Transducers For Instrumentation

Prof. Ankur Gupta

Centre for Applied Research in Electronics (CARE)

Indian Institute of Technology, Delhi

Lecture - 12

Thermal Sensors: MEMS Based

Hello, welcome to the course transducers for instrumentation. Last lectures we discussed some thermal sensors which are made up of silicon and last lecture we discussed a thermal sensor which is based on the nano materials such as graphene. Today in today's lecture we will discuss some thermal sensors using MEMS device. The MEMS is the micro electro mechanical systems. These devices, these are made up of materials which for example some metals or metal oxides and the property of these materials is such that some properties like mechanical properties of these materials change with the temperature. So we want to use these properties and make a thermal sensors which gives us the temperature in terms of the mechanical property change.

So many a properties for example the stiffness or the Young's modulus these are all mechanical properties which are greatly influenced by the temperature. So we want to use such materials which shows a corresponding change in the mechanical properties with temperature and such a material which is widely used is vanadium oxide which we generally use for micro fabrication and making MEMS devices and today we will see such a sensor which we can use for temperature sense. So we discussed today some thermal sensors which are MEMS based. So the full form of MEMS is micro electro mechanical systems. So we use a material which is called let us say vanadium oxide. Here for this material mechanical properties are temperature dependent. So we use vanadium oxide for sensor fabrication because along with the mechanical properties we need to take care of certain other parameters so that the material is compatible with the fabrication process. For example for almost all the materials the mechanical properties are very much temperature dependent but those materials are not very much compatible with the fabrication process we follow to make these MEMS devices. These MEMS devices are very small in nature. These are for example micro word is there micro electro mechanical system. These are mechanical systems which we excite using some electrical stimuli. So we fabricate these devices along with our normal CMOS kind of process. So the material which we choose to fabricate these MEMS thermal sensor this material should be compatible with the fabrication process we follow. So that's why we use vanadium oxide which is very much compatible.

Now we take this material and we want to make a resonator because the mechanical properties are very much used to make a resonator and the temperature change of a mechanical resonator this can be determined from the change in the resonant frequency. So we have here something called change in resonant frequency. So we have a MEMS device where this device is resonating at a particular frequency and if the temperature is changing then there is a corresponding increase or decrease in the quality factor of this and because of that we get a change in the resonant frequency. So this change in the resonant frequency with temperature we can detect and this gives you the corresponding output in terms of temperature. So we follow now the fabrication process of such a MEMS device. So for that we start with this silicon wafer. So we have a silicon wafer here. This is silicon wafer and the thickness is typically 200 to 300 micron. This is step one. Now we take this silicon wafer and we grow the oxide both side of this using a dry oxidation or wet oxidation whatever preferable. And second step we this is step B where we put the oxide both the side. Let's say this is our oxide and on top of this silicon oxide we put a thin layer of gold. This is layer of gold which is typically 100 nanometer and on top of this gold layer we put this vanadium oxide. This is our vanadium oxide or VOX we call it in short and the thickness is typically 400 to 500 nanometer. So this is the second step where we take this silicon and we put the oxide both the sides.

We just put a uniform layer of oxide both the side. On top of it we put a layer of gold very thin layer of gold to make a electrical contact and on top of this gold layer we put the vanadium oxide which is our material where the mechanical properties are dependent on temperature. So we take this as a second step now we in the next step we etch this pattern on top. So we have our silicon the oxide on top we have gold and we have vanadium oxide which we pattern as per our dimensional requirement. So this is our step C where we pattern VOC pattern vanadium oxide. In the next step we take this silicon and from the back side actually we remove oxide and micro machine it. We kind of etch the silicon from the bottom so our oxide looks something like this. This is our oxide. So in this step D we pattern the silicon. So what we do from the back side of the wafer we start etching the silicon. So first there is a oxide layer we etch that silicon oxide layer and start etching the wafer from the back side. So it is called the photolithography from the from the back side of the silicon wafer and we etch out all the silicon so that we reach oxide till oxide on the top. So one requirement of this kind of fabrication process is the silicon wafer which we start with that should be thinner than our normal silicon wafers. We cannot have a very thick silicon wafer to do this processing because in the next in the kind of last step we need to we need to etch whole of the silicon and reach on the top. So if the silicon wafer is too thick it will be difficult to etch all the way till to the top.

