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CNT-FETs with High Modulated Drain Current utilizing Size-classified Fe Particles as a Catalyst

Ikuo Soga[1,2], Masaaki Norimatsu[1,2], Daiyu Kondo[1,2], Yoshitaka Yamaguchi[1,2,3], Shintaro Sato[1,2], Taisuke Iwai[1,2,3] and Yuji Awano[1,2,3]

[1]Nanotechnology Research Center, Fujitsu Laboratories Ltd.
10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan
Phone: +81-46-250-8245, FAX: +81-46-250-8844
E-mail: soga.ikuo@jp.fujitsu.com
[2]Fujitsu Limited
10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197, Japan
[3]CREST/JST

1. Introduction

Carbon nanotubes (CNTs) have many attracting properties for electrical, thermal, and mechanical applications of the future. Diameter control of CNTs is important for such applications, since the properties of CNTs are affected by their diameters. This is especially true for CNT-transistor applications that require semi-conducting CNTs. It is well known that the diameter of CNTs depends on that of catalyst particles. Consequently the number ratio of single-walled carbon nanotubes (SWNTs) to multi-walled carbon nanotubes (MWNTs) is expected to increase as the mean diameter of catalyst particle decreases. Such a relative abundance of SWNTs brings a high modulated drain current to CNT-transistors.

In this paper, we report on CNT growth using size-classified Fe catalyst particles and the characteristics of transistors using CNTs as a channel. Fabricated CNT-transistors exhibited that drain current modulation depends on the size of catalyst particles. In fact, drain current modulation with 1.8 nm catalyst particles was drastically increased compared to that with 2.1 nm particles

2. Experiments

Catalyst particles were generated using the similar method reported in ref. 1. Figure 1 shows a SEM image of the Fe catalyst particles for the CNT growth. The substrate used in this experiment was heavily-doped p^+-Si wafer covered with thermal-oxidized SiO_2. This figure indicates that the particles were dispersed on the substrate. Figures 2(a) and 2(b) show the diameter distributions of size-classified Fe particles. The geometric mean diameters of the particles were 1.8 and 2.1 nm, and the geometric standard deviations were 31 and 34%, respectively.

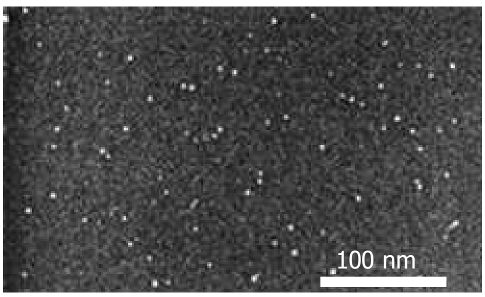

Fig. 1 SEM image of Fe particle catalysts which geometric mean diameter was 1.8 nm

CNT growth was performed by hot-filament chemical vapor deposition (CVD). The substrate with the Fe catalyst particles was brought into a thermal CVD chamber with a heating stage. A mixture of acetylene and argon gases at 125 Pa was introduced. The growth temperature was 590 °C.[2]

Raman measurements for the grown CNTs were performed at room temperature. Figure 3 shows the Raman spectra for the G and D bands of the two CNTs samples grown from the 1.8 and 2.1 nm catalyst particles. The spectra were obtained by 633 nm and 488 nm laser excitation. The G/D peak ratio, which was about 20, means that the quality of CNTs is good. The radial breathing mode (RBM) indicating the existence of SWNTs was confirmed.

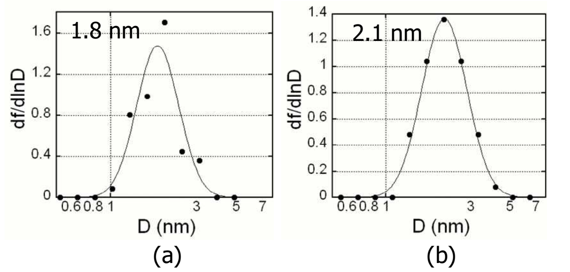

Fig. 2 Diameter distributions of size classified catalyst particles with geometric mean diameters of (a) 1.8 nm and (b) 2.1 nm.

