Origins of $1/f$ noise in individual semiconducting carbon nanotube field-effect transistors

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The temperature dependence of $1/f$ noise in individual semiconducting carbon nanotube (CNT) field-effect transistors is used to estimate the distribution of activation energies of the fluctuators $D(E)$ responsible for the noise. $D(E)$ shows a rise at low energy with no characteristic energy scale, and a broad peak at $\sim$0.4 eV. The peak, responsible for the majority of noise at room temperature, cannot be due to electronic excitations, carrier number fluctuations, or structural fluctuations of the CNT, and likely results from the motion of defects in the dielectric or at the CNT-dielectric interface, or very strongly physisorbed species (binding energy $\sim$0.4 eV) on the CNT or dielectric surface.

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$1/f$ noise is a limiting factor in the use of transistors for sensing and integrated circuit applications. Various researchers have predicted both large and small amounts of $1/f$ noise in carbon nanotube (CNT) transistors.[1] From one point of view, the strong carbon-carbon bonds in a CNT should reduce the amount of ion motion, which is a suspected source of $1/f$ noise in other systems.[2] However, CNTs have the disadvantage of every atom being a surface atom, and are thus susceptible to the influence of adsorbates.[3] Additionally, due to the one-dimensional electronic structure of the CNT, a local defect must globally affect the current.

Previous reports have discussed the $1/f$ noise behavior in mats and bundles of CNTs,[4–9] but there is little literature on the behavior of field-effect transistors (FETs) made from individual semiconducting CNTs[10–13] which are particularly relevant for technological applications. Recent reports found that $1/f$ noise at room temperature had a magnitude close to that of conventional transistors, but had only speculation as to the source of the $1/f$ noise.[10–13] Here, we show that the $1/f$ noise in single CNT-FETs is strongly dependent on temperature between 1.2 and 300 K. We use the model of Dutta *et al.*[14] to extract the distribution of activation energies of the fluctuators $D(E)$, which shows two features: a rise at low energy with no characteristic energy scale, and a peak at energy of order 0.4 eV. The latter feature is responsible for the majority of noise at room temperature. The magnitude of the peak energy rules out physisorbed gas molecules with low binding energy, and electronic excitations or structural fluctuations of the CNT itself, as sources of room-temperature noise. The gate voltage dependence of the noise additionally rules out potential fluctuations resulting from charge trapping and detrapping in the gate dielectric. The likely sources of the noise are the motion of defects in the gate dielectric or at the CNT-dielectric interface, or possibly strongly physisorbed (binding energy $\sim$0.4 eV) species on the CNT or dielectric surface.

A useful way of parametrizing $1/f$ noise is Hooge's phenomenological law,

$$S_I = \frac{A\langle I\rangle^2}{f^{\beta}}, \quad A = \frac{\alpha(T)}{N}, \tag{1}$$

where S_I is the current noise power, $\langle I\rangle$ is the average current in the device, f is the frequency, A is the noise prefactor, N is the total number of charge carriers, β is a constant near unity, and $\alpha(T)$ is the temperature-dependent Hooge parameter.[15] That $S_I \propto \langle I\rangle^2$ indicates that the noise results from resistance fluctuations, not current-driven fluctuations.[2] The dependence of the noise on the reciprocal of the number of carriers in the sample is taken as evidence that the $1/f$ noise originates in the bulk rather than on the surface; since N scales with volume Ω, the noise power $S_I \propto 1/\Omega$. However, we note that in a one-dimensional system such as CNTs, N is proportional to the *length* of the system; no useful distinction can be made between the surface area and the volume, hence no distinction between surface and bulk origins of the noise can be made from the N dependence. Originally Hooge proposed the α parameter in his equations to be a universal constant for semiconducting systems with $\alpha(T=300\text{ K}) \approx 2\times10^{-3}$. Further work indicated that values far below this are possible and that $\alpha(T)$ can vary as a result of sample preparation, material, defect density, and other effects.[16] Here, we use Hooge's relation simply as an empirical rule for characterizing the magnitude of the noise by a single (temperature dependent) parameter $\alpha(T)$.

Previous work by our group was done to determine if the source of the noise was from the nanotube channel or the contacts.[10] Hooge's law assumes that the $1/f$ noise varies inversely with the number of carriers, but if the noise is due to the contacts, the relation will not hold. Our previous experiments showed that $\alpha(T=300\text{ K})$ is the same for nanotubes from 1 to 30 μm long, and indicate that the fluctuating resistance responsible for the $1/f$ noise is indeed from the length-dependent diffusive resistance of the nanotube channel, not the contact resistance.

