Transducers For Instrumentation

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Lecture - 10

Thermal Sensors: Silicon Based

Hello, welcome to the course Transducers for Instrumentation. Last lecture we discussed about sub-conventional thermal sensors for example, thermistors, RTDs, thermocouples, they are all like conventional temperature sensors which we are using from quite some time and then we discussed some thermal RC networks. Now today we will discuss some silicon based sensors which we can actually integrate with all silicon devices and make them miniature. The kind of motivation for using these silicon based thermal sensors is silicon based technologies are very much matured and we can scale them down to save the cost and they take very less amount of area compared to other thermal sensors. So we want to integrate these thermal sensors along with other devices like MOSFETs and when we can integrate them, we can join them with some signal processing circuits and we can directly take the output in form of some digital data which we can process further. So going with the silicon based devices or silicon based sensors is very much advantageous in terms of the complexity, the amount of cost it involves to fabricate one sensor.

Though the cost of single sensor can be higher but if we scale them and we can make them silicon compatible and we can MOS production, we can produce them in mass then the cost of these devices drastically comes down. So today we are going to discuss some thermal sensors which are silicon based or which are compatible with silicon processing technology. So we discussed today thermal sensors which are now silicon based. So we are going to discuss silicon based.

So we need to have some property of silicon which is proportional to the temperature. We need to find out a property y of material which we can use it as a transduction principle and that property is changing almost linearly proportional to the temperature. So if we characterize the silicon, we know that the thermal diffusivity of silicon is very much proportional to the temperature. So before this actually these integrated sensors are widely used because of their small size, low cost and ease of fabrication and the output is digital. Traditionally we used BJTs or the bipolar junction transistors where the behavior of these BJTs are very much proportional to the temperature and BJTs are intrinsically sensitive to the process spread.

When we use these BJTs and if there is a process variation because of some process variation or the temperature variation or some other fluctuations in the manufacturing process, the performance of BJT is very much sensitive to these change in the process. So they are not very much immune to these process variations and that is the problem with BJT in using BJT as a temperature sensor. Though this can be improved by trimming individual devices, for example we make a BJT using a very controlled process but it is still sensitive to fabrication process. We can trim it down individually, we can reduce the number of fingers and so many other things but the cost of trimming individual device is very much high. So we don't want to do that individual processing.

So BJT in that sense is not very much advantageous because it is very much sensitive. And the other thing about BJT is this BJT suffers from the exponential increase in the leakage current with respect to temperature. So BJT we use earlier as a temperature sensitive device and this is the case with the BJT. But the problem with BJT is this is intrinsically sensitive to the process spread. So BJT is very much sensitive to the process spread.

What we mean by this process spread is when we are manufacturing these BJTs, let us say we have a process spread. So BJT is very much sensitive to the process spread. We have let us say emitter, this is base and this is collector and we are doing this doping here in the emitter and collector. So the performance of this BJT is very sensitive to this doping. If there is a 5 or 10 percent variation in this doping, then the current is very much sensitive to the process spread.

Actually it is very much sensitive to this change in the doping. So this is the problem with BJT having a wider process spread compared to the other devices. As we said this can be improved by trimming individual device. We can have certain techniques to reduce the current if the doping is high but that individual trimming is very much costly in terms of time as well as money. So individual trimming is possible.

This can be improved by trimming individual devices but increase cost. So this is the problem with BJT. And the other problem of BJT is the exponential increase in the leakage current when the temperature increases. So the leakage current of BJT is very much sensitive to the process spread. So the increase in the leakage current exponentially increases.

So we see that BJT increases exponentially and we use BJT as a device to sense the temperature and we form some sort of band gap reference circuits to detect this change. For example we have a typical band gap reference circuit which looks something like this. This is R1. This is R2. This is R3. This is R4. This is R5. This is R6. This is R7. This is R8. This is R10. This is R11. This is R12. This is R13. This is R14. This is R15. This is R18. This is output node and here we have this is the positive connection and this is the negative connection. This is our BJT T2 and this is BJT T1. This is R3. This is R4 and if there is a current flowing in this arm which is IC1 and this is IC2, this is our BJT T2. This is our BJT T2. Then we can write the delta VBE, the change in the base to emitter voltage is equal to KT upon Q where k is the Boltzmann constant, T is temperature and Q is the charge into log natural IC1 upon IC2. This is our BJT T2.

