# MEMS and Microsystems

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Lecture No. # 27

## MEMS Gyro Sensor

Today's lecture I will discuss on another MEMS sensor. That is inertial sensor and this has got lot of applications. This is gyro sensors. Gyroscope is a well-known device which is widely used in navigational purpose.

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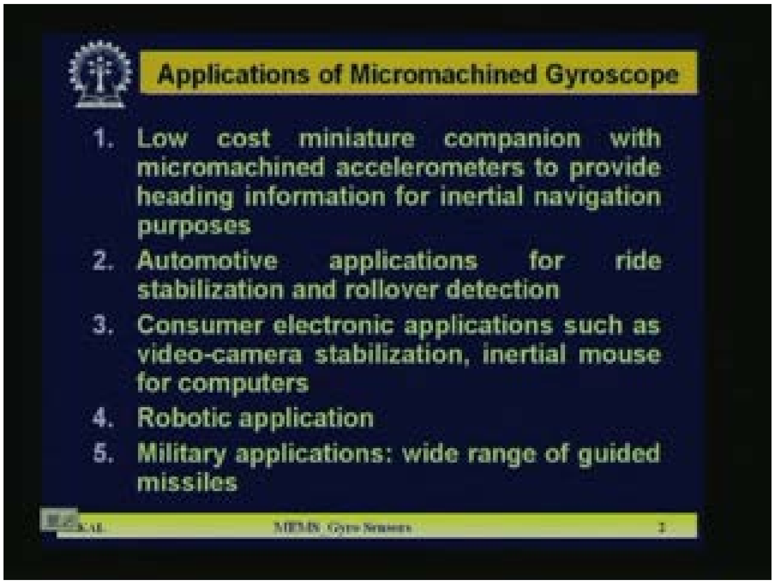

Applications of Micromachined Gyroscope

1. Low cost miniature companion with micromachined accelerometers to provide heading information for inertial navigation purposes
2. Automotive applications for ride stabilization and rollover detection
3. Consumer electronic applications such as video-camera stabilization, inertial mouse for computers
4. Robotic application
5. Military applications: wide range of guided missiles

And this particular sensor is used from 18th century even from there but that time MEMS technology was not available and people used the mechanical gyro and which was bulky and these sensors that time were expensive also. Each mechanical gyroscope cost is nearly starting from 10000 US Dollar to 100000 US Dollar even in some cases. The major application there, those expensive and high precision mechanical gyros are in case of inertial navigation systems and in inertial navigation particularly what does it do? What is the basic purpose? They collect the heading information and heading information of the aeroplanes that is in avionics, missiles and satellites. So those where the major areas we need such kind of sensors for getting the heading information and guided properly in proper direction.

So lot of research is going on since then how to reduce the size and weight of those gyros. So when the VLSI technology or integrator circuit technology is matured, then people try to use this technology to have such kind of mechanical structures. But that time MEMS technology or micromachine technology was not mature. So after the 1980s when bulk micromachining was standardized, then some of the devices came in the area of inertial MEMS sensors and some devices were reported by analog devices in the gyro area and this is basically the gyros are used along with the accelerometers. Accelerometers which I discussed in my last lecture, few lectures, that is for linear acceleration measurement but gyros are basically made for measurement of the rotation of the any of the system and the prices came down drastically when the MEMS gyros were reported from say 10000 US dollar.

It has brought down the price nearly 1000 US dollar. So now days some of the gyros which are not, that must critical and high precision which are used in some toys also. So Chinese people they are producing very low cost the gyros, that is of the order of say 100 US dollar only and there are other applications of gyros which are not that much high precision. Those are in the area of automotive applications for ride stabilization and rollover detection. Consumer electronics applications are also there. One important application Japanese people are using, that is in their video-camera for video-camera stabilizer in camcorder that using the gyros and those gyros cost nearly 100 US dollar per chip. Nowadays in many of the optical mouse for computer they use also gyros; miniature gyros.

Lot of applications is there in robotics. Because in robotics there are lots of moments, rotations are there. Different parts of a robot and we have to give the control moment of the parts with particular rotation. So we need gyros there also and above all, now days there are a great demand of gyros for missile technology which is basically the military applications. Because in a guided missile how much in what acceleration it will move and not only that, if you want to hit a target, then how much rotation, how much inclination you have to apply, so that it will take a definite path to hit an object. So that monitoring is necessary then you need gyros also. So those Gyros are very crucial and high precession they are call navigational great gyros. This is highly expensive. These are the various applications of gyro sensors.

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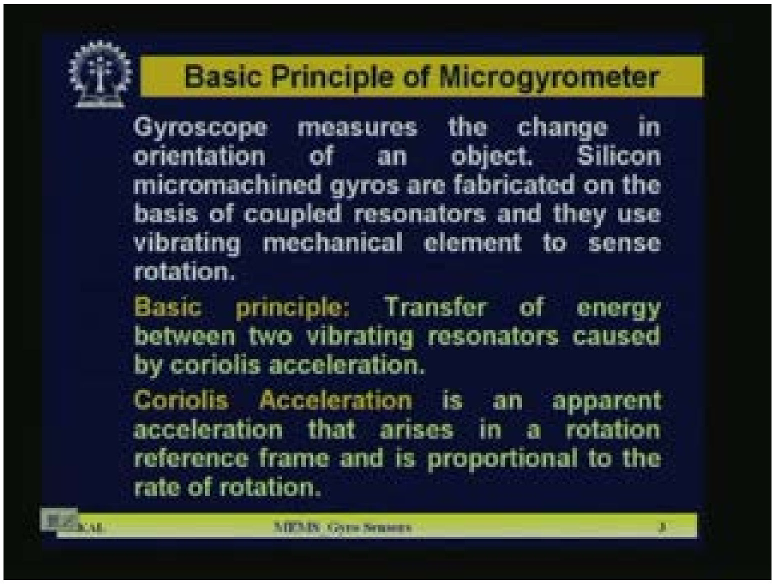

### Basic Principle of Microgyrometer

Gyroscope measures the change in orientation of an object. Silicon micromachined gyros are fabricated on the basis of coupled resonators and they use vibrating mechanical element to sense rotation.

**Basic principle:** Transfer of energy between two vibrating resonators caused by coriolis acceleration.

**Coriolis Acceleration** is an apparent acceleration that arises in a rotation reference frame and is proportional to the rate of rotation.

Now what basically gyroscopes measures? It measures the change in orientation of an object. Silicon micromachined gyros are fabricated on the basis of coupled resonators. I will come into that topic later on and they use vibrating mechanical element to sense rotation. So basically it is a coupled resonator. There will be two systems; one for driving, another is for sensing. So in that two systems we have to have separate arrangement for resonating. Some vibration will be given to particular parts or particular the electrodes and then due to the rotation, another force will be generated. That also will vibrate and that is again you have to arrange for pickup of that vibration which the resultant vibration is dependent on the rotation or angular velocity and angular moment of the system. The basic principal behind the gyros is transfer of energy between two vibrating resonators caused by Coriolis acceleration. The Coriolis acceleration is an important aspect in case of gyro action and gyro designed or gyro simulation you have to know the Coriolis acceleration. This is basically an apparent acceleration that arises in a rotation reference frame and is proportional to the rate of rotation. That is the Coriolis acceleration. Coriolis acceleration again I repeat is an apparent acceleration that arises in a rotation reference frame and is proportional to the rate of rotation.

