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Noise characteristics of single-walled carbon nanotube network transistors

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Abstract
The noise characteristics of randomly networked single-walled carbon nanotubes grown directly by plasma enhanced chemical vapor deposition (PECVD) are studied with field effect transistors (FETs). Due to the geometrical complexity of nanotube networks in the channel area and the large number of tube–tube/tube–metal junctions, the inverse frequency, $1/f$, dependence of the noise shows a similar level to that of a single single-walled carbon nanotube transistor. Detailed analysis is performed with the parameters of number of mobile carriers and mobility in the different environment. This shows that the change in the number of mobile carriers resulting in the mobility change due to adsorption and desorption of gas molecules (mostly oxygen molecules) to the tube surface is a key factor in the $1/f$ noise level for carbon nanotube network transistors.

(Some figures in this article are in colour only in the electronic version)

Carbon nanotubes have been recognized as an excellent candidate for future electronic device applications, for example, field effect transistors [1], field emission displays [2, 3], and various types of sensor [4, 5]. Since, in general, understanding the noise properties of the given materials is very important for low noise electronic and sensor applications, many studies have been performed and reported that carbon nanotubes exhibit much worse low frequency ($1/f$) noise compared to the other materials with comparable resistance [6–8]. The much larger $1/f$ noise level was explained by the relative importance of fluctuations between individual atoms in nanometer-sized junctions, even though carbon nanotubes are expected to have the noise immunity of a covalently bonded system [6]. On the other hand, Lin *et al* reported that much higher $1/f$ noise resulted from the small number of mobile carriers in the channel of a single single-walled carbon nanotube (SWNT) in a transistor form [9]. Kingrey *et al* [10] studied the weak relationship between device noise and ambient environments that were filled with inert gases.

In this paper, we report the low frequency $1/f$ noise for a nanotube transistor whose channel is formed with randomly oriented and networked SWNTs. This work was motivated to understand the significant factors for noise modulation, and to compare the results with those of previous work on a single SWNT transistor.

The fabrication process of carbon nanotube (CNT) network transistors using SWNTs grown by the water assisted PECVD method is described elsewhere [11]. The low frequency $1/f$ noise was analyzed with a spectrum analyzer (HP3562A) under ambient air and vacuum ($\sim 10^{-6}$ Torr).

Figure 1 shows the typical current–voltage (I–V) characteristics of our SWNT network transistors measured under ambient air (○) and vacuum environment (+), where the ON/OFF ratios are $\sim 10^5$. The inset shows a scanning electron microscopy (SEM) image of SWNT networks in the channel part of the transistor. The transistor exhibits p-type and ambipolar characteristics under air (○) and vacuum (+), respectively. The p-type behavior of CNT transistors is attributed to the oxygen molecule adsorption resulting from either p-doping [12] or work function increase [13, 14]. Kang *et al* emphasized the p-doping effect on the nanotube channel by the oxygen adsorption as the electron trapping centers which are formed by the lowest unoccupied molecular orbital (LUMO) level of O_2 adsorbators [15]. These charge trapping

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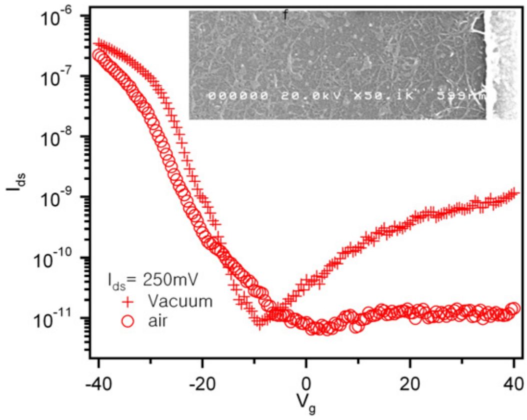

Figure 1. Gate voltage dependence of source and drain current (I_{ds}) at the voltage between source and drain ($V_{ds} = 250$ mV) measured under air (+) and vacuum (O), respectively. The inset is the SEM image of the SWNT network in the channel part.

