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

S. Hamian[1], A. Gauffreau[2], T. Walsh[2], K. Park[1]
1.Mechanical Engineering Department, University of Utah, Salt Lake City, UT, USA
2.Department of Mechanical, Industrial & Systems Engineering, University of Rhode Island, Kingston, RI, USA

Introduction: Atomic force microscopy (AFM) is used for data writing and reading, localized thermal analysis, and surface scanning in nanometer scale. In AFM, deflection of the cantilever changes reflected laser intensity measured by photo-detector. A Heated cantilever is made of high phosphorous doped legs and a lightly doped heater zone near the tip (Fig. 2). An experimental and numerical AC characterization of the heated cantilever using the 3ω method, done in this study, provides deep understanding of frequency-dependent electrothermal behaviors of the heated cantilever.

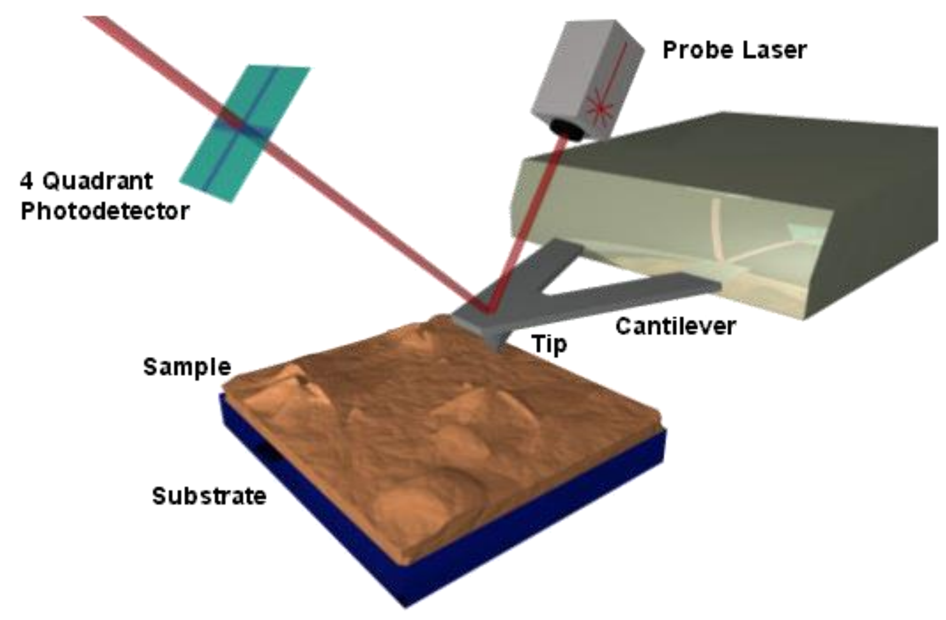

Figure 1. Schematic of atomic force microscope (AFM).

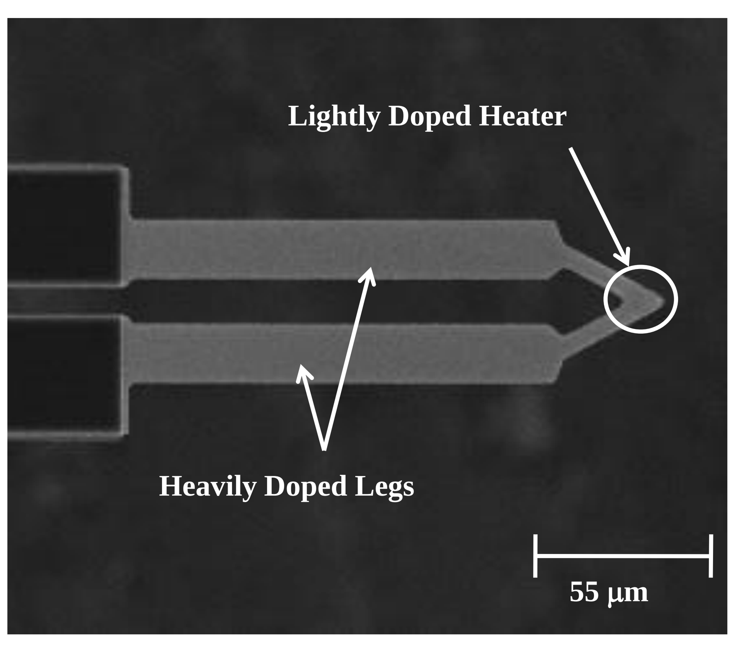

Figure 2. Heated cantilever with heavily and lightly doped legs and heater zone.

