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Transient thermal response of an individual carbon nanotube

Yusuke Ohshima, Takayuki Arie, and Seiji Akita

Department of Physics and Electronics, Osaka Prefecture University,
1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan.
Phone&Fax:+81-72-254-9261, E-mail: akita@pe.osakafu-u.ac.jp

1. Introduction

Recently, light emission from multiwall nanotube (MWNT) bundles under current flow has been reported[1]. On the contrary, we have observed light emission from a suspended individual MWNT under current flow[2], whose size is around 1µm. The average temperatures for the sublimation of the MWNTs have been measured from the emission spectra to be higher than 2,500 K[3]. We have proposed that the optical and the thermal radiations from the individual suspended nanotube caused by the Joule heating can be used as novel nanoscale-processing tools. The transient thermal response of individual MWNT has been roughly estimated from the thermal conductivity of steady state to be nano-seconds order under the ideal condition. However, in the experiment, the transient thermal properties of individual suspended MWNTs are still one of the open subjects. The transient properties are important for the applications of not only the nano-processing tool but also the interconnection in the integrated circuits. In this study, we investigate the transient thermal response of an individual MWNT under the Joule heating.

2. Experiment

An individual MWNT synthesized by CVD, which is ~ 60 nm in diameter, was suspended between Pt electrodes with a 2~3 µm gap fabricated on the SiO_2/Si substrate by the dielectrophoresis method, where the SiO_2 layer below MWNT was etched to fabricate the suspended structure by using an e-beam lithography. To improve the contact resistance, we evaporated Pt on the contact of MWNT by using an e-beam lithography as shown in Fig. 1(a).

In order to investigate the transient thermal response, the voltage pulse with the width of 100 ns ~ 10 ms was applied to the suspended MWNT in the vacuum. The optical emission spectra of the suspended individual MWNT under the pulsed current flow were measured by an optical-microscopic spectroscopy system with a cooled charge-coupled device, which has the sensitivity around the visible region (from 400 to 900nm). Corresponding temperature was determined from the fitting of the measured spectrum to the Plank's black body radiation law. It is noted that the accumulation time of the CCD for each pulse width was adjusted to the time that the total current flowing time was constant for each pulse width. According to the Stefan–Boltzmann law, the emission intensity of the black body radiation is directly proportional to the fourth power of the black body's temperature *T*. As a result, the observed emission spectrum corresponds to not the average temperature but the highest temperature during the transient state. Thus, we can measure the transient thermal response of the suspended MWNT by changing the pulse width and duty ratio as schematically shown in Fig.1(b) by using the conventional CCD detector.

3. Results and Discussions

Figure 2 shows an input electric power dependence of the steady state temperature. The temperature is almost proportional to the input power with a slope of 8.34x10^6 K/W in this temperature region. Assuming weak temperature dependence of the electrical resistance of the MWNT, we can expect the constant thermal conductivity in this temperature region. As a result, a thermal conductivity of the MWNT is estimated to be 133 W/m-K from the slope, the length (~ 2.5 µm) and the cross section of the MWNT. Using the thermal conductivity estimated in this experiment, the finite element method (FEM) calculation revealed that the suspended MWNT with ideal boundary condition shows the response time of ~ 30 ns for the temperature response. An inset of Fig. 2 shows an optical microscopy (OM) image of the light emission from the MWNT, where

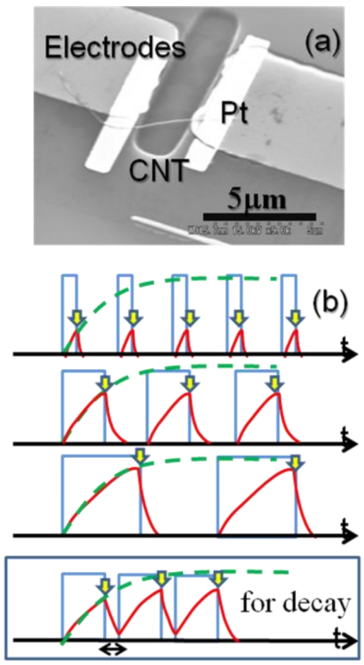

Fig. 1 (a) SEM image of the suspended MWNT after Pt deposition by e-beam lithography. (b) Timing chart of the pulsed voltage measurement for transient thermal response the applied voltage and the current are 2.7V and 470 μA, respectively. The light emission is observed only around the central part of the suspended MWNT. It is noted that the light emission on the electrode is observed when the electrical contact to the MWNT is insufficient. Thus, we can expect that the contact between the MWNT and electrodes is good enough for the measurement.

