Noise in carbon nanotube field effect transistor

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Low frequency noise power spectrum density of carbon nanotubes is presented. It is shown that the input-referred noise of carbon nanotubes increases quadratically as gate voltage is overdriven, suggesting that mobility fluctuation is the dominant mechanism contributing to the noise in carbon nanotube field effect transistors. The comparison of source-drain current noise power spectrum densities of carbon nanotubes in air and in vacuum indicates that a part of device noise is due to charge fluctuations from attached air molecules. © *2006 American Institute of Physics.*
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Due to ultrasmall diameters and large surface to volume ratios, carbon nanotubes (CNTs) are very sensitive to their environments, including charges, vacuum levels, and environment chemical components. Giant random telegraph signals (RTSs), i.e., random current or conductance switchings as a function of time, were observed in carbon nanotube field effect transistors (CNT-FETs) for both Coulomb repulsive and Coulomb attractive defects.[1] The work pointed out that there is a large device noise due to single defect centers located close to carbon nanotube channels. Hence, it is critical to understand the noise performance of the carbon nanotube devices so as to obtain good signal to noise ratio for different kinds of carbon nanotube applications, such as FETs (Refs. 2 and 3) and chemical and biological sensors.[4]

CNT-FETs used in the study are similar to those we used before.[1] The transport of the CNT-FETs is in the diffusive limit due to the relatively large device length (4 μm). Noise power spectrum density (PSD) of the source-drain current is obtained using a dynamic signal analyzer (Agilent 35670A) after passing the current through a low noise operational amplifier. For clarity, all the noise results are from the same CNT-FET with a single single-walled carbon nanotube, and the experiments are done for more than 20 CNT-FET devices.

To eliminate the ambient effect, the measurement is firstly performed in a vacuum environment with a pressure of 18 mTorr. The noise PSD has $1/f^{\alpha}$ behavior over the frequency range of interest at different gate biases and source-drain biases. As an example, Fig. 1 shows the source-drain current noise PSD ($S_{I_{ds}}$) from a CNT-FET measured at V_g = −2 V and V_{ds} = −0.05, −0.1, −0.25, −0.5, and −1 V, respectively, giving an α from 1.05 to 1.2. The data are taken in three steps (from 0.125 to 25, from 25 to 800, and from 800 to 25.6 kHz) for each bias condition in order to cover the entire frequency range. The magnitude of the $1/f$ noise increases as I_{ds}^2 with source-drain current up to 0.2 μA shown in the inset of Fig. 1. This relation between PSD and current follows Hooge's law: $S_{I_{ds}} = (\gamma/N_{tot})(I_{ds}^2/f^{\alpha})$, where γ

is Hooge's parameter and N_{tot} is total number of carrier in the device.[5] This has been observed by Collins *et al.*[6] and Snow *et al.*[7] for both individual isolated nanotubes and thin films formed by many interconnected nanotubes.

Because of the pronounced low frequency noise in the CNT-FETs, it is important to understand the mechanism of the $1/f$ noise. At V_{ds} = −0.1 V, the CNT-FET works in the linear region in vacuum as shown in Fig. 2(a). The gate bias is selected so that the device operates at strong inversion, while at the same time transconductance remains almost constant as indicated from the I_{ds}-V_g relation plotted on the right side of Fig. 2(b). The triangle data points are the average of source-drain current measured right before and after noise measurements for each gate bias. The scattering of the data fits reasonably well with the I_{ds}-V_g relation measured after the noise measurements, showing that the device did not change its characteristic during the noise study. $S_{I_{ds}}$ is measured at f_1 = 40 Hz (solid green square dots) and f_2 = 640 Hz (open blue square dots) with the same bandwidth of 3.125 Hz. For each gate bias, the $S_{I_{ds}}$ is averaged within the measured frequency bandwidth for 401 data points, and the input-referred noise (S_{V_g}) is obtained by dividing $S_{I_{ds}}$ by the transconductance square (g_m^2) of the CNT-FET. The S_{V_g} of 640 Hz is multiplied by the ratio of two frequencies: f_2/f_1 = 16 times in order to plot at the same scale with that of 40 Hz as shown in Fig. 2(a). The results show that the S_{V_g} of 640 Hz overlaps to the S_{V_g} of 40 Hz for all V_g, confirming that the PSD is $1/f$ noise in the absence of visible single defect centers (RTS)[1] or shallow recombination defect centers[8] for the gate region we are interested in. The input-referred noise in the CNT-FET is orders of magnitude larger than that in a standard metal oxide semiconductor field effect transistor (MOSFET) with the same device size. It is known that the input-referred noise is almost constant over gate biases in MOSFETs if defects are uniformly distributed in their energies. This is because the number fluctuation of the channel carriers is the main mechanism contributing to the $1/f$ noise of MOSFETs.[9] However, as indicated in Fig. 2(b) the input-referred noise is quadratically proportional to the gate overdrive voltage (V_g-V_{th}) as plotted in the red solid curve, from which it is concluded that the CNT-FET noise is most likely due to mobility fluctuation in contrast with number

