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OVERVIEW OF MEMS SENSORS AND ASSOCIATED ASPECTS

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Abstract

MEMS technology is pervading in all domains ranging from commercial to strategic sectors so it is imperative that application oriented development encompassing fabrication, characterization, assembly and packaging aspects to be looked into to get the reliable product. This article details the overview of MEMS sensors and various aspects such as thin film process, process characterization tools, assembly along with challenges in realization are presented. Reduction in measurement inaccuracy is extremely important and main parameters associated with the sensors are explained.

Keywords:

MEMS, Sensors, Fabrication Process, Assembly

1. INTRODUCTION

MEMS (Micro-Electro Mechanical System) is a method to create miniaturized mechanical devices or systems which is rapidly making stride in various domain. Improved reliability, accuracy, sensitivity and low power consumption are the important characteristics of this technology. Fabrication of MEMS stems out from micro fabrication process by which sensors, actuators and control functions are co-fabricated in silicon. Sensor is basically a device converting physical phenomena into an electrical signal and due to roots in integrated circuit process the manufacturing of the MEMS is economical as batch processing can easily be carried out. The primary advantage of MEMS is the integration of multiple functions and versa ability at the macro-size scale MEMS sensors are having modest power consumption, high reliability, low weight and small size. The advantages associated with the miniaturization is the lower power consumption, enhanced efficiency of a chemical reaction, improved thermal management, improved reproducibility, increased sensitivity and selectivity.

Future space mission consisting of number of microsatellites can be possible by the infusion of MEMS sensors such as inertial sensors, deformable mirrors, power supplies, thrusters, stirling coolers, reconfigurable antenna array which will potentially make system flexible and versatile to satisfy multi-mission requirements. The main challenge in the development of MEMS technology stems from its interdisciplinary nature encompassing physics, mathematics, chemistry, material science, mechanical engineering, chemical engineering, electrical engineering etc. MEMS sensors are increasingly being used in home theatre, camcorders, digital televisions, cell phones, laptops, navigation electronic toys, air bag deployment etc. [1].

Most commonly employed material in MEMS is basically polysilicon and crystalline silicon and variety of microstructures such as beams, membranes, cantilevers, grooves, orifices, springs, gears, and chambers can be fabricated. Silicon is preferred material as it is free from hysteresis and fatigue related failures as well as can provide better resolution compared to other materials. Also silicon is having better mechanical properties (strength to weight ratio), IC processing (coating with various materials), low cost and ease of availability. MEMS specific processes are deep etching, double sided wafer alignment, bonding, sacrificial layer etching which are different from standard IC processes [2].

Table1. Basic difference between MEMS and IC fabrication

Integrated Circuits	MEMS
Typically flat structure (2-D)	Generally not flat (3-D str.)
No moving part	Moving & non-moving
Insensitive to the environment	Sensitive to environment
Depends on buried layer	Surface effect devices
Highly dense with multiple functionality (IC tester)	Typically perform Single function (test instruments)
On chip compensation	Generic off chip compensation

Variety of wafer such as epi, SOI, high resistivity apart from standard silicon in various sizes and thickness are chosen keeping specifications into consideration and the overall realization cost [3]. Bow, warpage and surface smoothness are the key parameters to be looked for wafer selection in MEMS domain. Silicon micromachining is the main technology in MEMS and anisotropic etchants such as Ethyldiamine Pyroacetechol (EDP), Tetramethylammino Hydroxide (TMAH) and Potassium Hydroxide (KOH) are employed whereas Xenon Difluoride (XeF_2) is used for isotropic etching. This article provides overview of the sensors technology, its classification and applications, process, parameters and various challenges.

2. PROCESS REQUIREMENTS FOR THIN FILMS

Thin film deposition in MEMS is generally dielectrics and metal deposition. Most commonly employed dielectrics in MEMS domain are silicon dioxide and silicon nitride apart from polymers and polysilicon materials [4]. Mostly aluminium, tin, gold, platinum and doped poly are employed as metal layers. Main requirements of deposited layers are low stress, good conformality and adhesion, moisture barrier, better step coverage and low diffusion. The source material for oxide and nitride deposition using chemical vapour deposition is Thetra-Ethyl Ortho Silicate (TEOS) whereas Silane (SiH_4) gas as a source is employed only for nitride deposition. The quality of the dielectric is based on conformality and step coverage which is dependent on the sticking coefficient and surface mobility. The main parameters required for the dielectrics are thermal stability, planarization, low stress, low defect density, good adhesion, ease of surface etching, barrier to humidity, better step coverage and gap filling along with conformality. Dielectric deposition is carried out by Chemical Vapor Deposition (CVD) process and is mainly classified as Plasma enhanced CVD, Atmospheric Pressure CVD and High Density CVD. PECVD advantage is the high deposition rate with good control of compressive stress. The main parameters in CVD process are: silicon sources, oxide sources, nitride sources and heat or plasma is used as energy sources. Metal deposition can be carried out either using CVD process or Physical Vapor Deposition (PVD) process. Mostly PVD process is carried out which can further be classified based on various features such as reactive sputtering, magnetron sputtering, ionized metal plasma. The deposition conditions impacts the etch rate of the films which is shown in Table.2.

