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Recent Trends in Smart Technology

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ABSTRACT

Integration of a microsensor, microactuator and intelligent control at one place can provide a miniaturised system. Such devices go under different names, such as smart structures, smart sensors or microelectromechanical systems (MEMSs), etc. The functioning of these systems is analogous to biological pattern of functioning. The sensors gather information, analyse through electronic microprocessors and then actuate accordingly. These devices have applications in medicine, aerospace, automotive and defence systems. Though some systems have been developed, most of them are in the development stage or conceptual stage. This paper presents a review of smart technology and also describes a microflow meter integrated with an optical sensor developed in this Laboratory.

1. INTRODUCTION

The perfect smart structure made by nature is the human body. It has sensors, intelligent control (brain) and actuators. An effort has been made to develop a non-biological system, analogous to biological pattern of functioning. To achieve this target, it is necessary to develop microsensors, microactuators and intelligent control systems and also integrate them. Some of such smart sensors have already been developed and are being used in automobile industries. Japan has made their mark in the world automobile industry and are developing a microcar, as tiny as a rice grain, which could be used as a pipe inspection machine, and also for medical applications by threading through blood vessels. Smart technology is also going to be one of the major technology in weapons systems. These devices will find market in four major sectors, viz., aerospace/defence, automotive, industrial and medical sectors.

Si is now poised to bring another revolution as the base material for micromechanical devices. It has already been proven to be the backbone material of microelectronics. Both the mechanical and the electronics components can be fabricated on the same chip and such systems are known as micro-electromechanical systems (MEMSs). However, Japan, has not been ignoring the semiconductor-based technology, but is trying to find a variety of other materials which can be processed with a semiconductor-based approach. A brief review of smart technology including *Si* micromachining technology has been presented.

2. FABRICATION OF MICRO-MECHANICAL SYSTEMS

Most of the processes used in the fabrication of mechanical sensors are from integrated circuit (IC) technology, including photolithography, oxidation, diffusion, thin film deposition and metallisation. It is difficult to machine *Si* using traditional cutting

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tools, but it can be chemically etched in various shapes. Micromechining of *Si* is used for making a variety of microstructures that are sensitive to stress, strain, temperature and other environments. Micromachining of *Si* can be done either by dry or wet etching in different etchants. Isotropic etching is non directional but anisotropic etchants can be used for directional etchings. The commonly used isotropic etchants are mixtures of HF and HNO_3 in H_2O or CH_3COOH. In anisotropic etching, ethylenediamine pyrocatechol (EDP), KOH or hydrazine, ($H_2N.NH_2$) are used. These etchants have different etch rates for different crystal orientations of *Si*. The *p-n* junctions are also used to obtain a thin diaphragm by using etch-stop technique at the time of etching.

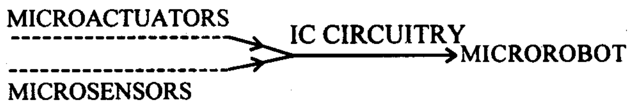
Si micromachining is of two types: (i) bulk micromachining, and (ii) surface micromachining. Bulk micromachining can be used to fabricate groves, probe sieves, channels and beams. Surface micromachining is used to fabricate micromotors[1], microturbines, gears and valves[2]. In surface micromachining, a sacrificial layer, usually of SiO_2, polyimide or phosphosilicate glass (PSG) is deposited on *Si* wafer. Required structures are formed by photolithography in this sacrificial layer before depositing the polysilicon layer. Later, the sacrificial layer is removed by chemical etching and this provides a free-standing, physical structure of polysilicon on *Si*.