So we start with the silicon wafer where the thickness is not very high. It is typically 200 to 300 micrometer. So in step D where we pattern this silicon we pattern from the back side and we pattern this and silicon till here. So this silicon is also removed in this pattern of silicon. So this part of silicon also gets removed and what we get as a final device is something like this. We have silicon here. On top of this we have oxide and then we have gold which is used for the contact and on top of this we have this V O X layer or vanadium oxide layer and this is other side of silicon. So this is our final structure. So in this final structure we see that this vanadium oxide this is a thin layer of vanadium oxide material which is joined on the one side of this layer which is in contact with other device other stack of layers and one side is actually hanging in the air. So if we see this is like a cantilever or you can say micro cantilever which one end of this micro cantilever is fixed on the wafer and the other end of this micro cantilever is free to move.

Now because of the material properties of this micro cantilever this micro cantilever is now going to resonate along with its axis up and down. So this micro cantilever will resonate at its resonant frequency. This resonant frequency depends on the material properties. We have vanadium oxide the material properties are different so resonant frequency will be different. If this micro cantilever is based on copper material then the resonant frequency will be different.So now this micro cantilever V O X based micro cantilever is now free to move in up and down direction and the frequency is fixed based on the vanadium oxide. Now this resonant frequency is a strong function of temperature because the mechanical properties of material are temperature dependent and these mechanical properties are giving rise to this resonant frequency. So let us discuss little bit about what is the resonant frequency and how it change and how we measure them. So let us discuss something called series resonant circuit. When we have a series resonant circuit something like a inductor or capacitor and a resistor connected in series they have a particular resonant frequency and a factor something called Q or the quality factor. This quality factor of resonant circuit is a measure of how good the quality is for this resonant circuit. For example if the quality factor is very good we have a sharp detectable change in the magnitude of this resonant circuit. So we have the quality factor or we call it Q it is a measure of quality of resonance. So a high value of Q or high value of this quality factor it means a narrow bandwidth of the circuit when we excite this electrical circuit because the Q is higher it means we have a very sharp response of this resonant circuit at that particular frequency where the quality factor is very high. If we have a very sharp change in the kind of impedance of this resonant circuit it is very easy to detect by electrical means and it is desirable for making a sensor.

So this high value of quality factor is desirable to make a sensor any kind of sensor in fact not only the temperature sensor. So we have a higher value of this Q this corresponds to a narrow bandwidth which is desirable in many applications. So for a definition Q is the ratio of power stored to the power dissipated Q is the ratio of power stored to power dissipated. Or we can write the Q or the quality factor is power stored in the circuit divided by the power dissipated. So the quality factor or Q of a resonant circuit is the ratio of power stored how much power is stored electrically in that resonant circuit divided by the power dissipated by this electrical circuit. So to improve Q either we need to increase the power stored in the circuit which is generally fixed and the second term is the power dissipated which means how much power is being dissipated at the resonance. So this value actually changes when we change the impedance of this circuit. For example beyond resonance the impedance actually increases and below the resonance also the impedance increases at particularly the resonance the impedance actually decreases and the current increases. So because of this sharp change in the impedance in at that particular resonant the quality factor is very high because the power dissipated is very less. So we have the definition of Q which is power stored divided by the power dissipated. Now a series resonant circuit looks like a resistance at a resonant frequency. So series resonant circuit looks like a resistance at resonant frequency means the XL the impedance of inductor is equal to XC which is the impedance because of the capacitor. So at resonance the impedance of capacitor actually nullifies the effect of inductor and because of this null we get the impedance as a purely resistive value because XL and XC cancels out each other and we get a net impedance as the resistance of this series resonant circuit. So XL equal to XC at resonance. So at resonance when this XL and XC cancels out we get a current which is at maximum at resonance.

