Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.72-73

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Piezoresistive Rotation Angle Sensor Integrated in Micromirror

Minoru Sasaki, Motoki Tabata, Tsukasa Haga, and Kazuhiro Hane
Tohoku University, Dept. of Nanomechanics
Aza-Aoba 6-6-01 Aramaki, Aoba-ku, Sendai 980-8579, Japan
Phone: +81-22-795-6965 E-mail: sasaki@hane.mech.tohoku.ac.jp

1. Introduction

Micromirror devices are fundamental elements in various optical MEMS applications (e.g., scanner, optical switch). Generally, the optical beam is required to be accurately controlled in its position or direction. The feedback control of the mirror angle is desired. The well-known Lucent optical cross connect uses the optical power sensor for monitoring the light intensity coupled with the fiber. Integrating the sensor inside the micromirror device is attractive for making the system simple and reliable.

In this study, a piezoresistive rotation angle sensor is integrated in the mirror device is examined. The compatibility and the performance of the sensor are examined.

2. Principle and Design

Piezoresistive effect is frequently used mechanism in the pressure sensor. The strain introduced in the crystal Si changes the conduction and the valence band structures. The resultant carrier density or the mobility change is observed as the resistivity change. There are two kinds of piezoresistive gauges. One detects the normal stress. The other detects the shear stress [1]. In case of the mirror device, the mirror rotation generates the shear stress inside the torsion bar. The transverse voltage type gauge is appropriate. Figure 1 is the schematic. This sensor consists of 2 pairs of electrodes. One is for flowing the bias current. The other is for detecting the signal voltage. Compared to the normal piezoresistive sensor which measures the resistance, the signal is the voltage between detection electrodes. The signal V_{out} is expressed as follows.

$$V_{out} = \frac{W\,p\,t\,V_{bias}}{L} \qquad (1)$$

W and L are width and length of sensing element, respectively. t is the shear stress, which is proportional to the mirror rotation. V_{bias} is the voltage for flowing the bias current. p is the shear piezoresistance coefficient. This value depends on the doping type, conductivity, and the crystal orientation. The sensor is prepared in the p-type region. The device Si layer has the electrical *pn* junction. P-type region is at the top surface inside which the electrical current is confined. The stress is measured at the top surface where the shear stress becomes maximum when the torsion bar rotates.

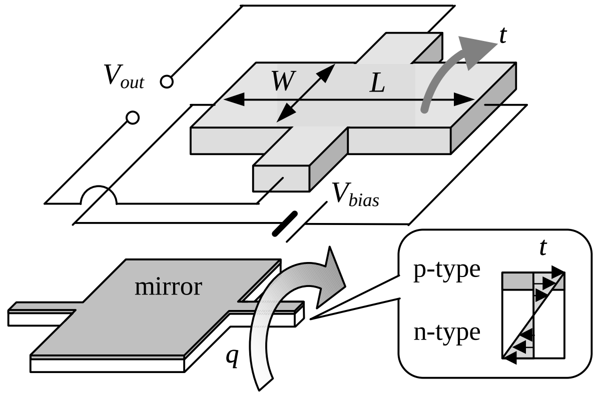


Fig. 1: Transverse voltage type gauge for detecting the shear stress.

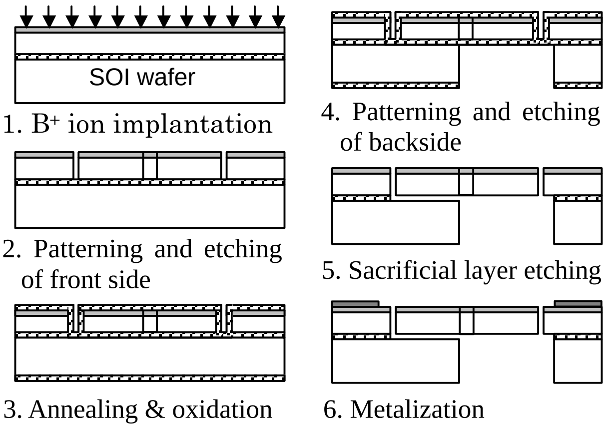


Fig. 2: Fabrication sequence.

Figure 3 shows the fabrication sequence. B^+ ion is implanted for making the pn-junction in the device Si layer. The front and back side Si layers are anisotropically plasma etched. Between etching processes, the device is oxidized for activating B, and for protecting the device layer against the subsequent Si etching. After the sacrificial SiO_2 layer etching, Al electrode is deposited through the stencil mask.

Figure 4 shows one fabricated device. The center mirror can be driven using the underlying electrode of the handle Si layer. The rotation angle sensor is included in the torsion bar as shown in the magnified image of the inset. The electrical wiring is carried out using the meandering Si spring. Since the sensor signal is voltage, the electrical conductivity does not become a severe factor by measuring with the large impedance. The offset is introduced between electri-

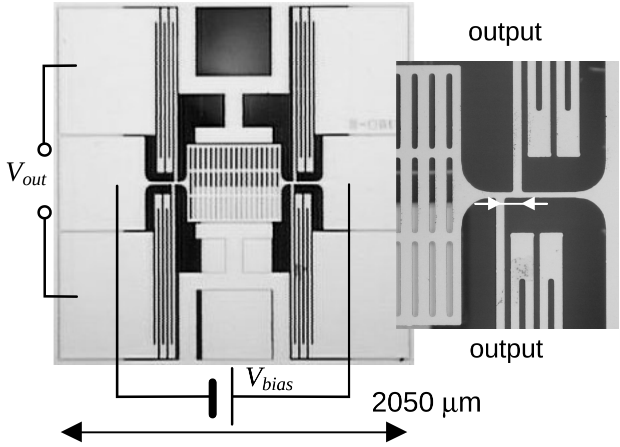


Fig. 3: One of fabricated mirror devices combined with rotation angle sensor.

