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Microsensors Based on MEMS Technology

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ABSTRACT

Sensors play an important role in most of the common activities that occur in our daily lives. They are the building blocks of or microelectromechanical systems (MEMS). This combination of micromechanical structures, sensing elements, and signal conditioning is the beginning of a new era in sensor technology. Sensing systems incorporated with dedicated signal processing functions are called intelligent sensors or smart sensors. The present decade of new millennium will be the decade of smart systems or MEMS. The rapid rise of silicon MEMS recently was due to major advances in silicon microfabrication technology, especially surface micromachining, deep-reactive ion etching, and CMOS-integrated MEMS. In this paper, an overview of the currently available MEMS sensors, materials for sensors and their processing technologies, together with integration of sensors and electronics is presented.

Keywords: Microsensors, microelectromechanical systems, MEMS, micromachining, signal processing, smart sensors, micromechanical sensing, smart structures, silicon microfabrication

1. INTRODUCTION

The emergence of microelectromechanical systems (MEMS)[1-15] in the present decade is considered as a major technology breakthrough since the invention of transistors. It is a combination of traditional silicon integrated circuit (IC) electronics with micromechanical sensing and actuating components. MEMS are considered as building blocks for complex microrobots performing variety of tasks and are used to make systems which function very close to biological systems existing in nature. With IC technology, MEMS can be mass-produced resulting in low costs. The other advantages of MEMS are small size, low power consumption, lightweight, and small volume. Fabrication of MEMS involves development of smart structures, which communicate via feedback in closed-loop systems. A smart structure senses a change in the environment and responds by changing one or more of its property coefficients. It tunes its response function in time and space to optimise behaviour. This requires merging computation with sensing and actuation into integrated micro-level systems that interact with the physical world. Most MEMS processes can be broken down into a repeating series of steps for metal deposition, patterning, realisation of released structures, dicing, packaging, testing and require the most advanced manufacturing line. Materials for MEMS include traditional microelectronic materials (e.g., Si, SiO_2 silicon nitride, polyamide, Au and Al) as well as non-traditional ones (e.g., ferroelectric ceramics, shape memory alloys, and chemical-sensing materials). The superior piezoelectric and pyroelectric properties of ferroelectric ceramics make these ideal materials for microactuators and microsensors. Microsystems

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are designed and fabricated by integrating different microcomponents into one functional unit comprising sensors, actuators, ICs for data processing, etc. In this development, a variety of micromachining technologies, ranging from the conventional silicon bulk and surface micromachining to LIGA and LASER techniques are employed, each one having specific advantage or merit for a specific product. Another process useful for MEMS application is substrate bonding. Silicon, glass, metal and polymeric substrate can be bonded together through several processes like fusion bonding, anodic bonding, eutectic bonding and adhesive bonding. Substrate bonding helps in achieving a structure that is otherwise difficult to form e.g., hermetically sealed large cavities, a complex system of enclosed channels or simply to add mechanical support and protection.

2. SMART SENSOR AND SILICON MICROMECHANICS

A sensor is the part of a data acquisition system (DAS), which in turn is a part of an electronic measurement, and control system. The DAS is designed to acquire information and to transform this data into a format suitable for manipulation in the data processor. A microprocessor is typically used for this, so analog-to-digital (A/D) conversion is required. The analog functions to be implemented in the signal processing part are highly sensor-specific which bring up the idea of realising the complete DAS on the same material carrier (silicon chip). Such a device is known as an integrated silicon smart sensor and provides a signal uncorrupted by non-idealities of the basic sensing element.

Many types of sensors and actuators are used in smart microsystems. Typical sensors consist of strain gauges, silicon cantilever-based accelerometers, optical fibres, piezoelectric films, and piezoceramics. Typical actuators consist of piezoceramics, magnetostrictives, electrostrictives, and shape memory alloys. Piezoelectric materials have proved to be the best for sensors and actuators in smart structures. Figure 1 shows the model of a smart sensor.

The on chip integrated smart sensor fabricated on silicon has the following main features.

