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REVIEW PAPER

Microelectromechanical Systems and Microsensors

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ABSTRACT

A highly promising technology that is set to revolutionise nearly every product category is microelectromechanical systems (MEMS). MEMS specifically are the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology. Silicon and quartz are now household names to consumers of electronic products, computers and automated appliances. Silicon is the material of microchips or very large scale integrated (VLSI) circuits. Quartz, a piezoelectric crystal made of silicon and oxygen atoms, provides stable clock pulses to the chips. These materials are also being used to fabricate micromachines and microelectromechanical structures and systems for a wide variety of applications for sensing and actuation. Extensive research and development work has been going on in the Microelectronics Laboratory, Advanced Technology Centre of IIT Kharagpur on both microelectronics and MEMS technology since last five years. Some of the MEMS-based microsensors develoed are silicon MEMS accelerometers, flow sensors, thermal detectors, pressure sensors, micro-thrusters and quartz MEMS gyro and accelerometers. An overview of micromaching and MEMS technologies developed at IIT Kharagpur along with the development of various silicon and quartz-based microsensors are described in this paper.

Keywords: Microelectromechanical systems, microsensors, microelectric material, single-crystal silicons, sensors, actuators, micromachining, microstructures, aerospace applications

1. INTRODUCTION

The journey of microelectronics began in 1948 from the invention of first transistor. Shockley proposed JFET in 1952. Recent revolution in computer and IT industry was possible due to the discovery of ICs by Kilby in 1958. The continual improvement in silicon IC processing since last 40 years has resulted a minimum feature size of 200 nm and the number of transistors in VLSI chip has risen to 100 million. The scaling of component-size from macro-dimensions to micro-or nano-dimensions has led to superior performance, low power, low cost, low material consumption, lightweight and high packing density.

Single-crystal silicon so far used as the unique microelectronic material for VLSI, has been recommended as an excellent mechanical material for fabricating micro-mechanical sensors and actuators. Silicon processing technology for ICs has been suitably adapted to fabricate microstructures for realising microsensors for applications in wide range of industries including telecommunications, medicine, automobile, defence space, avionics, and information technology. The application of IC technology to the fabrication of thermal, optical, and mechanical devices in the last 15 years has stimulated the Research and Development of micromachined silicon microsensors. Micromachining is a process that

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deposits, etches, or defines materials with minimum features measured in micrometer or less. This technique is used for fabricating various kinds of microstructues for microsensor and microactuator applications.

1.1 What are MEMS?

Today, micromachining and microelectromechanical systems (MEMS) technologies are used to produce complex structures, devices, and systems on the scale of micrometers. MEMS are devices, and systems produced by micromachining silicon or other microelectronic materials. Typical dimensions of MEMS devices are in the range of nanometers to centimeters. The field of MEMS radically transformed the scale, performance, and cost of a diverse set of traditional evolutionary engineering efforts to reduce size and power and while increasing performance by employing batch-fabrication techniques. MEMS technology has enabled many types of sensors, actuators, and systems to be reduced in size by orders of magnitude while improving sensor performance. Other popular names of MEMS in Europe and Asia are microsystems technology and micromechanics respectively.

Different piezoelectric, acoustooptic, thermoelectric, thermooptic, magnetic films may be deposited on silicon for realising a variety of miniature transducers. Silicon IC technology is in a very advanced stage. Both the sensor/actuator and the electronic monitoring and signal processing circuit can be integrated on the same chip, thus lowering down cost, improving measurement accuracy, and reliability of operation. With in-built programmable microcontrollers, a MEMS may be smart and intelligent. Such MEMS products can be directly interfaced with computer networks that help in automation and development of intelligent systems.

1.2 Evolution of MEMS

The evolution of MEMS is dependent on the development of micromachining processes which have been derived from IC manufacturing. In 1959, the famous lecture of Prof Feynman titled, "There is plenty of room at the bottom" described enormous amount of space available on the microscale, "The entire encyclopedia could be written on the head of a pin"[1]. He foresaw the miniaturisation of machines and in fact famously challenged the world to fabricate a motor with a volume less than 1/64 of an inch on a side. His dream has now become a reality. The invention of monolithic integration of ICs, and planar batch fabrication embarked the IC industry on a continuous effort to miniaturise increasingly complex circuits.

Perhaps the resonant gate transistor produced by Nathenson[2] in 1964 was the first engineered batch-fabricated MEMS device where the electrostatically driven motion of the cantilevered gold gate electrode modulates the electrical characteristics of the device[2]. The development of microprocessor in 1970 transformed our society and drove the demand ICs even higher. The number of transistors integrated into a chip doubles every 18 months as predicted by Moore, has held true for the past 30 years. During late 1970s and beginning of 1980s, MEMS commercialisation was initiated with the production of few parts for automotive industry.

The development of MEMS, also called microsystems in Europe, lies in the discovery of strong piezoresistive effect in silicon and germanium by Smith from Bell Laboratories in the 1950s[3]. Intensive research on micromachining and fabrication of microstructures like cantilevers, membranes, flexures, nozzles, gears, combs, etc for applications in sensing and actuation started in the early 1970s. The pioneering review article by Peterson[4] has been the instrumental at increasing the awareness of the possibilities that MEMS offer. The surface micromachining technology[5], served as the basis for many MEMS products.

A valuable technology driver for the MEMS was developed at UCB and MIT, USA, to produce first electrostatically-controlled micromotors that used rotating bearing surfaces. The access to third dimension in MEMS was given by the development of surface micromachined micro-hinges in 1991 at UCB by Pister[6], *et al*. Thus began the MEMS era in coexistence with VLSI. Many start-up companies were setup in Silicon Valley and other parts of the globe. The market has grown from a modest US $10 M in 1980 to a fabulous US $50 B today[7]. Many VLSI majors, in addition to a host of new

MEMS companies, are the players in the field. A tremendous increase in the number of devices, technologies, and applications has expanded the sphere of influence of MEMS and it will continue further.

2. MEMS TECHNOLOGY

Although the MEMS technology is derived from the mainstream IC technology, the field of MEMS incorporates some other microfabrication processes and materials not traditionally used by the IC industry. Such processes are anisotropic wet etching of single crystal silicon, deep reactive-ion etching (DRIE), x-ray lithography, electroplating, low stress LPCVD films, spin casting, micromolding, batch microassembly, etc. Other than silicon, silicon dioxide, silicon nitride, polysilicon, and aluminum, the additional materials used in MEMS are magnetic films (e.g., *Fe*, *Ni*, *Co*, rare earth alloys), high-temperature materials (e.g., *SiC* and ceramics), piezoelectric films (e.g., PZT, BST, *ZnO*), stainless steel, platinum, gold, sheet glass, polymers, plastics, etc.

Photolithography is the most important process that enables ICs and MEMS to be manufactured reliably with microscopic dimensions and in high volume. The main feature of MEMS technology is to integrate multiple patterned materials together to fabricate a complete MEMS device. The most general methods of MEMS integration are bulk micromachining and surface micromachining.

