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MEMS devices Analytical modeling and simulation with reference to cantilever-based MEMS devices

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Abstract -MEMS devices may be anything between a few micrometres and millimetres in size. MEMS have excellent potential for efficiently sensing physical, chemical, and biological factors, which might be combined with VLSI processors. MEMS make use of the mechanical characteristics of a variety of components, including reservoirs, channels, cantilevers, beams, comb drives, membranes, and reservoirs. The mechanical behaviour of these micromechanical devices in the presence of factors has to be thoroughly studied in order to make the most use of their characteristics.

Keywords - Analytical modeling, Simulation, MEMS devices, Cantilever

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INTRODUCTION

From the use of logic to integrated circuit (IC) technology, the area of electronics industry began to flourish. The manufacture of ICs encompasses 3D, 2D, and 1D surfaces that are enabled by fabrication processes and equipment. In the past, group 14 semiconductor silicon from period 3 was used as the wafer material owing to its exceptional electrical, elastic, and plastic limits.

Microsensor and micro actuator devices made using MEMS include grippers, tweezers, and tongs (acoustic wave, biomedical, chemical, inertia, optical, pressure, radiation, and thermal sensors, for example) and valves, pumps, and microfluidics.

Depending on the application, a microsystem created by coupling a MEMS microsensor and MEMS microactuator with a shared transduction unit will synergize sensing and actuating mechanisms.

MEMS SOFTWARE

Before sending them to the fabrication facility, MEMS-based goods must undergo a number of trials to be designed into real-time structures. The MEMS product designers will use simulation to validate several elements such as structural reliability and mode of operation. The MEMS device manufacturing process is expensive. To prevent architectural failures, particular consideration should be given to the material choice and the impact of surface pressures on the device.

A science fiction software platform for modelling and simulating physics-based issues is called COMSOL Multiphysics. A FEA programme called COMSOL Multiphysics is used to create models with both 2D and 3D geometry. COMSOL Multiphysics excels at building complicated geometries by creating 2D geometries and extruding them into the necessary dimension on the third axis. The COMSOL Multiphysics programme can do more than just generate geometry; it can also correct sources, sinks, boundaries, and add materials to models. With the aid of the COMSOL Multiphysics programme, MEMS and NEMS-based device performance may be evaluated and examined prior to manufacture. The construction of a new physical interface based on the domain equation input by the user is the port fit benefit of utilising COMSOL.

The MEMS application The Finite Element Method (FEM) analysis tool Intellisuite is used to design, model, and examine the properties of micro- and nanoscale components and devices. The programme can simulate MEMS devices at the system level utilising 2D and 3D models, as well as virtually fabricate devices that have been modelled using Intellisuite (1). For MEMS simulation, accuracy, capacity, and speed are the benchmarks.

MEMS SENSORS/ DEVICES CHARACTERISTICS

Size, Piezo resistance (PZR), Temperature Coefficient of Resistance (TCR), Stiffness, Adhesion, Vibration, and Resonant Frequency are a few parameters taken into account while designing MEMS-based sensors and devices. Size: Due to their low thermal expansion, small systems exhibit superior dimensional stability at high temperatures. A smaller system means less room is needed. This makes it possible to cram more functioning components into a single device (2). Low production and shipping costs result from lower material requirements. Piezoresistance [PZR] is the change in a solid's electrical resistivity brought on by the application of mechanical stress. Due to this piezoresistance, crystalline materials with bulk origins like silicon primarily alter their electronic structure, changing the effective mass of charge carriers. Temperature coefficient of resistance (TCR): One of the characteristics used to describe a temperature sensor is the TCR. TCR is characterised as the resistance variation as a function of ambient temperature. Commonly, TCR is stated as ppm/° C. Young's modulus determines stiffness, which is defined as the resistance or impediment to bending brought on by a certain applied stress. Adhesions: The influence of surface forces increases the likelihood of adhesion. In MEMS actuators, sidewall and in-plane adhesion both take place. Even stiction issues brought on by the adhesions have the potential to result in material failure. In order to prevent surface forces from causing adhesions, device modelling is done. Vibration: Oscillations around an equilibrium point are brought on by the mechanical phenomena known as vibration. The oscillations might be random or recurring. Studies on vibration and sound have a lot in common. Sound or pressure waves are produced by vibrating structures. (3) A resonant frequency is an inherent vibration frequency determined by the physical characteristics of the vibrating item. To determine the dynamic response, any MEMS device may be induced to oscillate in eigen frequencies.

