MEMS & Microsystems

Prof. Santiram Kal
Department of Electronic and Electrical Communication Engineering
Indian Institute of Technology, Kharagpur

Lecture No. #16

MEMS Microsensors Thermal

So till my last lecture we were discussing on various types of a micromachining techniques including conventional as well as many nonconventional techniques also we have discussed. Now onwards we will spend sometimes on microsensors. Various kinds of microsensors which are fabricated using MEMS technologies and which are integrated with microstructures that are fabricated using either bulk micromachining or surface micromachining or LIGA or stereolithography. The first kind of sensor I will address today is thermal sensors. So today's lecture will be on micromachined thermal sensors.

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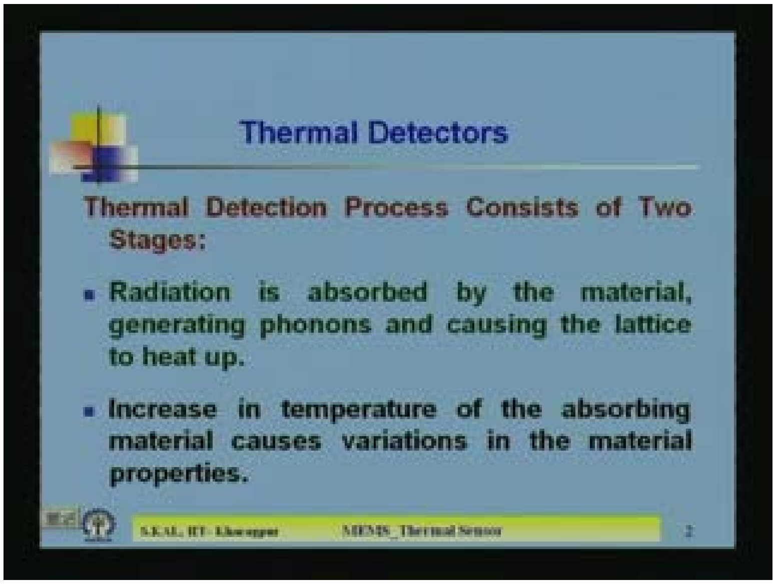

Thermal Detectors

Thermal Detection Process Consists of Two Stages:

- Radiation is absorbed by the material, generating phonons and causing the lattice to heat up.
- Increase in temperature of the absorbing material causes variations in the material properties.

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Thermal sensors are very important in respect of its various applications. In industrial some control, furnace, temperature control or in many of the experiments we need accurate control of the process temperature and not only that, in many cases environment temperature also is monitored with the help of certain sensors. Those kinds of sensors basic principles already we have discussed. I hope in my second or third lecture. Today we will highlight little bit in detail, the different thermal sensors, its basic principles and its fabrication techniques using micromachining technology. So thermal sensors are basically thermal detectors. It can detect thermal energy. So thermal detection process consist of two stages. First stage is a radiation which is absorbed by the material and after absorption of the material it generates phonons causing the lattice heat up. So, as soon as the radiation is absorbed, in a solid materials so then the lattice are started vibrating which are called phonon and because of the vibration of the lattice it heats up. Now because of the heating after absorption of the radiation local temperature will increase and this increase of temperature causes variations in the material properties? So that is the basic mechanism of the thermal detectors. That means it is basically a two-step process. In the first step the thermal energy is to be absorbed, in the second step the temperature heated and because of the heating of the localized heating the material properties will change. So this is a two-step phenomenon. So what are the thermal effects?

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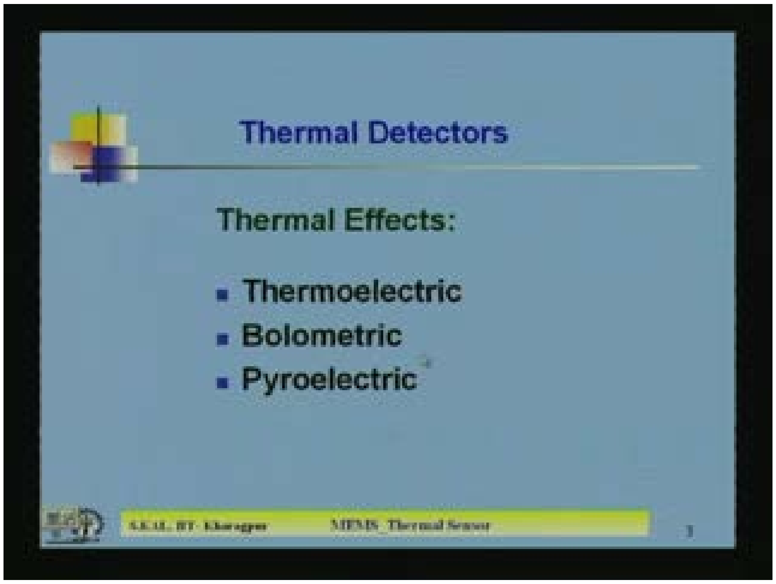

Thermal Detectors

Thermal Effects:

- Thermoelectric
- Bolometric
- Pyroelectric

So thermal effects are three-fold. Number one is thermoelectric, number two is bolometric and number three is pyroelectric. These are the three basic thermal effects which are utilized in making thermal sensor. Thermoelectric effect is well known to you. Basically it is Seebeck and Peltier effects which already have come across in your earlier classes. What is the principle of that? Basically when two different materials are connected to form junctions and if those junctions are kept at different temperature then a thermo emf will be generated in across the junctions and this thermo emf is directly proportional to the temperature difference between the hot and cold junctions. So that is known as thermoelectric effect and this is obviously is directly proportional to the thermoelectric coefficients or Seebeck coefficient and to make those kinds of sensors we have to see or we have to look for the material whose Seebeck coefficients is very high.

So that is the thermoelectric effect. The second kind of effect which is used in thermal sensors, that is the bolometric effect. What is that effect? Basically there are certain materials whose temperature, after absorption of temperature the resistance changes. All the material will have the temperature coefficient of resistance. After absorption of thermal radiation the temperature coefficient resistance will change. As a result of which the total resistance of the structure will change. That is known as the bolometric effect and the bolometric materials may be of different kinds that I will discuss later on. The third effect is a pyroelectric effect. There are certain materials which will have the charge accumulation at the surface. That is dipole movements in certain materials which will have certain orientation of the dipole movements. As a result of which on the surface of the materials will have certain amount of charges.

Now after absorption of thermal energy the dipole movement also changes and because of the change of the dipole movement, the surface charge are going to be changed and that effect is known as pyroelectric effect. So these three effects are used in thermal sensors and when those sensors are made on membrane or on some flexures or on some cantilevers then these are called MEMS thermal sensor. Obviously you can ask, what is the reason of bringing those microstructures in making those thermal sensors? Those thermal sensors were available before MEMS technology has been matured. But obviously we will the exploit the advantages of MEMS technology for making those kinds of sensor. What are those advantages? The advantages are many-fold. Number one in a MEMS micromachining technology you can miniaturize, the thing total structure you can deposit thin film, metallic thin films on the substrate and not only that if I concentrate on the thermoelectric effect or bolometric effect, there if I make the sensing element on a surface which has got very less thermal conductivity then the loss due to conduction will be less.

In that way if I can make the sensing portion of the total structure on a thin membrane or on a flexure, then what will happen? So localized heating of that membrane with the help of certain thermal absorber quickly changes the temperature of the sensing element. Before heat is dissipated with the material. Because if we make the sensing element on diaphragm or membrane or cantilever of thickness say 50 micrometer or say 20 micrometer or 30 micrometer. Then total thermal mass of the localized portion is very less. So automatically the dissipation of the thermal energy will be less in that particular region which will help the sensing element to sense precisely the thermal energy. So that is the great advantage and at the same time we will see in today’s class how this effect can be properly utilized by isolating the rest of the portion of the substrate by making certain groups. So that is a physical low connection of that membrane or that particular diaphragm with the bulk silicon material. So that is the advantage of the MEMS and not only that, with that we can integrate those sensors along with the conditioning circuitry that I have told many times in earlier lectures.

