FABRICATION OF DUAL- AND SINGLE-LAYER PIEZORESISTIVE MICROCANTILEVER SENSOR

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ABSTRACT

In this paper, the fabrication of piezoresistive microcantilever (PRM) sensor was realized through the utilization of bulk micromachining technology. Through a sequence of photolithography and etching processes, the device fabrication is realized. The fabrication of two PRM designs, dual-layer and single-layer has opened up the opportunity for device improvement especially in fabrication methods for simpler and reduced process steps. In single-layer design, the fabrication at reduced process steps which offers simpler and reproducible device has been successfully realized. This design offers simpler fabrication process by not only reducing the number of process steps but also eliminating the common fabrication issues encountered in bulk micromachining technology. With the development of single-layer doped silicon PRM sensor, the thermal strain issue, due to mismatch in coefficients of thermal expansion of multi-layered structure is not an issue. The novelty of this work lies in the design itself, in which the single-layer dual leg design not only simplifies the fabrication work, but also promotes an efficient current distribution along the piezoresistive dual-leg structure which is integrated with Wheatstone bridge configuration.

Keywords: piezoresistor, microcantilever, MEMS.

INTRODUCTION

Piezoresistive microcantilever sensor is one of the promising mechanical microsensors that have been around for many years. This cantilever-based device offers high sensitivity, reduced cost and possibility of miniaturization. In biosensing application, a device which is easy to use, cheap and highly sensitive is desired for its robust performance (Vashist 2007). Piezoresistive microcantilever sensor is therefore the ideal candidate which provides the outstanding platform for the development of microcantilever biosensor.

Concerted efforts on the piezoresistive microcantilever biosensor development generally focus on integrating different sensor elements and electronic functions on a single chip, and combining microelectronics with biologically related molecules such as deoxyribonucleic acid (DNA), or any other biological entities (Wee *et al.* 2005, Villanueva *et al.* 2007) . To achieve these long-term goals, current researches are now focusing on achieving smaller size device, simpler fabrication process, reduced cost and high performance of the fabricated biosensor (Bais *et al.* 2009, Bais *et al.* 2011, Park *et al.* 2010, Firdaus *et al.* 2010).Various microfabrication techniques, from bulk to surface micromachining, or a combination of both are considered. Still, not many of the fabrication approaches available today satisfy all the desired requirements. Very few commercial products of the piezoresistive microcantilever sensor are currently available in the market today, indicating that the device's fabrication processes have not matured yet. Fabrication of the device utilizing high-cost process of dry etching in microcantilever release have been widely used (Fang *et al.* 2006, Zhou *et al.* 2009). Using wet etching, the fabrication cost is significantly reduced but common issues in the fabrication of the suspended microcantilever structure, particularly in the microcantilever release process which revolve around the inherent problems such as stiction force and residual stress keep reoccurring and become a major concern. The art of modifying the fabrication techniques, together with a suitable design that can accommodate the concerning issues is of a great interest. Therefore, this work attempts to provide the process development of effective design of piezoresistive microcantilever (PRM) biosensor through simple and reliable fabrication processes.

A novel single-layer piezoresistive microcantilever integrated with Wheatstone bridge circuit is introduced, which utilizes doped silicon material as the piezoresistor and mechanical structures. This design offers simpler fabrication process by not only reducing the number of process steps but also eliminating the common fabrication issues encountered in bulk micromachining technology. With the development of single-layer doped silicon PRM sensor, the thermal strain issue, due to mismatch in coefficients of thermal expansion of multi-layered structure is not an issue. The novelty of this work lies in the design itself, in which the single-layer dual leg design not only simplifies the fabrication work, but also promotes an efficient current distribution along the piezoresistive dual-leg structure which is integrated with Wheatstone bridge configuration.

FABRICATION OF PIEZORESISTIVE MICROCANTILEVER

The fabrication of two designs of PRM; single-layer and dual-layer as shown in Figure-1 have been considered. The single-layer design refers to a single material, in this case; silicon used to form PRM structure while dual-layer refers to two materials; silicon and silicon oxide used to form piezoresistor and microcantilever structure, respectively. The comparison between both designs enables us to choose simpler and reproducible fabrication methods in devising PRM sensor.

