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Description	

Device characteristics of carbon nanotube transistor fabricated by direct growth method

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We have fabricated carbon nanotube (CNT) field-effect transistors (FETs) by direct growth of single-wall CNTs between the source and drain electrodes, and investigated their device characteristics. The FETs show ambipolar operation. The temperature and bias voltage dependence of device characteristics are consistent with device operation of the Schottky-type FET. The carrier injection barrier heights for both the electron and hole carriers show small values of 17–74 meV, without any additional specific treatment after device fabrication. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2949075]

Carbon nanotubes (CNTs) have attracted great attention as a next-generation material, because of their characteristic electronic, mechanical, and chemical properties. From the viewpoint of electronic properties, they can be either metallic or semiconducting, depending on the chirality and diameter of the CNTs. For the application of CNTs to transparent and flexible semiconductor devices, studies on field-effect transistors (FETs) using randomly networked CNT film have been performed.[1,2] In the fabrication process of FETs, the method for disposition of CNTs in the channel of FETs is one of the most important issues to be established.

There are three different methods to fabricate CNT-FETs. The first is the postdispersion method, where a dispersion of CNTs is dropped between the source and drain electrodes fabricated beforehand.[1,2] Although this method is the most popular and easiest, weak electric contact between CNTs and electrodes, and contamination of dispersion medium in CNTs are inevitable. The second is the predispersion or presynthesis method, where CNTs are first dispersed or synthesized on the substrate, followed by formation of electrodes on the CNTs by a lithography method.[3] In this method, electric contact between CNTs and electrodes can be greatly improved. The contamination problem, however, still remains. Some chemical residue remains on the CNTs after lithography. The direct growth method, the third method, where CNTs are directly grown from the electrodes and bridging the electrodes, is an ideal method. It is free from the problems of contact and contamination.[4] In spite of the advantages of the direct growth method, the optimization of the fabrication process has not been established; the properties of FETs fabricated by this method are unexplored.

In this letter, we report fabrication of CNT-FETs by means of direct growth technique for single-wall (SW) CNTs bridging the source and drain electrodes, and their characterization. We adopted an angled deposition technique for the formation of Mo/Co layers which act as the catalyst and the electrodes. We found that carrier injection barrier heights of FETs in this study show smaller values (without any additional specific treatment after the device fabrication) than those of FETs fabricated by a conventional postdispersion method.

The FETs used in this study were of the back gate configuration type. The device structure and procedure are shown in Fig. 1(a). The SiO_2 layer (thickness 400 nm) and the doped silicon layer of the wafer were used as the gate insulator and the gate electrode, respectively. A Mo/Co bilayer was used both as the catalyst for CNT growth, and as the source and drain electrodes. The electrodes were patterned on the SiO_2 layer, using a photolithography method with double resist technique [Fig. 1(a)]. The channel length L and the channel width W were designed to be 5 and 100 μm, respectively. The Mo layer (thickness 100 nm) was first deposited on the substrate at an angle of 8° to the normal by electron beam (EB) evaporation system, followed by EB deposition of the Co catalyst layer (nominal thickness 1 nm) normal to the substrate. The angled deposition technique was employed to deposit a single layer of the Co catalyst on the side of Mo to enhance the growth of CNTs [Fig. 1(a)]. CNTs were grown by fast-heating[5] alcohol catalytic chemical vapor deposition method,[6,7] with ethanol as the feed gas and Co as the catalyst. The growth condition was 900 °C for 30 min, with an internal ethanol-gas pressure of 3–5 kPa. The details of the CNT growth have been reported in Refs. 8 and 9. The CNTs grown on the substrate were characterized by means of scanning electron microscopy (Hitachi S-4100), atomic force microscopy (AFM) (Seiko Instruments SPA-400, SPI-3800), and Raman spectroscopy with laser excitation energy of 632.8 nm (Tokyo Instruments Nanofinder 30). Before transport measurements, the FETs were annealed at 120 °C under 10^{-3} Pa for 24 h in order to eliminate O_2 and/or H_2O molecules adsorbed in the CNTs. The transport properties of CNT-FETs were measured under 10^{-3} Pa using cryogenic prober system (Desert TT-prober, Keithley 4200-SCS).