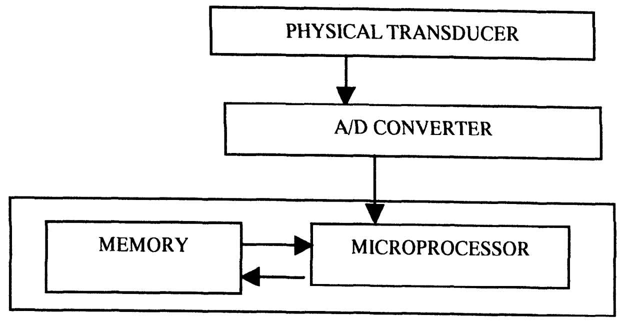

Figure 1. Smart sensor model.

Table 1. Comparison of properties of steel and silicon

Parameter	Steel	Silicon	Unit
Yield strength	2.1	7.0	(10^9 N/m^2)
Young's modulus	2.0	1.9	(10^9 N/m^2)
Density	7900	2330	(kg/m^3)
Thermal conductivity	46	157	(W/m K)

- Excellent mechanical performance of silicon[6], high strength, lack of hysteresis and high sensitivity to stress (Table 1).
- Silicon as a sensor material also shows transduction effects that are used to realise special types of sensors such as spring deflection sensors and piezoelectric sensors.
- Silicon can be micromachined into various mechanical structures such as

  Static: Nozzles, cavities, capillary columns, electrical connectors.

  Dynamic: Membranes, microbridges, cantilevers, and resonators

  Kinematic: Micromotors, microgears, pinjoints, springs, cranks, sliders.

Most common sensing technologies are piezoresistive, capacitive, and piezoelectric. Pressure sensors, strain gauges, vibration sensors, and gyroscopes have been made using these techniques.

3. SENSOR DESIGN AND SIMULATION

Various software packages are available to design and simulate the sensor performance. These tools are useful for improving the device performance with fewer fabrication trials, reduce development time, manufacturing costs, and to develop manufacturable device with higher yields. These packages provide fabrication database for creating 3-D solid models by defining process steps. An accurate model is generated because geometry and material information are based on the actual fabrication process. Material database is available which incorporates research data of various researchers. MEMS-specific CAD tool can be used to optimise device performance and determine static and dynamic effects[16, 17]. It is possible to do electrostatic, mechanical, and thermal analyses of sensors.

Real world mechanical behaviour is often the result of several physical factors acting simultaneously. Since MEMS devices have different forces acting on, one needs software, which can handle these forces efficiently. Mutiphysics software allows engineers to simulate device behaviour when these multiple physical factors interact. These multiphysics software generally have different modules like mechanical, electrostatic, electromechanical, fluidic, thermal, etc. Some software have MEMS- specific modules like mask, fab, anisotropic etching, etc. ANSYS (www.ansys.com), Intellisuite (http://intellisense software.com) and ALGOR (www.algor.com) are some of the software used for MEMS devices modelling and simulation.

Crystal orientation-dependent anisotropic etching is a phenomenon in which the etching rate of a single crystal differs substantially with the crystal orientation[6, 7]. AnisE (http://intellisensesoftware.com) is an easy-to-use anisotropic etch process simulation tool for MEMS design. Figure 2 depicts the simulated structure using a square mask on a <100> silicon wafer. Figure 3 shows the simulated picture of a membrane under pressure.

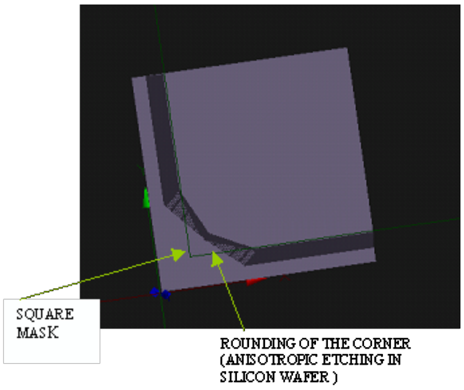

Figure 2. Simulation with AnisE module.

