

MEMS Piezoresistive Accelerometers

Tarun Kanti Bhattacharyya and Anindya Lal Roy

Abstract MEMS piezoresistive accelerometers are inertial sensors which measure acceleration of the reference frame to which they are attached. These devices provide extremely localized acceleration-induced stress sensing with low noise outputs and have been the subject of academic as well as commercial research for quite a few years. This chapter deals with the basics micromachined piezoresistive accelerometers, tracing their evolution and typical analyses to sensor fabrication and characterization.

Keywords MEMS · Piezoresistive accelerometer · Wheatstone bridge · SEM · LDV · Wafer probe station · Sensitivity · Cross-axis sensitivity · Offset

1 Introduction

Much of our understanding of and interaction with nature occurs through various forms of electromechanical signal transduction. As a result, engineering systems that replicate such transduction techniques have come into being for myriad applications ranging from our daily lives to industrial usage to strategic deployment. Miniaturization of such conventional electromechanical systems has become imperative today as the need for high sensitivity devices with smaller footprints grows, along with the prospect of integration with signal conditioning electronics in order to execute high precision operations.

The rapid evolution of the state of the art in integrated circuit and microfabrication technology over the past few decades has played a major role in the development and maturing of the integrated microelectromechanical systems

T. K. Bhattacharyya (✉) · A. L. Roy
Advanced Technology Development Centre, Indian Institute of Technology,
Kharagpur, India
e-mail: tkb@ece.iitkgp.ernet.in

(MEMS) industry. MEMS employ a wide selection of sensing and actuation schemes to carry out a varied range of specialized functions at microscale regimes, thereby effectively replacing power-hungry, area-inefficient macroscale bulk sensor, and actuator systems. Figure 1 shows a couple of MEMS accelerometer structures from both commercial as well as academic research and development laboratories that have been developed using different micromachining processes and operated through different signal transduction mechanisms.

2 An Overview of the Piezoresistive Effect

Piezoresistance in semiconductors (silicon, germanium) was discovered in 1954 [1] as a phenomenon whereby the application of stress induced a proportional alteration of material resistivity. This principle is schematically illustrated in Fig. 2 where the dependence of material resistance on all the terms found in its mathematical expression is shown. Dominance of resistivity changes in comparison to dimensional changes as observed in semiconductor materials have led to its usage in applications involving stress sensitivity.

Semiconductors like silicon exhibits anisotropic **E–J** relationship dependent on its crystallographic axes. The matrix equation governing semiconductor resistivity is given by

$$E = \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \rho_{\text{Anisotropic}} \begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \begin{bmatrix} \rho_{xx} & \rho_{xy} & \rho_{xz} \\ \rho_{yx} & \rho_{yy} & \rho_{yz} \\ \rho_{zx} & \rho_{zy} & \rho_{zz} \end{bmatrix} \begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \rho_{\text{Anisotropic}} J \quad (1)$$

where $\rho_{\text{Isotropic}}$ is the resistivity of metallic materials and $\rho_{\text{Anisotropic}}$ is the resistivity of semiconducting materials comprising ρ_{ij} , the components of the anisotropic resistivity matrix, and E_i and J_i denote the components of the electric field and current density vectors in Cartesian coordinates. The symmetry of this resistivity matrix (Onsager's theorem) [2] ensures six unique components: $\rho_1 \equiv \rho_{xx}$; $\rho_2 \equiv \rho_{yy}$; $\rho_3 \equiv \rho_{zz}$; $\rho_4 \equiv \rho_{yz} \equiv \rho_{zy}$; $\rho_5 \equiv \rho_{zx} \equiv \rho_{xz}$; $\rho_6 \equiv \rho_{xy} \equiv \rho_{yx}$

$$\rho_{\text{Anisotropic}} = \begin{bmatrix} \rho_1 & \rho_6 & \rho_5 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{bmatrix} \quad (2)$$

Applied stress on such anisotropically affected materials may be expressed as a matrix with six independent stress components corresponding to appropriate cause and effect directions similar to (3) which are given by

$$\sigma = \begin{bmatrix} \sigma_1 & \sigma_6 & \sigma_5 \\ \sigma_6 & \sigma_2 & \sigma_4 \\ \sigma_5 & \sigma_4 & \sigma_3 \end{bmatrix}$$

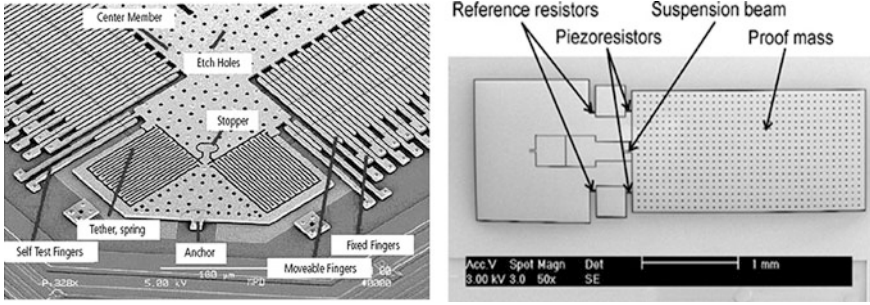


Fig. 1 (left) Analog Devices Inc. MEMS capacitive accelerometer. (right) MEMS piezoresistive accelerometer developed at the University of California, Irvine