2.1 Lithography, Electroforming & Micromoulding Process

The distinct advantage of lithography, electroforming & micromoulding (LIGA) process[3] is its ability to create three-dimensional structures as thick as bulk micromachined devices. It constitutes three basic processing steps: (i) lithography, (ii) electroplating, and (ii) micro-moulding. It starts with a thick photoresist coating between 300-500 μm on a conductive plate. Patterning is done through long exposure of highly collimated X-ray radiation from a cyclotron. The desired structures are formed by developing the exposed structures. Metal is subsequently electrodeposited on the exposed conductive area of the substrate. The metal structure is ready after removal of the photoresist. This structure can also be used as a mould for duplicating the microstructure.

2.2 Miniaturisation

Small size of mechanical components of the system is a very distinctive feature of this emerging technology. The possible fabrication of microactuators and micromechanical parts by IC based micromachining technology can provide microminiature systems.



The smart technology has three features: (i) miniaturisation, (ii) multiplicity, and (iii) microelectronics. In these systems, miniaturisation is essential but single device can only produce small force or perform simple motion. Therefore, an array of microdevices is added to produce a real practical motion. It is just like the joint work of many living beings, like a swarm of ants that can carry a big piece of food. Motion like that of an insect can be performed by connecting many microsystems in-parallel, and in-series. In biomedical applications, a microsystem becomes a building block like a cell in our body.

2.3 Microsensor

The IC processing semiconductor technology combined with micromachining can develop sensors to sense machanical, optical, magnetic, chemical, biological or any other phenomena. The output of such sensors can be measured in many forms like piezoresistive, capacitive, piezoelectric and photovoltaic, etc.

2.4 Microactuators

The technology is well-established for sensors and microelectronics but has recently started for microactuators. An actuator is a transducer which performs some action. Various *Si* actuation methods are being developed that are compatible with *Si* IC processing technologies. *Si* actuators are like diaphragms and beams which provide displacement or force through mechanical deformation. Microactution is generally done either by electromagnetic or thermal methods. In bimetallic method, the thermal expansion coefficient mismatch between the material components of actuator is used to generate action force. The other types of microactuators are developed by electromagnetic, electrostatic, piezoelectric or magnetic actuation methods. Micropumps and micromotors have been developed by electrostatic actuation method.

The system developed by Ataka, *et al*[4]. gives an understanding of the working of microactuators. Here, instead of making a single microactuator, an array of microactuators has been made. The idea is to coordinate simple motions of many actuators in order to perform a practical task and to obtain a real motion up to a few micrometers. It is also known as distributed micromotion system (DMMS). It proposes a ciliary motion system (CMS), that mimics the function of cilia in living organisms.

2.5 Signal Processing

Signal processing is a connecting link that deals with an input signal of the sensor in such a way that the desired network information is made available. This is conversion of signal, by other processes, into an output signal which causes desired action by the actuator.

3. MICROELECTROMECHANICAL SYSTEMS

3.1 Ciliary Motion System

CMS suggested by Ataka, *et al*[4]. consists of two layers of polyimide having different thermal expansion coefficients and a metallic microheater sandwitched between them. Polyimide with higher thermal expansion coefficient and lower thermal expansion coefficient are coated at the top and bottom of the heater, respectively (Fig. 1).

In the initial stage, it curls up above the substrate without heating because of the difference of residual stress of two polyimide layers, but on

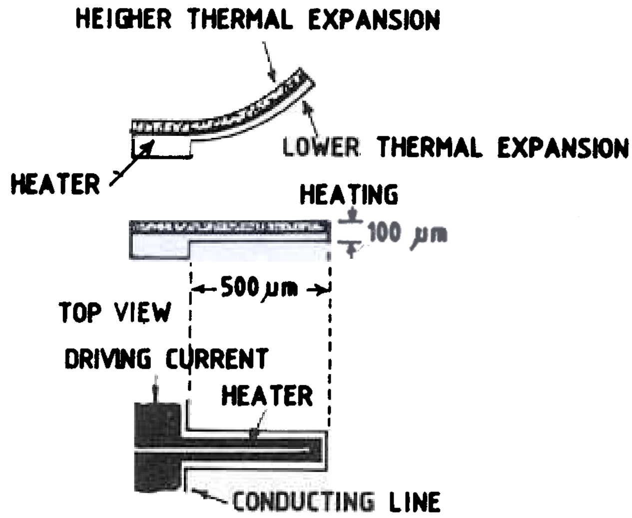


Figure 1. Cross-section of thermally driven cantilever actuator made of polyimide.