Figure 1(b) shows a typical topological AFM image of the CNT-FET fabricated in this study. Bright areas at the right and left sides are electrodes, and fine lines between electrodes depict CNTs. The CNTs were found to be SWCNTs with diameter of 1.1–1.4 nm, as calculated from the Raman frequency of the radial breathing mode (ω_{RBM}) with the known equation $d(\mathrm{nm})=248/\omega_{RBM}\ (\mathrm{cm}^{-1})$.[10] The heights of CNTs in the AFM image were estimated to be 1.2 ± 0.3 nm, showing that CNTs were individual SWCNTs,

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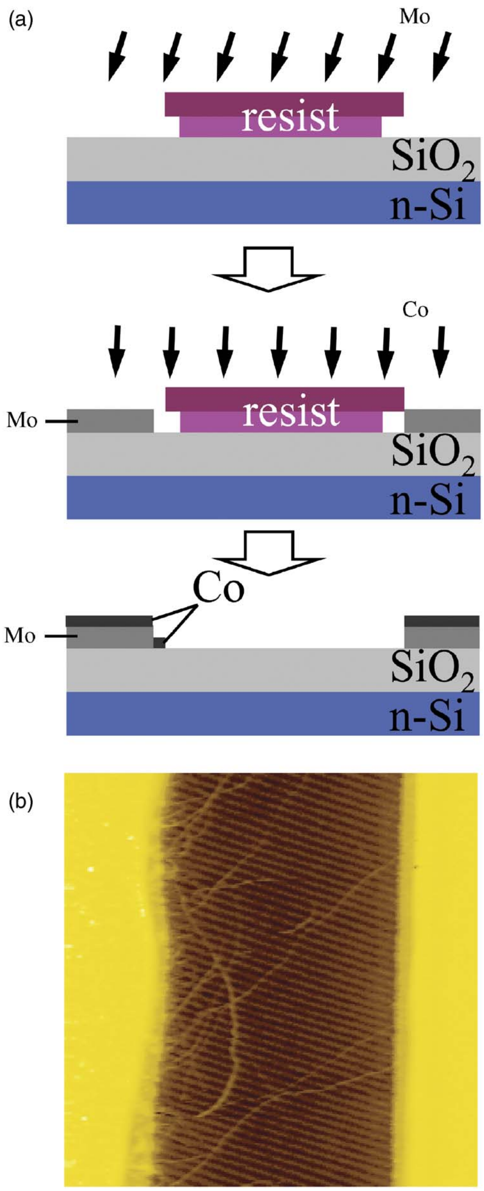

FIG. 1. (Color online) (a) Schematic fabrication sequence of Mo/Co thin films which act as catalyst and electrodes. (b) AFM image of a CNT-FET: the size of this image is $7.5 \times 7.5\ \mu m^2$. Scales of horizontal direction in (a) and (b) roughly correspond to each other.

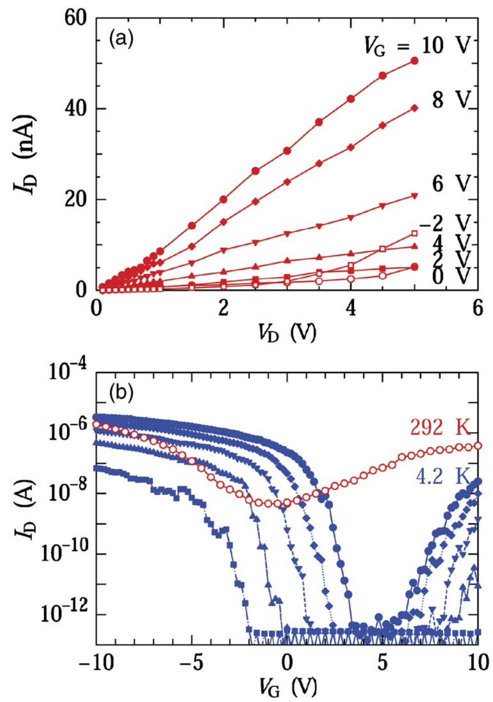

FIG. 2. (Color online) (a) Output characteristics for *n*-channel operation at 292 K for $V_G = -2$ V (□), 0 V (○), 2 V (■), 4 V (▲), 6 V (▼), 8 V (◆), and 10 V (●). (b) Transfer characteristics at 292 K for $V_{DS} = 5$ V (○) and at 4.2 K for $V_{DS} = 1$ V (■), 2 V (▲), 3 V (▼), 4 V (◆), 5 V (●).

or at most, bundles of a few SWCNTs. In this work, the number of SWCNTs in bundles could not be controlled. However, it may be related to the size of Co catalyst, namely, growth time.[8] Controlling the number of SWCNTs by growth condition is a very attractive and challengeable work. It was also found that CNTs were localized mainly at the edge of the left electrode, and some of them had grown across to the right electrode [Fig. 1(b)]. This shows that the CNTs were grown from single Co layer on the right side of the left Mo/Co electrode [Fig. 1(a)], and CNTs bridging the two electrodes can act as a channel.

