Paper

Silicon Micromachined Tunable Infrared Polarizer

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Active polarizers that consist of parallel metal wires are fabricated by silicon micromachining techniques. If wavelength of incident radiation is larger than the period of the wire grid, the wire grid reflects incident radiation with the electric field parallel to the grid line, while transmits the other. Polarization of infrared light can be succussfully modulated by changing the period of the grid or changing the geometrical configuration. Two kinds of silicon structures are fabricated and demonstrated. One of them is electrostatic driven structure composed of mechanically flexible grid. The period of the grid can be modulated by itself with electrostatic actuation. The other is piezo driven structure, which consists of a pair of fingers (wire grid) and a torsional resonator. It changes the geometrical configuration of the wire grid. These mechanical behaviors and optical characteristics for infrared modulation are presented.

Key words: Infrared Polarizer, Polarization modulator, Electrostatic Actuator, Silicon Micromachining

1. INTRODUCTION

Polarization modulator has been utilized for infrared (IR) analysis, such as an reflection spectroscopy $^{(1)}$ and an infrared ellipsometry. In these infrared analysis systems, IR is modulated by the polarization modulator to eliminate any background noise. The polarization modulation methods provide a real time sampling without the need for background measurements. Micromachining enables to develop a variety of micro optoelectromechanical systems by integration and miniaturization of micro-optics. Furthermore, micro miniaturized systems consist of micro IR optics, such as a filter$^{(2)}$, a mirror, a detector, an IR source, an interferometer $^{(3)}$ and an tunable IR laser will put IR micro systems for gas and surface analysis into practice.

It has been known that a grid of parallel metal wires acts as polarizer (wire grid polarizer)$^{(4)}$. There is an advantage that the wire grid can be made compact by photolithography. The wire grid polarizer reflects incident radiation with the electric field parallel to the grid line (P-polarization: TE-polarization) below a cutoff frequency, while transmits incident radiation with the electric field perpendicular to the grid line (S polarization: TM-polarization). The cutoff frequency of P-polarization radiation is expressed in terms of characteristic wavelength as follows: $\lambda c=2d$ Where d is the period of the grid. The wavelength of the radiation is larger than the period of the grid, the P-polarized IR transmits. If the period of the grid can be changed, the transmittanee of the polarized IR is also changed with an appropriate period of the grid. In this paper we present two types of active polarizers with flexible structures as a component for IR micro analysis systems.

2. ELECTROSTATIC DRIVEN INFRARED MODULATOR

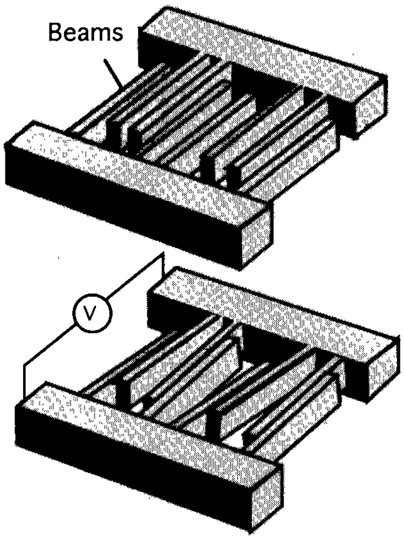


Fig.1. Schematic diagrams of electrostatic driven active polarizer and the operation principle.

2.1 Design and Fabrication Electrostatic actuation is an efficient actuation method because of the simplicity and the low power consumption. Figure 1 shows the schematic structure of the tunable polarizer and the operation principle. The polarizer consists of free-standing silicon beams which deflect in the lateral direction by electrostatic actuation, two fixed silicon electrodes which suspend the silicon beams. The periodically aligned beams are supported by one electrode at intervals of two beams. When a voltage is applied between the two electrodes, neighboring beams laterally move to the opposite direction relative to each other. If the electrostatic force is lager than the effective spring of the beam, the beams come in touch together, as shown in Fig.1. In this phase, the period of the grid can be regarded as two times larger than that of initial period. The beams are covered by insulating layer to prevent a current flow during the touch phase of the actuation cycle.

