Bonding of a Carbon Nanotube Film to a Au Film at Low Temperature and Contact Resistance of the Film under Micronewton Loads

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A process for bonding a carbon nanotube (CNT) film to a Au film at low temperature was developed with a view to using the CNT films as electrical contact materials in radio-frequency microelectromechanical systems (RF MEMS) switches. First, a CNT film was synthesized on a silicon substrate at 750 °C and subsequently coated with Au at room temperature. Finally, the Au-coated CNT film was bonded at 100 °C to a Au film, which was then deposited on a silicon substrate to act as a transmission line. An apparatus was developed to measure contact resistances and forces under contact conditions mimicking those that will be encountered in actual RF MEMS switches, such as micronewton loads and square-micrometer contact areas. Contact resistance and force of the bonded CNT film sample were simultaneously measured as a function of displacement between the sample and an electrode Au tip and compared with those for a Au film and Au-coated CNT film. The bonded CNT film sample had no adhesion force, but higher contact resistance than the other samples.

Keywords: RF MEMS, carbon nanotube, contact resistance, contact load

1. Introduction

As compared to solid-state semiconductor switches, radio-frequency microelectromechanical systems (RF MEMS) switches have potentially superior electrical properties such as low insertion loss, good isolation, low power consumption, and good linearity, especially in the high frequency range^{1,2)}. Although RF MEMS switches possess these advantages, there are problems with the electrical contacts: The mechanical relay switches in RF MEMS switches are micro-sized, and so the contact electrodes must be considerably smaller (less than 100 μm^2) than those of conventional relay switches. In addition, they can bear only low loads ranging from a few micronewton to several millinewton. Therefore, it is difficult to ensure reliable electrical contacts for RF MEMS switches, particularly for hundreds of billions of contact cycles. In order to address these problems, tribological knowledge and technology are necessary.

The materials used in the contact electrodes play an important role in solving the potential problems of RF MEMS switches. Although Au is one of the candidate materials for the contact electrodes³⁾, it has a high adhesion force and is easily deformed under relatively low loads. Carbon nanotubes (CNT) have not only

excellent mechanical properties^{4,5)} but also excellent electrical properties, which include high current density ($> 10^9 \text{ A/cm}^2$) and high resistance stability at 250 °C⁶⁾. Fundamental experiments for measurement of contact resistances of CNT films⁷⁻⁹⁾ and application of CNT films as contact electrodes for RF MEMS switches⁹⁾ have been carried out. However, these experiments used CNT films that were synthesized directly on substrates at high temperature ($> 700 \text{ °C}$). These high-temperature processes are not suitable for MEMS processes. In order to apply CNT films to contact electrodes of RF MEMS switches, low temperature process to build CNT films on RF MEMS switches is absolutely necessary. In addition, these experiments used relatively high contact loads ($> 1 \text{ mN}$), which caused plastic deformation of the CNTs.

In order to develop the low temperature process, we attempted to bond CNT film on an Au film used as transmission line at low temperature. Contact resistances and forces of the bonded CNT film, an Au film, and an Au coated CNT film under μN loads were simultaneously measured as a function of displacement between the samples and an electrode Au tip by a contact resistance measurement apparatus developed in this study.

Fig. 1 Schematic of the three steps for the formation of the bonded CNT film sample

2. Sample preparation

The bonding of a CNT film to an Au film was carried out by 3 steps as schematically shown in Fig. 1.

Step 1 (Synthesis of CNT film): In this study, we used silicon substrates with silicon oxide films of 100 nm thickness, which were formed by thermal oxidation. Deposition and annealing of an iron layer of 4 nm thickness were conducted on the silicon substrate to form catalytic nanoparticles. A mixture of C_2H_2 and H_2 gases was flowed at the substrate temperature of 750 °C for 20 min at a pressure of 300 Pa. Thus, CNT films consisting of multi-walled CNTs were synthesized on the silicon substrate. Figs. 2 (a) and (b) show the higher and lower magnification SEM images of the as-synthesized CNT film on the silicon substrate. The thickness of the CNT film was approximately 110 μm . As shown in Figs. 2 (a) and (b), CNTs were seen to be aligned vertically at low magnification, but at higher

Fig. 2 SEM images of CNT films. (a,b) Synthesized CNT film on the silicon substrate. (c,d) Au-coated CNT film. (e,f) Bonded CNT film.

magnification, a tangled structure was clearly seen.

Step 2 (Coating with Au film): A transmission line was synthesized by forming a Au film of approximately 30 nm thickness on the silicon substrate using a vacuum evaporator. We attempted simply to bond the as-synthesized CNT film to the Au film; however, the result was not successful. Au was therefore also coated on the as-synthesized CNT film in order to make it easy to bond the CNT film to the Au film in the subsequent step. Figs. 2 (c) and (d) show the higher and lower magnification SEM images of the Au-coated CNT film sample.

Step 3 (Bonding of the CNT films to the Au film): The Au-coated CNT film was turned over and bonded to the Au film (as shown in Fig. 1), i.e., the Au-coating face of the Au-coated CNT film and the Au film were bonded with loads on the order of a few newton at a temperature of 100 °C. The substrate on which the CNT film was synthesized was then removed at room temperature. Finally, a CNT film bonded to an Au film was obtained. Figs. 2 (e) and (f) show the higher and lower magnification SEM images of the bonded CNT film sample. The inset of Fig. 2 (f) shows the SEM image of the sidewall of the bonded CNT film. It appears that the CNTs were still aligned vertically after the pressing process. The thickness was decreased to be approximately 17 μm by the load. The top face of the bonded CNT film was originally the bottom of the as-synthesized CNT film, and appears to be more flat and of a higher density than that of the as-synthesized CNT film.