This is our BJT T2. This is our BJT T2. So, here we can see this change in the voltage delta VBE which is sensed by this comparator. This change in the voltage is proportional to the absolute temperature T and if temperature is changing, then we have a large change in the base to emitter voltage. So, in this way this circuit is actually detecting the temperature change, but the problem as we discussed here is the process spread. Our BJT is very much sensitive to the process spread.

If there is a slight fluctuation in terms of doping in terms of the area or the geometrical lengths, the parameters, then this change very much affects these IC1 and IC2 and because this is a delta VBE is now proportional to IC1 and IC2 as well. So, this is the process spread and this circuit is very sensitive to this process spread or this change in the current and this can be tuned, but the cost of tuning is very high and of course, the leakage current which we have not considered here in this formula, but the leakage current also increases exponentially with the temperature. So, these are the problems that exist with the BJT devices when we use BJT as a temperature sensing device. So, let us discuss some other type of temperature sensor where we do not use BJTs, we use some inherent property of silicon to detect the temperature. For that actually we need to find out a property of silicon or a property of material which changes with the temperature.

So, for silicon we know that the thermal diffusivity of silicon is a very good parameter which actually has a temperature dependence. So, we have a thermal diffusivity of silicon and this is the temperature of silicon. So, this is the temperature of silicon and this is the temperature of silicon has a temperature dependence which is 1 over T to the power 1.8. So, this is the relation of temperature with the thermal diffusivity of silicon.

So, this is the thermal diffusivity in case of pure silicon and because the silicon we use in IC fabrication process is very much pure. So, the thermal diffusivity actually shows this kind of relation in real life because the silicon is very much pure. Now, the question is what the thermal diffusivity is? So, thermal diffusivity is the rate of heat flow in the silicon is the thermal diffusivity. For example, we have silicon material the one side is at temperature T 1, other side it has temperature T 2, then the heat will flow based on the difference of temperature T 1 minus T 2. The rate of this heat flow this is called thermal diffusivity and this rate of flow depends on the actual temperature of silicon.

Let us say the silicon slab is at temperature T. So, the heat flow from T 1 to T 2 depends on the actual temperature of silicon which is T. So, the thermal diffusivity of silicon here is proportional to 1 upon T to the power 1.8. So, this is the relation experimentally measured for pure silicon and thermal diffusivity as we discussed let us say we have a slab of silicon. This slab is at temperature T and on one side I have a supply temperature

T 1, this is T 1, the other side temperature is T 2. So, the heat flow is proportional to T 1 minus T 2, but the thermal diffusivity the rate of this how much fast this heat will flow from T 1 to T 2 that depends on 1 upon T to the power 1.8. So, this is the relation experimentally known and now we want to use this information to make a thermal sensor and because this is all silicon base this is very much integrable. So, this is the relation experimentally known and now we want to use this information to make a thermal sensor and because this is all silicon base this is very much integrable.

So, this d or we call it the thermal diffusivity which is d here, this d can be determined by the energy of the silicon. So, this is the energy of the silicon. So, this is the energy of the silicon by measuring characteristic of ETF or the energy of the silicon. So, this is the electro thermal filter ETF is called electro thermal filter. So, the sensor which we can make will something look like this. We have a piece of silicon and this is the silicon. So, this is bulk silicon. In the silicon we grow a thermal oxide on top. Here, we have a layer of oxide and in this silicon on top of this silicon we have a layer of oxide. In this we have oxide, we fabricate two elements one is the heater and one is the temperature sensor.

