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Effect of Ar$^+$ irradiation on the behaviour of carbon nanotube transistor

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The characteristics of carbon nanotube field effect transistor are investigated after the whole device is irradiated with Ar$^+$ ions. The resistance become much higher due to the electron scattering at vacancies produced by Ar$^+$ irradiation. In addition, the subthreshold slop, S, ($\mathrm{d}V_G/\mathrm{d}(\log I_D)$) increases and the Schottky barrier height decreases after the irradiation, which imply the interface states generated within the band gap of the semiconducting single walled carbon nanotube. Therefore, we suggest a way that makes a transparent contact for electron transport by manipulating the vacancy formation at the interface between nanotube and metal leads.

1 Introduction

Various atomic-scale defects of carbon nanotube (CNT) such as vacancy and pentagone/heptagone Stone–Wales defect have been investigated using scanning tunnelling microscopy (STM), especially focusing on their effects on the electronic structure of CNT [1–3]. In these STM studies, the localized energy states placed within a band gap of semiconducting single walled carbon nanotube (SWNT) were observed at the end of SWNT and the CNT junction with different band gap. Recently, Gómez et al. [4] have reported that the density of defects would determine the transport of nanotube from ballistic regime to either weak or strong localization regime as the consecutive Ar$^+$ irradiation dose are applied to SWNT. On the other hand, it has been suggested theoretically that the electron scattering in the nanotube would play a significant role in lowering the contact resistance, which provide additional possibilities of the Fermi surface overlap between nanotube and metal [5, 6].

In this study, we investigated the influence of vacancies generated by Ar$^+$ irradiation on the characteristics of carbon nanotube field effect transistor (CNTFET). Since SWNT is placed on the top of the metal lead in this device, the vacancies were considered to exist at the interface between SWNT and metal lead as well as the bulk of SWNT acting as a transport channel.

2 Experimental

The SWNTs, synthesized by the HipCo procedure, were suspended in aqueous solution of sodium dodecyl sulfate (1wt%), and then adsorbed onto the palladium (Pd) electrode prepatterned on a highly doped Si substrate with a silicon oxide layer of 200 nm in thickness. The current–voltage characteristics were

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measured after ascertaining the placement of SWNT between source and drain electrode using atomic force microscopy (AFM).

Then, the whole device was irradiated with Ar^+ ions of 30 keV, with a dose of 5×10^{11} ions/cm^2. The irradiation has been done in an implanter, which is not commercial one, and the ionic dose is controllable with varying the exposure time. The electronic transport characteristics of the identical device was measured again and compared with that before the irradiation.

3 Results and discussion

At first, the characteristics of pristine CNTFETs were measured before exposing the device to Ar^+ ion. Figure 1(a)–(d) exhibit the $I_{sd}-V_{sd}$ curves obtained from an individual semiconducting SWNT and small bundles of SWNTs, respectively. As seen from the gate dependence in Fig. 2(a) and (b), both of the nanotube transistors behave like a p-type transistor. However, the device 1 of Fig. 2(b) does not completely turned off the current value to zero even at positive gate–voltage because it consists of metallic and semiconducting SWNTs.

In next, the whole CNTFET was irradiated with Ar^+ ions of 30 keV, with a dose of 5×10^{11} ions/cm^2 as explained above. Previous STM study [3] showed that the individual vacancies were produced separately on a multi walled carbon nanotube after same condition of Ar^+ irradiation with the above, at which an additional peak appears in the local density of state (LDOS) slightly above the Fermi level. So, we assume that the same kinds of defects are formed in our case, too. The number of vacancies is estimated using the Monte Carlo simulation under the same irradiation condition, and the rate of vacancy generation is roughly 0.5 vacancies per 100 nm in length of a nanotube having a diameter of 1 nm.

