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Bolometer-Type Infrared Sensors Fabricated by Plasmaless Dry Etching

Yoji Saito* and Hiroki Murotani

Department of Electrical Engineering and Electronics, Faculty of Engineering, Seikei University, 3-3-1 Kichijoji-Kitamachi, Musashino ,Tokyo180-8633, Japan.

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Bolometer-type infrared (IR) sensors were fabricated using undoped polycrystalline silicon (poly-Si) films, the temperature coefficient of resistance of which was 7 %/K. The device size was 50×50 μm^2. A bridge structure with an air gap about 50 μm deep was formed to reduce thermal conduction to the substrate from the sensing region, by plasmaless dry etching with chlorine trifluoride gas. The voltage responsivity of the fabricated sensor was 1.3×10^4 V/W at a bias voltage of 1.5 V.

1. Introduction

Currently, highly sensitive infrared (IR) sensors are required for security systems and intelligent transport systems (ITS). Quantum-type infrared sensors have high sensitivity and fast response, but they must be cooled for device operation and are usually expensive. In contrast, thermal-type infrared sensors can be operated at room temperature and have a simple structure, which can contribute to device integration and a low cost. The sensitivity of these thermal infrared sensors, however, is generally lower than that of the quantum sensors. The performance of the thermal infrared sensors depends on the temperature coefficient of the resistivity (TCR), the optical absorption, and the thermal isolation between the sensing material and the substrate.

Materials used for sensing resistors in a bolometer should have a large TCR. Doped poly-Si films(2) and doped poly-SiGe films(3–5) have been used in reported studies, the TCR values of which were 1.5 and 2%/K, respectively. In this study, bolometer infrared sensors were fabricated using undoped poly-Si films with a TCR of 7%/K,(6) which is larger than

*Corresponding author, e-mail address: yoji@ee.seikei.ac.jp

that described in the previous reports.[2–5] The high TCR of undoped poly-Si films is due to the high density of the deep defect levels at the grain boundaries.[6]

Moreover, the bridge structure was formed by plasmaless dry etching in order to reduce the thermal conduction between the poly-Si films and the substrates. For micromachining of silicon we used ClF_3 gas, which can etch silicon spontaneously without plasma but rarely attacks quartz, thermally grown oxides, aluminum, or positive photoresists near room temperature.[7–9] The highly selective etch rate with respect to mask materials is easily obtained by plasmaless dry etching due to a chemical reaction. The isotropic etch property is often useful for etching the area behind the mask material during micromachining. Studies of the application of chemical dry etching to micromachining have recently been initiated.

In this study, the voltage responsivity and the frequency response of the fabricated devices were evaluated.

2. Experimental Procedure

Single-crystalline silicon with a (100) orientation was used as a substrate in this study. Oxide films of 1 μm thickness were thermally grown on the substrates. Undoped poly-Si films of 400 nm thickness were then deposited by conventional low-pressure chemical vapor deposition at 620°C. After deposition the poly-Si films were annealed at 900°C for 20 min in nitrogen ambient. The average grain size in the poly-Si films was about 20 nm, according to measurements with a transmission electron microscope.

Poly-Si films were patterned to the shape of a sensing region of 50 μm width by plasmaless dry etching with ClF_3 at 1 Torr at room temperature. Under these etching conditions, the etch rate of silicon is about 100 nm/min.[7,9] Thermally grown oxide films were patterned to make holes for subsequent dry etching under the sensing region. Al films were evaporated and patterned to form the electrodes, which defined the length of the sensing region as 50 μm. The samples were sintered at 400°C in N_2 ambient to make ohmic contacts. Finally the substrate under the sensing region was etched by plasmaless dry etching at atmospheric pressure near room temperature. The substrate was introduced into the etching reaction chamber as shown schematically in Fig. 1(a). The substrate temperature was not controlled, but was monitored by a pyrometer. Argon gas was used as a diluent. The ClF_3 gas line was heated to 40°C to prevent liquefaction of ClF_3.

The typical etch rate of (100)-oriented crystalline silicon at room temperature is shown in Fig. 1(b) as a function of the partial pressure of ClF_3. The etch rate was proportional to the partial pressure of ClF_3 below 50 Torr when the total flow rate was 330 sccm. The etched depth was predicted by the etch time and the data of the etch rate as shown in Fig. 1(b). The deviation of the actual etched depth from the predicted value was within 10%, and was probably not very large because of the small or negative activation energy of the etch rate near room temperature.[7] A reproducible etch rate, however, was not obtained above 70 Torr, because the substrate temperature gradually increased due to the heat of reaction.