Table.2. Typical etch rate

Deposited layer	Typical etch Rate (A°/sec)	Etchant
Oxide (LPCVD)	20	CF_4,CF_4+O_2, SF_6,CCl_2F_2, BOE,H_3PO_4
Nitride (LPCVD)	30	
Oxide (PECVD)	120	
Nitride (PECVD)	90	

Dry etching involves plasma assisted etching of the material either by vapour phase or dielectric or sputtering mechanism whereas buffered oxide etch (BOE) and phosphoric acid (H_3PO_4) are used for wet etching of the films for which etch rate is influenced by temperature and agitation [5]. Film density and chemical nature of the film are the main parameters influencing etch rate. Metal requirements are low resistance, ease of etching, thermal stability, better adhesion, compatibility with other metals, ease of processing and high resistance to diffusion in dielectric. Also good coverage and long life time to be ensured for the various metal layer depositions. The basic MEMS flow consists of mainly deposition, implantation, photolithography, etching and micromachining. The Table.3 shows various tools for the process characterization and mode of measurement [6].

Table.3. Various tools for process characterization

Measurement tools	Principle	Mode
Film thickness	Elliposometer	In-line
Film stress	Stoney’s formula (light angle)	In-line
Optical microscope	Light reflection	In-line
SEM	Electron scanning	Off-line
Surface profiler	Interferometer	In-line
Current-Voltage	Modulated wave	Off-line
Resistance	Sheet resistivity	In-line
Reflectance	Infrared spectroscopy	In-line

3. MEMS SENSORS CLASSIFICATION

MEMS device employed three basic structures-diaphragm, micro bridge and beam. It can be classified according to the domain such as MOEMS, OptoMEMS and MEMS. The combination of optical and electrical domain constitutes MOEMS, optical and mechanical domain as OptoMEMS and combination of mechanical and electrical domain as MEMS. The MEMS devices are employed now days in automotive, medical, communication, defence and more interesting applications are opening due to its attractive features (Table.4).

Table.4. Common MEMS Applications

Devices	Applications
Accelerometer	Air bag technology
Digital micro mirror	Projection Display
Inkjet printer head	Printers
Pressure Sensors	MAP for automobile
Gas Sensor	Various gas detection
Bolometer	Night vision cameras
Miniaturised PCR	Pligonucletide
Oxygen/Glucose sensor	Protable blood analyzer

MEMS sensors are classified as Active or Passive sensor. Thermistors, strain gages, RTDs (Resistance Temperature Detector) are resistance based and are classified as active sensor due to resistance measurement which is dependent on the passage of external current. Thermocouples, photodiode and piezoelectric are classified as passive sensors as they generate electrical signal such as thermoelectric voltages, photocurrents and electric signal without external voltage or current excitation. Varieties of sensors are in use and Table.5 shows some of the classification of these sensors based on their nature [1,7].

Table.5. Common sensor classification and electrical parameters

Sensors	Type	Main parameters
Physical	Temperature Humidity Pressure	Sensor range, Sensitivity, TCR, Non linearity, Offset, Hysteresis, TCS,TCO,TCR
Inertial	Gyroscope Accelerometer	Random angle walk, Bias drift, Accuracy, Range, Resolution, Cross-axis sensitivity, Non-linearity, Natural frequency
Radio Frequency	Switch Phase shifter Varactor	Centre frequency, Insertion loss, Return loss, Switching speed, Voltage, Bandwidth