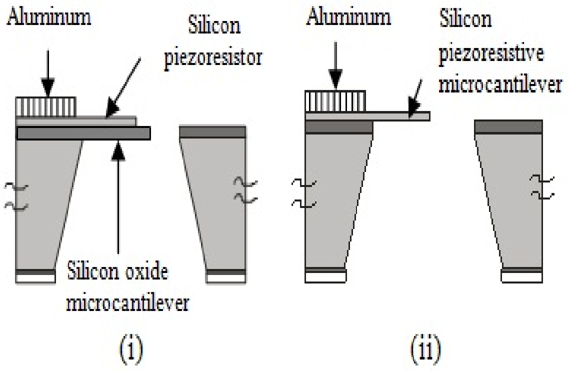

Figure-1. Cross section of (i) dual-layer and (ii) single-layer piezoresistive microcantilever sensor.

The fabrication process is started with the formation of dual-layer PRM sensor. In this design, doped-silicon layer is used as the piezoresistor while silicon oxide layer is used for the microcantilever structure. Figure-2 (i) illustrates the fabrication process flow for the design. Problems encountered during fabrication process leads to the consideration of another design which is single-layer PRM sensor. In the single-layer design, the doped-silicon layer is used for both piezoresistor and microcantilever structures while the silicon oxide layer acts as an etch stop layer. Following fabrication process flow as shown in Figure-2 (ii), the formation of single-layer PRM sensor is successfully realized.

For dual-layer design, steps (1) to (3) are conducted for piezoresistor development, steps (4) and (5) for microcantilever structure formation, steps (6) to (8) for Wheatstone bridge connection and steps (9) to (11) for microcantilever release. For single-layer design, steps (1) to (3) and steps (4) to (6) are done for PRM structure and Wheatstone bridge formations, respectively while steps (7) to (9) are meant for microcantilever release.

In overall, the single-layer design has the advantage of simpler process with only three photolithography steps. For dual-layer design, four photolithography steps are required as the patterning of piezoresistive and microcantilever structures have to be done separately. The significant reduction in fabrication process steps for the single-layer design can be translated into reduced processing time and cost.

