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A Micro-Machined IR Thermal Detector Using Torsional Oscillation: Improvement of Resonator Profile for High Sensitivity

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Abstract

A micro-machined infrared thermal detector using torsional resonators has been studied to achieve high sensitivity. The resonators have bimaterial structure consisted of a tense Si thin film (resonator body, torsion bars) and a metal film (IR absorber). IR incidence induces the out-of-plane displacement of the resonator. The displacement generates spring hardening in the torsion bars increasing the resonant frequency of torsional oscillation. To achieve larger shift, the resonator should have high inner tension and be flat before IR incidence. We fabricated a flat resonator with a tense poly-Si film obtained by metal-induced lateral crystallization (MILC) using biomineralized Ni nanoparticles. For the IR absorber, a light metal was deposited onto the resonator reducing the load on the resonator. Owing to the tense Si film realized by MILC and the light metal film, the resonator showed large resonant frequency shift. The sensor was characterized by heat and light incidence. Optical sensitivity was discussed.

1. Introduction

Infrared (IR) sensing is necessary in the fields of medical applications, security, and environmental monitoring. Generally, IR detectors are classified into two; photon detectors and thermal detectors. The photon detectors exhibit good signal-to-noise performance and a fast response under cryogenic cooling. In contrast, the thermal detectors can operate easily under ambient conditions. However, some technical issues are remained in sensitivity and response time [1]. To improve the sensitivity of a thermal detector, we have studied a vibrational MEMS IR detector in which torsional resonators were used as sensing elements (Fig. 1). The resonators consisted of bimaterial; a poly-Si thin film (resonator body, torsion bars) and a metal film (IR absorbers). The metal film absorbs incident IR photons and heat is generated. Due to the difference in thermal expansion of the materials, the resonator body bends upward. The bent-up resonator generates spring hardening in the torsion bars (hard spring effect), thereby increasing the resonant frequency of torsional oscillation. The fabricated sensor is an "IR-induced-heat-to-frequency" converter. By precisely measuring the resonance shift, high IR sensitivity can be achieved.

According to the previous study [2], the cross-sectional profile of the resonator before IR incidence has to be flat for high sensitivity because the IR sensitivity depends on the out-of-plane displacement of the resonator. The initial profile is determined by the residual stress in the films and the load applied to the suspended resonator. In this study, the resonator was fabricated with a poly-Si film, formed by metal-induced lateral crystallization (MILC) using bio-mineralized Ni nanoparticles (NPs). A light metal, which has absorption spectra in the IR range and high coefficient of thermal expansion (CTE), was used. The fabricated device was characterized in terms of heat and light incidence.

2. Design and Fabrication

A poly-Si thin film can be obtained by annealing a hydrogenated amorphous Si (*a*-Si:H) film. During the annealing, the unbound H atoms desorb from the film and a crystallization-induced tensile stress is generated [3]. In the poly-Si film, however, there are many grain boundaries which do not contribute to generate the tensile stress. To increase the tensile stress, we have applied MILC using *apoferritin* supramolecules with Ni NPs, which is called *Bio-Nano Crystallization* [4]. The advantage of applying *apoferritin* supramolecules is that homogeneously synthesized NPs can be used for the MILC.

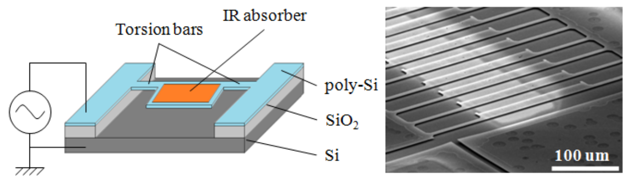

Fig. 1 Schematic diagram of a vibrational MEMS IR sensor (left) and SEM image of the fabricated device (right).

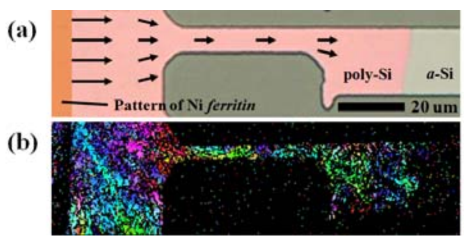

Fig. 2 (a) Micrograph of the resonators after MILC and (b) EBSD image of same area. The Si film is crystallized along the direction of arrows from the pattern of *apoferritin* with Ni NPs.

Because grain boundaries are reduced by expanding grains, the crystallization-induced tensile stress can be enhanced further. The measured residual tensile stresses with and without MILC were 461 MPa and 363 MPa, respectively [5]. By patterning the Ni NPs on the *a*-Si:H film, the stress distribution in the poly-Si film can be controlled.