In case of bulk micromachining, single crystal silicon substrate is patterned and shaped to form an important functional component of the resulting device[8]. Many high-precision complex 3-D shapes such as V-grooves, nozzles, membranes, vias, channels, pyramidal pits, cantilevers can be formed exploiting the predictable anisotropic etching of silicon. A typical bulk-micromachining process is illustrated in Fig.1.

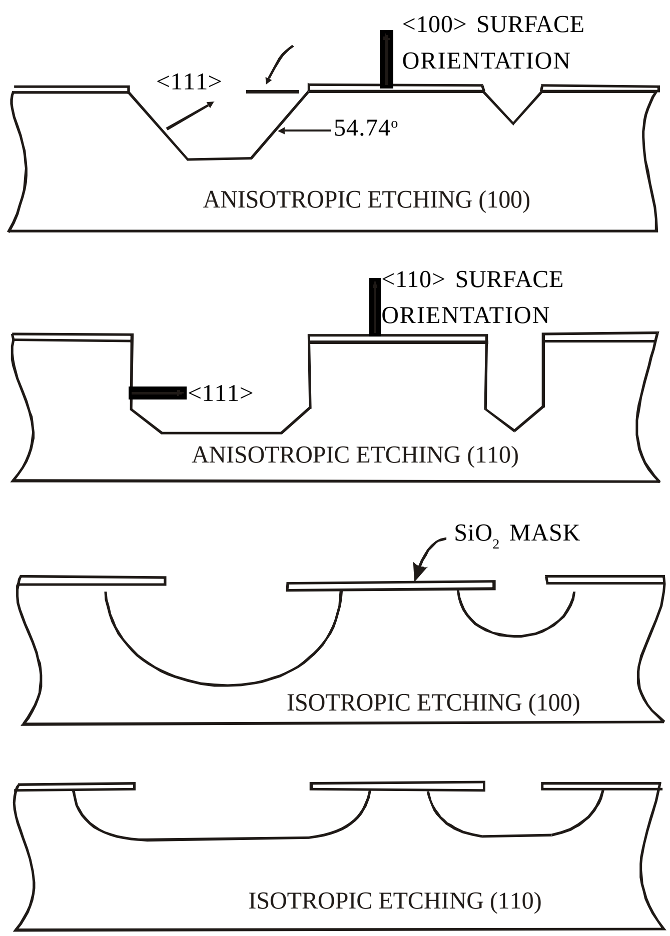


Figure 1. Bulk micromachining process.

A dry etch process can also be used to etch deeply into silicon wafer while leaving vertical sidewalls and is usually independent of crystallographic orientation. The flexibility and usefulness of bulk micromachining has greatly enhanced with DRIE.

Surface micromachining is a method of producing MEMS by depositing, patterning, and etching a sequence of thin films, typically 1 µm to 100 µm thick[9]. One of the most important processing step required for dynamic MEMS devices is the selective removal of an underlying film, referred to as a sacrificial layer, without attacking an overlaying film, referred to as structural layer. A typical surface micromachining process is illustrated in Fig. 2.

Another interesting technique used for making 3-D microstructure is micromolding[10]. This process combines DRIE and conformal deposition process, such as LPCVD polysilicon and silicon dioxide. Microstructures of nearly 500 µm thickness can be realised using this technique. Other non-silicon microfabrication techniques for MEMS are LIGA[11] and plastic molding with polydimethylsiloxane (PDMS), etc.

Substrate bonding is an important step towards fabrication of MEMS. Silicon, glass, metal and polymeric substrates can be bonded together through several processes such as anodic bonding[12], eutectic bonding[13], fusion bonding[14] and adhesive bonding[15]. This step is necessary to fabricate structures of complex system of enclosed channels, large cavities to be sealed hermetically or mechanical support. The integration of signal processing circuits with MEMS can greatly improve the performance of many MEMS. But fabrication processes of ICs are relatively longer, complex, and costly when compared to many MEMS fabrication. Manufacturing feasibility, complexity, reliability, yield and cost are the key issues to combine MEMS with IC fabrication.

3. MEMS AND MICROSENSOR ACTIVITIES AT IIT KHARAGPUR

The Microelectronics Laboratory under the Advanced Technology Centre at IIT Kharagpur was one of the first in India where experimental research on microelectromechanical sensors and systems began during the early 1990s. The IIT Kharagpur research team had developed silicon microelectronics fabrication facilities, such as photolithography, etching, oxidation, diffusion, metallisation and sputtering, during the early 1980s, capable of fabricating bipolar IC chips of 4 µm minimum feature

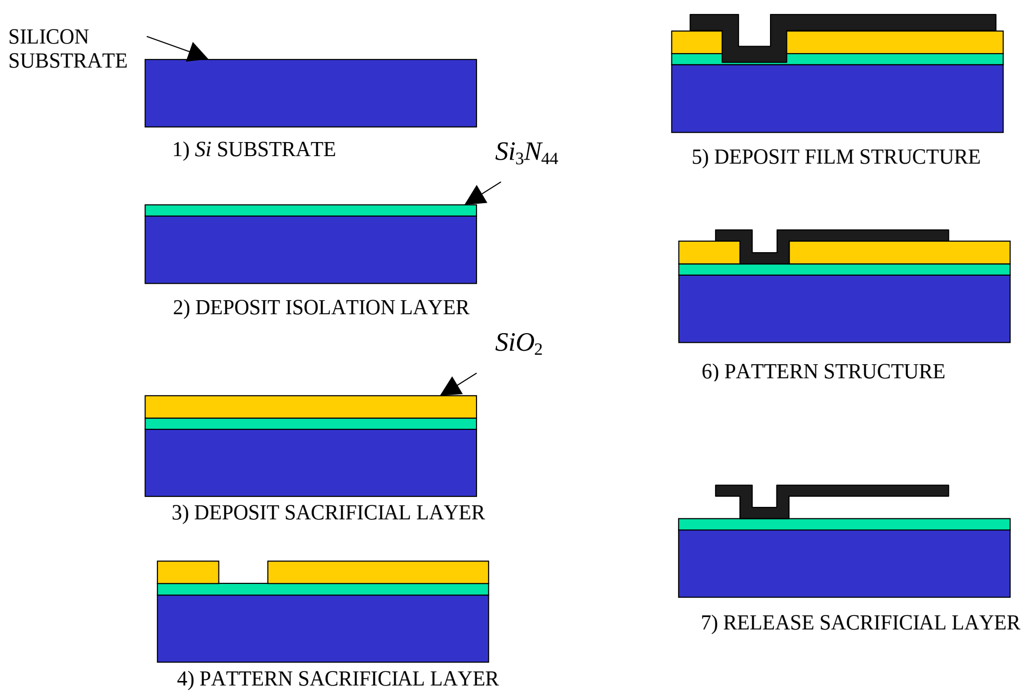


Figure 2. Surface micromachining process.

size. Although these facilities are not suitable for the fabrication of present-day VLSI chips whose dimensions have shrunk to deep sub-micron, typically 0.2 µm, it was decided to tailor this infrastructure for the fabrication of micromachined structures for MEMS and integrated optics. A state-of-the-art MEMS Design Laboratory has recently been set up in Advanced Technology Centre, IIT Kharagpur to facilitate the MEMS design activities in different R&D laboratories of the country.

