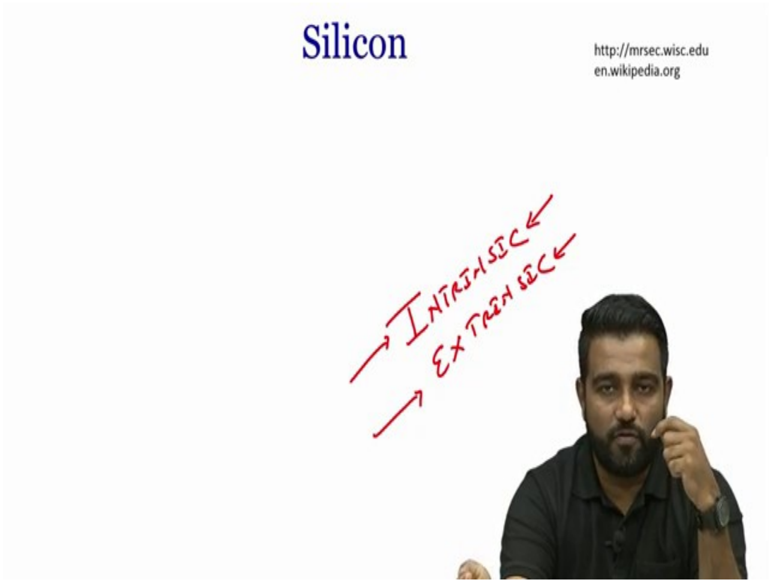

So, silicon is a semiconductor. You should know some of the basic prerequisites are required for understanding this particular course. For example, if I talk about intrinsic or extrinsic intrinsic or extrinsic semiconductors, what do you mean by intrinsic semiconductor and what do you mean by extrinsic semiconductor? So, this is what I expect that you should know right people who do not know for them I am just giving you definition of intrinsic and extrinsic. Intrinsic is where the material is not doped with any kind of impurity. That is how we say it is an intrinsic kind of material.

When you dope a silicon wafer with any dopant like n-type dopant or p-type dopant, then we say it becomes an extrinsic kind of material, alright. So, when you dope a silicon wafer with pentavalent impurities, it becomes n-type. When you dope a silicon wafer with travel and impurities it becomes p-type and then types of wafers that you can identify it is 1 0 0 orientation, it is 1 1 1 orientation, it is 1 1 0 orientation. Is it n-type or p-type? So, n-type 1 1 0, p-type 1 1 0, n-type 1 1 1, p-type 1 1 1, n-type 1 0 0 and p-type 1 0 0, these are the classes.

How so, if I give you a wafer, can you identify whether the wafer is n-type or whether the wafer is p-type and if the wafer is n-type, then within n-type which orientation the wafer has, so that you can understand with the help of Miller indices or Miller index. So, I expect that you understand Miller indices, I expect that you understand the types of silicon wafer and then from that knowledge we are going to talk further about how to fabricate sensors and actuators, alright. So, silicon when we talk about silicon especially silicon is fabricated using what? Silicon is fabricated using sand, then what is sand? Sand is nothing, but silicon dioxide SiO_2.

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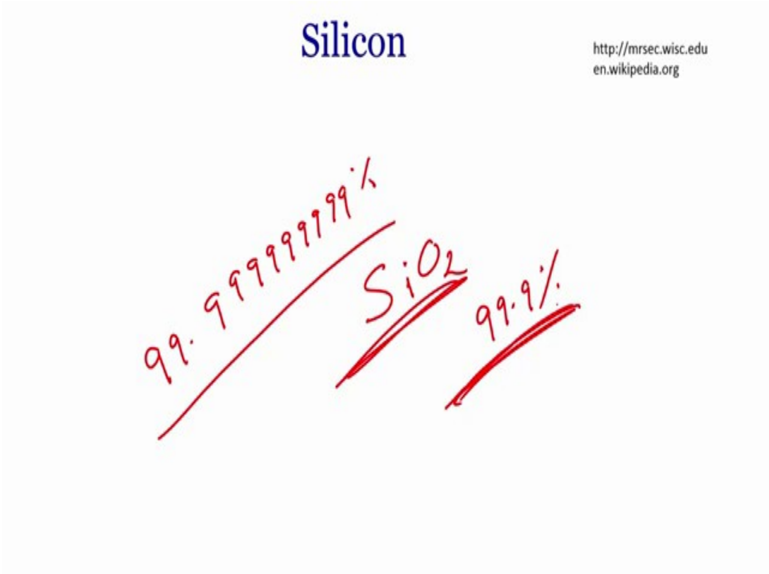

So, 99.9 percent pure sand is used and there are two processes. This is again within the prerequisite. There are two processes; one is Czochralski technique and one is Float-zone technique through which the silicon dioxide is processed, and we have a silicon wafer to work on, alright. So, and the final wafer that we have is pure has a purity of 99.9 times 9 1 2 3 4 5 6 7 8 and 9. This is the purity of the silicon wafer that we are looking at from the silicon dioxide which is 99.9 percent pure. So, there are silicon foundries which fabricate this silicon wafer from the silicon dioxide material, alright.