So the current is maximum at resonance and hence the impedance is at minimum. If we plot the graph of current versus frequency it will look something like this. This is the frequency axis on X. Let's say for example this is 100 hertz and this is 1 kilohertz. On the Y axis we have current which is in milliamp. So if we plot this current versus frequency graph for a series resonant circuit the graph looks something like it peaks up at certain point and the base goes down at beyond this frequency. This frequency is the resonant frequency and this is the resonance point. This is resonant frequency. Below this resonant frequency the effect of series resonant circuit is dominated by a capacitor because the impedance of capacitor dominates at low frequency and above this resonant frequency the effect of inductor dominates because XL or the j omega L the effect of this inductor dominates at high frequency. So below this resonance point this area is dominated by the capacitor and above this frequency these frequency ranges these are dominated by the capacitive nature of series resonant circuit and at this particular resonant point these capacitor and these inductor values they cancels out each other and the net impedance looking into this series resonant circuit is totally resistive. So this XL and XC cancels out leaving only the resistance part means the impedance overall decreases and because of this decrease in the impedance we see a sharp increase in the current here and this sharp increase in the current can be easily detected by electronic circuits which are placed alongside this sensor. So here we have this resonant point and the corresponding resonant frequency. So we can note down few points for example at resonance this circuit looks purely resistive. Below resonance it looks capacitive. And above resonance this looks inductive.

So here we see at resonant frequency the circuit behavior actually changes from the capacitive to the inductive behavior and sharp at resonance the circuit is purely resistive it means there is no inductive or capacitive effect these effects can be easily detected by external circuits. Now these resonant current peaks can also be changed by adding some external resistances. For example this resonant peaks can be changed by varying the series resistor. And if we change this resistor which actually change the Q or the quality factor.

And when we change the quality factor of a certain resonant circuit it means the peak of this resonant circuit actually changes and depending upon Q increases or decreases this peak comes down and the curve actually flattens out.

It does not remain same the peak also varies and the broadness of this curve also varies and depending upon the Q we have different different shapes of this current graph. So this also affect the broadness of curve. So we can say that a low resistance high Q circuit this has a narrow bandwidth and if we have a circuit where we have a high resistance or low Q there we will have a wider bandwidth. So if we plot these characteristic for a series resonant circuit we get something like this on the x axis we have frequency and on the y axis we have again the current and now we can plot multiple graphs for multiple Q. For example this is one graph where we have a high Q we can have another graph where for example let's say this Q is 10 we can plot another graph where we have Q is limited so this graph is let's say for Q equal to 5 we can have some other graph this graph is for Q equal to 2 and let's say one more graph we have this is for Q equal to 1.

So if we see in this graph when the quality factor increases we see there is a sharp change from the capacitive nature to the inductive nature of the circuit which is easy to detect compared to the graph where quality factor is just one there is a gradual change from capacitive to inductive nature and it is very difficult to change very difficult to detect where the circuit is changing from capacitive to inductive. So having a high quality factor is very good for a sensor we can very sharply and very easily detect where the circuit is changing its behavior from capacitive to inductive. So we see here that when the quality factor goes down the peak goes down the peak value is somewhere here which goes down as the quality factor decreases also the bandwidth of this circuit also changes because the bandwidth we measure for a particular graph which is the point where this graph reaches 70% of its peak value. For example this is the peak value for let's say we are talking about Q equal to 10 this is the peak value and the bandwidth of this graph or this graph for Q equal to 10 is the point where this graph reaches 70% of its peak value. For example this is let's say the 70% of if this is 100% this is 70% if we assume this is total 100% up to here.