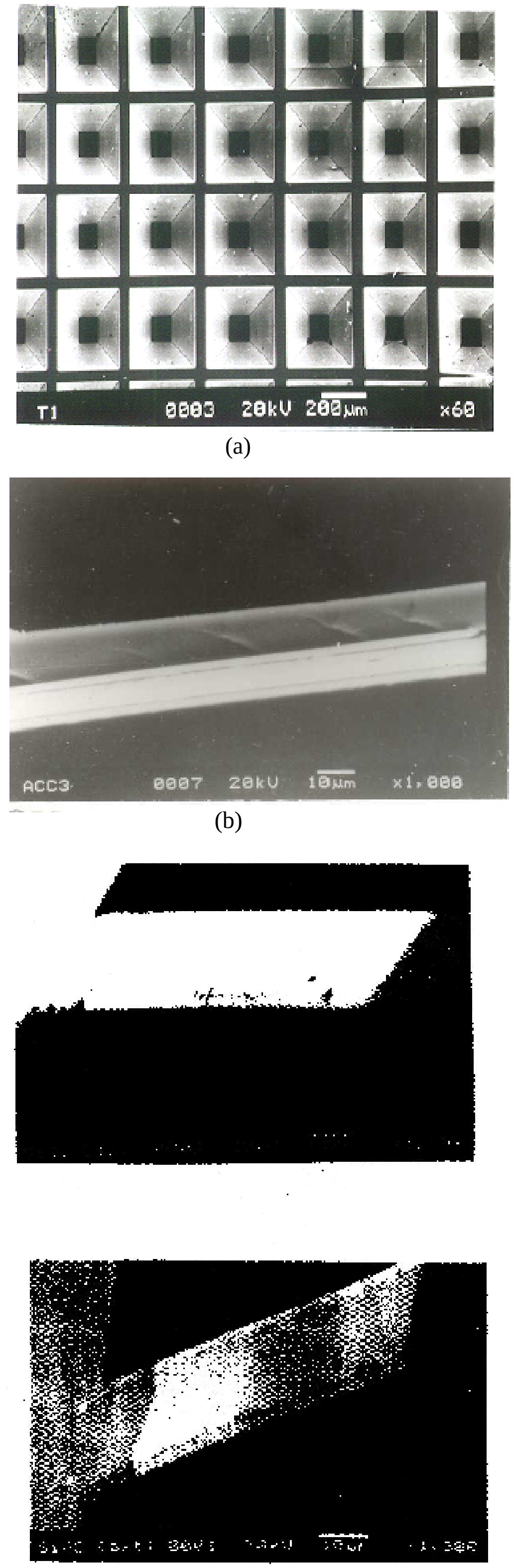
Silicon is not only the unique electronic material for VLSI chips but also a strong mechanical material[4] ideally suited for MEMS. The lithography, etching, and film-deposition techniques on silicon were well-established, and hence could easily be adapted to MEMS fabrication. Moreover, the technological compatibility between silicon IC and MEMS places silicon as the most preferred material for MEMS. The majority of MEMS products are therefore silicon-based.

3.1 Micromachined Infrared Sensor

In the area of silicon micromachining, Microelectronics Centre of IIT Kharagpur has developed tiny membranes, cantilevers, and nozzles. Microphotographs of some microstructures fabricated using *KOH*, TMAH, EDP etching are shown in Fig. 3. The membranes with built-in thermopiles have been developed for sensitive, high-speed, wide-band infrared detection used in industrial automation and space research. Thermopile type micromachined IR detectors have been fabricated in early 1990s using polysilicon-aluminum thermocouple[16]. The photograph of such a device is shown in Fig. 4.

3.2 MEMS-based Flow Sensor

MEMS-based flow sensor developed at the IIT Kharagpur is based on the principle of thermal anemometer, which is an indirect technique for measurement of fluid velocity[17]. In this method, fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium. The sensing element used in the present flow sensor was a metallic thin-film resistor with chromium/ gold contact lines and pads. The sensing element



(c)

Figure. 3. Microphotograph of microstructures fabricated using bulk micromachining technique (a) nozzles, (b) flexures, (c) cantilevers.

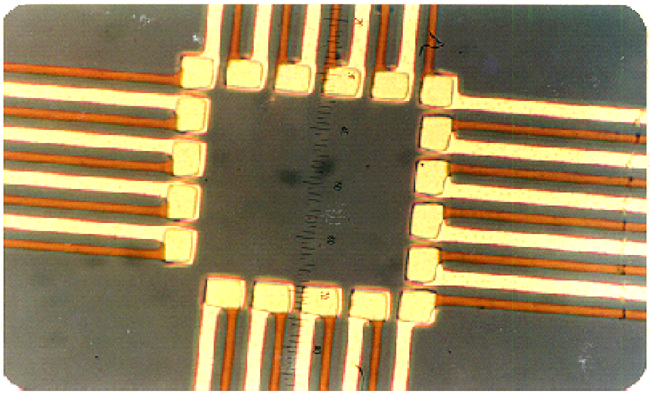


Figure. 4. Thermopile IR detector.

(nickel resistor) along with contact lines and pads were fabricated on the silicon dioxide covered <100> plane of the silicon cantilever. Furthermore, a very thin membrane was created at the free-hanging end of the cantilever on which the sensing element was placed. As the whole top portion (<100> plane) of the silicon cantilever was covered with thermally grown silicon dioxide, it offered complete electrical isolation as well as appreciable amount of thermal insulation between the sensing element and the bulk of silicon substrate. In constant-current anemometer mode, the current input to the sensing element was kept constant. The heat loss from the sensing element due to fluid flow reduceed its resistance, and hence there was a potential drop across the sensing element. The amount of voltage drop across the sensing element is an indication of the fluid velocity. The proposed flow sensor offers the advantage to select the fluid flow direction over the sensing element.

Photograph of the fabricated flow sensor is shown in Fig. 5. The flow sensors were tested with nitrogen gas flow. The gas flow rate was regulated and measured using a standard mass-flow controller. The thin nickel film resistor was powered with a constant current from an external constant current source. Due to Joules law heating ($Q = I^2R$, where I is the current flowing through the resistor and R is the resistance of the resistor), the temperature and resistance of the sensing element increases. Hence the voltage drop across the sensing element also increases. When regulated flow of nitrogen gas was passed through the pipe, the gas carried away a part of the heat from the sensor due to forced heat convection. Thus, temperature of the sensing element decreases which results in decrease of potential across the sensor. This potential drop, which is proportional to the flow velocity, was measured using a voltmeter, and hence, flow velocity can be calculated using King's law. It was observed that, the potential drop across the sensing element increases linearly with increasing gas flow rates. Fig. 6 shows the plot of flow rate with voltage drop across the sensor.

