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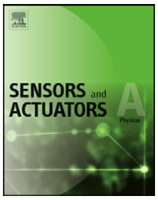

Silicon microcantilever hotplates with high temperature uniformity

Natalya L. Privorotskaya, William P. King*

Department of Mechanical Science and Engineering, University of Illinois Urbana-Champaign, Urbana, IL 61801, United States

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ABSTRACT

This paper presents microcantilevers with integrated heater–thermometers that are engineered to have regions of highly uniform temperature. The cantilevers are fabricated from doped single crystal silicon. Four cantilever designs are considered, where the regions of doping and the cantilever dimensions are selected to achieve the highest temperature uniformity over a region 100 μm × 100 μm at the cantilever free end. The cantilever electrical, thermal, and mechanical properties were characterized using laser vibrometry and Raman spectroscopy. The temperature uniformity achieved is 2–4%, varying slightly over the temperature range 25–200 °C and varying between the cantilever designs. The cantilevers are of size suitable for operation in AFM or as cantilever sensors.

1. Introduction

Microcantilevers with integrated heater–thermometers can be used as cantilever sensors or can be used in applications where a heated cantilever tip interacts with a surface. Published work on heated cantilevers mainly focuses on applications where a heated cantilever tip interacts with a substrate for data storage [1], detection of nanometer-scale temperature-dependant materials properties [2,3], or nano-manufacturing [4,5]. Other applications use the heated cantilever, rather than just the tip. Microcantilevers with integrated heater–thermometers have been used for thermogravimetry [6,7], explosives sensing [8], and characterization of microfluid flows [9]. Cantilever heating can be used to clean organic contaminants from the cantilever surface, which can reset the sensor into a pristine condition [10].

The first demonstrations of self-heated cantilevers were made with piezoresistive silicon cantilevers that used the piezoresistive region of the cantilever as a heater [6,11,12]. A piezoresistor fabricated into a silicon cantilever heater can provide several hundred degrees of heating, but it is usually fabricated at the base of a cantilever which is the wrong location as most applications require heating at the cantilever free end or along the length of the cantilever. By placing the heater at the free end of the cantilever, the heating time could be reduced [13] and performance could be improved for data storage applications [1,14]. For cantilever sensing applications, the cantilever heater can be distributed along the length of the cantilever [15].

For sensing applications, it is important to know the temperature of the cantilever or the temperature of the analyte on the cantilever. The uncertainty of the cantilever temperature is governed by the cantilever temperature calibration uncertainty and the temperature gradient along the cantilever. The thermal, mechanical, and electrical characteristics of heated silicon cantilevers is well understood for operation in air [16], vacuum [17], at low temperature [18], and in liquid [19]. Advances in the characterization and calibration of heated microcantilevers have provided cantilever temperature calibration accuracy to within a few percent of the cantilever temperature rise [20]. Thus the main uncertainty in temperature accuracy for heated microcantilevers is governed by the large temperature nonuniformity along the length of the cantilever. When an analyte covers enough of the cantilever such that it is not at a uniform temperature, it is not possible to sensitively detect a transition temperature, as different parts of the analyte are at different temperatures. Typical values for temperature gradient along the length of heated microcantilevers are in the range of 60–100 °C per 100 μm of length at the free end of the device at tested powers [15,16,21]. Thus improvements are needed in the temperature uniformity on heated microcantilevers.

This paper describes heated microcantilevers designed to have large regions of uniform temperature. The cantilevers are made from doped single crystal silicon. The doped regions are resistive heaters, the geometry of which is selected to optimize the temperature distribution within large areas at the free end of the cantilever. Four cantilever designs were considered using finite element simulations, and the cantilevers were then fabricated and characterized.

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* Corresponding author. Tel.: +1 217 244 3864; fax: +1 217 244 6534.
E-mail address: wpk@illinois.edu (W.P. King).

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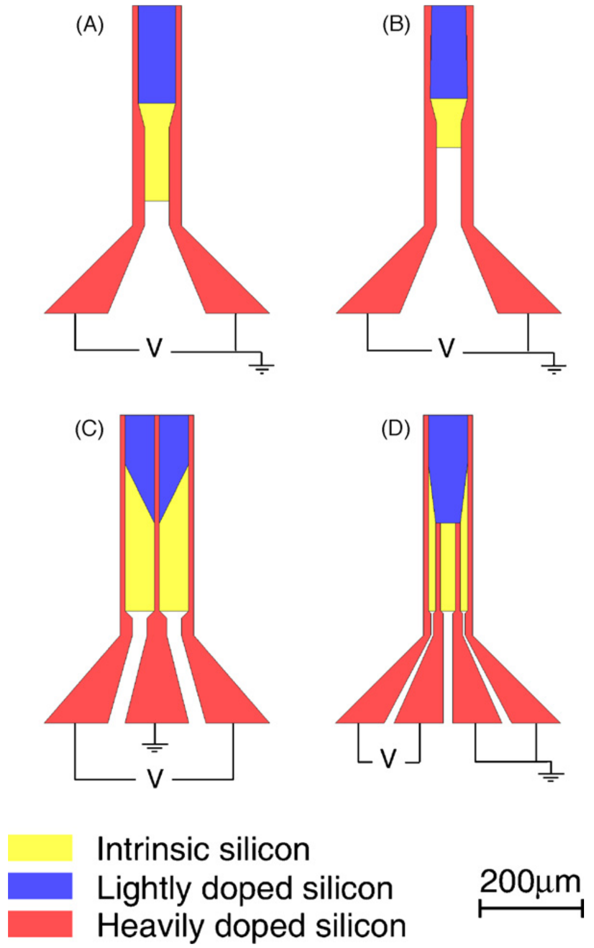

Fig. 1. Four heated cantilever designs. Each cantilever has different doping regions optimized to achieve the best temperature uniformity within 100 µm region at the cantilever free end. The cantilevers are 400 µm long. Cantilevers A, B, and D are 100 µm wide while cantilever C is 150 µm wide. Cantilevers A and B have one heater, cantilevers C and D have dual heaters.