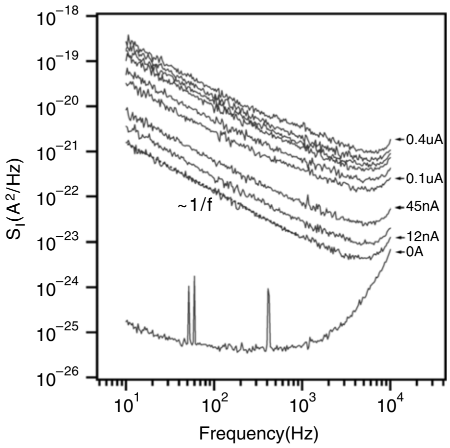

Figure 2. Frequency dependence of the noise density spectrum at various currents in the SWNT sample.

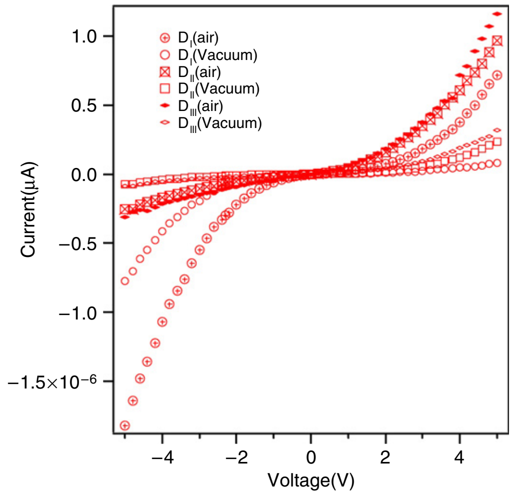

Figure 3. I_{ds} versus V_{ds} at zero gate bias measured under air (symbols filled with a dot at the center) and vacuum (empty symbols).

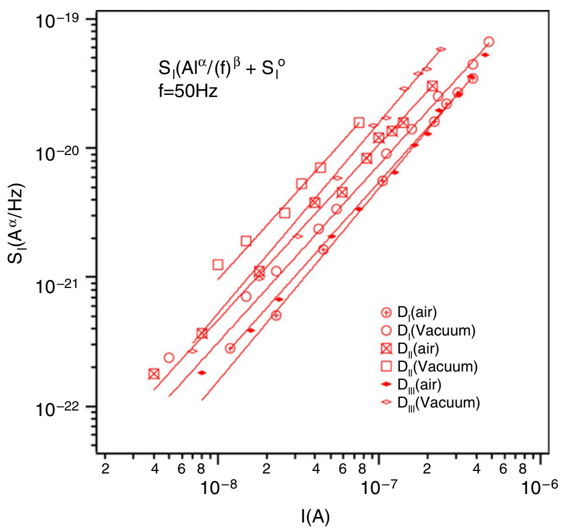

Figure 4. Current dependence of $1/f$ noise density, S_I, measured under air (symbols filled with a dot at the center) and vacuum (empty symbols).

centers could screen the electric field from the positively biased gate voltage, resulting in the suppression of electron channel formation.

Figure 2 shows a typical noise power spectrum ($S_I = \langle \Delta I^2 \rangle$) measured through the current range from 10 nA to 1 μA under ambient air by changing V_{ds} where the gate bias (V_g) remained zero. The background spectrum at the bottom of the figure is obtained at zero voltage bias ($V_{ds} = 0$); it is related to the frequency-independent white noise. It clearly shows a prominent $1/f$ dependence of S_I with increasing current. The power spectral density (S_I) varies as $1/f^{\beta}$, where β is close to unity within $\pm 10\%$.