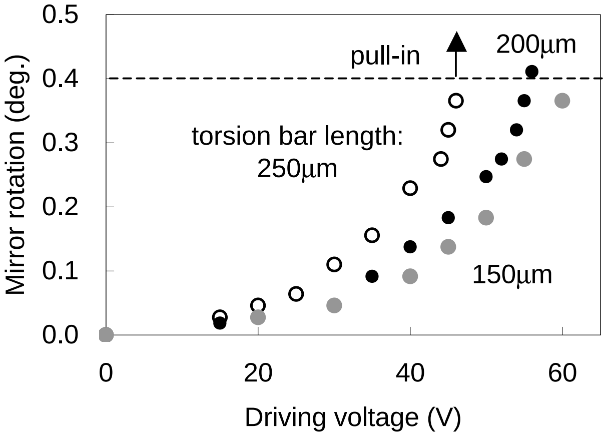


Fig. 4: Mirror rotation as a function of the driving voltage applied between the mirror and the underlying layer.

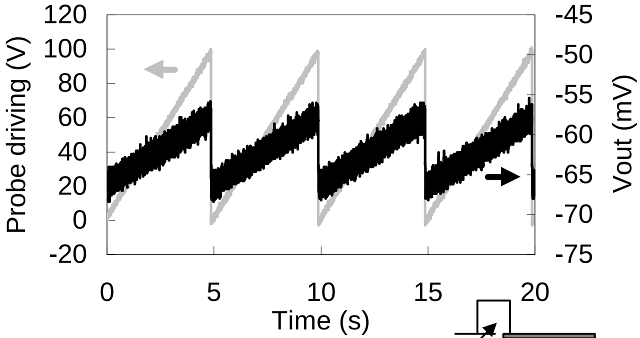
cal wires. This is for introducing the shear stress mechanically at the sensing region.

3. Results

Figure 4 shows the mirror rotation angle as a function of the driving voltage. Depending on the torsion spring constants, the rotation angle increases with the driving voltage until the pull-in instability, which is the feature of the planer plate type electrostatic actuator.

For the experiment of the sensor, relatively large rotation angle is generated pushing the mirror side using the mechanical probe driven by piezo actuator as shown in the inset of Fig. 5. The signal V_{out} is directly measured using the oscilloscope. The input impedance is 1MΩ. Figure 5 shows the signal. The mirror is rotated following the triangular driving waveform shown by gray color. The peak-to-valley of the driving voltage corresponds to 10.2 -degree rotation. The black curve is the sensor signal showing about 10 mV magnitudes. This signal clearly shows the same waveform indicating the linear relation with the mirror rotation. The hysteresis is little.

Figure 5 is obtained form the device aligning the torsion bar along <100> direction. The coefficient p becomes



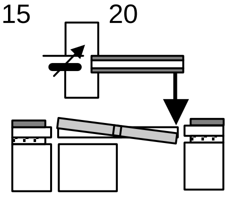


Fig. 5: Sensor signal (black) aligned to <100> direction when mirror is rotated being pushed by piezo actuator driven by triangular voltage (gray).

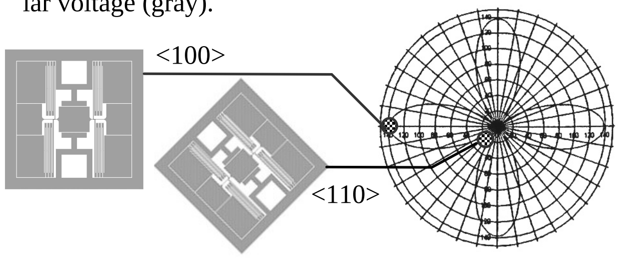


Fig. 6: Crystal orientation dependence of p on Si (100) wafer, and corresponding mirror layout.

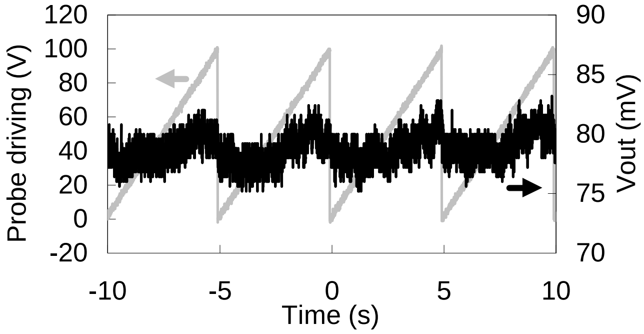


Fig. 7: Sensor signal (black) aligned to <110> direction.

maximum value. Figure 6 shows the relation between p and the orientation of the p-type Si (100) crystal [2]. The minimum value is at <110> direction. If the torsion bar is aligned along <100> and <110> directions, the signal will be maximum and minimum, respectively. Figure 7 shows the signal from the device having the torsion bar along <110> direction. As expected, the signal magnitude decreases and its shape does not show the similarity. The sensitivity against to the normal stress will be the reason. This value is known to be minimum and maximum at <100> and <110> directions, respectively. Therefore, the signal in Fig. 7 is considered to be influenced by the normal stress, which does not have linear relation to the mirror rotation.

The facilities used for this research include the Venture Business Laboratory at Tohoku University.

References

[1] T. Saigusa, T. Aga, S. Fukuhara, Proc. of the 7th Sensor Symposium 1988, 189-192.

[2] Y. Kanda, Jpn. J. Appl. Phys. 26 (1987) 1031-1033.