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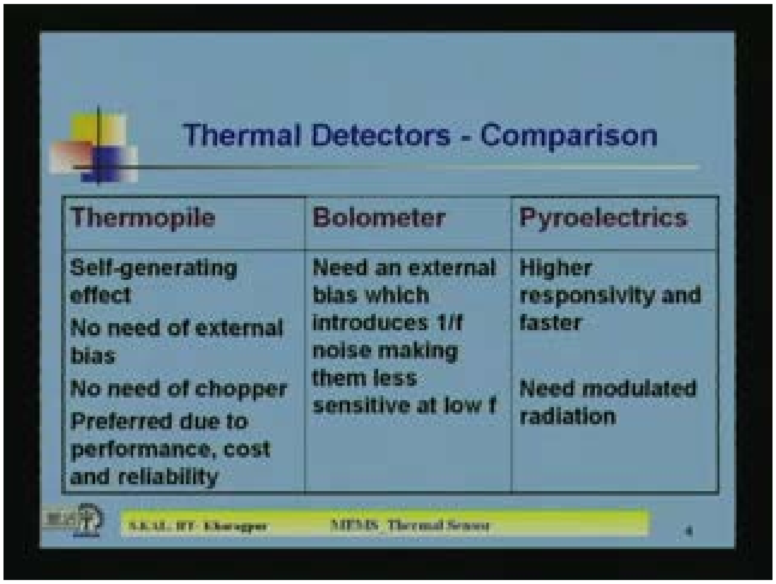

Thermal Detectors - Comparison

Thermopile	Bolometer	Pyroelectrics
Self-generating effect No need of external bias No need of chopper Preferred due to performance, cost and reliability	Need an external bias which introduces 1/f noise making them less sensitive at low f	Higher responsivity and faster Need modulated radiation

Now let us concentrate on the thermal bolometer and pyroelectric, the thermal effects a comparison and you can see here a table where the advantage and disadvantage of this kinds of thermal effects are mentioned. So thermopile kind of thing is a self generating effect for that you do not need any external supply. That is why it is self-generating if two thermoelectric, if two junctions of dissimilar materials are heated. So automatically the thermo emf will be generated. So that is, that means you do not need any externals supply or external source to pick up that voltage. That is the self-generating effect. No need of external bias because it is self-generating, we do not need any external bias. No need of chopper. Chopper means frequent, means on-off kind of things. That chopper technique is not required in case of thermopile sensors. Preferred due to performance cost and reliability. Because this particular thermoelectric effect or Seebeck effect is well understood and it will give a very good performance. Because it is being used long time in thermocouples you know.

Platinum radium thermocouple and other material silicon polysilicon aluminum or other metal various kinds copper tungsten and another thermocouple which are used for quite a long time for sensing the temperature of furnace or oven etcetera. So it known and cost is less and reliability is high. On the other hand if you look on the bolometer, bolometric effect or bolometer thermal detector, there it need an external bias. Why because, bolometer on absorption of thermal radiation its temperature changes on absorption of thermal radiation, its resistance changes. So now if resistances changes, direct resistance if you want to sense, then you have to have a supply voltage. So that if you send a constant current through the resistance, because the of the resistance change, so what will happen the voltage across the resistance will also change. So that means you will need a supply. So that is one of the thing you can in thermopile you do not need an external bias supply. But here you need external bias supply. If you need an external bias supply then automatically we introduced 1 by f noise and this noise makes the sensor less sensitive at low frequency because of that noise.

In the third effect is the pyroelectric effect. Pyroelectric effect is known but making thermal sensor using pyroelectric effect is not that much simple as compared to thermopile sensors. Now here in case of pyroelectric sensor its responsibility is very high and faster. Because it is not two-step process, thermal thermopile sensors are two-step process, this is a single step process. So automatically these kinds of sensors are faster than thermal sensor. But it needs modulated radiation. Because you see the charge which is accumulated at the surface, because of the dipole movement, orientation change or whatever it is, so then how do you detect those changes of charges. So change charge that means, if you need a chopper means radiation. On and off chopper means if the radiation is sent to a chopper, that mean sometimes on because your allowing radiation, not allowing and because of that there will be a delta Q change of charge will be the delta Q and this delta Q may be reflected for change of current through an external circuit, change of charge. So that means there you need a modulated radiation. The radiation has to be modulated to in order to sense or in order to pick-up the effect generated due to absorption of thermal radiation in this kind of pyroelectric sensors.

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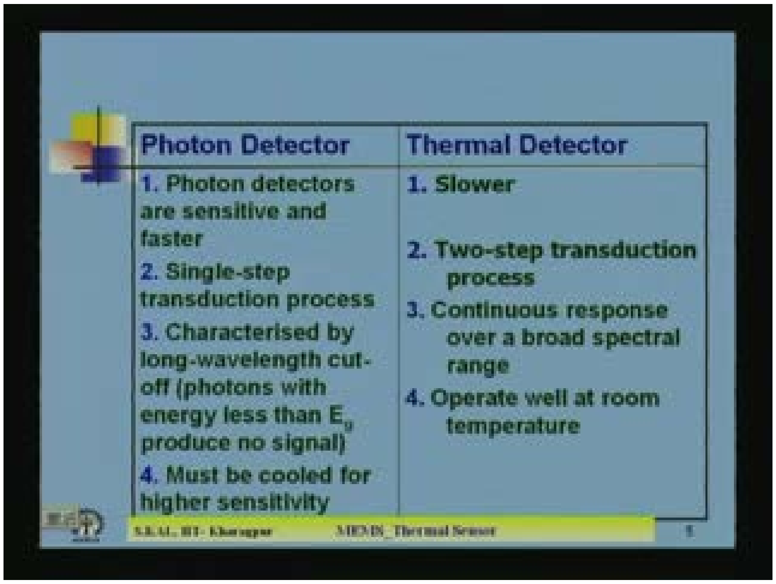

Photon Detector	Thermal Detector
1. Photon detectors are sensitive and faster	1. Slower
2. Single-step transduction process	2. Two-step transduction process
3. Characterised by long-wavelength cut-off (photons with energy less than E_g produce no signal)	3. Continuous response over a broad spectral range
4. Must be cooled for higher sensitivity	4. Operate well at room temperature

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Now there are two kinds of detectors; one is known as photon detectors, another is a thermal detector. You see detector can absorb radiation thermal radiation and another effect is also there. A detector can absorb photon means light and after absorption of the light, heat may be changing. So that is also a thermal effect. So that is why there are two kinds of detectors; one is known as photon detector, another is a thermal detector. A comparison is given here between the photon detector and thermal detector. Photon detectors are sensitive and faster, thermal detectors are slower. I can give a name of the photon detector is a photodetector PIN junction photodetector. PIN photodetector you know the device PIN photodetector that is a photon detector. Then what is the basic principle? When light is incident on such kind of detector depending on the E_g value.

The carriers will be generated and those carriers will jump from valence band to conduction band. As a result of which the semiconductor conductivity will change. That means it is a single step process. As soon as the photons are incident on those detectors, due to the absorption of the optical energy or photon energy depending on E_g if this H nu is greater than E_g then only those thermal a thermally generated carriers will cross the junction and as a result of which you will have a photo current. That means it is a single step transduction process. So that is why it is automatically first and it is not two-step, clear. At the same time those photon detectors will have a limitation. What is the limitation? Just now I told you that energy absorbed must be greater than H nu. That means the energy H nu must be the E_g band gap.

So band gap and the H nu, nu is the frequency means wavelength. So this is dependent on the wavelength. So this kind of photon detectors is dependent its responsibility or responses is dependent on the amount of energy it is absorbing. That energy must be greater that the E_g value. Otherwise it will not detect. That means it is frequency sensitive. That means its band width is very small. On the other hand the thermal detectors although it is slow, it does not depend on the E_g value of the material because it is the metal. Two metals dissimilar it it is going to give you the thermal detector. That means its band width, spectral band width is high compared to the photon detectors. Now that what I discussed is highlighted in this table thermal detectors are slower. It is a two-step transduction process continuous response over a broad spectral range.

As I just now told it is not dependent on the wavelength of the thermal energy or radiation. Its band width is very wide operates well at room temperature. But thermal detectors they must be cooled for higher sensitivity and there is a demand of uncold detector IR detector. Because if it also depends on the temperature you know because it since the photo current which is obtained from the PIN detector is also the some thermally generated current will be there. If the temperature changes, because of that the carriers also will cross the junction. So that mean total current which is getting, you are getting across the photon detector is some was due to the absorption of the photons and some was due to the temperature change. Thermally generated carriers, so in that way you see if the temperature is very low, so that thermal generation of the carriers will be extremely small. In that case you can say that whole thing is due to the absorption of photon. So that is mentioned here, it must be cooled for higher sensitivity and it is characterized by long wavelength cutoff. Photons with energy less than E_g produce no signal. So these are the comparison between photon detector and thermal detector. Now how do you characterize a detector?

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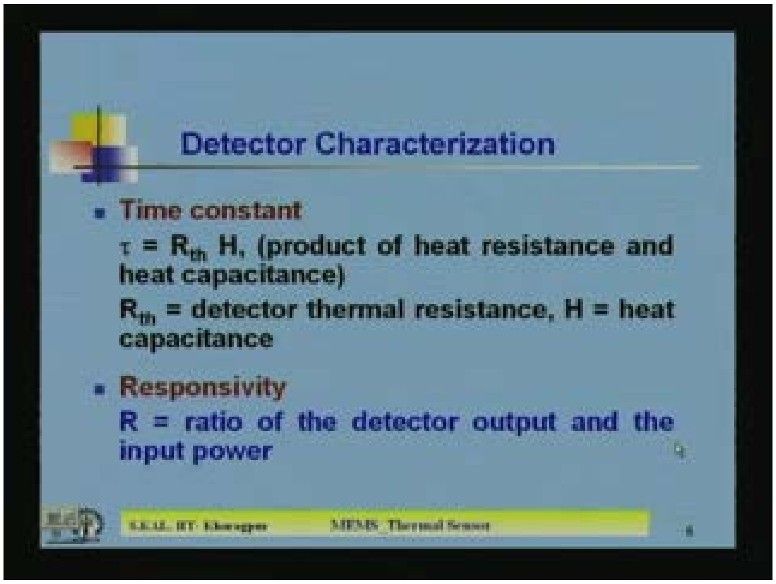

Detector Characterization

- **Time constant**

  $\tau = R_{th} H$, (product of heat resistance and heat capacitance)

  R_{th} = detector thermal resistance, H = heat capacitance

- **Responsivity**

  R = ratio of the detector output and the input power

There are certain parameter based on which we characterize the particular detector. What are those parameters? First is a time constant. Time constant has an important parameter because we always look for a sensor which works very fast whose time constant is low is the faster sensor. If you take some time, so that is slow sensors are normally not desirable in many cases. So this time constant is given by R_{th} into H where R is a product of heat resistance which is given by the R_{th} and another is H which is known as the heat capacitance. Heat capacitance and heat resistance product is known as tau which is a time constant and R_{th} is basically the detector thermal resistance. Sometimes it is known as heat resistance. Thermal resistance of the detector is R_{th} and h is the heat capacitor. Second parameter is responsivity. How it is responsive? The responsivity is characterized by the ratio of the detector output and the input power. How much input power you are consuming to achieve certain detector output. That is known as the responsivity. That is R.

