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Proposal of Carbon Nanotube Inductors

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Abstract. The inductors made of carbon Nanotube (CNT) have been proposed. Though the fabrication of the proposed inductor is still challenging and has many problems, merits of the proposed inductor are following,

(i) The magnetic field induced by the current in CNT is about one thousand times larger than that induced by the current in normal copper wire.
(ii) The large magnetic field results in the large inductance, according to the relation between magnetic field and inductance.
(iii) The inductor made of CNT is smaller than the inductor in IC circuits, because CNT can be bent with small curvature.

1. Introduction

New concepts of electronic components to fabricate further high-performance integrated circuits (IC) are required. One of the new concepts is the incorporation of large-inductance inductors into ICs. The incorporation into ICs, however, has the difficulty in three dimensional nano-fabrication technique, and it also has the small effect due to the small quantity of magnetic permeability of $\mu_o = 4\pi \times 10^{-7}$ H/m and the large diameter of the inductor's wires.

Recently we have reported the measurement of the large magnetic field produced by the current in CNT[1], and in this paper we propose the inductors made of CNT (CNT inductor). Though the fabrication of CNT inductor has many problems, CNT inductor's merits are following,

(i) Since the radius (r) of CNT are several nm, the magnetic field (H) induced by the current (I) in CNT is about one thousand times larger than that induced by the current in normal copper wire whose radius is about several μm. $H \approx \frac{I}{2\pi r}$.
(ii) According to the relation between magnetic field (H) in the inductor and inductance (L) of the inductor, $\int \frac{\mu_o H^2}{2} dV \approx \frac{LI^2}{2}$, the large magnetic field results in the large inductance.
(iii) Since CNT can be bent with small curvature, the inductor made of CNT is smaller than the inductor in IC circuits.

2. Fabrication and Measurement

Used CNTs were made by laser ablation method. The CNTs were thought to be single carbon Natotubes from the observation of radial-breathing mode peak in Raman scattering. After the

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dispersing CNTs on the SiO_2/Si substrate, metal electrodes interconnects to a CNTs. The CNTs sample image were observed by Atomic Force Microscopy (AFM) shown in Figure. 1. Though the CNTs sample shown in Figure. 1 look like one nanotube, the height of the CNTs were measured to be about 3 nm. The CNTs sample, therefore, thought to be a bundle of CNTs. Current-voltage characteristics of the CNTs sample shown in Figure. 2 was measured at room temperature. Since the resistance of the CNTs sample was measured to be 7.6 kΩ, the CNTs sample was thought to be metallic.

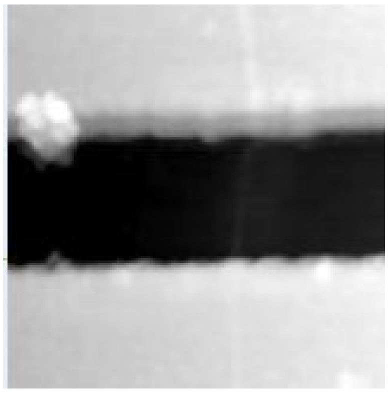

Figure 1. Measured CNTs sample with metal electrodes observed by AFM. The diameter of the CNTs $2r$ is measured to be about 3 nm by AFM. The metal electrode, deposited by the vacuum evaporation, consist of 10-nm-thick nickel and 40-nm-gold layer. Distance between the electrodes are 1.0 μm.

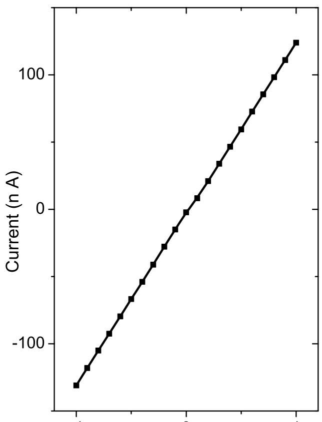

Figure 2. Current-voltage(I-V) characteristics of the CNTs sample shown in Figure. 1. I-V characteristics is linear and the resistance of CNTs are about 7.6 kΩ. For the measurement of the magnetic field produced by the CNTs current, the alternating voltage is applied between both electrodes.

In order to measure the magnetic field induced by the small current in CNTs, special technique similar to magnetic force microscope (MFM) was used[2]. The cantilever was covered with the ferromagnetic metal. By applying the alternating current (modulating frequency of 1280 Hz) in CNTs, the images of synchronized component in the force between the cantilever and the sample were obtained by using lock'-in measurement at room temperature under an atmosphere pressure. These synchronized images were observed at the current up to 250 μA.

