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Modelling the effect of stress on MEMS technology

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Abstract— In this paper we have discussed about MEMS technology and its fabrication. A simple model for fabrication of MEMS based absolute micro pressure sensor has been presented. This is useful for determining its complexity in fabrication steps. This will decrease the need for test iteration and cost, time can also be reduced significantly. Using DevEdit tool (part of SILVACO tool), a behavioral model of pressure sensor have been presented and implemented.

Keywords: MEMS, Pressure sensor, SILVACO.

I. INTRODUCTION

Micro-Electro-Mechanical Systems or MEMS Technology is a device technology that includes sensors, actuators, mechanical elements, and electronic elements on a common silicon substrate through micro fabrication technology.

Micro: Small size
Electro: Electrical Signal/ Control
Mechanical: Mechanical functionality
Systems: Structures, Devices, Systems

The most important elements are the microsensors and microactuators. These are categorized as "transducers", which are devices that convert energy from one form to another form. Microsensor is a device that converts a measured mechanical signal into an electrical signal.

II. MEMS FABRICATION

MEMS fabrication uses many of the conventional techniques that are used in the IC domain like diffusion, ion implantation, oxidation, LPCVD, sputtering, etc.

SILICON

Silicon wafers helps in the monolithic integration of mechanical and electronic functions. They also help building cheap and advanced sensor systems. Therefore, the Si wafers are generally used.

PHOTOLITHOGRAPHY

Basically, photolithography involves applying a layer of a light-sensitive material, called photo-resist on a flat substrate and then illuminating it by some source using some pattern i.e a mask thereby making the illuminated parts either soluble in case of positive photoresist or insoluble in case of negative photoresist and then removing the soluble parts.

GROWTH AND DEPOSITION

Low Pressure Chemical Vapour Deposition is the most suitable method used for depositing compound materials such as silicon-oxide, silicon-nitride poly-silicon and phosphor silicate glass.

DOPING

Doping of silicon is mostly done with either boron or phosphor. This is a means for changing the electrical properties and mechanical properties of silicon as well as the etching behaviour in certain etching solutions. Doping is accomplished by ion implantation where high energy ions penetrate to a certain depth when coming from an accelerator and hit the silicon surface. This is precisely controlled by the energy of the ions hitting into substrate. In-diffusion at elevated temperatures can also be used for doping.

BULK MICROMACHINING

Bulk micromachining is the technique by which structures can be made inside the silicon substrate instead of making on top of it by selectively removing material. This technology makes structures that are released or undercut such that elements come into existence that can somehow move with respect to the frame of the wafer.

There are many different methods for etching. The most commonly used are wet-chemical etching and dry etching (e.g. Reactive Ion Etching, RIE).

On the basis of etch profiles etching methods can be distinguished as:1. Isotropic where etch-speed is equal in all directions causing rounded structures,
2. anisotropic where etching speed is highly dependent on the crystallographic directions causing edges and corners and 3. directional that is due to geometrical effects of dry etching. Dry etching takes place in a vessel which has certain pressure of that of vacuum (10-5-0.5 Torr) and they all use accelerated and reactive particles like ions, atoms for etching. Additionally, chemical species may be added to enhance etching and passivation. Etching mechanisms involve physical removal due to bombardment (directional) and chemical reactions involving removal of volatile reaction products.

SURFACE MICROMACHINING

Surface micromachining technology enables us to make small features just above the silicon substrate that can move partly free from the substrate. This can be accomplished by using one layer as the sacrificial layer. Etching away this layer, we get the structural. In a first step a sacrificial layer is deposited on the silicon substrate. Subsequently this layer is shaped using photolithographic and etching techniques. Next a layer of the structural material is deposited over the sacrificial layer. Again using photolithography and etching the structural layer is shaped and holes are made to allow etching fluid to reach the sacrificial layer in selected areas. Finally the sacrificial layer is completely removed by wet-chemical etching thereby releasing the structural layer partly.