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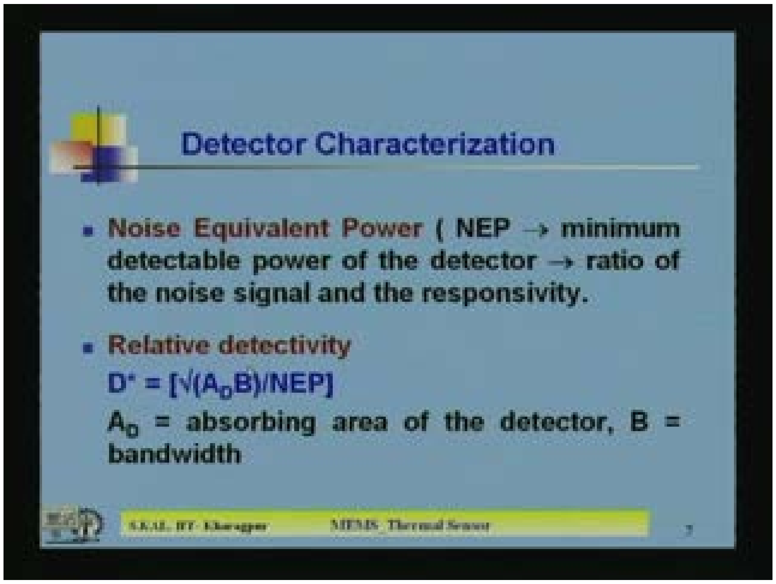

Detector Characterization

- **Noise Equivalent Power** (NEP → minimum detectable power of the detector → ratio of the noise signal and the responsivity.
- **Relative detectivity**

  $D^* = [\sqrt{(A_D B)}/NEP]$

  A_D = absorbing area of the detector, B = bandwidth

Other than time constant and responsivity there are other parameters which also characterizes the detectors. Those are noise equivalent power which is known as NEP and the second and the fourth one is relative detectivity or it is denoted by D star. Noise equivalent power or NEP, it is basically the minimum detectable power of the detector and is given by the ratio of the noise signal and the responsivity. That means noise equivalent power if your response, due to the thermal detection and is comparable with the noise. So you cannot make out your actual signal due to the thermal effect. So that is why your sensor the NEP is an important consideration. So in presence of certain noise will be there. You cannot say in environment which does not have any noise. So even in the presence of noise your request signal will be picked up. So that is given by the NEP is the ratio of the noise signal and the responsivity. In a relative detectivity is given by under root ADB divided by NEP. NEP is a noise equivalent power, AD is absorbing area of the detector because you are just making the detector over certain area in your putting some absorber. So that area is known as AD and B is the bandwidth. So ADB under root divided by NEP is known as the relative detectivity.

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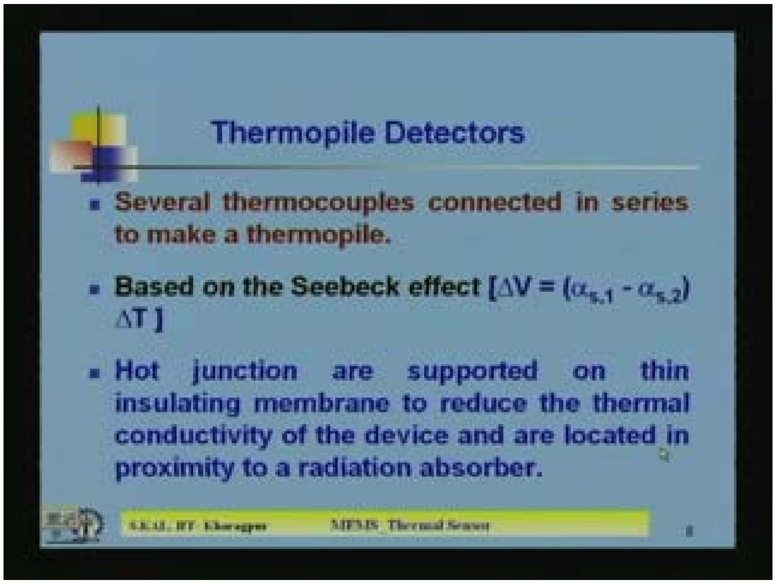

Thermopile Detectors

- Several thermocouples connected in series to make a thermopile.
- Based on the Seebeck effect [$\Delta V = (\alpha_{s,1} - \alpha_{s,2}) \Delta T$]
- Hot junction are supported on thin insulating membrane to reduce the thermal conductivity of the device and are located in proximity to a radiation absorber.

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Now thermopile structure. What do you mean by thermopile? Thermopiles are basically the series connection of number of thermal that is thermoelectric junctions. So many thermocouples when connected in series. So that is known as the thermopile. Why do we connect it? Because a particular thermocouple the thermo emf will be very small, that is may be say a few microvolts. Now if we add the thermo emf of number of thermocouples in series, then total thermo emf will be added. So we can have a considerable amount of the thermo emf . So that you can sense the minimum change of temperature, if you add like that. So that is why that is known as a thermopile. Thermocouples are piled up basically. So several thermocouples connected in series to make a thermopile. Now the Seebeck effect is given by delta V. That is the thermo emf generated due to the Seebeck effect is given by alpha s 1 minus alpha s 2 delta T, where alpha s are basically the Seebeck coefficient of metal one and metal two or material one and material two and delta D is the temperature change.

If you multiply these two, it will give you the delta V which is the thermo emf. Now here the hot junctions are supported on thin insulating membrane to reduce the thermal conductivity of the device. That is one of the requirements just I mentioned to improve the sensor performance and is located in proximity to a radiation absorber. So many of the thermopile sensor the use certain absorbing material that will immediately absorb the thermal radiation. In some cases black wax is used. A thin layer of black wax is put on the sensing element where the thermal energy is incident so that immediately the thermal energy will be absorbed and that will be transferred on to the hot junction of the thermocouple.

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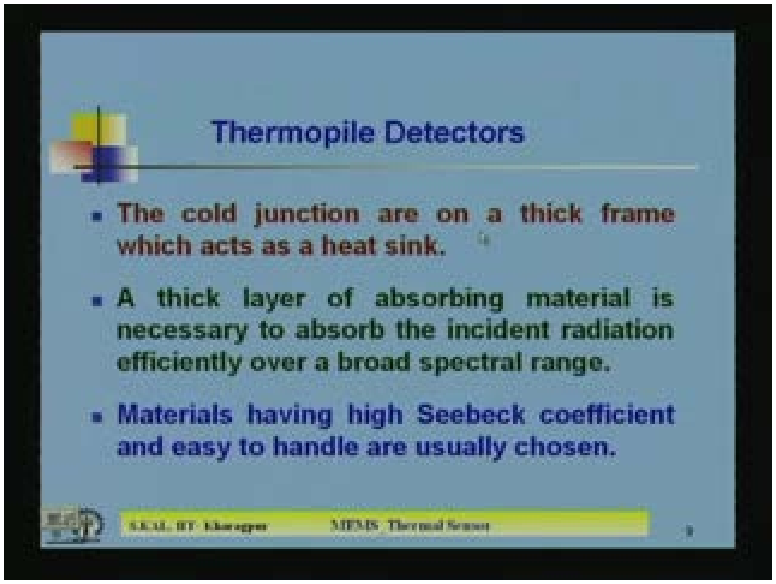

Thermopile Detectors

- The cold junction are on a thick frame which acts as a heat sink.
- A thick layer of absorbing material is necessary to absorb the incident radiation efficiently over a broad spectral range.
- Materials having high Seebeck coefficient and easy to handle are usually chosen.

Now the cold junctions are on a thick frame which acts as a heat sink. So the temperature difference more, means you will get more thermo emf. So obviously you cannot keep both the junction at the same temperature. So the sensing means hot junction we call it is on membrane. But other junction should be kept away from the membrane and that is on thick rim which has large thermal mask and which we call it as heat sink. From there the heat lost due to radiation is the conduction process is more. So that is why that we called as a heat sink. A thick layer of absorbing material is necessary to absorb the incident radiation efficiently over a broad spectral range. The absorber which you are placing on the sensing element must have broad spectral range. That means that absorption property should not depend on the frequency of the radiation. That is why you have to choose certain material which will absorb the thermal energy equally over wide spectral range.