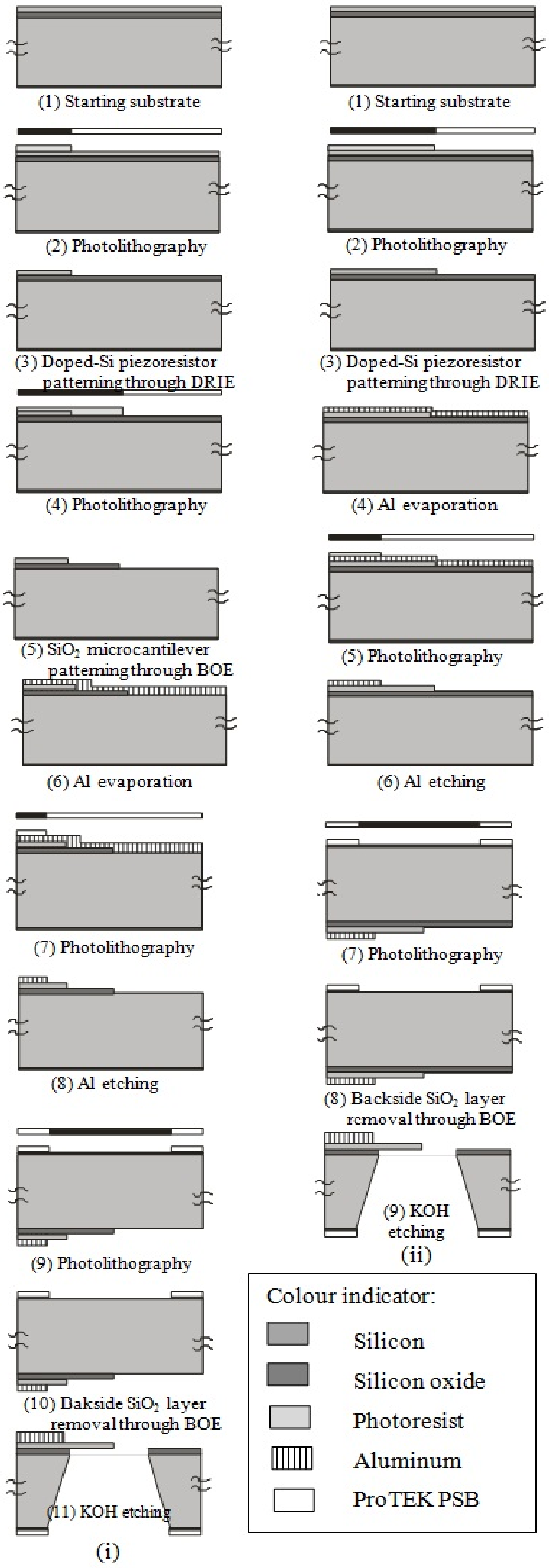

Figure-2. Simplified process flow for (i) dual-layer and (ii) single-layer PRM sensor.

RESULTS & DISCUSSIONS

Dual-layer piezoresistive microcantilever

For the dual-layer PRM sensor, the Al contact pads were patterned to the dual- legs of the piezoresistor for electrical connectivity in Wheatstone bridge configuration as shown in Figure-3 (a) and (b). At this stage, the silicon oxide layer was not only used as the microcantilever structure but also as the isolation layer between the Wheatstone bridge configuration and the bulk silicon substrate.

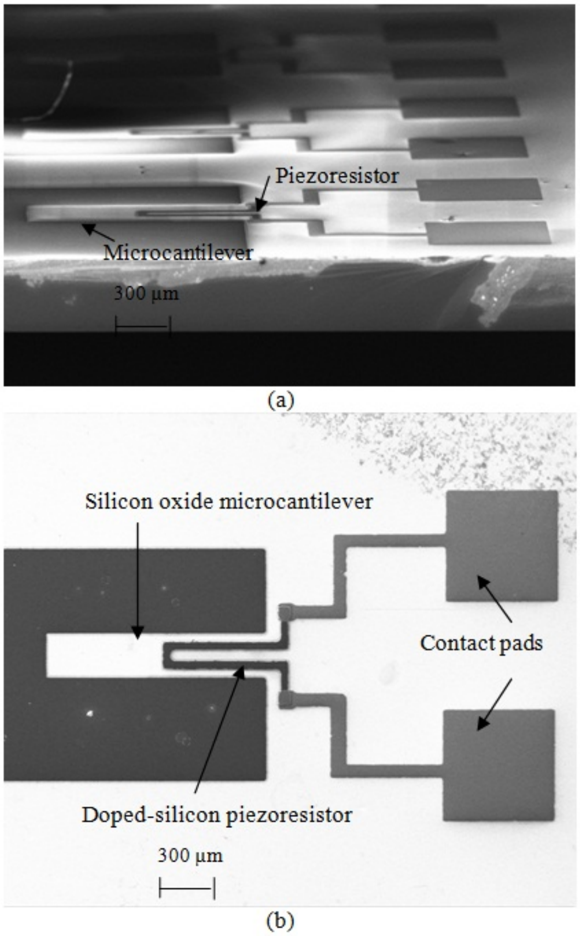

Figure-3. SEM micrographs of the dual-layer PRM structure connected to Al contact pads (a) Side view (b) Top view.

During microcantilever release, anisotropic wet etching, KOH 20% wt at a temperature of 80ºC was utilized (Williams *et al.*. 1996). However, this process stage cannot be accomplished due to the absence of an etch stop layer. The turbulence in the KOH etchant due to etching reaction resulted broken microcantilever structure as shown in Figure-4. It is also very difficult to control all the etching parameters as the etch stop time cannot be determined by a constant etch time method with sufficient precision.

Moreover, problems encountered during the fabrication process of the dual-layer PRM sensor such as undercutting, misalignments and distortion cannot be avoided. These problems complicate the fabrication process by causing additional process reworks which are cumbersome and time consuming. However, the fabrication issues related to the dual-layer PRM structure as observed in Figure-5 can be avoided with the fabrication of single-layer PRM structure.

