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Bimaterial microcantilevers with black silicon nanocone arrays

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ABSTRACT

The performance of infrared (IR) sensing bimaterial cantilevers depends upon the thermal, mechanical and optical properties of the cantilever materials. This paper presents bimaterial cantilevers that have a layer of black silicon nanocone arrays, which has larger optical absorbance and mechanical compliance than single crystal silicon. The black silicon consists of nanometer-scale silicon cones of height 104–336 nm, fabricated using a three-step O_2–CHF_3–Ar + Cl_2 plasma process. The average cantilever absorbance was 0.16 over the 3–10 μm wavelength region, measured using a Fourier transform infrared (FTIR) microspectrometer. The measured cantilever responsivity to incident IR light compares well to a model of cantilever behavior that relate the spectral absorbance, heat transfer, and thermal expansion. The model also provides further insights into the influence of the nanocone height on the absorbance and responsivity of the cantilever. Compared to a cantilever with smooth single crystal silicon, the cantilever with black silicon has about 2× increased responsivity. The nanocone array fabrication technique for silicon bimaterial cantilevers presented here could be applied to other IR sensors.

1. Introduction

Bimaterial cantilevers are sensitive thermometers that convert temperature into a mechanical displacement [1–6]. The thermal expansion mismatch of the two layers in the cantilever causes the cantilever to bend upon the temperature change. Bimaterial cantilevers can measure temperature with resolution near 4 μK and can also serve as heat flow detectors, measuring heat flow as small as 4 pW at room temperature [6]. Applications of bimaterial cantilevers include photothermal spectroscopy [7–9], IR imaging [10–12], and heat transport measurements [5,13].

The cantilever material is one of the key factors determining the cantilever sensitivity. Most publications report the cantilever material to be silicon or silicon nitride, which is paired with a metal layer such as aluminum or gold [1–13]. These materials are common in microfabrication processes, and are relatively easy to integrate into a cantilever. The metal layer has a large thermal expansion coefficient relative to the dielectric layer, enabling temperature-dependent cantilever bending. When the cantilever is used as an IR sensor, the dielectric layer additionally serves as an IR absorber. Unfortunately, the dielectric layers in commercially available cantilevers typically have relatively small optical absorbance, typically in the range 0.01–0.2 near 10 μm [2,4]. In general, cantilever responsivity to IR light, defined as the cantilever displacement per incident IR radiative power [2,14], is usually limited by this low absorbance.

The fabrication of high aspect ratio nanometer-scale conic structures (also known as nanocone arrays) on a silicon surface can improve the optical absorbance of silicon in the visible and the IR spectral regions [15–19]. The nanocone arrays reduce the optical reflectance at the air–silicon interface by serving as a buffer medium with gradually changing refractive index [15–19]. Recently, the nanocone arrays fabricated into a single crystal silicon wafer could achieve very high absorbance, namely above 90% in the 300–1000 nm spectral region [15]. Due to its black appearance, the silicon with nanocone arrays is known as one type of black silicon. This paper reports bimaterial cantilevers fabricated with black silicon nanocone arrays for use in the mid-IR (2–12 μm) region and their characterization. With the black silicon nanocone arrays, our goal is to increase the IR absorbance of the cantilevers, resulting in a responsivity increase that will enable the cantilevers as more efficient detectors for higher performance analytical measurements.

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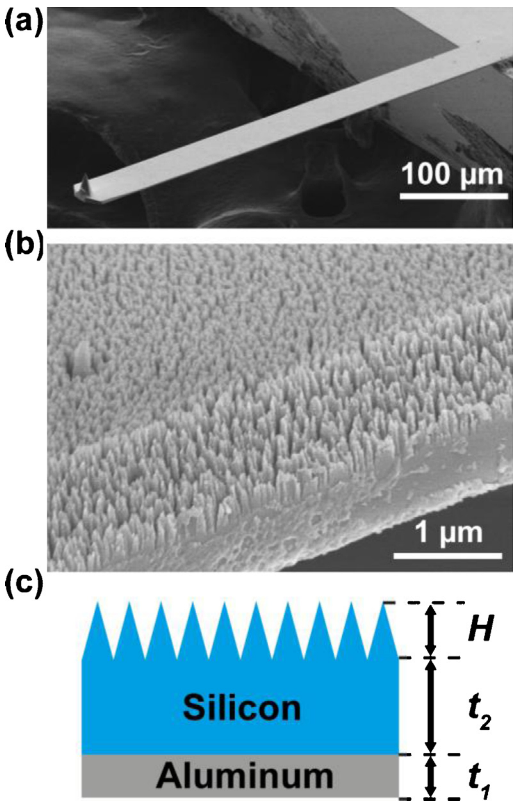

Fig. 1. (a) SEM image of a silicon–aluminum bimaterial cantilever. Nanocone arrays were fabricated on the top side surface of the cantilever. (b) Enlarged image of the cantilever edge showing the black silicon nanocones. (c) Diagram of the cantilever cross-section showing the layers of aluminum, silicon, and black silicon.