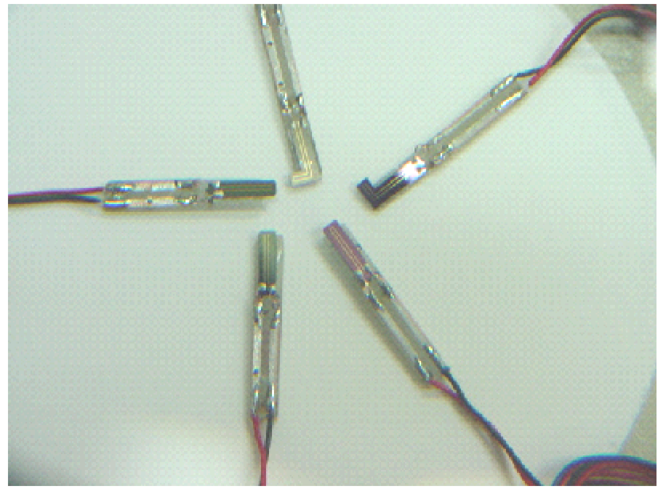


Figure 5. Micromachined flow sensors.

3.3 Silicon MEMS Acceleration Sensors

Inertial sensors have maximum applications in aerospace-aeroplanes, rockets, satellites, and other space vehicles. These are also extensively used in modern automobiles, guided missiles, robots, biomechanical systems, flying simulators, and many other machines[18]. Accelerometers and gyroscopes are the basic inertial sensors used for sensing and measurement of acceleration, velocity, displacement, rotation rate and angle under dynamic condition[19,20]. The conventional inertial sensors are complex electroechanical systems which are bulky, and highly expensive units, requiring higher operating voltage and power, incompatible with the present-day electronic systems. MEMS products are rather inexpensive, micro-sized, lightweight, reliable, and require low voltage, low power for operation. In many cases, the sensors can be integrated with the electronic circuits on the same chip for monitoring and signal processing. It leads to a drastic reduction of cost and overall size and weight, and increase of reliability. MEMS accelerometers fabricated using bulk

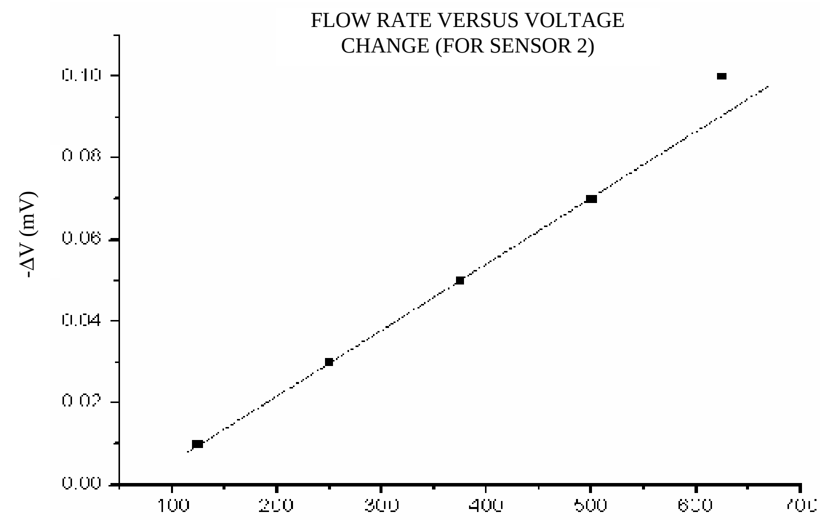


Figure 6. Plot of flow rate with voltage drop across the sensor.

micromachining technique, are relatively bigger in size but could be quite sensitive because of heavier proof mass. The newer, more advanced devices are fabricated using the surface micromachinig technique, which is usually compatible with CMOS/ BiCMOS VLSI fabrication technology.

Different approaches used in MEMS technology for sensing acceleration include[19]:

(a) Piezo-resistive measurement of stress on a flexure or cantilever beam from which a seismic mass (proof mass) is suspended

(b) Capacitive sensing of displacement of a proof mass suspended via flexures from a frame

(c) Measuring change of vibration-frequency of a beam or a double-ended tuning fork to which a proof mass is attached at the free end

(d) Measurement based on tunneling of electrons between fine tips on a cantilever and a base where the cantilever suspends a proof mass

(e) Piezoelectric sensing of stress on a cantilever suspending a proof mass using piezoelectric films deposited on the cantilever surface

(f) Optical sensing of strain or displacement in cantilever-proof mass system.

In all these devices, the inertia of the proof mass plays the key role. As the vehicle or body, to which the MEMS accelerometer is attached, experiences an acceleration, the suspended proof mass tends to retain its velocity, and hence exerts a force, which results in stress, strain, and displacement that is transformed into electrical quantities through one of the above mechanisms.

The CMOS-compatible bulk micromachined piezoresistive accelerometer developed at IIT Kharagpur consists of four flexures supporting a proof mass and a supporting frame[21-23]. The assembled accelerometer structure consists of: (a) middle silicon sensor and (b) top and bottom pyrex glass cap layers. The accelerometer structure is shown in Fig. 7. The top cap layer provides over retardation mechanical stop and air friction for damping and bottom cap layer provides over acceleration mechanical stop and air friction for damping. Four pairs of boron-diffused piezoresistors are located at maximum stress points on the flexures near the proof mass and frame ends. Because of the opposite nature of stress at the two ends, these piezoresistors can be connected to form a Wheatstone's bridge such that the off-axis responses are practically cancelled while the on-axis (along the normal) response is maximised. The device is simulated using coventor ware[21]. Since the change in resistivity of a piezoresistive material is directly proportional to the stress which induces this change, and therefore, it is important to place the resistors at these maximum stress points to get higher sensitivity.

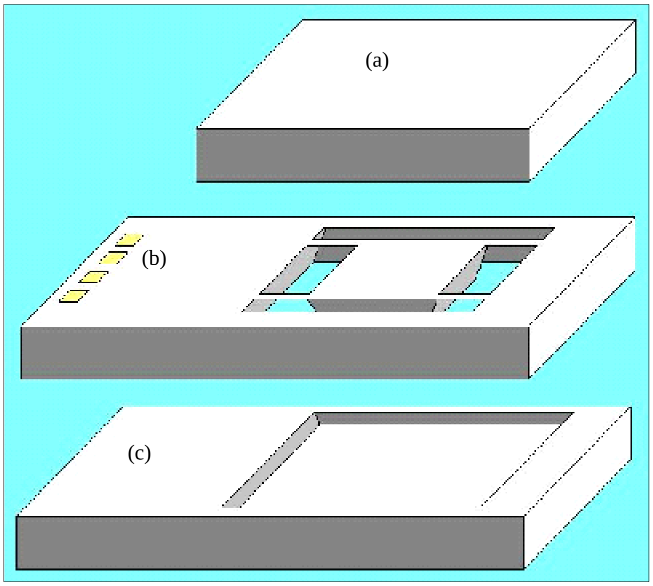


Figure 7. Bulk micromachined acceleration sensor: (a) top cap layer, (b) middle sensing layer, (c) bottom cap layer.