Various combinations of structural and sacrificial materials exist. However, the most widely used surface micromachining technology uses polysilicon as the structural material and either silicon-dioxide or phosphor silicate glass (PSG) as the sacrificial layer.

BONDING AND CHEMICAL MECHANICAL POLISHING

Anodic bonding is applied to a pair of a good conducting layer (such as metal, silicon) and a slightly conducting layer (such as glass). Using a voltage over the wafer pair will induce a small depletion layer in the glass wafer resulting in a large electrical field over a short distance near the interface of the wafers. The electrostatic field thus produces pressure that will bring the wafers in such close contact that they will join together. Executing the process at high temperatures (about 400-500 °C) will allow the formation of covalent bonds at the glass-conductor interface. Anodic bonding is possible for wafers with a roughness of less than 1 micrometre.

Another method of bonding is silicon fusion bonding. This type of bonding can occur between layers that have a roughness of 1 nanometre or less. The bonding energy of wafers covered with native oxide are thought to originate from hydrogen bridging formed by annealing in a wet-oxidation oven at temperatures of about 700 °C. Since the requirements for silicon fusion bonding, especially the extreme smoothness of the wafers, are generally hard to meet, it is a difficult process. However, there is a technology which can help to make the process more applicable: Chemical Mechanical Polishing (CMP).

In CMP the wafer is placed on a rotating polishing head and moved under a certain pressure over a polishing pad. A slightly alkaline slurry containing nanometre sized silica particles is also added. The combined action of wear and etching yields smooth surfaces.

III. MEMS PRESSURE SENSORS

The Pressure sensors are an integral part of many systems. MEMS Pressure sensors offer low cost, on chip pressure sensing capability. Among the various transduction topologies available for the sensor, piezo resistive type is the most widely used. MEMS sensors offer compatibility with the CMOS fabrication process.

Very often, the force to be measured is converted into a change in length or height of a piece of material, the spring element. In pressure sensors the spring element is always a membrane. Conventional pressure sensors used metal membranes. The combination of small size, high elastic modulus and low density of silicon results in sensors with a very high resonance frequency. The first silicon pressure sensors were based on a piezoresistive read-out mechanism. At the moment, piezoresistive pressure sensors are still the most widely used. Piezoresistors may be diffused in the membrane or deposited on top of the membrane. Usually, the resistors are connected in a Wheatstone bridge configuration for temperature compensation. The main advantages of a piezoresistive read-out mechanism are the simple fabrication process, the high linearity and the fact that the output signal is conveniently available as a voltage. The main problems are the large temperature sensitivity and drift. Furthermore, because of the low sensitivity of piezoresistors, piezoresistive devices are not suitable for accurate measurement of very low pressure differences. Capacitive read-out mechanisms are inherently less sensitive to temperature variations and an extremely low power consumption can be obtained. However, the capacitance to be measured is usually very small and an electronic interface circuit is required, which either has to be integrated on the sensor die or at least has to be positioned very close to the sensor chip.

The highest accuracy can be obtained by using resonant sensors where the output signal is in the form of a change in resonance frequency of a vibrating element.

PIEZORESISTANCE OF SILICON

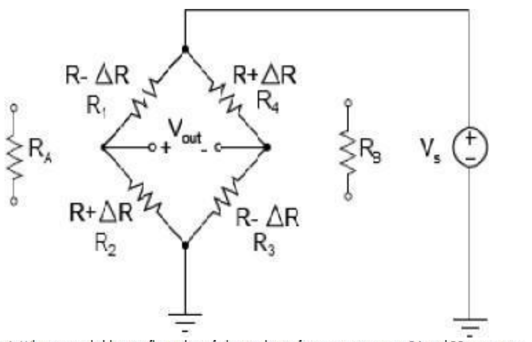

Fig. 1: Wheatstone bridge configuration of piezoresistors for pressure sensor. RA and RB are sensor resistors.