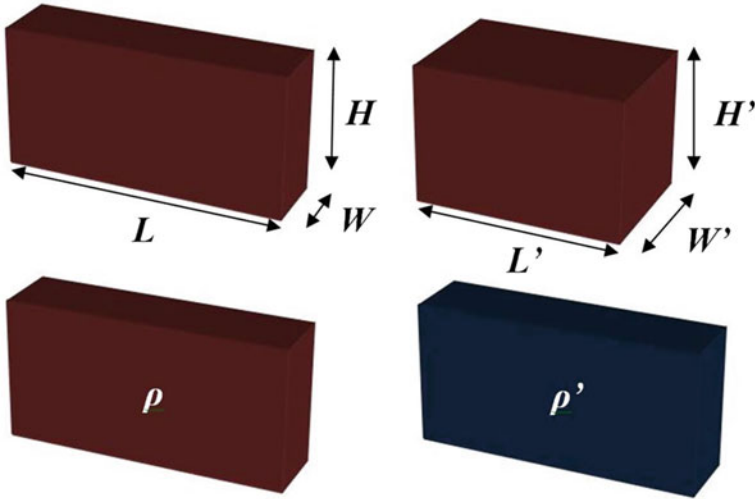


Fig. 2 (top left) Resistor to be subjected to stress-induced dimensional changes. (top right) Resistor after stress-induced deformation. (bottom left) Resistor to be subjected to stress-induced resistivity change. (bottom right) Resistor after stress-induced resistivity change

$$(\sigma_1 = \sigma_{xx}; \sigma_2 = \sigma_{yy}; \sigma_3 = \sigma_{zz}; \sigma_4 = \sigma_{yz} = \sigma_{zy}; \sigma_5 = \sigma_{zx} = \sigma_{xz}; \sigma_6 = \sigma_{xy} = \sigma_{yx}) \quad (3)$$

and the resistivity matrix of the material can be expressed as the superposition of unstressed (first matrix term) and stressed (second matrix term) conditions

$$\begin{bmatrix} \rho_1 & \rho_6 & \rho_5 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{bmatrix} = \rho_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \rho_0 \begin{bmatrix} \delta_1 & \delta_6 & \delta_5 \\ \delta_6 & \delta_2 & \delta_4 \\ \delta_5 & \delta_4 & \delta_3 \end{bmatrix} \quad (4)$$

where, $\delta_i = \frac{\rho_i - \rho_0}{\rho_0}$ for $i = 1, 2, \dots, 6$ and ρ_0 is the unstressed resistivity. The relative change in resistivity (with respect to the unstressed material resistivity) as defined above can be expressed as the product of the piezoresistive coefficient matrix and the stress matrix as shown in the following expression:

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_5 \\ \delta_6 \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} & \pi_{14} & \pi_{15} & \pi_{16} \\ \pi_{21} & \pi_{22} & \pi_{23} & \pi_{24} & \pi_{25} & \pi_{26} \\ \pi_{31} & \pi_{32} & \pi_{33} & \pi_{34} & \pi_{35} & \pi_{36} \\ \pi_{41} & \pi_{42} & \pi_{43} & \pi_{44} & \pi_{45} & \pi_{46} \\ \pi_{51} & \pi_{52} & \pi_{53} & \pi_{54} & \pi_{55} & \pi_{56} \\ \pi_{61} & \pi_{62} & \pi_{63} & \pi_{64} & \pi_{65} & \pi_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (5)$$

The relative change of resistivity with applied stress is formulated in [5] where the piezoresistive coefficient matrix plays a crucial role. By virtue of its octahedral diamond structure with a basic face-centered cubic (FCC) lattice, silicon possesses the symmetry of the O_h group [3]. Symmetric operations on such groups suggest that in the crystallographic coordinates of the material, there exist only three independent nonzero components of the piezoresistive coefficient matrix and the piezoresistive coefficient matrix of [5] reduces to

$$[\pi] = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \quad (6)$$

We can draw a couple of assumptions about the coefficients of the resistor elements based on the values of the matrix components [3]: for p -type, $\pi_{11} = \pi_{12} = 0$ and for n -type, $\pi_{44} = 0$. These allow us to calculate the relative change in material resistivity due to the magnitude of the applied stress. The relative change in resistivity (equivalently, relative change in resistance) for a generalized applied acceleration stress is given by the expression

$$\frac{\Delta\rho}{\rho} = \pi_l \sigma_l + \pi_t \sigma_t + \pi_s \sigma_s \quad (7)$$

where π_l , π_t , π_s are the longitudinal, transverse, and shear coefficients of piezoresistance and σ_l , σ_t , σ_s are the corresponding longitudinal, transverse, and shear stresses applied to the sensing element.