Materials having high Seebeck coefficient and easy to handle are usually chosen. Why easy to handle? Easy to handle means you can process that material. What do you mean by process? You can deposit that material and you can make structure out of that material very easily. That means that material must be friendly with the processes used in MEMS micro fabrication or integrated circuit process technology. The defining that particular line or the metal or the material should be very simple and it must be compatible with the available integrated circuit processing technique. That is why it is known as easy to handle.

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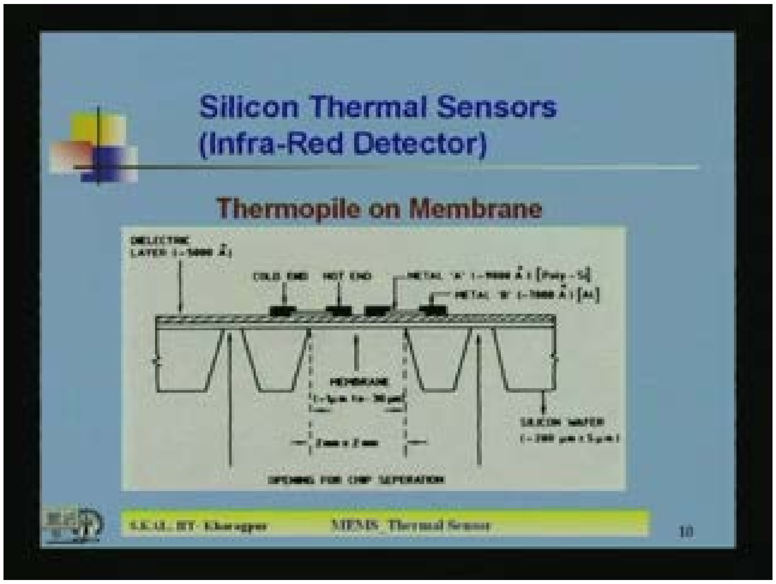

Silicon Thermal Sensors
(Infra-Red Detector)

Thermopile on Membrane

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Here in the diagram you can see the cross section structure of a thermopile on membrane. You can see here the top layer which is, this is basically insulator and that insulator is silicon dioxide, this one insulated. Now there you are making a membrane, this is the thin membrane you can see here. This is the thin membrane, this is a membrane, here is a membrane and its thickness is very small nearly 20 to 30 or say is in some cases 50 micrometers and this is the rim. Two rims and here in this place and this place you are thinning down again. Although you are not making any sensing element in this location and this location, but you are thinning because you have to break the wafer after complete fabrication. This is basically the separation mark and this portion is the thick rim where you place the cold junction.

The cold end you can see here in the cross section diagram. The cold junctions are here. Here two metals are used, metal A and metal B. In this diagram it shown one metal A is polysilicon and metal B is the aluminum. Aluminum and polysilicon the thermocouples are fabricated and that are connected in series to get the complete thermopile structure and at the same time you can see here the hot ends, the hot junction, are placed on the membrane. Here is the membrane and you have to have a dielectric layer below the thermocouples. Otherwise if it is on semiconductor, so the semiconductor is not at all insulating proper does not have insulating property. So seen metal and polysilicon will have short circuiting kind of thing. So the membrane you require only to reduce the thermal mass and thermal conductivity. On the top a thin dielectric layer either it is silicon dioxide or silicon nitrate is formed. Then you deposit metal A and metal B makes and then go for photolithography.

So that you can have the junction and those junction hot end circuit on the membrane and cold end are heat sink circuit on the thick rim. Then you will have, then at the end you will go for etching micromachining and you will have the structure. While membrane making here and here also we are thinning down the wafer. So that you can easily break each of the thermocouple. So the membrane size is 2 millimeter by 2 millimeter and thickness is nearly 20 to 30 to 50 micrometer range and total wafer thickness is 280 micron plus minus 5 micrometer. So now this is the thermopile on membrane. There is another approach where this kind of thermopile you can make on cantilever and that is shown in this diagram.

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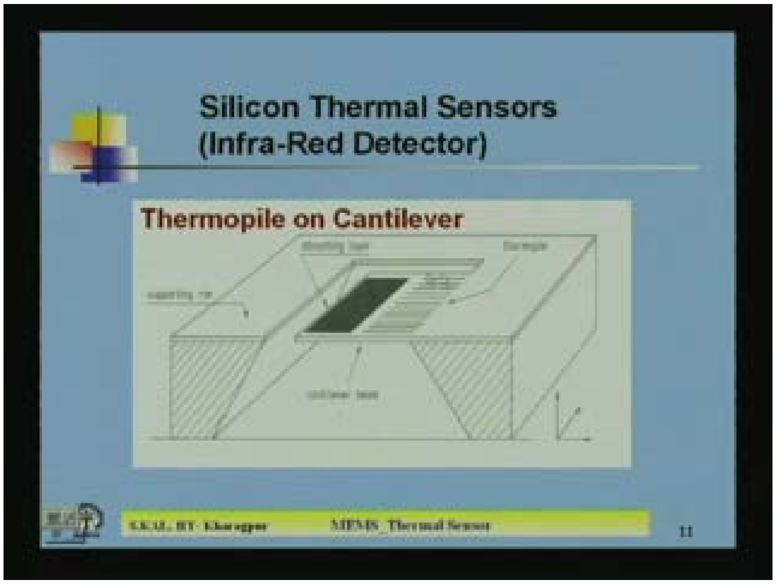

Silicon Thermal Sensors (Infra-Red Detector)

Thermopile on Cantilever

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You see thermopile on cantilever. Here what has been made, you see after thinning down the membrane this side, this side and this side you are just again you are making complete hole. So that this cantilever is hanging. Obviously this structure will have some added advantage over the earlier structure where physical connection between your hot junction and this hot junction and the rim is not there. So here the hot junction is near the absorber. This is a black portion is an absorber which absorb the radiation and below the black portion is your thermocouples. So now you see since there is no connection between these regions with the rim. So the heat sink and the source hot junction are well separated in the three directions. But one side it is connected because has to be there.

You have to have the metal lines over the rim to make the cold junction. So in this way since you are avoiding the physical link between the hot junction and the rim, so here your sensitivity will be much higher, a response you will get the output voltage of thermocouple is more because the difference of the temperature will be more in this kind of structure. But disadvantage is that, this kind of the cantilever, since it is held in one edge and one side, so automatically this is much more fragile. The cantilever may break easily, handling is very difficult. But its performance surely will be better than the earlier one.

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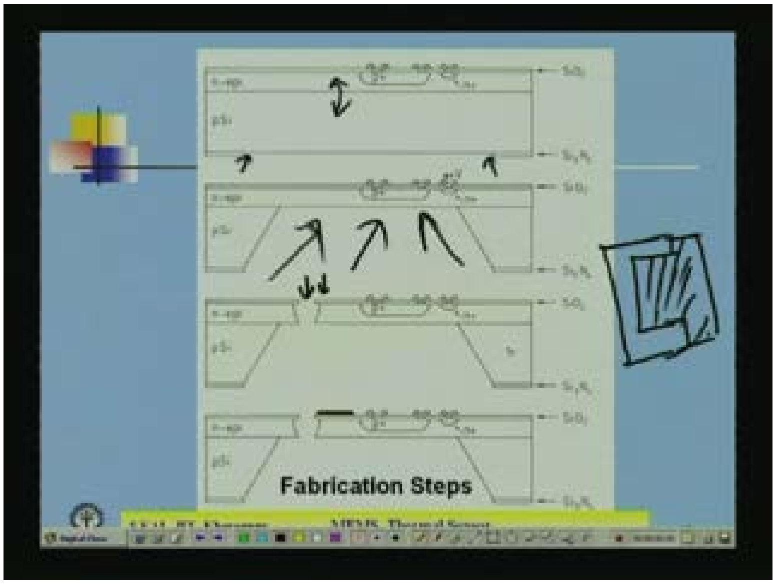

Fabrication Steps

Now how do you make this kind of the cantilever thermopile structure that is shown here. First you have taken p type silicon wafer, on top of it is an n epi layer. This is the n epi layer and p in silicon. Now on n epi layer first you formed P plus. P plus means we are making the silicon resistance versus one metal, two dissimilar materials. One material is silicon resistance, other is some metal we can make. Aluminum silicon will make also a thermocouple polysilicon aluminum we shown in earlier diagram. Here for example silicon resistance, doped silicon resistance is one material and one aluminum metal may be another material. So now first this one material with the doped silicon is found here and its connection is here and then we make the aluminum interconnection to make the thermocouple. Then what is done is another N plus diffusion is made here to have a contact of their n epi layer.

After making that contact you go for electrochemical etching, bias dependent electrochemical etching. For that here, this is one contact and substrate will be another contact. You apply bias and then due to the bias dependent etching, so you open at window here, the silicon nitrate is the masking layer. You have seen the opener window from this region to this region, window is open. Now by using BSE technique the micromachine the silicon will etch in this direction, in this direction. Now it will stop at the epi layer because this is a junction, PIN junction is this, this place is the PIN junction. So now here it will be stopped, so you will be getting the membrane here. Because during the BSE the top surface is basically protected from the electrolyte. So in the electrochemical etching you have to put the whole wafer inside an electrolytic cell.