The device is fabricated by means of silicon micromachining techniques as illustrated in Fig.2. First, SOI (Silicon On Insulator) wafer is oxidized and patterned by photolithography. After SiO_2 etching in buffered hydrofluoric acid (BHF), the wafer is wet-etched from back side using TMAH (tetramethyl ammonium hydroxide) to form the IR window and the upper side of SiO_2 is removed. The grid pattern is formed by photolithography and the top silicon layer (15μm thick) is dry etched using ICP-RIE. After surface cleaning in H_2SO_4/H_2O_2 solution, intermediate SiO_2 (μm thick) of the SOI wafer is etched in BHF to release the silicon grid. Subsequently supercritical drying is performed to avoid stiction during drying after SiO_2 etching. Silicon grids don't act as a polarizer because it is transparent in IR range. Therefore, thin Cr-Au (Cr: 50nm, Au:200nm) film is deposited by sputtering in order to form metal grid and ensure the electrical contact on the electrodes. Finally, SiO_2 thin film is deposited from backside of the wafer by sputtering in order to insulate each beams during the touch mode operation. Without the insulating layer, voltage drop makes it difficult to actuate in the touch mode.

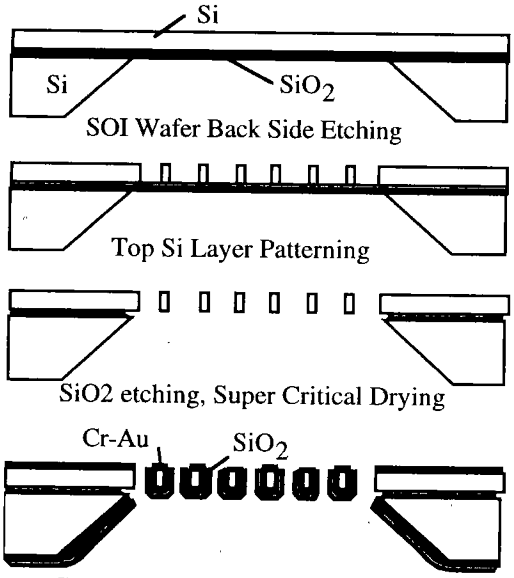
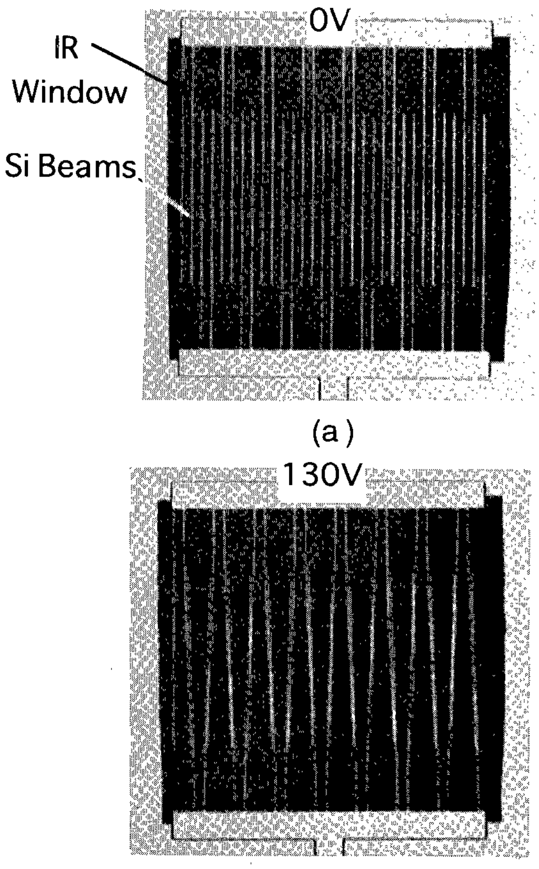


Fig.2. Process flow for electrostatic driven active polarizer.



(a)

(b)

Fig.3. Photograph of fabricated device (a) and stacked state (b) by the electrostatic actuation with applied voltage of 130V.