Perfect $1/f$ noise (i.e., $\beta=1$) would require a perfectly flat spectrum of fluctuators $D(E)$ at all energies E. This is un-

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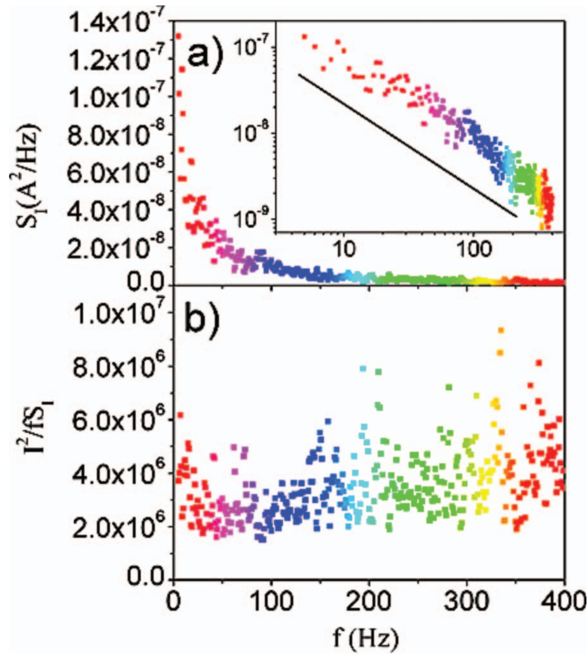

FIG. 1. (Color) (a) Spectrum of $1/f$ noise from a CNT FET at a bias voltage of 100 mV with each frequency point color coded, a gate voltage of −8 V, and a temperature of 150 K, shown on linear-linear scale (main panel) and log-log scale (inset). The color coding is consistent from Fig. 1 to Fig. 2 and allows the display of the frequency information in the next figure. The solid line in the inset indicates a slope of −1. (b) Presentation of the data to show the value of $1/A=(I^2/fS_{\rm I})$ at each frequency, as discussed in the text.

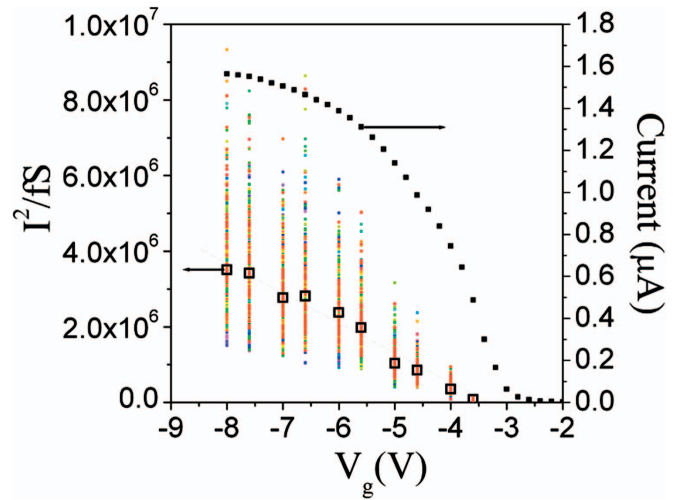

FIG. 2. (Color) Reciprocal of the noise prefactor $1/A=I^2/fS_{\rm I}$ (colored squares) and current (filled squares) versus gate voltage for device 1 at 150 K. Current data are taken with source-drain voltage of 100 mV. The $1/A$ data are color coded to indicate frequency as in Fig. 1. The open squares indicate the mean values of $\langle 1/A\rangle$ at each gate voltage, and the dotted line is a linear fit to these points. The standard deviation of the mean for these points is smaller than the size of the boxes used to indicate the mean value. Note that larger $1/A$ values correspond to less noise.

physical, so it is assumed that the spectrum of fluctuators is broad, but may have a well-defined characteristic energy.[2] Dutta *et al.*[14] derived the temperature dependence of $\alpha(T)$ for a nonuniform spectrum of fluctuators. In general, the temperature dependence of the Hooge parameter $\alpha(T)$ reflects the energy dependence of the spectrum of fluctuators. Assuming that the density of states $D(E)$ is smooth on the order of kT, the density of states will be

$$D(\tilde{E}) \propto \frac{\alpha(T)}{T}, \quad (2)$$

with $\tilde{E}=-k_BT\ln(2\pi f\tau_0)$, where k_B is Boltzmann's constant, T is the temperature, and τ_0 is a characteristic attempt time for the fluctuators, of order 10^{-14} s (i.e., inverse of a typical phonon frequency). The value of τ_0 may be different if the process is not controlled by a phonon process, but the energy depends only logarithmically on τ_0. Thus $-\ln(2\pi f\tau_0)$ is a factor of order 30 for f between 0.1 and 100 Hz. [Note that this factor also introduces a weak (logarithmic) dependence of $\alpha(T)$ on frequency; we ignore this.] Thus, measurement of the temperature dependence of the magnitude of the $1/f$ noise can be used to estimate the distribution of activation energies of the fluctuators responsible for the noise.[14,17] The exponent β also varies with temperature, but the deviation of β from unity is proportional to $-1/\ln(2\pi f\tau_0)$ and is therefore characteristically small and difficult to measure experimentally.

Our samples are made using chemical vapor deposition grown CNTs, and contain single nanotubes contacted by Pd/Nb leads.[18,19] The devices are above a layer of 400 nm of thermally grown SiO_2 with a heavily doped Si substrate to allow for backgating of the devices down to cryogenic temperatures. We present data from two devices taken in a gas flow helium cryostat, with temperatures ranging from 1.2 to 300 K. Device 1 has a diameter 1.4 nm, and device 2 has a diameter of 1.9 nm, as determined using atomic force microscopy. The devices each have a length of 3 μm.