Using MemMech solver, the maximum stress points along the flexure length were found for vertical acceleration. Figure 8 shows the stress distribution along the length of the beam for 13g acceleration applied in Z-direction. It indicates that the first stress peak, which occurs near the frame-end is tensile stress, whereas the second peak near the mass-end is compressive stress. These stress peaks define the optimal positions where the piezoresistors must be placed to get higher sensitivity. It is evident that the damping ratio (ξ) has an important role in the design of accelerometer. If $\xi \ll 1$, i.e. practically with no damping, then the structure may collapse. On the other hand, if $\xi \gg 1$, then the settling time for the oscillation for the suspended structure will be large, which means slow response. The damping ratio is mainly determined by the dimension of the accelerometer structure, generalised mass of the seismic mass, pressure, density, and viscosity of the gas in the enclosed volume inside the accelerometer module. Thus, gap between the proof mass and top and bottom cap layers is designed optimally to achieve ξ=0.8 for the accelerometer structure. In the proposed accelerometer[23], air is used as gas and the air gap between the sensing layer and top and bottom lids is optimised as 27 µm to achieve ξ close to 0.8.

Most of the bulk micromachined accelerometer use *KOH*-based wet etching, RIE and DRIE. Among

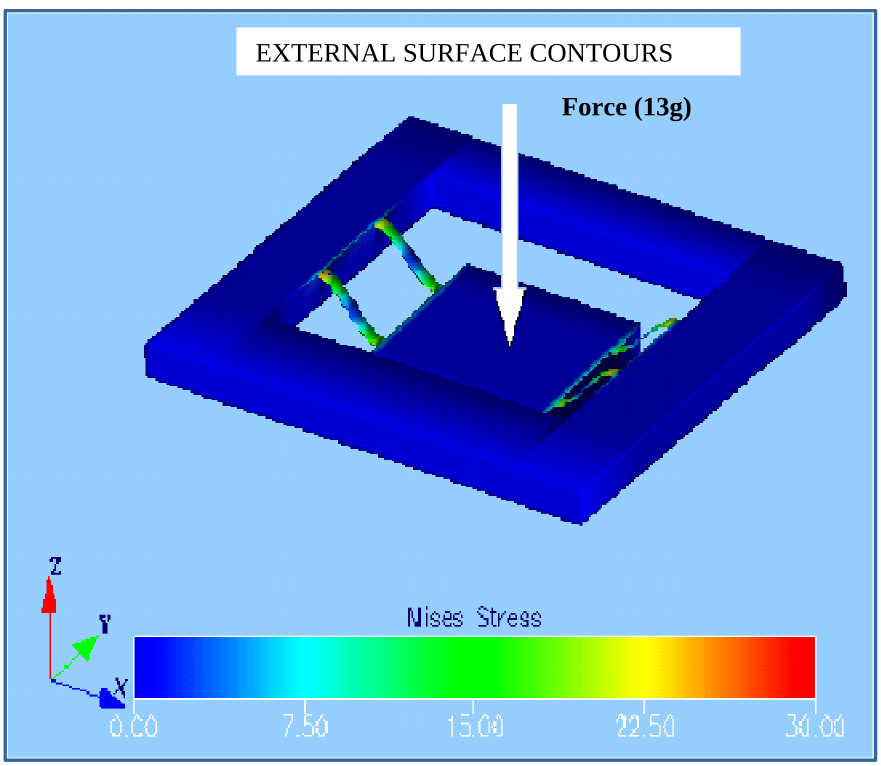


Figure 8. Stress distribution along the length of the flexure under 13 g vertical acceleration.

the most common wet anisotropic etchants of silicon namely, hydroxide-based (*KOH*, *CsOH*, etc), ethyl diamene pyrocatocal (EDP) and tetra methyl ammonium hydroxide (TMAH), TMAH is the only silicon etchant which is fully CMOS compatible[24,25]. Dual-doped TMAH solution has been used for wet anisotropic etching and a very simple accelerometer fabrication process flow using 5 masks has been developed at IIT Kharagpur[22]. The novelty of this process is that the bulk micromachining can be performed after aluminum metallisation. The etched surface is also smooth. The fabrication is thus CMOS-compatible. The micromachined top and bottom pyrex layers were bonded with middle silicon chip as shown in the microphotographs of Fig. 9. The acceleration measurement was carried out using a Rate table. Figure 10 shows the response of two accelerometer devices for positive Z-axis acceleration. Device 1 shows the sensitivity of 506.22 µV/g and linearity of 0.25 per cent, whereas the sensitivity and linearity of device 2 were 573.55 µV/g and 0.19 per cent, respectively.

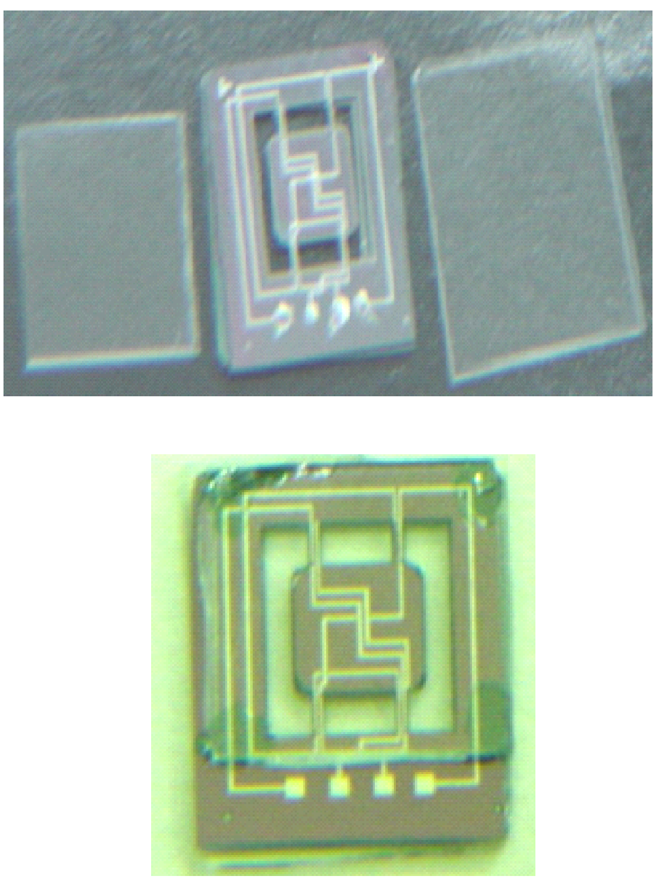


Figure 9. Microphotograph of the accelerometer chip: (a) top, middle, and bottom layer, (b) three layers bonded.