heating, it flattens just like a bimetal. The details of its fabrication and other characteristics are discussed. When the cantilever was heated by flowing current in the heater, it moved downwards from its original position and vibrated in the vertical direction with double the frequency of input sinusoidal current. Resistance of each heater was 30-40 ohms and about 25 mA could be supplied without damaging polyimide by overheating. They have also made an array of CMS of 512 elements on a 1 cm^2 substrate and observed its motion on applying a load (a *Si* piece of 2.6 x 1.5 x 0.26 mm^3 size and 2.4 mg weight). They intend to integrate CMS with sensors and logic circuits into one module. This will enable CMS to control its motion by itself.

3.2 Infrared Focal Plane Array Based on Micromachined Bolometers

The ability to 'see at night' has been the subject of research for the last many decades. Various types of thermal imagers, ranging from electron tubes to array of *HgCdTe* detectors, have been developed. These infrared (IR) imagers have created a revolution in defence capabilities. Present-day IR imagers use cryogenic coolers, complex IR optics and expensive IR materials. A second revolution is now underway due to the development of *Si*

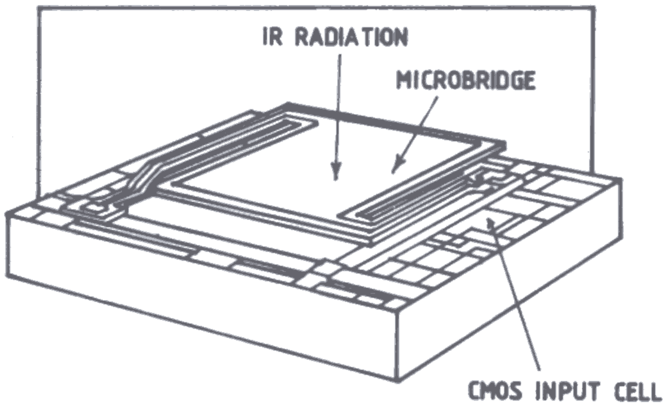


Figure 2. Microbolometer focal plane array

IR-sensitive focal plane arrays(FPA), which do not require cooling and are also quite cheap.

There are two types of IR detectors, quantum detectors that rely on the interaction of individual photons with electrons in the detector material itself, and thermal detectors that measures the change in temperature due to the absorption of heat energy. In quantum detectors, incoming photons bounce the electrons from valency to the conduction band across the energy gap. In these detectors, band gap of the semiconductor material defines the wavelength which can be detected by a particular material.

3.3 Thermal Detectors

Like quantum detectors, thermal detectors are also of different types like thermopile, thermocouples, pyroelectric detectors and bolometers. Bolometers are perhaps the most versatile thermal detectors. In these, the resistance of the absorber varies with temperature. The microbolometer arrays are beginning to have an impact on IR-sensing technology for the past few years (Fig. 2). Microbolometers have much higher responsivity than thermopile detectors.

The performance of a bolometer detector is characterised by factors like temperature coefficient of resistance (TCR), responsivity (R_v), and detectivity (D^x)

$$\text{TCR or } \beta = R^{-1}\frac{dR}{dT}$$

$$R_v = \frac{I_b R \beta \eta}{G\sqrt{1+W^2\tau^2}}$$

where

I_b	Bias current
R	Resistance
η	Absorbivity of IR sensitive film
G	Thermal conductance
W	Modulation frequency
D^x	Detectivity $= \dfrac{R_v\sqrt{A\Delta f}}{V_n}$
β	Temperature coefficient of resistance
T	Temperature
A	Effective area of detector
f	Bandwidth of the signal
n	Noise voltage

Hence, a good detector should have low noise, large β and R_v to have high detectivity (D^x).