So obviously the top surface is protected by certain arrangement, so that it will not come across the electrolyte. So this is protected and etching from the back side only. So it will stop here. Next step what will you do? So next step you open a window, here in the top here window is open you see. So after opening window then you go for the KOH etching simple KOH anisotropic etching. So if you etch KOH, so this will be etching from the top as well as from the bottom immediately the n epi layer thickness. There is a puncture and this portion means you are getting the cantilever in the surrounding area. If you see in the, you have seen earlier diagram, so this is the cross section, this one layer means the over. Actually this kind of hole will be created. If you see the top surface similar thing and this portion is connected with the substrate. This is the substrate. If you see the tops are look then here holes has been created. This is the portion. So you are getting the cantilever structure. So after getting the cantilever structure here you can see the black region is absorber. You can deposit the absorber and pattern it. So there you can get the complete thermopile on cantilever.

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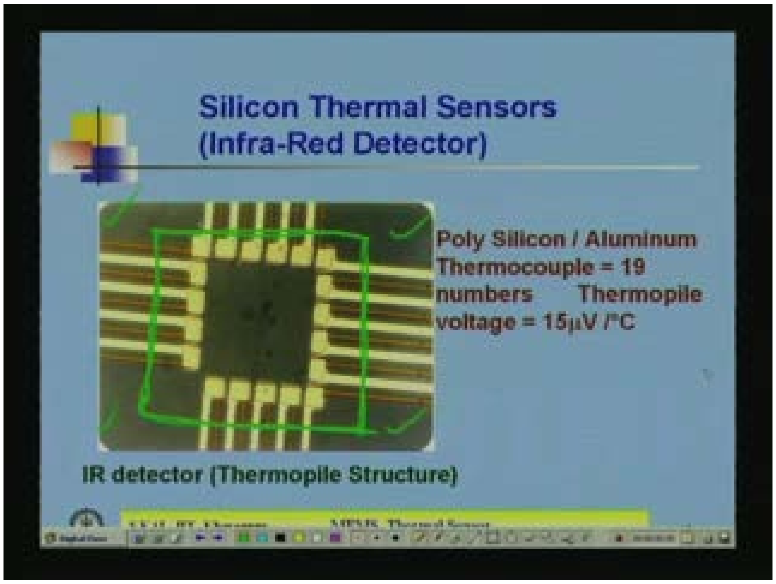

Silicon Thermal Sensors
(Infra-Red Detector)

Poly Silicon / Aluminum Thermocouple = 19 numbers Thermopile voltage = 15μV /°C

IR detector (Thermopile Structure)

So now I will show you the diagram or microphotograph of a thermopile kind of sensor on silicon membrane. So this you can see, this is a fabricated device in our laboratory and here the materials. Two material used are one is polysilicon another is aluminum. You can see the bright lines white is that is the polysilicon that is the aluminum and the reddish line you can see here, that is the polysilicon. So here are the junctions, you can see. How many junctions are there? So this junction, this is one junction, this is 1 , this is second, third, fourth, fifth, sixth, seventh, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19. Total thermocouple is 19 numbers. So these thermocouples are connected, this is only the hot junction area and after connecting you can see here, this particular portion if you draw a line you can see. This is the basically the membrane. Now this portion from the back side has already been etched so that the thickness of the silicon over this portion is nearly 50 micrometer.

But this portion or this portion or this portion here, this is the thick silicon substrate which is to if you take 2 inch wafer, that is 280 plus minus 10 micrometer. So this way we fabricate, this thermopile kind of sensor on aluminum on silicon substrate using the aluminum and polysilicon metal lines and here the thermopile voltage we measured is a

15 microvolt per degree centigrade. The change of thermo emf for each degrees and temperature change is 15 microvolt. Now some of the measured results I will show you.

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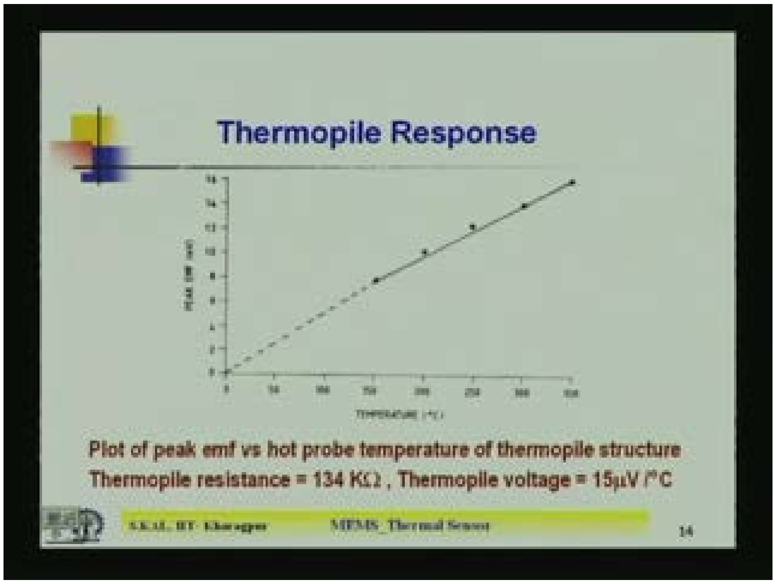

Thermopile Response

Plot of peak emf vs hot probe temperature of thermopile structure

Thermopile resistance = 134 KΩ , Thermopile voltage = 15μV /°C

So this is here, the plot of peak emf versus hot probe temperature of the thermopile structure. So those thermopiles we put on a hot chop near the thin membrane. So that locally the temperature will change and we have just measured the thermo emf and we got that 15 microvolt per degree centigrade is the result and you can see the from 50 degree to 350 degree centigrade, we have change the temperature and then we found that is almost linear nature and is a peak emf. So total thermopile resistance is 134 kilo ohm.

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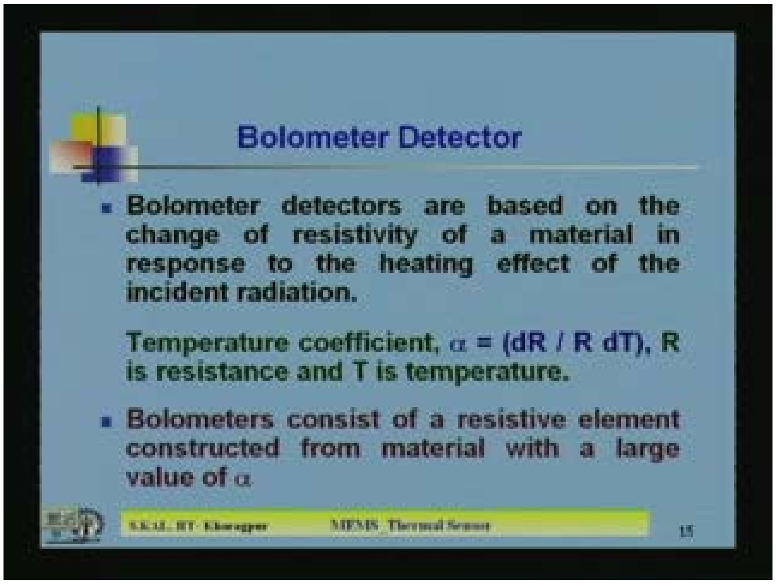

Bolometer Detector

- Bolometer detectors are based on the change of resistivity of a material in response to the heating effect of the incident radiation.

  Temperature coefficient, $\alpha = (dR / R\ dT)$, R is resistance and T is temperature.

- Bolometers consist of a resistive element constructed from material with a large value of α

Now next kind of detector is a bolometer detector. We will spend some time on bolometer detector. Both thermopile detector and bolometer detector has been fabricated in our laboratory and has been tested. Some of the testing results also I will show you. Bolometer detectors are based on the change of resistivity of the material in response to the heating effect of the incident radiation. If you a radiate the material bolometer material its resistivity will change. That is the basic principle of the bolometer and its temperature coefficient alpha is given by dR by RdT when R is the resistance and T is the temperature. dR is the change of resistance and R is basically the resistance with no radiation. The basic structure its radiation in absorb. That means when there is no radiation then resistance is R. So now bolometer consists of a resistive element constructed from material with a large value of alpha. Alpha is the temperature coefficient of a resistance.