An *a*-Si:H film was deposited on a SiO_2/Si substrate, and B ions were implanted into the film for electrical conduction. The IR sensing elements of torsional resonators were fabricated in the *a*-Si:H film by reactive ion etching. *Apoferritin* supramolecules containing Ni NPs were patterned at the clamping ends of the torsion bars, and MILC was conducted 550 °C. Dopant activation was carried out at 800 °C. To release the resonators, a sacrificial layer (SiO_2) was etched with vapor-HF. A film of a light metal Al was evaporated through a stencil mask. Al has absorbance spectra for IR ray. CTE of Al is 23.6 ppm/°C, which is higher than that of Si (2.6 ppm/°C). Because of density of Al is 2.7 g/cm^3 (ex. Au: 19.3 g/cm^3), the out-of-plain deformation caused by the load of the deposited Al film can be small.

3. Results and Discussion

During the MILC, Ni silicides are formed and diffuse along the torsion bars crystallizing the Si film. The crystallization was observed by optical microscopy and electron backscatter diffraction (EBSD) analysis (Fig. 2). In the dark area where the silicide did not diffuse [Fig. 2-(b)], EBSD signal was weak and grain structures were not detected. The grain sizes in the area were reported to be less than 1 μm [5].

The resonator profiles were measured by white-light interferometry. The initial profile at room temperature is flat compared with that of our previous devices [2]. With increasing the substrate temperature, the fabricated resonator bent upwards (Fig. 3). The bent-up rate was 1 nm/°C.

Optical response characteristics were measured using a probe system with two lasers. One laser was irradiated onto the Al film of photon absorber to heat the body of resonators. The other probing laser was irradiated onto the oscillating resonators. The reflected laser was detected with a photo-diode. The photo-diode signals were analyzed with a frequency response analyzer (Fig. 4). Below 0.5 W/cm^2, the resonant frequency was kept almost constant

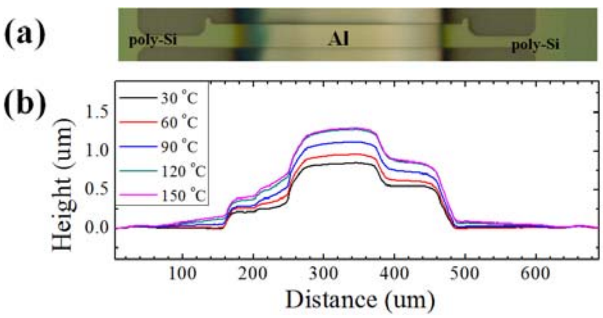

Fig. 3 (a) Micrograph of the resonator surface and (b) its cross -sectional profile as a function of substrate temperature.

The out-of-plane displacement was small so that resonant frequency shift by hard spring effect was not observed. Beyond 1 W/cm^2, the resonant frequency increases with increasing heating laser power (Fig. 5). The ratio of frequency-shift to laser power was evaluated to 300 Hz/(W/cm^2). When the laser power exceeded 3.6 W/cm^2, the resonator reached the limit of deformation and the changes of resonant frequency saturated.

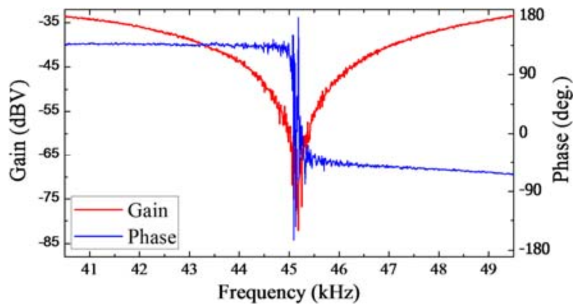

Fig. 4 Resonant curves of the fabricated resonator.

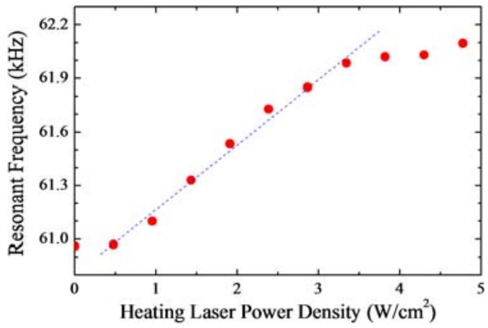

Fig. 5 Resonant frequencies as a function of heating laser power.

4. Conclusions

To achieve high sensitivity, the torsional resonators were fabricated with bimaterial structure; a tense poly-Si film formed by MILC, and an Al light metal film of high-CTE. The fabricated torsional resonators were flat before light incidence. The thermal deformation rate was evaluated to be 1 nm/°C. With regard to the optical response, a ratio of the resonant frequency shift to the heating laser power was evaluated to be 300 Hz/(W/cm^2). Improving the sensing element structure, the higher sensitivity of the thermal IR sensor can be achieved.

Acknowledgements

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