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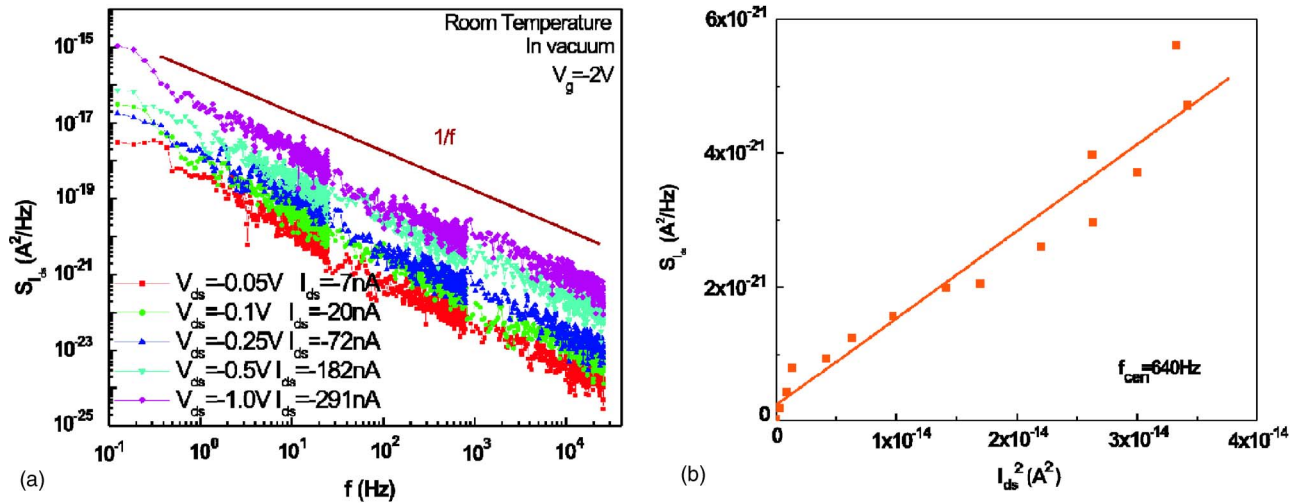
FIG. 1. (Color online) (a) Source-drain current noise power spectrum density ($S_{I_{ds}}$) for the frequency range of 0.125 Hz–25.6 kHz at different source-drain biases plotted in double log scale, showing $1/f^{\alpha}$ behavior with α from 1.05 to 1.2. (b) The $S_{I_{ds}}$ is linearly proportional to I_{ds}^2.

fluctuation as happens in most of conventional MOSFETs. In the narrow channel nanowire devices, the current fluctuations mainly come from mobility fluctuation: $\Delta I \propto N \Delta \mu$, where ΔI is the current fluctuation, $\Delta \mu$ is the mobility fluctuation due to the charged defect scatterings, and N is the total mobile carriers in the channel, which is linearly proportional to the gate overdrive voltage from standard MOSFET theory. Therefore, the noise power spectrum density is quadratically proportional to the gate overdrive voltage. The mobility fluctuation in CNT-FETs could be also understood physically. Using a simple classical model, the current fluctuation is $S_T = S_N + S_M + S_C$, where S_T, S_N, S_M, and S_C are the total PSD, the PSD due to number fluctuation, the PSD due to mobility fluctuation, and the cross term of number and mobility fluctuations, respectively. With the device width scaling down to $1/k$ ($k > 1$) of its original value W, $S_N \propto k$, while $S_M \propto (W - \lambda_{\text{eff}})/(W/k - \lambda_{\text{eff}})$, where λ_{eff} is the effective Coulomb length of a single charged defect. If the width of the channel is scaled to nanometers, comparable to λ_{eff}, the S_M increases much faster than k. Thus, the mobility fluctuation becomes the dominant mechanism for the noise in nar-