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So, when we talk about silicon you will see that silicon boule is there from which the wafers are sliced and the boules are nothing, but the large logs of silicon and then this log are sliced to form the uniform silicon wafers. So, how and where would these silicon boules would be fabricated or where the silicon wafers would be sliced and fabricated, alright and what kind of environment it would be? So, that is our second part.

So, when you talk about silicon boule, you can see this particular picture and looking at this picture. What do you think the or where do you think the silicon boules are made and why do you think so? You can see that this person is wearing that the technician is wearing or engineer is wearing the gown and it is a foundry, but what kind of environment is that. So, this is a clean room environment and then within the clean room, there are several classes of clean room.

If I say clean room, then there are several classes of clean room starting from class 1 to 10 to 100 to 1000 to 10,000 to 100,000. So, this has several classes of clean room and depending on what kind of fabrication of sensors or actuators we are going to see, we can use that particular class of clean room for our experiments. We will be focusing more on last 1000 and 10,000 kind of clean room where you want to go for boundary, you have to go for class 100 kind of clean room. Sometimes you can also go for class 10 kind of clean room.

So, now we identify that this fabrication of boule should be in a clean room environment, but the second question is why we think so? The requirement of the clean room is to avoid any impurities. So, if the more the room the class if it is 1 or 10 or 100, the room is much more cleaner and less of the impurities are present in the in the room compared to room which are not clean and we want our silicon wafer to be not doped with impurities isn't it, because even one small single impurity of 0.5 micron will kill your entire chip because now, we are talking about few nanometers of technology where you are going to fabricate MOSFETs and if you see the technology to fabricate metal oxide semiconductor field effect transistors, it is a few nanometer technology. So, in terms of few nanometers technology if there is a 0.5-micron particle that sits on the wafer, it will kill thousands of transistors at the same time. So, to avoid that we require to have a clean room facility.

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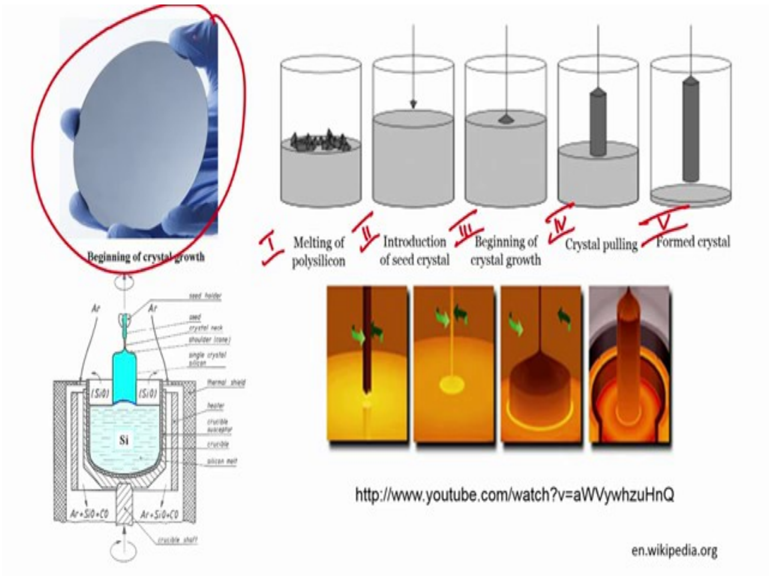

Now, if you talk about fabrication of the silicon wafer, then this is how the silicon wafer is fabricated. There is a video which you can go to YouTube and you can see how exactly this the silicon wafer is fabricated, but it starts with the crystal growth and seed crystal, this is a seed holder. And then there is a seed crystal which is inserted into the silicon melt and these are polysilicon which are heated at a high temperature, so that it becomes a melt and then this rod is inserted and it is pulled out slowly in a uniform fashion such that you start forming the single crystal silicon alright. This system consists of a crucible shaft. The direction of this shaft is opposite to the direction of rotation. The rotation of this particular crucible shaft is in opposite direction to the rotation of the seed holder as you can see here. This is a opposite rotation compared to this one.

Second thing is that there is a silicon melt. As you have seen there is a crucible susceptor and then there is a heater. See there is a heater that will heat this material and that is a material in which or the chamber in which the silicon melt is held or poly silicon is held is a crucible and there is a crucible susceptor and as you can see this is a silicon melt , this one a silicon melt.

Now, finally you have to cover this with a thermal shield and that is why you can see here there is a thermal shield covering the entire system and when you pull out the silicon seed slowly, this is at lower temperature compared to this one and that is why you start forming the single crystal silicon. So, it starts with this is a these are the stacks. It starts with the melting of poly silicon is a step number 1, and then there is an introduction of cell crystal step number 2 following by beginning of crystal growth.