From the perspective of extrinsic (doping and temperature) dependence of piezoresistance, the piezoresistive coefficient Π for a doping concentration N at a temperature T is given by

$$\Pi(N, T) = P(N, T)\Pi(300 \text{ K}) \quad (8)$$

where P is the (N, T) -dependent piezoresistance factor and $\Pi(300 \text{ K})$ is the lightly doped piezoresistive coefficient at 300 K. The variation of the piezoresistance factor P of both n-type and p-type silicon with doping concentration and temperature is illustrated in Fig. 3. It can be clearly seen that the piezoresistance factor decreases in magnitude with both temperature and concentration. Temperature dependence can be attributed to band structure properties while concentration dependence can be due to increased metallic nature of the material, both of which leads to a degradation in the piezoresistive property.

3 MEMS Piezoresistive Accelerometers

Physical sensing systems such as pressure sensors, accelerometers, and gyroscopes comprise the largest fraction of the industrial implementation of MEMS technology and among these, the MEMS accelerometer has been in the forefront in terms of its widespread utility and successful system realization. Research on piezoresistive accelerometers began through simple beam-mass structures [4, 5] with piezoresistive elements thermally diffused at the stress maxima of the compliant mechanical element in a Wheatstone bridge topology [6] for sensing the inertial forces experienced by the seismic mass. This fundamental sensor evolved into a wide array of diffused piezoresistive element multiple beam-mass systems [7, 8].

Advancement of semiconductor doping technology has led to the replacement of thermal diffusion with ion implantation [9, 10] techniques which were preferred for their accurate doping capabilities, precision profiling of the doped elements along with reduced thermal spread of resistors. Later, anisotropic bulk micromachining methodologies [11, 12] gave way to precision high aspect-ratio dry etch techniques [13] which resulted in greater refinement of the mechanical structure and added flexibility to the types of geometries explored [14, 15]. Piezoresistive sensors provide good sensitivity but are also extremely susceptible to ambient temperature conditions [16] as well as self-heating [17] which has led to a research decline recently. With the level of progress in modern microfabrication technology, a very robust sensor with high sensitivity can be realized for automotive and aerospace applications. Commercial piezoresistive accelerometers [18, 19] have maintained simple geometries with practicality in implementation and its resulting sensitivity being the primary figures of merit.

4 Design Analyses of MEMS Piezoresistive Accelerometers

Sensor specification requirements drive the design phase of the MEMS piezoresistive accelerometer structure which comprises one of the most critical steps in any microsystem development and involves the establishment of the

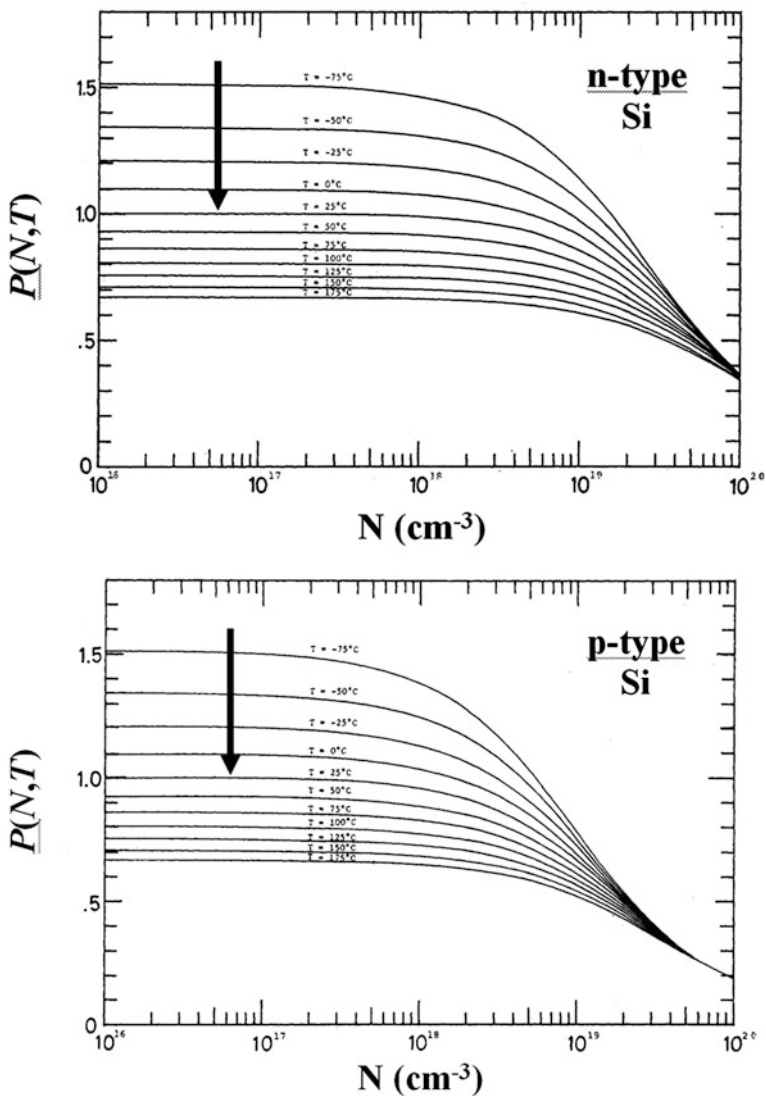


Fig. 3 Variation of the piezoresistance factor P for n-type (*top*) and p-type (*bottom*) silicon with dopant concentration and temperature

micromechanical structure and electrical transducer element design specifications through analysis and simulations. The basic design of the MEMS accelerometer comprises generic flexure beam/seismic mass structure attached to a rigid frame with acceleration-induced stress sensing piezoresistor elements positioned at the stress maxima of the beam flexures and connected in the form of a Wheatstone bridge as shown in the variant of Fig. 4. Wheatstone bridges form the backbone of

