Electrical hysteresis of single-walled carbon nanotube field-effect transistors and its modulation by an external magnetic field

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Abstract: Electrical hysteresis in single-walled carbon nanotube (SWNT) field-effect transistors has been observed in 2002, which is a key factor to determine the performance of carbon nanotube field-effect transistors and related systems. Meanwhile, the mechanisms of the hysteresis are controversial and in-depth understanding is still required. In this work, we report the observation of hysteresis in a three-terminal SWNT FET at room temperature under atmospheric conditions. The hysteresis is found to be modulated by an external magnetic field. And there is a significant difference for the modulation of the hysteresis between the positive and negative magnetic fields. Possible mechanism is proposed and discussed.

1. Introduction
As the miniaturization trend based on silicon field-effect transistors (FETs) will soon reach its physical limitation, the demand for FETs using other nanomaterials and devices structures has been steadily increasing[1-3]. Single-walled carbon nanotubes (SWNTs) have been considered to be ideal materials for nano-scale transistors, owing to the nanoscale dimensions, high current density and simultaneously high carrier mobility[4-8]. Meanwhile, electrical hysteresis in FETs based SWNTs has been reported by Fuhrer et al. in 2002[9]. Since electrical hysteresis may degrade system-level performance, its mechanism has attracted a lot of research interests. The mechanisms of hysteresis are different for single-walled carbon nanotube field-effect transistors (SWNT FETs) implemented fabrication methods. Currently, the common belief is that the sources of hysteresis in SWNT FETs mainly comes from the following aspects[10-12]: interface traps (traps at the interface of the SWNT and the dielectric), surface traps (traps along the surface of the dielectric, not directly in contact with the SWNT). In addition, the hysteresis of suspended carbon nanotubes has also been observed, it has been suggested that that hysteresis is due to the combination of the water molecules which behaves as medium or charge trap[13]. Therefore, some previous work attempted to eliminate hysteresis implemented fabrication methods such as passivating the SWNT with PMMA or other polymers, surrounding the SWNT with oxides to form gate-all-around geometries, or suspending the SWNT above the substrate.
In this work, we report a three-terminal device of field effect transistor based on a single-walled carbon nanotube. The device shows a characteristic hysteresis that can be modulated by external magnetic fields at room temperature under atmospheric conditions. This indicates that the mechanism of hysteresis originates from magnetic moment, which is attributed to the defect-induced magnetic moment in SWNTs.

2. Experimental section
The SWNTs used in this work was grown by floating catalytic chemical vapor deposition[14]. The device is patterned with electron beam lithography (Vistec EBPG 5000plus ES). The fabrication process of SWNT device is schematically shown in Fig. 1. Firstly, some isolated SWNTs were deposited on a SiO₂ (300 nm)/silicon substrate. And an individual, straight SWNT was selected and their positions were recorded with Nova Nano SEM 430 (Fig. 1a). Secondly, a layer of thin poly(methyl methacrylate) (PMMA, ~260 nm thick) was spin-coated onto the sample (Fig. 1b). Thirdly, according to the position and orientation of the SWNT, two electrodes (S, D) were patterned using electron beam lithography (Vistec EBPG 5000plus ES). The exposed PMMA was developed with 1: 3 MIBK: IPA solution at room temperature. Then 50 nm thick Mo was deposited with magnetron sputtering followed by lift-off in 80°C acetone. Electrical characterizations were performed using an Agilent B1500A Semiconductor Device Analyzer and a probe station at room temperature under atmospheric conditions. Finally, the device was measured with a back gate and an external z-direction magnetic field. The magnetic field was produced with an NdFeB cylindrical permanent magnet (Φ40mm×10mm). The magnitude of the magnetic field was measured with a BST200H Gaussmeter and the direction of the magnetic field is perpendicular to the SWNT. For clarity, the size is not in scale in this figure.

Figure 1. Schematic diagrams showing fabrication processes and measurement of SWNT FET device. (a) An individual, isolated SWNT on a SiO₂/Si substrate. (b) A layer of PMMA covering the SWNT and the substrate. (c) The SWNT and the two electrodes. The source and drain electrodes were patterned by EBL, followed by deposition of 50 nm thickness Mo film and a standard lift-off process. (d) Measurement scheme. M: a cylindrical NdFeB permanent with dimension (Φ40mm×10mm). The
direction of the magnetic field at SWNT is perpendicular to the SWNT and its magnitude is measure with a magnetic sensor.