Step number 3, then the seed crystal is pulled out and then there is a crystal pulling and formation of the silicon boule step number 4 and finally, the crystal is formed step number 5. So, this is how the process is done. Like I said there are two techniques; Czochralski technique and Float-zone technique. You have to go to any VLSI book. You will find it out and that is how we finally end up in a having a silicon wafer. Of course, there is a slicing required and many more things are required.

Before we understand that that particular process, now let us see that what kind of sensors we are going to study in this particular course. I am giving you a few examples that does not mean that we are only going to study this few, but we will study in detail how to fabricate those senses, alright and what are the application of those sensors that is our understanding and our idea to understand this particular course.

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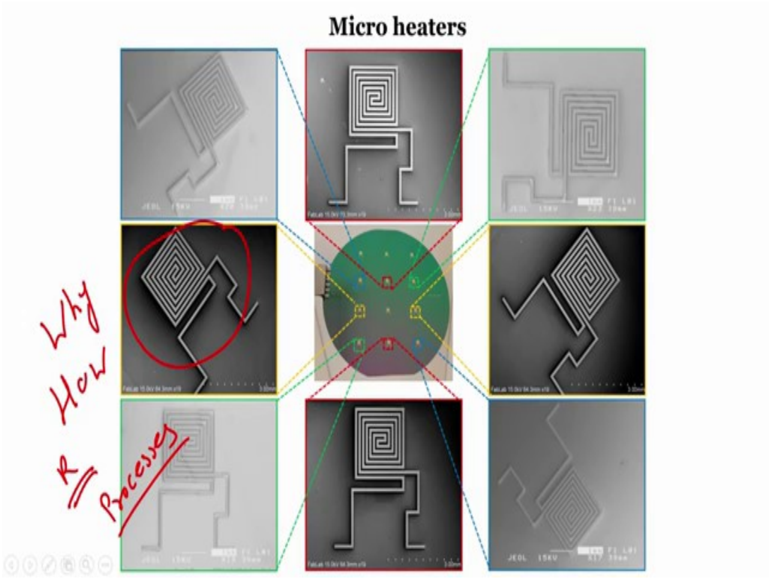

So, if you see the first one, first one is a micro heater. So, if I say what exactly this particular micro heater is, then what I can show it to you that what you mean by heater and where the application of the heater would be. So, if you see this particular slide what is the slide showing micro heaters, but first thing is why we require a micro heater why? Second question is how we are going to fabricate this micro heater, how we can decide the resistance of the micro heater and third question is what the processes are involved processes involved um.

Why we want to fabricate a heater for fabricating of a heater? Heater is used in many applications, in sensors in micro fluidic, in medical applications as well as in understanding electronic nose. I will discuss with you what exactly electronic nose means and if you want to fabricate this heater, why it is called micro because the width of this particular line that is forming the heater is of few microns. As you can see this is 3 millimeter here the bar. So, this is close to about 100 microns, the width is 100 microns, alright.

So, I first of all how you are going to design a heater such the for a particular resistance what I mean by a particular resistance.

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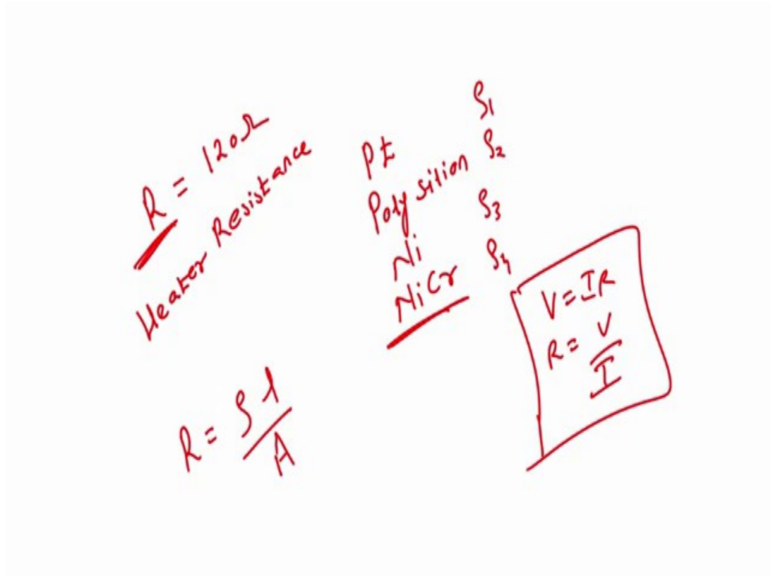

Suppose I say that I want a resistor which is of 120 ohms. Now this is what? This is the heater, register heater resistance. If I have a heater, it should have a resistance because this is nothing, but a metal coil. It is a coil. So, I should have a heater resistance. Now, how can we get 120 ohms of resistance? So, first thing is what kind of metal you will be using. Whether the metal is platinum or metal is or you are you going to use polysilicon instead of metal or you are going to use nickel, or you are going to use nichrome.

Now, why we are discussing about these particular metals? We are discussing this matter because the resistivity of each metal would be different. The resistivity of each metal would be different. So, say that you select one particular metal, let us say we are selecting nichrome, alright. So, my resistivity is constant because I am not going to change the metal. What else forms a resistance?

