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Material Selection and Fabrication flow for MEMS Energy Harvester A study

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Abstract. Improving overall performance of MEMS devices is one of the key necessities. Energy harvester output comes accurate if material chosen has mechanical properties to fulfill requirements. During analysis of devices on simulation tools input parameters include Young`s modulus, bulk modulus, shear modulus which are mechanical constants utilized. Hence, material selection based on mechanical, electrical and chemical properties is necessary. Fabrication flow is highly dependent on material selection as well as properties for material to respond to temperature, pressure, stress, strain and performance after going through fatigue. This paper discusses about material selection based on mechanical properties and fabrication flow for same material.

Keywords: MEMS, energy harvester, mechanical properties, fabrication flow.

Introduction

The mechanical properties of material chosen has a wide impact on the performance of micro electro mechanical systems (MEMS). While designing MEMS devices it is crucial to evaluate mechanical properties of the material being used. Precise standards of mechanical properties (fatigue, internal stress, strength, elastic properties) are necessary for obtaining the optimum performances. Material strength sets device operational limits, amount of deflection depends largely on elastic properties and benefits in predicting results when some particular amount of force is applied. Also, device operational limits can be foreseen from its material strength. The mechanical characterization of MEMS materials becomes increasingly important in perspective of reliability and lifetime necessities. MEMS devices are often very small in size which makes them to be used in harsh environments. Due to tough environmental conditions device needs to be rigid hence good knowledge of mechanical properties leads to elimination of any kind of mechanical failure. Accurate material selection, design fabrication and package processing are crucial to avoid any mechanical failure. As the interest grows further a lot of applicable data is required. Repeatability of evaluation methods, accuracy and reliability also became an issue.

Material Selection based on Mechanical properties

The properties of thin films have been evaluated so far mainly to meet the requirements of semiconductor research, but the evaluation mainly focuses on electrical properties and the investigation of mechanical properties mainly only stop at internal limitations. For that reason, the bulk properties were adopted whenever mechanical properties were needed, but as the application of thin films to various mechanical structures increases, there is an increasing need to better understand their mechanical and electrical properties. Therefore, the mechanical properties of thin films used in MEMS must be accurately evaluated. Because of the different properties of bulk materials, they must be measured on the same scale as micro and nano devices. Thin films and bulk materials often differ in composition, phase and microstructure, and the thin film formation process (implantation, thermal treatment, deposition and oxidation). In mechanical processing as there are several processing methods and for most bulk structures as in case of thin films processing method that is used is photolithography and etching. When a structure is formed or processed the finishing of this surface is different. It is necessary to have volume more than surface area or there are chances of size effect to occur. In case of energy harvester size effect is matter of concern. When device dimensions decrease the ratio of surface area to volume increases and hence, needs to be checked. In MEMS when small sizes are to be made then thin films are most preferred which leads to more surface area. The size effect of bulk materials is less recognizable than that of thin films as the structural magnitudes of MEMS devices vary from micrometers to millimeters. Many sizing approaches have been technologically advanced and diverse standards have been measured to appraise mechanical thin film lines. Quantities for MEMS material and their dimensional methods are acquainted due to the lack of wide-ranging and significant research to test the reliability, accuracy and reproducibility of different sizing test tactics for mechanical properties of MEMS materials.

Mechanical Properties to be considered for MEMS Energy Harvester

MEMS uses very different microscale active materials, which may require re-evaluation of bulk material in MEMS applications. There are three main types of features to consider in MEMS industrial processes that are elastic, inelastic and drag properties. Other properties such as optical, electrical, thermal and optical also depends to a great extent on the precise application for which the MEMS device is used. Generally considered properties comprise of dielectric strength, resistivity, thermal conductivity, coefficient of thermal expansion, chemical strength, and opacity.

Elasticity. Elasticity is important to the performance of MEMS devices and is governed by two main parameters, Young's modulus and Poisson's ratio. Material stiffness can be measured by young's modulus (E). Young's modulus is the slope of the linear part of graph that represents stress-strain (ε-σ) of a material. Poisson's ratio is a measure of the directional expansion or contraction of a material when it is subjected to axial stress in the elastic region. The deflection of the membrane centre (d) is measured with the applied pressure (P) across the membrane. Then, the pressure-deflection behaviour of a circular membrane is expressed by

$$P = \frac{4\sigma^0 t}{a^2} d + \frac{8Et}{3(1-v)a^4} d^3 \qquad \text{(Eq.1)}$$

where P is the applied pressure, d is the centre deflection, a is the radius, t is the thickness, E is Young`s modulus, $\sigma_0$ is Poisson`s ratio, v is strain. From equation it is clear that the range of Poisson's ratio of materials is not wide. By making use of bulk properties and rough estimation of the ratio is acceptable.

Inelastic properties. Fatigue causes plastic deformation and in turn, causes failure or a decrease in the performance of a MEMS device.

Strength properties. There are several critical strength-related properties in MEMS era, such as tensile strength, fracture strength, flexural strength, and yield strength. They all indicate the reliability and robustness of MEMS devices. Geometry design and its optimization has great impact on strength properties, hence good geometry can be designed to obtain better outcome.

Fatigue. All such conditions may cause fracture in device geometry and failure of device during operation as a consequence. Fatigue behaviour of a MEMS device also largely depends on its surface effects, resonant frequencies, effect of the environment such as temperature and humidity, size etc.