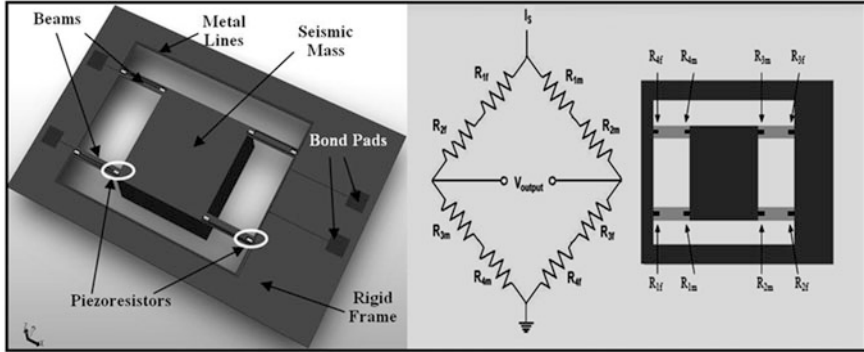


Fig. 4 (left) MEMS piezoresistive accelerometer variant discussed in this test. (right) Wheatstone bridge arrangement of stress sensing piezoresistors and their mapping on the MEMS accelerometer

resistive sensing as their balanced and unbalanced conditions correspond to different perturbation inputs along different axes of operation.

Piezoresistive accelerometers may be designed for single-axis as well as multi-axis inertial sensing. In this chapter, we primarily deal with single-axis accelerometers with minimal cross-axis sensitivity. As seen from Fig. 4, mass edge-alignment of the beams imparts maximum immunity to off-axis perturbations for the geometry in question while maintaining sensitivity along the desired axis. In theory, the Wheatstone bridge implementation of the piezoresistive sensing elements has two very important consequences:

- (i) Enhancement of desired axis signals and auto-cancellation of the off-axis perturbations
- (ii) Auto-compensation of temperature variation of individual piezoresistor values.

The basic operation of the accelerometer along its axis under external sinusoidal mechanical excitation can be approximated as a single degree of freedom (SDOF) mass-spring-damper (MSD) system which is defined by

$$m_{\text{eff}} \frac{d^2 z}{dt^2} + c_{\text{eff}} \frac{dz}{dt} + k_{\text{eff}} z = F_M = mA \sin(\Omega t) \quad (9)$$

$$c_{\text{eff}} = 2\zeta\omega_0 m_{\text{eff}} = 2 \frac{(0.42\mu LB^3)}{l^3} \quad (10)$$

$$k_{\text{eff}} = m_{\text{eff}}\omega_0^2 = \frac{4Eb h^3}{l^3} \quad (11)$$

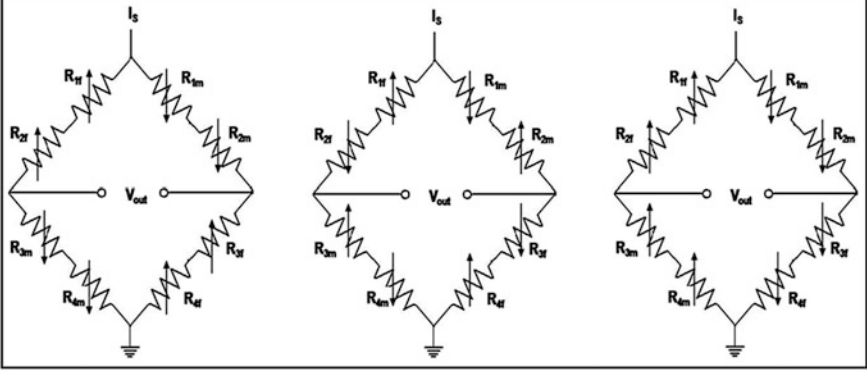


Fig. 5 Wheatstone bridge configuration changes due to acceleration along (*left*) out-of-plane z -axis (*middle*) in-plane x -axis and (*right*) in-plane y -axis

where m_{eff} is the seismic mass, c_{eff} is the damping coefficient, t is the air gap, k_{eff} is the equivalent spring constant of the quad-beam structure, ω_0 is the natural frequency (angular), A denotes the amplitude of excitation and Ω is the input excitation frequency. Here, F_M is considered sinusoidal because of its relevance to vibration shake table characterization of the system where the MSD sensor oscillates relative to the rigid frame. From beam mechanics and fluid (squeezed-film) damping [3], we can extract the effective spring constant, the natural frequency of the structure and the damping coefficient, thereby enabling us to tune the structural dimensions according to requirement. Eight piezoresistors occupy the stress maxima regions of the four beam flexures supporting the mass and are connected by metal lines in the form of a current biased Wheatstone bridge as shown in Fig. 4. The sensor is wafer-encapsulated using etched glass caps on either surface for over-range protection and fluidic squeezed-film damping. The separation between the sensor surface and the glass cap can be evaluated from the damping coefficient calculated. The Wheatstone bridge configuration serves to nullify the effect of temperature drifts in individual piezoresistors as well as canceling out off-axis acceleration inputs as illustrated in Fig. 5.

