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Optical amplification of the resonance of a bimetal silicon cantilever

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This letter reports a photothermal transducer consisting of an ultrathin Au/Si bimetal cantilever that functions as a resonator having a total thickness of 45 nm and a quality factor of ~12 000. Due to its high-quality factor and small volume, this transducer is sensitive to the photothermal effect and its thermal response frequency is comparatively high. The authors demonstrated that the irradiation of a weak laser beam can enhance the transducer's response due to the nonlinear photothermal effect. Mechanical frequency-modulated detection of modulated light is demonstrated using this bimetal transducer. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2748848]

Miniaturized resonators have been developed for use in ultrasensitive sensors including mass sensors,[1] chemical sensors, force sensors,[2] and photothermal transducers.[3] A strong motivation for scaling down the size of resonators is that scaling down reduces the effect of thermomechanical noise, thereby increasing the resolution of resonance sensors and also enhancing their response time.

Other promising applications of miniaturized resonators are thermal sensors and photothermal transducers. A silicon resonator is integrated onto an absorber, which converts radiation such as IR into heat. This heat induces thermal expansion and thermal stress in the resonator and changes its resonant frequency.[4] This type of resonant thermal sensor exhibits a high sensitivity having a thermal resolution of the order of femto joules,[3] and they can operate even at room temperature.

Another heat sensitive structure is a bimetal structure that functions as a transducer, converting heat or incident radiation into mechanical deformation or vibrations. Bimetal structures have thus been employed in high-sensitivity thermomechanical sensors and thermal actuators. Microscale structures generally exhibit a slow thermal response of the order of microseconds, and thus do not respond to high-frequency thermal modulations. Smaller bimetal structures with lower thermal capacitances will respond faster, but their fabrication is more difficult because of the internal and thermal stress of the bimetal layer. The resonant frequency of bimetal structures depends on thermal stress and temperature variation. Therefore, bimetal transducers can be used to demodulate a frequency-modulated (FM) thermal input. This type of transducer can be used as a highly sensitive detector for miniaturized Fourier modulation spectrometers,[5] including miniature infrared spectrometers if the transducer absorbs infrared radiation.[4]

In this study, ultrathin bimetal cantilevers (40-nm-thick Si/5-nm-thick Au) were fabricated for miniature fast-response high-sensitivity FM detectors and photothermal transducers. The fabrication and properties of the photothermal transducer are described.

40-nm-thick Si thin cantilevers were fabricated from a silicon-on-insulator wafer. The details of the fabrication process have been described elsewhere.[6] The quality factor (Q factor) of a fabricated silicon cantilever with a length of 20 μm and a width of 7 μm was approximately 5000 in vacuum. In order to make bimetallic cantilevers as thermal transducers, an approximately 5-nm-thick Au layer was deposited in vacuum under a pressure of $\sim 10^{-7}$ Pa by thermal evaporation. The fabricated bimetal cantilevers exhibited almost no bending, as the representative micrograph shown in Fig. 1 demonstrates. The resonant frequency of the cantilever decreased from 137.4 to 92.25 kHz as a result of depositing the Au layer; in addition, it reduced the Q factor to approximately 2500. However, the Q factor increased to 12 000 following annealing at 400 °C for 5–10 s (see Fig. 2). This annealing in a high vacuum produces a silicide layer on the cantilever surface. The resonant frequency decreased slightly to 89.5 kHz. The spring constant was estimated from the thermomechanical noise at room temperature and found to be 0.014 N/m.

All experiments were performed in a vacuum of $\sim 10^{-7}$ Pa. The vibration of this cantilevered transducer was measured using a laser Doppler vibrometer and the signal was detected using a lock-in amplifier or a phase-lock-loop (PLL) circuit. The cantilever was vibrated by an electrostatic force or a photothermally generated force. A metal electrode was placed above the cantilever for electrostatic actuation. The beam from a laser diode with a wavelength of 680 nm could be used to irradiate the cantilever at an oblique angle of 30° through an optical window; this laser light could be modulated by an external signal. The elliptical spot size of

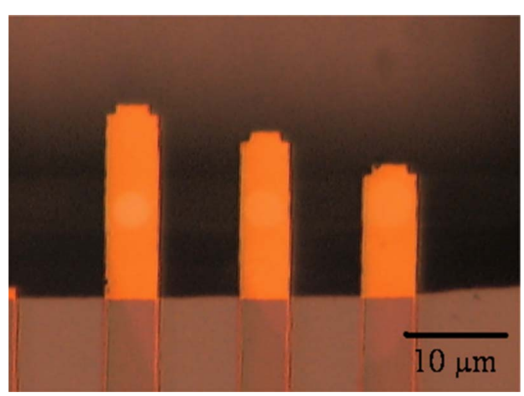

FIG. 1. (Color online) Micrograph of the fabricated bimetal cantilever with a 40-nm-thick Si layer and a 5-nm-thick Au layer.