A wide-range of micromachined *Si* sensors have been demonstrated. There are microbolometers fabricated by micromachining *Si* having thermal isolation 1×10^7 C/W close to the attainable physical limit (10^8C/W for a 50 µm^2 sensors). In these bolometers, a typical incident IR signal of 10 nw can increase the microbolometer temperature by 0.1 °C, an easily detectable temperature.

A typical microbolometer design consists of a 0.5 µm thick plate suspended clear of the underlying *Si* by two 'legs' that provide the required high thermal resistance between the suspended plate and its surroundings, allowing the plate to respond to incident IR radiation by getting warmer or cooler. Compact portable uncooled IR cameras have been demonstrated by Honeywell, USA. The spacing between the pixel and the substrate was selected to maximize the absorption in the range 8-12 µm wavelength. Good thermal isolation is achieved by a microbridge structure formed by etching of *Si*. In this resistive bolometer, change in pixel temperature is detected by a thermoresistive element. A detector material with high TCR, defined as I/R dR provides maximum sensitivity to the thermal variation in the detector. It has been seen that metal films make the best bolometer detectors. Recently, a semiconductor film of 500 Å thickness, having TCR significantly higher than metal films, has been developed. It has low $1/f$ noise. The pattern of the thin film to form detectors is done using standard photolithographic technique for individual pixel. The combination of high TCR material and the microbridge structure has resulted in pixels with a responsivity of 7×10^4 V/W in response to 300 K black body radiation. The responsivity is sufficient to yield arrays with less than 0.1 °C noise equivalent temperature difference (NETD) with a $f/1$ lens. Further improvements in the readout electronics design, pixel structure and materials, may bring NETD close to 0.040 K.

Based on this technology, Honeywell[5], USA and NEC, Japan[6] have developed IR camera which requires no cooler. Honeywell approach is a monolithic one in which V_2O_5 resistive material is deposited as thin film on *Si* microstructure containing transistor switches at each pixel while NEC has made the 128 x 128 pixel IR FPA which employs *Ti*. The device is monolithically integrated with a *Ti* bolometer detector over a complementary metal oxide semiconductor (CMOS) circuit readout. They have achieved NETD 0.09 °C wih an $f/1$ lens. The fabrication process is compatible with *Si* IC process.

3.4 Microrobotics Self-Running Machines

Microrobotics is another area, which is also in the developmental stage using this technology[7-9]. Several small models such as travelling machines, swimming microrobot in water and flying microrobot have been proposed. Flying machine is very attractive because it is free from surface-to-surface friction and can thus move freely in space. In fact, in all movable microstructures, friction is a serious problem. Friction is proportional to the surface area and becomes dominant when compared to other forces. In conventional robots, it is usually referred to the human model because the size of the robot is equivalent to that of a human. But for microrobots, insects are a better model. Insect structure which includes sensors, actuators and control systems is small and simple. The motion of insects is produced by a simple mechanism, such as reflection. These insects exhibit many interesting features, including external skeleton, elastic hinge and contracting-relaxing muscles.

There are three major problems in a microflying machine:

- Cableless power supply
- Control without contact guide
- To produce lifting force larger than gravitational force

Two principles govern flying using wings. First, by using drag generated by flapping of wings as in insects, another like an aeroplane, Arai, *et al*[7]. made small flying machine driven by magnetic film as wings and a soft magnetic wire as a body (Fig.3) The flapping of wings are due to torque generated by magnetic field. There are hings in the wings, which generate different drag during up and down strokes and produce lifting force. The small flying machine flew like a butterfly or a mosquito, without any power supply but only in the field limited area.