For three cantilevers with 100 µm width, the temperature nonuniformity within 100 µm × 100 µm was 2–3%, and for a cantilever having a width of 150 µm, the temperature nonuniformity was 4% in the same area.

2. Design

The main design constraints for heated silicon cantilevers with regions of uniform temperature are the desired temperature range and the size of the region in which temperature should be uniform. Most chemical and biochemical reactions proceed at temperatures below 200 °C and so this is the target temperature range for this work. A square region at the cantilever free end of size 100 µm is chosen to provide sufficient surface area to conduct most desired sensing. The cantilever electrical resistance should be below 10 kΩ in order to interface well with standard instrumentation. Finally, the fundamental resonant frequency of the cantilever should be less than 100 kHz to interface with conventional atomic force microscope instrumentation.

Fig. 1 shows the four cantilever designs. The cantilevers are 400 µm long and 2 µm thick. Design C is 150 µm wide, while the rest have a width of 100 µm. Cantilever of this size is appropriate for most cantilever sensing applications [22–24]. Furthermore the cantilevers are comparable in size to commercially available cantilevers so that the cantilevers may be easily integrated into AFM. The goal is for a square 100 µm region at the free end of the cantilever to achieve highly uniform temperature. When a heating voltage is applied to the cantilever, electrical current flows through the structure mainly via highly doped (10^{20} cm^{-3}) regions positioned along two longer sides of the cantilever. A lightly doped (10^{17} cm^{-3}) area is located at the free end, where most power dissipation occurs. Intrinsic, lightly, and highly doped regions are indicated with yellow, red, and blue colors, respectively. Cantilevers A and B have one heater, while cantilevers C and D have dual, parallel heaters. The size of the heaters and doped regions is optimized to achieve cantilever designs that could be operated at the desired temperature while maintaining the best temperature uniformity.

In order to predict cantilever temperature distribution, an electro-thermal finite element model of silicon cantilever was configured in ANSYS. The model was used to predict heated power and temperature distribution in the cantilever in response to applied voltage, as well as to predict cantilever electrical properties. The mesh is composed of 8-node three-dimensional solid69 elements with thermal and electrical conduction capabilities. This element also accounts for Joule heat generated from the current flow. An approximate mesh size of 4 µm was chosen from mesh optimization studies. In order to mesh the entire model, each line was first divided according to the desired mesh size using manual controls, after which the mesh was applied to each volume. Dependence of thermal conductivity and electrical resistivity on temperature were obtained from literature [21,25]. Cantilever mechanical properties were not specified in the model because simulation efforts focused only on electro-thermal behavior.

Heat flow from the cantilever is different for cantilever heating near a substrate [26,27] compared to cantilever heating away from a substrate [28]. However in both cases heat transfer is dominated by thermal conduction, and both thermal convection and thermal radiation can be ignored. Considering thermal convection, for one of the present hotplate cantilevers heated to 200 °C in air, the Grashoff number is about 10^{-9}, meaning that the buoyancy forces in the heated air near the cantilever are about 10^{9} times smaller than the viscous forces. It is therefore unlikely that significant advection in the air is caused by density gradients. While the fundamentals of natural convection at small length scales are not fully understood, it is reasonable to assume that thermal conduction dominates over convection for these conditions. For the same heating conditions, thermal radiation is less than 25 µW. Since this value is less than 1% of the heat generated in the cantilever, it is reasonable to assume that thermal conduction dominates over thermal radiation for these conditions. Thus the simulation considers only thermal conduction. Room temperature boundary conditions were applied to the anchor because it acts as a heat sink [16]. Only a small portion of the anchor was modeled in order to minimize simulation size. Thermal conduction to the air can be modeled as an effective convection coefficient, although the temperature distribution in the cantilever is relatively insensitive to the actual value. In the simulation, thermal convection boundary conditions ($h = 200\,\mathrm{W/m^2\,K}$) were applied to all external cantilever surfaces [29,30].

The cantilever designs were developed and optimized in two stages. First, the overall cantilever dimensions were varied to understand their effect on temperature distribution. While cantilever thickness was constrained by the thickness of device layer on the wafer, cantilever length and width were allowed to vary. Cantilevers less than 200 µm in length were not desirable because this length was required to achieve a temperature rise of 200 °C at the free end. Length greater than 500 µm was not necessary to achieve the desired temperature and temperature uniformity, and at this length the cantilever begins to exceed what is commonly appropriate for AFM integration. Cantilever width did not significantly affect temperature rise if the width is less than the length. Since a 100 µm region was chosen as the uniform temperature area, the width must be at least this value.