3. Results and discussions

A typical scanning electron microscopy (SEM) image of the SWNT FET is shown in Fig. 2(a). It can be seen that the SWNT is connected to two molybdenum electrodes with a spacing about 800 nm. Figure 2(b) is a typical transfer characteristics of SWNT FET devices. In this figure, the red and blue arrows indicate the sweeping-up and -down directions of $V_g$, respectively. It is obvious that there is a hysteresis between the sweeping-up and -down directions of $V_g$.

Due to the electrical hysteresis, the output characteristics of the device are dependent on the sweeping direction of the gate voltage. The output characteristics of the SWNT device is shown in Fig. 2(c), which corresponds to the sweeping-up of the gate voltage. The linear current-voltage characteristics at small drain-to-source bias ($V_d$) indicate ohmic contacts of the Mo electrodes with the SWNT. In figure 2(d), the output characteristics of the device corresponding to the sweeping-down is shown.

![Figure 2. Typical structure and electrical properties of SWNT FET devices. (a) SEM image showing the structure of SWNT FET device. The SWNT is connected to Mo source and drain electrodes (thickness: 50 nm.). The two electrodes (S, D) are patterned with electron beam lithography and colored with blue. (b) Typical transfer characteristics of the SWNT device. Electrical hysteresis is observed in this device structure between the sweeping-up and the sweeping-down. The red curve represents gate voltage sweeping from -15 V to 10 V (the sweeping-up) and the blue curve represents the gate voltage sweeping from 10 V to 15 V (the sweeping-down). (c) Output characteristics of the SWNT FET device ($V_g$ changes from -15 V to 10 V in steps of 5 V). (d) Output characteristics of the device ($V_g$ changes from 10 V to -15 V in steps of -5 V).]
In order to have a better understanding about the mechanism of hysteresis in the SWNT device, an external magnetic field is applied to the SWNT device. During the measurement, the SWNT device is placed at the centre of the cylindrical magnet, thus the direction of the magnetic field (z-direction magnetic field) is perpendicular to the SWNT in the device. The results are shown in Fig. 3. It can be seen that the hysteresis of the SWNT FET device can be modulated by magnetic fields at room temperature under atmospheric conditions. In figure 3, the orange dotted curve represents the gate voltage sweeps from -15 V to 10 V, the purple dotted curve represents the gate voltage sweeps from 10 V to -15 V. When the magnetic field is positive, the orange dotted line is always above the purple dotted line, which is different from the hysteresis characteristics of SWNT FET without magnetic field. On the contrary, when the magnetic field is negative, the orange dotted line is always below the purple dotted line, which is consistent with the initial hysteresis characteristics. The threshold voltage can be changed by the strength of the magnetic field, so the hysteresis characteristics of SWNT FET device also changed. These results indicates the mechanism of the hysteresis of the SWNT device may originate from the magnetic moments in SWNT; such as the magnetic moment at the open ends of carbon tube[15-17]. Therefore, the SWNT FETs have great potential in spintronic devices, which may open a new way for the development of non-traditional integrated circuit with high-density and low-power.

![Figure 3](image-url)

Figure 3. Hysteresis characteristics of the SWNT FET device under different z-direction magnetic fields. The orange dotted curve represents the gate voltage sweeps from -15 V to 10 V, the purple dotted curve represents the gate voltage sweeps from 10 V to -15 V.

4. Conclusions
The major experimental findings from this work can be summarized as follows: (1) the hysteresis phenomenon in a SWNT FET was observed at room temperature under atmospheric conditions, (2) the hysteresis is found to be modulated by an external magnetic field, and (3) there is a significant difference for the modulation of the hysteresis between the positive and negative magnetic fields. The mechanism of the hysteresis of the SWNT device may originate from the magnetic moments in SWNT. Hence, the SWNT FETs have great potential in spintronic devices. These results may help to develop and interpret schemes for control of gate hysteresis, and provide a new way for the development of non-traditional integrated circuit with high-density and low-power.

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