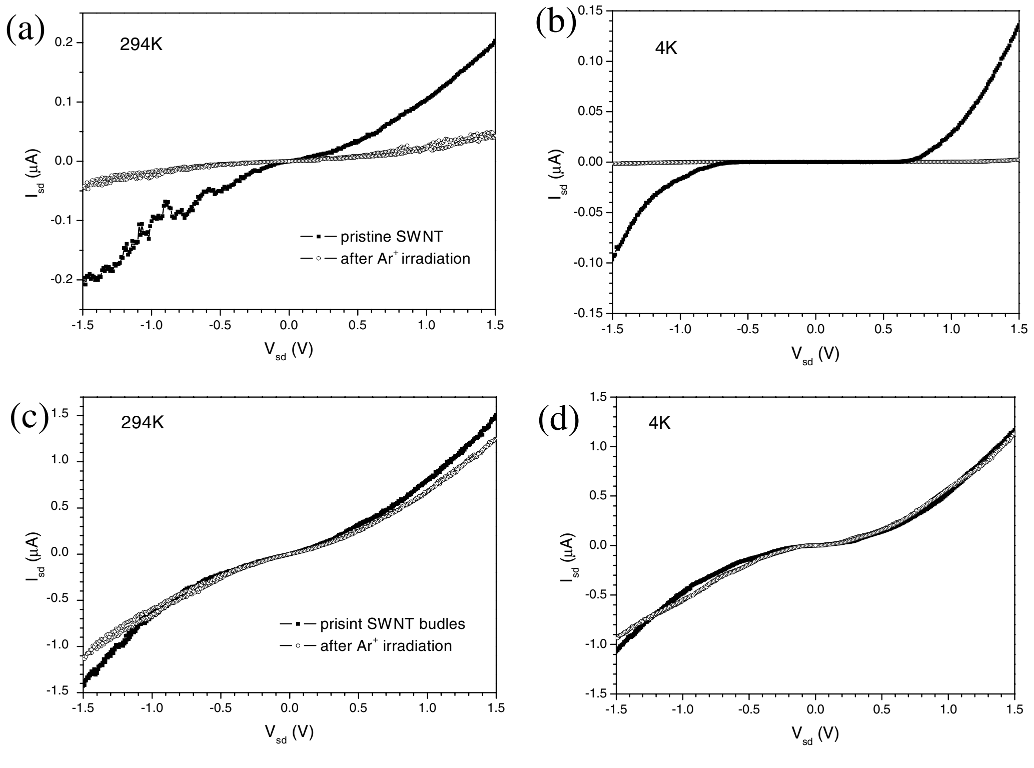

Fig. 1 (a), (b) $I_{sd}-V_{sd}$ curves obtained from an individual SWNT at room temperature and 4 K, respectively and (c), (d) those from small bundles of SWNTs at room temperature and 4 K, respectively as well.

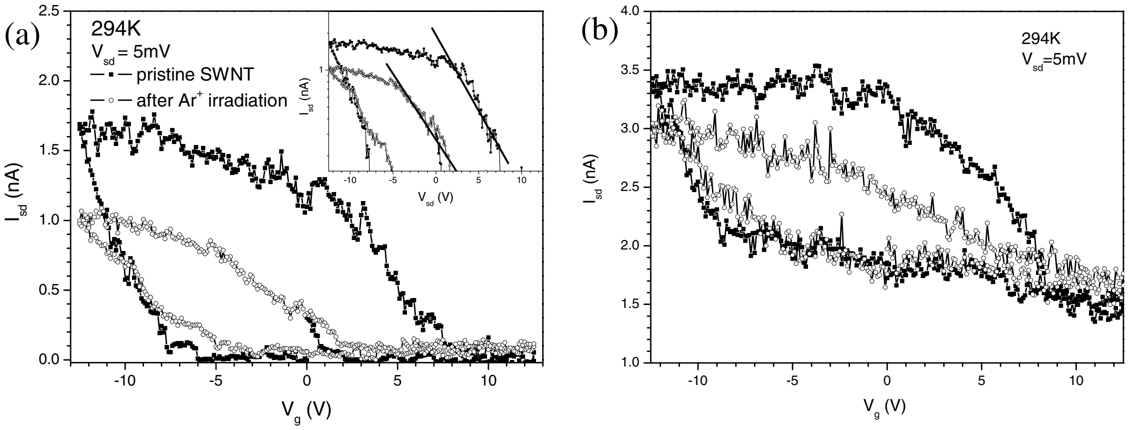

Fig. 2 $I_{sd}-V_g$ characteristics measured from (a) an individual semiconducting SWNT and (b) small bundles of SWNTs at $V_{sd} = 5$ mV and room temperature. The inset in Fig. 2(a) shows an increase of the subthreshold slope, S, $(dV_g/d(\log I_{SD}))$ after Ar$^+$ irradiation.

As presented in Fig. 1(a) and (b), the resistance obtained from the device consisting of an individual SWNT become much higher after the irradiation, changing from 25 MΩ to 172 MΩ at room temperature. This device has a distance of 600 nm between source and drain electrode, and this length corresponds to be about 3 vacancies existing along the nanotube channel according to the simulation result. On the other hand, the resistance of small bundles of SWNTs does not change largely and increase slightly from 2.61 MΩ to 3.14 MΩ after the irradiation. Gómez et al. [4] have reported that 0.03% of divacancy produces the increase of three orders of magnitude in the resistance. However, the resistance in our experiment was not increased so much as their case even though the vacancy density of 0.045% is quite similar. In any cases, it is obvious that the electron scattering at atomic defects will obstruct the electron transport through the channel and hence cause an increase of the electronic resistance exceedingly.

The gate dependence of CNTFET was also influenced by the vacancy formation after the irradiation as shown in Fig. 2(a) and (b). Besides the degradation of the 'on' state current at the negative gate voltage, the subthreshold slop, S, defined as $dV_g/d(\log I_{sd})$, become higher after the irradiation in both devices. In the conventional MOSFET, the value of S is higher if the silicon-oxide has many interface states. Resembling the behaviour of MOSFET, the additional energy states at the interface between SWNT and metal could make a higher value of S in the case of CNTFET as well. However, their principle role in changing the characteristics of CNTFET is totally different with the conventional MOSFET. As explained in the scheme of Fig. 3(b), the charge carriers – here is hole – can move from the electrode to the valence band of SWNT before the hole at the metal Fermi surface tunnel through the barrier directly and move to the valence band of SWNT if the interface states exist within a band gap. Therefore, the current increases gradually at the transition regime from 'off' to 'on' state as the gate voltage is applied from positive to negative when the device was irradiated with Ar$^+$ ions.

