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Piezoresistive Rotation Angle Sensor Integrated in Micromirror Device

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1. Introduction

Micromirror devices are used in various optical MEMS applications such as optical switches and scanners[1,2]. The optical beam must be reflected by the mirror with the accurately controlled rotation angle so that the beam can be transmitted to the designated area. Therefore, based on some sensor signals, the feedback control of the mirror angle is inevitably required. So far, the optical power sensor is integrated to monitor the light intensity for the feedback control of the optical system. This method, however, makes the system complex and large. Integrating the sensor inside the micromirror device is attractive for making the system simple and reliable. The piezoresistive rotation angle sensor is integrated in the micromirror device[3]. In this study, the compatibility between the sensor and the mirror device is demonstrated and the performance of the sensor is investigated.

2. Principle and Design

Strain introduced in a crystal Si changes energy state of the conduction and valence bands. The resultant changes of density/mobility of carrier are observed as the resistivity change (piezoresistance effect). In the case of the mirror device, the mirror rotation generates shear stress inside a torsion bar. Principle of our sensor is schematically shown in Figure 1. The sensor consists of two pairs of electrodes. One is used to flow bias current. The other is used to detect signal of rotation. The signal V_{out} is given by

$$V_{out} = \frac{\rho_0 \pi}{t} \tau \, I_{bias} \tag{1}$$

(t: sensor thickness, ρ_0: specific resistance of the sensor, τ: shear stress, π: shear piezoresistance coefficient, I_{bias}: bias current). The shear/normal piezoresistance coefficients π depend on the crystal orientation. As shown in Eq. (1), the signal induced by the shear stress can be monitored as the voltage between detection electrodes. Since a bridge circuit is not necessary to detect V_{out}, the sensor setup becomes simple.

The sensor can be prepared using a p-type Si region fabricated on an n-type Si substrate. The electrical current is confined at the top surface, or the p-type region. The rotation angle sensor is included in the torsion bar as shown in Fig.2. The torsion bars are fabricated along <100> direction of the Si substrate, which gives the maximum and minimum piezoresistance coefficients for shear[4,5] and normal stresses, respectively. Electrical wiring is carried out from the torsion bars using meandering Si springs. The rotational spring constant is designed not to disturb the mirror rotation. The normal stress inside the torsion bar has a little influence on the sensor signal. The offset between the two meandering Si springs affect the sensitivity of the rotational signal because it changes the stress distribution inside the sensor.

3. Experimental

The device fabrication is the preparation of the sensor using B^+ ion implantation followed by the deep reactive etchings for preparing the micromirror structure. One of fabricated devices is shown in Fig. 3. This device design has the gap-closing type actuator. Another device used for the simultaneous driving with the sensor has the vertical comb type actuator. In measurement, a laser beam was irradiated on the mirror and reflected onto a position sensitive detector (PSD). The rotation angle of the mirror is obtained from PSD signals. A lock-in amplifier is used to monitor minute signal of the rotation angle sensor. The bias current is modulated at 100kHz, which is much higher than the resonance frequency (14kHz) of the mirror.

4. Results and Discussion

Figure 4 shows the output of the rotational angle sensor with a parameter of the offset in the inset of Fig. 2. In this experiment, the mirror rotation angle is generated by pushing the mirror edge with a mechanical probe driven by a piezo actuator to investigate the characteristics of the sensor with the large angle. The output of the rotational angle sensor is shown with a parameter of the offset in the inset of Fig. 2. The sensor with larger offset shows the higher sensitivity. However, over 10 degrees, the sensor signals show a decrease (45μm-offset) or a saturation (30μm-offset). It is assumed that the stress inside the torsion bar works towards unexpected direction (e.g., downward bending).

Figure 5 shows the time response of the sensor signal and the mirror rotation angle. Simultaneous driving of the actuator and the sensor is realized. This sensor has the offset of 30μm determined by the results of Fig. 3. One driving cycle takes 7s keeping the static condition. The shape of the sensor signal is fundamentally similar to that of the mirror rotation angle except the small peak at the smaller rotation angle. This can be explained by the mixed normal stress in the sensor due to the stress of passivation film introduced to protect the sensor. Additionally, it is considered that the misalignment of the torsion bar direction from <100> axis cause piezoelectric effect in <010> axis to exaggerate the peaks. Nevertheless, sensor signal clearly resolved the angle of 0.02 degrees.