In these steps, we formed three samples as enclosed by dashed line boxes in Fig. 1: the Au film, the Au-coated CNT film, and the bonded CNT film samples.

Fig. 3 Schematic drawing of the contact resistance measurement apparatus

3. Contact resistance measurement method

Figure 3 shows a schematic drawing of the contact resistance measurement apparatus. To measure low force ($< 1 \mu\text{N}$), the apparatus has a phosphor-bronze cantilever that is 1 mm wide, 6 mm long, and 0.05 mm thick. Additionally, the apparatus has a laser diode and a position sensitive detector for the optical lever method¹⁰⁾. A Au tip with an apex radius of $25 \mu\text{m}$ was used as a contact electrode to realize a small contact area. The tip was formed by electrochemical etching, then cleaned in ethanol for 5 min and in water for 5 min. Displacement between the samples and the Au tip was adjusted by a PZT actuator with closed-loop control. Contact resistances (R_c) were measured by the four-wire measurement method. An AC constant current source provided a steady output current on the substrates of $1.5 \mu\text{A}$ at 1 kHz between the Au tip and the Au transmission line, independent of resistances. Measurements were carried out in air at a temperature of 25°C and a relative humidity of 25%.

4. Contact resistances and forces

Figure 4 represents the contact resistances and forces of the three samples as a function of displacement between the sample and the Au tip. Dashed and solid lines show contact resistances and loads, respectively. The approaching and the retracting curves are indicated by black and grey, respectively. The maximum load was $11.5 \mu\text{N}$. The zero of displacement was defined at the value where the load reached the maximum value.

For the Au film sample shown in Fig. 4 (a), the lowest contact resistance was 2Ω . An adhesion force of $6.5 \mu\text{N}$ was observed, which arose from water adsorption between the Au tip and the film. As shown in Fig. 4 (b), the lowest contact resistance of the bonded CNT film sample was 636Ω , which was much higher than that of the Au film sample. There was no adhesion force for the bonded CNT film sample, which may be the result of less water adsorption¹¹⁾. The lowest contact resistance of the Au-coated CNT film sample in Fig. 4 (c) was 72Ω , which was lower than that of the CNT film, but higher than that of the Au film sample. The

(a) Au film sample

(b) Bonded CNT film sample

(c) Au coated CNT film sample

Fig. 4 Relationships between contact resistances and loads. (a) Au film sample. (b) Bonded CNT film sample. (c) Au coated CNT film sample.

adhesion force was observed but it was very small ($< 0.1 \mu\text{N}$). As shown in Fig. 4, hystereses of the contact resistances and forces of all these samples were observed. These hystereses did not arise from the PZT actuator, as a closed-loop PZT actuator was used. The cause of the hysteresis is unfortunately unknown to us at this time.

The contact resistance of the bonded CNT film sample was high and should be decreased for RF MEMS switches. Yunus et al. previously reported that contact resistances of the sputter-coated Au film, as-grown CNT film, and Au-coated CNT film were $\sim 0.39 \Omega$, $\sim 108 \Omega$, $\sim 0.46 \Omega$, respectively, with the $\phi 2 \text{ mm}$

Au-sputter-coated stainless ball at the maximum load of 1 mN⁹⁾. These contact resistances were lower than those in our study, which may result from the larger ball and higher load, i.e., a larger contact area in comparison with our study. The resistances of individual CNTs with Au/Ti electrodes were dominated by the contact resistance and were not significantly affected by the intrinsic resistance of the CNTs¹²⁾. It was also reported that contact resistances of the individual CNTs that were not tightly deposited on Au were over 100 MΩ¹³⁾. Contact resistances of individual CNTs on which tungsten electrodes were tightly deposited were on the order of a few kilo-ohm⁶⁾. These results indicate that when CNTs that have not been tightly deposited onto the substrate make contact with electrode surfaces, their contact resistances are high. In the bonded CNT film sample, individual CNTs were in contact only with the electrode Au tip, thus, the contact resistance was high. For the Au-coated CNT film sample in this study, the Au tip was in contact with the Au coating that was tightly deposited on the individual CNTs. The Au coating provided lower contact resistance. Contact resistances between CNTs and metals depend on metal elements. For example, bondings of Sc, Ti, and V on single-walled CNTs are expected to have low contact resistances¹⁴⁾. In order to decrease the contact resistance of the bonded CNT film sample, experiments for various metal coatings should be carried out.

Since the reliability of RF MEMS switches is very important for their practical applications, future experiments for long-term operation will be carried out.

5. Summary

In this study, a process was developed for bonding a CNT film to a Au film at 100 °C such that it is suitable for MEMS devices. A contact resistance measurement apparatus for micronewton loads and square-micrometer areas was also developed. Contact resistances and forces of the bonded CNT film sample, an Au film sample, and an Au-coated CNT film sample were measured and compared. The bonded CNT film sample had no adhesion force, but exhibited higher contact resistance than the other samples.

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7. References

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