So, we have a heater here, this is a heater. So, this is the heater and apart from this let us say we have 100 micron distance, we fabricate another structure which is a temperature sensor. So, this is the temperature sensor. This is temperature sensor. Now, this distance is very much precise. That we can decide based on our layout and design technique. This 100 micron we can fix it as per the geometry of this sensor. So, now we have this silicon on top we have oxide and we have two elements which is heater and the other element is temperature sensor. So, this is the temperature sensor. We have a filter which is a temperature sensor. This is the temperature sensor. Now we have this heater and the other element is temperature sensor. Now, this silicon has a temperature of T. Let us assume this the temperature of this slab is T. Now, this heater this can be excited electrically which we can apply a electrical pulse and this is the temperature it will generate the heat accordingly. So, we have let us say the input is a pulse something like that.

So, this is the input which we are applying to the heater. Now, when the input is high the heater is going to generate heat and when the input goes low the heater is going to shut down. So, if we see the heater is going to generate the heat pulses as per the input applied. Input is a pulse. So, the output of heater will also be pulsating in nature, but that will be heat way heat pulses. So, this is the heat pulse. So, this is the heat pulse. There will be heat pulses generated here by this heater. Now, this heater is surrounded by all silicon. This is this heater is residing in the bulk silicon. So, the part which is very close to this heater of this silicon is going to heat up and the other the temperature of this bulk silicon is at different temperature which is T.

It means the heat these heat pulses generated by this heater are going to diffuse now in all the direction. So, this heat pulses which are being generated here they will be kind of diffusing in all the directions. They will go in all the direction in bulk silicon. They will not go on the top because the oxide is not a very good conductor of heat. So, these heat pulses are going to diffuse now in silicon in all the direction. So, these heat pulses which are generated by this heater they are now going here, here, here, here and this direction as well. Apart from this heater 100 micrometer which is the precise distance we have placed a thermal sensor or the temperature sensor. We will discuss what that kind of temperature sensor is that in the next page, but let us say we have a temperature sensor which is placed 100 micrometer apart from this heater. This temperature sensor is going to sense now these pulses. So, this heat pulses which are transmitted by this heater they travel from heater all the way through temperature sensor.

They appear here and this temperature sensor will produce its output based on those heat pulses and the output of this temperature sensor will be electrical in nature. So, at the output here I get a electrical signal which is proportional to the heat pulses received by the temperature sensor. So, at the output what we are going to receive is like heat pulses something like this. They will not be as sharp as we have applied at the input because the whole bulk silicon is not going to be applied at the input. So, this heat pulses will act like a electro thermal filter. This mass of this silicon will act like a filter and it will damp down all the high frequency component. Only the low frequency component will pass through. These heat pulses are now received by this sensor and generated these electrical pulses. So, now we have two signals. One is the input signal which is very accurate digital signal which we have applied at the heater and the second is the output.

This is the electrical signal generated by temperature sensor. Now, these heat pulses which are being generated by heater and going all the way to temperature sensor they will take certain amount of time. So, this is the output and the output time. These heat pulses from heater to sensor they will take certain amount of time because there is a distance of 100 micrometer in between these two objects and the time taken will be proportional to the speed of these heat pulses. So, this time taken will be equal to 100 micrometer which is the distance between these two objects divided by the effective velocity of these heat pulses.

This velocity of heat pulses is nothing but the thermal diffusivity. How fast the heat can diffuse in the silicon from one point to other. So, this velocity is proportional to the thermal diffusivity which in turn proportional to my absolute temperature. It means if my bulk silicon this whole slab if this whole slab is at higher temperature my thermal diffusivity will be lower means the heat pulses will take more time in going from heater to sensor if the temperature is high. If the temperature is low then the thermal diffusivity will be high as per this relation and it will take less time going from heater to the sensor because the distance is fixed which is 100 micrometer here in this case.

So, because of this velocity or thermal diffusivity dependence on temperature now my this formula the time taken is actually temperature dependent. My temperature of bulk silicon affects my time taken. So, now what we can do we take both of these input and output let us say this is my input which is my pulse which I apply at the heater and this is my output which I generate with using this temperature sensor. This generated output will be slightly delayed because pulses will take time in travelling from heater to sensor. So, my output will look something like this and there is a phase difference between input and output.

If we see closely the rising age of input is at this point and the rising age of output at this point and this is the phase difference. This difference is between input and output. This phase difference is actually now proportional to the absolute temperature of silicon. So, input we already know because we are applying this input through some digital electronics and output is generated by this sensor and this is a electrical output which goes to some electronic circuitry. There we can compare both of these input and output and figure out how much is the this how much is the phase difference between these two waveforms.