Figure 3 shows the I–V dependence of three different transistors that were measured under air (empty symbols filled with a cross at the center, or solid symbol) and vacuum (empty symbols). An interesting observation is that the current levels of all transistors become lower by up to about an order of magnitude when they are exposed to a vacuum (10^{-6} Torr), without exception. Even though molecule adsorption under air results in either p-doping on the nanotube channels or a work function increase, we can simplify the transfer characteristics in ambient air by the dominance of the channel effect, since the sample configuration is specified by long channel length (2–10 μm) and long channel width (40 μm) with many nanotubes in the channel (nanotube density >50 tubes μm^{-2}). The excess carriers of electrons and holes are generated by tunneling through the source and drain junction with potential differences (V_{ds}). In air environment, the number of excess electrons is reduced because of capturing by the bound states between nanotube bands, which are mainly the LUMO states of the adsorbed oxygen molecules [10]. On the other hand, the number of excess electrons is unchanged in vacuum environment. We suggest that the current at a fixed potential in vacuum environment should be lower than in air environment after the recombination process of electrons and holes during the drift motions of carriers.

Figure 4 exhibits the current noise power (S_I) measured at 50 Hz as a function of current under air (empty symbols filled

Table 1. The noise amplitude and the exponent α obtained from the fitting to the Hooge's empirical formula. $D_{\rm I}$, $D_{\rm II}$ and $D_{\rm III}$ indicate the devices shown with the circle, square and triangle in figures 3 and 4.

	$D_{\rm I}$	$D_{\rm II}$	$D_{\rm III}$
$A_{\rm vac}/10^{-11}$	4.53	12.31	37.46
$A_{\rm air}/10^{-11}$	3.55	3.81	15.58
$\alpha_{\rm vac}$	1.38	1.39	1.51
$\alpha_{\rm air}$	1.40	1.36	1.48

with a cross at the center, or solid symbol) and vacuum (empty symbols) for three different transistors. These experimental data were fitted to Hooge's empirical formula [16], $S_{\rm I} = A/f^{\beta} \times I^{\alpha} + S_{\rm I}^{0}$, where A is inversely proportional to the total carrier number (N), i.e., $A = \alpha_{\rm H}/N$, where $\alpha_{\rm H} \approx 2 \times 10^{-3}$. The value of $S_{\rm I}^{0}$ is chosen from the background noise spectrum obtained at 50 Hz, with $V_{\rm ds} = 0$, as shown in figure 2. The fitting results are summarized in table 1. As shown in the first and second row, the $1/f$ noise amplitude (A) is enhanced after the SWNT network transistors are exposed to the high vacuum. The exponent α is generally taken to be 2, according to the literature for ordinary semiconducting and metallic materials [17, 18]. However, the value of α for the SWNT network transistors is seen to be 1.4–1.6, as shown in table 1. This is understood to be a result of Schottky barrier formation. (Note: the exponent α has been investigated with dependence on the contact barriers between multiwall carbon nanotubes and various metals [19].) This study shows that the exponent tends to be smaller than 2 when the contact is non-ohmic. This deviation from 2 has been suggested to be due to Schottky barrier formation between the nanotube and the source/drain metal electrode. The data in figure 4 show a noticeable change in the current dependence of the noise power ($S_{\rm I}$) under ambient air and vacuum. However, the exponent α exhibits no significant change under vacuum and air. This suggests that α is insensitive to the ambient environment change.