Material Selection for Energy Harvester Electrode

Energy harvester harvests energy from atmospheric vibrations. In environment there is continuous presence of vibrations with frequencies in range of 1 Hz to 200 Hz. When these vibrations come in contact with harvester sensor, they tend to exert force and cause sensor to vibrate with acceleration around 2g. Thus, causes stress and strain in piezoelectric material which is present in the structure of electrode as the top and most important layer of material. Hence it is required to select a suitable material which will convert most of the stress and strain. There are layers of material in cantilever beam as shown in Figure 1. Piezoelectric layer, electrodes made of metal and silicon as structural layer or substrate.

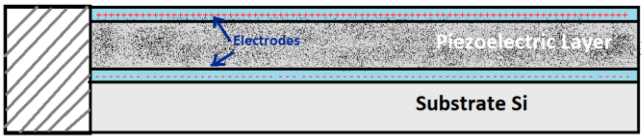

Figure 1. Structure of cantilever beam with three layers

Material for Piezoelectric layer. Piezoelectric materials permit direct electromechanical coupling either with the generation of strain proportional to an applied electric field or the development of an electric charge under an applied external stress. There are very less materials in the group with this unique property. The spontaneous polarization also changes with temperature enabling pyroelectricity. In addition, there is a special class of materials in which the spontaneous polarization can be permanently reoriented between crystal orientation defined states by applying an electric field. This is the key parameter that distinguishes strictly polar materials from ferroelectric materials such as (PZT) (i.e., ZnO, quartz, and AlN). In addition, zero-temperature coefficient properties can be achieved in certain orientations or cuts of quartz, which are extremely important for military and aerospace applications. Quartz-based devices can be found in military and aerospace, research and metrology, industrial, consumer, and automotive applications. All those variety of applications in which quartz is of use, surface waves are in high demand and resonators using both bulk for high-precision oscillators for global positioning systems to everything from low-cost timing devices.

Substrate Material for structural layer. In MEMS, common substrate materials (gallium arsenide GaAs , silicon Si, germanium Ge) all fall in the category of semiconductors. They are at the marginal between insulators and conductors, so they can be made either a conductor or an insulator as needed. Semiconductors can be transformed to a conducting material by doping (p- or n-type) to obtain desired charge density and conduction. for these materials The fabrication processes (e.g., etching) and the obligatory equipment by now have been developed. Silicon becomes most desirable substrate due to its mechanical properties like high Young`s modulus, Poisson ratio, Bulk modulus and density. Silicon can be integrated in electronics for signal transduction on same substrate. High melting point at 1400℃ which is about twice as high as that of aluminium. Hence during material deposition silicon has benefits.

Material for insulation layer. Material to be chosen as insulator must have high electrical resistance and least thermal conduction. SiO_2 has this property. Also, while deciding this layer, it is necessary to note that melting point of insulator layer should be more than piezoelectric layer and less than that of substrate to avoid melting of substrate. SiO_2 has much stronger resistance to most etchants than silicon. Hence, surface micromachining can be used for deposition of silicon dioxide.

Properties	**Shear modulus (Pa)**	**Young`s Modulus (Pa)**	**Poisson`s Ratio**	**Bulk modulus (Pa)**	**Density (kg/m^3)**
Si	7.22e+10	1.9e+11	0.28	1.40e+11	2330
ZnO	4.78e+10	8e+10	0.32	1.42e+11	5860
Al	2.59e+10	7e+10	0.35	7.77e+10	2689
SiO_2	3.20e+10	7.5e+10	0.18	3.78e+10	2220

Table 1. Mechanical properties of material used in Energy Harvester

Fabrication of Energy Harvester sensor

The material used for electrode on sensor is aluminum to reduce cost and stability of electrode function. The manufacturing process starts with n-type silicon wafers. First, the silicon substrate was treated with a solution of RCA1 and RCA2 through a conventional cleaning procedure to remove foreign matter from the substrate. After oxidation, Si_3N_4 (LPCVD) is deposited on the surface of silicon oxide (SiO_2), then shaped and etched. PECVD is the most widely accepted process for depositing SiO_2, Si_3N_4, BPSG and amorphous silicon films. For high performance and excellent control over film characteristics. The deposition of the structural polysilicon layer is carried out by thermal deposition. SiO_2 and ZnO are coupled by sputtering. ZnO thin films can be deposited by various methods such as sol-gel, metalorganic chemical vapor deposition (MOCVD), pulsed laser deposition (PLD), hot water and sputtering increase. This is the most preferable of these RF sputtering methods and sol-gel methods.

Diagram	Step description
	**n type <100> silicon wafer cleaning process with RCA1 and RCA2**
	**800 nm silicon dioxide is grown using thermal oxidation**
	**Silicon Nitride is deposited using LPCVD.**
	**Silicon nitride is patterned and etched using Buffered HF (Phosphoric acid)**
	**Polysilicon is deposited using thermal oxidation.**
	**SiO_2 is deposited by PECVD process**
	**The ZnO thin films deposited by various methods such as sol-gel**

Table 2. Fabrication flow in detail using material Si, SiO_2, ZnO.

Conclusion

Thus, material that is most appropriate for energy harvester sensor are silicon for structural layer, zinc oxide for piezoelectric layer and silicon dioxide for insulator layer. Better Young`s modulus gives better stress to strain ratio which is observed in zinc oxide. SiO_2 is found most suitable in the fabrication process as shown in Table 2. as it has least reactivity to many etchants for silicon. Silicon shows mechanical properties for stress and strain performance leading to long life of device. It also has melting point highest among all chosen materials to withstand any process in fabrication flow.

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