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Design and Fabrication of Piezoresistive Based Encapsulated Poly-Si Cantilevers for Bio/chemical Sensing

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Abstract

Cantilever-based sensing is a growing research field not only within micro regime but also in nano technology. The technology offers a method for rapid, on-line and in-situ monitoring of specific bio/chemical substances by detecting the nanomechanical responses of a cantilever sensor. Cantilever with piezoresistive based detection scheme is more attractive because of its electronics compatibility. Majority of commercially available micromachined piezoresistive sensors are bulk micromachined devices and are fabricated using single crystal silicon wafers. As substrate properties are not important in surface micromachining, the expensive silicon wafers can be replaced by cheaper substrates, such as poly-silicon, glass or plastic. Here we have designed SU-8 based bio/chemical compatible micro electro mechanical device that includes an encapsulated poly-silicon piezoresistor for bio/chemical sensing. In this paper we report the design, fabrication and analysis of the encapsulated poly-Si cantilevers. Design and theoretical analysis are carried out using Finite Element Analysis software. For fabrication of poly-silicon piezoresistive cantilevers we followed the surface micromachining process steps. Preliminary characterization of the cantilevers is presented.

Keywords: Nanotechnology; Piezoresistivity; Surface micromachining; Encapsulated Polysilicon; SU-8; Coventorware

1. Introduction

Micro/Nano Cantilever based biosensors have attracted considerable interest to monitor a specific substance in applications such as clinical analysis, environmental control and industrial processes [1]. The technology offers a method for rapid, label-free, on-line and in-situ detection of specific bio/chemical analytes by detecting the nanomechanical response of a cantilever sensor [2, 3]. Cantilever sensors can be operated either in dynamic mode or static mode. The adsorption of molecules onto the surface of the cantilever generates a small-magnitude (5 to 0.5N/m) surface stress, which results in a bending of the cantilever to the tune of a few tens of nanometers [4]. The signal detection mechanisms could be optical, mass change or piezoresistive (strain-induced resistance change) [5].
Piezoresistivity is an important characteristic which has resulted in the widespread utilization of such materials for sensors [6-7]. The piezoresistive effect, first reported by Smith [8] in 1954 in silicon, produces an approximately two orders of magnitude larger resistance change than that due to the dimensional change under an applied stress in a typical conductor. Piezoresistive sensors fabricated on micromachined diaphragms dominate pressure, acceleration and force sensing applications. For small deflections of thin diaphragms, the change in resistance is

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linear with the applied pressure [9]. Silicon obeys the Hooke'slaw up to 1% strain, much higher a range than most metal alloys. The resistance of the resistors used for these types of piezoresistive microsensors is proportional to the external stress when the resistivity change is ignored since the dimensional change is proportional to the applied pressure.

In this paper for the first time, we present the design and fabrication of a novel polymeric cantilever, with an embedded nano poly-Si piezoresistor. These cantilevers can be used for bio/chemical sensing. The polymer used to fabricate the encapsulation layer was SU-8, which is a negative tone chemically amplified near UV photoresist. It is highly resistant to chemicals and hence can be used as a component material [10]. Fabricating a structural layer SU-8 is a low-cost extremely low thermal budget process. Based on the structural requirements SU-8 can be thinned, spin coated and can thus provide a very thin film without recourse to the conventional deposition techniques. Secondly, SU-8 with its low Young's modulus (5 GPa), has a higher propensity for bending, compared to silicon nitride (150–350 GPa), for a given surface stress.

The basic design and fabrication issues in polymeric cantilevers for bio-microelectromechanical system (bio-MEMS) applications were studied and reported in this paper. Thermal budget limitation was the critical unresolved technology issue that prevented the integration of a poly-Si film with a polymer such as SU-8.Very expensive Low pressure, plasma-enhanced and low-temperature hotwire CVD [11-12] processes normally used for poly-Si deposition. However, we are presenting a new process flow using the cost effective and simple sputter deposition system for poly-Si deposition resolving the thermal budget limitations.

2. Design Analysis:

The piezoresistive effect is the change in electric resistance of the material caused by an applied mechanical strain or stress. The change in resistance of a piezoresistive material when subjected to a mechanical deformation is used to measure physical quantities such as pressure, force and acceleration. Analysis of the mechanical deformation and piezoresistive property of the beam as coupled field simulation has been carried out with MemMech and MemPZR modules from Coventorware. The applied stress and the material's piezoresistive (PZR) coefficients are used to compute sensor's potential field and resulting change in current. The module facilitates the design of multiple piezoresistive sensors of arbitrary shape and size in MEMS devices.

