ELECTROTHERMAL MICROCANTILEVER WITH INTEGRATED SOLID-STATE HEATER-THERMOMETER AND NPN BACK-TO-BACK DIODES

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ABSTRACT

This paper reports the integration of both electrical and thermal elements into an atomic force microscope (AFM) cantilever, where the electrode and heater-thermometer are electrically isolated by an NPN back-to-back diode. The electrothermal (ET) cantilever can be self-heated to more than 400°C while the tip voltage can be measured or controlled independent of tip temperature, up to 10 volts. To our knowledge, this is the first microcantilever to have a solid-state junction and heater integrated near a tip.

INTRODUCTION

Microcantilevers with integrated heaters [1] can be used to control nanometer-scale temperature fields for data storage [2], nano-manufacturing [3], and materials analysis [4]. However, such probes are not well suited for nanoelectronic measurements, as they cannot independently control temperature and measure or apply electric potential. We report an electrothermal AFM cantilever which combines the functions of heated and electrically-conductive AFM cantilever tips.

DESIGN

The microcantilever consists of doped single-crystal silicon and has three legs serving as electrical paths to the cantilever free end. The cantilever free end has an N-type heater, N+-type tip, and region of P+-doped silicon that electrically isolates these two functional regions. The N⁺P⁺ junction is a Zener diode whereas the P⁺N junction is a standard diode. While the heater and electrode are electrically isolated, heat conduction between the two devices allows tip temperature control.

The key challenge in designing the cantilever was the integration of a high-quality NPN junction at the cantilever free end. The dopant distributions are critical to device performance and depend upon device thickness and diffusion process parameters. The dopant must diffuse through the thickness of the cantilever (1.5 μm) to avoid current leakage, but this process also narrows the P+-type region (5 μm) and risks current leakage at the top of the NPN junction. Fig. 1 (a) shows the doped NPN junction near the cantilever free end and Figs. 1 (b)-(d) shows simulation results for the doping concentrations near the NPN junction for the process used, which balances these competing requirements.

RESULTS

Fig. 2 shows the cantilever fabrication process, which begins with an N-type silicon-on-insulator wafer doped with 10¹⁸ atoms/cm³ antimony. We fabricate sharp silicon tips and define the cantilever using DRIE etching down to the SiO₂ layer. Next, the cantilever legs are doped N+-type to 10²⁰ atoms/cm³ with antimony ion implantation and a short initial diffusion. Similarly, the P+-type regions are doped to 10¹⁹ atoms/cm³ with boron ion implantation and the critical diffusion. The cantilever is released with a backside etch through the handle wafer and a hydrofluoric acid etch. One 4" wafer yields ≈300 devices with >90% yield. Fig. 3 shows micrographs of a fabricated cantilever and cantilever tip.

We characterized the cantilever electrical and thermal properties. Fig. 4 shows the current-voltage (I-V) characteristics for a back-to-back diode device using a current controlled sweep

across the solid-state heater and the NPN junction. The NPN isolation region is a Zener diode (N⁺P⁺) and a standard diode (P⁺N) facing away from each other. Breakdown voltages across

Figure 1. (a) Cantilever design with doping as indicated. (b) Simulation results of lateral and vertical doping concentrations for the NPN junction. A cross-section of the NPN junction is shown in (c), with the lateral X-X' doping concentrations shown in (b) and the vertical Y-Y' doping concentrations shown in (d). Target concentrations for the N⁺, P⁺, and N-type regions are 10²⁰, 10¹⁹, and 10¹⁸ atoms/cm³, respectively.

Figure 2. Fabrication process for NPN junction electrothermal cantilever. (a) Starting with an antimony-doped SOI wafer, we form and sharpen the tip using oxidation sharpening and define the cantilever shape using deep-reactive ion etching (DRIE), (b) then selectively dope the cantilever N+-type with antimony and P+-type with boron. (c) Electrical connections are formed with sputtered gold and the cantilever is released (d) with backside DRIE and an HF etch to remove the sacrificial SiO₂.

Figure 3. Single-crystal doped silicon microcantilever with integrated solid state heater and electrode using NPN doping to form back-to-back diodes.

Figure 4. Current-controlled current-voltage electrical characterization of an NPN junction ET cantilever. (a) The solid line shows a current sweep across the N-type heater region and the dashed line shows a current sweep across the NPN region. Diode breakdown occurs at ± 10 volts and thermal runaway occurs at ± 20 volts. (b) The solid line shows the leakage current at I_1 while the heater temperature is ramped using -2 mA to 2 mA across $I_3 - I_2$. Note the magnitude of the y-axis in comparison to the swept current, indicating current leakage two orders of magnitude lower than heater current.

Figure 5. Raman spectroscopy temperature calibration at the heater apex and cantilever tip for the NPN junction ET cantilever. The diode design has a 30°C temperature difference between the tip and heater at a heater temperature of 466°C .

the back-to-back diodes are ± 10 volts, indicated by the sudden increase in leakage current in Fig. 4 (a). Thermal runaway in the heater region occurs at about ± 20 volts.

Fig. 4 (b) shows that leakage current is nearly zero during static heater operation at 450°C , up to the breakdown voltage of about ± 10 volts. Current flow is impeded in forward and reverse directions for the back-to-back diode design, and hysteresis is not observed during current-controlled I-V measurements. Current leakage is two orders of magnitude lower than heater current during heater operation between -2 mA and 2 mA.

Laser Raman spectroscopy calibrated the heater temperature during electrical excitation in air, with no electrode bias voltage. Fig. 5 shows this data, where the heater operates at $>400^{\circ}\text{C}$ with 40 mW of dissipated power.

CONCLUSION

We report an AFM cantilever having an NPN junction device integrated into the cantilever free end, which combines the functions of heated and electrically-conductive AFM cantilever tips. Such a device facilitates combined nanoscale electronic and thermal measurements. These microcantilevers make it possible to measure temperature-dependent electronic properties of a surface or induce electro-thermal modifications to a surface with nanometer-scale resolution.

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