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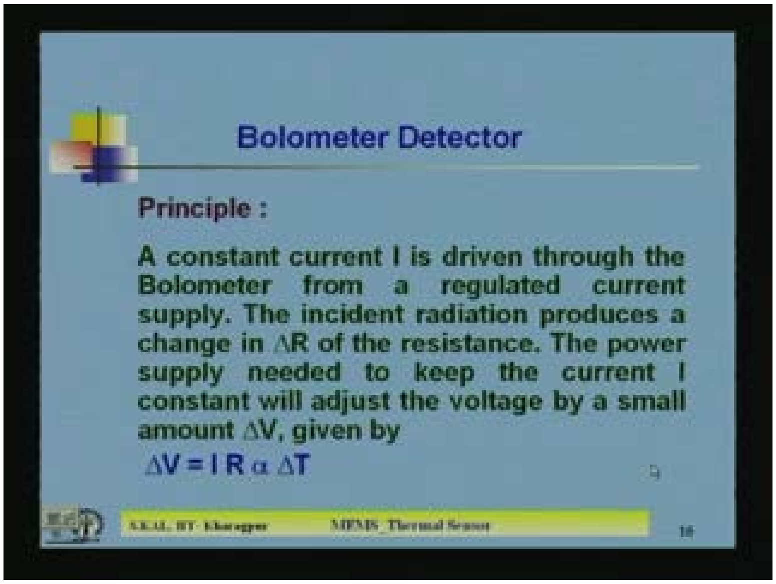

Bolometer Detector

Principle :

A constant current I is driven through the Bolometer from a regulated current supply. The incident radiation produces a change in ΔR of the resistance. The power supply needed to keep the current I constant will adjust the voltage by a small amount ΔV, given by

$\Delta V = I R \alpha \Delta T$

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Now its basic principle, how do you measure the peak up that I just briefly mentioned at the beginning. What do here? A constant current I is driven to the bolometer from a regulated current supply. Now the incident radiation produces a change in delta R of the resistor, after absorption of the radiation. The power supply needed to keep the current I constant will adjust the voltage by a small amount delta V which is given by delta V equal to IR alpha delta T. The delta V is I is a constant current, alpha is the temperature coefficient of resistance. R is the resistance without any temperature, now the alpha the temperature coefficient of resistance will change. Because of that R into alpha will change because the delta D changes. So automatically deltaV changes but for change of delta V you have to keep the, I constant. So that is why through that the bolometer a constant current source is used which is kept constant throughout your measurement. Change of resistance will change the current but you have to change the power supply at, so that change the power, so that the current remains constant to the earlier value and how much power required that will give you the how much voltage you change to keep the constant current same, to keep the current same. So in this way you can just measure the bolometer output voltage.

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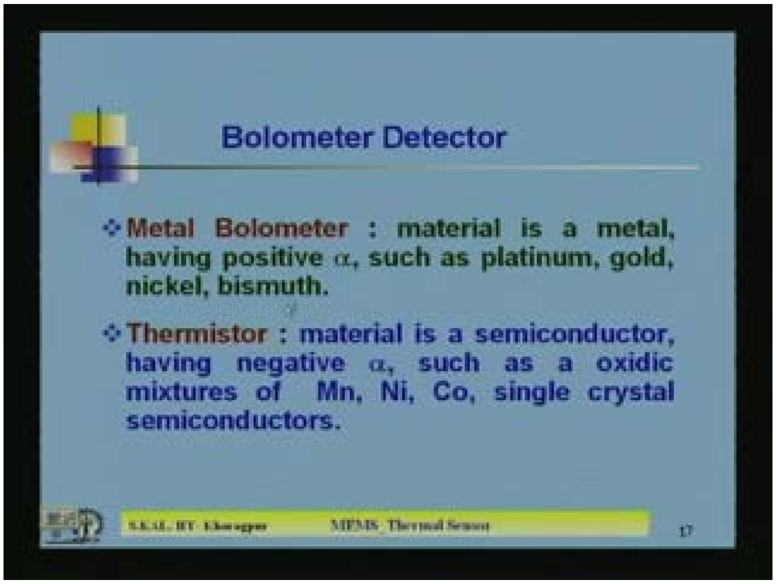

Bolometer Detector

- **Metal Bolometer** : material is a metal, having positive α, such as platinum, gold, nickel, bismuth.
- **Thermistor** : material is a semiconductor, having negative α, such as a oxidic mixtures of Mn, Ni, Co, single crystal semiconductors.

Now there are two kind of bolometer; one is known as the metal bolometer, other is known as the thermistor. In case of metal bolometer material is a metal having positive alpha temperature coefficient of resistance alpha is a positive and examples are platinum, gold, nickel, bismuth. These are the four material which have lot of application is metal bolometer. Other kinds of bolometers are thermistors. There the material is a semiconductor having negative alpha. Metal bolometer and semiconductor material when we are used that is known as thermistor and other than the semiconductor there may be oxide materials also. Oxidic mixtures of manganese, nickel, cobalt, that also will have negative temperature coefficient and mixture oxides from manganese, nickel or cobalt are some times used for as a thermistor material also other than the semiconductor. Single crystal semiconductors are obviously in many cases used as a thermistor.

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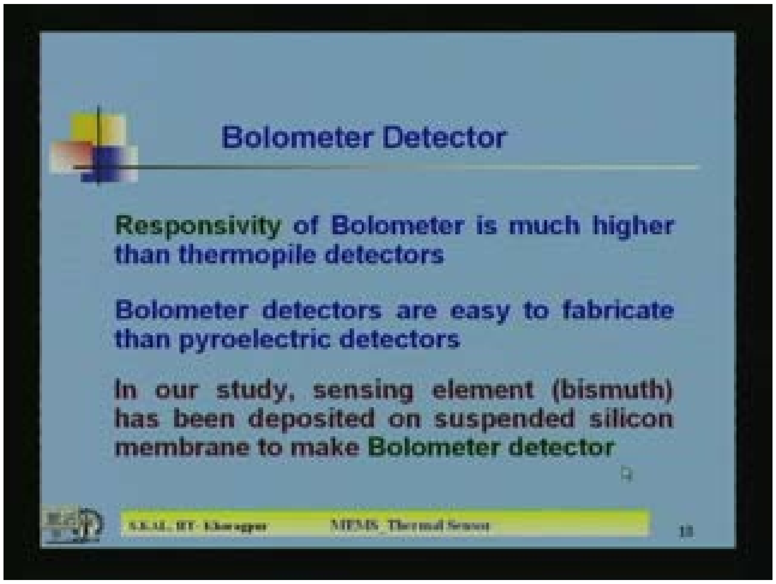

Bolometer Detector

Responsivity of Bolometer is much higher than thermopile detectors

Bolometer detectors are easy to fabricate than pyroelectric detectors

In our study, sensing element (bismuth) has been deposited on suspended silicon membrane to make Bolometer detector

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So metal and thermistor bolometer. Now it is characteristics parameters or parameters based on which the bolometer is characterized. They are again reponsivity is the main thing and reponsivity in this case of bolometer is much higher than the thermopile detectors. Bolometer detectors are easy to fabricate than pyroelectric detectors and in our study which has been made in our laboratory, we have used the nickel and bismuth. Both the material as the metals for making the bolometer structures and we have used those bolometer on suspended silicon membrane I will show you the structure.

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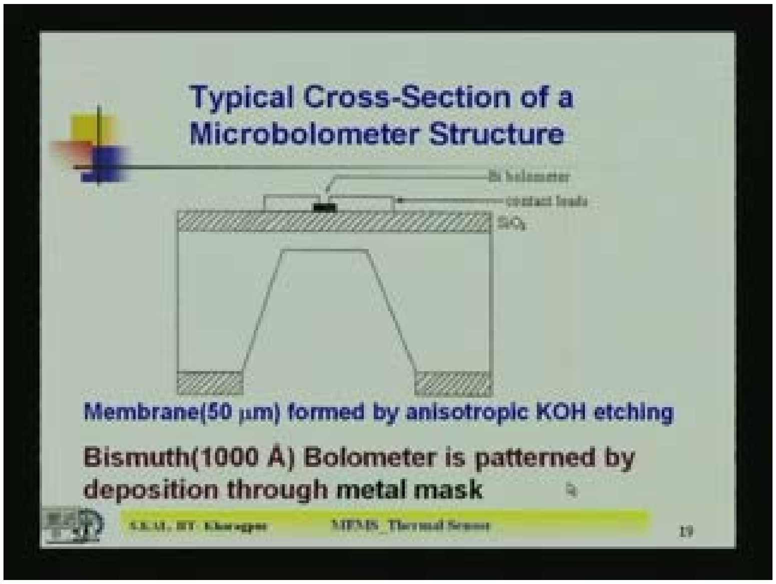

Typical Cross-Section of a Microbolometer Structure

Membrane(50 μm) formed by anisotropic KOH etching

Bismuth(1000 Å) Bolometer is patterned by deposition through metal mask

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Here is a cross section systematic diagram of microbolometer structure. Again you see this is the silicon dioxide, bottom is also silicon dioxide, is a silicon bulk and on insulated material, this is the black portion here is the basically bismuth bolometer Bi bolometer but here we have used the bismuth and these are the contact leads basically a thin film resistance, metallic thin film resistance and here the membrane is 50 micron formed by anisotropic KOH etching. Bismuth of 1000 angstrom here is patterned by deposition through metal mask. So here one what you can see metal mask. So why metal mask is used because the conventional lithography if you use then you need etching solution of the bismuth. First you have to etch the bismuth for getting the structures, resistance structure, then you are depositing the contact material. But the problem is when you define the contact material is normally gold. Then gold etching solution will attack the bismuth at the contact regions and the whole thing is spoiled.

So here some kind of standardization or some kind of search, how can we get pattering both the bismuth material as well as the metallic bond pads. Or metallic interconnections lines, so that other will not affect it with etching solution of either material. So here what we did just you deposit initially the contact leads or if it is a gold, then pattern it, then in a vacuum evaporation through holes through mask, we can just deposit selectively in this particular portion just kind of additive method. Some kind of additive method, that is why we called it as a vacuum mask technique that we are not going for lithography, those vacuum masks has been made again using micromachining technique. Silicon wafer micromachine to make certain holes on the selected regions and that mask which is called is tensile mask we can place properly on the silicon substrate and through the holes of this tensile. We can evaporate the bismuth material. So in that way we succeed to make that kind of the micro bolometer structure.