For sensing micro-g acceleration, tunneling current accelerometer has been developed at the IIT Kharagpur[26]. The basic principle is to use a constant tunneling current between one tunneling tip attached to a movable microstructure and its counter electrode to sense displacement, as shown in Fig. 11. It combines capacitive actuation with tunneling sensing. As the tip is brought sufficiently close to its counter electrode (few A°) using electrostatic force generated by bottom deflection electrode, a tunneling current is established and remains constant if the tunneling voltage and distance between the tip and counter electrode are unchanged. Once the proof mass is displaced due to acceleration, the readout circuit responds to the change of current and adjust the bottom deflection voltage to move the proof mass back to its original position, thus maintaining constant tunneling current. Acceleration can be measured by reading the bottom deflection voltage in this closed loop system. As tunneling current changes by a factor of two for each angstrom displacement,

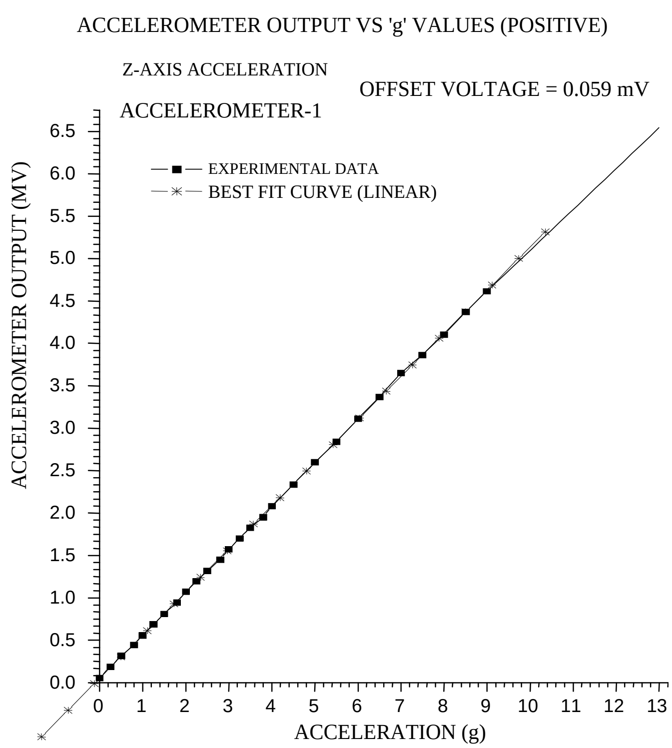


Figure 10. Response of the accelerometer for positive acceleration.

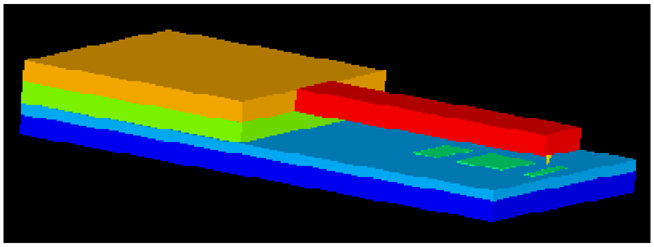


Figure 11. Micromachined tunneling accelerometer.

accelerometer using this principle achieves very high sensitivity and is capable of measuring mg acceleration. These devices have large low frequency noise level (~ 4 mg/√Hz at 0.5 Hz and 0.1 mg/√Hz at 2.5 kHz). Requirement of high supply voltage (10 - 100 V) sometimes limits application of these devices. This kind of sensor has wide applications in space, defense, seismic science and upper atmospheric studies.

3.4 MEMS Microthruster for Space Applications

MEMS is meant not only for sensing but also for actuation applications. A novel MEMS actuator for space application is a micro-propulsion system or micro-thruster used for ultra precise orbit control of satellites and micro-satellites. Traditionally, micro-rockets are used for producing controlled thrust of very small values[29]. These are miniaturised versions of propulsion systems used for the launching and control of satellites. The traditional micro-systems, however, cannot produce extremely small thrust in the range of micro-Newtons to milli-Newtons, which are required today for the control of micro-satellites. In recent years, silicon MEMS technology is being explored to develop microthrusters[30].

Of the different types of micro-thrusters, the vapourizing liquid microthrusters[31] are used for attitude control of microspacecrafts. The change of phase from liquid to gas is exploited to produce a thrust. Micromachined silicon microthrusters using the above principle have been reported by several groups[32,33]. Schematic diagram of the microthruster developed at IIT Kharagpur is shown in Fig. 12. It uses water as the liquid propellant[34-36] and consists of a micromachined cavity, an internal diffused-resistance heater, an inlet hole for introducing water, and an outlet nozzle. The lower part has a micromachined rectangular tub containing a heavily boron-diffused resistor and a V-groove channel for introducing liquid. The upper piece of wafer is the lid on the lower part. It contains a micromachined rectangular tub (the upper-half of the cavity), a bigger nozzle for liquid inlet, and a smaller, properly shaped nozzle for vapour outlet. The two pieces are bonded together so that a closed shallow cavity is formed. Water is introduced via a capillary tube sealed to the bigger nozzle. As water enters the cavity via the V-groove channel, it comes in direct contact with the oxide-coated resistance heater while passing towards the output nozzle. Adequate electrical power is applied to the heater so that water while passing over the heater gets vapourized and a jet of steam exits through the output nozzle. The emerging jet of liquid vapour exerts micro-order thrust in a direction opposite to the direction of the jet.

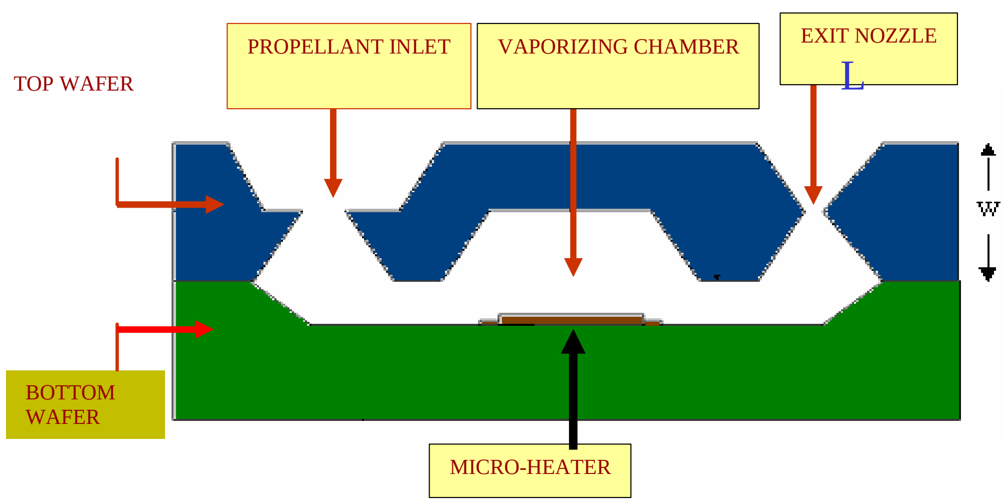
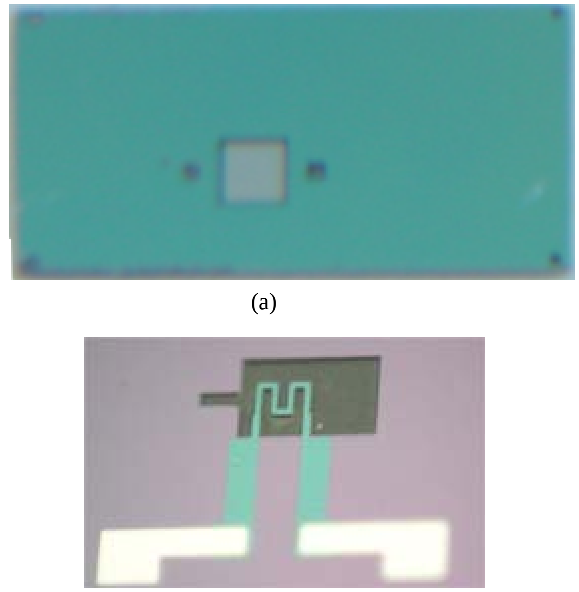