2.2. Mechanical Behavior Figure 3(a) shows the photograph of the fabricated device. When a voltage of 130 V is applied, two beams are stacked together, as shown in Fig.3(b). The beam width, the length and the height are 4μm, 140μm and 15μm, respectively. Also the period of grid is 16μm. The threshold voltage V_t and distance z_t for touch actuation are calculated using simple plate-to-plane geometry by taking no account of the insulating layer on the beam as follows.

$$V_t=\left(\frac{4d^3k}{27\varepsilon_0 A}\right)^{1/2} \quad \text{and} \quad z_t=\frac{d}{6} \qquad (1)$$

Where d is the initial gap of beam, k is the spring constant of beam, A is the capacitor of area, ε_0 is the dielectric constant.

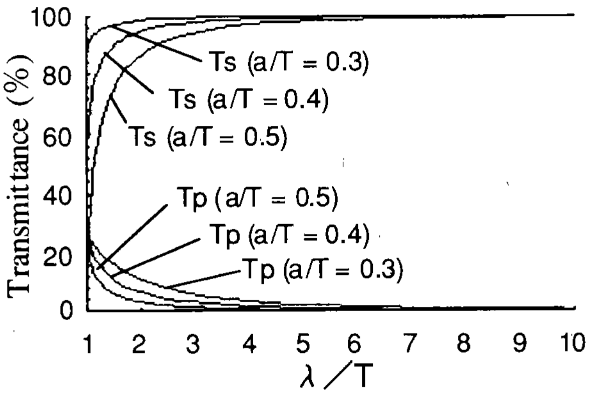


Fig.4. Calculated transmission spectra for P polarization and S-polarization.

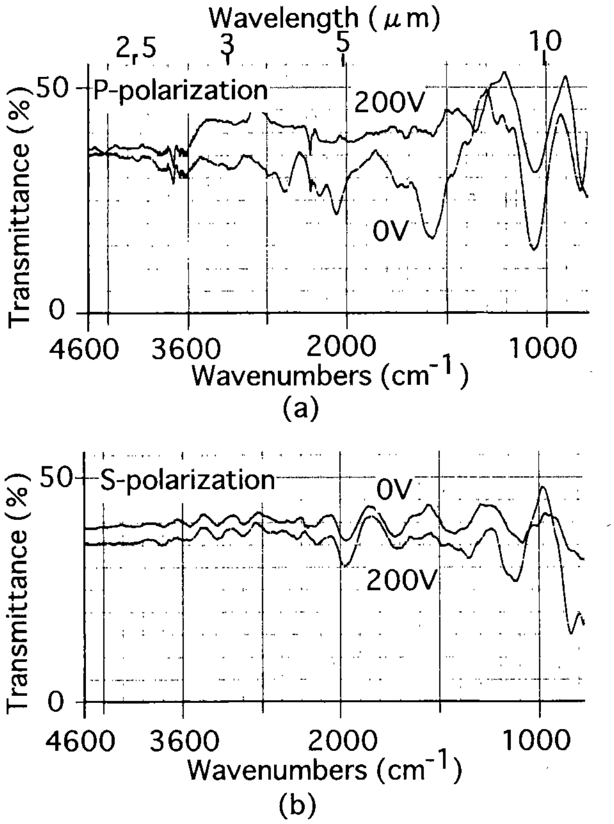


Fig.5. Measured spectral transmittance changes from initial state to stacked state for P-polarization (a) and S-polarization (b).

Calculated threshold voltage V_t is 92V that given by above equation with d=12 μm for the gap, k= 0.63 N/m for calculated spring constant, A=288×15 (μm^2) for capacitor area. It is not matched with observed value (130V) owing to existence of the dielectric layer of SiO_2.

2.3 Characteristics of polarizer Figure 4 shows calculated transmission spectra for P polarized and S-polarized IR as a function of λ/T (wavelength / period of grid) with various a/T (width of wire / period of grid). The calculation method is given by Marcuvitz(5). The transmittance is depending on the λ/d and a/d. From this calculation, it is found that the transmittance for S-polarized light (Ts) decreases and the transmittance for P-polarized light (Tp) increases with decreasing λ/d near λ/d= 1~2. As the beams are stacked together by electrostatic force, the period of the gird comes to be two times larger than that of initial state, which will decrease the transmission of S polarization (Ts) and increase the transmission of P polarization (Tp).