Figure 2(a) shows output characteristics (drain current I_D versus drain-source voltage V_{DS}) at 292 K. In this measurement, the right electrode of the device shown in Fig. 1 was grounded as the source electrode. The *n*-type [Fig. 2(a)] and *p*-type (not shown) operations were observed in the same device. An ambipolar operation was also confirmed by transfer characteristics (I_D versus gate voltage V_G), as shown in Fig. 2(b). We fabricated 60 devices; more than half of them show FET action. On-off ratio and subthreshold swing S depend on device; the best values at 292 K were 2.9×10^6 and 0.2 V/decade. The cause of variation can be attributed to the different populations of metallic and semiconducting CNTs. The on-off ratio and S for data measured at 292 K (with $V_{DS} = 5$ V) shown in Fig. 2(b) were 4.3×10^2 and 2.5 V/decade, respectively. We did not estimate mobility, because of difficulty in estimation of effective channel width. At 4.2 K, the values improved to 2.4×10^7 and 0.3 V/decade, respectively. The improvement was caused by a decrease in off current, while on-current values remained almost the same as those at 292 K. The trend is well explained by reduction in carrier injection from the electrode to the CNTs. Off-state window, i.e., V_G region, where $I_D < 10^{-12}$ A in Fig. 2(b), becomes narrower with increasing V_{DS}. This behavior can be attributed to the decrease in potential barrier due to mirror-charge effect and/or to the decrease in barrier width. These phenomena are all well explained in terms of carrier injection barrier modulation, namely, operation of the Schottky-type FET.[11]

The carrier injection barrier at the contact can be estimated from temperature dependence of I_D. Figure 3(a) shows temperature dependence of I_D at $V_G = 10$ V (*n*-type operation). In all cases, the temperature dependence is activation type above 77 K, which is consistent with previous reports.[11,12] Here, the right side electrode of the device (Fig. 1) was grounded as the source electrode: activation energy E_a corresponds to the carrier injection barrier of the right side electrode. Plots of E_a as a function of $V^{1/2}$ are shown in Fig. 3(b). Here, open circles and open squares show E_a for electron and hole injection barriers from the right electrode to the CNTs. We also investigated electron and hole injection barrier heights from the left electrode to the CNTs, by changing the measurement configuration. Corresponding data are shown by closed marks in Fig. 3(b). The extrapolated E_a

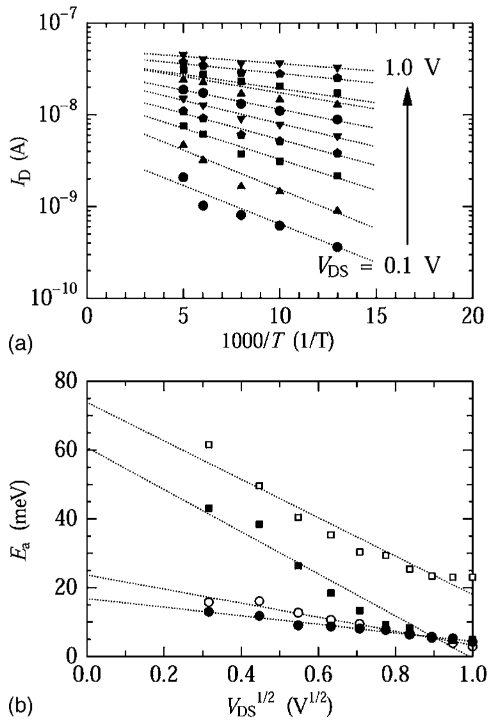

FIG. 3. (a) Arrhenius plots of I_D at V_G=10 V for various V_{DS} in 0.1 V steps. (b) E_a vs $V_{DS}^{1/2}$ plots for the electron injection barriers (circle) and hole injection barriers (square). Closed and open marks show data for carrier injection from the left and right electrodes, respectively, of the device in Fig 1. Dotted lines are fitting results.

values to $V^{1/2}$=0 V correspond to the intrinsic potential barrier heights.[11] E_a values for electron injection from the left and right electrodes are estimated to be 17 and 24 meV; those for hole injection are estimated to be 61 and 74 meV, respectively. In spite of asymmetric device structure (Fig. 1), E_a values for the left and right electrodes are similar.

The values obtained using our method (17–74 meV) are smaller than those of CNT-FETs as previously fabricated by conventional postdispersion method (170 meV).[13] The cause of small values in our study can be attributed to good electric contact between CNTs and electrodes. Also, previous studies achieved reduction in E_a values by postannealing above 700 °C (13–15 meV) (Ref. 11) or chemical doping (70 meV).[12] In contrast, our method results in small E_a values without any additional specific treatment except for low temperature vacuum annealing.

In conclusion, we have fabricated CNT-FETs by means of direct growth technique for SWCNTs bridging the source and drain electrodes, and characterized their device properties. Device operation was consistent with operation of the Schottky-type FET. We found that carrier injection barrier heights of FETs in this study show small values (17–74 meV) without any additional specific treatment after device fabrication. The values are similar to those of CNT-FETs after posttreatment by annealing or chemical doping of molecules, but smaller than those of CNT-FETs fabricated by conventional postdispersion methods. The method presented in this study will contribute to fabrication of high performance CNT-FETs.

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