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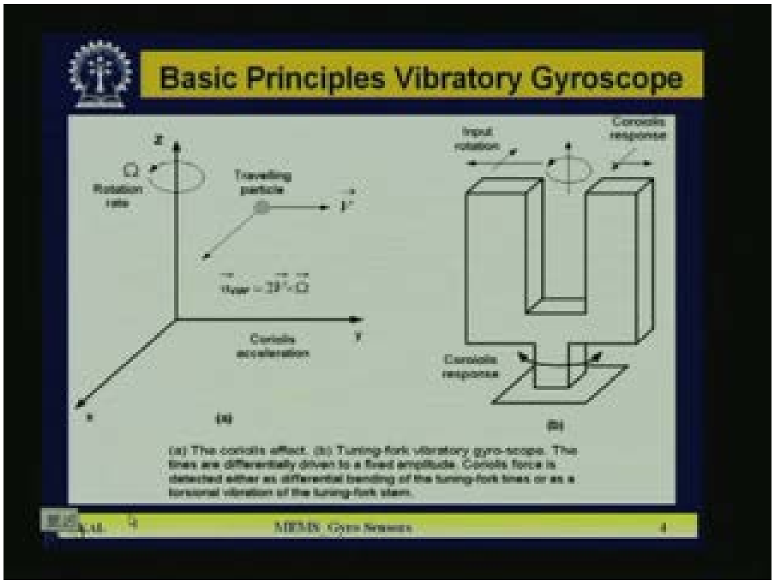

Basic Principles Vibratory Gyroscope

(a) The coriolis effect. (b) Tuning-fork vibratory gyro-scope. The tines are differentially driven to a fixed amplitude. Coriolis force is detected either as differential bending of the tuning-fork tines or as a torsional vibration of the tuning-fork stem.

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Now later see what is Coriolis force? How it is generated? In this diagram the Coriolis Effect is explained if you see the diagram A. So there in X Y Z system a particle which is moving along Y direction with velocity V. Now if it moves with acceleration or there is motion along V, there is a linear motion. Now if you apply a rotation of the particle along Z direction, these are rotation rate you have seen here. You can see here these are rotation along Z is omega, that angular velocity in which it is rotates along Z axis. Then due to the interaction of linear velocity V, a Coriolis acceleration will be developed and that Coriolis acceleration is along the X direction which is perpendicular two both Y and the Z direction and that acceleration alpha Coriolis acceleration is equal to twice V cross omega. So that is the basic idea of coriolis acceleration and this kind of acceleration can be very easily generated in tuning fork structure.

So in the B diagram a tuning fork, vibrating tuning fork is shown. Now here if you excite the two times of tuning fork, then these two tuning forks will vibrate in plane. You can see in these directions that will be this. That is normal tuning fork vibration if you hit one time, so then it will be some natural vibration along the plane of this tuning fork in plane vibration. In these directions that will in these directions you tuning fork natural vibration you will be there. Now if you rotate these tuning forks along the vertical axis, so this is shown by the circle. As a result of which a Coriolis acceleration will be developed and because of that there is a force which will be generated which is perpendicular to both the driving or in plane vibration and the rotation axis. That mean that is shown because it is perpendicular in this direction. Because you can see here, you can see that is, you can see here. So this direction it is moving, this is in the direction, this is the out of plane via motion.

So in plane is these one these direction and that is in these direction that you are driving, you are applying. So now you are rotating the tuning fork. So because of that another vibration will start, that is in this direction. So first, vibration is in this direction. Now you are rotating the thing. As a result of which the vibration will be generated this out of plane vibration. Now that vibration if you can pick up by certain mean and that vibration is dependent on the rotation. Degrees of rotation is proportional directly root degree of rotation.  Now how much angle the tuning fork is rotating, so that can be measured with help of this out of plane vibration. If you can pick up that vibration by some electronics, so that will give you the idea of the gyro or rotation, so this is the basic mechanism of the vibratory gyroscope. Now let us see now how this kind of gyroscope are fabricated in MEMS technology or microminiaturation manufacturing technology.

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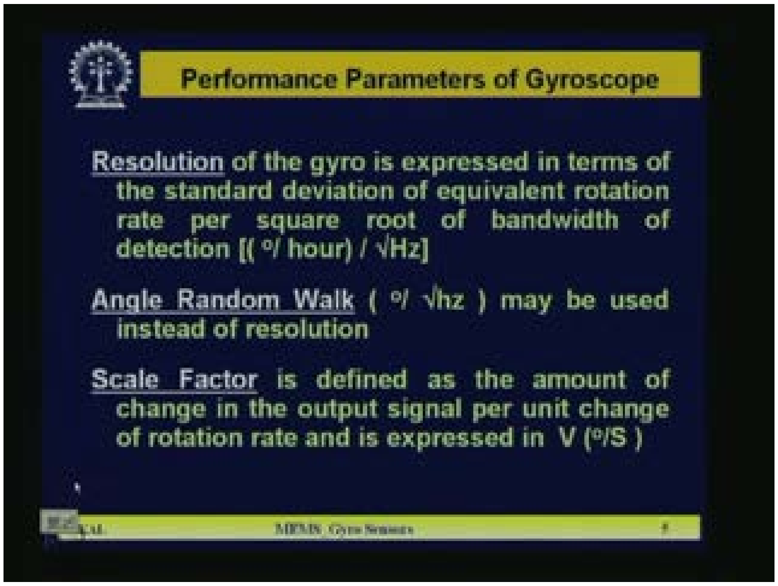

## Performance Parameters of Gyroscope

**Resolution** of the gyro is expressed in terms of the standard deviation of equivalent rotation rate per square root of bandwidth of detection [( °/ hour) / √Hz]

**Angle Random Walk** ( °/ √hz ) may be used instead of resolution

**Scale Factor** is defined as the amount of change in the output signal per unit change of rotation rate and is expressed in V (°/S )

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Now there are certain parameters of gyroscope. Let us define those parameters which are necessary. When you pick up a particular device for certain application. Those parameters obviously one is resolution and resolution of the gyro is expressed in terms of the standard deviation of equivalent rotation rate per square root of bandwidth of detection. That is definition of resolution in case of gyro. Standard deviation of equivalent rotation rate per square root of bandwidth of detection. Degree per hour per root hertz, so that is its unit. Another terminology used in case of gyro that is angle random walk. Basically this is equivalent to resolution. Resolution is a common term which is used in many sensors that we know. But in particularly gyro one terminology used, that is angle random walk. That is a basically it is another terminology instead of the resolution and its unit normally define the degree parts root hertz. Degree per root hertz sometimes degree per root h is written. So that is an angle random walk. Another parameter is scale factor. Scale factor of the gyro is defined as the amount of change in the output signal per unit change of rotation rate expressed in volt degree per second. That is the scale factor. The amount of change in output signal per unit change of rotation rate and is expressed in volt and degree per second.

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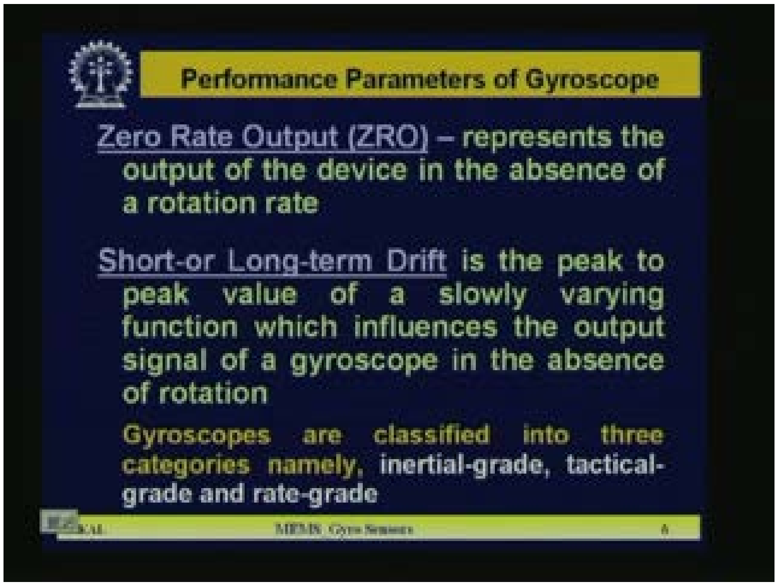

## Performance Parameters of Gyroscope

Zero Rate Output (ZRO) – represents the output of the device in the absence of a rotation rate

Short-or Long-term Drift is the peak to peak value of a slowly varying function which influences the output signal of a gyroscope in the absence of rotation

Gyroscopes are classified into three categories namely, inertial-grade, tactical-grade and rate-grade

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Now other few terminologies are mentioned here. One is zero rate output or ZRO and short or long term drift. What is ZRO? It represents the output of the device in the absence of a rotation rate. That is basically normal sensor we call something is offset. No input has given, but you get some output. So here in gyro it is called ZRO or zero rate output. That means you are not giving any rotation and even then if you get some output, so that is a ZRO or zero rate output. Another important terminology is a drift. That is short or long term drift. This is the peck to peak value of a slowly varying function which influences the output signal of a gyroscope in the absence of rotation. The short or long term drift means the performance changes with time.

