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Fermi Level Modulation of n-type Doped Single Walled Carbon Nanotube using Buried Local-Gate FET Structure by Oxygen Ion Implantation with Ultra-low Energy Ion Beam of 25eV

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1. Introduction

Many attempts of applications of semiconductive single walled carbon nanotube (s-SWNT) to the field effect transistors (FETs) and other quantum effect electron devices have been reported in recent decade. However, there has been no optimum technique to control the carrier density of s-SWNTs. In this paper, we have developed new techniques of the oxygen ion implantation doping to the s-SWNT and achieved the control of carrier density. We used the ion implantation system with the ultra low acceleration energy of only 25eV which is almost the same as the displacement energy of carbon atom in graphene sheet. Oxygen ions could be substituted for the carbon atoms in SWNT without the formation of defects. In order to estimate accurately the shift of Fermi level of the SWNT-FET by the oxygen ion implantation, the bulk modulation of the Fermi level at the channel was examined by the local gate electrode which can separate the effect of the modulation of the Schottky barrier by the back gate electrode.

2. Sample Structure

The sample was prepared as follows. A p-type silicon wafer with a thermally grown oxide of 300 nm thick was used as a substrate. The Pt/ Ti (50/ 5nm) was patterned as a buried local gate (BLG). The width of the BLG was 2 μm. SiO_2 layer of 200nm thick was deposited by the plasma enhanced chemical vapor deposition (P-CVD) as the gate insulator for the BLG. The layered catalysts of Fe/ Mo/ Si (3/ 10/ 10 nm) were patterned on the P-CVD SiO_2 layer using the conventional photo-lithography process. The distance between catalysts for the drain and source was 5 μm, where SWNT was grown by thermal CVD using mixed gas of hydrogen and Argon-bubbled ethanol gas. After the growth of SWNT, Ti/ Au (30/ 200 nm) electrodes were deposited on the patterned catalysts for the source and drain and on the back side of the Si substrate for the back gate. Thus, a back gate type SWNT-FET with BLG structure was fabricated as shown in Fig. 1 (a). Figure 1 (b) shows the top view of the sample before the fabrication of the electrodes observed by scanning electron microscopy (SEM), in which the positions of the electrodes were indicated by the shadowed region. The BLG was separated from the source and drain electrodes at 1.5μm. The region of the channel on the BLG was named as channel region B, and the other regions of the channel were named as channel region A and C, respectively as shown in Fig. 1 (b).

The fabricated sample was then implanted by the oxygen ion at room temperature with the acceleration energy of as low as 25 eV under an ultra high vacuum pressure of 10^{-7} Pa, and the amount of the dose was 7.5×10^{13} ions/cm^2. Electrical measurements were carried out before and after the oxygen ion implantation under the vacuum pressure of 1×10^{-2} Pa at room temperature.

3. Results and Discussions

Figure 2 (a) shows the drain current I_D - BLG voltage V_{BLG} characteristic before and after the oxygen ion implantation, in which the back gate voltage V_{BG} was set constant at V_{BG}=-40 V and the drain voltage V_D was set constant at V_D=1 V. In the case of the V_{BG}=-40 V, the Schottky barriers at the contacts between SWNT and electrodes were thin enough for hole tunneling transport, and hole at the channel region A and C were fully accumulated, which acted as extended electrodes for the channel region B as shown in Fig. 2 (b) and (c). In this case, it is quite hard for electron to be injected into SWNT. The channel region B can be modulated by the BLG without modulating the Schottky barriers. In Fig. 1 (a), the hole current before oxygen ion implantation was four times higher than that after oxygen ion implantation at V_{BLG}=-20 V. The threshold voltage of hole current shifted 7V, which indicated that the position of the Fermi level of the SWNT before oxygen ion implantation was closer to the valence band than that after oxygen ion implantation as shown in Fig. 2 (b). At V_{BLG}= 0V, though the electron can be accumulated at the channel region B, it is difficult for electron to conduct through the channel region A and C as shown in Fig. 2 (c). Therefore, almost no electron current observed at V_{BLG}=0 V.

Figure 3 (a) shows the drain current I_D - BLG voltage V_{BLG} characteristic before and after the oxygen ion implantation, in which V_{BG} was set constant at V_{BG}=40 V and V_D was set constant at V_D= 1 V. At V_{BG}=40 V, the Schottky barriers at the contacts between SWNT and electrodes were thin enough for electron tunneling transport, and electron at the channel region A and C was fully accumulated and the electron could be injected into SWNT. The electron current after oxygen ion implantation was ten times higher than that before ion oxygen implantation at V_{BLG}=0 V. The threshold voltage of electron current shifted 7.5 V as shown in Fig. 3 (a), which also indicated that the position of the Fermi level of SWNT before oxygen ion implantation was closer to the valence band than that after oxygen ion implantation as shown in Fig. 3 (b). At V_{BLG}= -20V, though the hole can be accumulated at the channel region B, it is difficult for the hole to conduct through the channel region A and C as shown in Fig. 3 (b). Therefore, only small current observed at V_{BLG}=-20V. The gate modulation coefficient α which was the ratio of the applied gate voltage and the modulated potential energy at gate was estimated to be 0.097 obtained from the same structure sample. The shifts of the threshold voltages of hole and electron current were 7 V and 7.5 V, respectively. The shifts of potential energy which indicated the shifts of Fermi level by the oxygen ion implantation were estimated to be 0.68 eV and 0.73 eV, respectively.

4. Conclusions

Oxygen ions with ultra-low-energy of 25 eV were implanted to SWNT-FET with the BLG electrode. The implanted oxygen ions doped the SWNT as donor. The dose was 7.5×10^{13} ions/cm^2. The shift of the Fermi level of SWNT after oxygen ion implantation was observed on the electrical measurements at room temperature, and, was estimated to be about 0.7 eV.