The design of encapsulated Poly-Si cantilever has been virtually fabricated in Coventorware. Fig. 2(a) shows SiO2 as bottom layer /Poly-Si as piezoresistive layer /SU-8 as top conformal layer. The conformability of the SU-8 layer plays a critical role in the encapsulation of Poly-Si cantilever and in the compatibility of bio/chemical analyte. The conformability factor is assumed as unity and the step profile in SU-8 has an advantage of proper positioning of the analyte or biomass sample.

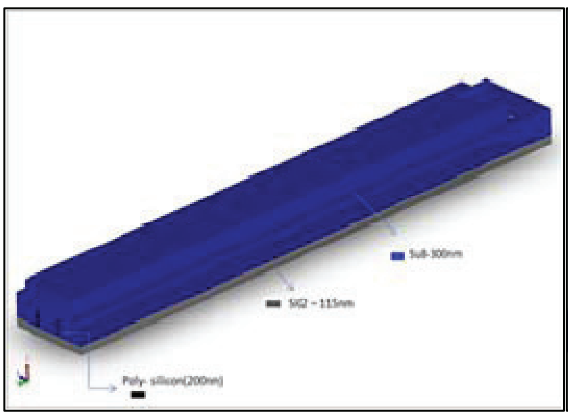

Fig. 2(a) Encapsulated Cantilever

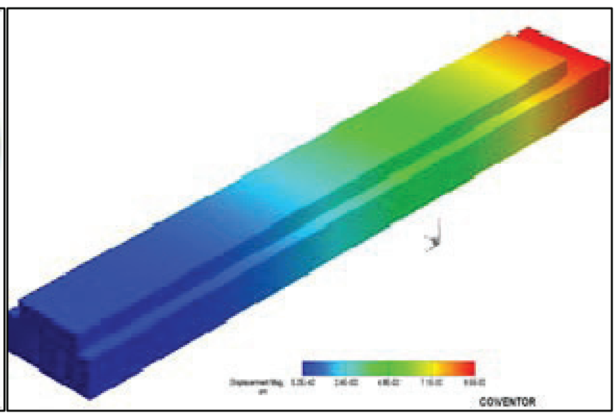

Fig. 2(b) Mechanical deformation at applied load

The virtually fabricated cantilever is loaded in mechanical deformation analysis for load patch effects. The load patch is defined as the pressure applied on the confined area. The step profile due to the conformability is an advantage in defining the area as 1.5µm X 0.5µm. The estimated load values to analyze the piezoresistive effect are from the 10e-17grams to 10e-9grams in steps of 10e-1. The design is meshed with the Manhattan Bricks (Finite Element Model) by 0.125µm X 0.125µm X 0.125µm and the mechanical deformation analysis has been carried out in MemMech module. The Fig. 2(b) shows the mechanical deformation at applied load of 10e-14grams.

The MemPZR module analyzes the coupled field simulation between mechanical and piezoresistive energy domains. To transfer the stress to Poly-Si piezoresistive material, mechanical deformation data has been created in MemMech module, which is in turn transferred to the MemPZR. This helps in analyzing the change in current or resistance of the Poly-Si. The mechanical strain influenced piezoresistive Poly-Si is shown in Fig. 2(c). The varying lengths of the encapsulated beam vs. change in resistance after applying a voltage of 5V is shown in Fig. 2(d). From the plots it is clear that the change in resistance is proportional to the length of the beam and this is because, maximum deformation is occurring when the length is maximum. The change in resistance of the cantilever beam denotes the sensitivity of cantilever. Piezoresistive coefficients of piezomaterial will be optimized based upon doping concentration and these affects are to be included in the part of simulation to optimize the highly sensitive encapsulated piezoresistive cantilever.

