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Observation of n-type conduction in CNTFETs with Au contacts in vacuum

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1. Introduction

Carbon nanotube field-effect transistors (CNTFETs) have attracting growing interest because of their potential for nanoelectronics. It is well known that the CNTFETs show p-type conduction in air when contact metal with a large work function such as Au was used. On the other hand, it was reported by IBM group that the device showed n-type conduction in vacuum after annealing [1, 2]. They ascribed this phenomenon to the oxygen desorption from the device. However, taking into account the work functions of Au (5.1 eV) and CNT (4.8 eV [3]), it is difficult to explain the result of IBM by using simple tabulated work function. Moreover, first-principle calculation of Au/CNT contact indicated that the Fermi level position of Au is located in the vicinity of valence band [4]. If this is the case, the device conduction type is expected to be p-type based on the Schottky barrier transistor model [5, 6]. This contradicts the result of IBM.

In this study, we compared current-voltage characteristics of the device before and after annealing in vacuum and observed n-type conduction after annealing. Contact potential difference (CPD) measurement of the Au/CNT junction by Kelvin probe force microscopy (KFM) [7] revealed that the local work function change of Au contacts after annealing caused the conduction-type change.

2. Results and Discussion

Figure 1 shows the outline of the experiment. The devices used for the measurements were fabricated on p^+-Si

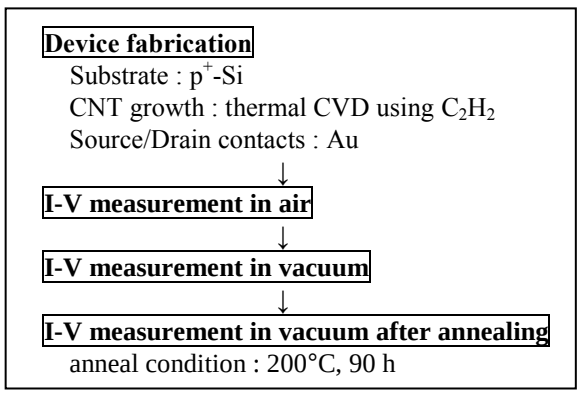

Fig.1 Outline of experiment.

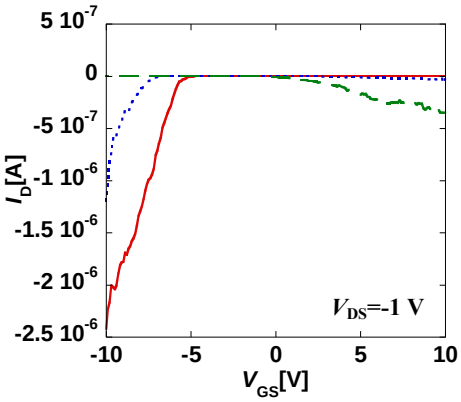

Fig.2 I_D-V_{GS} characteristics of CNTFETs with Au contacts (red : in air, blue : in vacuum, green : in vacuum after annealing).

substrate with SiO_2 thermal oxide with a thickness of 100 nm using conventional fabrication technique. The substrate acts as a back gate. CNTs were grown by thermal chemical vapor deposition (CVD) using C_2H_2 as a source gas. Au was used as the source and drain contact electrodes and p^+-Si substrate was used as a back gate. I_D-V_{GS} characteristics were measured at three conditions; in air, in vacuum and in vacuum after annealing (200°C, 90 h, in vacuum). Figure 2 shows the measured results. The conduction type of the CNTFETs were p-type in air (red solid line) and p-type or ambipolar in vacuum (blue dotted line). In the case of in vacuum after annealing, on the other hand, most of the devices showed n-type conduction as shown in the figure (green broken line). The result is similar to that of IBM group.