Computational Methods: The AC electothermal behaviors of the heated cantilever suspended in the environment box has been computed in the frequency domain using the governing equations:

Transient Heat Equation
$$C_i \frac{\partial T_i(\mathbf{r},t)}{\partial t} = k_i \nabla^2 T_i(\mathbf{r},t) + \frac{\dot{Q}_i(\mathbf{r},t)}{V_i}$$

Fourier Transform
$$j\omega_H C_i \tilde{T}_{\omega_H,i} = k_i \nabla^2 \tilde{T}_{\omega_H,i} + \frac{\tilde{Q}_{\omega_H,i}}{V_i}$$

Complex Decomposition
$$-\omega_H C_i T_{I,i} = k_i \nabla^2 T_{R,i} + \frac{\tilde{Q}_{R,i}}{V_i} \quad \text{In-Phase}$$

$$\omega_H C_i T_{R,i} = k_i \nabla^2 T_{I,i} + \frac{\tilde{Q}_{I,i}}{V_i} \quad \text{Out-of-Phase}$$

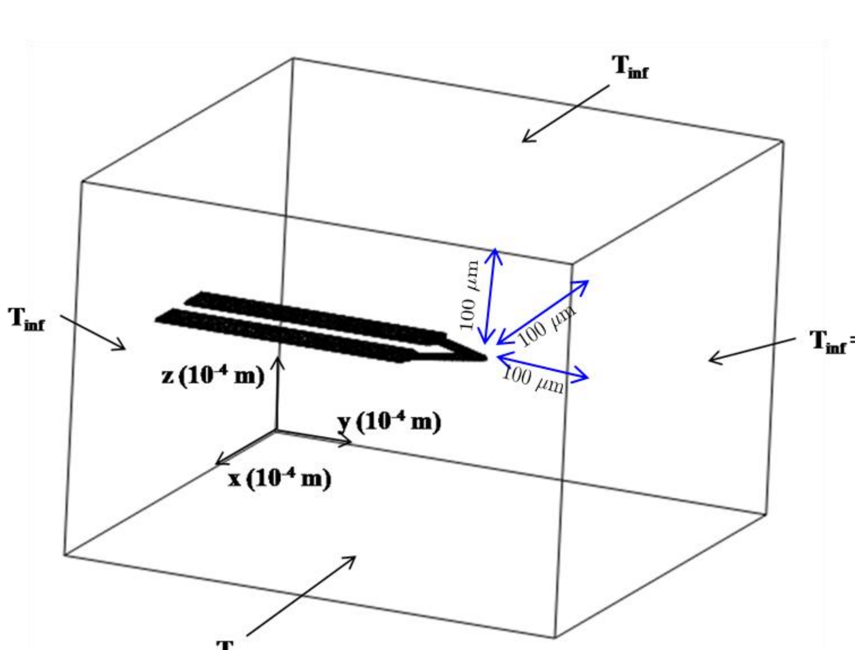

Figure 3. Schematic of 3-D heated cantilever geometry in air box.