So, if I ask you the definition of write down the equation of a resistor what is the equation of resistor? Most people will answer it is V equals to IR and that is why R will be equals to V by I, but that is not a correct answer. This is this is not really wrong, but this is what you are saying is the ohms law at how resistance depends on voltage ratio of voltage and current. I am not talking about how the resistance is depending on voltage and current. I am talking about how you are going to form a resistor of a particular value and that is why this equation will not hold true for a resistor. So, for resistor our equation would be rho into length by area, correct.

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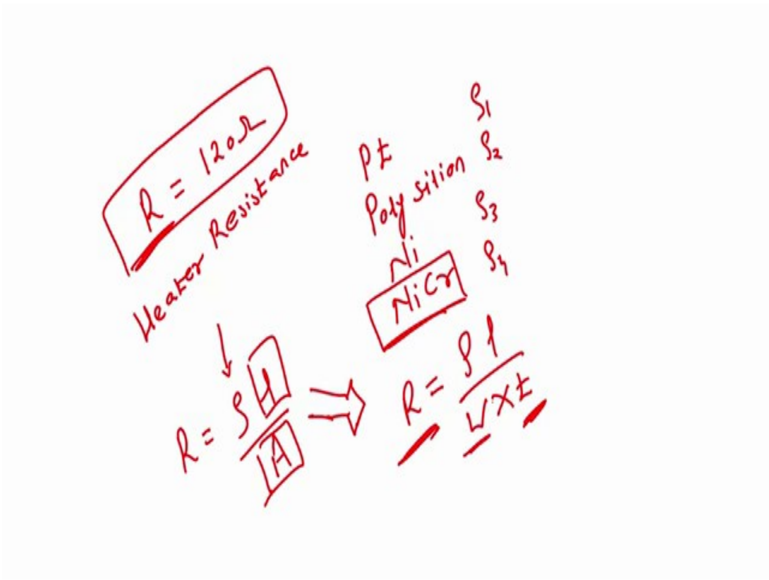

So, I now know what the resistivity is because I have selected a particular material. So, I know the resistivity value, length I can play with and so, is the area. So, I will decide the number of turns and the area that a heater will cover and depending on that I will have a resistor value. Now what is area is nothing, but R I can write. So, this will further if I further equation will give us R equals to rho L by W into T, where T is your thickness, W is your width correct.

So, now my resistor will depend on the length of the coil, the width of the coil, the width of each you know line and the thickness of the material, correct. So, the by calculating here we can form a resistor of a particular value. You got it easy extremely easy.

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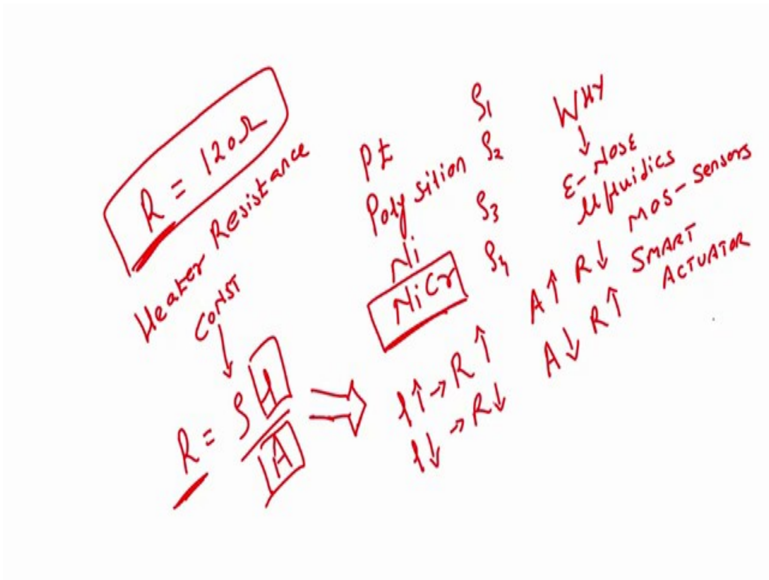

Now, what does it mean? That means, that if I increase the length if I increase the length, my resistance will increase. If I increase the length, my resistance will increase. If I decrease the length, resistance would decrease. If I increase my area, my resistance would decrease and if I decrease my area, resistance would increase. Thus, my resistivity remains constant for a given temperature, my resistivity will remain constant. So, from here we can design a resistor of a particular value.

Thus, the different designs that you see here are based on the resistance that I want and what is this green color thing? You must have guessed that this is nothing, but a silicon wafer. This is a silicon wafer, but why silicon wafer is this green and purplish color? So, let us understand. I said that why you require heater? Heater is used. Why you require heater? Heater is used for several application including e nose micro fluidics e nose. This is electronic nose.

I will discuss with this particular topic in detail micro fluidic, then we require heater for each individuals metal oxide semiconductor-based sensors. So, there are a huge application of the heaters in this particular domain, but also micro heater is required for other applications. For example, if you want to have a smart actuator where you want to heat and cool the system in real time, so for heating then you require a micro heater alright.

