AC Electrothermal Characterization of Doped-Si Heated Microcantilevers Using Frequency-Domain Finite Element Analysis

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Abstract

This work investigates the frequency-dependent electrothermal behaviors of freestanding doped-silicon heated microcantilever probes operating under the periodic (ac) Joule heating. Figure 1(a) indicates an SEM image of the heated microcantilever showing the leg, constriction and heater regions. Although initially developed for data storage [1,3], heated microcantilevers have been used in other tip-based nanoengineering applications, including localized thermal analysis [4-7], thermally driven topography mapping [8,9], self-cleaning nanosampling [10], and synthesis and characterization of carbon nanotubes [11,12] and graphene oxides [13]. It should be noted that most of these applications operate the heated cantilever at steady state or with short electrical pulses to harness its highly localized heating capability. Operating the heated cantilevers under the periodic heating will expand its use for precision micro/nanoscale thermoelectric metrologies [7]. However, the previous studies to date have been limited to a simple 1-D analysis that often oversimplifies the structural and operational complexities embedded in doped-Si heated cantilevers. It is imperative to understand the periodic electrothermal behaviors of the heated cantilever.

To address the existing challenges, we have conducted a finite element analysis (FEA) that computes the steady periodic solutions in the frequency domain. Figure 1 (b) indicates the 3-D geometry of the heated microcantilever suspended freely in the environment box for the FEA. The transient heat conduction equation for each component (i.e., the low-doped heater region, the high-doped constriction region, and the high-doped leg region) was solved using the general heat transfer module for DC component: see Figure 2. To include the AC current harmonics and the periodic heating operation, the joule-heating module under the electrothermal interaction on COMSOL Multiphysics® software was used. As shown in Figure 3, the computed 3ω voltage output across the cantilever agrees very well with the measurement, overcoming the limitation of the previous 1-D approximation that could not convey the high-frequency behaviors. The results demonstrate that the high frequency behavior of the cantilever is closely related to thermal diffusion restricted in the heater region. With the developed FEA model, design parameters of the cantilever, such as a heater size and doping concentration of the heater, and their effects on the ac electrothermal behaviors of the cantilever can be carefully investigated. In addition, the cantilever ac behaviors in the vacuum and in the air were compared, through which the frequency-

dependent heat transfer coefficient of the air was quantified (Figure 4). Although this work focused on doped-Si heated microcantilever probes, the developed model and obtained results will allow thorough ac electrothermal characterizations of various microelectromechanical devices, leading to further advances in localized thermal analysis.

Reference

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Figures used in the abstract

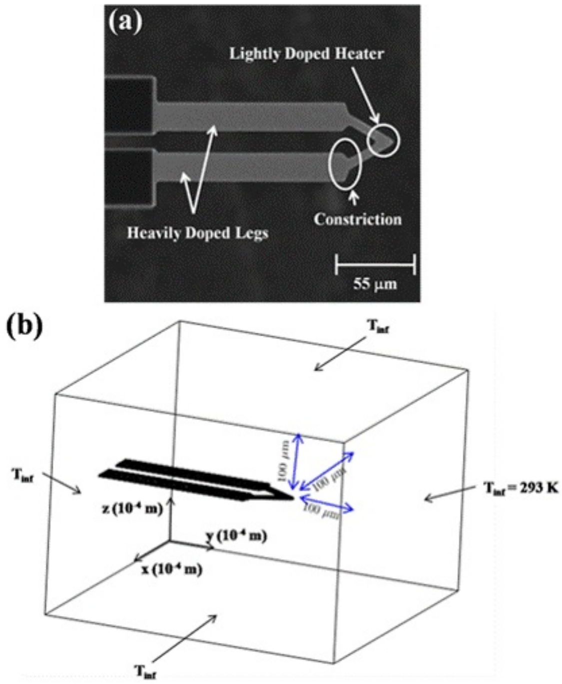

Figure 1: (a) An SEM image of the heated microcantilever showing the leg, constriction and heater regions and (b) its FEA model with an air box. The cantilever base was anchored flush to the left wall of the air box and the remaining cantilever facets were spaced 100 µm away from the other air box sides.

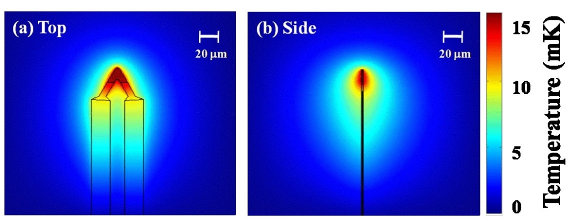

Figure 2: temperature distribution of the cantilever when 0.35 mW of a DC power is dissipated, viewed from (a) the top and (b) the side.