So when the value the peak value decreases to 70% of its peak value this difference in the frequency is the bandwidth of the circuit this is the bandwidth that this f1-f2 we can call it let's say frequency 1 and this point is frequency 2 this bandwidth is f2-f1 the difference in the frequency where the magnitude reaches 70% of its peak value. We can write it the bandwidth is equal to fc over Q where fc is the resonant frequency divided by the quality factor and we measure the bandwidth or we can call it delta f between 70.7% amplitude points of series resonant circuit. So here we see when we have a series resonant circuit it changes the behavior from capacitive to inductive and how sharp it changes the behavior that depends on the quality factor of this circuit. So for example we have a very high quality factor circuit where the Q is very high then we have a very noticeable change in the behavior of the circuit we have this peak value which is very high so it is easy to detect and make a sensor which is very much sensitive to this change in the peak value.

However if we have a quality factor which is very less then it is very difficult to detect that change this change can be little bit on the left on the right which is difficult to detect by electronic circuit so we want a higher and higher Q. So the same quality factor we will measure now for our fabricated device which we just did it two slides back we made this MEMS device which is based on vanadium oxide material where this micro cantilever is hanging in the air fixed at the one end and it is resonating at its resonant frequency. So based on this resonant frequency we can measure how much is the temperature change because the resonant frequency is a very strong function of the temperature or the mechanical properties are dependent very much on the temperature. So now we see the behavior of this MEMS circuit so we have that MEMS that vanadium oxide based sensor. If we plot the resonant frequency versus temperature on the X axis we have temperature and on the Y axis we have now the resonant frequency.

Let's say this is origin this typical value is 40 kilohertz this is 20 kilohertz this is 30 kilohertz just for an example and the temperature is changing from 0 to 100 degrees. This frequency is the resonant frequency is now going to change and for the fabricated device which is based on vanadium oxide the graph looks something like this which is fairly linear graph with change in the temperature. So now we see the resonant frequency which means that this vanadium oxide micro cantilever is actually fixed at one end and it is swinging at the other end with certain resonant frequency. This resonant frequency is now decreasing with increase in the temperature for this vanadium oxide based thermal sensor and if we plot the quality factor of this MEMS device which will look something like this. On the X axis we have temperature again between 0 and 100 and on the Y axis now we have quality factor this is 500, 400, 300. If we plot the quality factor of this micro cantilever this looks something like this. The quality factor has this kind of behavior. So now we see the resonant frequency is a function of temperature in fact it is a very strong function of temperature and the behavior of this resonant frequency is fairly linear with temperature. To make a sensor the desirable property of a sensor is the output should be linear compared to the measurement or the input quantity and here we see the resonant frequency is fairly linear with the change in the temperature. Linear output is very much desirable to make a sensor of very good quality.

Now this quality factor actually varies from let's say 400 to 600. Of course it depends on the dimensional properties of micro cantilever and this exhibits no significant change or significant dependence in 20 degree to 80 degree centigrade range. So these are the some measured value in a particular vanadium oxide cantilever it's not that these are very fixed these values can be changed if you change the geometrical properties of your sensor these are one these are one measured value for a particular thermal sensor. The next point is there is a linear shift in the resonant frequency with the temperature. So as we can see in the first graph there is a linear shift in the resonant frequency with temperature change. Which can be used for temperature sensing applications. So today we saw a MEMS based temperature sensor where we are having this MEMS device or the micro electromechanical system where we fabricated a micro cantilever fixed end and which is resonating at a particular resonant frequency because of the thermal vibrations. Now this resonant frequency is a very strong function of temperature and we see that the resonant frequency is very much linearly dependent on the temperature change. So there is a one degree change in the temperature gives a linear change in the frequency change the resonant frequency change which is very much desirable function of a thermal sensor or in fact any kind of sensor.

So this is all for today.

Thank you.