Figure 12. Schematic cross-section of vaporising liquid microthruster.

Based on the above considerations, the microthruster has been designed. The micro cavity has a volume of 0.475 mm^3. Three different nozzle sizes, 30 m, 50 m, and 70 m, and three different heater configurations of resistance 250 Ω, 350 Ω and 400 Ω have been used in a number of test devices. With an estimated mass flow rate of 476.7 x 10^{-8} kg/s, a microthrust of the order of 2.0 mN is expected to be produced from the 50 μm x 50 μm nozzle for the heater power dissipation of 200 mW. Standard silicon micromachining technique is used to fabricate the microthruster. The top wafer is made by a two-mask process and the bottom wafer by a three-mask process. The wafers are n-type <100> with a resistivity of 4–6 Ω-cm. The heater resistors are fabricated by diffusion of boron from a BN1100 solid diffusion source yielding a sheet resistance of 8 Ω/square after drive-in diffusion. The passivating oxide film is 0.5 μm thick. The heater design was intuitive on the basis of contact area and travel time of water passing over the resistor. After processing, the two wafers were bonded together. The photograph of a microthruster is shown in Fig.13.



(a)

(b)

Figure 13.SEM photograph of the microthruster: (a) top wafer, (b) bottom wafer along with embedded microheater.

3.5 Micromachined Quartz Inertial Sensors

In the field of inertial sensors, quartz (a thermally stable compound of silicon and oxygen (SiO_2)) has received wide attention because of its excellent piezoelectric property, low temperature coefficient, and higher stability[37]. Quartz has therefore been established as a reasonable alternative to silicon in realising inertial sensors based on vibrating beam or tuning fork[38]. Vibration can be induced piezoelectrically with the help of suitably designed electrodes deposited on the beams. Piezoelectricity being a reversible process, vibration in quartz may also be detected in a similar way as an electrical output across electrodes.

IIT Kharagpur was the first in India to develop quartz micromachining technology[39]. The indigenous development of the quartz technology is considered significant because quartz micromachining is a protected technology with very little details available in the scientific literature. This technology has been used to fabricate tiny dual tuning fork structures with built-in electrodes via flexures, for sensing rotation (gyro), and double-ended tuning forks (DETF) used in MEMS accelerometers[21].

Quartz lacks any centre or plane of symmetry and is therefore highly anisotropic in nature. Although photolithography can be applied to quartz substrates without any problem, the etching is more complex and problematic due to the asymmetry and strong anisotropy of quartz crystal as compared to silicon crystal. While the chemical and reactive-ion etching techniques of silicon are well documented, it is not so for quartz. Generally, Z-cut quartz crystals are used for MEMS devices. It is therefore required to etch the substrates normal to Z-axis to a large depth, around 500 m or more. It requires a highly directional etching. Special masks are required to withstand prolonged etching in strong reactive environment. The wet etchants used for quartz micromachining are HF and NH_4HF_2 or a suitable combination of both. The masking material generally used is a chromium-gold thin film deposited by vacuum evaporation or sputtering. The quality of surface finish prior to chromium-gold deposition is an important parameter. Poor surface quality causes mask pill-off during prolonged etching in HF-based solution. Good surface finishing and special surface treatment are needed for accurate definition of deep microstructures on quartz. Different crystal planes of quartz have different etch rates in anisotropic etching. It results in sharp kinks protruding from the sidewalls after etching. Making the sidewalls nearly vertical with complete removal of kinks is a challenge. It requires critical adjustment of *HF* and NH_4HF_2 concentrations and temperature during etching. Quartz micromachining technology has been standardised at IIT Kharagpur[40].

3.5.1 Double-ended Tuning Fork as Accelerometer

The double-ended tuning fork (DETF) is made by micromachining a 150 μm thick Z-cut quartz

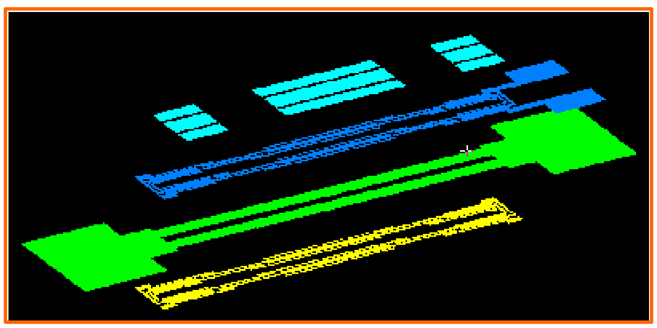


Figure 14. Layout of quartz DETF accelerometer with thin film electrode.

substrate. Its axis is along the Y-axis or mechanical axis. The tines vibrate along the X-axis or electrical axis. The dimensions of the DETF are adjusted to fix the fundamental resonance frequency of in-plane vibration at about 40 kHz. The two ends of the DETF are designed to maximise the quality factor (Q). The high value of Q results from the anti-phase vibrations of the tines, leading to very low loss of energy via the clamped ends due to phase cancellation of vibrations propagating out of the tines[18].

A special electrode structure comprising planar and sidewall electrodes is designed. The electrodes have three segments compatible with the nature of stress distribution along the length of the tines. A seven mask process has been used to fabricate DETF[21]. The definition of planar electrodes and the micromachining of the structure are performed using appropriate photolithographic and etching techniques. Chromium (0.02 μm) and gold (0.2 μm) electrodes were used. The deposition on sidewalls is carried out through silicon stencil masks by angular evaporation. Special arrangement was made for proper alignment of stencil mask on both sides of the substrate. The accuracy of structural definitions and the removal of protruded kinks from sidewalls are the key issues for increasing the value of Q. A typical DETF after fabrication is shown in Fig.15.