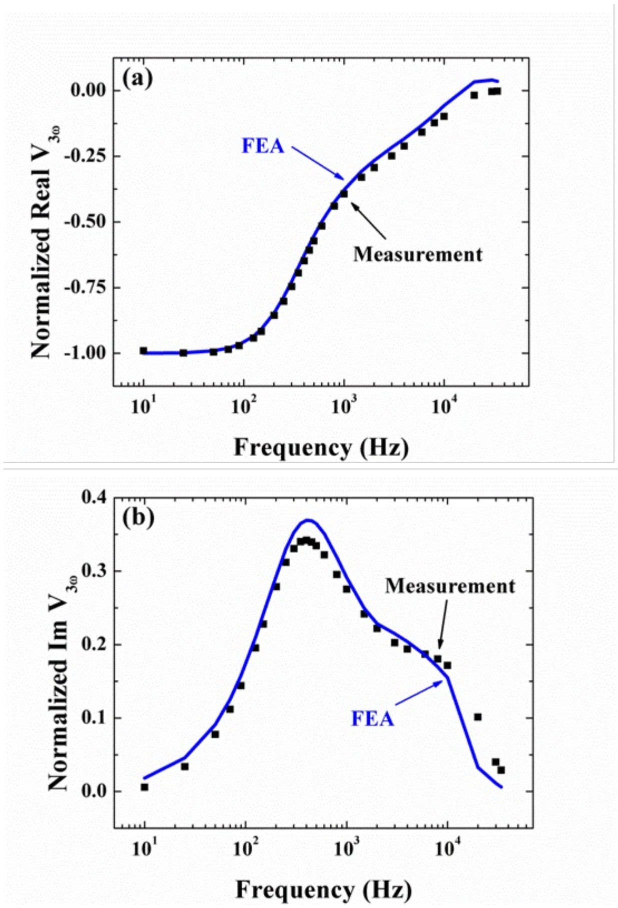

Figure 3: (a) In-phase and (b) out-of-phase 3ω voltage signals as a function of frequency for both the experimental data, represented by the square marks, and the FEA results, represented by the solid blue line. Plots are normalized with the magnitude of the 3ω voltage at 10 Hz for comparison. The experiment and model were run at thesame total input current of 112µA-rms.

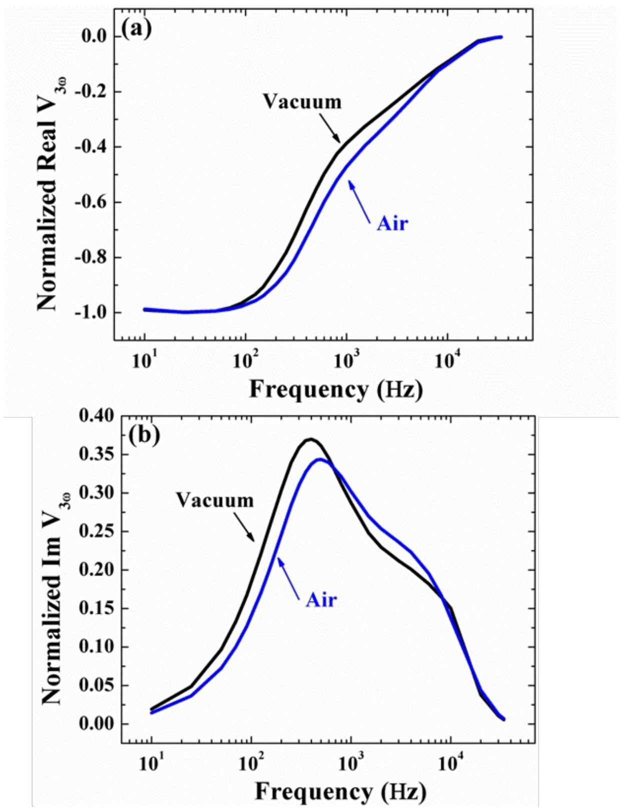

Figure 4: Normalized 3ω voltage signalscomparing the vacuum and air operations. All values are normalized with the maximum amplitude of the 3ω signal in the vacuum. The difference indicates the effect of heat conduction to the air on the AC behaviors of the cantilever.