The spectral transmittance is measured by microscopic FTIR (Fourier Transform InfraRed spectroscopy). Polarized IR is focused on the grid area after passing an another polarizer. Figure 5 shows the transmission spectrum of P-polarization (a) and S polarization (b) for the grid polarizer with a period of 8μm and a beam width of 4μm. The spectra are observed at initial state (applied voltage 0V) and stacked state (applied voltage 200V). Maximum transmittance change is seen at 1600 cm^{-1} (6.25μm) for the P-polarized IR. As expected from above calculation in Fig.4, fabricated device modulates the polarized IR, where the transmittance for S-polarized IR increases and that for P-polarized IR decreases by applying the voltage for the touch mode actuation. However, unexpected behavior is observed in the spectrum near 1100cm^{-1} where the change of transmittance is opposed to values as expected. It seems that the unexpected behavior is caused by IR absorption due to SiO_2 coated on the beams for electrical insulation. The fabricated device acts as a tunable polarizer below 50Hz in a frequency. However, failure operation that the beams don't put in touch together occurs at high frequency operation. Furthermore, mismatch of motion phase is observed frequently. These failures may be caused by a charge remaining on the SiO_2 layer and a thin water layer on it.

3. PIEZO DRIVEN INFRARED MODULATOR

3.1 Design and Fabrication Piezo driven type of active polarizer is fabricated and demonstrated. The device consists of the interdigital figures and the torsional resonator, as shown in Fig.6. Mass of the torsional resonator on which figures are formed is supported by two beams. A pair of fingers composes the grid wire polarizer. When vibrating the resonator by a piezo actuator, the movable fingers are displaced in the vertical direction, which modulate the polarization consequently.

Fabrication sequence is similar to that of the electrostatic driven type, as shown in Fig.2, except for the final SiO_2 deposition step. The SEM photograph of the fabricated device is shown in Fig.7. The beams are slightly bending due to the stress of Cr-Au film on the flexible structure. The beam length, the width and the thickness are 115μm, 5μm and 2μm, respectively. The period of the grid is 8μm.

3.2 Mechanical Behavior and Characteristics of polarizer Piezo actuator mounted on the device is used for the vibration of resonator. The mechanical response is measured using laser Doppler vibrometer by focusing the laser probe on the torsional mass when vibrating a piezo actuator. The torsional motion of the resonator is observed at 189.6kHz. The measured fundamental resonant frequencies of the finger beams are about 154kHz.

The spectral transmittances of P and S polarization with the grid polarizer are measured using the FTIR, as shown in Fig.8. There is about 20% of difference between the transmittances of S and P polarization. The characteristics agree qualitatively with that calculated as shown in fig.4. Transmitted IR is measured during vibration near the resonance of torsional mode. Figure 9 is output signal of IR detector measured by oscilloscope. It is found that the P-polarization is strongly modulated in comparison with S-polarization, where 14 times lager modulation intensity is obtained. The output waveform is not well ordered sine wave. The reason is probably due to the asymmetrical motion of fingers against the fixed fingers in the vertical direction, since silicon beams are slightly bent by the stress of Cr-Au film.

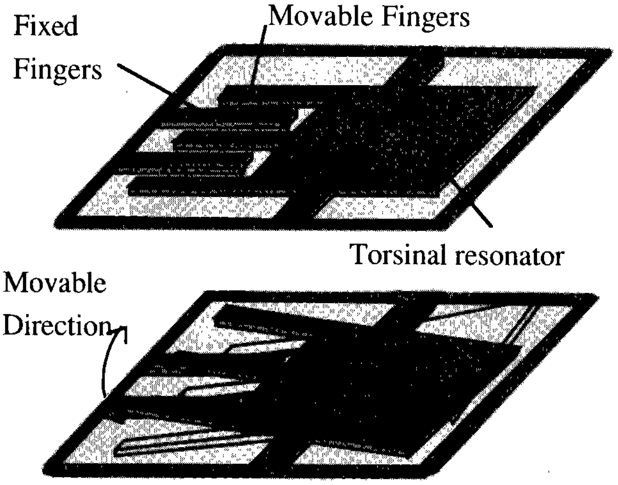


Fig.6. Schematic diagrams of piezo driven active polarizer and the operation principle.