So, there is a lot of application of why to use the micro heater, why do understand the micro heater is a part of this course , but the second point was that how we are going to fabricate this micro heater and at least we understand now is that we can design the resistance of the heater with the help of a situation . Now, the third point is how you are going to fabricate this particular. So, what are the processes? What are the processes involved in fabricating this particular heater?

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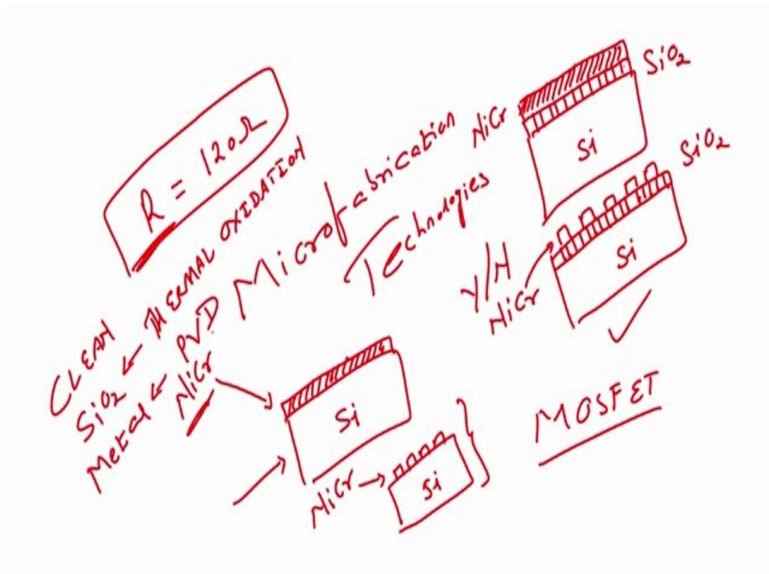

So, the processes that are involved in fabricating the heater is are called Micro Fabrication Technologies; Micro Fabrication Technologies. So, in micro fabrication technologies there are several things that we will be learning starting from the silicon wafer which is our substrate and then on the substrate we have two. So, if I have a silicon wafer that was my earlier thing that I wanted to teach you this is a silicon wafer.

Now, if I deposit a matter on silicon wafer, these are metal. This metal is let us say we have selected nichrome; we have selected nichrome. So, if I pattern this nichrome using a micro fabrication technology, then I will have this particular heater silicon and this is my nichrome heater, alright. Will it work like whatever we have understood till now what the heaters will it work properly? Yes or no. If I directly deposit a metal on a semiconductor and I fabricate a heater and I ask a question, will it work properly or not? What is the answer? No. We require an insulating material between the silicon wafer and metals in silicon is a semiconductor. If I cannot directly deposit metal on semiconductor, otherwise I cannot follow or have the parameters of the heater and working of the heater in the same manner that I have decided.

So, what I will do, I will grow an insulating layer as a sandwich between my metal and a silicon wafer. So, what does that mean. What I mean is you take a silicon wafer and then you grow silicon dioxide. This silicon wafer, this is silicon dioxide. Silicon dioxide is an insulator. On this you deposit your metal which is your nichrome and then you fabricate your heater silicon dioxide silicon and you have your heater here. I will teach you how to fabricate the heater. Now you just assume that you have patterned this heater, and this is a correct way of fabricating a micro heater.

So, here what we have learned, we have learned that you require a silicon wafer, then you need to clean the silicon wafer. So, cleaning process is what several processes I told you what kind of processes are involved. The process for fabricating the heater requires a silicon wafer which needs to be clean and followed by you have to grow silicon dioxide. So, silicon dioxide we are to grow using thermal oxidation.

Thermal oxidation you may have said if you are from electronics background. You may have said it how the MOSFET is fabricated. MOSFET in MOSFET there is a gate oxide, thin layer of gate oxide and then there is a field oxide. The gate oxide is formed with the help of thermal oxidation process and that is a dry oxidation while the fill oxide which is thicker is formed using a thermal oxidation process, but wet oxidation.

So, dry oxidation, wet oxidation, wet oxidation for field oxide by oxidation for gate oxide easy. So, for growing silicon dioxide now what is the difference between dry oxide and gate oxide? Dry oxide is of higher purity compared to wet oxide. Sorry they are not dry oxide and gate oxide, dry dioxide and wet oxide. Dry oxide is of higher quality compared to wet oxide, but wet oxide can grow faster compared to dry oxide. Why there is a higher quality because there are no hydrogen atoms involved in that.

The wet oxidation is done with the help of water vapor where dry oxidation is done only in oxygen. So, you have to clean the wafer, you have to grow silicon dioxide using thermal oxidation. Next step is what you have to deposit a metal. So, deposition of a metal will require you to understand physical vapor deposition, physical vapor deposition techniques.

