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Ambipolar Conversion of Polymer-Coated All Single-Walled Carbon Nanotube Field-Effect Transistors

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1. Introduction

Single-walled carbon nanotubes (SWNTs) are a strong candidate for realizing flexible light-emitting devices due to their mechanical robustness and strong confinement of electron-hole pairs in SWNTs, which arises from their quasi one-dimensional structure. However, since optoelectronic devices using SWNTs that have been published were fabricated on a rigid Si substrate [1], their flexibility, one of the key features of SWNTs, is sacrificed.

We have fabricated all-SWNT field-effect transistors (FETs) on Si substrates [2]. Such all-SWNT devices can easily realize not only fabrication of a flexible device by transfer onto a plastic substrate, but also conversion to ambipolar transport. This makes it possible to simultaneously inject electrons and holes into channel because the electrodes and channel consist of the same work function material.

Here, we report carrier transport conversion of all-SWNT FETs from p-type to ambipolar using a simple polymer coating technique. An extremely flexible device is also fabricated by transfer to a polymer substrate.

2. Device Fabrication

The fabrication process of flexible FETs is demonstrated in Fig. 1. Patterned catalyst deposition (Co thickness: 0.5 nm) was performed on a master Si substrate (t_{ox}: 300 nm) by a conventional photolithography and lift-off process. A SWNT film was then produced using the standard alcohol catalytic chemical vapor deposition (ACCVD) method at 800 °C for 10 min. The details of SWNT synthesis procedures have been described elsewhere [3,4]. A poly(vinyl alcohol) (PVA) solution with 10% concentration was spin coated (1500 rpm, 30 s) over the substrate and then dried at 65 °C for 10 min. A PVA-coated SWNT film without any pattern was prepared by a similar process to be employed as the flexible gate electrode [Fig. 1(c)]. The transparent conductive film was peeled off from the substrate, then attached to the master substrate as shown in Fig. 1(b). After drying, both layers were adhered to each other, so the entire plastic film could be peeled off from the Si substrate [Fig. 1(e)]. Figure 1(f) shows the layered structure of the all-nanotube flexible FET. The devices were characterized

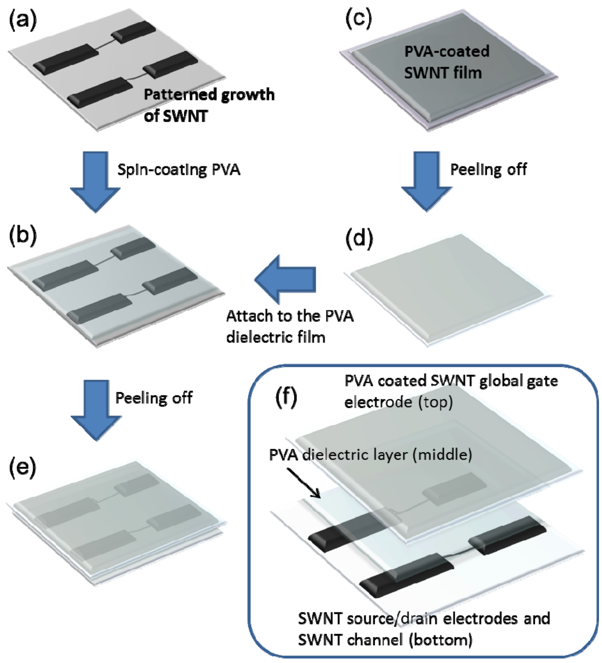

Fig. 1 Schematic diagram of fabrication process. (a) Patterned SWNTs are produced using a conventional photolithographically defined catalyst deposition followed by alcohol CVD; (b) PVA solution is coated onto the substrate and then dried; (c) by a similar process, a uniform, PVA-coated SWNT film is obtained; (d) the transparent conductive film is peeled off from the substrate, and then attached to the patterned substrate; (e) After drying, the entire plastic film is peeled off from the master substrate; (f) layered structure of the final all-carbon-nanotube flexible FETs.

using a semiconductor parameter analyzer (Agilent 4156C) at room temperature under ambient conditions.