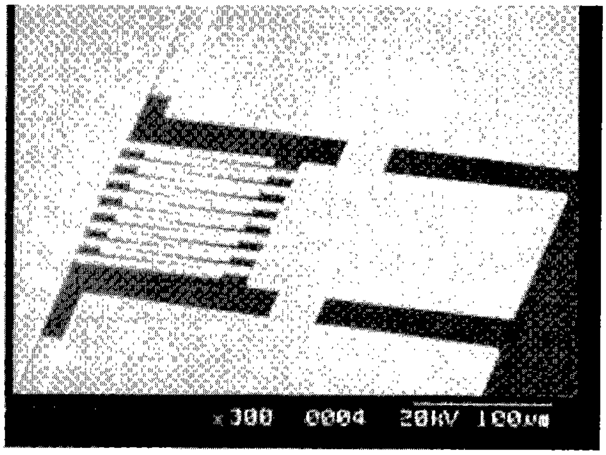


Fig.7. SEM photograph of piezo driven active polarizer.

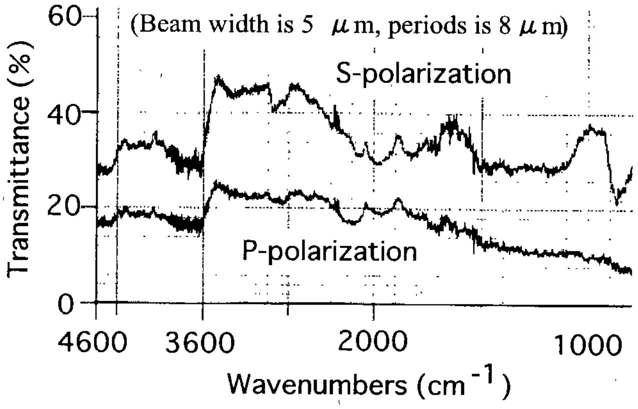


Fig.8. Transmittance spectrum for P-polarization and S-polarization.

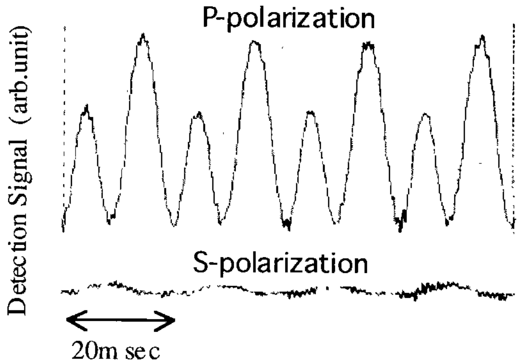


Fig.9. Modulated IR signal for P-polarization and S polarization.

4. CONCLUSION

Two types of active polarizers for polarization modulation were fabricated by micromachining techniques and the characteristics were measured. We confirmed that the active polarizer act as a polarization modulator by actuating to change the geometrical configuration of the grid wire polarizer. Electrostatic driven type of the polarizer changes the period of the grid by the electrostatic actuation. Fabricated device shows that the transmittance for S-polarized IR increases and that for P polarized IR decreases by applying a voltage for the touch actuation. This tendency is qualitatively agree with that calculated.

Piezo driven type polarizer which consists of two pairs of fingers can modulate polarized IR with the modulation frequency of 379.2kHz by vibrating the one fingers-comb with torsional resonator. It is found that the P polarization is strongly modulated in comparison with S-polarization.

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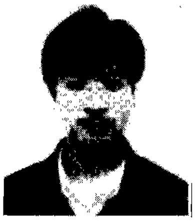

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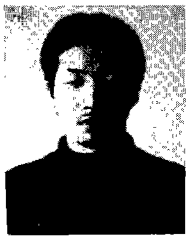

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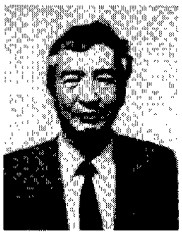

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