The resistance of the silicon piezoresistor is a function of stress in the material and the orientationof the piezoresistors. The variation of resistance due to stress is given in Eqn (1)

$$\Delta R/R = \pi t\ \sigma t + \pi l\ \sigma l$$

where,

'σt' Transverse stress
'σl' Longitudinal stress
'πt' Transverse piezoresistive coefficient
'πl' Longitudinal piezoresistive coefficient
'ΔR' Change in resistance
'R' Resistance of piezoresistor

DESIGN OF PRESSURE SENSOR

The pressure sensor can be designed using four piezoresistors arranged in Wheatstone bridge configuration along <110> axis on the membrane. The maximum stress on the piezoresistor with a square membrane which has a width of '2a', a thickness of 'h' and uniform pressure of 'P' is given by eqn (2) as

$$\sigma edge = P\,(a/h)^2$$

Using Eqn. 2 and Eqn. 1 we get Eqn (3) as

$$\Delta R/ R = \pi l\,(a/h)^2\,(1- \nu)\,P$$

where 'ν' is Poisson's ratio.
For silicon 'ν' is ≈ 0.3. Thus, we get ΔR/R = 0.13825. In wheatstone bridge configuration when all the resistors are equal then we will get the output voltage as shown in Eqn (4)

$$Vout =(\Delta R/ R)\, Vs$$

where,
'Vs' Supply voltage
'Vout' Output voltage

MICROMECHANICAL SENSORS PRINCIPLES

These sensors has some mechanical structure whose properties depend on specific environmental conditions. If the mechanical structure is deformed in some way this deformation is sensed and converted into an electrical signal. The way in which mechanical structures deform, depends on their shapes as well as on the mechanical properties such as Young's Modulus 'E', Poisson ratio 'υ', mechanical load or stress distribution 'σ(x,y,z)'and the way these are connected to their surroundings and some environmental parameter(s) like pressure, acceleration, rotation, temperature, humidity etc. Mechanical changes can also be well observed in dynamic behaviour. For example considering the influence of stress on the resonant frequency of micro-bridges we can observe that by increasing the stress the resonant frequency will increase as well as in the case of macroscopic string-instruments. Resonant sensors can achieve high resolutions of 100 ppm or even better.

IV. MODELING FOR FABRICATION OF PIEZORESISTIVE PRESSURE SENSOR BY USING SILVACO TOOL

SOFTWARE DETAILS

SILVACO is an Electronic Design Automation (EDA) software, that helps in device modelling and simulation. This tool was founded in 1984 by Dr. Ivan Pasee. The tool has different parts like Tony Plot, Maskview, Deckbuild, and Optimizer. DevEdit is a powerful tool for structure modelling, editing and remeshing. It helps to either create a device on the mesh or edit the same. DevEdit creates a standard structure which can easily be integrated into Silvaco 2D or 3D simulators.

DESIGNING

In the designing process, Micro Pressure Sensor has resistors, arranged in wheatstone bridge configuration, on the membrane, which has etch holes on it from where the etch materials enters in the bulk of substrate, towards the contact pads and the lines from resistors to these pads are the metal contact lines. Main challenge is change in the resistance of the resistors due to strain on the membrane, which creates a potential difference thus giving the pressure output. In order to increase the sensitivity of the bridge the resistor is placed on the membrane to obtain the maximum potential difference. Piezoresistors over the membrane are made of boron-doped polysilicon because of its good piezoelectric effect. On increasing the polysilicon layer thickness, the sheet resistivity decreases. The design parameters of above-mentioned structure are shown below:

Chip size: 1 mmx 1 mm
Membrane Size: 100 µm x µm
Membrane Thickness: 0.7 µm
Resistor's Configuration half-Wheatstone Bridge
Resistor's Length: 110 µm
Resistor's Width: 10 µm
Resistor's Pad Size: 20 µm x 20 µm
Resistor's thickness: 1.0 µm
Metal Contact Pad size: 100 µm x 20µm
Metal contact line width: 20 µm
Resistor's value: 0.22 Kohm
Sheet resistivity of resistor's: 20 Kohm-m