In order to clarify the reason of the change in the conduction type, CPD on the Au/CNT junction was measured by using KFM. Figure 3 (a), (b) and (c) are the measured results at three different conditions; in air, in vacuum and in vacuum after annealing (250°C, 5 h in vacuum), respectively. Figure 3 (d) shows line profiles of CPDs in the direction from Au contact to CNT for three different conditions. CPD of Au is smaller than that of CNT in air and in vacuum. In vacuum after annealing, on the other hand, the CPD of Au is larger than that of CNT. That is, relative

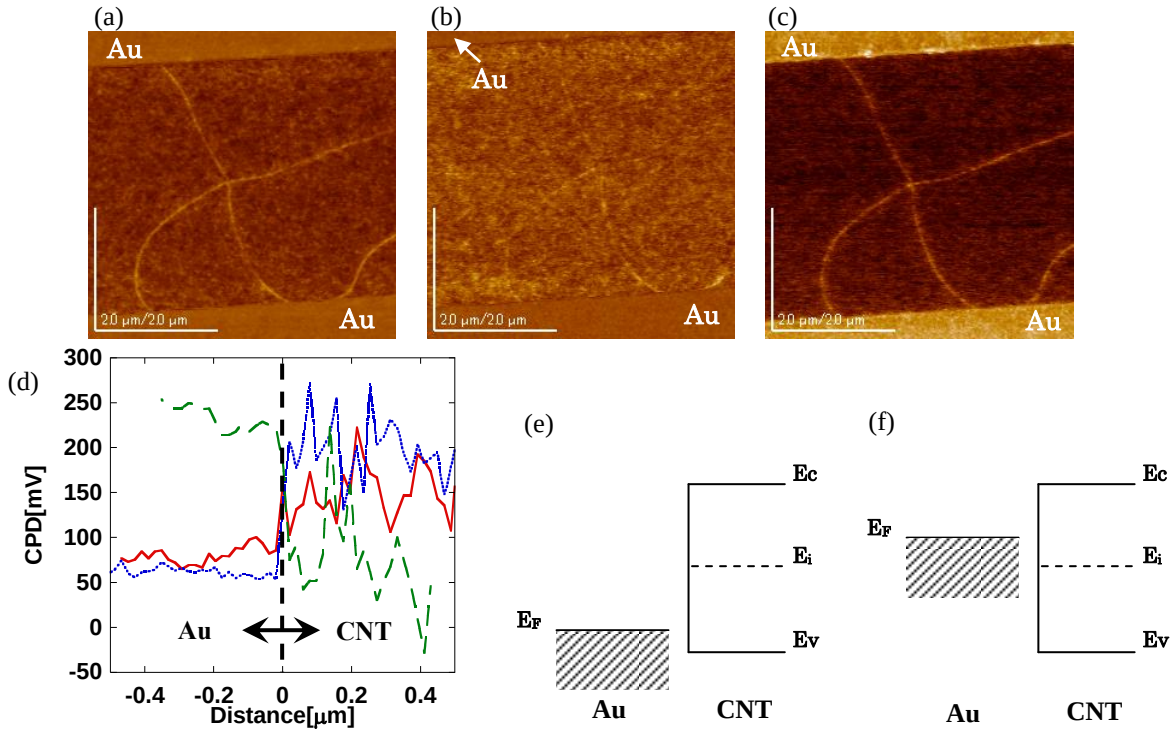

Fig3 .(a), (b) and (c) KFM images in air, in vacuum and in vacuum after annealing, respectively. V_{GS}= V_{DS}=0V. (d) Line profiles of CPD at Au/CNT contact (red : in air, blue : in vacuum, green : in vacuum after annealing) (e), (f) Energy level for the Au/CNT material system (e) before and (f) after annealing.

value of the Fermi level between the Au contact and the CNT is reversed. Then, the energy level for the Au/CNT material system before and after annealing can be written as shown in Figure 3 (e) and (f), respectively. This energy level alignment will be possible if the work function of the Au contact changes.

There is a systematic study on the work function change in Au/organic material system [8]. The relation between Au and many organic materials were studied in detail by XPS. It was reported that work function decreased for almost all organic materials. The amount of decrease in the work function was 0.4~1.0 eV. We can expect similar phenomenon occurs in the Au/CNT junction. When the adsorbed oxygen is desorbed by annealing, the local work function change of Au/CNT contact becomes evident leading to the conduction-type change from p type to n type.

As one of the origin of the work function change, rearrangement of electron cloud at the Au surface with the reduction of tailing into vacuum by CNTs, so called "push-back" effect [8], can be pointed out. In this case, surface dipole opposed to the surface dipole of clean and free Au is formed and locally reduces the Au work function.

3. Conclusions

We observed the change in the conduction type of CNTFETs with Au contacts from p type to n type by annealing the device in vacuum. The result was explained by the local work function change of the Au contacts based on the measurement of the contact potential of the Au/CNT junction by KFM.

Acknowledgements

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