Figure 3 shows the pulse width dependence of the measured temperature, where the duty ratio of all of the pulse width was 10% and the applied voltage was 2.62 V. In this condition, we can measure the rising edge of the temperature. The temperature increases with increasing the pulse width and is almost saturated at the pulse width of 1 μs around 1100 K which equal to the temperature at the steady state shown in Fig. 2. It is noted that the transient response of the input electrical power of the examined device shows very similar to the response of the temperature. This implies that the temperature of the suspended MWNT follows well to the electrical pulse within the time constant of ~100 ns.

Figure 4 shows the rest time width dependence of the measured temperature, where the pulse width is 100 ns and the applied voltage was 2.7 V. In this condition, we can measure the decay edge of the temperature. The temperature is down from 1180 K to ~ 1000 K for 50 ns and saturate sufficiently at 100 ns. This indicates that the heat generated at the MWNT is well dissipated through the contact.

These rise and decay time constants are comparable to the time constants calculated from the FEM calculation with the ideal boundary condition. Thus, the contact between the MWNT and the electrode is good enough for not only the electrically but also the thermally.

4. Conclusions

In this study, we have investigated the transient thermal response of an individual MWNT under the Joule heating by applying the voltage pulse. The transient response of the temperature less than 100 ns was successfully measured by the proposed pulse voltage method. The suspended MWNT nano-heater device showed the response time within 100 ns corresponding to the transient properties of the electrical input power. Thus, the suspended MWNT is one of the promising candidates for the nanoscale thermal radiation source with a high speed response.

Acknowledgement

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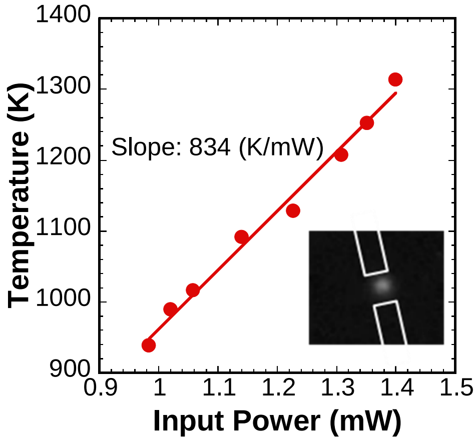

Fig. 2 Input electrical power dependence of the steady state temperature for the suspended MWNT.

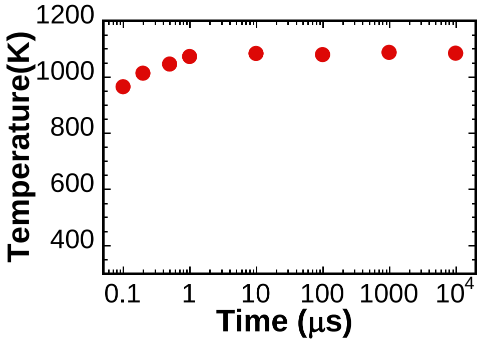

Fig. 3 Pulse width dependence of the temperature corresponding to the rising edge property.

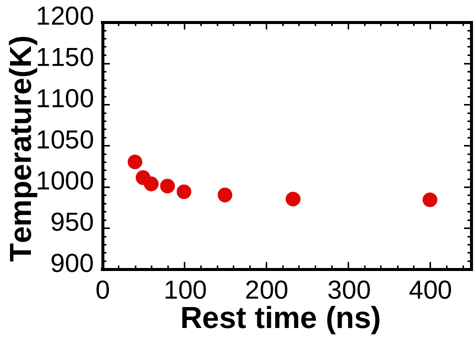

Fig. 4 Rest time width dependence of the temperature corresponding to the decay edge property.