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Heated atomic force microscope cantilever with high resistivity for improved temperature sensitivity

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ABSTRACT

We report a heated atomic force microscope cantilever with a heater region engineered to have high temperature sensitivity. The high resistivity (HR) heater region is phosphorous-doped silicon with a doping concentration of $1 \times 10^{16}\,cm^{-3}$ and a resistivity of 0.53 Ω-cm. The heater has a temperature coefficient of resistance of $102\,\Omega\,C^{-1}$ over the temperature range 100–300 °C, which is more than one order magnitude higher compared to heated cantilevers from previous publications. When used for thermal sensing of substrate nanotopography, the HR cantilever has a sensitivity of 0.37 mV/nm at 300 °C. Because the HR cantilever has high sensitivity at relatively low temperatures, it can be used to measure substrates that cannot withstand high temperatures, demonstrated here as a polymer film grating of thickness 110 nm.

1. Introduction

The atomic force microscope (AFM) typically measures surface topography by tracking the AFM cantilever deflection using a laser-photo-detector setup [1,2]. However, this technique cannot be easily scaled up to an array of cantilevers. An array of cantilevers significantly improves the imaging speed and measurement area of AFM, but requires each cantilever to have its own independent sensor [3,4]. Several methods have been explored to integrate a tip height sensor into a cantilever. These methods include tracking tunneling current [1], mechanical strain using a piezoresistor [5], or the flow of heat using a heater and thermometer [6]. A silicon cantilever with an integrated heater-thermometer measures the surface topography by monitoring the heat flow from the cantilever to the substrate [3,7]. This paper explores nanotopography sensing using two heated cantilevers of different heater doping concentrations. Previous work has shown decreasing the heater doping concentration of the cantilever improves vertical displacement sensitivity, one of the main metrics for quantifying topography sensing [8].

The sensitivity of a heated cantilever depends on the cantilever temperature-dependent properties, such as the temperature coefficient of resistance (TCR). As the cantilever scans over the topography of a surface, the cantilever heater region dissipates heat into its surroundings. The cantilever heat flow decreases when the cantilever traces a topography feature that moves the cantilever away from the substrate and increases when the cantilever is closer to the substrate. Increasing the TCR of the cantilever causes the cantilever electrical properties to be more sensitive to temperature change, resulting in a larger temperature signal per given topography height. Therefore, increasing the cantilever TCR enables the cantilever to produce higher sensitivity. The cantilever TCR can be increased by lowering the doping concentration of the heater region. The previously studied low-resistivity (LR) heated cantilever has a TCR of $8\,\Omega\,C^{-1}$, and a heater region with a doping concentration of $3 \times 10^{17}\,cm^{-3}$ and a room temperature electrical resistivity of 0.04 Ω-cm [7,9–11].

This paper reports the design, fabrication, and thermal imaging results of a high-resistivity (HR) cantilever, which has a heater doping concentration of $1 \times 10^{16}\,cm^{-3}$, and a room temperature electrical resistivity of 0.53 Ω-cm. The HR cantilever has higher temperature sensitivity and better thermal imaging performance compared to heated cantilevers reported in previous publications.

2. Cantilever design and fabrication

Fig. 1 shows a schematic and a scanning electron microscope image of the cantilever studied here. The cantilever free end consists of a tip that is 1 μm tall with a radius of curvature of 20 nm. The silicon cantilever is electrically activated by n-type phosphorus doping [12]. The cantilever free end is low doped ($1 \times 10^{16}\,cm^{-3}$) forming a resistive heater region, while the cantilever legs are highly doped ($1 \times 10^{20}\,cm^{-3}$) to carry current. When current is passed through the cantilever, the heater region dissipates more

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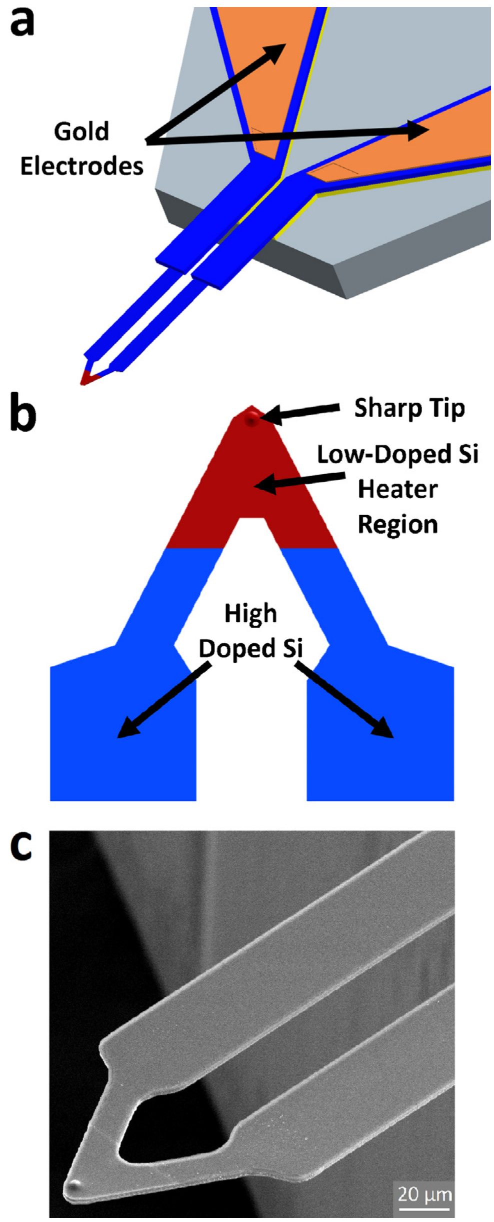