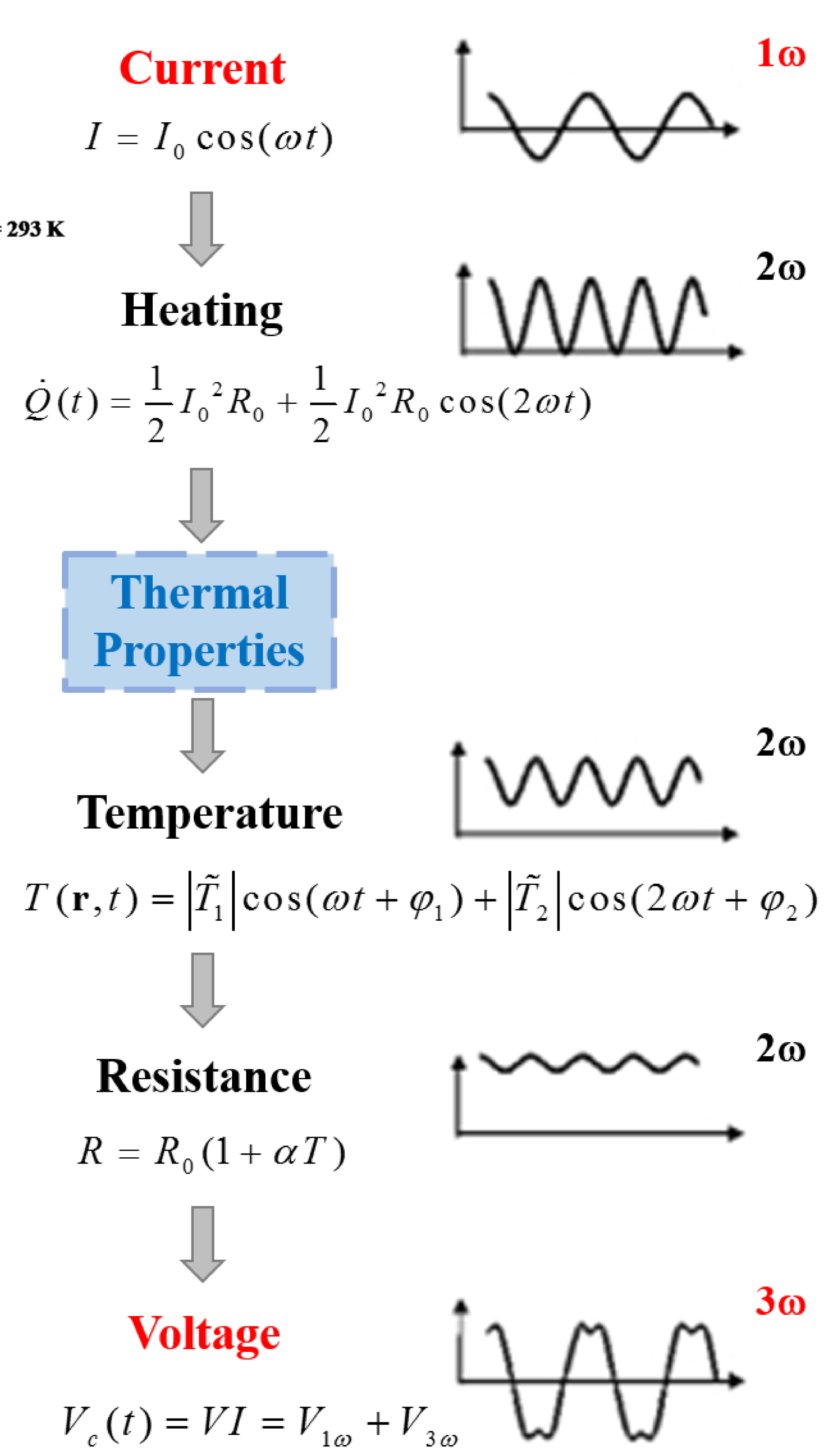

Figure 4. applying the AC input current results in the oscillation of the temperature and electrical resistance of the cantilever at the 2nd harmonic of the input current. The voltage signal of the cantilever will thus have the 3rd harmonic component, which is directly related with the thermal transfer function.

Results: 3ω voltage signals of the cantilever in vacuum is calculated by the frequency-domain COMSOL simulation. Largest error is 6.05%. Temperature distribution of the cantilever suspended in air is calculated for different frequencies. The heater size effect on the 3ω voltage signal is also studied.