This phase difference is proportional to the thermal diffusivity or in turn the temperature of the bulk silicon. So, by this measurement of phase difference we can find out how much is the temperature of this bulk silicon. So, this is how this acts like a temperature sensor which is fully silicon based sensor because we are using all the silicon material only and this phase difference is proportional to my thermal diffusivity and in turn the temperature. The output of this we can write which is phi is the phase difference is equal to minus R where R is the distance between heater and the temperature sensor under root pi the frequency of the signal which we apply divide by D which is the thermal diffusivity of silicon. So, this is how the phase actually is dependent on the thermal diffusivity and in turn the temperature of the whole silicon.

So, this is the silicon based temperature sensor and this is the cross sectional view of silicon based sensor. So, this is the cross section view where we take the silicon and we take a cross section of this and we see the device from on the surface through this cross section. Now, let us discuss some more properties of this thermal sensor which the first is this thermal diffusivity is very weak function of process variation. As we discussed in first slide the BJT actually suffers from process variation if there is a slight process change or there is a fluctuation in the fabrication the performance of BJT or the current of the BJT increases very drastically. But here the thermal diffusivity this property of silicon it does not depend very much on the doping.

We take this thermal diffusivity of pure silicon and if there is a slight amount of doping is there present in the thermal in the silicon then the thermal diffusivity is not very much related to that process variation or that the small amount of doping. So, we can say this thermal diffusivity is weakly sensitive to process doping. So, let us see. So, this thermal diffusivity is very weakly sensitive to doping fluctuation what the doping generally used in CMOS process which is typically 10 to power 14 to 10 to power 20 or 21. In this amount of doping the thermal diffusivity is very much very least sensitive to this kind of doping fluctuation.

It means from wafer to wafer or lot to lot process variation will not impact the performance of the thermal sensor if we make thermal diffusivity waste temperature sensor. The other point is these ETFs they do not require trimming these ETF or electro thermal filters they do not require trimming. The thermal diffusivity D is very well defined very well defined for IC grade silicon. When we take pure silicon which in case we use for IC fabrication the silicon wafer this D the thermal diffusivity is very well defined and very well experimented. So, it does not change with wafer to wafer because the IC grade silicon is very much pure.

So, this ETF or this structure the thermal sensor it does not need individual trimming which is very cost effective. So, now let us see the top view of this structure how it look like. So, we have a heater there for example we make a heater something like this. So, this is a heater with two terminals where we apply electrical input. On the periphery of this heater at a certain distance let us say 100 degrees.

We have the temperature sensor which we are going to place now around this. So, these are the thermopiles or thermocouples. Which we are placing around this heater and if you see this heater is kind of equidistance to all the thermopiles. All this distance from this heater to these thermopiles these are constant which is like 100 micrometer which we have discussed last time. So, this these are thermopiles or the thermocouples where we need two metals as we discussed. In thermocouple we need two different materials to make this thermocouple. And this thermocouple is connected in series with other and this is connected in series with the other thermocouple. So, this is how these thermopiles are connected. So, we have here one thermocouple this is one thermocouple where we have two different materials. So, these thermopiles or thermocouple is made of n plus diffusion layer. This heater is made of n plus diffusion and this thermopiles are made of p plus diffusion and this connection is made up of aluminum.

So, we can see this p plus diffusion and aluminum they form a thermocouple which is going to sense the temperature change. This is my sensing edge which is close to the heater. Now if we see closely we have placed all these thermocouples equidistance from the heater and we are joining all of them in series because the first end of goes to the second end and second thermocouple and the first end of the second thermocouple goes to the second end of the third one and so on. So, all these thermocouples are in series all thermocouples are in series to increase the output voltage and they are placed equidistance. So, that when the heat is generated by this heater this is going to diffuse in all the direction.

So, we need to make sure when these heat pulses are reaching at the thermocouple it reaches at the same time to all the thermocouple. We have 8 thermocouple here. So, this heat pulse which is generated at the center this need to reach at the same time to all the thermocouples. So, we have placed this sensing edge such that this has same distance from this heater which is fixed like 100 micrometer and now this aluminum and P plus diffusion they are different materials.

