Random Telegraph Noise in Individual Single-walled Carbon Nanotubes

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ABSTRACT

The switching of resistance between two discrete values, known as random telegraph noise (RTN), was observed in individual single-walled carbon nanotubes (SWNTs). The RTN has been studied as a function of bias-voltage and gate-voltage as well as temperature. By analyzing the features of the RTN, we identify three different types of RTN existing in the SWNT related systems. While the RTN can be generated by the various charge traps in the vicinity of the SWNTs, the RTN for metallic SWNTs is mainly due to reversible defect motions between two metastable states, activated by inelastic scattering with electrons.

INTRODUCTION

Single-walled carbon nanotubes (SWNTs) have been widely investigated to use them in nanoelectronics, based on their remarkable electrical properties [1]. However, a report on the noise properties of SWNTs manifests a barrier in their low-noise electronic applications. According to Collins et al. [2], SWNT conductors exhibit $1/f$ excess noise four to ten orders of magnitude larger than that observed in more conventional conductors at room temperature. The understanding of their noise mechanism is necessary to suppress the excess noise and characterize the performance of nanotube nanoelectronic devices. Up to now, many researches on the noise properties of carbon nanotubes confirmed the dominance of $1/f$ noise for the low frequency range ($f < 1$ KHz) [2-8]. The various charge traps in the vicinity of carbon nanotubes are expected to play a role in the observed $1/f$ noise, since the nanotubes are prepared on the dielectric substrates. However, the noise behaviors in Coulomb-blockade regime studied for a multi-walled carbon nanotube (MWNT) single-electron-transistor (SET) could not be explained by the charge fluctuations alone as pointed out in ref. 3. Also, the similar experiment performed on a SWNT-SET device [5] showed a complete deviation from the gain dependence of the noise,
the typical sign of the noise caused by the charge fluctuations [9]. Moreover, Nygård and Cobden reported no consistent improvement of the noise in their etched devices, where the nanotubes were suspended over the substrates [10]. The origin of the excess noise in nanotubes, therefore, should be attributed to the other mechanism than background charge fluctuations. Recently, the random switching of resistance between two discrete values, known as the random telegraph noise (RTN), was observed in individual metallic SWNTs [11]. Since $1/f$ noise is generally regarded as a superposition of such two-level resistance-fluctuations, the study of the RTN provides a powerful means of investigation into the origin of the $1/f$ noise.

EXPERIMENTAL DETAILS

Experiments have been carried out on SWNTs produced by various methods (arc discharge, laser ablation and HiPco methods). The samples were then dispersed by sonication in the sodium dodecyl sulfate (SDS) solution and deposited on Si/SiO$_2$ substrates. The heavily doped Si was used as a back-gate and the thickness of oxide layer was 300 nm. For electrical contacts, Ti / Au (5 nm/ 15 nm) electrodes were defined on individual SWNTs using conventional e-beam lithography. Low temperature measurements have been performed both in Janis variable temperature cryogenic system and in simple liquid He bath. The samples were biased at a constant voltage and the current fluctuations were monitored with either the preamplifier (Ithaco 1211) or the semiconductor characterization system (Keithley 4200). In general, the RTN can be characterized by three parameters, namely the RTN amplitude ($\Delta I_{ds}$) and the mean lifetimes staying in high-current states $\tau_{\text{high}}$ and low-current states $\tau_{\text{low}}$ [12]. To obtain reasonable statistical values of these parameters, 5000 to 20000 current points were registered under a fixed drain-source bias-voltage ($V_{ds}$). The observation window of $\tau_{\text{high}}$, $\tau_{\text{low}}$ ranged from 0.1 s to 1000 s.