ADVANTAGES OF MEMS DEVICES

Some of the advantages of MEMS devices are

- High surface to volume ratio
- Very small size, mass, volume
- Very low power consumption
- Easy to integrate into systems or modify
- Low cost
- Can be highly resistant to harsh situations such vibration,shock and radiation
- Small thermal constant
- Batch fabricated in large arrays
- Parallelism
- Improved thermal expansion tolerance

APPLICATIONS OF MEMS DEVICES

MEMS may be used in several applications. Bio-MEMS, a ground-breaking innovation, is bridging the gap between hitherto unconnected disciplines like biology and microelectronics. MEMS is used in a variety of industries, including transportation, consumer products, medical care, space travel, and manufacturing (4).

Automotive and Consumer Applications

A few MEMS devices include airbag systems, anti-braking devices, vehicle security systems, inertial brake lights, headlight levelling, rollover detection, automatic door locks, and active suspension. There are several uses for accelerometers, including air bag deployment in contemporary vehicles to prevent crashes. Additionally, consumer gadgets like gaming controllers, portable media players, mobile phones, and specialised digital cameras also make use of accelerometers. When free-fall is detected, the hard disc head in PCs is moved into place. This guards against hard disc damage and data loss. MEMS gyroscopes are employed in contemporary automobiles for location and other purposes, such as to deploy a rollover bar or activate dynamic stability control, in order to detect yaw rotation. Examples of silicon pressure sensors are tyre pressure sensors for automobiles and disposable blood pressure monitors. A DLP-based projector's DMD chip contains several hundred thousand tiny mirrors on it. Data communications switching and alignment using optical switching technology. Applications of interferometric screen modulators (IMOD) in consumer electronics, particularly in displays for portable devices. With the development of RF-MEMS technology, inductors and capacitors have performed better (5).

Healthcare Applications:

Polymerase Chain Reaction (PCR) microsystems for DNA amplification and identification are used in Bio-MEMS antigen detection systems to discover infections in blood samples. STM (Scanning Tunnelling Microscope) tips that have been micromanufactured may be used to map the topography of tough microstructures. Biochips are utilised to find dangerous biological and chemical agents. Microsystems for selecting and screening drugs with high throughput. Lab-on-Chip, biosensor, and chemosensor development are all examples of how bio-MEMS are used in medical and health-related technology (6).

Space Exploration Applications

MEMS devices were utilised in the fields of signalling, location, and information transfer in space due to the many opportunities they offered.

For inertial navigation, accelerometers and gyroscopes are employed, and pressure sensors are used to highlight the nontrivial conditions that occur in space. RF switches, tunable filters, tunable mirror arrays for adaptive optics, micro-power sources, and turbines are all used to connect with base stations on the ground (7). About the launch vehicle, the regulation of thrust and attitude in satellite communication.

Industrial Applications:

In all production-based sectors, hazardous gas detection and gas shutoff are important tasks that must be completed. Deep earth excavation is done in mining regions and stone-purchasing chambers. In such locations, hazardous gas limitations must be continuously monitored (8). Large machines must have their shock and vibration levels measured since these factors determine how well the equipment will hold up over time. Some industrial devices that monitor shock and tilt sensing are tested in harsh environments.

CHALLENGES AND COMMON MEMS FAILURE MECHANISMS

In all industries, from the automobile sector to the medical diagnostic business, developing micromachined components and devices is the focus of attention. Few failures arise as a result of incorrect selection of materials for devices and background operation (9). In Table 1, common MEMS technology failure mechanisms are given.

Table 1: Common MEMS failure mechanisms

Failure Mechanism	Degradation mechanism	Reason forfailure	Failure category
Fracture	• overload fracture • fatigue fracture	Improper selection of material	Mechanicalfailure
Creep	• applied stress • intrinsic stress • thermal stress	Interlayermismatch	Mechanicalfailure
Stiction	• capillary forces • vanderwaalsmolecular forces • electrostaticforces • solid bridging	Dimensions ofthe Microstructures are small, suchthat adhesion forces may tendto act.	Interactioncaused mechanicalfailure
Wear	• adhesive • abrasive • corrosive	Rubbing of twosurfaces or motion of onesurface over the other.	Architectural failure
Degradation of dielectrics	• Leakage • charging • breakdown	At high frequency operation, parasitic capacitance, resistance, leadinductance willcome into role.	Thermalfailure
Delamination, Contamination, Pitting of contacting surfaces, Electrostatic discharge (ESD), Electromigration		Material interfaces losing adhesive bonds,when the deviceis mishandled, radiation effects, interconnection in the structures	Chemicalfailure

The table shows that mechanical failures account for the majority of failure modes. It is important to carefully examine the material matching of the contacting surfaces on moveable components or neighbouring layers for coherence in material qualities (10). Figure 1 displays a scanning electron microscope (SEM) picture of an adjacent layer mismatch that led to a chemical failure.

