Transducers For Instrumentation
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Lecture - 11
Thermal Sensors: Nano-Materials Based

Hello, ah welcome to the course Transducers for Instrumentation. Last lecture we discussed some thermal sensors which are silicon compatible means they follow the fabrication process of silicon and we can integrate them with other semiconductor devices such as MOSFETs and BJTs. So, ah from scaling point of view those sensors are beneficial we can scale them as per our requirement and we can batch process them which decrease the cost. So, the last lecture we discussed those silicon based sensors. Today we are going to talk about some thermal sensors which are not silicon compatible they are like emerging technologies. For example we will first talk about the carbon nanotube based sensors we can make a thermal sensors using carbon nanotube and let us see how we can make a thermal sensor using these CNTs.

So, for carbon nanotubes we know that the temperature coefficient of CNT that temperature dependence resistivity of carbon nanotubes that is a proportional to the temperature increase. So, we can use this property of CNT to make thermal sensors. So let us talk about carbon nanotube based thermal sensors. CNT is the abbreviation for carbon nanotube.

So now we know by experiments that carbon nanotubes or CNTs show a temperature dependence and therefore, can be used as a thermal sensor. So by the experiment we come to know that temperature coefficient of resistance the temperature coefficient of resistance or we call TCR in short this is approximately negative 0.15 percentage per k. This is the measured value of temperature coefficient of resistance which is TCR for CNTs this is minus 0.15 percent per degree.

So, it means that the resistance of carbon nanotubes it changes 0.15 percent per degree change in the temperature and we can see that this is negative. So here we see in the number is negative it means the resistance decreases with increase in the temperature. So we can say this is a NTC or the negative temperature coefficient NTC which stands for negative temperature coefficient is very similar to the thermistors we have seen earlier. They also have the negative temperature coefficient for a certain range, and they are very beneficial in that particular NTC range.

So, the CNTs they also have a negative temperature coefficient which is minus 0.15 percent per degree and this number is very competitive with other materials just like some other thermocouples or some other sensors. So we can use the CNT as a temperature sensor. This number is very competitive with other materials. The next which is very important thing about these CNTs is these are all nanomaterials and when we make a sensor using nanomaterials these sensors tends to be very sensitive for any, any sensing because for when we go for the nanostructures the surface to volume ratio actually increases when we decrease the size of nanoparticles.

So here in the case of CNTs these are also very fine nanoparticles. So the surface to volume ratio actually increases when we go for finer and finer particles. So this is another important point about these nanomaterials. These nanomaterials could lead to new type of extreme miniaturized sensors. With very high sensitivity.

Of course, ah some other benefits are also there. For example, the low power consumption and fast response time. So as we discussed earlier as well if the size of the sensor is very small the response time actually improves. We have a very fast response time of sensor if the size of sensor is small because this needs very less amount of energy transfer from hot-to-hot body to this sensor to come to the same temperature of the body. So when we go for nanomaterial based sensors the fast response time we get as a benefit.

Other benefit is low power consumption because the sensor actually takes less amount of power because the size itself is very small and the more important thing is the high sensitivity. We have here a very high sensitivity in case of nanomaterials because in case of nanomaterials the surface to volume ratio actually improves. So we can consider these nanoparticle as a kind of sphere. So we can write the surface the formula for the surface and formula for the volume and we can take the division and we come up with this relation. So we have surface to volume ratio for a sphere is surface is 4 pi R square and the volume is 4 by 3 pi R cube which comes out 3 upon R.

So, the surface to volume ratio for these nanoparticle comes out to be 3 upon R and if we start reducing the size of our nanoparticles for example if we apply the limit here where the limit R tends to 0 we see this term almost approaches to infinity. So, this surface to volume ratio actually improves very much if we have finer and finer particles. So, when we have more area available for all these nanoparticles to react with the surrounding it means the sensitivity of these materials goes very high when we decrease their sizes. So, we can see here that surface area surface to volume ratio actually effective surface area actually improves, and we have more and more sensitivity if we go for smaller and smaller radius on the size of the sphere. So, this is one benefit we get when we go for nanomaterials such as CMTs.