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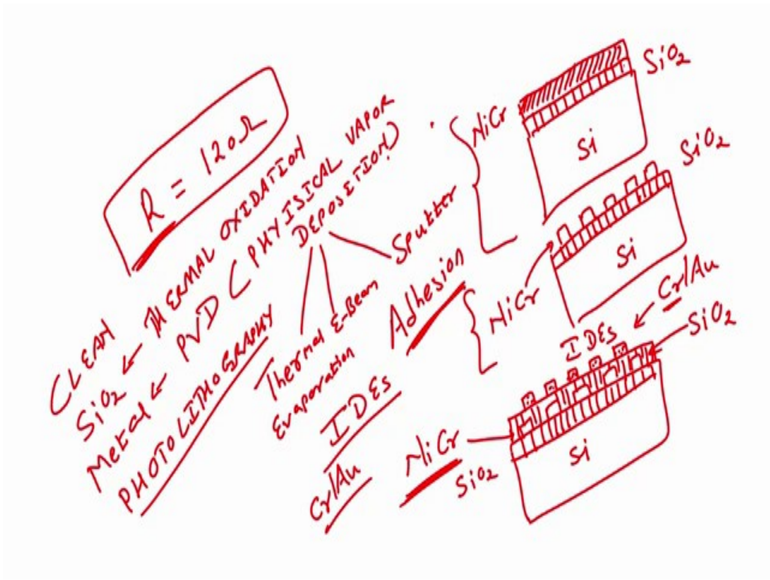

This stands for Physical Vapor Deposition alright. Physical vapor deposition this is for depositing nichrome. Now, in physical deposition techniques there are several techniques that we will learn. I will teach you all these techniques when the lecture comes and those techniques three main techniques; one is called Thermal evaporation, not oxidation

Thermal evaporation, second is called Electron Beam evaporation and third one is called Sputtering. Thermally Evaporation, Electron Beam Evaporation and Sputtering, these three are physical vapor deposition techniques that we will be learning in our course right after metal you deposit right from metal to fabricating this particular heater. This is a cross-sectional view of a heater.

What we require? We require to understand Photolithography and when you understand photolithography, photolithography is considered as a heart for any micro fabrication technique. Once you understand photolithography and you use it on this particular wafer which has a metal and silicon dioxide, you can fabricate a micro heater as a these are the processes that are involved in fabrication of a micro heater. We will see process in detail when we talk about that slide. So, this is the micro heater.

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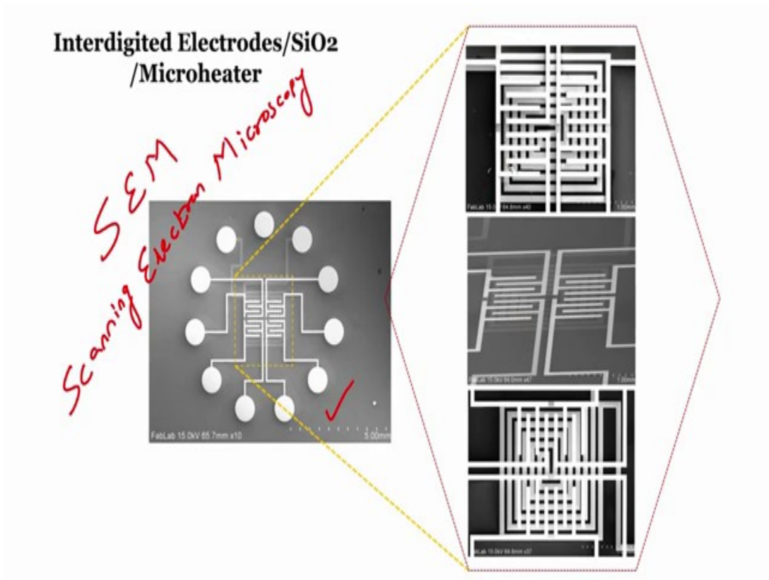

And let us go to the next section which is your Interdigited Electrodes on Silicon Dioxide on Microheater. So, what you can see here? You can see a micro heater and then there are interdigitated electrodes on the micro heater. So, how you can fabricate this interdigitated electrode on the micro heater? So, if I go back what I have is a micro heater. So, I will just if I further it I will have a micro heater. This is silicon dioxide; this is silicon and this one is my nichrome micro heater. On this micro heater what I want is inter digitated electrodes, but if I directly deposit metal on this, is it correct. No because heater is also made up of metal and my interdigitated electrodes will also be fabricated using metal chrome gold.

So, what should I do? I cannot put one metal on second metal. That is why it will be sorted. That is why I had to again deposit silicon dioxide as a sandwich layer between my heater and then on this I will deposit I will deposit a metal which is my chrome gold, alright. Why you I had to use thin layer of chrome to improve the adhesion of gold? The of gold on the oxide is poor and to improve the adhesion we use a thin layer of chromium. That is a roll of chromium that that is why you always be say chrome gold.