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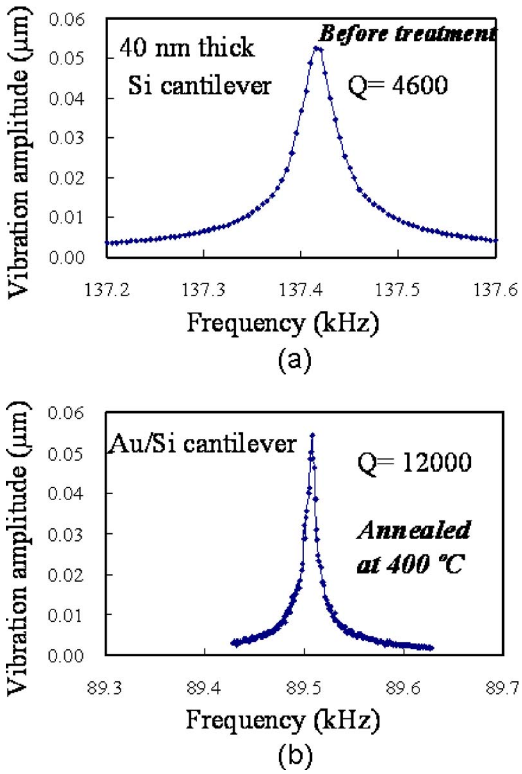

FIG. 2. (Color online) Mechanical response spectra of the cantilever (a) before and (b) after deposition of a 5-nm-thick Au layer and annealing.

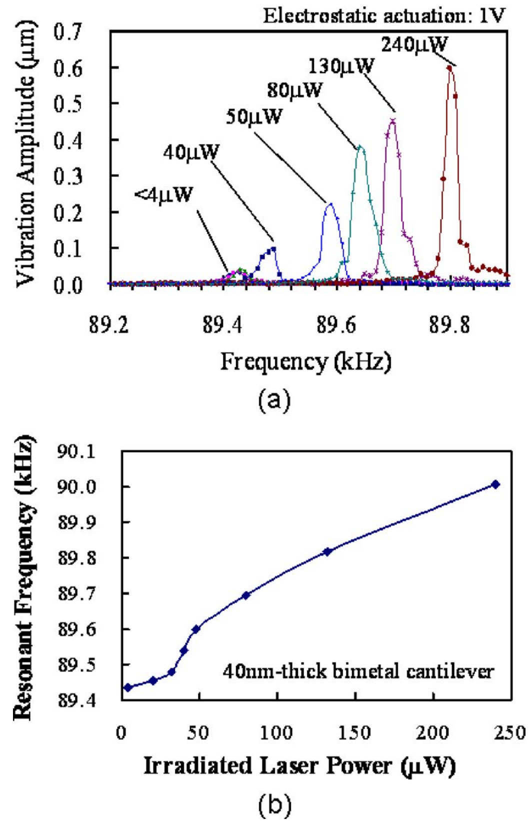

FIG. 3. (Color online) (a) Mechanical vibration spectra under cw laser irradiation. The photothermal effect induces the frequency change and enhances the amplitude of the vibration. (b) Relationship between the irradiated laser power and the resonant frequency.

the focused laser light was about $150 \times 80\ \mu m^2$. The total laser power irradiating the cantilever was approximately 4% of the total power.

First of all, the effect of continuous wave laser irradiation on the bimetal cantilever was investigated. The cantilever was vibrated electrostatically by 1 V ac voltage and the incident laser power was varied. The amplitude signal from the laser Doppler vibrometer was detected using the lock-in amplifier that scanned at the same frequency as the applied ac voltage. Figure 3(a) shows the mechanical response spectra for various incident laser powers. Increasing the laser power onto the cantilever from 4 to 240 μW resulted in its resonant frequency shifting from 89.4 to 89.8 kHz due to the photothermal heating effect. In addition, the vibration amplitude increased from 35 nm to 0.6 μm at a laser power of 240 μW, which corresponds to amplification by a factor of 17. This amplification is possibly caused by a periodic change in the photothermal absorption since the adsorption intensity of laser beam at an oblique angle is slightly modified in the vibration cycle due to a slight change in the incident angle onto the cantilever.

Figure 3(b) shows that the frequency response to the laser power is nonlinear. The temperature dependence of the resonant frequency of a silicon resonator is known to be approximately -35 ppm/K.[7] However, the resonant frequency of the bimetal cantilever exhibited a positive temperature dependence of 82 ppm/K at room temperature (i.e., ~296 K). This is due to the nonlinear spring effect of the relatively thin cantilever structure due to distortion along the cantilever width.