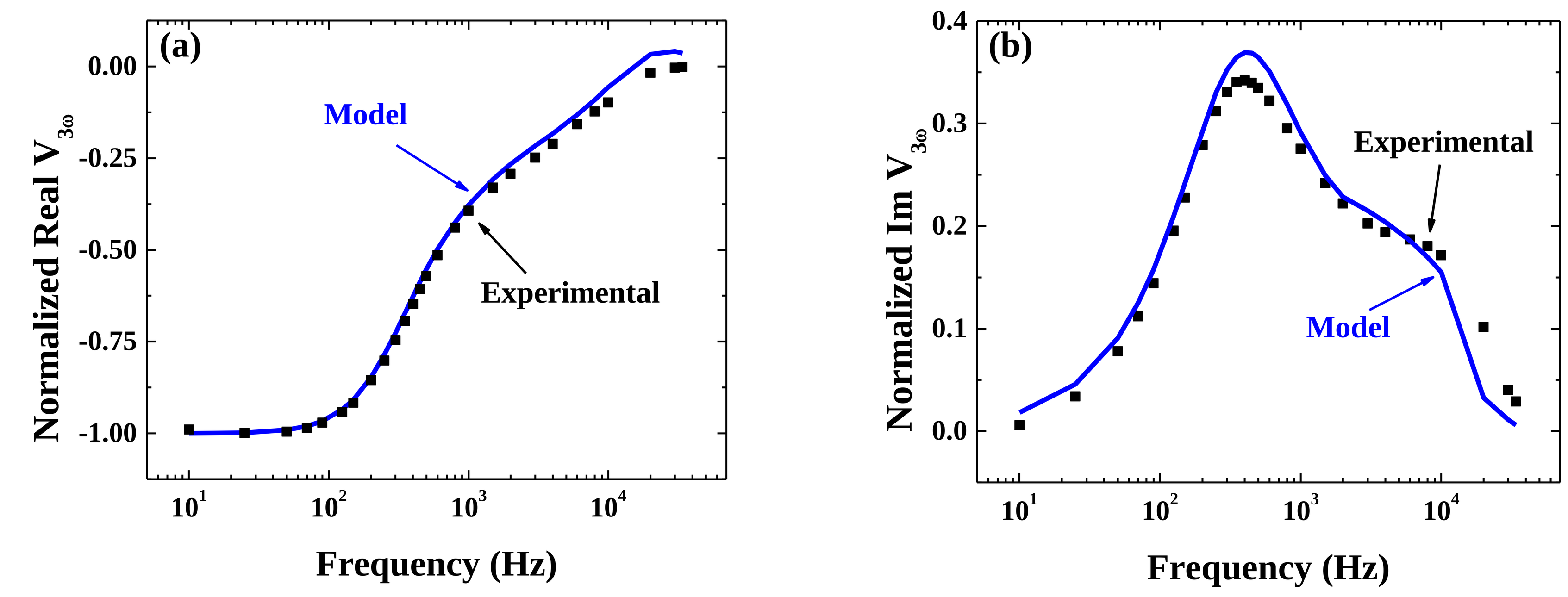

Figure 5. Nondimensional In-phase and out-of-phase 3w voltage. Larger peak in (b) represents cantilever legs effect and smaller peak represents the heater dominancy in higher frequencies.

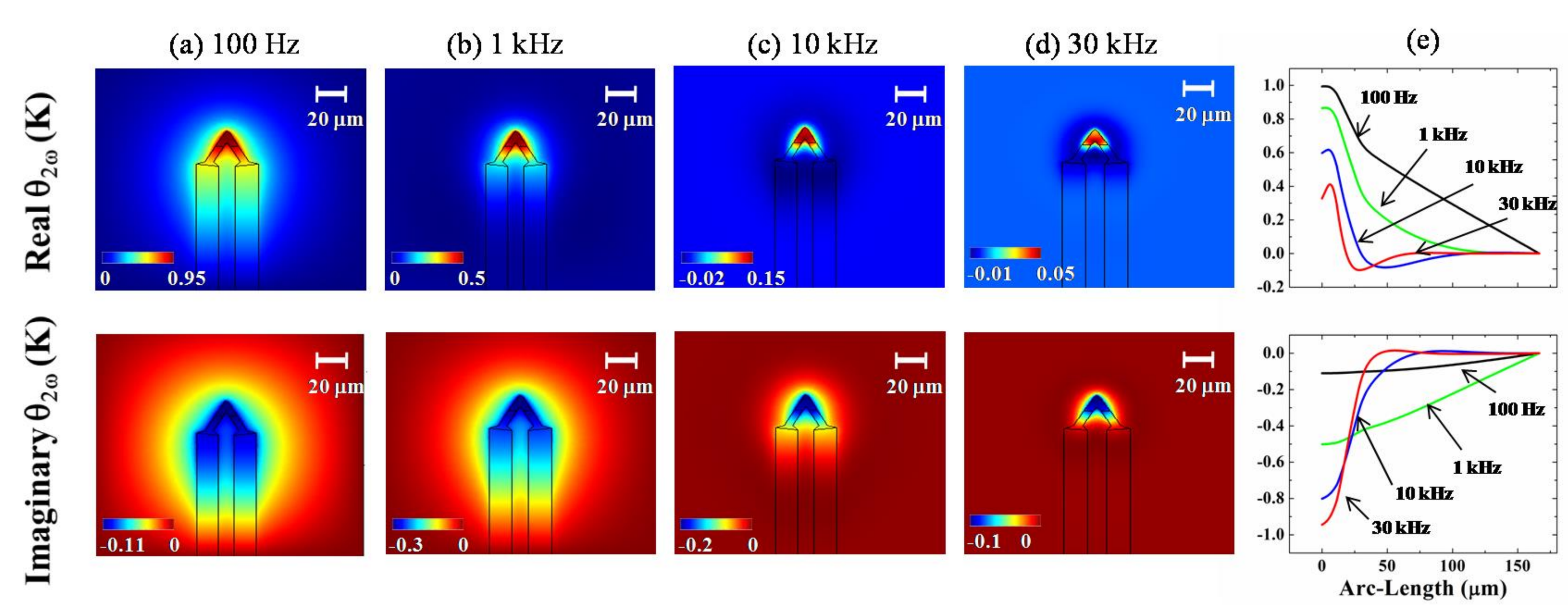

Figure 6. In-phase and out-of-phase temperature distribution for different frequencies. As the frequency increases, temperature oscillation becomes more out of phase and restricted to the heater zone. The oscillation amplitude of cantilever temperature becomes smaller at high frequencies.