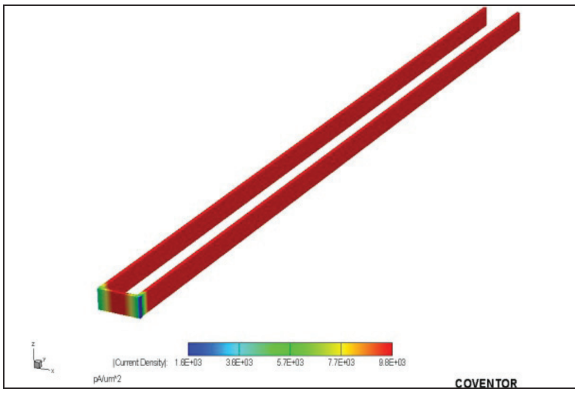

Fig. 2(c) Mechanical strain in Poly-Si Cantilever

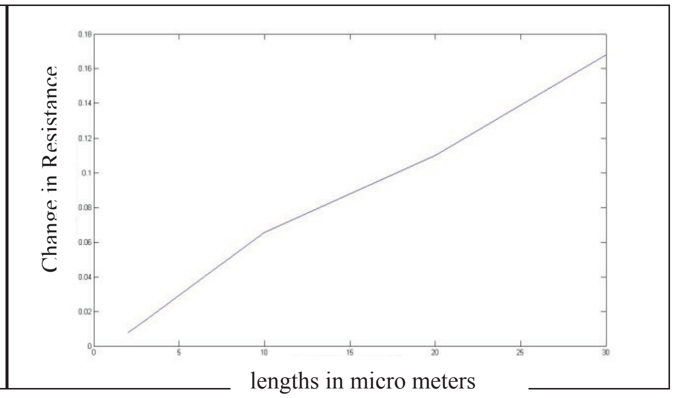

Fig. 2(d) Cantilever length vs. Change in resistance

3. Device Fabrication

A. *SiO2/Polysilison/SU-8 Cantilevers:* To fabricate the structure, a series of deposition, patterning and etching steps were employed Fig. 3(a)–(h) shows the main steps of the fabrication process. First, Silicon <100> wafer was cleaned with piranha (1:3 H_2O_2 : H_2SO_4) and followed by the RCA cleaning procedure.

B. *Structural Layer:* Dry oxidation is carried out on the wafer for 210 minutes at 1100^0c and 115nm of SiO_2 is grown. This step yielded the bottom layer, i.e., structural layer of the cantilever, which is shown in Fig. 3(b)

C. *Poly-Si layer Lithography:* Poly-Si layer was obtained by lift off process using electron beam lithography. PMMA/EL9 (Poly(methyl methacrylate)) were spin coated to get a total thickness of 300nm. Sample was prebaked at 180 degrees for 5 min on hotplate. Exposure was done using Raith E LiNE direct write electron beam lithography system at an acceleration voltage of 10kV and beams current of 240pA. Samples were developed in MIBK: IPA (1:3) for 30 seconds.

D. *Piezoresistive Layer Sputtering:* 200nm Poly-Si is sputtered using the Anelva RF Sputtering unit with following parameters; Target material is P type silicon, target to substrate distance is 5.2 cm, deposition pressure is 0.008mbar, plate voltage is2KV, plate current is 130m amp, incident power is 189 watts, reflected power is approx 0 watts, pre sputtering time is 15 min and with deposition time of 5 min. Lift off is carried out using acetone and the sample is annealed in forming gas ambient at 950^0c for 3 hours. SEM image of the Poly-Si is shown in Fig. 3(i)