So, when we deposit chrome gold on the heater, we have to make sure that there is a silicon dioxide or an insulating layer between the heater and the interdigitated electrodes after depositing chrome gold. I will perform a photolithography. So, that so that I will have I will have my inter digitated electrodes. Got it? So, I will have my interdigitated electrodes made up of chrome gold. This processor will learn and that is how it looks like that there is inter digital electrodes over silicon dioxide. You can see here that silicon dioxide is a sandwich layer between micro heater and inter digitated electrodes, and then below silicon dioxide there is a micro heater which you can see here.

So, this is how the SEM image looks like. SEM stands for what Scanning Electron Microscopy; Scanning Electron Microscopy: SEM. These are all this one, these are all SEM images of interdigitated electrodes on silicon dioxide on the micro heater, alright guys easy. So, let us move to the next one.

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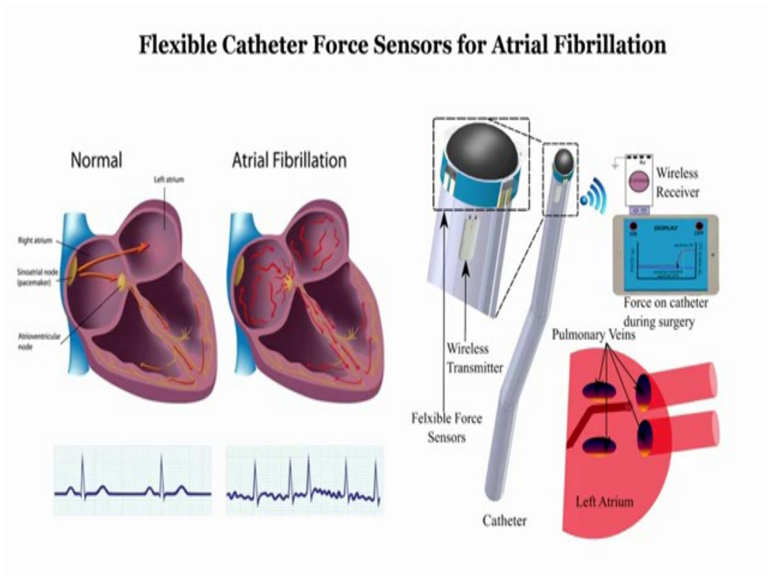

So, lot of sensors lot of sensors we will be talking about very important application during our course which is on atrial fibrillation and why we are talking about atrial fibrillation because we want to understand how we can fabricate a sensor which can measure the force in real time, . We can measure the force in real time during the surgery. So, what exactly atrial fibrillation means, we will discuss in detail in one of the one of the classes. For now, let us understand that we all know our heart pumps uniformly everybody has a heart, everybody has a heart and it pumps otherwise we will be dead. It pumps a certain number of beats per minute. Isn't it?

Now, the question is if it pumps faster, what will happen? It will pump slower, what will happen? It will pump on you uniformly then what will and non uniformly then not on your sorry my mistake non-uniformly, then what will happen? So, generally when you run a heartbeat faster you are you are you are waiting for your exam results, your heart beat faster. But, that is fine because it gains back its normal rhythm as soon as you are less stressed or you stop running and you are at your standing position, suddenly it comes back to its normal rhythm, but in a disease called arrhythmia this pumping is very fast.

It does not come to normal rhythm without taking medicines and in one other application, other disease within that arrhythmia is called atrial fibrillation where your heart starts pumping unevenly. Now when it starts pumping unevenly, it causes clots. So, how it is treated? This pumping unevenly is because of the misfiring of signals. You have to understand the physiology of heart, then you will understand how the heart works and then you will understand there are electrical signals is our pulses that are fired for the uniform pumping of your heart. That uniformity is lost because of the misfiring of signals and we can restore that uniformity by burning that particular tissue which is causing misfiring of signal.

How it is burnt? So, the surgeon will put a tool called or a tube called catheter on the particular tissue and the surgeon will burn that particular tissue. I will teach you in detail how that is the process is done. Now just understand what I am saying. Now, when I am saying directly like this, it does not happen like this. It goes from the groin area all the way to your heart and then it is forced. I am just showing you an example. So, now let us understand this is the heart and the tube is inside. This is your catheter, catheter and to burn the tissue burning is called ablation. Catheter ablation use RF energy, RF ablation.

So, catheter ablation RF energy RF ablation, how much force you apply on the tissue on the heart tissue is extremely important.

More force if I apply suppose I say that if I can show it to you in a way, so that you understand. Let us understand this thing. Can you see on my heart please? Yeah let us understand that this is the area which I want to heat which I want to burn when I apply force. If a force is more than the other areas of the heart would burn and that is, I do not want it should not happen like this. If a force is less, then what will happen the recurrence will be higher a subject. So, patient will feel that again disease has disease is not cured properly and he or she will feel the non-uniform pumping of heart after few days of the surgery.

So, less force is not, more force is not. Optimize force is what we are looking at and how we can apply an optimized force to the catheter, that means we need to have a force sensor integrated on to the catheter that can measure the real time contact force. How to fabricate this force sensor will be the objective, one of the objectives of our course alright. So, I will discuss this thing in detail in the one of the courses.