The main bottleneck about the development of these nanomaterials is the integration of these materials with the other micro fabrication for example silicon based fabrication which is actually dominates all the fabrication process and these new nanomaterials they are not very much compatible with the silicon process. So, we cannot batch process them along with the silicon devices. So, this is the limitation of these CNT based or some other fancy nanomaterial-based sensors. So, the limitation we can write of these nanomaterials sensors. Integration of nanostructures with microfabrication.

So, these newer and newer materials we cannot batch process them with the silicon devices or in the silicon fabs because these materials when we use them along with silicon they act as a impurity for the silicon devices and the performance of those silicon devices goes bad. So, we cannot have the same fabrication process where we can use silicon as well as these CNT or some other nanomaterials. So, we need to fabricate them separately in a very different fabrication line and then we connect them with electronics extra electronics through discrete components. So, this is what we do to make a complete sensor using nanomaterials. So, let's see the fabrication process of these CNT based thermal sensors.

So in these CNT based sensors we are using the property of CNT that the resistance of a CNT changes with the temperature. So effectively we want to measure the resistance of CNT and to measure the resistance we need two points, two input and output port where we can apply electrical signal a known voltage and we will measure the current ratio V and I gives us the resistance. So we need two points along a CNT or carbon nanotube where we can apply a known electrical voltage. To do that what we do we start with a with a substrate we have let's say this substrate first we do the pattern a certain catalyst here for example this red is the catalyst. This is the first step where we pattern catalyst.

In the next step we grow CNT so we have this substrate where we have put these catalyst. Now the CNT will grow only on where the we have put the catalyst. So for example CNT will grow something like this on the CNT on these pattern catalyst. This step is grow CNT. The third step we actually join them we put a glue in this in this structure for something called condensed liquid.

This will look something like this we have wafer with pattern catalyst on top of this we have grown these CNTs and now we pour some sort of a liquid on this on this structure. So when we pour the liquid on this structure this whole assembly will come to that come in contact with this that liquid that liquid will fill up here in this structure. So this liquid is some sort of a glue when we put this this liquid on this structure this whole of these whole of these CNTs will kind of stick to each other all other CNTs and then we can heat it up or we can evaporate this liquid which will come out from here and the CNT which are stick together they will remain in contact with each other. So after this third step when we pour this condensed liquid or glue on this assembly the fourth step is we evaporate this liquid. So the structure will become like this.

The CNTs will be joined to each other and now we can see that there is a electrical contact made here at this point where these are all joined. So we have connected two

CNTs more than two CNTs with each other and now this makes a electrical contact. So in this way we can join two CNTs together because the problem with single CNTs we on the bottom we have a contact with CNT but on the top when we are growing these CNTs there is no way to form a second connection on the CNT and for resistance measurement we will need at least two terminals to apply a potential difference. So when the CNT is growing after the growth there is no way of putting a one more contact on top of the CNT. So for this problem we are growing two or more than two CNTs together and join them on the top so that they make electrical contact and now two CNTs which are connected on the top these two CNTs has two contact pad at the bottom where we have put the catalyst.

For example if we can number them together let's say we have one, two, three, four, five. So similarly we have one, two, three, four, five. Now we have these pad numbers pad number one and two so between pad number one and pad number two we can apply a potential electric potential and the current will flow between these two CNTs this CNT and that CNT and it will give us a resistance drop across this CNT and we know the thermal resistance of CNT is minus 0.15 accordingly we measure the temperature of temperature through this assembly. So this makes a kind of CNT based temperature sensor.

So let's discuss the fabrication process of CNT in more detail. So the first step is we start with a silicon wafer and we pattern and we put a 1 nanometer thick film of iron or nickel catalyst. So this layer of iron or nickel catalyst is patterned on this silicon wafer using photolithography. So we have this silicon wafer on top of this we put a nickel or iron layer which is very thin layer and then in the next step we pattern it to make pads. In this step now we do photolithography and make the pattern this is the pattern we make.

In the second step now in the second step we grow the CNT which is vertically aligned CNTs and we grow those CNTs on these patterned structures which is iron and nickel which act as a catalyst. So when we start growing these CNTs these CNT will start growing on these pads only because these act as a catalyst. So as a second step we grow CNTs. CNTs by thermal CFT CVD or we can say chemical vapor deposition. So in the next step what we have this is our silicon wafer where we have patterned our pads and now CNT will grow on these pads.