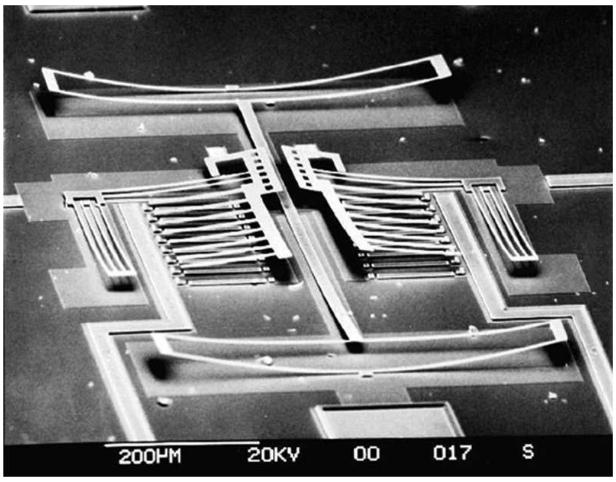

Figure 1: SEM image showing MEMS structures bending due toadjacent layer mismatch.

Surface forces became a significant design parameter with the introduction of MEMS, although numerically they were mostly unknown due to their small levels. These stiction concerns are more interesting from the perspective of dependability evaluation. Surface forces and adhesion energy between surfaces are the primary causes of these stiction issues. Figure 2 shows the cantilever surfaces with no adhesion, lateral adhesion, and both lateral and vertical adhesions. The stiction may also be induced by both lateral and vertical adhesion (11).

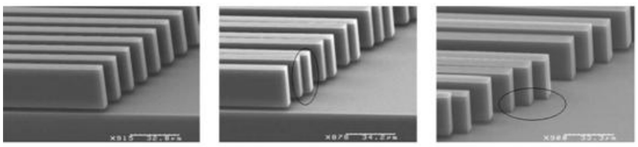

Figure 2: (a) no adhesion (good release) ; (b) only lateral adhesion; and (c) lateral and vertical adhesion. (Courtesy of IOP Publishing Ltd).

The right materials must be used when developing any kind of MEMS construction in order to ensure mechanical dependability. Any structure's surrounding layers must be thoroughly examined for resemblance in material properties; otherwise, chemical failures may occur. By keeping adequate distances between buildings, surface forces acting on the lateral and vertical sides will be negated.

Modes of microcantilever operation

Cantilever sensors are now used in static mode and dynamic resonant, respectively. Figure 3 illustrates how different modes have unique ideas about transduction. Surface stress adjustments allow for the determination of the bending in static mode, and the addition of mass allows for the measurement of the resonance frequency during dynamic mode transitions. Microcantilever defluxion calculations, resonance frequencies, and damping properties are among the sensors employed in touch and tapping modes of AFM (3). Static microcantilever deflections are caused by external pressures acting on the microcantilever (like in AFM) or intrinsic pressure created on the lifting surface and within the lifting device. While suspended beams may be produced virtually stress-free using microcantilever production techniques, additional stress is caused by physicochemical changes, thermal expansion, and interfacial activities. Microcantilever dynamic sensors depend on the mass and viscoelastic characteristics of the medium linked to them and are basically mechanical oscillators. For instance, the increased suspended mass of the resonator caused by the adsorption of analyte molecules on a resonant surface lowers the resonance frequency.

A micro-species with a light weight and a high resonant rate should be employed to achieve excellent sensitivity in bulk detection. Systems that effectively detect masses in the zeptogram regions are being proposed right now, and nanosensor-based sensors have even been used to identify single molecules (12).

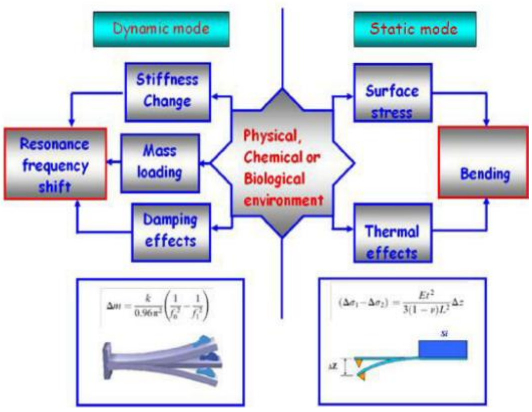

Figure 3: Modes of operation of microcantilever

STIMULATION TECHNIQUES

Piezo stimulation: In this method, MC is mounted atop a piezoactuator that is driven by a frequency generator.