From the changes in the bridge arm resistances, the corresponding bridge output voltage is given by

$$V_{output} = I_{bias} R_{input} \frac{\pi_{44} \sigma_l}{2} \quad (12)$$

considering the assumptions of purely longitudinal stress (σ_l) and the sole influence of π_{44} . As far as the bridge offset and sensitivity [20] are concerned, their origins and dependence on temperature have been explored in theory and are presented as subsections below.

4.1 Wheatstone Bridge Offsets

Bridge offsets are a result of mismatch in the resistance values of the piezoresistive sensing elements comprising the acceleration sensor and can be attributed to the following reasons:

- Process variations resulting from the tolerances of the nonideal MEMS fabrication techniques employed result in resistor nominal value mismatch.
- Post-release stress relaxation mechanisms occurring in compliant MEMS structures results in the generation of residual stresses which in turn causes mismatch in the nominal piezoresistance values.
- Bias current flow induced localized heating within the wafer-level device causes the piezoresistive sensing elements to be subjected to different temperatures due to asymmetric crossing of the isotherms over the resistors creating mismatch in the nominal values.

Of the above, the thermal effect is shown to dominate this variation in resistance values and thus, symmetry of the sensing element layout is essential in the design as well as the allowance of sufficient stabilizing time before carrying out measurements at different temperatures. From the above discussion, it is clear that the bridge offset voltage is quite a complex quantity dependent on individual resistances (with their foundry tolerances) and their individual variations (due to the reasons outlined above) and as such, theoretical approximations have not been attempted.

4.2 Wheatstone Bridge Sensitivity

Bridge sensitivity, on the other hand, is a highly nonlinear function of temperature and occurs despite the equality of nominal resistance values (at 300 K). An individual piezoresistor and bridge output at temperature T and stress σ (neglecting bridge offset) can be defined as

$$R(\sigma, \Gamma) = R_0(1 + \alpha_{P1}\Gamma + \alpha_{P2}\Gamma^2 + \dots)[1 \pm S_0(1 + \alpha_{N1}\Gamma + \alpha_{N2}\Gamma^2 + \dots)\sigma] \quad (13)$$

$$V_{\text{output}}(\Gamma) = V_{\text{bias}}S_0\sigma(1 + \alpha_{P1}\Gamma + \alpha_{P2}\Gamma^2 + \dots)(1 + \alpha_{N1}\Gamma + \alpha_{N2}\Gamma^2 + \dots) \quad (14)$$

where R_0 and S_0 are the nominal values of resistance (at 300 K) and the coefficient of stress sensitivity (+ for tensile, – for compressive), respectively, α_P and α_N are the resistance and stress sensitivity temperature coefficients (in practice, $|\alpha_P| < |\alpha_N|$ which results in the second bracketed term dominating the first bracketed term), σ is the stress due to the applied acceleration, I_{bias} is the bridge biasing current and Γ represents the difference between T and the reference temperature T_0 (300 K). The bridge sensitivity is defined as the derivative of the bridge output with respect to the applied stress (due to acceleration) as:

$$\frac{\partial V_{\text{output}}}{\partial \sigma} = I_{\text{bias}} R_0 S_0 (1 + \alpha_{P1} \Gamma + \alpha_{P2} \Gamma^2 + \dots)(1 + \alpha_{N1} \Gamma + \alpha_{N2} \Gamma^2 + \dots) \quad (15)$$

implying that sensitivity estimation requires accurate curve fitting of experimental data. In case of piezoresistance in semiconductors, the temperature coefficient of resistance is negligible in comparison to the temperature coefficient of stress sensitivity and as a result, calculations are often made on the basis of the assumption that the first bracketed term is approximately unity.

5 Sensor Fabrication Processes

The MEMS accelerometer design presented earlier can be implemented on silicon substrates for integration with interfacing circuits to create a complete monolithic or multichip MEMS-CMOS sensor system. The basic outline of the fabrication process followed for realizing the MEMS piezoresistive accelerometer is presented below:

- (a) High resistivity and high purity silicon substrates are generally used such that substrate resistivity does not interfere with the functioning of the Wheatstone bridge. In addition, defect-free substrate surface layers are preferred since the electrical sensing element is laid out on the wafer surface.
- (b) Piezoresistors can either be diffused or ion implanted at the surface with implantation providing greater precision in the definition of resistor profile and junction depth. As a result, the piezoresistors can be accurately localized to the stress maxima positions for maximum sensitivity.
- (c) Wheatstone bridge metallization may be carried out using any metal depending upon the requirements. In general, metals with high melting points and nonsusceptibility to oxide formation are preferred due to structural release issues and wafer-level packaging constraints.
- (d) Structural release can be achieved using either wet or dry etching. Wet etching is relatively cost-effective when compared to dry etching techniques but raises issues such as reduction of the seismic mass due to trapezoidal etch profiles, thereby reducing mechanical sensitivity. In addition, certain metals must be avoided as the etchant often attacks the metal layer as well. The advantages of dry etching include accurate profile definition of the mechanical elements with no such decrease in the seismic mass due to vertical sidewall generation as well as lack of etch affinity toward metals.
- (e) Wafer-level encapsulation is a technique whereby the device wafer is capped on either surface by an appropriately patterned wafer for the provision of air damping. In case of bulk micromachined structures such as the one being explored in this text, wafer bonding is the only viable option for encapsulation. Wafer bonding can be of many types based on the wafer materials. In this case, glass wafers are patterned to form cavities which are then bonded

on to the device wafer on either side. Hermetic or air-tight seals can be obtained using anodic or eutectic bonding techniques while quasi-hermetic seals can be realized using simpler adhesive bonding processes.

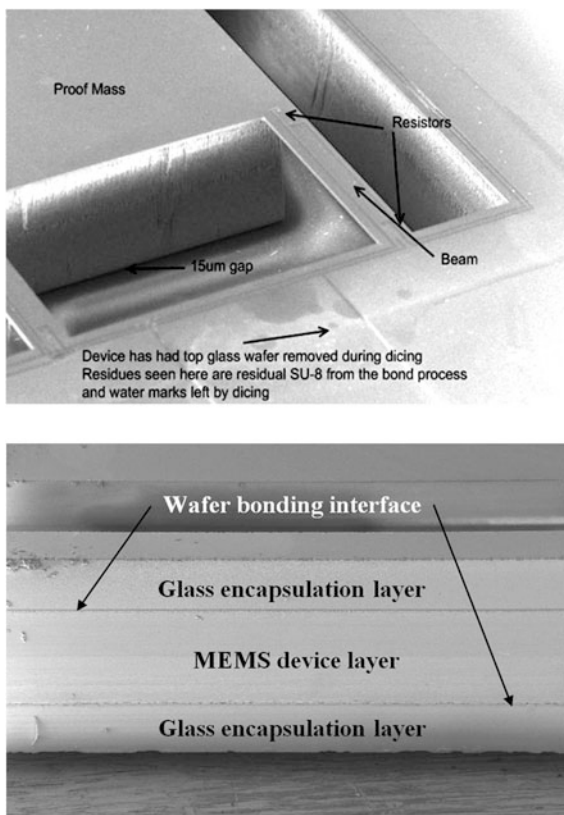
A wide range of fabrication processes may be employed to realize MEMS piezoresistive accelerometers, as is apparent from the literature reviewed in this chapter, that are tailored to meet specific goals and as such, there is no optimum process technology that can be used to implement all piezoresistive variants. The above process flow merely serves as a possible guideline for fabricating structures similar to the one being developed in this chapter. Quality of sensor fabrication directly determines operational performance of the accelerometer and can be estimated using standard tests developed over time to characterize such electro-mechanical systems. Subsequent tuning of process tolerances based on characterization data serves as a critical “feedback” loop in the quest to realize even better devices. The next section deals with the various characterization tools and techniques used for micromechanical inertial sensor testing in general.

6 Characterization of MEMS Accelerometers

MEMS accelerometers and most other micromechanical sensors and actuators are subjected to detailed testing using different testing equipment and measurement setups. Such tests are conducted at various levels, as defined below, in order to obtain the most accurate estimate of device performance. Testing level, as is apparent from the name, is defined by the “state” of the subject being tested and may be classified broadly into three types:

- (i) *Wafer-level tests*: These tests are conducted on whole or diced wafers which provide an estimate of characteristics such as sheet resistance, film thicknesses, and feature dimensions to name a few. This level of testing is mostly concerned with the bulk substrate properties and the proper handling of the same so as to enable the realization of devices as close to ideal as possible.
- (ii) *Device-level tests*: Placed higher in the testing hierarchy, these tests are carried out on individual devices that may or may not be wafer-encapsulated. Perhaps the most critical stage of testing, the device-level experiments reveal information about the natural frequency of the device, signal transduction reliability, electrical characteristics under bias such as offsets and output signal levels and the like. This level deals with individual devices without any external support and is useful in predicting integrated behavior to some extent.
- (iii) *System-level tests*: The most complete level of characterization, these tests are done by interfacing the MEMS with all the accessories such as signal conditioning front-end and back-end electronics and subjecting the entire system to the perturbations that emulate real-life conditions to which the

Fig. 6 (top) Scanning electron micrograph of the beam-mass configuration. (bottom) Wafer-encapsulated accelerometer system (encapsulated wafer details not visible) (image courtesy [21])



system is to be exposed in practical applications. This advanced level of testing gives an estimate of how the system behaves under standard operating conditions and is strongly dependent on the wafer-level and device-level performance of the MEMS.

These different levels of tests generally require corresponding characterization equipment although there are multipurpose tools which can be effectively employed at more than one level. A few most important of these are explored in the rest of this section starting with visual characterization using advanced imaging techniques.