Apart from the parameters as mentioned in the Table.5, the requirement for sensors performance is to meet the specified criteria in the operating voltage and temperature ranges. Generally sensors are either resistive types or capacitive type and measurement techniques are based on the wheatstone bridge circuit or capacitance bridges as inductance is also considered to be a resistive element. MEMS sensors based on these principles are accelerometers, gyroscope, pressure and flow sensors, microphones, oscillators, RF switches and digital light projectors. Pressure sensor is based on the effect of piezo resistivity in silicon due to its higher sensitivity, better linearity and ability to withstand higher temperature. The piezoresistive effect is due to changes at the atomic level which is two order higher in magnitude compared to the metal. The change in resistance of silicon alters its carrier mobility and hence its resistivity. The change in resistance of the piezoresistive material is given by,

$$\frac{R}{\Delta R} = \pi_t \sigma_t + \pi_l \sigma_l \tag{1}$$

where, R is the piezo-resistance, ΔR is the change in piezo-resistance, π_t, π_l are the piezo-resistance coefficient, σ_t and σ_l are the stress coefficient. The material properties of the wafer play an important role and Table.6 shows the characteristics of *p*- and *n*-type wafer.

Table.6. Silicon wafer for pressure sensor application

Material properties	***p*-type wafer**	***n*-type wafer**
Young’s modulus (GPa)	169	169
Poission’s ratio	0.28	0.28
Gauge factor	200	-125
Density(kgm^{-3})	2330	2330
Dopant	Boron	Phosphorus
Thermal conductivity (Wm-1K-1)	149	149
Transverse piezoresistance coefficient (Π_t)	-66	-18
Longitudinal piezoresistance coefficient (Π_l)	72	-31

Pressure sensor is having generally four piezo resistors arranged in single wheatstone bridge configuration which is prone to temperature effects and offset errors. To circumvent the same, double wheatstone bridge can be employed. Temperature sensor is based on the principle of resistance variation due to temperature and generally fabricated with a base layer of Ti for better adhesion on standard silicon followed with the platinum layer [8]. Thickness and width of the platinum layer are optimized using Eq.(2),

$$R = \frac{\rho.L}{t.w} \tag{2}$$

where, R is the nominal resistance in ohms, t is the metal thickness, ρ/t is the sheet resistance (Ω/μm).

A case study of RF switch and patch antenna is shown which are based on the surface and bulk micromachining techniques. The switch actuation mechanism is achieved using an electrostatic force between the top and bottom electrodes due to actuation voltage V_a, and is given as,

$$V_a = \sqrt{\frac{2Kg^2\left(g_0 - g\right)}{\varepsilon_0 wW}} \tag{3}$$

where, g_0 is the initial gap height and g is the gap after actuation the beam attained. The power consumption is zero due to negligible current flow. The analysis of the same needs electrostatic, mechanical, fluidic and electromagnetic simulation and full wave parametric analysis is shown in Fig.1.

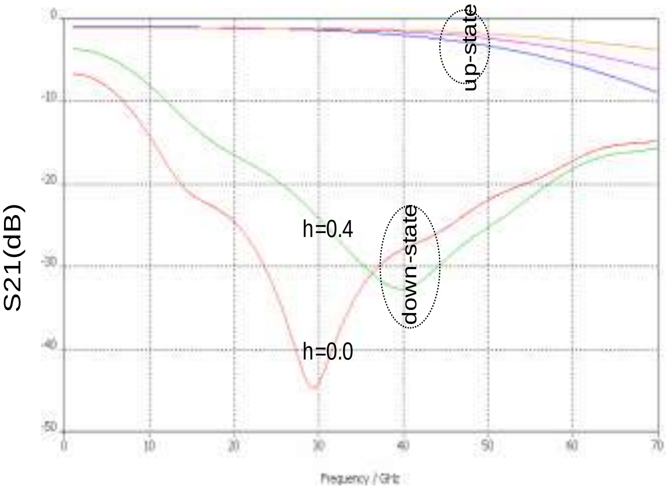

Fig.1. Full wave simulation result of shunt capacitive switch

The switch is realized on high resistivity wafer and characterized using the probe station as shown in Fig 2.