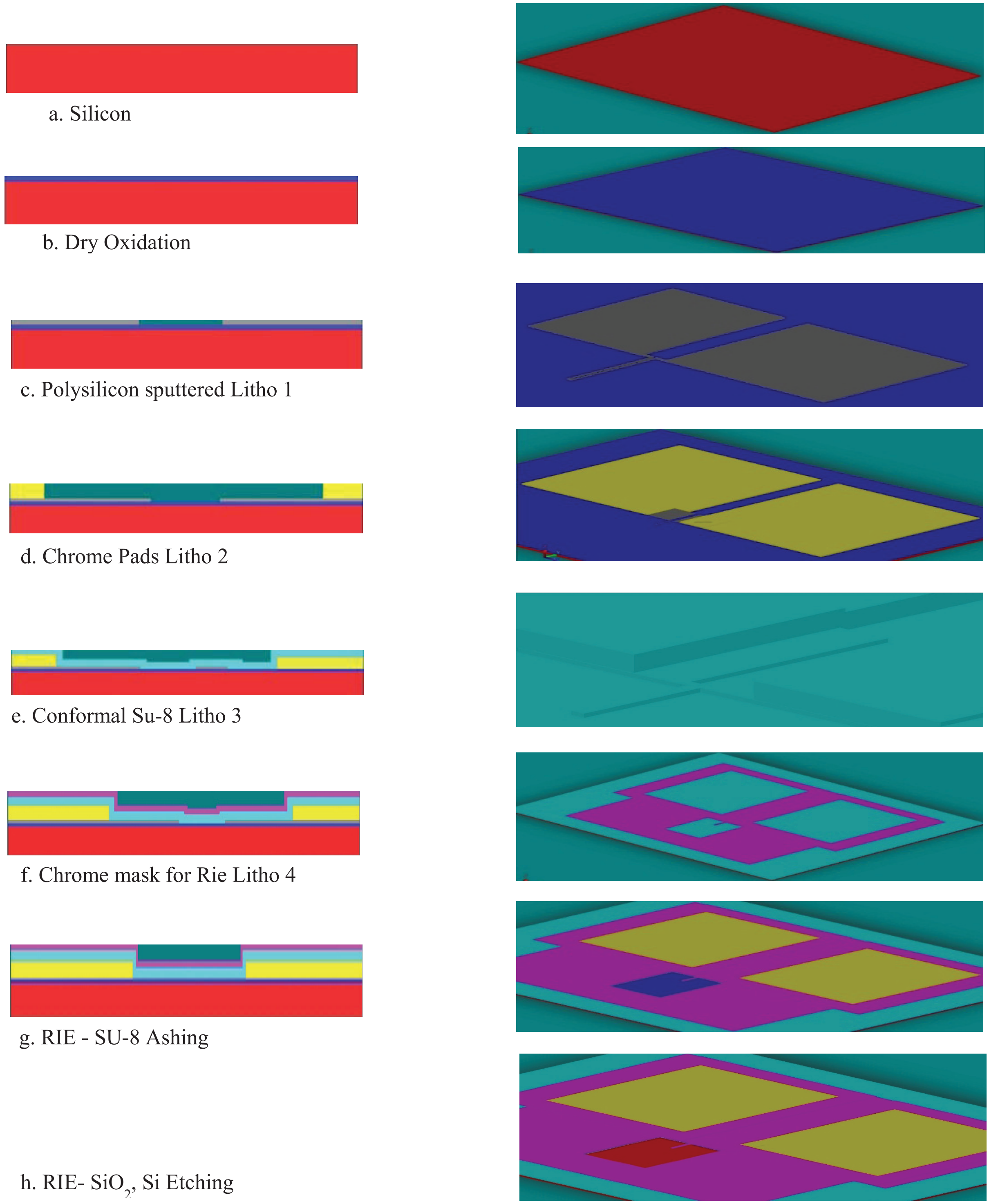

Fig.3 (a-h) Cross section and top view of the process steps

E. *Contact pad Lithography (Mask 2):* 100µ/100µ contact pad lithography is carried out over the poly-Si. A 1.4 µm AZ5214E positive photoresist layer was spun at 4000 rpm on the substrate. It was then subjected to a soft bake at 90^0C for 1 min, followed by laser writing. The substrate was then immersed in AZ351B developer for 1 min.

F. *Contact pad deposition and lift off:* 180nm chrome is sputtered using the Anelva RF Sputtering unit with following parameters; Target material is Chrome, target to substrate distance is 7 cm, deposition pressure is 0.008mbar, plate voltage is2.5KV, plate current is 98m amp, incident power is 180 watts, reflected power is 55 watts, pre sputtering time is 10 min and with deposition time of 4 min. Liftoff is carried out using acetone, which is shown in Fig. 3(d)

G. *Immobilization Layer:* The encapsulation of the poly-Si piezoresistor was essential so that the biochemicals do not short the piezoresistors. The top SU-8 encapsulation layer was also the immobilization layer of the device. A 300 nm of thinned SU-8 2002 (SU8: thinner 1:2) layer was spun at 7000 rpm on the substrate. It was then subjected to a soft bake at 65^0C for 1 min and 95^0C for 1 min followed by UV flood exposure at 200mj/cm^2 in the steps of 2. The exposed SU-8 was subjected to a post exposure bake of 65^0 1 min and 95^0C for 1 min. The substrate was then hard baked at 300^0 C for 10 minutes and then allowed for a relaxation time of 20 minutes. This step yielded the top layer of the cantilever; image is shown in Fig. 3(e)

H. *Chrome mask for RIE (Mask 3):* 70µ/80µ contact pad lithography is carried out over the SU-8. The parameters for the lithography were same as the contact pad lithography. Then chrome is sputtered and the liftoff is carried out. The parameters for the chrome sputtering were same as the contact pad chrome sputtering; the image is shown in Fig. 3(f). Su-8 is getting washed off in RIE and is affecting the other layers when thick SU-8 was used as mask, so metal chrome mask was chosen.