4. MICROFLOW METER INTEGRATED WITH AN OPTICAL SENSOR

It is extremely difficult to make microstructures and integrate them. To start this work, a microflow meter has been designed and fabricated in this Laboratory. Many systems have been made to measure the flow of the gas. The most commonly used method is to put a hot wire in stream of the gas with a constant heating power and measure the change in the temperature of the wire as a function of the flow, or alternatively, keep the wire at a constant temperature and measure the power required to do so. These conventional hot wire flow meters of metal filament are usually bulky and power consuming. Due to large thermal mass, the response time is very large, of the order of several seconds. *Si* micromachining technique has been used succesfully to generate devices in which

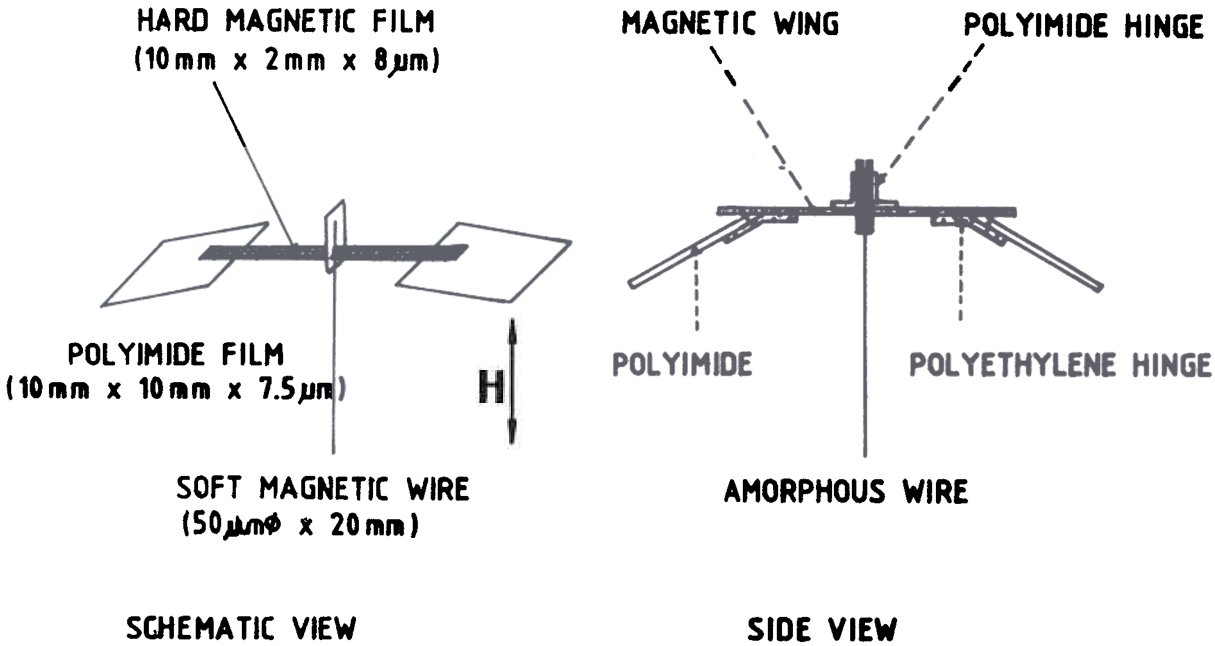


Figure 3. Flying machine

a small, thermally isolated area acts as a sensitive part. The whole system is miniaturised and made in *Si*. In 1988, Tai, *et al.*[10] suggested a new design of a polysilicon bridge (Fig. 4) as a flow meter, which can be made by surface micromachining. In this bridge, the central portion is lightly doped but heavily doped on both the sides with the impurity. The heavily doped portions provide both thermal isolation and a low resistance path for electrical conduction. It is possible to operate this flow meter at a very low d.c. power level. The lightly doped central region in this bridge is 1.9 μm long and the gap between the wire and substrate is 3 μm.