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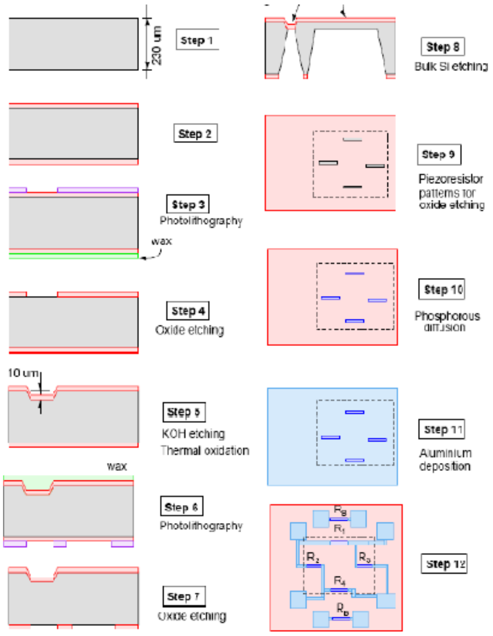

Steps to fabricate membrane for MEMS pressure sensor

MODELING PROCEDURE FOR FABRICATION PROCESS THROUGH SILVACO

1. Click on Dev Edit icon in SILVACO tool.
2. Select the work region parameters from the region menu.
3. For <100> boron doped silicon wafer, select ADD region from Region menu. From right side window select siliconfrom material tab.
4. For thermally grown SiO2, from region menu select add region, then from right window from material tab select SiO2.
5. For SI3N4 layer, again repeat the same process.
6. For window opening (PLG-I) use the Reactive Ion Etching(RIE) of Si3N4 and wet etching of SiO2, select Add Region from Region menu and select the particular part where etching is required and then from right window click on Apply button. Another window appears. Right click on the particular layer from where a window pops-up and select delete region. Finally, that layer will be deleted.
7. Finally we obtain the etched layer.
8. Similarly we can also etch the SiO2 layer.
9. Now apply the same method for Polysilicon Layer.
10. We use the same method for PLG-2 + RIE of polysilicon.
11. For patterning of different layers like Si3N 4+SiO2+Si3N4, apply the same process that is mentioned above; thus etched structures appear in sequence.
12. Now deposition of polysilicon layer and its patterning is done.Resistors are defined for PLG-3+etching of polysilicon.
13. Metallization of Al for contact lines and resistors pads is done.
14. For PLG-4 and wet etching of Al is done.
15. APCVD is carried out for SiO2 and PECVD for Si3N4.
16. PLG-5 + RIE of composite layer (Si3N4 +SiO 2+Si3N 4) for etching hole, so that KOH etchant can enter into the bulk of the substrate to form the V shaped cavity.
17. KOH etching is done for Poly Si & Si in bulk of substrate for forming the cavity after which the cavity is sealed by LPCVD techniques.
18. Finally the 2-D structure is obtained and final pressure sensor model appears.

V. CONCLUSION

We conclude that the MEMS pressure sensor model developed is based on the principle of piezoelectric effect that occurs due to the pressure applied over the membrane and hence changes the resistance deposited over the membrane. This model uses half-Wheatstone bridge, consisting of four resistors, two of which are lying over the membrane i.e in the active region and the rest of the two are out of active region. The membranes are developed by using wet chemical etching techniques of bulk silicon and the n-type single crystal piezoresistors are fabricated using phosphorous diffusion.

Absolute Piezoresistive Micro Pressure Sensor using MEMS technology are the most useful sensor for the future electronic system because of its wide application in health care to transportation. They satisfy industrial and biomédical demands such as sensitivity and linearity.

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