Even the same device after calibration, today if you measure after say 1year or 2years and you will find the calibration has changed. That means the whole thing has been changed and what is reason for that, which is why that is function which is slowly varying function peak to peak value of a slowly varying function. That influences the output signal and that is a responsive for long or short term drift and what is that function you have to identify. Gyroscopes are classified into three categories. One is inertial grade, second one is tactical grade and third one is rate grade. Three kinds of gyros are available; inertial grade, tactical grade and rate grade.

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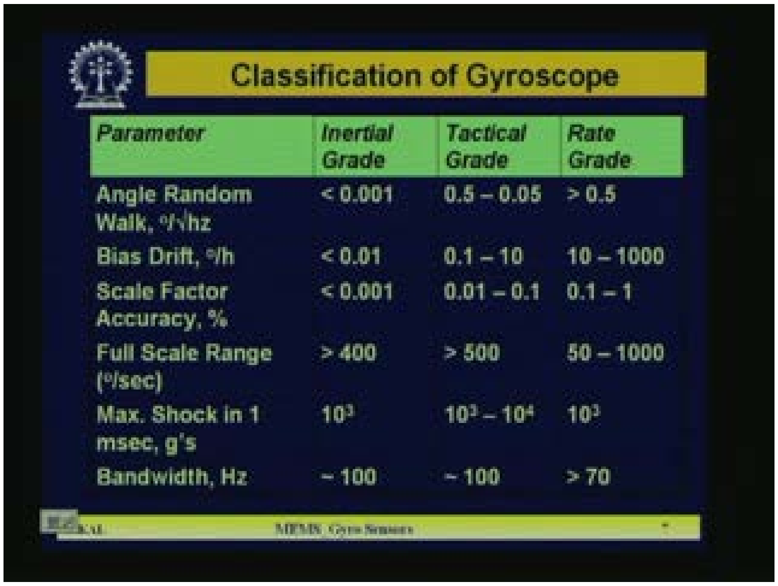

## Classification of Gyroscope

| Parameter | Inertial Grade | Tactical Grade | Rate Grade |
|---|---|---|---|
| Angle Random Walk, $^\circ/\sqrt{hz}$ | < 0.001 | 0.5 – 0.05 | > 0.5 |
| Bias Drift, °/h | < 0.01 | 0.1 – 10 | 10 – 1000 |
| Scale Factor Accuracy, % | < 0.001 | 0.01 – 0.1 | 0.1 – 1 |
| Full Scale Range (°/sec) | > 400 | > 500 | 50 – 1000 |
| Max. Shock in 1 msec, g's | $10^3$ | $10^3 - 10^4$ | $10^3$ |
| Bandwidth, Hz | ~ 100 | ~ 100 | > 70 |

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So now the difference between these inertial grades which is use basically for navigational purpose and tactical grade are not that much high precision. So there parameters are compared in this table. You can see angle random walk which is basically the another terminology for resolution, degree per root hertz. In inertial grade is less than zero 0.001 tactical grade is 0.5 to 0.05 and rate grade is greater than 0.5. Now you can see here inertial grade is a resolution is very fine less than 0.001 bias drift degree per hertz is a here is less than 0.01 in tactical grade is a 0.1 to 10 rate grade is 10 to 1000, Scale factor accuracy percentage, it is less than 0.001 percent 0.01 to 0.1 and 0.1 to 1. Full scale range in case of inertial grade is greater than 400 tactical are greater than 500 and rate grade is 50 to 1000.

So now if your bandwidths are almost same 100 hertz in all cases. Now you see if compare the table that will find why the inertial grade which is navigation use for navigational purpose is highly expensive. Because these are very high pressures in gyros compare to the tactical and rate grade. So rate grades are very crude. These are used in many of the household appliances or in some cases of entertainment electronics is used. Tactical grade is little bit crucial which is used for say automobile in other applications. But particular for navigation means avionics, the missile technology and as well as satellite application, there you require the inertial grade which are highly expensive because it is a very high precision.

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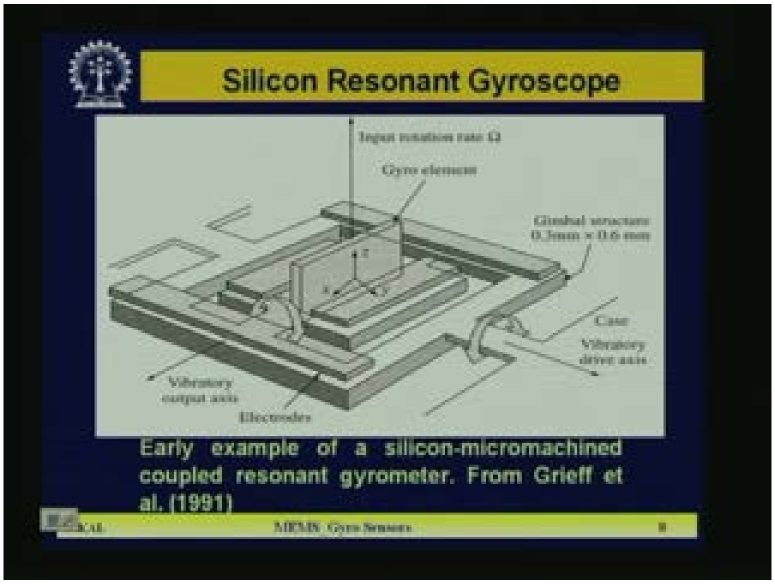

Silicon Resonant Gyroscope

Early example of a silicon-micromachined coupled resonant gyrometer. From Grieff et al. (1991)

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Now the slide next slide we are showing here the silicon resonant gyroscope. This is an early example which walks on the based of coupled resonant more principal and here you can see there is a gyro element at the middle which will basically rotate. This is the gyro element is shown here and this can rotate. Now as per the vibrating gyro principal what we mentioned earlier, you have to have an arrangement for driving some of the electrodes for vibration. So here the vibratory drive axis is here. So here the energy gives the electrostatic energy for moment of that. By electrostatic you can give, piezoelectric you can give. So different kind of the transduction mechanism you can add up in silicon, you can have to have a piezo. That is in piezoelectric can be used in case of quartz. But here you can give the electrostatic drive. So by electrostatic drive you give a moment of this particular electrode here and here in both the cases you can see here and here you give that. So there is a vibration of that.

Now in the middle, there is these gyro element which if you rotate, input rotation rate is omega. If you rotate here these along z axis, so as per that rotation gyro principal the Coriolis acceleration developed along this axis. So that is the vibratory output axis. It is called vibratory output axis and these are the electrodes, this one and these one. So now an initial vibration has been initiated along this axis. Now because of the rotation of these elements so another vibration will be developed along this axis, this vibration say this electrode will vibrate. Now this vibration you have to take it out. So that vibration is dependent on the rotation along this Z axis. So that is a basic principal of silicon resonant gyros. But as you have seen, this structure is highly complicated. So different elements have to be fabricated and it has to be coupled and fixed in proper manner. So that it can pick up the rotation. That means important is this rotation should be directly proportional to the output vibratory axis for a fix value of drive energy. So that is the silicon resonant gyroscope basic thing.

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Microphotograph of Micromachined Ring Gyroscope

Fabricated by electroforming nickel into a thin polymide mold on a silicon substrate

Then another class of gyro which are used later on, so that is micromachined ring gyroscope. So a very popular gyro in the beginning of 19 century was used, that was not MEMS based that is ring laser gyre. What is that? So in a ring laser gyro to laser beams where guide it in a circular path in opposite mode. So those laser beams will interfere each other and if you rotate the system, the laser which guided through the fiber optics and if you rotate the total system, then interference pattern will change and from the interference pattern you can get some idea about the rotation of the total system. That is known as ring laser gyro.