The schematic diagrams of the top surface and a cross-section of the fabricated bolometer are shown in Figs. 2(a) and 2(b), respectively. The depth of the air gap was approximately 50 μm. The calculated thermal conductance was 1.2×10^{-6} W/K, using the

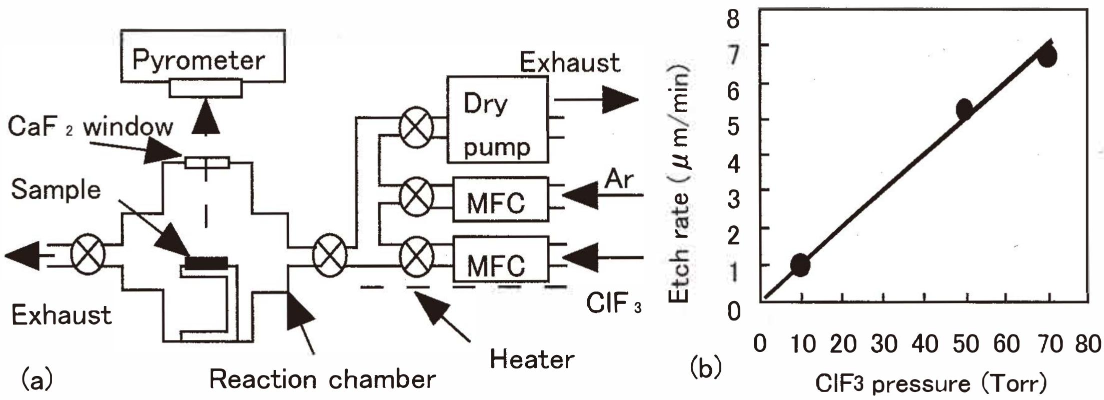
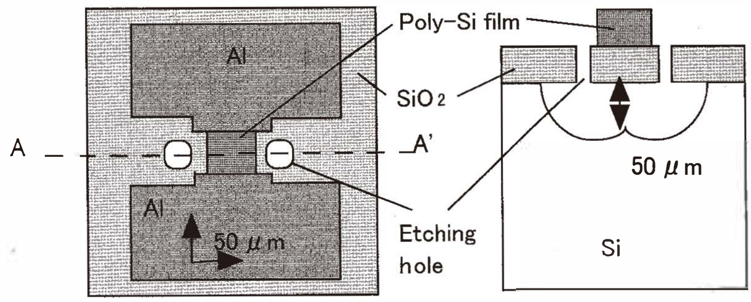


Fig. 1. (a) Schematic diagram of plasmaless etching apparatus. (b) Etch rate of crystalline silicon by ClF_3 at room temperature as a function of the partial pressure of ClF_3, where the total pressure was 1 atm.



(a) Top surface. (b) Cross section A–A'

Fig. 2. Schematic diagrams of the fabricated infrared sensor using undoped poly-Si films, (a) top surface, (b) cross section.

value of 2.4×10^{-2} W/(K·m) as the thermal conductivity of air. The expected voltage responsitivity of the fabricated bolometer is then 2.2×10^{4} V/W at a bias voltage of 1.5 V, assuming the emissivity of the sensing materials is unity and the TCR of the undoped poly-Si film is 7%. Poly-Si resistors without an air gap were also prepared.

Figure 3(a) shows a schematic diagram of the measurement system. A blackbody furnace, Model P-10NC by Tokyo Seiko Co. Ltd., Japan, with a light chopper was used as an infrared light source, where the furnace temperature was typically set at 900°C. The region visible from the light source was cut by the single-crystal Si of 0.6 mm thickness. The main light power was distributed in the range between 1.5 and 5 μm. The optical power density onto the samples was estimated to be about 0.18 W/cm^2. The ac component of the current induced by the chopped infrared light was measured using a lock-in ammeter/voltmeter, Model 5560 by NF Electronic Instruments Co., Japan, as a function of the chopping frequency. The dc current was measured using an ammeter.