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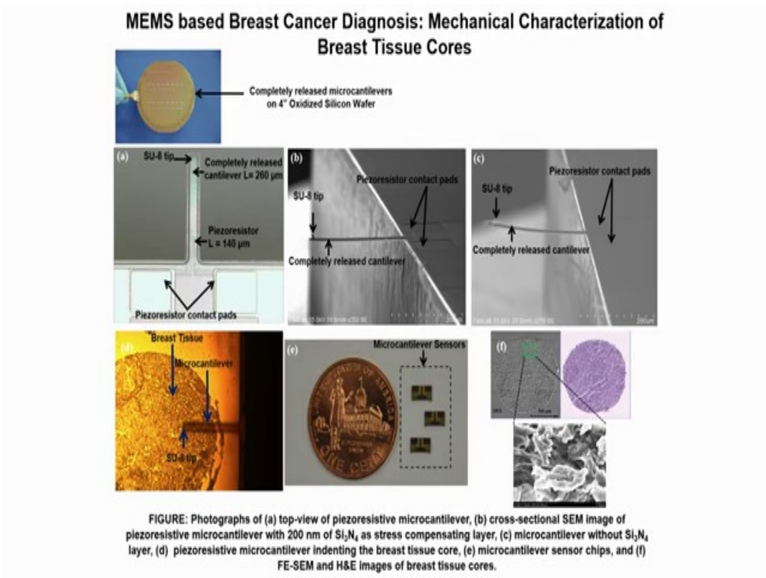

Let us go to the next topic and here if you see the slide, we are interested in understanding the change in mechanical properties of the breast tissue cores, alright. So, if you know that breast cancer is the second largest cause of cancer related death in women and when there is a tissue related cancer that the tissue properties are will change a lump would be more stiffer or less stiffer compared to other parts, other tissues. So, the stiffness of the lump would be different.

Now, if I give you a slice of a tissue and ask you to understand or tell me what is the elasticity of the tissue, what is the mechanical property of the tissue or you can you measure the stiffness of the tissue, then there is a way to measure it and that is by using a micro fabricated micro cantilever. So, what I mean by a micro fabricated micro cantilever? I say micro cantilever it is assumed that we use back a fabrication. What is the cantilever?

Can you give me an example of a cantilever a simple example of a cantilever? A simple example of a cantilever would be a diving board. So, if you have seen in a swimming pool, a diving board is where a person will dive into the pool, but before that it is held at one end and it is it can move at another end. This is a cantilever. Even simpler example: if you take a ruler or a scale and place it on a bench, then if I press it, it will vibrate like this. Correct? That is this is a cantilever.

So, there are example the poles, the night lamps, night poles in the street, light poles. They are also cantilevers. So many examples but now, I want to fabricate a cantilever which is of micron size and I want to embed a piezoresistive sensor on to the or into the micro cantilever. How can I fabricate a micro cantilever with a piezoresistive sensor, I will teach you.

Now, let assume that there is a piezo resistor embedded in this particular micro cantilever. What is piezo resistor? I am assuming that you know these terms. Piezo resistor, Piezoelectric, Ohms law, Miller Indices, Silicon everything, Intrinsic Extrinsic that is what my what I mean by prerequisite. So, still to help your piezo resistor is when you apply a pressure or a force, you know force and pressure how they are related you will see the change in resistance.

So, now if there is a piezo resistor embedded into this particular cantilever and I am pressing this cantilever, what will happen? There will be a generation of stress onto the cantilever beam. This stress will cause change in the piezo resistivity and that is why I can see the change in resistance. Now if I have a tissue and I am pressing the tissue with the cantilever, depending on the stiffness of the tissue, depending on the stiffness of tissue, my cantilever will bend. How much it bends will cause change in the resistance of the piezoresistive cantilever since this the piezoresistive cantilever, since this micro cantilever has a piezo resistor embedded into it.

So, if the tissue is stiffer, my piezo resistor my cantilever will bend more, and I will see more change in resistance. If my tissue is less stiff, I will see less bending in the cantilever. You got it? That is how it is related. So, you will see in one of the class how the piezo resistive cantilever works and what how can we fabricate it. So, there are many more sensors that we need to understand. For this particular module let us understand these many sensors. For next module I will show you few more sensors that we will be learning in our course.

And, then we will see what are the actuators and what kind of actuators we will be learning as a part of this particular course and then later on we will start understanding what is PVD, what is the photolithography and we will start fabricating each sensor and when I say fabricated, we will see the process flow in the in the class and then we will see how exactly a sensor looks like. I will ask one of my TA to take a lab class where you will be, where we will know how the cleanroom looks like.

What are the things within inside the cleanroom and how the devices can be seen, what are the microscopes, having to use the microscope when you have when you have a chip how can you make the electronic system? So, to understand different properties of a given material we will discuss all the things in this particular course. For today I think this is enough for you to get the glimpse of some of these sensors and I will discuss a few more in the next module followed by the actuators. Now, if you have any questions feel free to ask us on in the forum.

Till then, you take care and I will see in the next module. Bye.