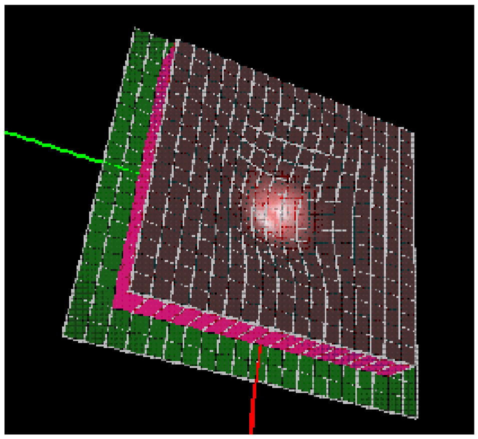

Figure 3. Simulation of membrane under pressure with MEMS design software.

4. MICROFABRICATION TECHNIQUES

Many of the microfabrication techniques and materials used to produce MEMS have been borrowed from the IC Industry[6]. The field of MEMS has also driven the development and refinement of other microfabrication processes and materials, not traditionally used by the IC industry. Two important fabrication techniques are described:

4.1 Micromachining

Fabrication of silicon micromechanical devices involves controlled selective etching[6] as the main processing step. Wet chemical etching using various chemical etchants, as well as advanced dry etching techniques are used. Micromachining can be divided into two main groups: (i) bulk, where the structures are etched in the substrate, and (ii) surface, where the micromechanical structure are formed from layers deposited on the surface. The latter makes it possible to include electronics on the same chip. To achieve this, a micromachining process has to be combined with a CMOS or bipolar process without influencing the characteristics of the electronics devices. A single postprocessing etching step is introduced to form free-standing micro-structures on a CMOS IC for producing micro-mechanical sensors for signal conditioning. Polysilicon microbridges, sandwitched oxide microbridges, and cantilevers are produced using this technique.

The etching capabilities of silicon have changed drastically with the advent of currently available deep reactive ion etching (DRIE) tools. DRIE, a dry etch process, patented by the Robert Bosch Corporation, can be used to etch deeply into a silicon wafer while leaving vertical side walls and is independent of the crystallographic orientation. This unique capability has greatly expanded the flexibility and usefulness of bulk micromachining. The deep silicon etching machines developed can easily achieve etching rates in excess of 3 m/min, selectivities to photomasking materials > 70:1, excellent profile control, and non-uniformities across the wafer of 5 per cent or less.

The combination of DRIE and deposition processes, such as LPCVD polysilicon and silicon dioxide, can be used to create micromolded structures.

4.2 Wafer Bonding

Various bonding techniques, e.g., fusion, eutectic, and electrostatic bonding, have been developed for fabrication of ICs. The demand for small, low cost, and reproducible sensors and actuators has lead to the use of the silicon IC technology for the realisation of these devices. Micromachining, thin film deposition, wafer-to-wafer and silicon-to-glass bonding processes[18-20] have been developed for the realisation of sensor and actuators systems. By making these processes compatible to silicon IC processing, MEMs have been developed.

Mirror-polished, flat and clean silicon wafers, when brought into contact at room temperature are locally attracted to each other by van-der-waals forces and adhere or bond to each other. The bonded area spreads within a couple of seconds over the whole wafer area. There are three main types of interface forces: Van-der Walls attraction, electrostatic (Columbic) attraction, and capillary forces.

Fusions, eutectic, and anodic bondings are main bonding techniques used now a days. These bonding processes operate under two basic conditions. First, the two bonding surfaces must be flattened to have intimate contact for bonding. Second, proper processing temperature, pressure, and voltage are required to provide the bonding energy.

The conventional silicon-to-silicon fusion bonding process takes place at a bonding temperature of > 1000 °C. According to the fusion bonding principle, flat surfaces, hydrophilic surface treatment, sufficient high bonding temperature, and reasonable bonding time will give useful results.