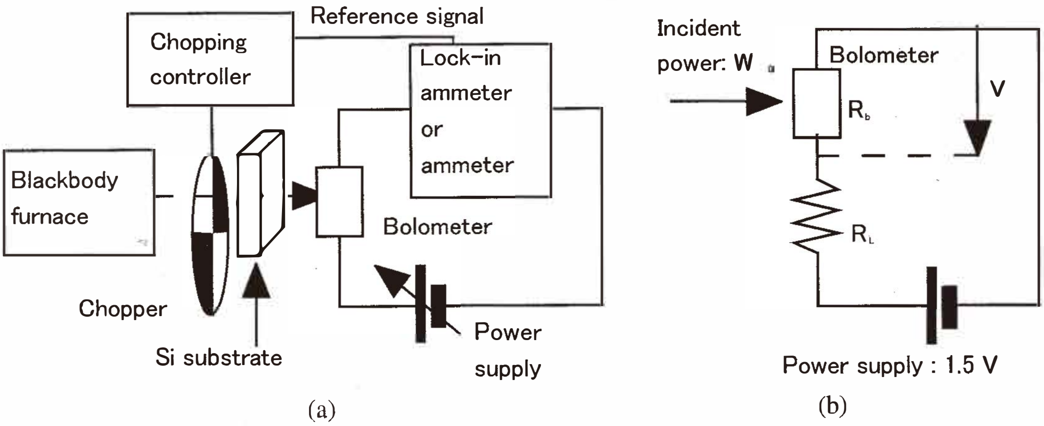


Fig. 3. (a) Schematic diagram of measurement system. (b) Schematic diagram of a model circuit for definition of voltage responsivity.

Figure 3(b) shows the model circuit for obtaining the value of voltage responsivity of the sensors.[10] In this figure, R_b and R_L are resistances of the bolometer and the load resistor, respectively, where these two values are assumed to be almost equal. The responsivity, Rv, is defined as

$$R_v = \Delta V / W_O, \tag{1}$$

where W_O is the light power incident onto the sensing area. The term ΔV is the change of the voltage on the bolometer, V, with illumination compared to that without illumination.

3. Results and Discussion

3.1 *Infrared absorption of poly-Si film*

Infrared absorption by the 400-nm-thick poly-Si film used in this study was investigated with Fourier transform infrared (FTIR) absorption spectroscopy. We used a silicon substrate with a thermally grown dioxide film as a reference sample. The absorption spectrum of the poly-Si film was obtained by subtracting that of the reference sample from that of the sample with the poly-Si film/SiO_2 film/Si substrate structure as described in the previous section. The spectrum of the poly-Si film is shown in Fig. 4(a), where the vertical axis is normalized by the maximum value of the transmissivity. In this work, the main wavelength region contributing to the infrared absorption is estimated from this figure to be in the range between 3.5 μm and 5 μm. The three large absorption peaks are observed in this spectrum at least, although the band-gap energy of the poly-Si films is about 1.1 eV, which is almost equal to that of single-crystalline silicon, and corresponds to a wavelength of 1.1 μm. The main mechanism of optical absorption is likely due to the electron states distributed in the band gap induced by the dangling bonds of Si at the grain boundaries.[11]

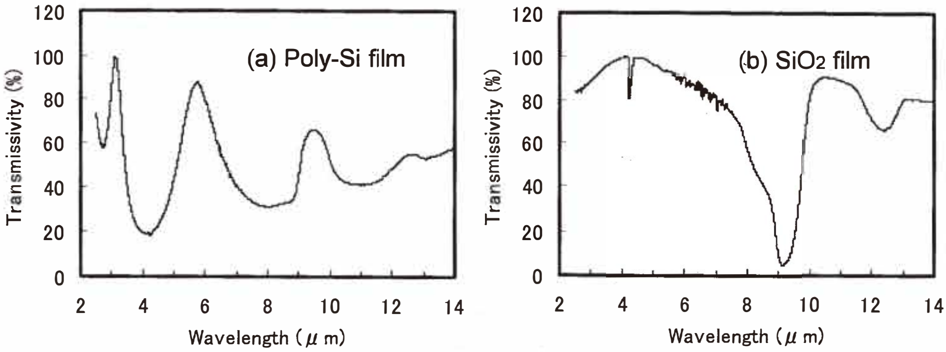


Fig. 4. Infrared absorption spectra of the poly-Si film with the thickness of 400 nm, (a), and the SiO_2 film with the thickness of 1000 nm, (b).

The absorption spectrum of the 1-μm-thick SiO_2 film is shown in Fig. 4(b). The main absorption peak of the SiO_2 film is found around 9 μm, but this does not contribute to the infrared detection in this work, because the range of the illuminated light was below 5 μm.

3.2 *Evaluation of the fabricated sensor*

The I–V characteristics of the fabricated bolometer devices with and without an air gap were measured without infrared illumination. The resistances of the devices were obtained from the linear region. The average resistance of the bolometer devices with an air gap is about 2.5×10^{10} Ω and is four times larger than that of the poly-Si resistor without an air gap.

A typical SEM image of a perspective view of the fabricated device is shown in Fig. 5. In this figure, two etching holes are found adjacent to the sensing region of the poly-Si film. The poly-Si film is slightly deflected, probably because of an internal stress induced by the thermal expansion deference between the films and the substrate. We consider that the cause of the high resistivity of the poly-Si film with an air gap compared to that without an air gap could be due to a piezoresistive effect induced by the deflection of the film. The deflection of the poly-Si film may be reduced by the decrease of the deposition temperature.