Increased amplification by the laser beam can enhance the response of the bimetallic cantilever. Detection of chopped light was demonstrated on the basis of the FM detection of the self-oscillated bimetal cantilever. The cantilever was self-oscillated by an optically generated force produced using a pulsed laser. The detected vibrational signal from the laser Doppler vibrometer was fed back to the driving power of the laser via a gain and phase adjuster, which self-oscillates the cantilever. The vibration amplitude was kept constant using an amplitude-control circuit.

Figure 4(a) shows the frequency response to the chopped light from a halogen lamp that was focused using a lens. The intensity of the halogen lamp's beam on the cantilever was approximately 14 μW. Under self-actuation with a pulsed laser power of 4 μW, an increase in the frequency of 8.3 Hz due to the chopped light was observed [see Fig 4(a)]. In order to investigate the optical amplification effect, we compared this result with the result obtained without laser irradiation. The same experiment was performed except that the bimetal cantilever was vibrated by an electrostatic force. In this case, the frequency variation was approximately 1.6 Hz [see Fig. 4(b)], which is five times smaller than that obtained using optical vibration. These results demonstrate that optical actuation at a moderate power can enhance the frequency response due to the photothermal effect.

In order to demonstrate the possibility of using the bimetal cantilever as a vibration radiation sensor, the cantilever was irradiated by a modulated laser beam and the modulation was detected by a FM demodulation technique using the PLL. The bimetal cantilever was electrostatically self-oscillated and irradiated by a laser beam, the intensity of which was modulated by a triangular wave or a square wave. The frequency of the self-oscillated bimetal cantilever was also modulated in accordance with the laser intensity modulation. Figure 5 shows a comparison of the FM demodulated

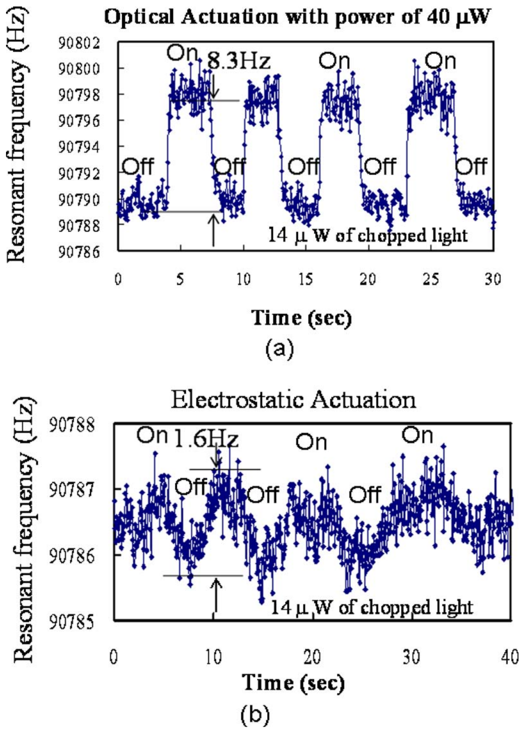

FIG. 4. (Color online) Frequency response to the chopped light from a halogen lamp (a) with optical actuation and (b) electrostatic actuation.

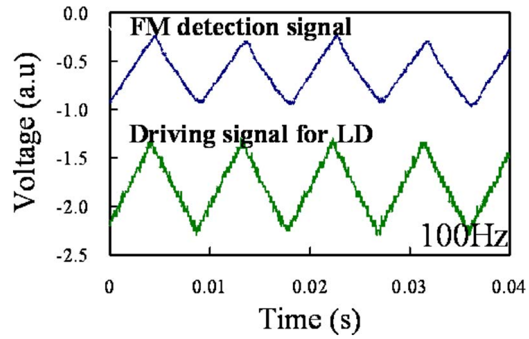

FIG. 5. (Color online) Comparison of the FM demodulated vibration signals with the driving signals for the laser diode.

vibration signals with the driving signals for the laser diode. When the modulation frequency was 100 Hz, the bandwidth of the PLL was approximately 1300 Hz. This result demonstrates that this bimetal cantilever can be employed as a transducer for converting photothermally induced heat into a frequency signal.

In summary, this letter reports the fabrication and evaluation of a high-Q ultrathin cantilever. The fabricated bimetal cantilever exhibits a Q factor of $\sim$12 000 and a high sensitivity and rapid response to the photothermal effect. It was found that irradiation by a weak laser beam can enhance the response to an external vibration; in particular, the frequency change induced by the photothermal effect was enhanced. Furthermore, FM detection of a weak light signal was demonstrated.

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