Figure 6 shows a scanning electron microscope image of the beam-mass system of the MEMS piezoresistive accelerometer that has been used as reference in this chapter as well as its complete wafer-encapsulated implementation. Proper feature realization can be inferred from these images which corroborates the validity of the design realization processes. Scanning electron microscope (SEM) imaging is a wafer-level visual characterization technique which uses the reflection of a focused beam of electrons to assess substrate features and topography. In case of encapsulated MEMS accelerometers, observation of device features requires the removal

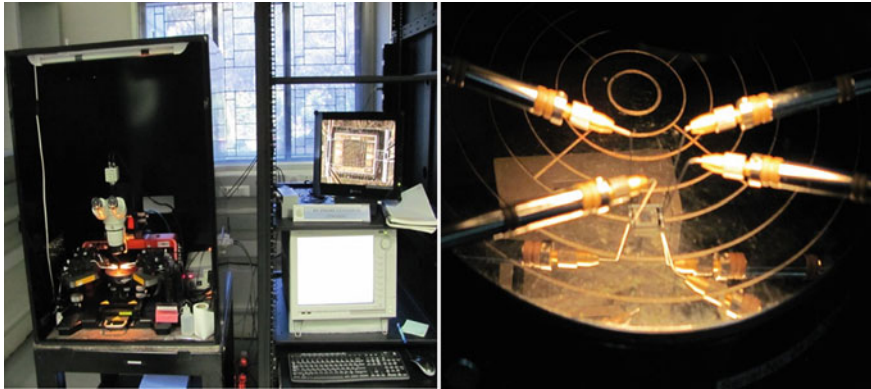


Fig. 7 (*left*) Wafer probe station interfaced with device analyzer. (*right*) Encapsulated MEMS piezoresistive accelerometer probing on thermal stage

of the capping layers as the impinging electrons cannot penetrate the capping surface and provide imaging of underlying layers as can be seen in Fig. 6. SEM images can also be used to study interface integrity, possible delamination defects and dimensional aberrations resulting from process tolerances and wafer handling.

The wafer probe station is an essential electrical characterization instrument which is used to measure the electrical and electronic properties of the MEMS device under test (DUT). The probe station is not stand-alone equipment and it is necessary to interface instruments like device analyzers to evaluate various performance metrics. An open stage wafer probe station interfaced with a device analyzer is shown in Fig. 7 and is used to study the current-voltage (I-V) characteristics of MEMS accelerometers. It is to be noted that the wafer mounting stage of many probe station variants is temperature regulated such that studies on temperature dependence of certain parameters may be carried out. In addition, there are vacuum chamber probe stations which have the stage enclosed in vacuum for precision measurements.

One of the most important device-level characterization tool for vibratory MEMS devices is the laser Doppler vibrometer (LDV) shown in Fig. 8, which estimates vibration amplitudes and frequencies of MEMS device surfaces using frequency heterodyning and laser interferometric techniques. LDV measurements yield precise vibration frequencies and their corresponding mode shapes using Fourier transform methods and device surface sampling. Frequency response of inertial sensors is extremely critical for optimal performance as operating frequencies and device natural frequencies should often be isolated so as to prevent amplitude resonance and consequent device damage. Additionally, damping characteristics of MEMS accelerometers need to be studied carefully for the design of precisely damped systems in the future due to the fact that most accelerometers are critically damped and deviations from specified values may lead to unwanted oscillations and response delays.

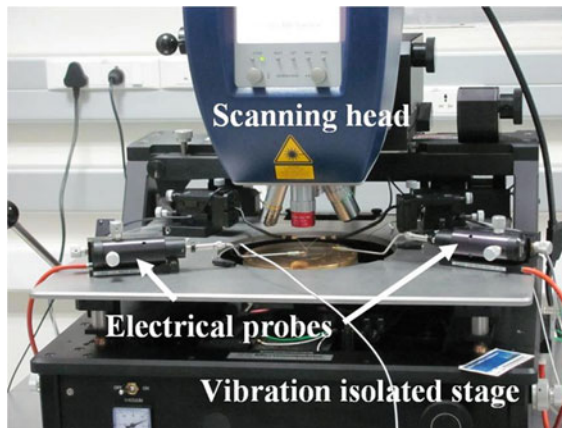


Fig. 8 Laser Doppler vibrometer used for vibration analysis of MEMS components

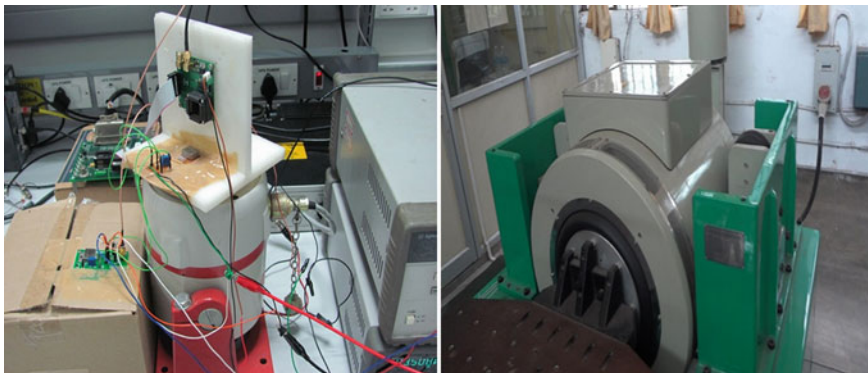


Fig. 9 (left) A table-top electromagnetic shaker. (right) A large-scale hydraulic shaker