The barrier height between SWNT and metal lead was estimated from the Arrehnius plot before and after the irradiation to see any change in the contact properties. Interestingly, it was found that the barrier height at 'on' state is higher after Ar$^+$ irradiation than before, but this tendency is reversed at 'off' state, as seen in Fig. 3(a). Such a contradictory of a barrier height at 'on' and 'off' state could be explained from the different role of vacancies depending on whether they are on the bulk of SWNT or at the interface between SWNT and metal. At 'on' state, the electron transport is dominated by the state of the bulk of SWNT acting as a channel because the contact barrier is already overcome by the high gate bias. On the contrary, the contact property is very crucial at 'off' state because most of the 2-terminal resistance is obtained from the Schottky barrier formed between SWNT and metal electrode. Therefore, the current at

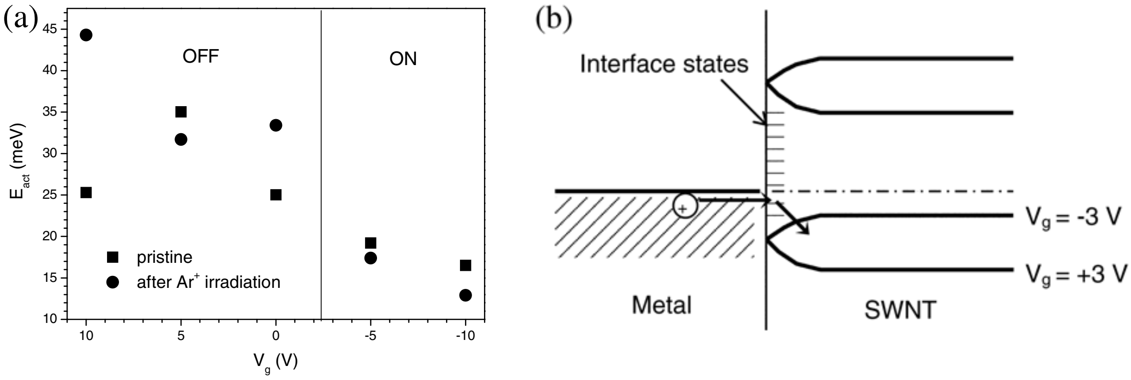

Fig. 3 (a) Variation of Schottky barrier height upon the applied gate voltage before and after Ar^+ irradiation, respectively. (b) The role of the interface states within a band gap of SWNT, which cause the gradual increase of the current in the transition regime from 'off' to 'on' state.

'on' state decrease much exhibiting a higher barrier height due to the electron scattering at the vacancies after the irradiation. However, the barrier at 'off' state represents the Schottky barrier height (SBH) between SWNT and metal, and this seems to be modified by the interface states created by Ar^+ irradiation. From the larger subthreshold slope, *S*, and the lower SBH at 'off' state of CNTFET after Ar^+ irradiation, therefore, it could be considered that the vacancies created by the irradiation provide not only the electron scattering during the transport through the channel, but also the additional energy state within a band gap of SWNT which can play a key role in determining the contact properties between SWNT and metal.

4 Conclusion

We have investigated the effect of vacancy on the characteristics of CNTFET after the device is irradiated with Ar^+ ion. As a result, it was found that the vacancies created by the irradiation not only cause the electron scattering through the channel, but also modify the contact properties between SWNT and metal electrode by inducing the additional interface states within a band gap of SWNT. Based on these results, we suggest a way of controlling contact properties by modulating the defect formation at the place between SWNT and metal.

References

[1] Ph. Kim, T. W. Odom, J.-L. Huang, and Ch. M. Lieber, Phys. Rev. Lett. **82**, 1225 (1999).
[2] H. Kim, J. Lee, S.-J. Kahng, Y.-W. Son, S. B. Lee, C.-K. Lee, J. Ihm, and Y. Kuk, Phys. Rev. Lett. **90**, 216107 (2003).
[3] Z. Osváth, G. Vértesy, L. Tapasztó, F. Wéber, Z. E. Horváth, J. Gyulai, and L. P. Biró, Phys. Rev. B **72**, 045429 (2005).
[4] G. Gómez-Navarro, P. J. De Pablo, J. Gómez-Herrero, B. Biel, F. J. Garcia-Vidal, A. Rubio, and F. Flores, Nature Mater. **4**, 534 (2005).
[5] J. Tersoff, Appl. Phys. Lett. **74**, 2122 (1999).
[6] Tongcang Li, Q. W. Shi, Xiaoping Wang, Qin Chen, Jianguo Hou, and Jie Chen, Phys. Rev. B **72**, 035422 (2005).