A special mechanical device was fabricated to clamp the highly fragile DETF chip at one end and to attach a proof mass at the other end. Necessary

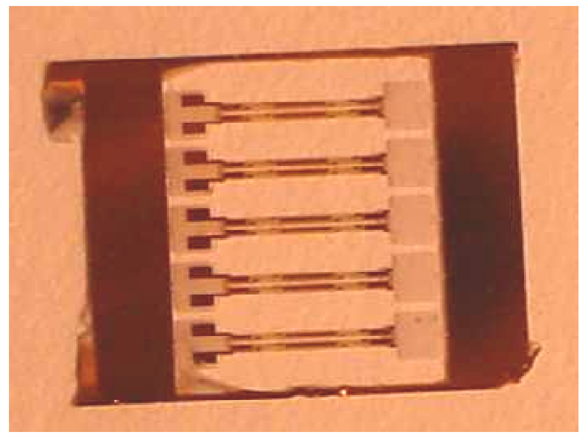


Figure 15. Microphotograph of quartz DETF structure.

protections against lateral movement of the proof mass were incorporated in the mechanical block. This is essential for reducing damage due to vibrations and shock. The DETF was excited by making it a part of an electronic oscillator in the feedback loop. The DETF response was also studied and the Q value was measured using an external variable-frequency source with very high stability. The Q values so far achieved are in the range 7000 to 8000 in vacuum. The frequency change observed is 30 Hz/g. The accelerometer output can be integrated by an OPAMP integrator circuit to obtain velocity.

3.5.2 Dual Tuning Fork GYRO Chip

For gyroscopes, DETF is not needed. Conventional free-tip tuning forks serve the purpose. If the tuning fork is micromachined from quartz, the vibration can be excited and detected by utilising the piezoelectric property. However, the sensitivity of detection is poor, if both the driving and sensing electrodes are deposited on the tines of the same tuning fork. A dual tuning fork configuration was adopted as shown in Fig.16. The two mirror-image tuning forks with a common stem were suspended via two thin flexures or microbridges from two posts or a frame. The microbridges were much thinner than the thickness of stem or tines but relatively wider. The length was chosen considering various design aspects. The entire configuration was micromachined from Z-cut 500 µm quartz substrate with the axis of the tuning fork along Y-axis. The electrodes in the upper tuning fork are in-plane electrodes for driving purpose, and those in the lower tuning fork are suitable for sensing or detection. The critical aspects in the fabrication of the structure are:

(a) accurate definition of the tines with nearly vertical sidewalls and no kinks,

(b) fabrication of thin microbridges symmetrical wrt thickness,

(c) lithographic definition of chromium-gold electrodes which are to pass via the microbridges to the bond pads on the two posts (or frames). Many technical challenges had to be overcome to fabricate such highly fragile structures. The photograph of a fabricated gyrochip at IIT Kharagpur is shown in Fig.17.

For practical use, the gyrochip posts (or frame) are glued to the moving vehicle or body. Both the tuning forks are freely suspended. The upper fork is to be driven into in-plane vibration at the fundamental mode by connecting the driving electrodes in the feedback loop of an electronic oscillator. As the gyrochip rotates around the common axis of the tuning forks, the Coriolis force induces out-of-plane, anti-phase vibrations in the two tines of the upper fork. Since the microbridges are wide but thin, the in-plane vibration of the upper fork cannot be transmitted to the lower fork appreciably because of stiffness in the Z-plane, but the out-of-plane vibrations can be transmitted easily to the lower

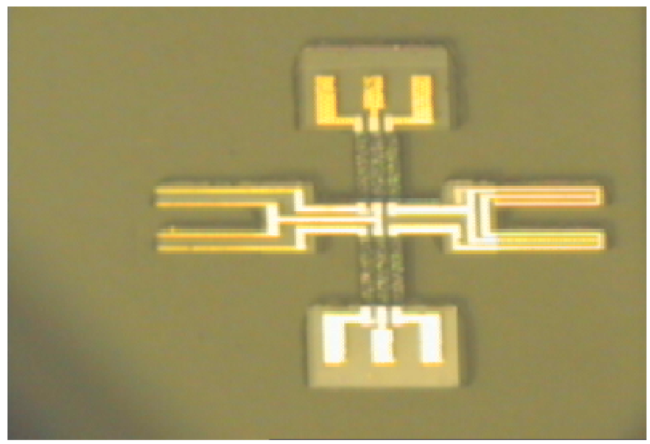


Figure 17. Microphotograph of dual tunning fork gyro chip with electrode pattern.

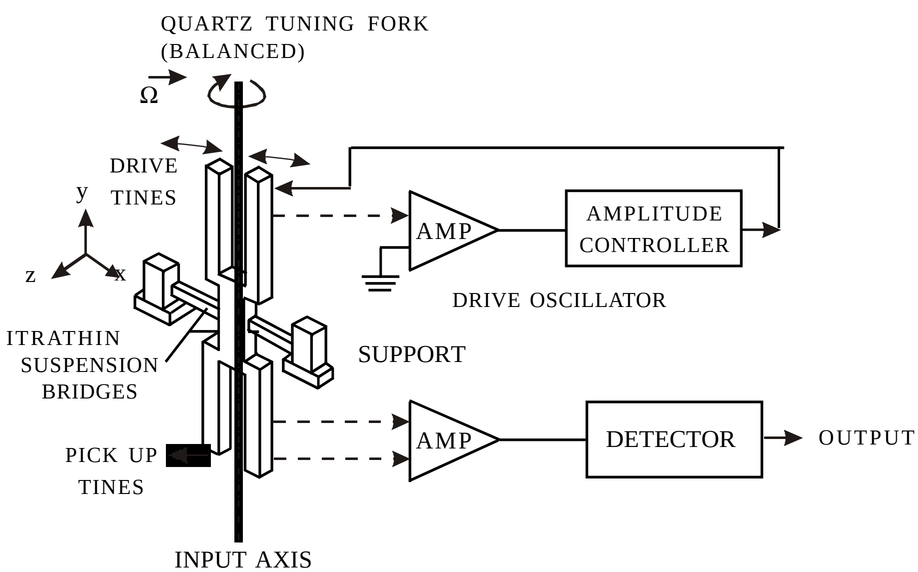


Figure 16. Schematic diagram of dual tunning fork.

fork due to less stiffness offered by the microbridges over the X-plane in the normal direction. Thus, the sensing electrodes on the lower tuning fork will detect the magnitude of out-of-plane vibrations, which is proportional[21] to the rotation rate Ω.

4. CONCLUSIONS

An overview of micromachining and MEMS technologies has been made. IIT Khargpur is involved in research and development work on MEMS and microsensors for the past 15 years. Some of the research works on MEMS sensors have been reported in this paper. IIT Kharagpur is the only institution in India involved in the design and fabrication of quartz MEMS. This study reports the recent work on micromachined silicon and quartz inertial sensors and silicon microthrusters undertaken at IIT Kharagpur. The DETF accelerometer is the first successful quartz MEMS developed in India.

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