3. Results and Discussions

Since the cantilever is covered with the ferromagnetic metal, the cantilever can be affected by the the the electric force (Kelvin force) and magnetic force of the sample at same time. The obtained image as shown in Figure. 3, therefore, was the convolution of Kelvin force microscopy

(KFM) and MFM images. The magnetic field distribution is extracted from Figure. 3 by using the space anti-symmetry of the magnetic field and the electric field distribution is also extracted by using the space symmetry of the electric field.

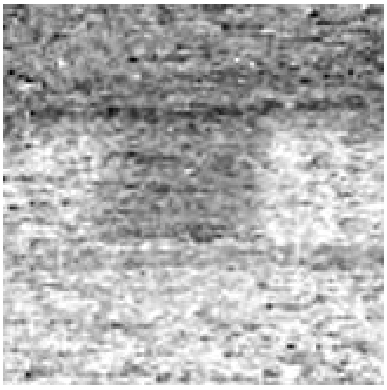

Figure 3. Convoluted image of KFM and MFM of CNTs sample. Since the convoluted image and AFM image shown in Figure. 1 were obtained at the same time, their observed areas are same. By comparing the AFM image, the bright-dark contrast between top area and bottom area corresponds to the potential difference between the electrodes. Therefore, the bright-dark contrast between both electrodes results in KFM image.
Also by comparing the AFM image near CNTs, the CNTs corresponds to the boundary between the bright and dark area. Since the directions of magnetic field induced by the CNTs current are opposite each other at both side of the CNTs, the bright-dark contrast between the both side of CNTs should be due to the MFM image.

Since Figure. 1 and 3 were obtained at the same time, their observed areas are same. The bright-dark contrast between bottom and top area in Figure. 3 corresponds to the potential difference between the electrodes, resulting in KFM image.

The CNTs being from bottom to top in Figure. 1 correspond to the bright-dark boundary between the right-hand side area and left-hand side area in Figure. 3. Since the magnetic field directions both side of the CNTs are opposite each other, the bright-dark contrast between the both side of CNTs should be the MFM image. Since the bright-dark contrast become clearer at the larger amplitude of alternating current, observed magnetic fields were proportional to the amplitude of the alternating current. Relationship between induced magnetic field and the amplitude of alternating current is shown in Figure. 4. The estimated magnetic field near CNTs is 8 mT at 250 μA.

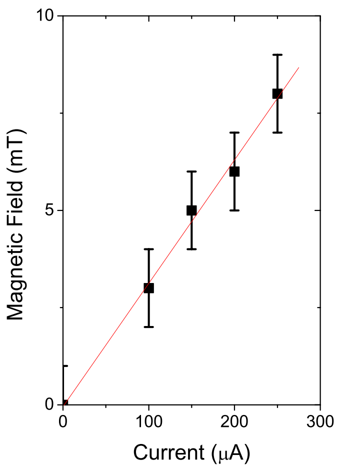

Figure 4. Relationship between induced magnetic field and the amplitude of alternating current. Induced magnetic fields are estimated by the calibration table between the large coil's magnetic field and the large coil's alternation current. Error bar is estimated to be 1 mT. Relation between the magnetic field and the current is linear. From the regression line shown in red line, the minimum height of the cantilever from the sample surface, z, is estimated to be 3 nm.

The maximum value, H_{max}, in magnetic field distribution induced by the CNTs current, I, is expressed as,

$$H_{max}(z) = H(r, z) = \frac{\mu_o I}{2\pi} \frac{r}{r^2 + z^2},$$

where, z is the height of the cantilever from the surface.

From the regression line shown in Figure. 4 and the above equation, z (the minimum height of the cantilever from the surface) is estimated to be 3 nm, which is not contradictory to the AFM measurement conditions.

The measured maximum magnetic field near CNT of 8 mT is also very large compared with that produced by the copper wire ($2r \approx 0.1$ mm) in the normal inductor. Though the inductance of 1.0 μm long CNTs is estimated to be about 1 pH using the electromagnetic theory, normalized inductance is estimated to be about thousands times larger than that of the usual coil made of the copper using the relation of $\int \frac{\mu_o H^2}{2} dV \approx \frac{LI^2}{2}$.

4. Conclusions

The estimated magnetic field near CNTs was 8 mT at 250 μA. This value roughly agreed with the theoretical one and was also very large compared with that produced by the copper wire in the normal inductor. Since the inductance of 1.0 μm long CNTs are estimated to be about 1 pH, normalized inductance is found to be larger than that of usual inductance. Therefore, CNT inductors are promising passive electric component for IC.

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[1] Tsubaki K, Shioya H, Ono J, Nakajima Y, Hanajiri T, Yamaguchi H, 2005 *The 63rd Device Research Conference*, (Santa Barbara, CA) III-33

[2] Saida D and Takahashi T, 2003 *Jpn. J. Appl. Phys.* **42** 4874