This is one CNT wire and this is another CNT. We can name it this is silicon this is CNT and this is catalyst. In the next step we put the solvent. It is such as acetone. So in this step we take this condensed liquid which is which can be acetone or some other glue. This acetone is poured on this structure on this forest of CNTs when we pour this acetone all the CNTs will stick to each other and due to the capillary rise thus the solvent is actually drawn into this forest of CNT independently. So if we draw this step now we have this wafer. These are our patterned catalyst and these CNTs are now grown. Now when we pour the liquid here this acetone is poured here. These two wires of CNTs will come into contact of each other these wires and in the next step when we evaporate this CNT this acetone this liquid will evaporate and the structure this CNT which are now gelled together and made the physical contact now they will remain in that contact after that after this evaporation of acetone.

Now during infiltration and evaporation the CNTs with each within each structure densifies and each structure which is shaped individually by the forces resulting from the capillary action. The final structure when we done this evaporation of this acetone the final structure will look something like this. We have this silicon wafer on top we have this pattern catalyst and these CNTs will kind of connect to each other on the top. These are basically two CNTs which are connected on the top and on the bottom we have two separate pads let's name this pad 1 and pad 2 and we can apply the potential difference across these pads 1 and 2 so that we can measure the resistance of this whole assembly. So when we apply a potential difference across 1 and 2 the current will flow from pad 1 to pad 2 and accordingly we can measure the resistance of this whole assembly R equal to V upon I where we apply a known voltage and measure the current and the resistance is calculated.

So this is how we can make a CNT based thermal sensor where we are measuring the resistance of these CNTs by applying a electrical signal. Now this is the fabrication process what we follow in the lab to make this kind of CNT based thermal sensor. The actual for to improve the yield of our process we actually don't do only with two pads we actually do multiple pads at a time because this is a natural process when we put the acetone and evaporate it, it's not guaranteed that two CNTs from pad 1 and pad 2 they will come in contact with each other. So it's not 100% guaranteed that it will happen so we increase the chances by putting more number of pads and whichever gives us the resistance the close loop formation between one pad and another pad we can take that assembly that pad 1 and 2 into account. So in actual process we put multiple pads for example this is one pad, this is second pad, this is third, this is fourth, fifth and sixth.

So this is the top view of wafer where we are putting these all these six pads let's name it as 1, 2, 3, 4, 5, 6 and we pattern the catalyst on this, this is the catalyst pattern and on top of this catalyst we grow the CNTs, these CNTs there will be multiple CNTs growth on a single pattern. So there will be so many CNTs coming up here and here it will look like a forest of CNT and when we put acetone here and evaporate that acetone these all CNTs will stick to each other and will give rise to the electrical connection between them. So actual structure of this CNT look something like that these are all mixed up or juggled up with each other. So now we see let's say between pad 1 and pad 2 we can apply a potential difference and the current will flow from this pad to this CNT and then we will come back here, this is how the current will flow and we can measure the resistance of this whole CNT structure is R equal to V upon I. And now we know that this resistance of CNTs this is this has a temperature coefficient or TCR which is minus 0.15 it means the resistance of this whole assembly will decrease with the temperature change. If the temperature goes high the resistance of this structure will decrease by 0.15% with every increase in the degree increase in the temperature. So now if we plot the measured value of this resistance for this structure it will look something like this. On the x axis we plot temperature, let's say this is 0, this is 20, 40, 60.

And on the y axis we have the resistance which is in ohm and the measured data let's say the axis is something like 1100, 1200, 1300, 1400 and so on. And the measured value of this resistance will have a negative temperature coefficient so the resistance will decrease with increase in temperature. So the measured value will look like something like this. If we measure across multiple paths the data the measured data will look something like this. So now here we have the negative temperature coefficient, the resistance is actually decreasing and we have multiple values because this we can use any number of paths with any for example the resistance between pad 1 and pad 6 will be different resistance between pad 1 and pad 5 will be different between pad 1 and pad 3 will be the different resistance because this is all not a very controlled kind of connection of CNTs this is all natural CNTs maybe between pad 1 and pad 3 there are 100 CNTs which are joined together but between pad 1 and pad 4 maybe 1000 CNTs have are joined together so the resistance effective resistance of between pad 1 and pad 4 is less compared to earlier.