So, they will act like a thermocouple. In thermocouple we need two different materials. So, here we have P plus diffusion and aluminum the pair of this P plus and aluminum makes a thermocouple and now we use 8 thermocouples connect them in series to get more output voltage. So, we apply this input here at the heater and we get the output in terms of electrical pulses generated by this thermocouples. These thermocouples hot junctions are located roughly circular contour or the equidistance from the heater. We can write it down the hot junctions of thermocouples is roughly circulated equidistance from heater.

So, when a heat pulse is generated from this heater and reaches this thermocouple this edge. So, this heat pulse reaches at the same time to all these thermocouples and these are placed roughly in circular fashion. So, that the distance is same. Now, when this heat pulse reaches this edge let us say this is the heat pulse which is reaching this edge this thermocouple this sensing end becomes hot junction and the other end which is far away we assume it is far away compared to this hot junction this act like a reference junction and this reference junction is far away from this heater which we can assume let us say at some fixed temperature T. So, this reference node and this hot junction the difference the temperature difference between this hot junction and the reference junction this gives rise to the thermocouple voltage which is added up in series by all these thermocouples and generates the output at the top end.

So, in this way this thermal sensor works and it senses the temperature of the silicon slab and gives the output as electrical signal. So, now let us discuss what is the output of this structure this thermal sensor with respect to the temperature measurement or when we increase the temperature how much is the response of this thermal sensor. So, at constant frequency this output of ETF is near linear function or we can say T to power 0.9 if we remember from last slide the diffusivity is proportional to T to the power 1.8 inversely proportional and because these comes in the under root. So, the at the effective phase output pi is actually is almost a near linear it is not perfectly linear it is not T to power 1. In fact, if this comes out at T to power 0.9, but it is very much kind of very close to linear. So, phase output of this is near linear with temperature. It means this structure can be used very well as a temperature sensor because the output of this sensor is very close to linear. So, this is the output of this sensor x axis is the temperature which we are changing and on the y axis we have the phase difference and the output of this structure is something like this. So, this is not perfectly linear because the dependence is only T to power 0.9 it is not T to power 1 and this is the output of this structure which is silicon based sensor. The phase difference is actually a near linear function of temperature is almost in nearly almost a linear function linear can be something like this, but it is more or less linear.

So, this is the case when we use bulk silicon. This is the behavior of phase difference with respect to temperature when we use a silicon wafer which is a bulk silicon wafer then this is the this is the behavior if we use another kind of wafer for example, we have SOI wafers or silicon on insulator wafer then the behavior of the structure will be something like this. So, this is the case for SOI wafer. So, we can see that the performance of this temperature sensor is almost similar for SOI wafer as well as bulk silicon, but in case of SOI wafers the amount of phase difference is little higher that is because the SOI wafers we have a another oxide layer which is below the silicon oxide. So, when we are generating heat pulses the heat does not diffuse through the oxide layer and we have on the top we have oxide layer and the bottom we have oxide layer. So, this SOI device is the silicon which is trapped between all these between these two oxide layers the heating of these SOI devices are much higher compared to the bulk devices that is why we see a difference in the phase difference here for SOI wafers as well as the bulk silicon.

So, SOI wafers we get more phase difference compared to the bulk silicon. These SOI devices are also comes in two subsets one is the partially depleted SOI or we call it PDSOI and the other one is FDSOI we call it fully depleted SOI. So, we have two terms here for SOI wafers we have PDSOI we call it partially depleted SOI and we have fully depleted SOI. So, we have two terms here for SOI wafers we have fully depleted SOI and we have another FDSOI is called fully depleted SOI. In case of PDSOI which is partially depleted SOI this amount of silicon is more on top of oxide.