3. Results and discussion

Figure 2 shows typical transfer characteristics of as-fabricated (black) and PVA-coated (red) devices. Both electrical properties were measured employing a Si substrate as a back-gate electrode at V_{DS} = −10 V. The difference between them is the coating of the device by PVA. The uncoated device showed typical p-type conduction. In

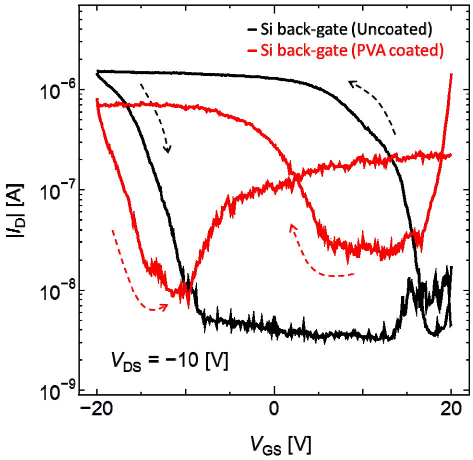

Fig. 2 Influence of polymer coating in the transfer characteristics. The black and red lines indicate as-fabricated and PVA-coated devices, respectively. Both cases were measured on a Si substrate employed a back-gate electrode: $V_{DS} = -10$ V.

contrast, the PVA-coated FET showed ambipolar behavior. The reason for this change is attributed to the suppression of charge transfer from the SWNT.

When an SWNT channel is exposed to air, electrons are transferred to surrounding oxygen molecules [5], which are adsorbed onto the SWNT or onto the substrate surface. Therefore, the electron conduction through the channel is suppressed as shown in Fig. 3(a). On the other hand, the PVA layer acts as a potential barrier for charge transfer; hence electrons can pass through the channel at positive gate voltages [Fig. 3(b)].

If charge traps on the substrate could be removed, we can imagine that hysteresis–which is also caused by oxygen molecules [6]–would be reduced. Figure 4 shows *I-V* characteristics of PVA-coated (red) and PVA-laminated devices (blue). A Si substrate was used as a back-gate electrode in the former FETs, whereas the latter was measured using an attached SWNT/polymer global gate electrode after peeling

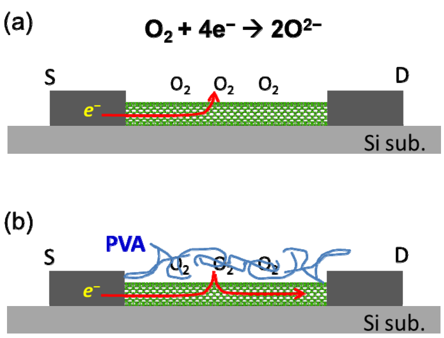

Fig. 3 Schematic diagram of charge transfer mechanism. (a) In an as-fabricated device, electrons injected from the source electrode are transferred to surrounding oxygen molecules. Due to the suppression of electron conduction, the resulting transport behavior therefore becomes p-type. (b) On the other hand, PVA acts as a potential barrier to charge transfer; hence ambipolar behavior appears.

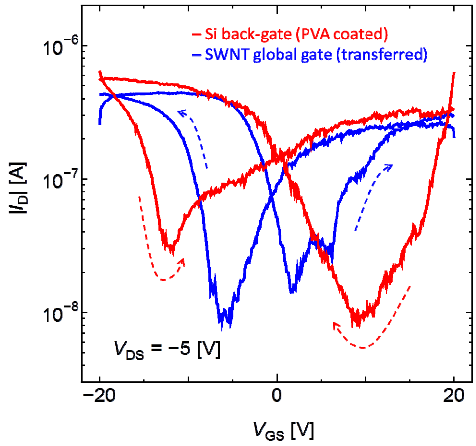

Fig. 4 Influence of substrate in the transfer characteristics. Red and blue lines indicate PVA-coated and PVA-laminated devices, respectively. A Si substrate was used as a back-gate electrode in the former, while the latter was measured after peeling off from the master substrate and then attaching an SWNT/polymer global gate electrode. $V_{DS} = -5$ V.

off from the master substrate. The result clearly reveals that, before transfer, charge traps still remained on the substrate surface even though the substrate was fully covered by polymer. By peeling off from the Si substrate, charge-trapping sites are dramatically reduced. The hysteresis would be small because polymer wrapped around the SWNTs makes a potential barrier, which suppresses charge transfer from the SWNTs to surrounding acceptor molecules. However, an observed overlap between forward and backward direction of the transfer curve in Fig. 4 has not been observed. This may be because no annealing processes were performed prior to PVA coating.

4. Summary

We fabricated PVA-coated, flexible, all-SWNT FETs. By using a simple transfer process, electrical properties were easily converted to ambipolar behavior. Since electrons and holes can be simultaneously injected into SWNT channel in ambipolar transport, this is an important step toward realizing flexible optoelectronic devices.

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