For long time before the MEMS gyro came into the picture, people uses this ring laser gyro. This also high precision and not that much bulky as the mechanical gyros. So some kind of similar principal is used in some form of MEMS structure which is from by electroforming nickel into a thin polymide mold on a silicon substrate. So this rotation system is there and here the nickel electroforming plates are there. So there some of the energy whether this structure is ring like, so here is not laser. But some form of electromagnetic energy is this circulated and some interaction will be there due to the rotation of these wheels and that may be reflected back, so that is some form of ring gyro, but that is not that much popular.

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Integrated Micromachined GYRO

**Single Chip Rate Sensor**
5V Operation
Std Atmosphere
150 deg per second
Self-Test
0.03 deg/sec/sqrt hz
Compensated 5%

Source: Analog Devices

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Here one complete micro system is shown in this picture. So which is a rate sensor with single chip rate sensor and it is what is with 5 volt supply, 150degree per second is its resolution. Self-test 0.03 degree per second per square root of hertz and 5 percent compensated is analog device. So here the along with the gyro the peripheral, the electronic circuits are integrated inside the chip. So is a complete, you can say the smart gyro sensor because the sensing and electronics parts, all are together intergraded so it is from analog device.

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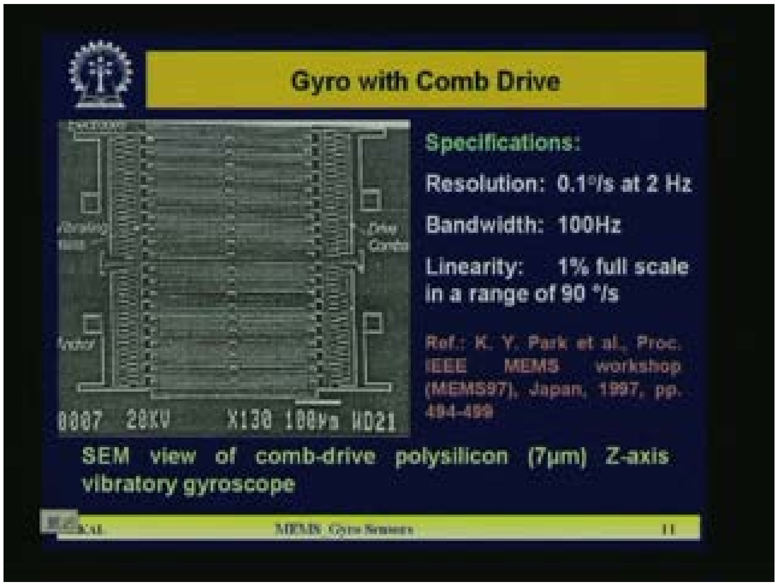

Gyro with Comb Drive

Specifications:

Resolution: 0.1°/s at 2 Hz

Bandwidth: 100Hz

Linearity: 1% full scale in a range of 90 °/s

Ref.: K. Y. Park et al., Proc. IEEE MEMS workshop (MEMS97), Japan, 1997, pp. 494-499

SEM view of comb-drive polysilicon (7µm) Z-axis vibratory gyroscope

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Another picture I am showing it is reported by some Japanese group and it has been reported in 97 in some workshop; a truly MEMS workshop. This is a gyro with comb drive and that is fabricated using this surface micromachining technology and its resolution here is 0.1 degree per second at 2 hertz bandwidth is 100 hertz, linearity 1 percent full scale in range of 90 degree per second. So this is basically comb drive polysilicon gyro and Z axis vibratory. Z axis rotation axis it can sense. So that is comb drive.

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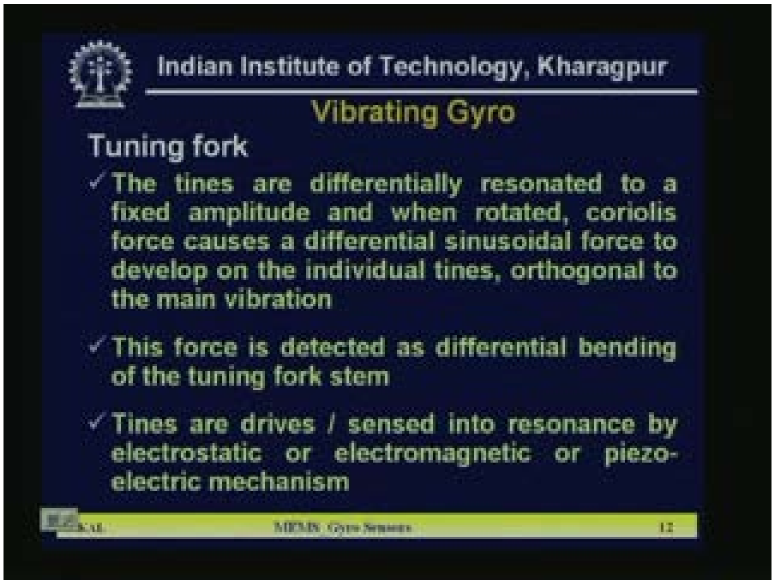

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Vibrating Gyro

Tuning fork

- ✓ The tines are differentially resonated to a fixed amplitude and when rotated, coriolis force causes a differential sinusoidal force to develop on the individual tines, orthogonal to the main vibration
- ✓ This force is detected as differential bending of the tuning fork stem
- ✓ Tines are drives / sensed into resonance by electrostatic or electromagnetic or piezo-electric mechanism

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Now I will discuss little bit in detail the vibrating gyro tuning fork type which is developed in our laboratory also using quartz micromachining technology. In tuning fork the tines are differentially resonated to fixed amplitude. When rotate it the Coriolis force causes a differential sinusoidal force to develop on the individual tines orthogonal to the main vibration. This force is detected as differential bending of the tuning fork stem I will discuss with a diagram in the next slide. So the tines are drives sensed into resonance by electrostatic, electromagnetic or piezoelectric mechanism.

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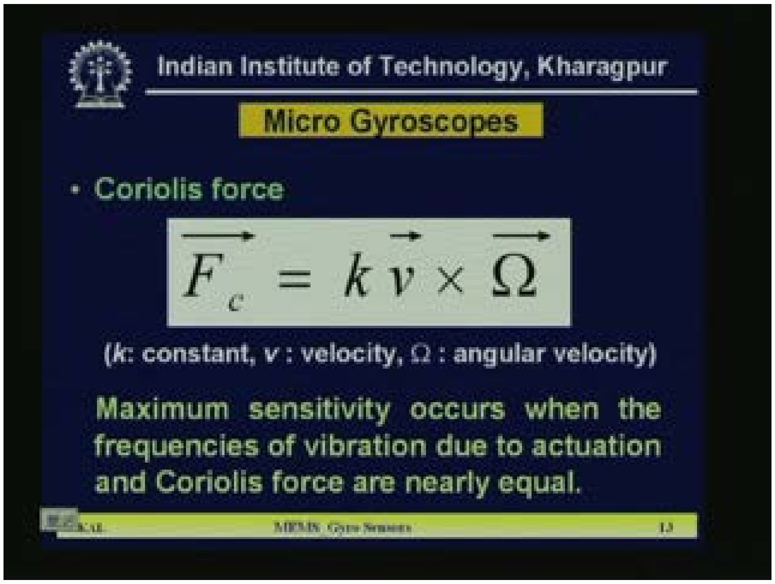

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## Micro Gyroscopes

- Coriolis force

$$\overrightarrow{F_c} = k\,\vec{v} \times \overrightarrow{\Omega}$$

($k$: constant, $v$ : velocity, $\Omega$ : angular velocity)

Maximum sensitivity occurs when the frequencies of vibration due to actuation and Coriolis force are nearly equal.

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In micro gyroscope the Coriolis force, this $F_c$ is given by k into v cross omega; k is a constant, v is a velocity, omega is angular velocity which is shown in earlier diagram also. Maximum sensitivity of the micro gyroscope occurs when the frequencies of vibration due to actuation and Coriolis force are nearly equal.