So because of that there will be a difference when we measure between different paths so that's why we see multiple lines here. The resistance actually goes down with temperature with every degree centigrade. One more point to notice here is that the response is very linear. We can see that resistance change is with temperature is very much linear means we can very easily make a sensor using these CNTs response will be linear. Linear is always a good output if we have coming from a sensor we always desire to have a linear output with respect to the measurement or the input quantity.

So here we have a quite linear output with respect to the temperature change. So the only two electrodes are enough only two electrodes are enough for measurement the above has six electrodes just to increase the yield. So this is how we can make a thermal sensor using carbon nanotubes where we have seen how to join these CNTs together we saw that when we grow the CNTs very difficult to make a second connection on top of CNT. So what we do we grow two CNTs together and we join them on the top using this condensed liquid or acetone we put the acetone so that they kind of mix up or juggle up with each other then we evaporate this acetone so that they will remain in contact and when we make a contact between two CNTs on the bottom they have different pads. So we can measure the resistance between these two pads electrically and we see the response the resistance is changing with temperature.

So this is how we can make a temperature sensor using CNTs. Now we make another temperature sensor using different material which is something called graphene. Graphene is a very popular material from at least last 10-15 years and people are making many kind of sensors using graphene. For graphene as well we know that the resistance of the graphene or the graphene flakes is actually changes with temperature and that also has a negative temperature coefficient. It means the resistance of graphene actually decreases when we increase the temperature.

So this we now we see how can we make a temperature sensor using graphene. So to start the fabrication of graphene based thermal sensor we again start with the substrate which is kind of a polyamide is used as a substrate for graphene because this has a strong adhesion with the other metals and this the thermal capacity of the polyamide which the thermal the temperature which this can handle is the same as the thermal capacity of the polyamide which the thermal the temperature which this can handle is high compared to other substrate. So for graphene based thermal sensor fabrication we start with the polyamide as a substrate. This polyamide or in short we call it PI or PL whatever we call it. This polyamide is been increasingly used as substrate due to these two reasons.

The first is this has strong adhesion to metal coatings which provides a high degree of strain delocalization. So because of this strong adhesion to metal coatings we have a very high degree of strain delocalization. There is no strain actually developed on the substrate because of this coating the other coatings. The second point why we use polyamide for graphene-based fabrication is the wide temperature range. This can sustain a temperature of typically minus 270 degrees to 400 degrees.

It is a vast temperature range which polyamide can handle and this is ideal for many deposition techniques. Such as such as sputtering and E beam evaporation. So, we have these two benefits of polyamide why we use this polyamide for graphene based thermal sensor or where we want to fabricate a graphene based structure we start with polyamide. Polyamide is flexible as well so we can use the polyamide substrate for wearable electronics where this the substrate need to be flexible which can bend along with the body movements. So polyamide is good in that sense as well we can use it for wearable electronics.

So now why do we want to use graphene? So we have certain properties of graphene which are very good and attractive to make a sensor. So let's discuss some properties of graphene. The first one is the excellent mobility of charge carriers. So the graphene has very good mobility of charge carriers. The second is the high electrical conductivity which is because of the high mobility of course.

So we have a high electrical conductivity. The third property of graphene which is very interesting is the high optical transmittance. And the fourth property of graphene is high mechanical stability. So these are the few properties of graphene where we have a very high electron mobility of in graphene and because of this high mobility we have very high electrical conductivity of graphene. We have very high optical transmittance that the light can actually pass through the material. And the fourth is the high mechanical stability that the material is actually very much stable against the mechanical stress.

So these are the properties which make graphene a good candidate for making some kind of sensors. Now we are looking at making the thermal sensor. So as we discussed the graphene has a temperature coefficient or the TCR thermal coefficient of resistance which is proportional to temperature and which actually has a NTC or the negative temperature coefficient. Let's see how it look like for the graphene. Let's plot the resistance versus temperature for graphene. On the x axis we have temperature and on the y axis we have the resistance in ohm. That temperature is in degree C and the resistance, this is zero. The resistance will look something like this. This has a NTC or the negative temperature coefficient.

This is for graphene or graphene flakes. Sometime instead of using graphene flakes we use the other material which is made up of graphene only which is called strontium graphene oxide. We call it SRGO or the strontium graphene oxide. And if we plot the resistance versus temperature for strontium graphene oxide this also has a negative temperature coefficient. It looks something like this. We have the NTC or strontium graphene oxide, SRGO where we have this NTC is more negative compared to the graphene flakes.