References

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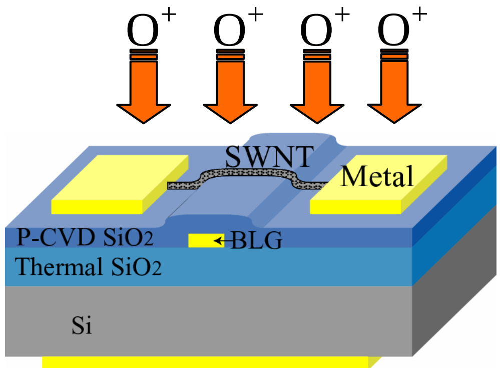

Fig. 1 (a), Schematic sample structure of SWNT-FET with BLG and back gate.

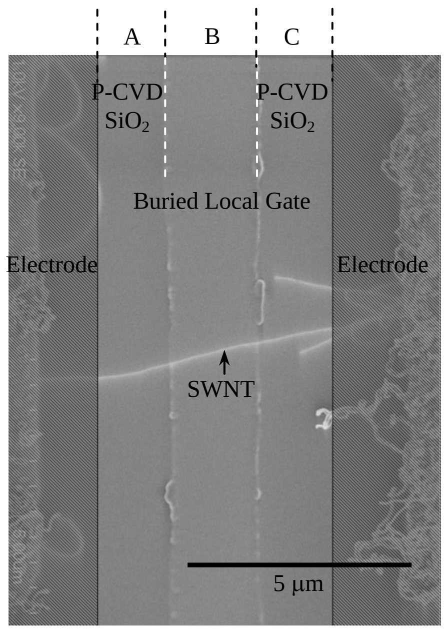

Fig. 1 (b), Top view of SWNT-FET with BLG by SEM observation.

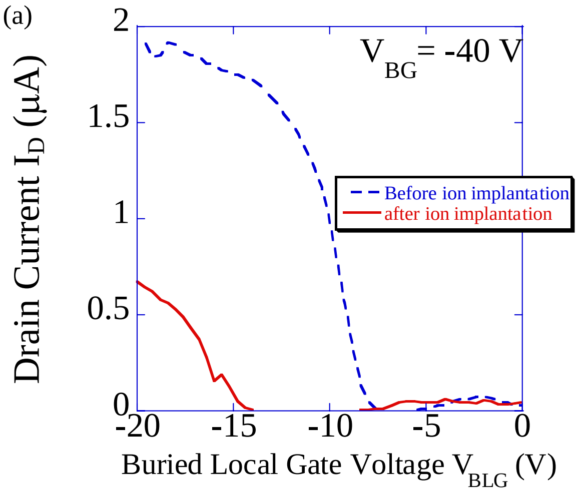

Fig. 2 (a), I_D – V_{BLG} characteristics at V_{BG}= -40V before and after oxygen ion implantation.

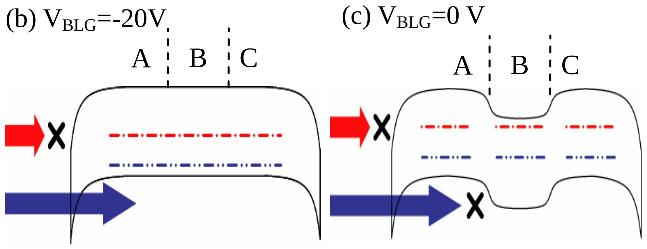

Fig. 2 (b), (c), Schematic band diagram of SWNT-FET with BLG (b) at V_{BLG}=-20 V, (c) at V_{BLG}= 0V.
The line - ・・・ - (- ・ ・ -) indicates the Fermi level before (after) ion implantation.

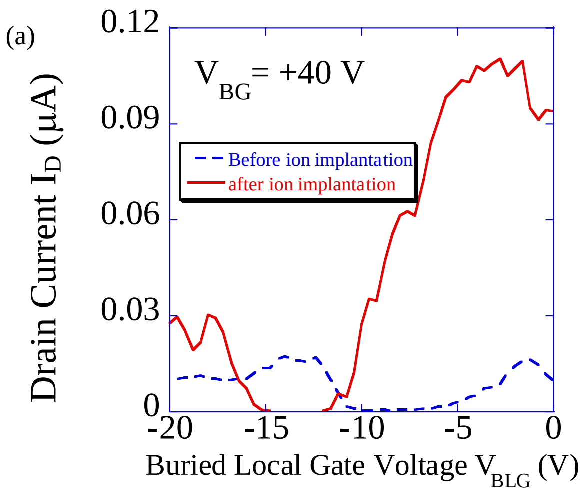

Fig. 3 (a), I_D – V_{BLG} characteristics at V_{BG}= 40V before and after oxygen ion implantation

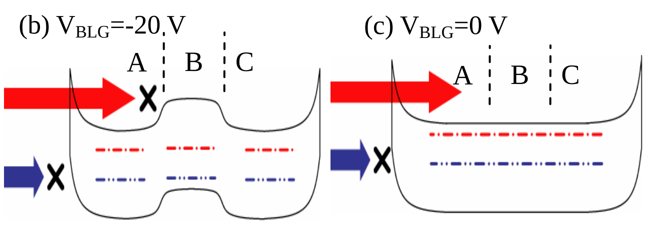

Fig. 3 (b), (c), Schematic band diagram of SWNT-FET with BLG (b) at V_{BLG}=-20 V, (c) at V_{BLG}= 0V.
The line - ・・・ - (- ・ ・ -) indicates the Fermi level before (after) ion implantation.