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## Vibrating Gyro

Technology:

I. Silicon bulk micromachining and wafer bonding
II. Polysilicon surface micromachining
III. Metal electroforming and LIGA
IV. Combined bulk – surface micromachining

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Now what are the technologies is used for vibrating gyro? They are silicon bulk micromachining and wafer bonding technology. Polysilicon surface micromachining which is a comb like gyros, metal electroforming and LIGA process is also used.

Combined bulk surface micromachining are used now days with some typical type of the high precision gyros.

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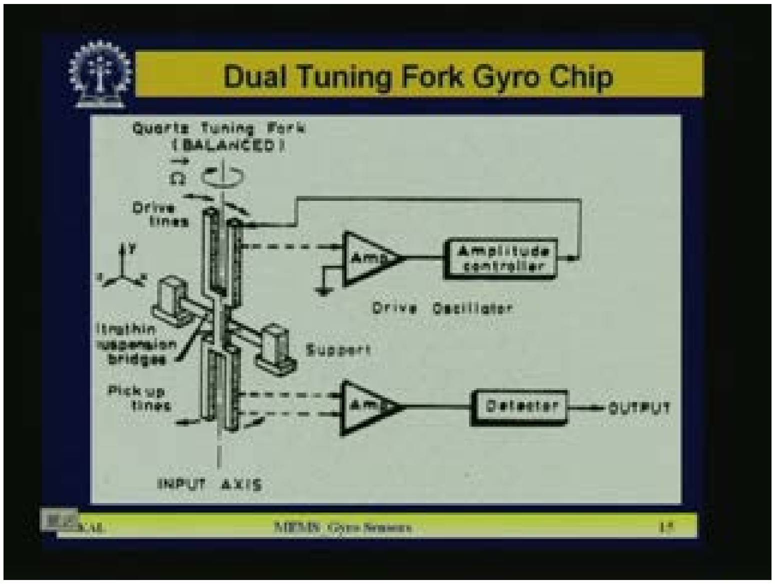

Dual Tuning Fork Gyro Chip

So here is one kind of gyro which is dual tuning fork gyro chip. This has been designed in our lab and we have also fabricated that. Here let me explain this particular structure. How it works? Now here you can see is a dual tuning fork. One tuning fork at the top and another tuning fork in the bottom. They are connected by stem. So now this dual tuning fork is supported by an ultra-thin suspension bridge. You can see this is ultra thin suspension bridge here and here. This particular bridge thickness is very small but is width is large. Now this bridge is fixed with support. These are the two supports and these two supports with the help of these support the whole structure is fixed. Now let us try to understand how it works. Now the upper tines of the tuning forks is called drive tines. That means is some driving energy for driving force we have to generate here. If you make this particular gyro, using quartz, then quartz is a piezoelectric material.

So if you apply electrical voltage along the surface of this material, so it will vibrate to its resonance frequency. You use a piezoelectric material. So now here through electrodes we connected some source and you can control that source to drive the tines at a particular frequency. Now if you apply some driving force, some voltage here the tines will vibrate in this direction. Out of plane direction you see here it shown in this diagram. So these two tines will vibrate in this direction, in plane vibration. Now what will happen? This support is fixed now you try to rotate it. If you rotate it, then as I mentioned earlier, a force will be generated which is out of plane. That means in this direction this because these two tines will vibrate. One in this direction, this one in this direction. Now this vibration, how do you pick up? How you will transmit? Then those vibrations if you want to sense, then you have to pick that vibration in other tuning fork. Because here there are two vibrations; one is in plane, another is out of plane.

So they will couple but from there you have to take only the out of plane vibration and that transferring the vibration to the lower tines is a challenge. How can you do it? Let us see here the bridge. The micro bridge which is formed here, that thickness of the micro bridge in the vertical direction. That is thickness is very small. But the inplane vibration, which is in these directions to these directions along X direction, that thickness you see say long and width is small. So that means because of the support beam, so that vibration cannot be transmitted into this. But the out of plane vibration can easily be transmitted to the lower tines because the thickness here of this bridge is very thin, small. So this vibration which is in this direction that will be transmitted easily to the microwave to the down tuning fork. So down tuning fork will selectively respond to the out of plane vibration and then it is started vibrating in this direction.

What is shown and because that vibration, what will happen? EMF will be generated because it is a piezoelectric material. Because of the vibration some EMF will be generated at the surface of electrodes, so those feel which is generated because of the piezoelectric effect is amplified in an amplifier and that is then send to a detector and you detect the signal. Now how much the lower tines will vibrate, it depends on how much the Coriolis acceleration is generated and it depends on how much rotation you are giving to this system, so that means the output voltage which is obtained from lower tines is directly proportional to the rotation. In this way using the piezoelectric drive you can easily get the micromachine gyro using quartz micromachining. So this kind of gyro has been designed and fabricated using quartz micromachining technology in our MEMS laboratory.

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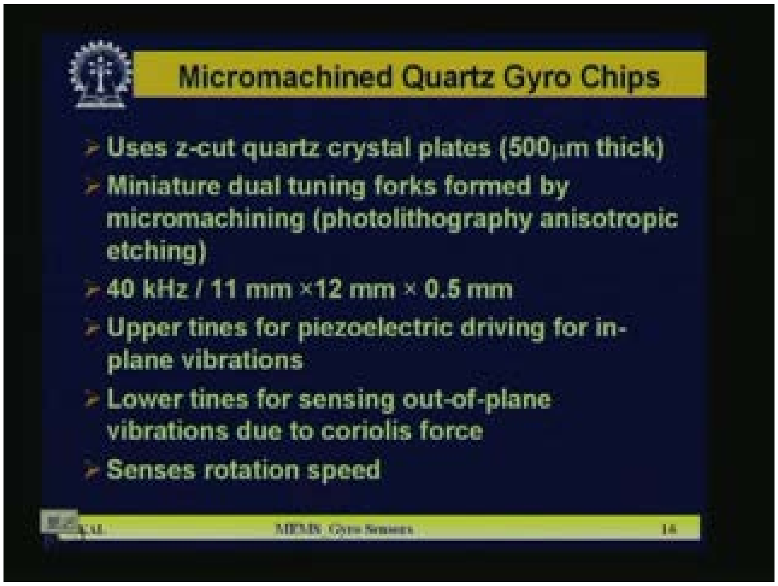
## Micromachined Quartz Gyro Chips

- Uses z-cut quartz crystal plates (500μm thick)
- Miniature dual tuning forks formed by micromachining (photolithography anisotropic etching)
- 40 kHz / 11 mm ×12 mm × 0.5 mm
- Upper tines for piezoelectric driving for in-plane vibrations
- Lower tines for sensing out-of-plane vibrations due to coriolis force
- Senses rotation speed

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So here we use z-cut quartz crystal plates of 500 micrometer thick. The miniature dual tuning fork formed by micromachining. Photolithography anisotropic etching of quartz and the resonance frequency of the structure which we have designed is 40 kilo hertz. Natural resonance frequency of that every tuning fork is having some resonance frequency. Natural frequency of the structure and its dimension is these 11 millimeter, 12 millimeter and 0.5 millimeter; length, width and thickness. Upper tines are used for piezoelectric driving for in plane vibration just know I mentioned upper tines, lower tines for sensing out of plane vibration due to Coriolis force. Senses the rotation speed, these are the highlight of that particular structures.