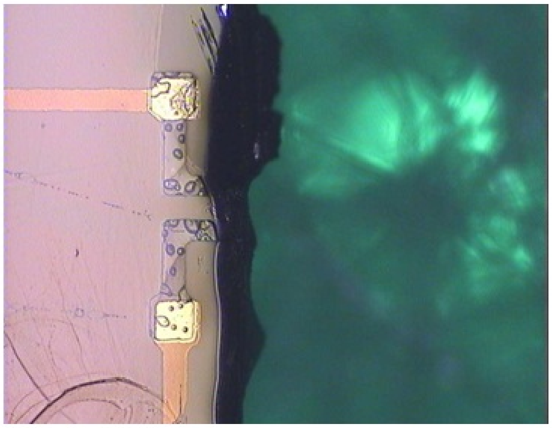

Figure-4. The broken microcantilever during microcantilever release process for dual-layer PRM sensor.

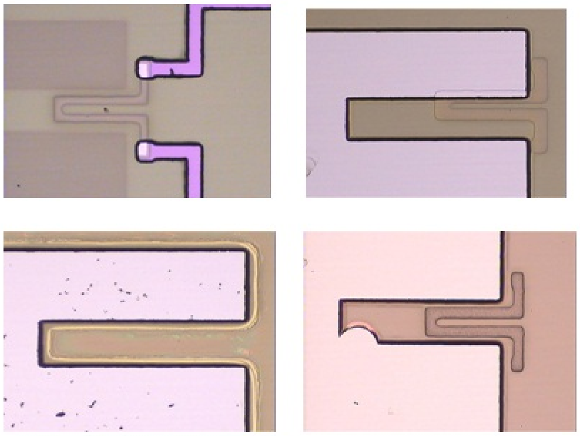

Figure-5. Problems encountered during the formation of dual-layer PRM structure (a) Misalignment of Al lines during third photolithography process (b) Misalignment between doped-silicon piezoresistor and silicon oxide microcantilever (c) Undercutting during BOE resulted in improper dimension of microcantilever (d) The distorted shape during the microcantilever patterning.

The misalignment issues during photolithography as shown in Figure-5 (a) and (b) can be significantly eliminated due to less optical masks used at reduced fabrication process steps in single-layer PRM structure. In addition, the undercutting and distorted issues of the microcantilever structure during BOE etching as shown in

Figure-5 (c) and (d) are not relevant to the single-layer type as the microcantilever is anisotropically etched through DRIE, not using the isotropic etching of BOE as in dual-layer PRM structure. Considering the critical fabrication issues shown in Figure-4 and Figure-5 for the dual-layer PRM sensor, selection for a single-layer PRM sensor was conducted. A comparison between both designs in terms of fabrication issues is summarized in Table-1.

Table-1. Comparison between dual-layer and single-layer designs in terms of fabrication issues.

Dual-layer PRM sensor	Single-layer PRM sensor
1. More fabrication process steps as shown in Figure 1 2. Critical mask misalignment issues due to more optical masks used 3. Undercutting and pattern distorted issues during BOE etching of silicon oxide microcantilever 4. No etch stop layer making the microcantilever release process impossible	1. Less fabrication process steps as shown in Figure-1 2. Less mask alignment issues due to fewer optical masks used 3. No issue at all with BOE etching as the silicon microcantilever was etched using DRIE 4. Silicon oxide etch stop layer was used in microcantilever release process

Single-layer piezoresistive microcantilever

For single-layer PRM sensor, the doped-silicon layer was used for both piezoresistor and microcantilever structures. Meanwhile, the underneath silicon oxide layer was used as an isolation layer between the Wheatstone bridge circuitry and the silicon substrate, and also served as an etch stop layer for bulk KOH etching during microcantilever release. The formation of the single-layer doped-silicon piezoresistive microcantilever structure was realized through anisotropic dry etching, DRIE.

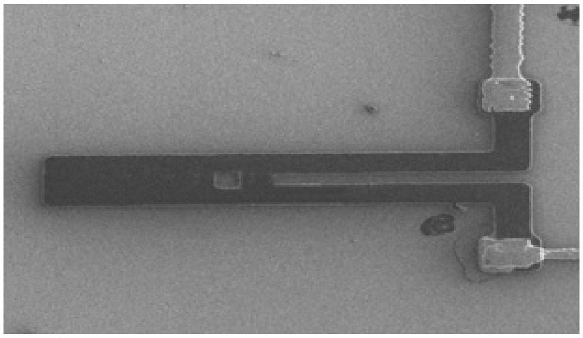

Figure-6. SEM micrograph showing the formation of piezoresistive microcantilever structure through DRIE for single-layer PRM sensor.