row channel nanotube devices. This is consistent with the random telegraph signal data observed in the similar CNT-FETs.[1] Hence, this could be the reason for the large Hooge's parameter in CNTs.[6] Furthermore, the carbon nanotube transistor is operated in the strong inversion region, where the Fermi level is pinned and the number of carriers transporting in the carbon nanotube is relatively large, which further weakens the noise contribution from number fluctuation. Another possible noise source for the CNT-FET is the noise from contact Schottky barrier regions.[10] However, our noise measurements from different samples with different gate stacks of various quality seem to suggest that the channel noise is still the dominant noise component in the CNT-FETs.

Moreover, the ambient effect is studied by comparing the noise PSDs in both vacuum and air.[11] The currents are measured for both the cases under the same bias conditions. It is shown that the current in air increases 1.6 times as compared to that in vacuum [Fig. 3(a)] at the source-drain bias of −0.1 V. This phenomenon has been observed and discussed by several groups. The enhanced current in air is
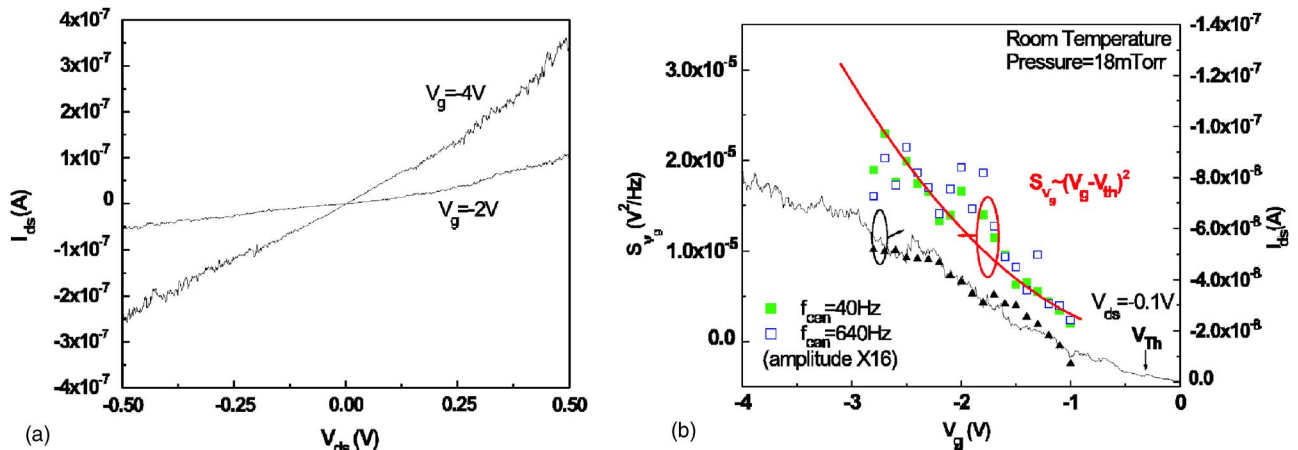