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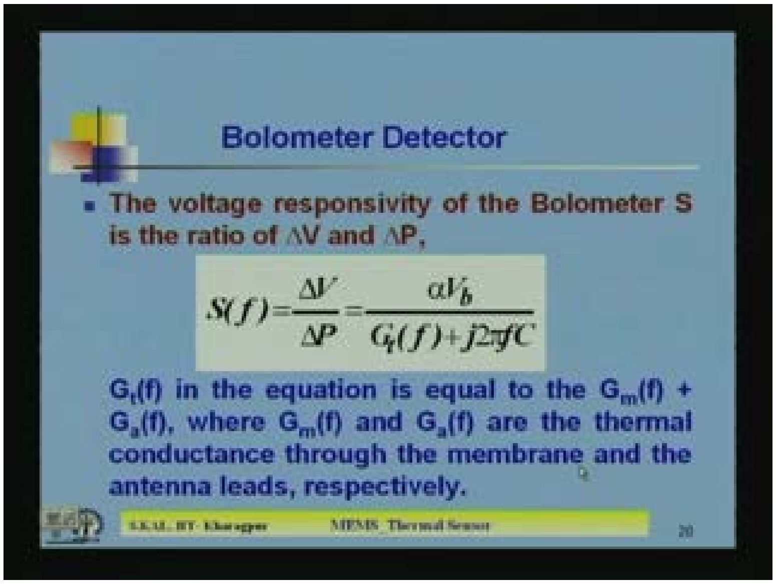

Bolometer Detector

- The voltage responsivity of the Bolometer S is the ratio of ΔV and ΔP,

$$S(f)=\frac{\Delta V}{\Delta P}=\frac{\alpha V_b}{G_t(f)+j2\pi fC}$$

$G_t(f)$ in the equation is equal to the $G_m(f)$ + $G_a(f)$, where $G_m(f)$ and $G_a(f)$ are the thermal conductance through the membrane and the antenna leads, respectively.

Now the voltage response of the bolometer S is ratio of delta V and delta P and is defined by that. Delta V is the voltage which is produced by the constant current adjustment of the power supply and delta P is the power input and it is given by alpha V_b by G_{tf} plus twice j pi fc. Where G_tf is in the equation is equal to G_mf plus G_af, where G_m and G_a both are frequency dependent and they are known as thermal conductance through the membrane and the antenna leads that is G_a and G_m

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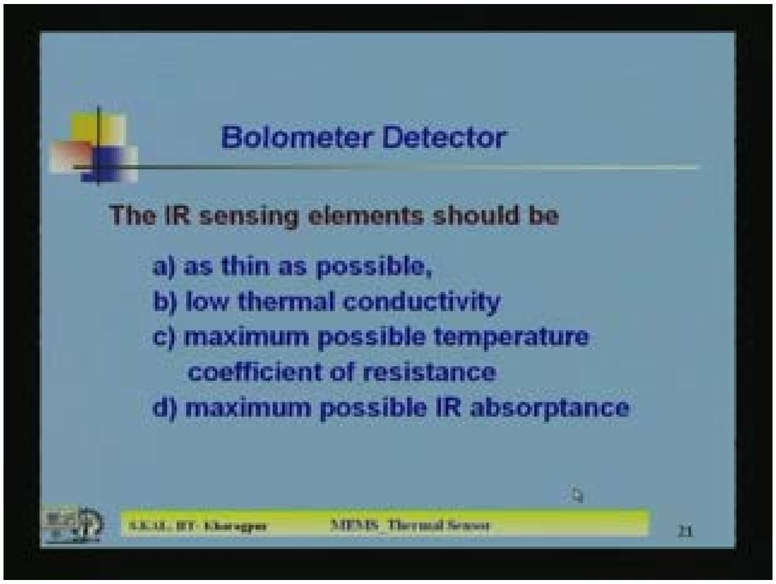

Bolometer Detector

The IR sensing elements should be

a) as thin as possible,
b) low thermal conductivity
c) maximum possible temperature coefficient of resistance
d) maximum possible IR absorptance

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Now the IR sensing elements in case of bolometer should be as thin as possible. These are the requirements. Should have low thermal conductivity, maximum possible temperature coefficient of resistance. So that our small absorption you can change of resistance will be more, maximum possible IR absorptance. So infra-red absorption capacity should be more.

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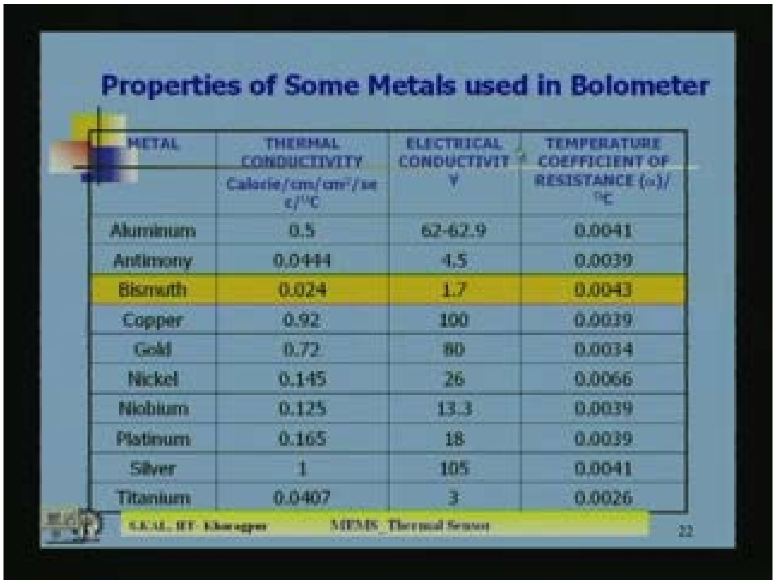

Properties of Some Metals used in Bolometer

METAL	THERMAL CONDUCTIVITY Calorie/cm/cm²/sec/°C	ELECTRICAL CONDUCTIVITY	TEMPERATURE COEFFICIENT OF RESISTANCE (α)/°C
Aluminum	0.5	62-62.9	0.0041
Antimony	0.0444	4.5	0.0039
Bismuth	0.024	1.7	0.0043
Copper	0.92	100	0.0039
Gold	0.72	80	0.0034
Nickel	0.145	26	0.0066
Niobium	0.125	13.3	0.0039
Platinum	0.165	18	0.0039
Silver	1	105	0.0041
Titanium	0.0407	3	0.0026

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That material we have to select and there are table here which shows different properties. Thermal conductivity, electrical conductivity, temperature coefficient of resistance. For a good bolometer material, thermal conductivity should be low. At the same time temperature coefficient of resistance should be high. If you look in the table aluminum, antimony, bismuth, copper, gold, nickel, niobium, platinum, silver and titanium, if you look this table of alpha you can see here that the temperature coefficient of resistance alpha is large in case of bismuth, is also large in case of nickel and is also large in case of gold. So but also in case of silver, but at the same time if you look for the thermal conductivity, the same material which you having higher alpha will have also higher thermal conductivity. But fortunately this material bismuth will have low thermal conductive 0.024 as well as high temperature coefficient of resistance. So comparing these two parameters, the bismuth may be a choice of material for making the bolometer. So that is why we have selected bismuth in our study.

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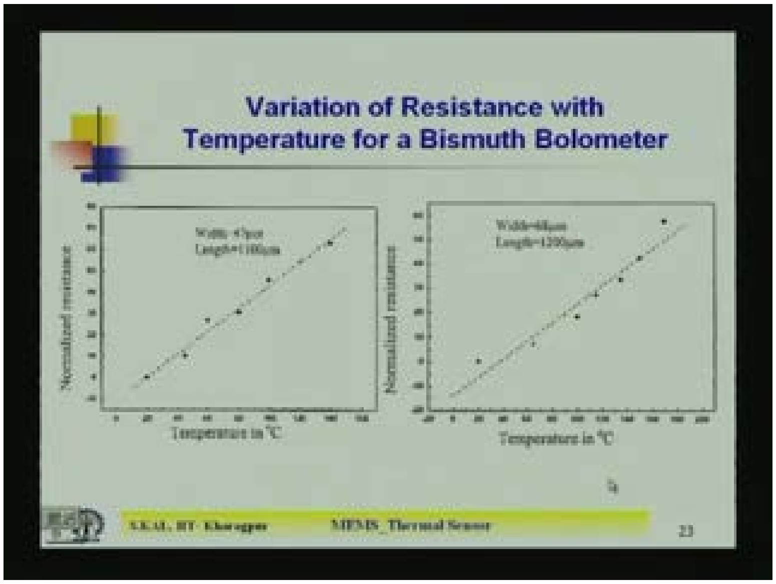

Variation of Resistance with Temperature for a Bismuth Bolometer

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Now these are the response of the bolometer which we made in our laboratory. This is a temperature versus normalized resistance. The plots are there from which you can measure the alpha value. Temperature coefficient of resistance value you have to measure, this is the first job and for different structure width is 68 micrometer, length 1200, here is width is 47 micrometer, length is 1100 micrometer. So for 2 bolometers we measure this resistance change versus temperature. So these are the variations.