Electrostatic stimulation: In this approach, the microcantilever functions as an electrode in parallel electrodes. By supplying a potential difference between the driver plate and the microcantilever, a periodic force is provided to the microcantilever, enabling it. This works better in a vacuum since air dampens the resonator's movement. Electrostatic stimulation often works well when used in combination with capacitive detecting methods.

Dielectric stimulation: This method often uses two electrodes with a dielectric differential that acts as the microcantilever for the whole system, much like electrostatic stimulation. At the top of the bottom sheet, there can be a gap between the electrodes. This voltage creates lateral stress, which destroys a microcantilever, and pulls both layers together, distorting the dielectric layer.

Integrated piezoelectric stimulation: In this process, a silicon microcantilever is placed on a single-crystalline quartz after a piezoelectric film is pushed onto its two metal contacts. Utilizing a potential gap near the piezoelectric component, the microcantilever is constructed.

Stimulation of resistive heat: In this method, the heating resistor is positioned above the microcantilever. Due to the stress of a local temperature rise near to the heating resistor, the microcantilever expands.

Bimorph-effect stimulation: This method is similar to the previous one in that the predominant deflection occurs in the microcantilever due to differences in the thermal expansion coefficients of the microcantilever material and furnace (14).

MODELLING AND SIMULATION OF MEMS BASED SENSORS

An instrument known as a sensor converts a physical quantity into a corresponding electrical signal. MEMS heavily relies on sensors. The MEMS sensor is made up of a sensing component and related electronics that are used to extract the required electrical output. For multi-sensing applications, sensors may be combined with additional sensors. Three categories are used to categorise these MEMS sensors.

- MEMS chemical sensors (Gas sensors, Cantilever array sensor)
- MEMS Inertial sensors (Gyroscopes, Accelerometers)
- MEMS pressure sensors

COMSOL MULTIPHYSICS

Use the COMSOL Multiphysics programme to simulate geometries into thorough 3D or 2D models or 1D plots using the finite element method (FEM). According to Figure 4, the procedure begins with the constructing geometry in the submicron or micrometre domain. After the geometry has been optimised, the suggested or created model's physics are implemented (15). A better understanding of the science behind the suggested design's functioning is required for assigning physics. Structure mechanics, thermal stress, diluted species movement, Joule heating, thermal expansion, and other physics are only a few of the ones used in model simulation. The physics that have been built may be examined in both static and dynamic modes. Selection of the domain and assignment of materials come after the physics implementation. The materials might either be chosen from the built-in materials or from user-defined materials (16). Basic parameters like the young's modulus (E), poisson ratio (v), density (), and unique properties of the material must be known for the user-defined materials. The next step is to mesh the provided model using the user's constraints. To compensate for computational slowness and relative tolerance, free tetrahedral or free triangular elements with element sizes ranging from very coarse to extremely fine would be preferable. The simulation's last phase involves setting up a stationary solver or a user-defined setup with simulations to produce the desired results on 3D or 2D models in the software program's 3D graphics window.

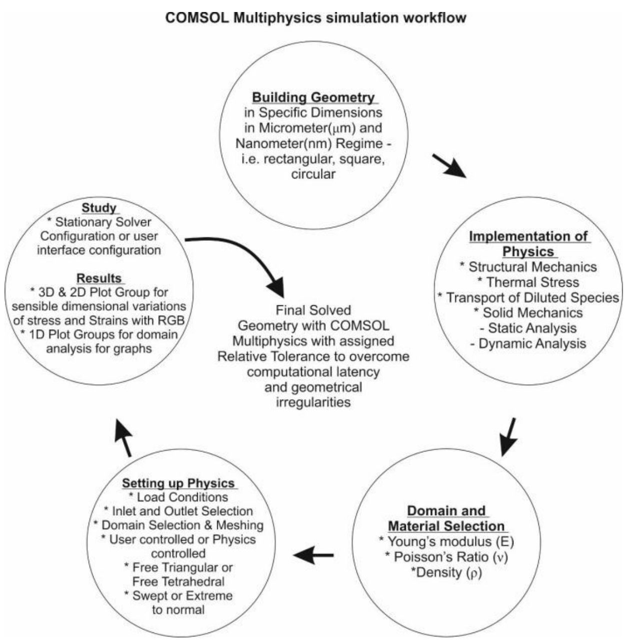

Figure 4: COMSOL Multiphysics model simulation workflow

CONCLUSION

Different sizes and materials have been used to build MEMS-based Microcantilevers. The corresponding displacement increases as beam length increases. Compared to polysilicon and silicon nitride, this SiO_2 material achieves the highest displacement.

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