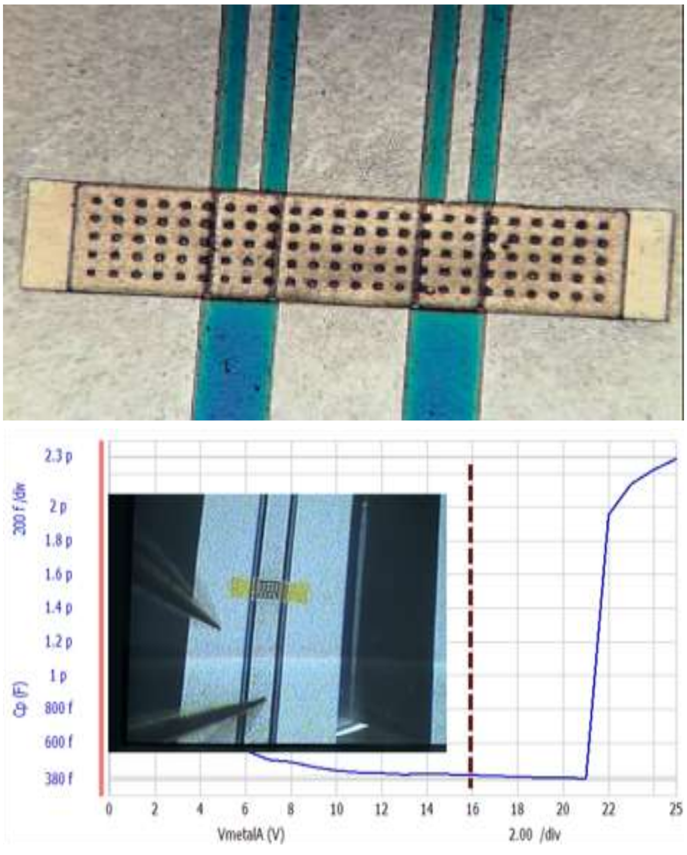

Fig.2. Realized switch and DC characterization

The switch employs surface micromachining concept whereas patch array antenna employing bulk micromachining [9] and the SEM of the same is shown in Fig.3.

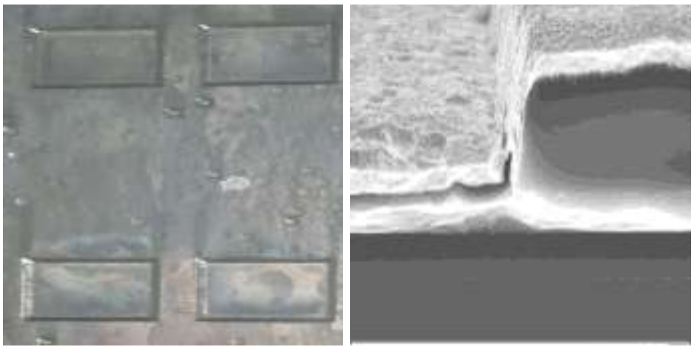

Fig.3. SEM images of surface and bulk micromachined circuits

Lead resistance, stray capacitance and output impedance measurement also to be considered in the overall measurement to accurately measure the sensor parameters. The Table.7 shows the accelerometer example with basic parameters and their corresponding unit [10].

The accelerometer applications are categorized as inertial, tilt and vibration. The major specifications for choosing the sensor are noise, sensitivity, drift, linearity, shock survivability and power consumption. The total noise equivalent acceleration $(m/s^2\sqrt{Hz})$ can be expressed as,

$$Noise - acceleration = \sqrt{\frac{4K_bT\omega_r}{QM}} \quad (4)$$

where, K_b is the Boltzmann constant, T is the temperature in Kelvin, Q is the quality factor and M is the mass. In case of vibratory gyroscope, the minimum detectable signal for a capacitive detection mechanism can be shown as:

$$Signal \;\; \alpha \;\; \frac{\omega}{Q}V_n\sqrt{BW} \quad (5)$$

where, V_n is the readout electronic noise

Table.7. Sensor parameters and description

Sensor Parameters	**Generic description**	**Measurement /Comparison**	**Example (Accelerometer)**
Transfer Function	Functional relationship between physical input signal and electrical output signal	-	-
Sensitivity	Minimum input of physical parameter that will create a detectable output change	Volts/Kelvin, mV/V/mmHg	mV/g
Dynamic Range	Total range of input physical signal that may be converted to electrical signal	Kelvin,Pascal, Newton	±γ
Accuracy	Maximum difference between actual and ideal output signals	Kelvin (% of FSO)	
Resolution	Smallest detectable incremental change in the input parameter that can be detected in the o/p signal	Absolute value	μg
Hysteresis	Same output is not achieved with the input stimulus	Kelvin (% of FSO)	
Offset/Drift	Difference between the actual output value and the specified output value under some particular set of conditions	-	-
Nonlinearity	Deviation of linear transfer function over the specified dynamic range	% of nonlinearity	% of the FSO
Noise	Distributed across the frequency spectrum and same at all frequencies	Volts/√Hz (noise density)	μg/√Hz
Resolution	Detectable minimum signal fluctuation	Signal/√Hz	μg/√Hz
Bandwidth	Frequency range correspond to upper and lower cut off	Hz	……….
Temperature Coefficient Offset Sensitivity	Sensitivity change with temperature	%/°C	mg/°C ppm/°C
Response Time	Time required for a sensor output to change from its previous state to final settled value	time	sec

Meanwhile accuracy and uncertainty are interchangeable terms, whereas accuracy is termed as qualitative term and uncertainty as quantitative. Noise is also having detrimental effect on the sensor performance and it limits the system performance due to its higher amplitude. Bandwidth and measurement time are inversely related so noise decreases with the square root of the measurement time.