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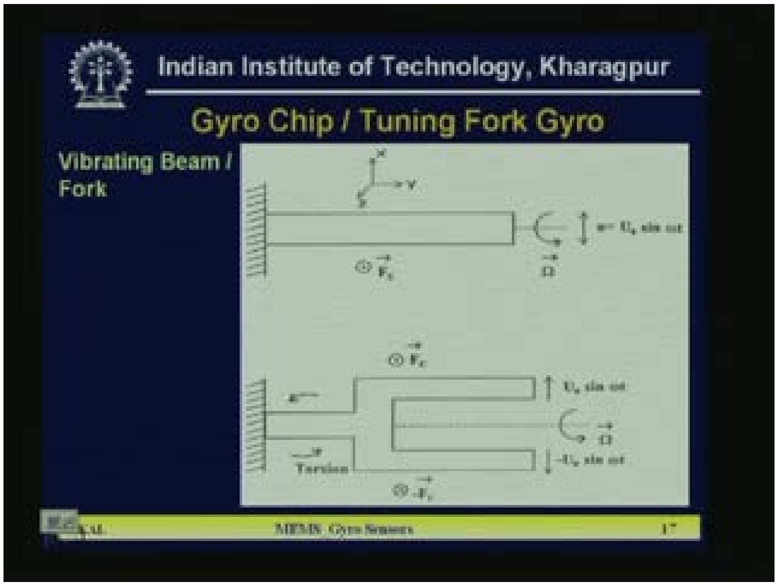

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Gyro Chip / Tuning Fork Gyro

Vibrating Beam / Fork

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Now here again the vibrating beam tuning fork how it works, that is also shown is basically you can see this kind of structure can be used for acceleration purpose also with certain modification. Here is again it shown that the $U_0$ sign omega T and minus $U_0$ sign omega T. So if you hit a tuning fork, it will always vibrate out of in this kind of thing. Isn't it? So it will be vibrated in this way. So that is one displacement is $U_0$, another is minus $U_0$ from there. So these because of that know the tuning fork is rotation here, torsion is given and torsion is with angular velocity omega. Then it shown the one is the perpendicular in the bottom line and another is perpendicular in the top is plus $F_c$ and minus $F_c$. So that is shown one is minus $F_c$ another is plus $F_c$ dot. Dot means perpendicular the structure, that force will be generated. That is the basic principal of vibrating tuning fork.

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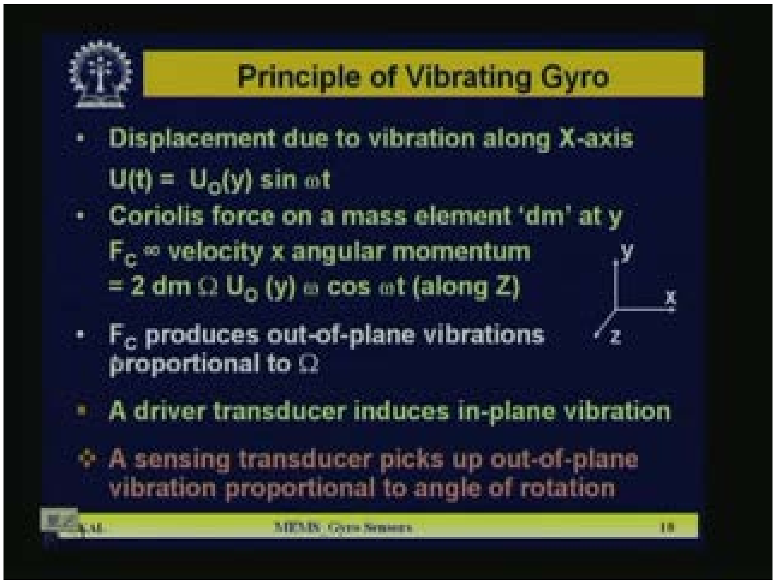

## Principle of Vibrating Gyro

- Displacement due to vibration along X-axis
  $U(t) = U_0(y) \sin \omega t$
- Coriolis force on a mass element 'dm' at y
  $F_c \propto$ velocity x angular momentum
  $= 2\, dm\, \Omega\, U_0(y)\, \omega \cos \omega t$ (along Z)
- $F_c$ produces out-of-plane vibrations proportional to $\Omega$
- A driver transducer induces in-plane vibration
- A sensing transducer picks up out-of-plane vibration proportional to angle of rotation

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Now displacement due to the vibration along X axis use U to that is a displacement is $U_0$ y sin omega t. Coriolis force on a mass element dm at y is given by twice dm omega $U_0$ y omega cos omega t along Z axis and that $F_c$ which is rate is proportional to velocity into angular momentum. I told you earlier also the $F_c$ which is shown in earlier diagram produces out of plane vibrations proportional to omega $F_c$. A driver transducer induces in plane vibration, a sensing transducer picks up. Out of plane vibration proportional to angle of rotation. That is the whole the designed calculations or the principal is narrated in this slide.

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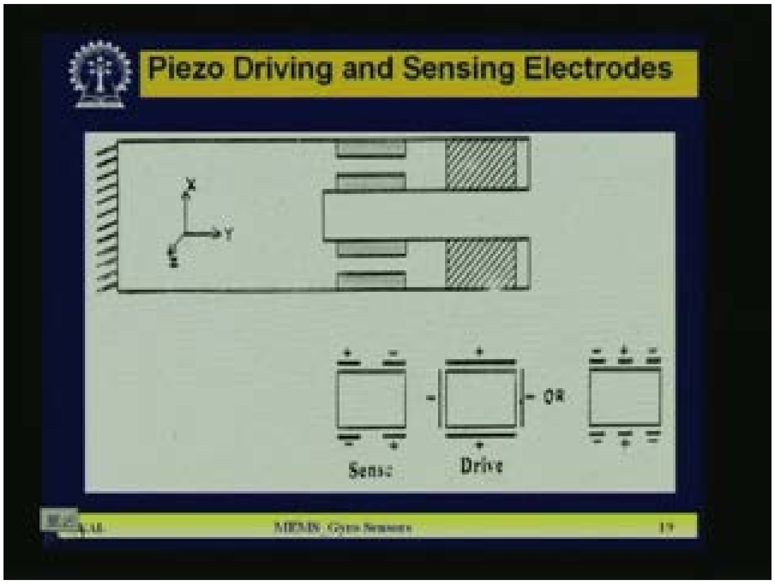

## Piezo Driving and Sensing Electrodes

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Now the thing comes into our mind how you go for the electrodes. This is again a real challenge. Because the driving tines depends on how the electrical energy is fitting into the tuning fork structure, tuning fork kinds and on the other hand the sensing tines will sense the vibration and that vibration will picked up by the electrodes in the form of voltage. How will you form the electrodes there? It has been observed that the efficient sensing pickup of sensing and efficiency driving is possible to a piezoelectric material with an optimum design of the electrodes and that is shown here and we have simulated by driving in different by driving the electrode with different electrode geometry and it has been seen that, for driving if you apply positive here and here the top and bottom you can see in this diagram and negative in the sidewall, then the maximum easily you can drive the tines with maximum efficiency with no loss of energy. But here the problem you can foresee that you are making the electrodes in all the 4 planes. So you can make electrode in the top plane, in evaporation and then lithography. You can make electrode in the bottom plane also.

By reverting back to the substrate topside bottom, but how do you make the electrodes at the sidewalls, that is a very difficult situation. So then some people are purposing that this structure can be modified to that where the positive electrodes are here and in the both side to negative electrodes are there similarly in the bottom also. Positive at the center and both side to negative electrodes are there. Now if you connect the positive and negative like this, so it will be efficiently driven and maximum energy will be transfer to the tines. So that is, that means it is a planer, top and bottom, both the plane you can make the electrodes like that. Electrode means the metal strips which is connecting to the power supply. For sensing similarly, that means bottom tines lower tines of dual tuning fork, so then the electrode patterns like plus and minus l minus plus because this is out of plane vibration. So that you can if you make the electrodes designed in this fashion the pickup signal will be efficiently picked up from the sensing tines. So now this kind of the electrodes has to be front on both the tuning from lower and bottom tines which is not very simply even if you modify the planer also.