The resistance of the sensor was measured under constant infrared illumination, and the voltage responsivity of the sensor was 1.3×10^4 V/W, where the emissivity of the device was assumed to be 1. This experimental value is roughly half of the theoretical value mentioned in the previous section. The difference is mainly due to the reflection and transmission of the incident light through the sensing region, considering the absorption spectrum of the poly-Si film shown in Fig. 4.

The frequency response to infrared light was investigated for the fabricated sensor. The ac current was measured by a lock-in ammeter synchronized with the optical chopper at a constant bias voltage. The result is shown in Fig. 6. The cutoff frequency is obtained to be 800 Hz from this figure, which corresponds to a time constant of 1.2 ms.

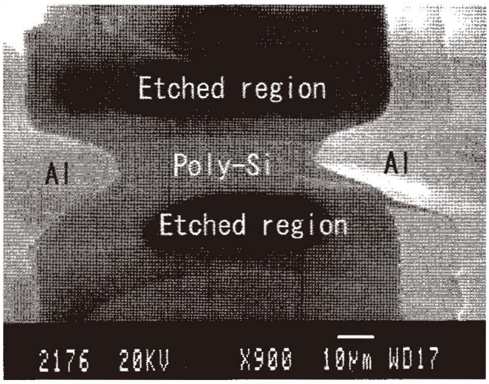


Fig. 5. SEM image of a perspective view of the fabricated sensor with an air gap.

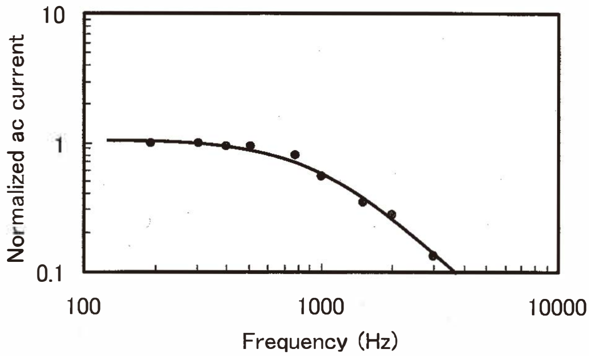


Fig. 6. Frequency response of current of the fabricated sensor with an air gap.

These results are summarized in Table 1. The reported values for sensors with the same size sensing area as that of our sensor are also indicated in this table. Both the voltage responsivity and time constant are improved in comparison with those reported previously. The voltage responsivity is improved by using a sensing material with a high TCR and a large air gap. The improved time constant in this work is mainly due to the small heat capacity of the fabricated device without a thermal absorber. The addition of a thermal absorber onto the sensing material improves the sensitivity but affects the time constant.

A disadvantage of the undoped poly-Si films is a high resistivity on the order of 10^5 Ω cm. It is difficult to obtain both a low resistance and a high TCR in the poly-Si resistor, because both the resistivity and its activation energy of the undoped poly-Si films are dominated by the defect level.[6] The noise problem caused by the high resistance is

Table 1
Summary of the experimental results of this work and those from the previous works.

Sensing material	This work	Doped poly-Si[2]	Doped poly-SiGe[3]	Doped poly-SiGe[4]
TCR (%/K)	7	1.25	2	2
Voltage responsivity (V/W)	2.2×10^4	2.1×10^3	1.0×10^3	8.4×10^3
Time constant (ms)	2	4.9	2.1	7.8

discussed below. The voltage of the Johnson noise in the fabricated device was calculated to be 1.4×10^{-5} $VHz^{-0.5}$, using the resistance of the fabricated poly-Si resistor at 300 K. The detectivity of the fabricated sensor was estimated to be 4.5×10^6 $cmHz^{0.5}W^{-1}$, and was much smaller than that of the bolometer using a VOx film as a sensing material.[12] The high resistance affects the detectivity. A sensing material with a large TCR and low resistivity is favorable for realizing a bolometer having a high performance in practical applications.

4. Conclusion

We fabricated bolometer-type infrared sensors 50×50 μm^2 in size on silicon substrate using undoped poly-Si films as a sensing material. The sensing films were thermally isolated from the substrate by dry etching with ClF_3 gas without plasma. The atmospheric plasmaless dry etching exhibits highly selective and reproducible etch properties at partial pressures of ClF_3 below 50 Torr. The voltage responsivity obtained for the fabricated sensor was 1.3×10^4 V/W at a bias voltage of 1.5 V, and is better than the reported value for bolometer-type sensors of the same device size as ours. The sensitivity may be improved by depositing a thermal absorber onto the sensor.

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