Fig. 1. Schematic of cantilever design showing (a) isometric view of the silicon cantilever (b) top view of the cantilever free-end containing a 14 μm × 20 μm heater region with a dopant concentration of 1×10^{16} cm^{-3}. (c) Scanning electron microscope image of the cantilever.

than 95% of the power resulting in an increase in the cantilever free-end temperature.

A three-dimensional finite-element model was developed using COMSOL to better understand the electrical and thermal behavior of the cantilevers. The simulations compared cantilevers having heater doping concentrations of 1×10^{15} cm^{-3} or 3×10^{17} cm^{-3} via a steady-state joule-heating model. Each cantilever was suspended in a large block of air while the base of the cantilever and the walls of the air block were held at room temperature. The simulations accounted for the temperature-dependence of the cantilever electrical resistivity and thermal conductivity. The simulation evaluated the heater temperature, the power dissipated by the cantilever, and the cantilever electrical resistance for a range of heating voltages. The 1×10^{16} cm^{-3} heater doping concentration is a compromise between having a high enough TCR to attain a significant increase in sensitivity while not requiring a high voltage

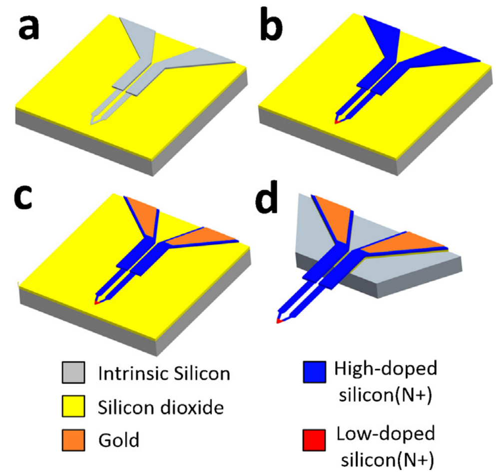

Fig. 2. Fabrication process for a cantilever with integrated resistive heater. Fabrication starts with a silicon-on-insulator wafer. (a) Anchor and cantilever formation with inductively coupled plasma (ICP) deep reactive ion etching (DRIE). (b) Low dosage and high dosage phosphorus implantation. (c) Electrical contact formation using 250 nm-thick gold deposition and etching. (d) Backside ICP-DRIE of a 500 μm-thick silicon handle layer followed by removing the sacrificial oxide layer using a hydrofluoric acid solution.

to heat. The simulation predicted the HR cantilever to have a room temperature electrical resistance of 12 kΩ and a TCR of 93 Ω C^{-1}.

Fig. 2 shows the batch fabrication process for the heated cantilevers. The cantilever fabrication started with a 4-in. n-type silicon-on-insulator (SOI) wafer of <1 0 0> crystallographic orientation. The SOI wafer had a device layer thickness of 5 μm, a buried oxide layer thickness of 1 μm, and a device layer thickness of 500 μm. The tip, cantilever structure, and anchor were formed via deep-reactive ion etching (DRIE). The tips were formed via a HNA (hydrofluoric acid, nitric acid, acetic acid) isotropic wet etch, and sharpened through dry oxidation. The cantilever was electrically activated by doping the heater region to 1×10^{16} cm^{-3} and the legs to 1×10^{20} cm^{-3}. The doping technique involves ion implantation of phosphorus, followed by thermal diffusion of the dopants. The parameters of the doping procedure were determined using a doping process simulation software, Sentaurus TCAD. Electrical contacts were formed by sputtering 10 nm of chromium and 250 nm of gold. The cantilever was released via DRIE through the backside of the wafer followed by sacrificial etching of the silicon dioxide layer using hydrofluoric acid.

3. Cantilever characterization

We characterized the cantilever mechanical, electrical and thermal properties [9]. The cantilever was measured to have a stiffness of 1.3 N/m and a resonant frequency 78 kHz using a commercial AFM system, Asylum Research MFP-3D. The cantilever steady temperature was measured with an accuracy of approximately 1% by determining the Stokes peak shift, using a Renishaw inVia Raman spectroscope with a 488 nm argon laser [9]. The electrical characterization involved operating the cantilever in series with a current-limiting sense resistor of equal electrical resistance to the cantilever at room temperature, which is typical of thermal imaging operation [13]. Fig. 3(a and b) show the cantilever current and the cantilever electrical resistance as a function of cantilever voltage for the LR and HR cantilevers. Fig. 3(c and d) show the cantilever electrical resistance and the cantilever steady temperature as a function of cantilever power for both cantilevers. Despite the differences in the electrical characteristics of the two cantilevers, the thermal conductivity of the cantilevers vary only by about 5%, resulting in similar heat flow characteristics [14]. Thus, the two