System-level characterization forms the final level of testing the functionality of MEMS accelerometers. Generally, the MEMS sensors are interfaced with their signal conditioning and readout circuits and mounted on a vibratory stage. These vibratory stages are designed so as to provide precision vibrations like sinusoidal and shock impulse for evaluating the dynamic performance of the device. Such setups are called “shakers” and may of different types. Two versions are shown in Fig. 9 with one being an electromagnetic table-top shaker targeted toward testing miniaturized assemblies while the other is a hydraulic shaker meant for vibration analysis of large structures.

7 Conclusions

MEMS piezoresistive accelerometers have been covered in this chapter with their usage being overviewed. The basic principle behind the sensing mechanism is discussed and the subsequent evolution of the MEMS piezoresistive accelerometer is covered ranging from academia to industry. A sample device structure is chosen for description purposes and its design is analyzed for mechanical functionality and subsequent electrical signal transduction issues. Various forms of characterization of such MEMS sensors are explored at different levels with the utility of each being presented with the hope that the overall content of this chapter shall enable the understanding of such sensors at the basic level in the very least.

Acknowledgments The authors would like to thank the National Programme on Micro Smart Systems (NPMAS) for their financial support without which this work would not have materialized.

References

1. Smith CS (1954) Piezoresistance effect in germanium and silicon. *Phys Rev* 94:42–49
2. Smith CS (1958) Macroscopic symmetry and properties of crystals. *Solid State Phys Adv Res Appl* 6:175–249
3. Roylance LM, Angell JB (1979) Batch-fabricated silicon accelerometer. *IEEE Trans Electron Devices* 26:1911–1917
4. Bao M (2008) Micro mechanical transducers elsevier handbook of sensors and actuators, vol 8. Elsevier, Oxford, pp 215–217
5. Crazzolara H, Flach G, von Miinch W (1993) Piezoresistive accelerometer with overload protection and low cross-sensitivity. *Sens Actuators, A* 39:201–207
6. Kal S et al (2006) CMOS compatible bulk micromachined silicon piezoresistive accelerometer with low off-axis sensitivity. *Microelectron J* 37:22–30
7. Shen S, Chen J, Bao M (1992) Analysis on twin-mass structure for a piezoresistive accelerometer. *Sens Actuators, A* 34:101–107
8. Sim JH et al (1998) Eight-beam piezoresistive accelerometer fabricated by using a porous-silicon etching method. *Sens Actuators, A* 66:273–278
9. Partridge A et al (2000) A high performance planar piezoresistive accelerometer. *IEEE/ASME J Microelectromech Syst* 9:58–66
10. Park WT et al (2000) Encapsulated submillimeter piezoresistive accelerometers. *IEEE/ASME J Microelectromech Syst* 16:507–514
11. Kwon K, Park S (1998) A bulk-micromachined three-axis accelerometer using silicon direct bonding technology and polysilicon layer. *Sens Actuators, A* 66:250–255
12. Ravi Sankar A, Lahiri SK, Das S (2009) Performance enhancement of a silicon MEMS piezoresistive single axis accelerometer with electroplated gold on a proof mass IOP. *J Micromech Microeng* 19:11
13. Amarasinghe R et al (2005) Design and fabrication of a miniaturized six-degree-of-freedom piezoresistive accelerometer IOP. *J Micromech Microeng* 15:1745–1753
14. Atwell AR et al (2003) Simulation, fabrication and testing of bulk-micromachined 6H-SiC high-g piezoresistive accelerometers. *Sens Actuators, A* 104:11–18
15. Lin Y (2011) Micromachined piezoresistive accelerometers based on an asymmetrically gapped cantilever. *IEEE/ASME J Microelectromech Syst* 20:83–93

16. Kim SC, Wise KD (1983) Temperature sensitivity in silicon piezoresistive pressure transducers. *IEEE Trans Electron Devices* 30:802–810
17. Doll JC, et al (2011) Self-heating in piezoresistive cantilevers. *Appl Phys Lett* 98:3
18. Endevco Meggit Sensing Systems <https://www.endevco.com>
19. Honeywell Sensing and Control <https://measurementsensors.honeywell.com>
20. Dutta A (2012) Design and implementation of high precision variable-gain amplifier with on-chip temperature compensation scheme for MEMS sensors (MS Dissertation), IIT Kharagpur
21. Roy AL, Bhattacharyya TK (2013) Design, fabrication and characterization of high performance SOI MEMS piezoresistive accelerometers *Microsystem Technologies* (in press)

Micro and Smart Devices and Systems

Vinoy, K.J.; Ananthasuresh, G.K.; Pratap, R.; Krupanidhi,
S.B. (Eds.)

2014, XXVI, 508 p. 326 illus., Hardcover

ISBN: 978-81-322-1912-5