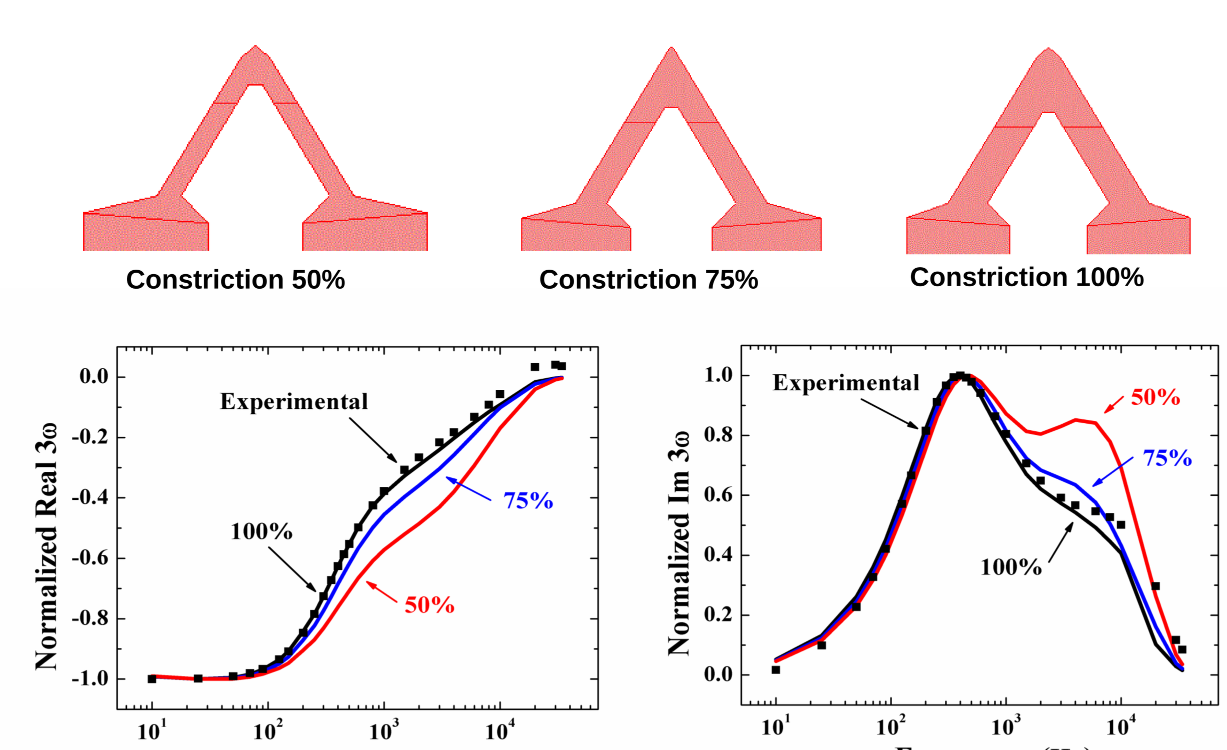

Figure 7. heater constriction size effect indicates the sensibility of heater effect around higher frequencies for smaller heater size which enables more accurate study of thermophysical properties of materials.

Conclusions: A frequency-domain FEA model is developed using COMSOL Multiphysics to predict the frequency dependent of electrothermal behaviors of the heated cantilever. The developed method can be applied for the simulation of the frequency-dependent thermal behaviors for different MEMS devices.

References:

1.Lee J., Beechem T., Wright T. L., Nelson B. A., Graham S., and King W. P., “Electrical, Thermal, and Mechanical Characterization of Silicon Microcantilever Heaters,” Journal of Microelectromechanical Systems, **15**, pp. 1644–1655 (2006).
2.Park K., Marchenkov A., Zhang Z. M., and King W. P., “Low temperature characterization of heated microcantilevers,” J. Appl. Phys., **101**, p. 094504 (2007).
3.Dai Z., King W. P., and Park K., “A 100 nanometer scale resistive heater–thermometer on a silicon cantilever,” Nanotech., **20**, 095301 (2009).
4.Park K., Lee J., Zhang Z. M., and King W. P., “Frequency-dependent electrical and thermal response of heated atomic force microscope cantilevers,” Journal of Microelectromechanical Systems, **16**, pp. 213–222 (2007).
5.Dames C., and Chen G., “1ω, 2ω, and 3ω methods for measurements of thermal properties,” Review of Scientific Instruments, **76**(12), p. 124902 (2005).