Generally, the noise amplitude (A) in semiconductor devices is known to be determined on the number of carriers in the device. Since the carrier number in the nanotube network FET should be much larger than that in single nanotube FETs, the noise amplitude (A) of the network FET is expected to be much smaller than that of single nanotube FETs. However, the noise amplitude (A) of the SWNT network transistors is comparable to or slightly lower than that of the isolated single SWNT transistor reported by Lin *et al* [9]. The comparable noise level in the SWNT network FET to that in the single tube FET could originate from the geometrical complexity in the channel area. Since the average length of the SWNTs in our device is less than 1 μm, and the channel length ranges from 2 to 10 μm with 40 μm of channel width, carriers should flow by percolation from one end to the other encountering tube–tube junction barriers. In addition, the SWNT network transistors have a large number of the Schottky barriers, in contrast to the single SWNT transistors. The large number of junction barriers and possible dangling bonds and loops [20] of the SWNT networks in the channel area of the transistors can significantly lower the output current. This lowered output current (reduced number of carriers) can be a reason for the comparable noise level in the carbon nanotube network FETs and single tube FETs. (Note: the nanotube density for our transistor is >50 tubes μm^{-2}, which is expected to be much denser than the percolation threshold [21].)

Single-walled carbon nanotubes are considered as a quasi-1D material because they are composed of only surfaces. Thus, in the semiconducting carbon nanotubes exposed to the ambient air, gas molecules adsorbed on the carbon nanotube surfaces can be expected to generate significant noise. Since gas molecules adsorbed on the nanotube surface may act as scattering centers for the carriers in the nanotube network, a significant reduction in $S_{\rm I}$ could be also expected after removing the adsorbed molecules under high vacuum. Contrary to our expectation, the noise density $S_{\rm I}$ still tends to be higher under vacuum, as shown in figure 4 and table 1. This result can be explained by the arguments provided for figure 3. The output current of nanotube network transistors ($V_{\rm g} = 0$) is observed to be lower under vacuum by about an order of magnitude in figure 3. This is suggested to originate from the electron–hole recombination in ambipolar characteristics under vacuum where the carrier numbers are much reduced compared to those in air. This lowered current under vacuum is a key factor to interpret the higher noise density ($S_{\rm I}$) rather than adsorbed molecules as noise generating scattering centers. From Hooge's relation with $\alpha = 1.5$ from our experimental data, and the net current, $I = \sigma E = (N_{\rm e} e\mu_{\rm e} - N_{\rm h} e\mu_{\rm h})E$ (where $N_{\rm e}$ and $N_{\rm h}$ are the number of electrons and holes, respectively, $\mu_{\rm e}$ and $\mu_{\rm h}$ the mobility of electrons and holes, respectively, E the electric field, and e the electronic charge), the noise density $S_{\rm I}$ is approximately proportional to $N^{0.5} \times \mu^{1.5}$. From this relation, both the carrier number (N) and mobility (μ) contribute to the noise density $S_{\rm I}$. The mobility term changes $S_{\rm I}$ faster than the carrier number. Thus, a larger $S_{\rm I}$ is expected in a vacuum environment since the mobility of carriers will be increased as the number of carriers is reduced due to the recombination process for the constant current. Moreover, the nanotubes may possess even higher mobility due to clean surfaces without adsorbed molecules. This will enhance the noise power $S_{\rm I}$.

The difference between the noise powers in vacuum and air has a wide range, 30–300%. But these differences are not so large compared to the variations in the noise powers for the different samples in the same environment. This indicates that the SWNT transistor is not sensitive to the ambient environment change. It should be also noted that Kingrey *et al* reported an opposite result with noise fluctuation of about one order of magnitude decrease from one single metallic nanotube device after degassing at 150 °C [10]. The opposite result may be due to a difference between semiconducting and metallic nanotubes.

In conclusion, the change in the number of mobile carriers is a key factor for the $1/f$ noise level for carbon nanotube network transistors. Due to the barrier junctions in the complex geometry of the SWNT networked structure, the noise level is of the same order of magnitude as that of an isolated single SWNT device.

We also investigated the noise characteristic under air and vacuum by using Hooge's empirical law. The noise power in the vacuum environment is higher than that in air. It is understood as resulting from the mobility increase by reduction of the carrier numbers for the constant current due to the electron–hole recombination process in the ambipolar transport. However, the difference in the noise power is not so large. This shows that tolerance of the low frequency noise for the ambient environment change is a good indication for nanotube electronics using the network forms.

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