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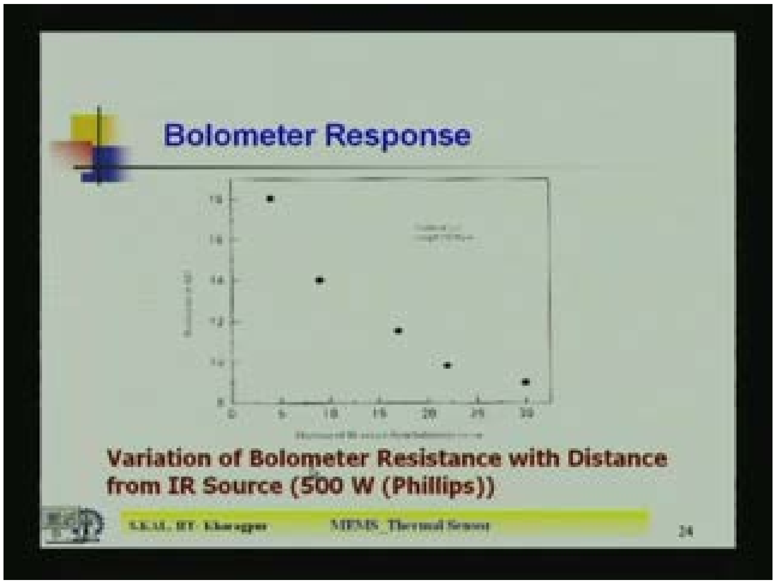

Bolometer Response

Variation of Bolometer Resistance with Distance from IR Source (500 W (Phillips))

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Now here you can see the resistance variation with the distance from the IR source. So with the intensity of IR, how much because we did not have adequate facility to characterize the bolometer. What we did? We collected IR source and the bolometer has kept certain distance. Now if this is the IR source fixed, if the bolometer is changing, the distance automatically the amount of absorption of the IR will be changing if we change the distance. So that is indirectly measure of whether your bolometer response is changing with the intensity of IR. So that test we did it and here you found if the distance increases, we found the resistance value reduces. That means with the reduction of the intensity of the IR, we found resistance value is less. That is experimental result obtained from the bolometer fabricated in our laboratory and we have use the IR source is from Phillips 500 Watt.

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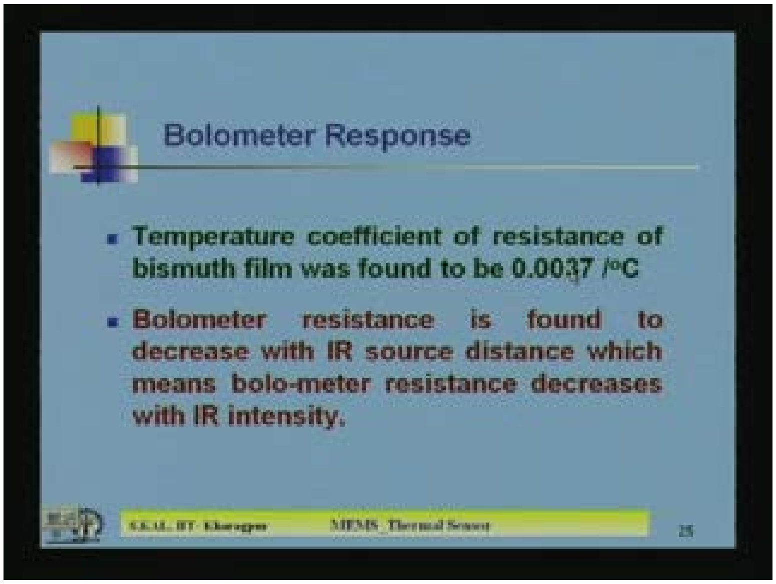

Bolometer Response

- **Temperature coefficient of resistance of bismuth film was found to be 0.0037 /°C**
- **Bolometer resistance is found to decrease with IR source distance which means bolo-meter resistance decreases with IR intensity.**

Now the bolometer response temperature coefficient resistance of the bismuth film was found 0.0037 per degree centigrade which is very close to a theoretical value. Bolometer resistance is found to decrease with IR source. This IR source distance which means bolometer resistance decreases with IR intensity it is clear.

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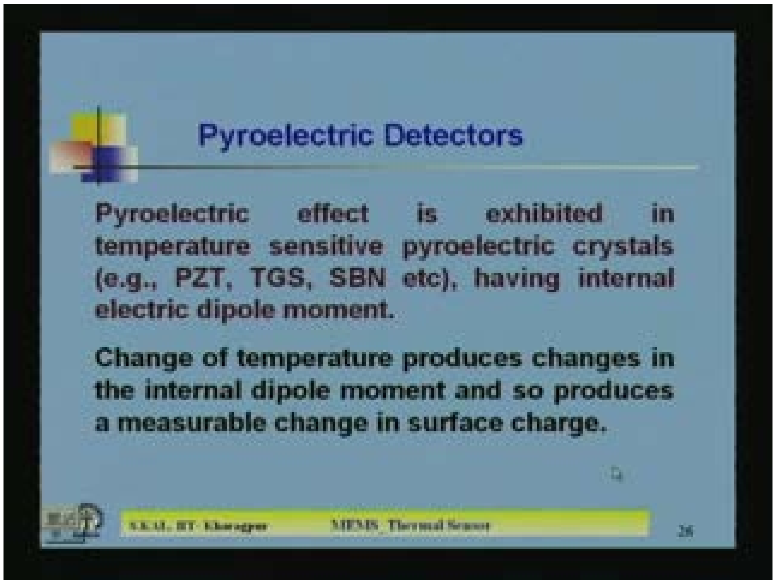

Pyroelectric Detectors

Pyroelectric effect is exhibited in temperature sensitive pyroelectric crystals (e.g., PZT, TGS, SBN etc), having internal electric dipole moment.

Change of temperature produces changes in the internal dipole moment and so produces a measurable change in surface charge.

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Now the pyroelectric detector. Pyroelectric effect, I explained at the beginning is exhibited in temperature sensitive pyroelectric crystals. Temperature sensitive pyroelectric crystal examples are PZT, TGS, and SBN. Out of that PZT is a well known material, lead, zirconium, zirconate titanate. So it is PZT and these materials will have internal electric dipole moment. Change of temperature produces changes in the internal dipole moment and we get a measurable change in the surface charge. So that is the principle. So change of temperature produces the change in the internal dipole moment and as a result, these charges will change. Then how to detect the thing? Detection principle is like this.

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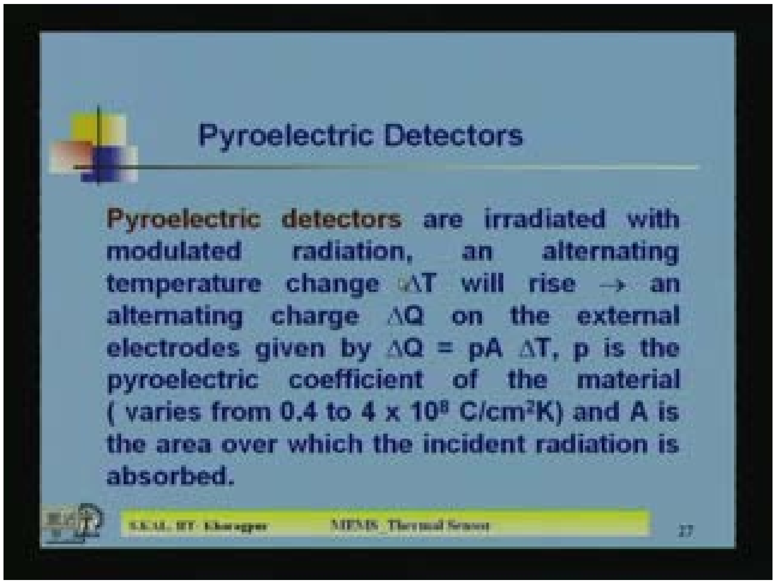

Pyroelectric Detectors

Pyroelectric detectors are irradiated with modulated radiation, an alternating temperature change ΔT will rise → an alternating charge ΔQ on the external electrodes given by $\Delta Q = pA\ \Delta T$, p is the pyroelectric coefficient of the material (varies from 0.4 to 4 x 10^8 C/cm^2K) and A is the area over which the incident radiation is absorbed.

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Pyroelectric detectors are irradiated with modulated radiation. Why need modulation? I explained earlier modulation radiation and alternating temperature change delta T will rises and alternating charge delta Q. So by change of delta T by the chopper, you can alternating charge delta Q will get on the external electrodes which is given by delta Q is equal to p into A into delta T where p is the pyroelectric coefficient of the material and this pyroelectric coefficient vary from 0.4 to 4 into 10 to power 8 coulomb per centimeters square Kelvin and A is the area over which the incident radiation is absorbed. So this is the basic detection principle of the pyroelectric detectors. Now today in the thermal sensor micro vision thermal sensor we discussed on thermopile, structure and how the thermopile structures are fabricated on membrane or cantilever, the advantage disadvantage. Then we discussed on the bolometers and detailed study has been made in our lab on thermal bolometer not the thermistor, metallic bolometer and some of the experimental results we discussed and the comparison of the pyroelectric detectors. Bolometer detectors and thermal detectors for IR absorption have been made. So let me stop now here. We will extend the lecture in next hour on some other kind of detectors MEMS sensors. Thank you.