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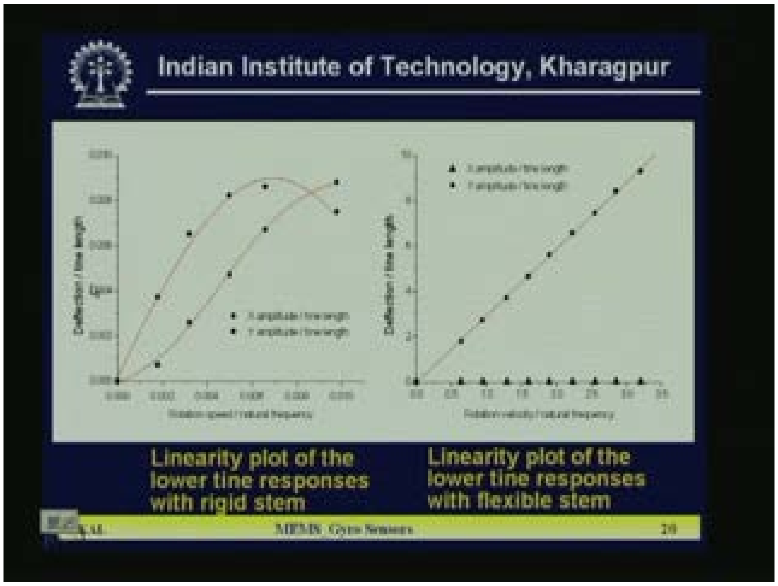

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Linearity plot of the lower tine responses with rigid stem

Linearity plot of the lower tine responses with flexible stem

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Now some simulation has been made and rotation speed or natural frequency with deflection of the tine. Because tines will be deflected if you change the speed of rotation then the because of the transfer of the energy Coriolis accelerations to the lower tines. So it will be it is vibration will change and infrequency also will change. So that has been simulated and sprouted here. One is x amplitude for tine length, another is y amplitude for tine length. In the other curve shows the rotation velocity or natural frequency versus deflection of the tine with flexible stem. One is rigid stem, another is flexible stem. Rigid stem means the stem which is fixed. It cannot move I have shown in one diagram which is rigid, so here this is rigid stem one side is fixed. So another is a rotation which is not rigid and which you have fabricated in the double tune fork. That stem is not rigid there it can flexibilities there. So because you have fix the both lower and upper tuning fork with a microbridge. So in both the cases it a simulated.

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## Development Micromachined Quartz Gyro Chip

Layout design for mask fabrication

Mask-1: Electrode patterning (Cr-Au)
Mask-2: Controlled etching for microbridges
Mask-3: Deep micromachining
Mask-4: Silicon tubs formation
Mask-5: Silicon stencil mask for electrodes over microbridges

Now the fabrication mask layout and fabrication and there are 5 mask require for that. One is for electrode patterning, when electrodes are use chromium gold. Second mask is controlled etching for microbridges. Because microbridges is not fully etch control amount of flexure thickness we have do give. So if use 500 micrometer the quartz crystal of 500 micrometer thickness, so microbridge is of the order of say 20 to 30 micrometer. That means it is told controlled etching of the microbridges. So show thin you can make so that the structure will be stable as well as the energy will be transfer of upper tines to the lower tines. The desired energy which is out of plane vibration will be transfer depends on how thin you can make the microbridges. Third is a deep micromachining. Deep micromachining means releasing the tuning fork structure.

Because is from the silicon, not silicon quartz substrate you have release the tuning fork structure, maximum portion you will complete dissolve, so that you will get the structure. That is the deep micromachining, quartz micromachining. Silicon tub formation, so that is for separating each of the sensors from other. Mask 5 is silicon stencil mask for electrodes over microbridges. So here you can see there is a problem, even you go for planer electrode not sidewall. But if you make the electrodes you can see next diagram I will show you that at bridges there is a large step. Because at the microbridges thickness is very small of the order of 20, 30 or 40 micrometer. Whereas other place is the thickness is nearly 500 micrometer of quartz. So 500 it will go down then the electrode will move.

So that means because of the large step the metallization or metal lines fabrication cannot be done normal planer technology. You have to have special technique for making electrodes which will run over the microbridge and the support stem. So for that a stencil mask has been made and using the vacuum masking which you called is a just the evaporation of material through the stencil which will deposit as per the electrode structure, that is used. That means in that case you do not have to go for lithography. So that vacuum masking technique using stencil mask has been developed in our laboratory and we made the electrodes nicely over the microbridge as well as the tuning fork surface.

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## Development Micromachined Quartz Gyro Chip

- Deep micromachining of quartz substrates (Z-cut)
- Photolithography for electrode patterning
- Shadow evaporation on micro bridges through silicon stencil mask
- Cr-Au metallisation
- Test packaging / bonding

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Now what are the steps? Deep micromachining of quartz substrate Z cut quartz is written, that micromachining of quartz is has to be standardized. Photolithography for electrode patterning is on important issue. Shadow evaporation on micro bridges through silicon stencil mask which I called is vacuum masking. Because it is done vacuum machine that so you call it vacuum masking not lithography. Lithography is done normal atmospheres pressure and this shadow evaporation on micro bridges is done in vacuum machine itself using stencil mask. Then chromium gold metallization and the last are test packaging and bonding. These are the steps we have to standardize for fabrication of these quartz gyros.

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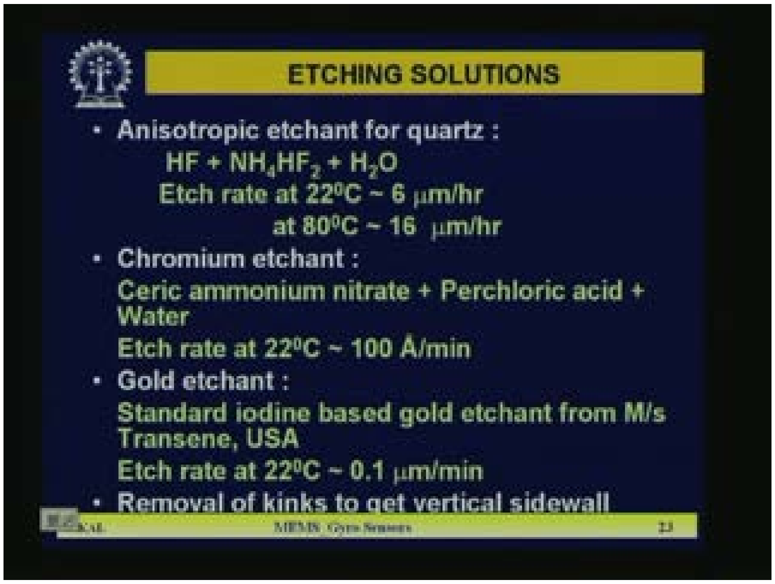

## ETCHING SOLUTIONS

- Anisotropic etchant for quartz :
  $HF + NH_4HF_2 + H_2O$
  Etch rate at 22$^0$C ~ 6 μm/hr
  at 80$^0$C ~ 16 μm/hr
- Chromium etchant :
  Ceric ammonium nitrate + Perchloric acid + Water
  Etch rate at 22$^0$C ~ 100 Å/min
- Gold etchant :
  Standard iodine based gold etchant from M/s Transene, USA
  Etch rate at 22$^0$C ~ 0.1 μm/min
- Removal of kinks to get vertical sidewall

And the anisotropic etching for quartz is different from silicon and we use hydrofluoric acid, ammonium fluoride and water for etching quartz, micromachining quartz and etch rate of quartz in that solution at 22 degree C is 6 micron per hour and an 80 degree C obviously etch rate will be higher 16 micron per hour. For patterning the chromium gold we have to searched for chromium etchant and gold etchant also. For chromium etchant we can use ceric ammonium nitrate plus Perchloric acid plus water. This is the etchant for chromium which is used for proper addition of the gold frame with the quartz and for gold etchant to use standard iodine based gold etchant from a renowned company from USA Transene, they sell it is not cyanide based etchant. But it is iodine based etchant.

Cyanide based gold etchants are not advisable to use in laboratory because that highly poisonous you know. That is why some other form of etchant gold etchants are available which standard etchant solution you can use and for that etch rate is 22 degree C means room temperature is 0.1 micron per minute. But one issue is important there, they are removal of kinks to get vertical sidewall. So that I think you remember in quartz micromachining class I told you, in a quartz micromachining the problem is the formation of kinks and then kinks can be removed by etching at low temperature for long time and certain chemical composition is to be changed in order to avoid the formation of the kinks. So now these are the various etching solution which are used for making the structure.