I. *SU-8 Ashing in the pads region:* As SU-8 was blanket coated without mask; the SU-8 ashing has been carried in Anelva Reactive Ion Etch tool in oxygen plasma environment. The parameters used were as follows: O_2 - 204 sccm, incident power of 150 watts. Reflected power is approximately 0, Plate current is 100m amps with etch pressure 0.1 mbar and etch time is 5min. After RIE image is shown in Fig. 3(g)

J. *Releasing Cantilever:* After a gap of 5 minutes, silicon and silicon dioxide etching has been carried in the same equipment with the following modified parameters: Cf_4- 51 sccm, O_2- 11 sccm, incident power is 150 watts. Reflected power is approximately 0, Plate current is 100m amps with etch pressure 0.1 mbar and etch time is 20min (in two steps- 15+5 min). The 115 nm of SiO2 would have been selectively etch in around 2 min and then silicon which was acting as the sacrificial layer is isotropically etched from the bottom of the cantilever and then released the cantilever. Image of the same is shown in Fig. 3(h). The Dry RIE release of the cantilever process is in the process of optimization. This Dry release of the cantilever is chosen because to eliminate the issues of the wet chemical etching. SEM image of the sample after RIE displaying the contact pads is shown in Fig. 3(j) and released cantilever is in Fig. 3(k).

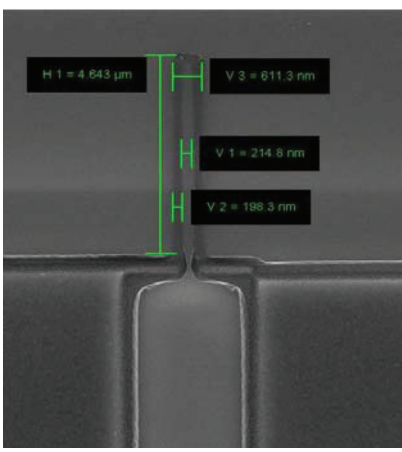

Fig. 3.i Poly-Si Sputtering

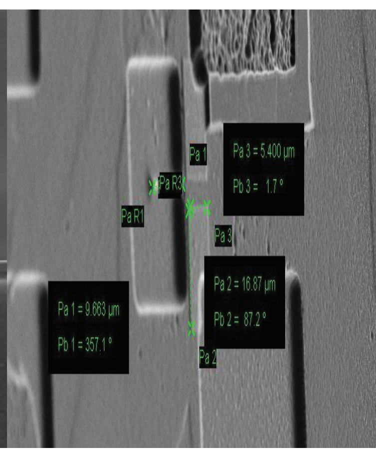

Fig. 3.j Cantilever and pads

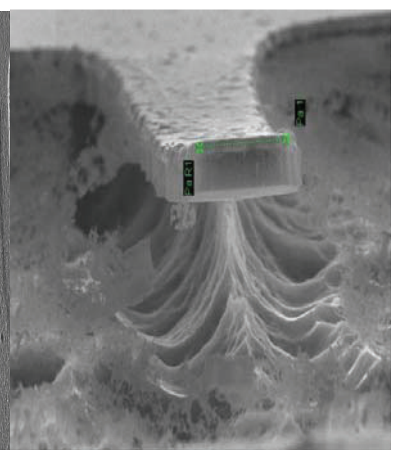

Fig. 3.k Released Cantilever

4. Conclusion

In this paper, we have reported the design and fabrication of a novel polymeric cantilever, with an embedded nano poly-Si piezoresistors using a three-mask process. These cantilevers can be used for bio/chemicals sensing. The poly-Si piezoresistor was fully encapsulated by SU-8 and SiO_2, which helps in protecting the piezoresistive material from bio/chemical analytes. The basic design and fabrication issues in polymeric cantilevers for bio-microelectromechanical system (bio-MEMS) applications are discussed. We have proposed a new process flow using the cost effective and simple sputtering system for poly-Si deposition, resolving the thermal budget limitations. The change in resistance with varying lengths of the beam and varying loads are analysed.

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