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Bonding Process for Nano-Scale Wiring using Carbon Nano-Tube by Scanning Tunneling Microscope Tip

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1. Introduction

Carbon nano-tube (CNT) is expected to be applicable for various types of nano-scale devices such as single-electron transistor [1], field emitter [2], and so on, because of the scale of the size. Recently, there is a great attention on the ability of the carrier transmission. It could be used as a material of wiring line in future LSI circuits, if the handling technique of CNT is established enough. Because it is predicted the carrier transport in CNT would be described as a ballistic regime, if there was no defect on it [3]. Moreover, it should be remarkable that a maximum current density of CNT is more than 2 orders comparing with a conventional wiring material in a LSI such as Cu or Al. Although one could reduce the size of semiconductor device, there remains a crucial problem of an electrical migration of metallic materials. In this matter, the usage of CNT for the wiring has highly advantageous for nano-scale circuit. However, because of the difficulty of the handling of CNT, it is difficult to realize such a CNT wiring system. If we could use the system like a wire bonding machine, it would be convenient and show a high performance for a bonding in nano-scale regions. In order to realize such a system, it is necessary to establish roughly two important processes. One is the positioning of CNT at an aimed area. Nowadays, a development of nano-manipulation techniques using a probe of atomic force microscope (AFM) or nano-tweezers using a pair of CNT attached on the top of a probe, a manipulation and a positioning of CNT is getting developed somewhere. Another important process is the bonding of CNT on metallic electrodes to have a good ohmic contact between CNT and metallic pads. As for such a possible method, we propose a nano-scale bonding process induced by a voltage pulse using a scanning tunneling microscope (STM) tip. The advantageous of this method is that we can deposit nano-scale metallic dots at anyplace on a metallic pad and also cover a CNT by them, which would bring a good electrical and mechanical contact between CNT and a pad. In this paper, we demonstrate a nano-scale bonding process of CNT-CNT or CNT-metallic pad by using STM tip and show the development of the electrical transport properties.

2. Experimental Procedure

The CNT used in this study is a multi-wall type made by dc grow-discharge method having about 30 nm in diameter and 8 μm long. It is purified by thermal annealing at 500 ℃ for 50 hours in O_2 environment [4]. The CNT is diluted in an ethanol with an ultra-sonic and dispersed on the SiO_2 layer on a Si wafer using a spin coater. On the wafer, there are 360 pad of 100×100 μm^2 square Ti electrode separated for 4 μm each other. For all the process of the bonding, we employed a scanning electron microscope (SEM)/STM combined system, which provides a good aliment between a STM tip and CNT on a metallic pad within 100 nm scale [5]. Observing the SEM image, we approached a tip just onto CNT with a bias voltage of 1.25 V in a vacuum of 10^{-6} Torr. After that, we applied a single voltage pulse of 7~12 V peak and 50 μs duration on the tip, then one or some metallic dots were fabricated on the CNT underneath the tip. After that, we measured the current-voltage (*I-V*) characteristics by ac curve-tracer and compared the variation before/after the bonding processes.

3. Result and Discussions

A typical bonding on a junction of two CNTs by an Au dot is demonstrated in Fig. 1. The CNTs are mounted on a Ti/Au pad and connected each other by an Au dot by applying a voltage pulse of 10 V peak and 50 μs duration on a tungsten (W) STM tip coated by Au thin film. The dot is deposited precisely on the junction of two CNTs, and the size is about 50 nm in diameter.

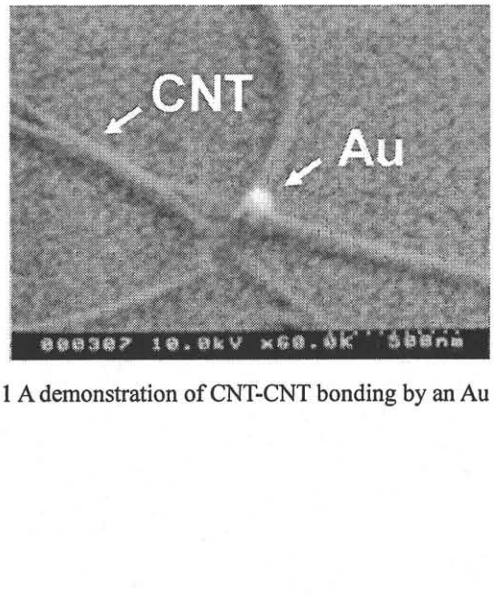

Fig. 1 A demonstration of CNT-CNT bonding by an Au dot.