Sensor parameters such as offset, hysteresis, accuracy, repeatability are having greater impact due to contamination. Amplification, level translation, linearization, impedance transformation, filtering etc. are the signal conditioning operations to be carried out before further processing [11].

Sensors are subjected to various environmental tests such as high temperature storage, low temperature storage, thermal cycling, moisture resistance test, radiation test and the subsequent degradation in the above parameters are correlated with the process to freeze the process parameters.

4. PACKAGING AND ASSEMBLY CONSIDERATIONS

MEMS sensor packaging is challenging and unconventional as it needs protection along with the access to the stimuli. Also in MEMS devices, passivation layer is generally not employed and vacuum pick up tool is avoided due to fragile diaphragm. Dicing, die-attach, encapsulation and sealing are the main steps in MEMS packaging. Dicing is carried out using diamond saw wheel rotating at very high rpm. Compared to laser dicing, diamond wheel dicing provides better cut quality, width control along with desired depth and edge quality [7].

Die attachment is a critical step as it provides mechanical support, survival of die from shock and vibration as well as thermal or electrical insulation or conductivity between the die and package as per the application requirements [4]. Methods for die attachments are eutectic or adhesives and adhesives such as silicone gels, epoxies, polymers are employed for the die assembly as they have low temperature processing apart from lower built in stress whereas solder bases process are prone to humidity related aging process. The epoxy selection is based on various parameters such as curing, viscosity, outgassing, glass transition temperature, coefficient of thermal expansion, pot and shelf life, dielectric strength, low stress, minimal mass, chemical resistant and low temperature process [12].

The prominent among them are H70E2, H70, H20E, NPR-100, Epotherm 130, E140, RTV and are selected based on the application requirements. Materials for packaging are silicon, metals, polymers, ceramics and composite and the selection criteria is based on optical, electrical, thermal, mechanical properties apart from ease of processing. Encapsulation and sealing process is carried out either in inert gas or in vacuum which leads to long term reliability. An example of the above is the bulk micro machined pressure sensor packaging which consists of various packaging steps such as- dicing, die attachment, wire bond, wire protection (epotherm/dot NPR), gel or oil filling followed by sealing. Drift due to thermo-mechanical stress created due to mismatch between silicon and package base material is one of the major concern for which assembly of the die apart from bonding plays an important role.

5. MEMS CHALLENGES

Residual stress is one of the main concerns in MEMS devices as it can cause voids, cracks, poor adhesion and even breakage of the wafer. Several phenomena are responsible for introducing film stress such as deposition process, nano-structural film growth, thermal profile and moisture content. The stress can be shifted by change of various parameters such as pressure, chuck temperature, deposition rate or high temperature annealing [13]. It is calculated by measuring the change of bow in a wafer before and after deposition of the film and is classified as tensile or compressive. MEMS challenges are manifold due to miniaturized size [7]. Following are the main challenges associated with the MEMS based sensors:

- Capillary, electrostatic, atomic forces as well as stiction phenomena
- Thermal properties associated with heat dissipation
- Fluidic or mass transport properties due to blockages
- Material properties such as Young’s modulus, Poisson’s ratio, grain structure, residual stress, wear and fatigue may vary
- Integration with on-chip circuitry is device specific
- Device packaging, assembly and testing is sensor specific
- Hermetic sealing and dedicated testing having mechanical stimulus

6. CONCLUSION

This article details the overview of MEMS based sensors and description of testing parameters, process and assembly aspects, inspection tools and challenges for its realization. Future circuits require portability, low power, high throughput and MEMS sensor are having multiplicity and miniaturization inherent in them. Materials such as SiC and SOI are proved to be much better and integration with electronics is the concern. MEMS system comprising of sensor and signal condition unit and system accuracy is dependent on the sensor characteristics such as environmental effects and dynamic characteristics. Environmental effects such as humidity, pressure, temperature, gases, magnetic and RF fields, vibration, radiation are the important element to check for reducing measurement errors apart from cables and connectors. On-chip signal conditioning minimizes the parametric tolerances of the MEMS sensor. The work related with improvement in interface circuitry and reliable low cost packaging will make MEMS more attractive. This article provides an insight of the MEMS sensor domain needed to be considered for realization of reliable product.

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