FIG. 2. (Color online) (a) I_{ds}-V_{ds} measured after the noise study, showing that the CNT-FET works in the linear region for $V_{ds} = -0.1$ V at the gate bias of interest. (b) The input-referred noise power spectrum density (S_{V_g}) of the CNT-FET measured at room temperature in vacuum with a pressure of 18 mTorr at center frequencies of 40 Hz and 640 Hz, respectively. The quadratical increase of the S_{V_g} as a function of gate overdrive voltage indicates that noise in CNT-FET is mainly due to mobility fluctuation. The black solid curve is the I_{ds}-V_g characteristic of the carbon nanotube. The solid triangle points are the average currents obtained before and after noise measurements at each gate bias. From the current characteristic, the device works in the strong inversion for a gate bias smaller than −1 V.
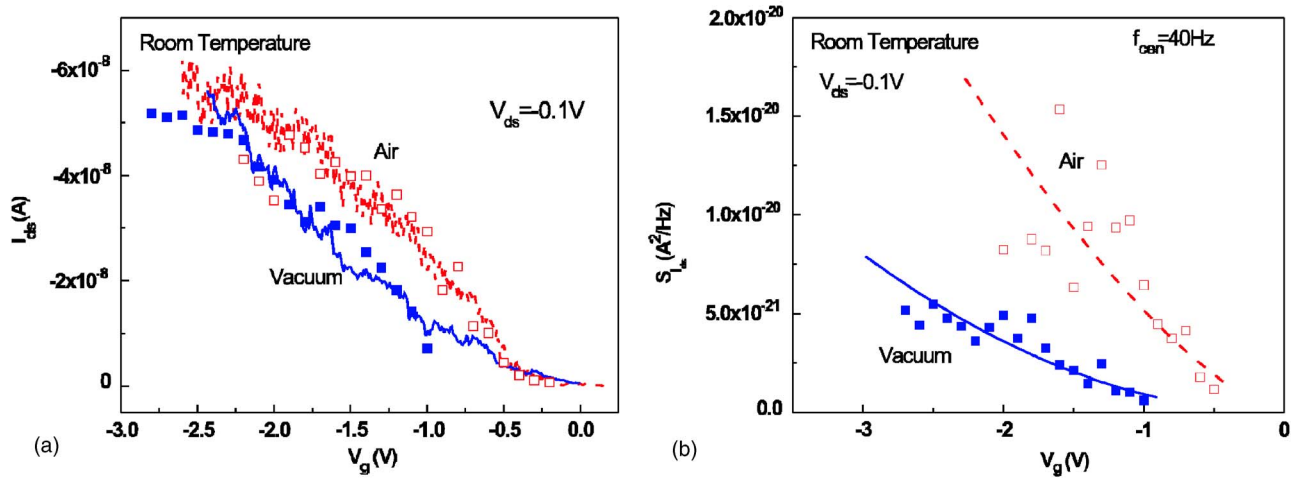
FIG. 3. (Color online) (a) Comparison of I_{ds}-V_g characteristics of the carbon nanotube in air and in vacuum. (b) Comparison of $S_{I_{ds}}$ characteristics of the carbon nanotube in air and in vacuum.

contributed either to the charged transfer[12] or to the change of Schottky barrier height[13] in the presence of oxygen in the ambient. Because $S_{I_{ds}}$ is proportional to I_{ds}^2, the current enhancement corresponds to the increase of $S_{I_{ds}}$ 2.56 times of that in vacuum at a gate bias of −1.2 V. Figure 3(b) plots the measured $S_{I_{ds}}$ for both cases. As shown in Fig. 3(b), the source-drain noise PSD increases quadratically with the gate overdrive voltage in air similar to that in vacuum; however, the amplitude of $S_{I_{ds}}$ in air increases 5 times of that in vacuum at $V_g = -1.2$ V. With the consideration of the current enhancement in air, the equivalent input-referred noise of the CNT-FET in air increases twice of that in vacuum. The pronounced noise in air may suggest that air molecules, such as O_2 and/or H_2O, attach to the carbon nanotube surface, acting as extra scattering centers for the carriers transporting in the nanotube. The suitable carbon nanotube passivation technique is highly necessary for high performance nanoelectronic devices.

In summary, carrier mobility in carbon nanotubes is very sensitive to the charge fluctuations from defects located at the carbon nanotube/oxide interface, inside the oxide, and/or attached air molecules. The pronounced fluctuations result in large $1/f$ noise. The mobility fluctuation is the dominant $1/f$ noise mechanism for the narrow channel carbon nanotubes operating in strong inversion region with a small source-drain bias.

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