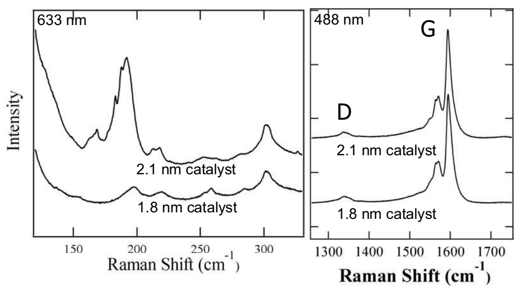

Fig. 3 Raman spectra of the two CNTs samples grown from 1.8 and 2.1 nm catalyst particles

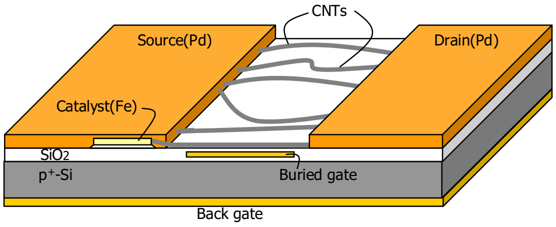

Fig. 4 Schematic device structure of fabricated CNTs transistors

3. Results and Discussion

Figure 4 shows illustration of device structure. The devices were fabricated using the conventional processes, such as photolithography, metal deposition, metal lift-off and low-pressure CVD. Figure 5(a) and 5(b) show the typical current-voltage characteristics of the fabricated CNT transistors with the 1.8 nm catalyst particles. Here the modulated drain current is defined as I_{mod} as shown in Fig. 5. Figures 6(a) and 6(b) show the modulated drain current, I_{mod}, of the CNT-transistors with the 1.8 and 2.1 nm catalyst particles, respectively, as a function of the total drain current. In these figures, the points on the diagonal lines correspond to the devices whose drain current was perfectly modulated by the gate voltage. It is clear that the transistors with the 1.8 nm catalyst particles have large I_{mod} and many devices show good pinch-off characteristics. On the other hand, most of the transistors with the 2.1 nm catalyst particles have poor pinch-off characteristics. This is probably because more large-diameter CNTs including MWNTs showing metallic behavior exist for the devices from the 2.1 nm particles. In fact, it was confirmed by transmission electron microscopy that the ratio of MWNTs is larger for the CNTs from the 2.1 nm particles than those from the 1.8 nm particles (not shown).

4. Conclusions

Transistors were fabricated using CNTs as a channel grown from Fe catalyst particles whose mean diameter was1.8 or 2.1 nm. The drain current modulation was drastically increased for the transistors with the 1.8 nm particles. Many devices with the 1.8 nm particles show good pinch-off characteristics, while most of the devices with the 2.1 nm particles do not. This is probably due to the difference in CNT diameter reflecting the particle size. Therefore, it is expected that, by optimizing the catalyst size, most of transistors will exhibit good pinch-off characteristics, which is suitable for practical transistor applications such as RF front-end.

Acknowledgements

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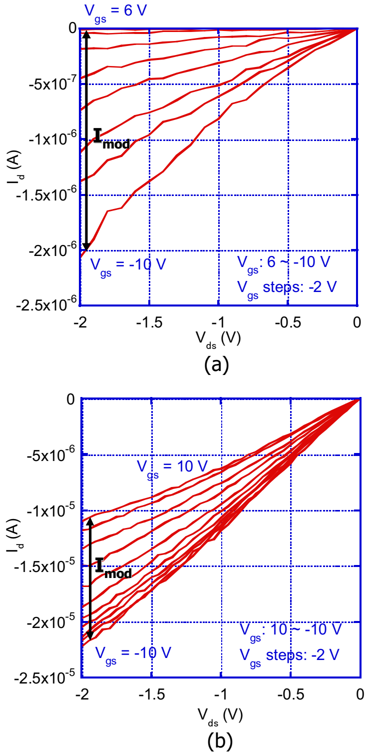

Fig. 5 Current-voltage characteristics of the (a) good pinch-off and (b) poor pinch-off transistors

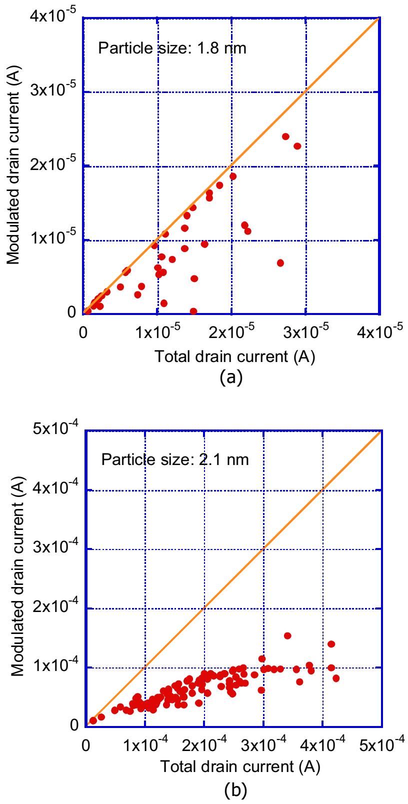

Fig. 6 Modulated drain current of CNT-transistors with (a) 1.8 nm and (b) 2.1 nm catalyst particles as a function of the total drain current