The fabricated single-layer PRM sensor is shown in Figure-6. As can be seen, the dual-leg design of the doped-silicon PRM structure was successfully patterned through single etching process of DRIE. The incorporation of 50 x 50 µm^2 square hole located not far away from the dual legs as can be clearly observed in Figure-6 ensures an efficient current distribution along the PRM structure.

The formation of the Wheatstone bridge circuit and Al contact pads on the single-layer PRM structure was carried out using the same method of the dual-layer design, Al wet etching. The Al contact pads connected to the Wheatstone bridge circuitry which was successfully patterned is depicted in Figure-7. At this stage, the underneath silicon oxide layer was used to isolate the electrical connection in the Wheatstone bridge circuit from the bulk silicon substrate. It should be noted that the same silicon oxide layer was also used as an etch stop layer for subsequent KOH bulk etching process during microcantilever release. As can be observed from Figure-7, the on-chip Wheatstone bridge circuit which consists of one single-layer PRM structure and three other identical resistors was successfully fabricated.

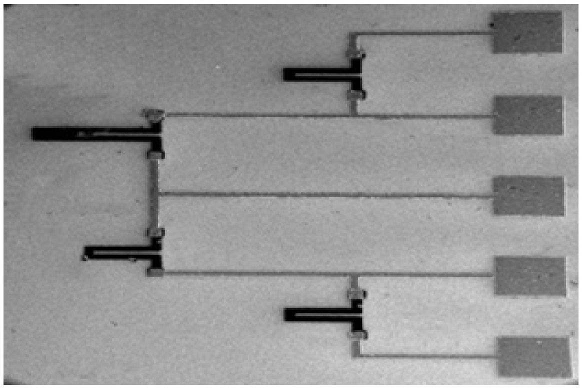

Figure-7. SEM micrograph of the single-layer PRM structure connected to Al contact pads and other resistors in Wheatstone bridge circuit.

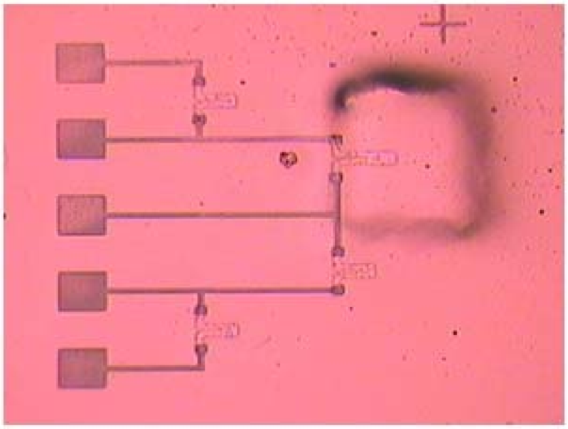

Figure-8. The microcantilever structure attached to the silicon oxide etch stop layer. (Note the rectangular window pattern due to the backside KOH etching).

The utilization of silicon oxide etch stop layer and low etching temperature during final stage of microcantilever release process ensures successful removal of bulk silicon substrate without damaging the front side structure of the sample. Complete bulk etching of silicon substrate which reveals the PRM structure attached to silicon oxide membrane is depicted in Figure-8.

The final step in microcantilever release is the removal of silicon oxide membrane to release the PRM structure in realizing the fabrication of piezoresistive microcantilever sensor. Utilizing BOE (10:1) procedure, the suspended single-layer PRM structure was successfully fabricated. The released doped silicon piezoresistive microcantilever is depicted in Figure-9.

Figure-9. SEM micrograph of the released PRM sensor.

CONCLUSIONS

The fabrication of single-layer piezoresistive microcantilever sensor has been successfully realized at IMEN-MEMS UKM Fabrication Lab. Selection of single-layer design over the dual-layer in the fabrication process has opened up the opportunity to improve the device parameters as well as to obtain simpler fabrication process.

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