2. Experimental methods

We fabricated the black silicon nanocone arrays into the silicon surface of silicon–aluminum bimaterial cantilevers based on a three-step O_2–CHF_3–Ar + Cl_2 process at room temperature (25 °C) [19]. In step 1, a thin film of oxide (~10 nm) is formed on silicon surface by O_2 plasma, with flow rate of 10 sccm and pressure of 40 mTorr. Step 1 is completed in 5 min. In step 2, O_2 flow is shut down and CHF $_3$ is flowed in for 2 min, with a flow rate of 20 sccm and pressure of 40 mTorr. This short-period CHF_3 plasma etches the thin oxide layer into dispersed nanoparticle islands instead of completely removing the oxide. In the step 3, CHF_3 flow is shut down and a mixture of Cl_2 (20 sccm) and Ar (2 sccm) is flowed in, with a pressure of 40 mTorr. This step is to etch the silicon by sculpturing into silicon nanocone structures with the nanomask of the oxide islands formed in step 2. The Cl_2 etches the silicon, while Ar boosts the etching rate by physical bombardment of the silicon surface. The length of nanocones is controllable by the etching time of step 3. Under the above settings, the etching rate is 40 nm/min. Finally, the remaining oxide was removed by dipping the cantilever in ammoniumfluoride-base acid (PAD etch 4, KMG Electronic Chemicals Inc.) for 10 s. The fabrication of 300 nm tall nanocone arrays takes about 30 min including the time needed for the three-step O_2–CHF_3–Ar + Cl_2 process and other miscellaneous steps.

The experiment tested four cantilevers: three cantilevers with nanocone arrays and a cantilever without nanocones. We purchased commercially available cantilevers consisting of a silicon and aluminum layers (Mikromasch, CSC17), and fabricated nanocone arrays into the silicon surface of the cantilevers. Fig. 1a shows a scanning electron microscope (SEM) image of one of the cantilevers. Fig. 1b shows the enlarged SEM image of the cantilever

Table 1
Description of cantilevers.

	Cantilever			
	A	B	C	D
Nanocone height, *H* (nm)	–	104	253	336
Nanocone base diameter, *d* (nm)	–	39	65	93
Si, Thickness t_1 (μm)	1.61	1.26	1.23	1.15
Al, Thickness t_2 (nm)	16	14	13	7

with nanocone arrays. Table 1 lists the average heights, *H*, and the average base diameters of nanocone arrays, *d*, silicon layer thicknesses under the nanocone arrays, t_1, and aluminum layer thicknesses, t_2 of the four cantilevers. The ratio of nanocone height to base diameter is close to 3:1. Fig. 1c shows the schematic of the lateral surface of the cantilever. Cantilevers are rectangular with length L = 460 μm and width w = 50 μm.

We measured the optical properties of the cantilevers in the wavelength range 3–10 μm using an FTIR imaging microspectrometer [20]. The FTIR microspectrometer system consists of a spectrometer (Agilent, 680-IR) coupled to an optical microscope (Agilent, 620-IR) equipped with a focal plane array. We obtained spectroscopic images of the cantilevers with the spectral resolution of 8 cm^{-1} both in transmittance and reflectance modes. To achieve a satisfactory signal to noise ratio, we scanned 16 times in the same area, and averaged the data. The imaging system had a pixel field of view of ~5.65 μm × 5.65 μm which was approximately 9-fold smaller than the width of the cantilevers. The influence of light diffraction at the cantilever edges was expected to be insignificant, because we used only the data collected within the pixels along the cantilever centerline [21]. To obtain spectral transmittance, we took the ratio of the transmitted intensity through a cantilever to the transmitted intensity through air. Similarly, to acquire spectral reflectance, we took the ratio of the reflected intensity from a cantilever to the reflected intensity from a cantilever with ~100 nm thick gold coating.

Fig. 2 shows the experimental setup that measured the spectral responsivity of the cantilevers. A resistive heating element (CoorsTek, 301 ceramic igniter) at ~1200 °C emitted broadband

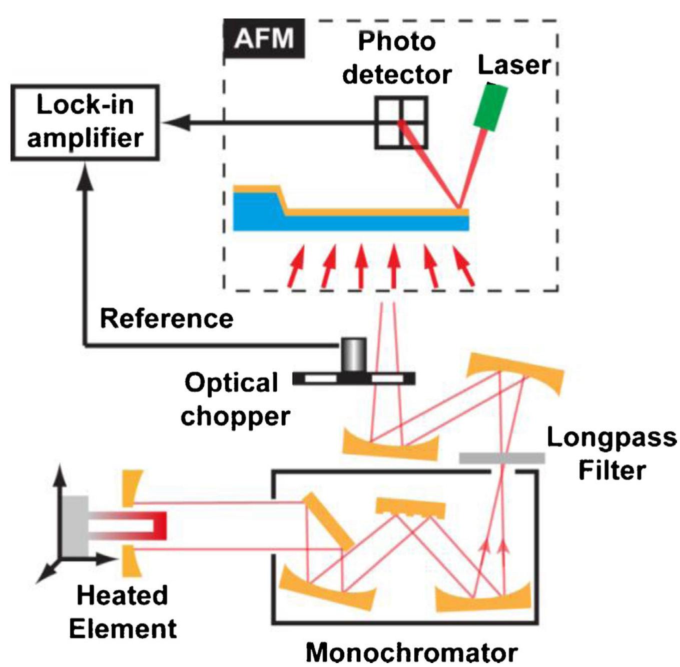

Fig. 2. Schematic of the measurement setup. An intensity-modulated narrow-band light beam was focused onto a bimaterial cantilever mounted in a commercial AFM.