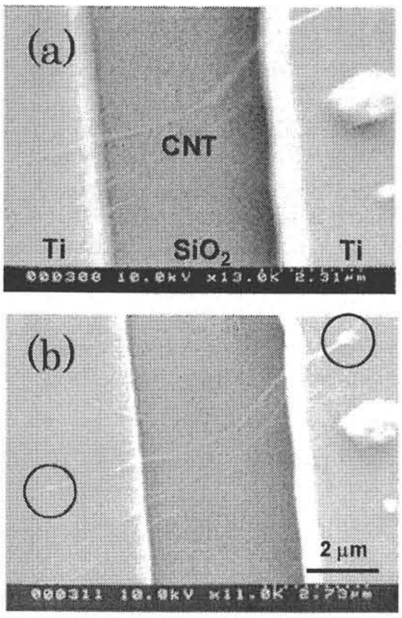

Fig. 2 SEM images of CNT connecting two Ti pads before (a) and after (b) the bonding process. Only a single CNT is connected the two electrodes. The fabricated regions are indicated by circles.

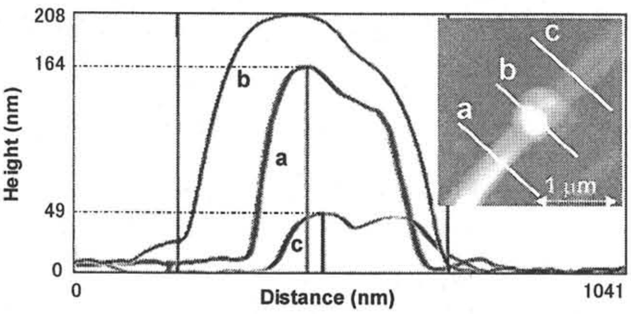

Fig. 3 AFM image and the cross sectional view of the fabricated region on the right side of the CNT.

To demonstrate a bonding between a CNT and a metallic pad, we used an array of Ti pads and dispersed CNT solution on the wafer. As shown in Fig. 2a, we selected a pair of the pads connected by a single CNT. After measuring the *I-V* characteristics between the pads, the sample was introduced into the SEM/STM system. Firstly, for the preparation of the tip, we approached a W tip on the Ti pad near the connected CNT, and a single voltage pulse of 15 V peak was applied on the tip, then some Ti clusters are evaporated from the Ti pad and deposited on the top of the W tip. After above operation, we lifted the tip once and approached again just above one of the side of the CNT. Next, three voltage pulses of 12 V were applied again. Then, some Ti clusters are deposited on the CNT. Consequently, almost same operations were done on the other side of it (see Fig. 2b, indicated by circles). An AFM image of the fabricated region on the right side was shown in Fig. 3. The typical size of the dot covering the CNT is about 500 nm in diameter and 200 nm high, and consists of 3 large Ti clusters. The CNT consists of some of multi-wall CNT and has formed a bundle, however after applying the voltage pulse, the bundle was apart each other.

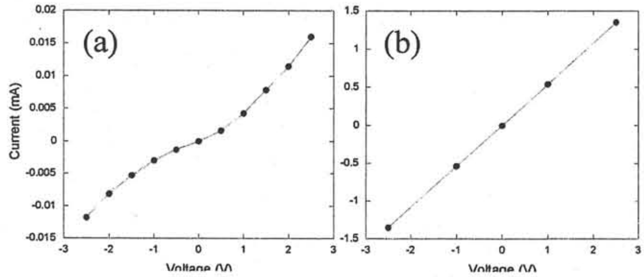

Fig. 4 *I-V* characteristics between a pair of Ti pads connected by a single CNT before (a) and after (b) the bonding process.

The *I-V* characteristics between the two Ti pads having the CNT are shown in Fig. 4. Before the STM bonding process (a), it shows non-linear behavior and a current of 1.2×10^{-5} A at 2.5 V, however, the property is clearly improved to be linear after the process and the current increases to 1.4×10^{-3} A, which is higher than two orders of magnitude. It indicates that this STM tip bonding method is very effective to make a good electrical contact and applicable to a nano-scale bonding process using CNT.

The details of this bonding process are explained by field evaporation in a STM regime [6]. The difference of the critical field for evaporation of each material is important. The critical voltage estimated from the field for Au and Ti is 8.5 V and 7.0 V, respectively. However, the critical voltage for carbon is higher than -20 V, where the polarity of the voltage is negative because we apply it on the tip but not on the substrate. Therefore, employing a voltage of around 10 V, it would be possible to deposit metals onto CNT without introducing a serious damage on itself.

4. Summary

We demonstrated a bonding process for CNT nano-wiring by using a STM tip. Applying a voltage pulse on the tip, we deposited dots of Ti cluster on a CNT connecting two Ti pads, and established a good electrical connect with the pads. After the process, the non-linear *I-V* characteristic was improved to be linear and the current was increased more than two orders of magnitude. Such a method would be applicable for one of a wiring process in future nano-scale devices.

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