Johnson and Higashi[11] have fabricated a highly sensitive air flow microtransducer. Due to very high thermal isolation in device, the responsivity is very high. In such structures, disadvantage is due to the measurable flow velocity which is relatively small. Recently QIU, *et al.*[12] have found a solution to this problem by integrating a heat sink and flow guide, which modifies the temperature distribution of the diaphragm and also enhances range of flow velocity.

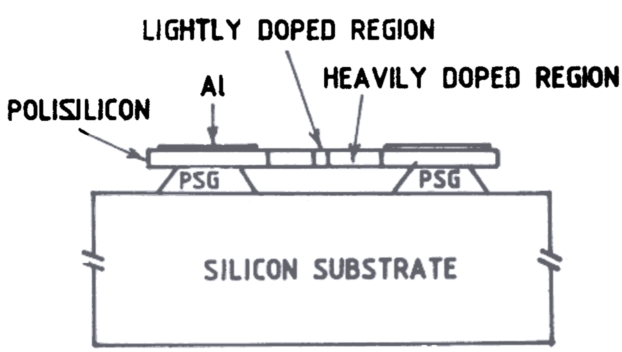


Figure 4. Cross-section of a lightly-doped polysilicon bridge

4.1 New Type of Microflow Meter

Due to the development of fast computing, the measurement of flow of the gas by flow meters, based on the hot wire system, is not adequate. Some method, fast enough to couple with fast computing should be devised. Also needed is the development of a smart system which can measure the flow of the gas and also control the input flow of the gas automatically. A new type of microflow meter has been developed in this Laboratory, which is integrated with an optical sensor and a control circuit (Fig. 5). Bulk micromachining is used to fabricate this microflow meters. It is small in size and has fast response time in microseconds because of the optical sensing system.