5. Conclusions

The piezoresistive rotation angle sensor integrated in the micromirror device is demonstrated. The proposed structure with the offset in the electrical wirings can take the balance between the mirror actuator and the sensor for controlling the mirror micro displacement. The obtained sensor signal is promising to resolve the mirror rotation angle.

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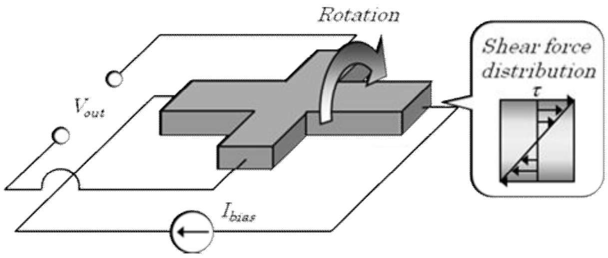

Fig.1: Schematic illustration of the principle of rotation angle sensor. Rotation causes shear stress distribution in a torsion bar. Piezoelectric effect generates voltage depending on the shear stress.

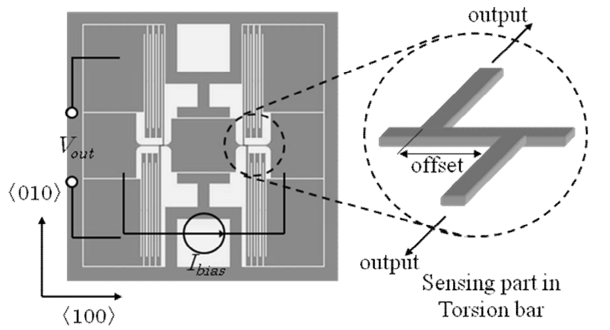

Fig.2: Schematic drawing of a micromirror device. The rotation angle sensors are integrated in the torsion bars.

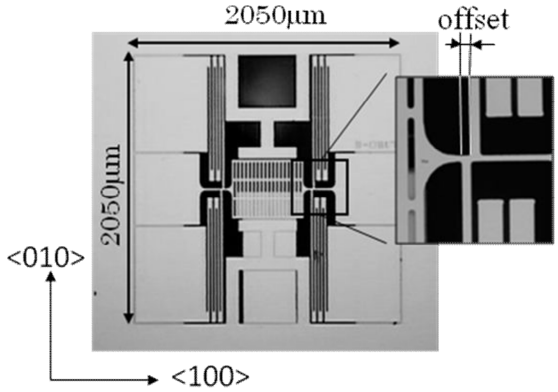

Fig.3: Photograph of the fabricated device. The inset shows the rotation angle sensor integrated torsion bar.

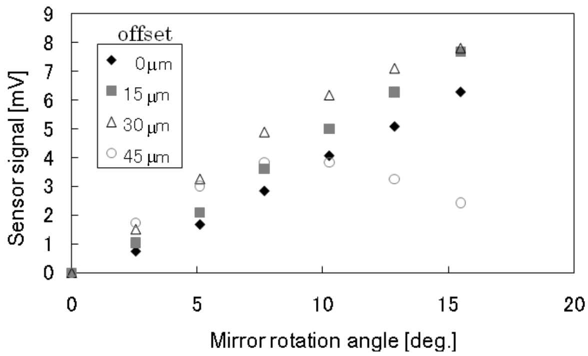

Fig.4: Comparison of signals from sensors having different offsets between the electrical wires.

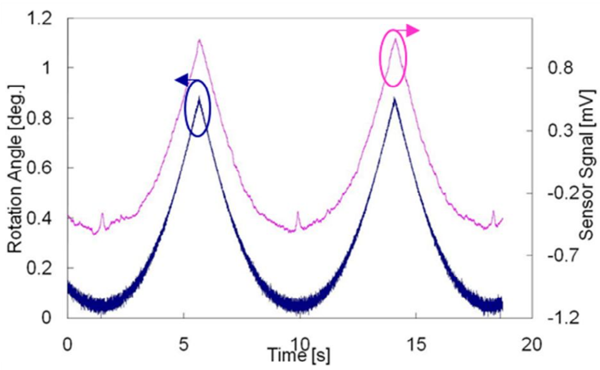

Fig.5: Time responses of the sensor signal and the mirror rotation angle under the static driving.