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Focused Ion Beam In Thermal Science And Engineering

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In this paper, utilizing a focused ion beam source for applications in thermal science is demonstrated. Focused-ion-beam (FIB) nanolithography has been used to make electrical contacts on nanometer-sized materials. However, a foreseeable damage occurring in these materials by highly energetic ion bombardment during metal deposition restrains its use. The appearance of the dual beam (conventional FIB with a scanning electron microscope) has facilitated the use of dual-beam FIB nanolithography owing to the possibility of acquiring electron beam images in situ and dissociating metalorganic compounds, giving rise to electron-beam-induced metal deposition [1]. Because interaction between electrons and the sample is less destructive than using ions, performing an electron-assisted deposition on the nanostructure can minimize undesired surface damage and structure modification of the nanostructure.

The thermal properties of individual multi-walled carbon nanotubes was measured by utilizing the 4-point-probe 3-ω method, based on the fact that the third harmonic amplitude and phase as a response to applied alternate current at fundamental frequency, ω, can be expressed in terms of thermal conductivity and diffusivity. To this end, a microfabricated device composed of four metal electrodes was modified to manufacture nanometer-sized wires by using a focused ion beam source as shown in Fig. 1a. A carbon nanotube could then be suspended over a deep trench milled by the focused ion beam, preventing heat loss to the substrate (Fig. 1b). To deposit individual carbon nanotubes, we utilized the principle of dielectrophoresis (DEP). The dielectrophoresis has been considered as an excellent method for CNT manipulation. Herein, we applied a high-frequency (5 MHz) ac field combined with dc offset between the pads, 1 and 4. When a CNT touches the electrodes, it will stick to them and stays there by Van der Waals force [2]. Finally, to minimize the electrical contact resistance between carbon nanotubes and the metal electrodes, electron beam "soldering" was performed. The pads 1 and 4 have round shapes on the tip, which aids carbon nanotube deposition.

Fig. 2 shows three different measurements of 3-ω signals for carbon nanotubes submerged in vacuum, air and deionized water. To this end, the 4-wire configuration (Fig. 1c) was utilized for measuring the 3rd harmonic signals in fluids and in vacuum and the measurement results are directly correlated to the convective heat transfer coefficient and thermal conductivity (for details of equation see reference [1]). The 3-ω signals measured in vacuum and air follow the 3rd power law represented in the equations. The exponents were obtained to be 2.9 in vacuum and air. The best fitted exponent obtained for the sample submerged in deionized water turned out to be 2.7. The convective heat transfer coefficients for air and water were obtained to be 5.0×10^5 ($\pm3.3\times10^4$) and 2.9×10^6 ($\pm2.6\times10^5$) W/m^{2}K, respectively. The experimentally measured data were compared with the classical natural convection theory. The Nusselt number ($Nu = hD/k$) for the carbon nanotube submerged in a fluid is 0.36. From the known CNT diameter and thermal conductivity of the fluid, the theoretically predicted convective heat transfer coefficients are 4.5×10^5 W/m^{2}K (in air) and 11.0×10^6 W/m^{2}K in water. The predicted value in air agrees well with the experiment. However, the

convective heat transfer coefficient measured in water strongly deviates from the theoretical prediction. This result is attributed to the hydrophobicity (not taken into account in the theoretical prediction which assumes perfect thermal contact) of carbon nanotubes which hinders the physical contact and thermal communication between the water and the CNT surface.

In conclusion, compared with the 2-point-probe technique, a significant improvement in accuracy is assured by using four probes (nanofabricated by FIB milling), because the contact contribution to the determination of the thermal conductivity is eliminated, making it possible to measure the correct signals of 1st and 3rd harmonics. The multi-walled carbon nanotube was modeled as a one-dimensional diffusive energy transporter and its thermal conductivity was measured at room temperature under vacuum to be 300±20 W/mK.

References

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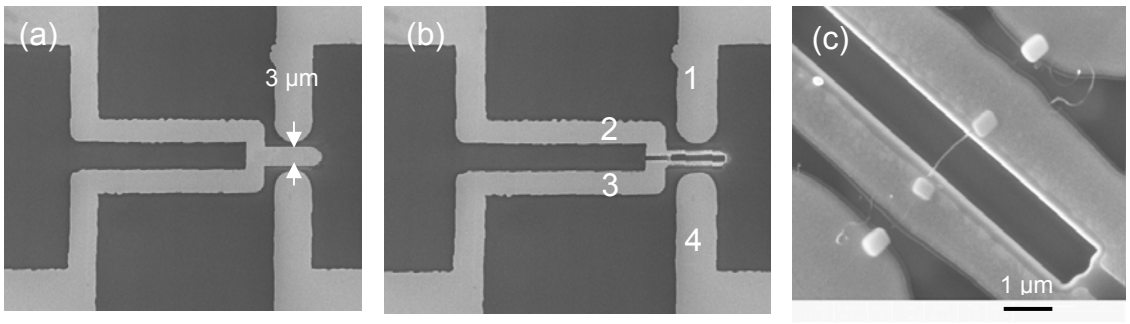

Fig. 1 Process flow of micro/nano fabrication of measurement platform. (a) Pt coating on silicon nitride wafer by lift off; (b) focused ion beam milling for nanofabrication of electrodes; nanotube deposition and soldering with 4-wire (c) configuration.

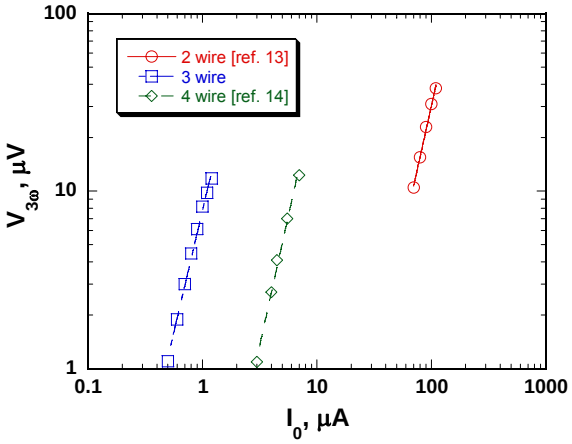

Fig. 5 The third harmonic voltage measurements for carbon nanotube samples with three different wire configurations. The signals strongly depend on the carbon nanotubes. They do not depend on the size of the nanotubes. The exponents from the best fitting of the measured data are close to 3 for all three samples.