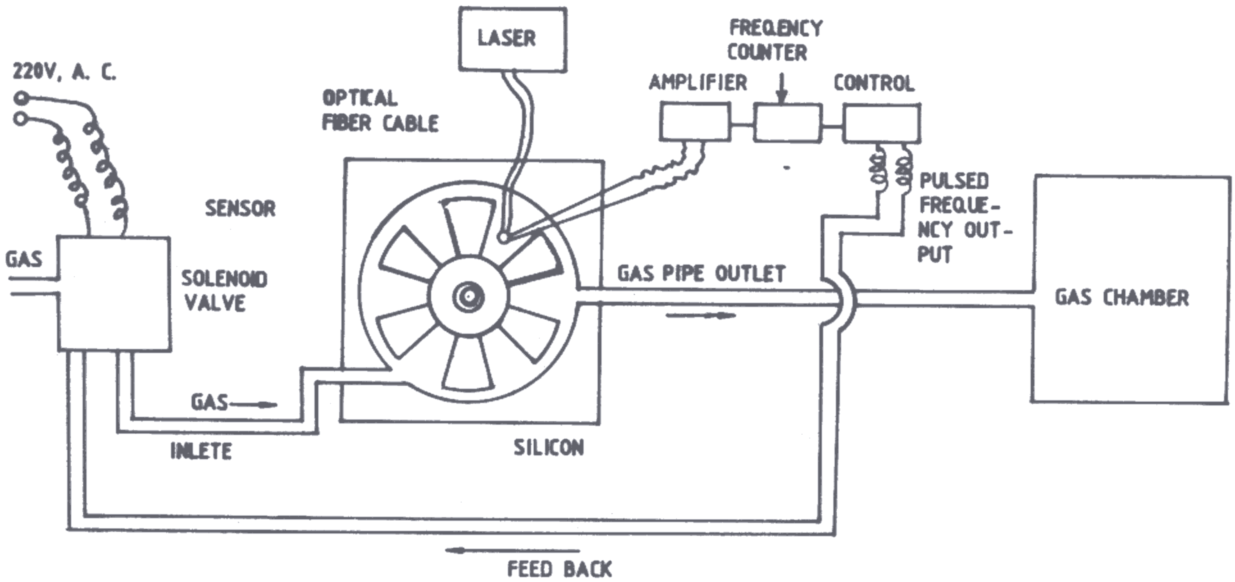


Figure 5. Microflow meter

4.2 Fabrication of Microair Turbine

The complete microair turbine of 2000 μm radius has been generated on *Si* chip by bulk micromachining technique. The rotor has six blades of 60 μm thickness. It can rotate at a speed of 40,000 rpm with the help of air jet. The rotor has a hole of 110 μm radius in the centre and is placed on a *Si* post of 100 μm radius and 150 μm height, just at the centre of the *Si* cavity. The system is housed in the *Si* cavity, about 200 μm deep in *Si* wafer. *Si* cavity also has two channels of fine metallic tubes for inlet and outlet of the gas. The entire system is sealed by placing a quartz plate cover over the cavity.

4.3 Integration of Optical Sensor

An optical sensor is generated in the cavity of *Si* substrate, which is a *p*-type, with a resistivity of 1 ohm cm. and (100) orientation. This sensor is of 200 μm radius and positioned at a distance of 1500 μm from the centre of cavity. It has been fabricated by following many processing steps (like oxidation, diffusion, photolithography and metallisation) used in making a solar cell. It is a photovoltaic cell and a contact from top and backside of the wafer provides the required photovoltage during illumination by light. The connections from the top contact has been taken from the extended metal contact.

4.4 Working of Optical Sensor System

The optical sensor in the turbine is illuminated by d.c. light emitting diode (LED). When the rotor rotates, the optical sensor gives a.c. signal i.e. in the form of frequency due to chopping of the incident light. The pulse counter gives the exact number of pulses and the oscilloscope gives the shape of the pulses. The number of pulses are corelated with the flow of the gas. If the flow increases, the number of pulses also increase.

4.5 Mechanism of Air Turbines

In most of the moving mechanical systems, the bushings and bearings are the two parameters responsible for effective motion. Similarly in the air turbine, air cushions and air bearings are responsible for effective rotation of air turbines at high speeds with least friction encountered during rotation of the top cover plate. The design of the air cushion and air bearing is considered while designing the stator and rotor. The centre post of stator is 500 μm in diameter but while etching isotropically up to a depth of 150 μm, the centre post gets tapering shape. The 10 μm gap between the surfaces of centre post and circular hole of rotor acts as air bearing, when a jet of air is applied to input channel of well. Both input and output channels in the well are designed in such a manner that air gives thrust to rotor tangentially at the curved tips of blades, and passes out through the output channel, giving motion to rotor. But at the same time, part of the air which has deviated from output channel and has passed inside bending along the circular wall of well underneath rotor, helps lifting the rotor upwards. Thus the rotor is always kept above the surface of stator and also momentarily comes in contact with the centre post continuously under rotation, as long as air is there which provides a constant source of propulsion. This is the mechanism of its rotation at such high speeds inspite of its high inertia.

The new microflow meter, integrated with an optical sensor has a response time in microseconds instead of milliseconds. This flow meter besides measuring the flow of gas also controls its input flow. The overall size of the microflow meter chip is 10 x 10 x 0.3 mm^3 with metallic nozzles attached to its channels and an extended ohmic contact of optical sensor. The flow sensitivity is 4 cc/min. This flow meter has a large number of industrial applications.

5. CONCLUSION

A smart or MEMS is a combination of microactuator, intelligent control and microsensor, all at one place. A microflow meter integrated with an optical sensor based on microturbine principle is developed here on *Si* chip. It can measure the flow of the gas and can also control the input flow. The system has very fast response time. Only a few systems have been discussed here, but these have numberless applications. Although, it is doubtless if any area of science or technology will escape from their impact, but there is a lot to be done.

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