So, the behavior for PDSOI is very much similar to the bulk silicon. So, the bulk silicon is PDSOI is very much similar to the bulk silicon, but in case of FDSOI the fully depleted SOI the silicon layer thickness is very small and the heat cannot be effectively removed from the top or the bottom because of the oxide layers. So, fully depleted SOI gives you more phase difference compared to the bulk silicon and this is the difference between PDSOI and FDSOI. So, now let us discuss about the doping sensitivity of this structure. So, we have two terms here so these ETF or this electro thermal filters these are electrical devices where we are measuring the electrical performance of these thermocouples. They are not very much sensitive to the process fluctuations for example, doping fluctuation or little bit of geometrical fluctuations they are not very much sensitive to those kind of fabrication based changes.

So, these ETFs are much less sensitive to the process fluctuations. So, this ETFs are much less sensitive to spread in doping concentration. So, doping concentration if there is a change it does not impact much the performance of ETF though if the doping levels are very high then it can contribute to the performance change in ETF because in that case the performance change in ETF is very high. So, doping concentration if there is a change it does not impact much the performance of ETF though if the doping levels are very high then it can contribute to the performance change in ETF because in that case if the doping is really high then the second order effects will also come into picture. For example, the thermal diffusivity of silicon which we have assumed 1 upon T to power 1.8 that is in case of pure silicon, but if the doping levels of silicon is very high then we can no longer assume that silicon is in pure state.

Then this thermal diffusivity factor changes and because of that the performance of ETF will actually change. So, the high levels of doping can contribute to the performance change in ETF can contribute to the performance change in ETF. So, this is the high level of doping. We can consider case where the experiments are performed using N plus plus implant which is very high implant and normally used to reduce the resistivity of silicon well.

So, there is experiment which was conducted. In this experiment we use N plus plus implant plus means it is very high doping. This is normally used for the high level of doping and normally used to reduce the resistivity of silicon. So, in this experiment N plus implant was used which is very high doping. It was doped into the silicon and we measured the output of this structure and the result is this highly doped structures they give they have significant batch to batch variation when we measure the performance of the silicon.

So, this is the high level of doping. So, this is the high level of doping. So, this is the high level of doping. So, this have significant batch to batch variation when we compare the performance of these different batches when we use very high doped implants then there is a significant error in terms of the output. So, these highly doped ETFs was found to have significant batch to batch variation. So, for example, we have the same structure as we discussed earlier. We have this silicon and this is SiO2 substrate. So, we have this is SOI wafer. So, we have the same structure as we discussed earlier. So, we have this silicon and this is SiO2 substrate. So, we have this is SOI wafer. So, we have oxide layer below the silicon. We have silicon here and then we have again silicon oxide and we have this heater and this temperature sensor which goes out.

This is again oxide layer, SiO2 and now we do N plus implant here. This is a heavy implant we put in this device. Now, we cannot assume that this silicon is in pure state and the d is not now proportional to T to power 1.8 because this formula is for the pure silicon and now we have this silicon which is very much or very heavily doped with N plus. So, if we use very high doping then we have batch to batch variation and if we see the output of these ETFs with respect to temperature this is on the x axis we have temperature here on the y axis we have phase which is pi. If we plot this is let us say our normal SOI ETF without then if we plot this on the same graph if you plot the performance of SOI ETF with N plus plus doping it will look something like this.

There is a significant change with respect to the doping this is the performance of SOI ETF with N plus implant. So, this is the performance change of this ETF if we have a very high doping placed in the silicon device with though which is very unlikely because when we make this silicon devices we allocate a separate space for this wafers and we do not put this kind of heavy dopings when we are fabricating this structures. So, this is unlikely, but for to understand what is the effect of doping this is beneficial to analyze these cases when we have doping. So, in a reasonable amount of doping which is 10 to power 14 to 10 to power 20 this does not impact very much the performance of these ETFs and this kind of sensor which is completely silicon based this silicon based sensor can be used as a temperature sensor this is for fully integrable with silicon devices all the process steps are compatible with CMOS fabrication and this is the performance of these ETFs which are fairly linear having a linear performance linear output with respect to the input measurement is very advantages and very beneficial for all the sensors and here we see this silicon based sensor is the output actually is very much linear with the input measurement which is temperature. So, today we discussed the thermal sensors which is completely silicon based or silicon integrable devices.

So, this is all for today.

Thank you.