DISCUSSION

RTN due to charge traps

RTN has been extensively observed in a variety of mesoscopic systems such as submicron metal-oxide-semiconductor field-effect-transistors (MOSFETs) [13], metallic nanoconstrictions [14], and small tunnel junctions [15]. It is now well established that the RTN in MOSFETs is associated with charge fluctuations, i.e., capture and emission of carriers by the oxide traps located near the interface. If the trap energy level is located within a few $k_B T$ of the Fermi level
of the FET channel, the electron in the channel can move in and out of the trap. The random switching produces the RTN in MOSFETs not only by the fluctuation in carrier numbers but also by the fluctuation in channel mobility affected by the Coulomb field of the charged trap. Recently, there were several reports on the hysteresis in current-gate voltage ($I_{ds}$-$V_g$) curves of SWNT-FETs. The hysteresis was attributed to the various charge traps in the vicinity of SWNT [16-19]. The RTN was also encountered in a semiconducting SWNT-FET while Fuhrer et al. studied the memory element using the hysteresis behavior caused by trapped charge [16]. This type of RTN, related to the charge traps, was sensitive to $V_g$ and usually observable over a limited range of the gate-voltage, since the capture and the emission of carriers is strongly dependent on the potential of trap site [13,16]. Figure 1 shows our observation of this type of RTN in an individual SWNT at $T = 1.9$ K. In time-traces of current for a fixed drain-source bias-voltage, $V_{ds} = 2$ V, the RTN reproducibly appeared as soon as we applied 5 V to the gate, while it disappeared as we turned off the gate-voltage. Although the presence of such RTN indicates that charge traps in the vicinity of carbon nanotubes indeed play a role in the observed excess $1/f$ noise, the origin for the excess noise cannot be attributed to the charge fluctuations alone as we already described in the introduction. In the following section, we introduce another type of RTN extensively observed in individual metallic SWNTs.

**RTN due to reversible defect motions**

In Figs. 2, we present typical noise results from a representative sample ($R \sim 500$ KΩ at room temperature). However, this type of RTN was observed in nearly all the metallic samples (more
than 10 individual metallic SWNTs) when we carefully studied the time-traces of currents for many different $V_{ds}$. Figure 2 (a) shows the $I_{ds}$- $V_{ds}$ characteristics at $T = 4.2$ K and $T = 285$ K. The curve was obtained from the voltage sweep in both direction. Current fluctuations were observed in the curve for $T = 4.2$ K predominantly over a range of $V_{ds}$ from $= 50$ mV to 100 mV. When plotted as a function of time, the random switching of the current between two distinct levels was observed as shown in the Fig. 2 (b). The time-traces of the $I_{ds}$ for nine different $V_{ds}$ were registered at $T = 4.2$ K. With increasing $V_{ds}$, the fluctuation rate became faster and the switching became faster than the experimental bandwidth for $V_{ds} \geq 90$ mV. Thus the RTN was usually observed only in a narrow range of $V_{ds}$, which corresponded to our observation window of $\tau_{\text{high}}$, $\tau_{\text{low}}$ lying between 0.1 s and 1000 s. Interestingly, the mean lifetimes of high-current states ($\tau_{\text{high}}$) and low-current states ($\tau_{\text{low}}$) showed an exponential dependence with respect to the inverse $V_{ds}$ in all the metallic samples where we could observe this type of RTN. The magnitude of the current fluctuation lay between 10% and 30% of total current. As the bias voltage was raised further, the sample resistance began to change irreversibly in time.

The effect of gate-voltage on the RTN was investigated in the range of $V_{g} = -16$ to 16 V. $\tau_{\text{high}}$ and $\tau_{\text{low}}$ showed no gate-voltage dependence, indicating that this RTN is different from the RTN generated by the charge traps (data not shown). Through the whole range of $V_{g} = -16$ to 16 V, the RTN was observable with no significant change in $\tau_{\text{high}}$ and $\tau_{\text{low}}$.

To investigate the temperature dependence of the RTN, the time-traces of current was studied fluctuation rate was nearly independent of temperature for $T < 20$ K. With a further increase of

![Figure 2](image_url)
temperature, the rate became faster and the magnitude of the current fluctuation became smaller until the fluctuation was finally smeared out at higher temperatures. Another two-level resistance-fluctuation sometimes appeared in other samples during the increase of temperature, thus exhibiting several two-level fluctuations acting at the same time. In that case, the frequency dependence of the noise became close to the $1/f$ spectrum.

What is the origin of this type of RTN? The exponential behavior of the characteristic lifetimes with the inverse $V_{ds}$ led us to suggest that the reversible defect motion between two metastable states is responsible for the noise switching mechanism, since similar exponential dependence has been found in metallic nanoconstrictions [14, 20-22]. In our another publication [11], after we analyzed the statistics and features of this type of RTN, we suggested that this noise was due to the random transition of defects between two metastable states, activated by inelastic scattering with quasi-ballistic electrons. The activation energy for this transition was evaluated from the bias-voltage dependence of the RTN, adopting the model used to describe RTN in metallic nanoconstrictions.

CONCLUSIONS

With an increasing interest in nanoelectronic devices based on carbon nanotubes, an understanding of their noise mechanism is of importance to improve the performance of such devices. By analyzing the features of the RTN observed in individual SWNTs, we suggest two different noise mechanisms for the SWNT related systems; The various charge traps in the vicinity of SWNTs, the reversible defect motions between two metastable states for the metallic SWNTs.

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