Anodic bonding, on the other hand, is performed at a much lower temperature, of about 300-600 °C with the assistance of high electric field. Intermediate layer thermal bonding resembles direct fusion bonding except that an additional layer is deposited to lower the annealing temperature of the bonding process. The silicon-aluminium eutectic state occurs at 577 °C and silicon-gold eutectic occurs at 370 °C. These are the lowest bonding temperatures for these types of systems. In fusion bonding technique due to the high temperature requirement, temperature-sensitive materials and ICs will be damaged or degraded during the bonding processes. Therefore, high temperature bonding processes are not applicable in fabricating or packaging where temperature-sensitive materials are used. Therefore, efforts have been made to find a reliable bonding process that can be conducted at low temperatures. These bonding processes depend mainly on the bonding material, surface treatment, and surface flatness.

Physical processes involved in the two main low temperature-bonding techniques developed are discussed below:

4.2.1 Anodic Bonding

This technique[20] is used for silicon-to-glass bonding. The two surfaces are brought into contact in a furnace and electric field is applied. At an elevated temperature, Na^+ ions in the glass become so mobile that these are attracted towards the cathode as a result of the applied voltage. This leaves behind relatively immobile oxygen anions at the glass side of the silicon-glass interface, at which a space-change region is formed. This in turn creates an equivalent positive charge (image charge) on the silicin-side of the silicon-glass interface resulting in a high electric field ~ 106 V/cm across the Silicon-glass interface. Under the high field, oxygen anions are drifted away from the Na^+ depletion region to the silicon surface. As this happens, oxidation of silicon by the oxygen anions is presumed to occur and a thin oxide layer is formed at the interface, which contributes to the migration of the bonding front. However, at small applied voltages, i.e., at reduced electric field, the oxygen anions cannot sustain a high oxidation rate at the bonding front of the silicon-glass interface, thus a larger bonding time is required. Since the bond occurs at temperature higher than the ambient temperature, special attention is needed to avoid warping and undesired stray stresses at the interface, which can lead to fracture. Ideally, the glass and substrate should have matched thermal expansion coefficients. For bonding to silicon substrate, corning glass 7740 offers the closest match. This glass can be sputtered on any other substrate, allowing the anodic bonding of various types of substrates.

4.2.2 *Thermal Bonding using an Intermediate Layer*

In anodic bonding, the glass-substrate interface experiences high electric fields that can damage active devices, thermal bonds are desirable when these fields can affect the performance of these devices. Here, formation of the *Si-Al* alloy at the eutectic temperature is used to bond the *Si* wafer to glass. A thin aluminium film on top of the glass is evaporated in vacuum for this purpose. Metallised glass and silicon surfaces are brought under intimate contact at elevated temperature and pressure. The diffusion of aluminum in silicon at elevated temperature gives rise to formation of alloy that bonds the two surfaces together. No electric field is required for this purpose. This type of bonding is commonly used for bonding of sensors to packages.

Table 2 summarises various bonding techniques. Wafer bonding is also being investigated as a means to integrate other materials and to combine micromechanical structures with microelectronics.

5. INTEGRATION OF CMOS AND MEMS FABRICATION PROCESS

One of the key challenges in micromachining process is combining the electronic devices with the mechanical, optical or chemical function of the MEMS device. Earlier, a hybrid approach was used in which the MEMS device was fabricated independently of the interface electronics, however, presently there are several examples of integrated sensors and other devices being fabricated. There have been several approaches for combining CMOS

Table 2. Wafer bonding technique

Bonding technique	Material	Surface treatment	Temperature (°C)	Time	Comments on bond
Anodic bonding	*Si*/7740 Pyrex glass	Clean	350-450 °C (500-1000 V)	~1-10 min	Uniform, reliable hermetic bond formed
Silicon-silicon	*Si-Si* SiO_2 –*Si* and SiO_2 –SiO_2	Hydrophobic Hydrophilic	500-1100	h	Difficult to avoid voids unless processed at higher temperatures
Borosilicate glass	*Si*/SiO_2 and Si_3N_4		450	30 min	--
Eutectic	*Si-Au*-SiO_2	Clean and oxide-free	350	--	148 MPa/ Non-uniform bonding area
Solder	SiO_2 – *Pb*/*Sn*/*Ag*- SiO_2	Needs solder flux	250-400	min	Large difference in thermal expansion coefficient can lead to mechanical fracture
Glass frit	SiO_2- glass *Ag* mixture-SiO_2	Clean	~ 350	< h	Difficult to form thin layers

circuits with MEMS structures[21, 22], summarised as follows:

- *Post-processing*: Protecting the CMOS circuit with a chemically resistant film and carrying out the micromachining after the circuits are complete and avoiding any high temperature steps.
- Combined processing integration in a custom MEMS /CMOS process or utilising the CMOS layers themselves for MEMS devices.
- Pre-processing etching wells in the wafers of a depth equal to the total height for the formation of the MEMS device. Fabrication of MEMS devices and protection with an encapsulation layer that is planar with the silicon surface CMOS circuit fabrication then follows, and removal of the encapsulating film releases the MEMS structure.

6. PRESENT/PROSPECTIVE APPLICATIONS OF SMART SENSORS/MEMS

Micromechanical devices are increasingly finding applications in a number of fields like automobile, civil, and military aviation, biomedical, robotics, manufacturing control, etc. Market outlook for MEMS is quite strong. Accelerometers for automobile industry are being mass-produced for use in airbags during a crash and for active suspension control. Another important use is in vibration monitoring of rotating machinery. Microscopic pressure sensors embedded in automobile tyres have led to huge savings in oil. Tiny blood pressure sensors[23] are popularly used in many medical applications. Piezoelectric acoustic sensors are designed for both audible and high frequency sensing and have use in hearing aids. An IR focal plane array (FPA) of microbolometers with read out electronics on monolithic silicon chip is an important application in night vision devices[24,25]. MEMS technology is able to provide probe tips close to atomic dimensions integrated with sense and drive electronics for the probe of an atomic force microscope. The miniaturisation of a complete microsystem represents one of the greatest challenges to the field of MEMS. One well-known example of a chip-scale microsystem is the ADXL50 accelerometer by Analog Devices Inc. This is a closed-loop microsystem where capacitive displacement detection is used to measure the motion of the proof mass, integrated circuit to determine the voltage necessary to balance initial motion and electrostatic actuators to control the position of the proof mass.

Microfluidic systems[26, 27] constitute the majority of present microsystem efforts due to their broad applicability, particularly as biochemical analysis systems. There have been increasing interaction between MEMS and microfluidic world. Researchers have been working to integrate not only fluidic elements but also electrical, optical or other types of elements into microfluidic devices. The ability to electrically control fluid flow in micromachined channels (i.e., pumping and valving) without any moving parts has enabled the realisation of micromachined complex chemical analysis systems. Sensors integrated at the end of the flow channel can reveal a time-domain spectrum of the fluid composition. With multiple independently controlled fluid flow, complex sample preparation, mixing and testing procedures can be realised. Micromachined electrophoretic devices[28] have been used to separate ions and DNA molecules in few minutes–much faster than the conventional macroscale capillary electrophoresis systems.

The MEMS technology has many promising RF/microwave applications[29]. There is recurring demand for flexible, lightweight, and low-power wireless systems. MEMS technology can drastically reduce manufacturing costs, size, weight, and improve performance as well as battery life of these systems. Some of the applications include wireless handsets for messaging, wireless internet services for e-commerce, and wireless data links. RF MEMS technology promises to enable on chip switches with zero standby power consumption, high quality inductors, capacitors and varactors, and high performance filters operating in the tens of MHz to serval GHz frequency ranges.

Futuristic applications of MEMS include: Embedded sensors in aircraft skins[30], jet engines and onboard systems for continuous monitoring of stresses, temperature histories, pressure and other parameters resulting in on condition maintenance practice. *In situ* sensors and analysers for continuous monitoring of internal engine parameters such as air flow rates and turbulence. Defence applications include MEMS-based guidance systems built into projectiles and air-dropped weapons. In the near future, smart sensors and MEMS may also play a significant role in space missions.

Therefore, potential exists in smart sensors based on MEMS to establish a second technological revolution with an impact on society that exceeds that of IC industry.

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