So these are the two response of the resistance of graphene flakes and strontium graphene oxide with respect to temperature and both has negative temperature coefficient. The resistance actually decreases with each degree increase in the temperature. So now we can make a thermal sensor using them. So the fabrication of fabrication process of this graphene based thermal sensor is. So first we start with a silicon substrate and on top of the silicon substrate we put a polyimide layer.

So let's say polyimide is let's take a yellow color for polyimide. So this is polyimide layer and this is on top of silicon substrate which is on the bottom of the silicon substrate. We have this silicon on top of this we have put a polyimide layer. This is polyimide and this is silicon. Now the next step is we define the electrodes on this structure using photolithography. We define electrodes using photolithography. And the structure will look like. So we have silicon on the bottom and on top we pattern these pads or electrodes. So these are the two electrodes we pattern the rest is the photoresist. This is the pad we have patterned. And rest is the photoresist. This is the electrodes. This is the positive photoresist or PPR we can call it. Now the next step is to sputter copper on top of this so that these electrodes are conductive. On the bottom we still have silicon. Now these pads will look something different because now we put copper on top of it. So let's take the metal as blue. Now these electrodes we have sputtered the copper to make them electrically conductive. This is first electrode and this is second electrode. This is the step where we sputter copper. This is followed by lift off process. So now we have electrodes which are patterned on this polyimide substrate. And now we have put copper on top of these electrodes. Now these electrodes are conductive. We can use these electrodes as electrode 1 and electrode 2 and we can apply a potential difference across it. But still these electrodes are far apart. There is no interconnection between these electrodes. So now the next step is we take the solution where this solution contains this SRGO or the strontium graphene oxide which is dissolved in this. We take this solution and pour on these electrodes where these are in close proximity. Here these two electrodes are very much close. So we pour this liquid on top of this and evaporate this liquid.

So when we evaporate this liquid, the flakes of these SRGO or the graphene flakes, these flakes will stick there and make a conductive path between these two electrodes and then we can apply the potential difference. So the next step what we have is drope casting of SRGO or strontium graphene oxide. We take this liquid in a dropper and we pour this on this area. In this area we pour this liquid which is the solution of this strontium, germanium oxide and then we evaporate this liquid. The flakes of SRGO will remain there and make an electrical contact between these two pads. So our structure will look something like this. This is first electrode and this is second electrode. And when we have dropped this, drop casting of this SRGO and evaporated the liquid, there will be a fine flakes of strontium graphene oxide that will stay there and make electrical contact between pad 1 and pad 2 and this black dot, this is our graphene. So now we have the complete structure on polyamide. These two pads are connected through the graphene and this graphene has a negative temperature coefficient which the resistance will decrease with the temperature and we can measure the temperature or sense the temperature by measuring the electrical resistance, how much the electrical resistance changes. Based on that we can measure how much is the temperature is changed outside. So this is the complete structure though this is still on the silicon wafer and silicon wafer is not flexible. So we can now remove the back silicon wafer which act just like a handle wafer just for our convenience or to give the mechanical strength to polyamide. So now we can remove this silicon wafer from below of this polymide sheet and this polymide sheet will come out. Now, we will remove all of polyimide tape from the silicon substrate.

And then finally we have a polymide sheet only with this electrical structure. We have this polymide sheet. These are metal pads which is made up of copper. Let's say this is pad one and pad two. This is pad one and pad two and in between this pad one and pad two we have a drop of graphene which is there acting as a temperature sensor. Now we apply an electrical voltage between this pad one and pad two and we can measure the resistance and this resistance is changing with the temperature.

So this is the complete assembly of graphene-based temperature sensor and now this temperature sensor is on the polymide sheet which is very flexible in nature. So we can use this polymide sheet or this thermal sensor as a variable electronics because This substrate this polymide can bend with the physical movement of the body. So unlike silicon, which is kind of has a mechanical strength, and it cannot be bent, This polymide sheet is very much flexible and can be used as a variable electronics sensor as a thermal sensor for variable applications. So these are some thermal sensors which are based on nanomaterials. They are not compatible with the silicon process but as a new nanomaterials, we can make some temperature sensors using these nanomaterials itself.

So, this is all for today.

Thank you.