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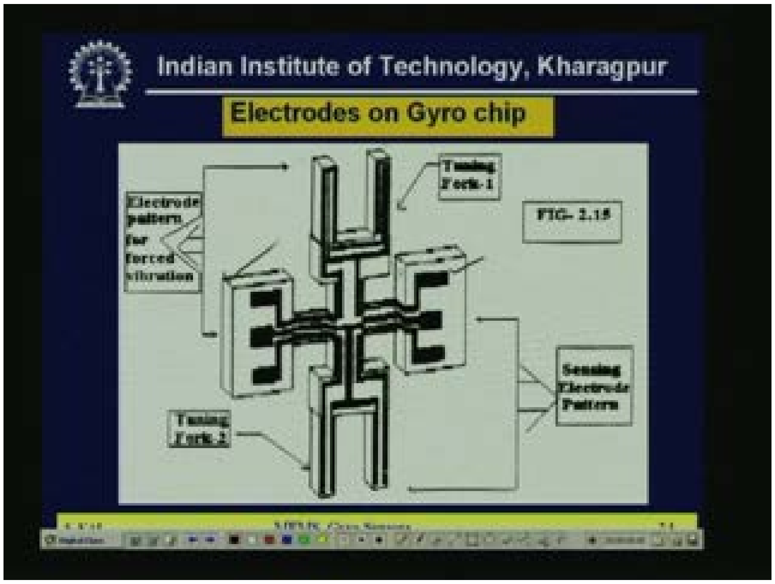

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Electrodes on Gyro chip

Now in this diagram you can see how the electrodes are coming. You can see this is some short of the picture we have taken from the quartz itself. These are two supports, you can see here. This is one support and this is another support and now the planer electrodes are using. So electrodes are you see the one will be positive and another will be negative. So these are metal lines; one this is metal lines, these are metal lines are connecting. But you have to drive how because this will vibrate you cannot have the bonding pad on the upper kind. Bonding pad one is here, another is here, and these two are bonding pads. So now this two bonding pad if you apply to amplify the electrical signal. So this will vibrate. Now through the bonding pad you see it is going down, because this a step and then this is microbridge. It is running to the microbridge then it is going here, then it is going in the surface of the tines. Similarly from the bonding pad it is going down because microbridge thickness is very less compared to bulk. So here you can thickness you can see is a 500 micrometer. But here thickness is only say 30, 40 or 50 micrometer.

So it will go down, then it draws here, and then travels to this, then it goes here. So in that wave this one and this is another. For bottom electrode also you can have the bonding pads here. All bonding pads are formed at the support frame. So that easily you can sense and drive the electrodes. This is the electrode pattern for forced vibration. This one in this axis, but here the sensing electrode pattern is here for tuning fork from second. So in this way electrodes are formed which will run over uneven surfaces and that uneven is huge. So this kind of metal pattern you cannot make using normal photolithography process. So for normal photolithography process substrate surface will be plainer. In VLSI this surface is not exactly plainer but this up and down is not that much like here. May be 1,2 or 3 micron difference of the surface evenness is there, windows and the passivated dioxide. But here is of the order say more than 300, 400 micrometer steps are available in this case. So that is not possible using normal lithography. Now this kind of structure we made in our laboratory and that is shown in the next view graph.

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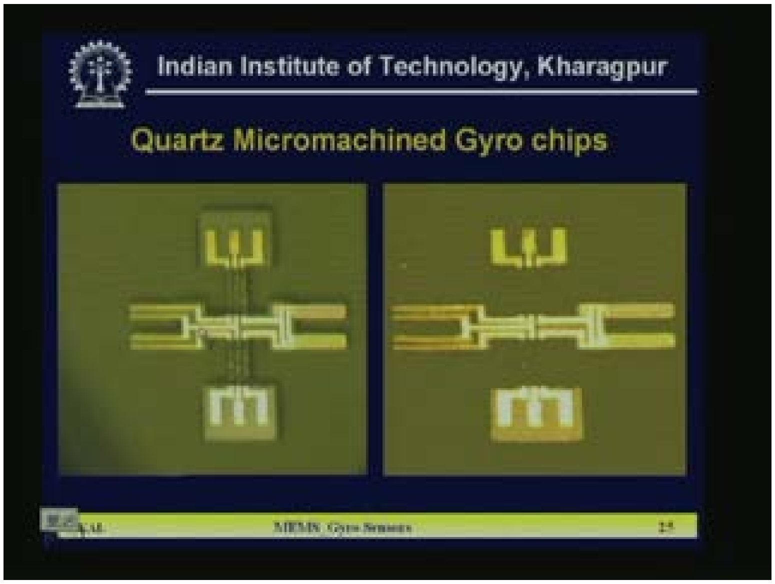

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Quartz Micromachined Gyro chips

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Here you can see the quartz which is transparent and the golden colors are the electrode. How the electrodes are just moving from this is upper one tine, this is another tine, this is support in the bottom and support in these two are support. So this is the support frame is one here, this is another support frame, this is the one tines, this is one tines and this is second tines on top and bottom. So electrodes are running there, so two photography shown and here by because the picture you cannot say see where the electrodes are coming here. The reason that if you take photograph, so there are two different planes. So separation between the top plane and bottom plane is around say more 300, 400 micrometer. So both the planes cannot be focused simultaneously. That is why you cannot see the golden line here. But some shadow things you can see this side, this, this and this in the same plane.

But this particular zone and this zone there is a step of more than 300, 400 micrometer. So both the planes together you cannot focus it in microscope. That is why you cannot see here and here. But in race of portion which and the same plane you can see the metal lines. So these are, this is the fabricated the gyro chip and next question is mounting is very difficult. So you can fabricate it, then mounting and testing. Here comes the problem. People facing lot of problem and even now we are trying are best to characterize that using certain facilities and we are running to different places for accessing there facilities. One facilities surface available with the these Space Research Organization and the characterization of this sensors are not complete. That is why I cannot show even in the characterization curve here at the moment, so after fabrication we are in the process of the packaging.

This mounting in test fixture and the testing and characterized of the chip. So that we can get some idea about it sensitivity and what is its frequency change due to the rotation. Vibration change means some frequency change also will be there and that characterization is yet to be done. So just in this lecture I can give you certain ideas of the gyro sensors, different class of gyro sensors silicon and quartz both and some idea regarding and how it is fabricated. There are lot of recent gyros are coming which some of the picture I will showed you, that is the comb line gyros and another is a rotation wheel gyros. Those are really complicated fabrication process is also not that much easy. So that you can just go through if somebody wants to take up these activities in your projector work or maybe further researcher work. So let me stop here. Thank you very much.

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Preview of Next Lecture

Preview of Next Lecture

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Lecture # 28

MEMS for Space Application

## Lecture No. # 28

## MEMS for Space Application

Today we will discuss on a very interesting topic. That is MEMS for space applications. Already we discussed on the accelerometer as well as gyro chip which are also used in space craft technology. But topic which I will discuss today is only meant for satellites. Positioning a satellite in a particular orbit is an important issue. So how the MEMS devices are playing an important role for satellite positioning that is the topic of discussion in today's lecture. You know whatever the, either aero plane or satellite or the missile whatever you are going to send in space, one of the major concerned is the weight. So miniaturization is one of the important issue miniaturization of the devices and a different component is one of the major issues when you are going to integrate them either in a space craft or airplane or missile wherever it is.

So the weight and small size, small weight miniature size is the issue and you know MEMS will give you a process or a technology where you can miniaturize the devices as much as possible with lot of micromechanical action also. So today we will discuss on micro thrusters which are basically used for pico satellite program. Micro satellite and pico satellite is a topic of research today in many of the advance level institutions around the globe. So Indian Space Research Organization, ISRO is also thinking in near future for micro satellite or pico satellite program. So they have initiated an R&D effort to miniaturize different components and to get highly reliable space qualified, low small mass and small size devices which may be helpful for reducing the weight of the space vehicle.