First, we will look at data taken at a fixed temperature, $T=150$ K. Figure 1 shows a typical plot of the low-frequency noise we observe in our CNT-FETs. The data at each frequency are color coded so that the frequency information can be retained when the data are plotted against gate voltage. As can be seen in the inset, this is typical $1/f$ noise, with an exponent $\beta\approx 1$. Plots such as these are used to extract the prefactor A in Eq. (1) for each device as a function of gate voltage and temperature. By calculating I^2/fS_I, which by Hooge's law should be equal to $1/A$, at each frequency, we can determine a mean value $\langle 1/A\rangle$ over the spectrum of collected data. The entire spectrum of I^2/fS_I values can also be directly plotted versus gate voltage to depict how the noise varies as the number of carriers in the nanotube is varied. Noise data were taken for bias voltages ranging from several millivolts to 100 mV, and gate voltages ranging from −10 to 10 V. After fitting to a temperature-dependent $\alpha(T)$ and determining N as below, we find that our data are well described by Eq. (1) for different gate and voltage biases. Figure 2 shows the gate voltage dependence of the parameter $1/A$ for our CNT-FET.

Since we measure A, determination of $\alpha(T)$ requires that the charge-carrier number N be known [see Eq. (1)]. In our

devices, we determine the number of carriers by assuming that the device is in the linear regime. This gives the number of carriers to be linearly proportional to the gate voltage: $N=C_g|V_g-V_{\rm th}|/e$, where C_g is the capacitance of the CNT to the gate electrode, V_g the gate voltage, $V_{\rm th}$ the threshold voltage, and e the electron charge. The gate capacitance is determined by modeling the CNT as a wire over a two-dimensional plane: $C_g=2\pi\varepsilon\varepsilon_0 L/\ln(4h/d)$, where ε_0 is the dielectric constant, $\varepsilon=2.45$ is the average of the dielectric constants of vacuum and SiO_2, h is the dielectric thickness, L is the length of the tube, and d is the CNT diameter. The value of the Hooge parameter $\alpha(T)$ can then be determined from the slope of the $\langle 1/A\rangle$ versus V_g plot [Fig. 2(b)], which is equal to $C_g/e\alpha(T)$. We note that our extraction of $\alpha(T)$ is insensitive to changes in carrier number caused by, e.g., changes in the threshold voltage with temperature.

It should be noted that despite the nonlinear behavior of the current vs gate voltage, $\langle 1/A\rangle$ is linear in V_g, as seen in Fig. 2. This indicates that the noise power is indeed varying inversely with the number of carriers, and Hooge's law may be used. This is also strong evidence that the fluctuations are in mobility, not carrier number. Specifically, global fluctuations of the carrier number (caused by, e.g., fluctuations in gate voltage or thermal excitations of carriers) give a much stronger dependence of $1/A$ on V_g.[20] Thus, we can eliminate carrier number fluctuations due to potential fluctuations in the dielectric or elsewhere as a source of noise in our CNT devices, at least in the linear regime.

It is interesting that Hooge's phenomenological law appears to be obeyed despite the one-dimensional nature of the device (in which the carriers are strongly interacting). This also may indicate that the causes of the noise are similar to those in three-dimensional systems since the noise still scales with the number of carriers. We also note that the number of carriers is the only parameter of the CNT (besides the Fermi wavelength) that should vary linearly with gate voltage; for example, effective mass, Fermi velocity, Fermi energy, and mobility do not vary linearly.[21,22]

We note that we have used *all* the data from the noise spectra to determine $\alpha(T)$ according to the method above. The method assumes implicitly that $\beta=1$. However, β is predicted to vary slightly from unity for a nonconstant $D(E)$. We find that the choice of a particular frequency range does not significantly change the magnitude and temperature dependence of $\alpha(T)$. This can be seen in Figs. 1 and 2, where the color code indicates the frequency. It can be seen that the choice of frequency range does not affect the value of $1/A$ or the behavior of $1/A$ vs V_g; points of different colors (different frequency ranges) appear similarly distributed along the vertical axis.

Figure 3(a) shows the temperature dependence of the Hooge parameter $\alpha(T)$ for our two CNT-FETs, extracted from the slopes of graphs such as Fig. 2, taken at different temperatures. The room-temperature value $\alpha(T=300\text{ K})$ is approximately 10^{-3}. This indicates that semiconducting CNTs are not intrinsically noisier than many other semiconductor systems in terms of their $\alpha(T=300\text{ K})$ value. The high surface-area-to-volume ratio does not create an increase in the amount of $1/f$ noise, which is a first indication that physisorbed molecules are not the primary cause of $1/f$ noise in our devices. Figure 3(b) shows the distribution of activation energies of the fluctuators $D(E)$ extracted from $\alpha(T)$ using Eq. (2). $D(E)$ shows two features: a rise at low energy with no characteristic energy scale, and a broad peak at energy of order 0.4 eV.

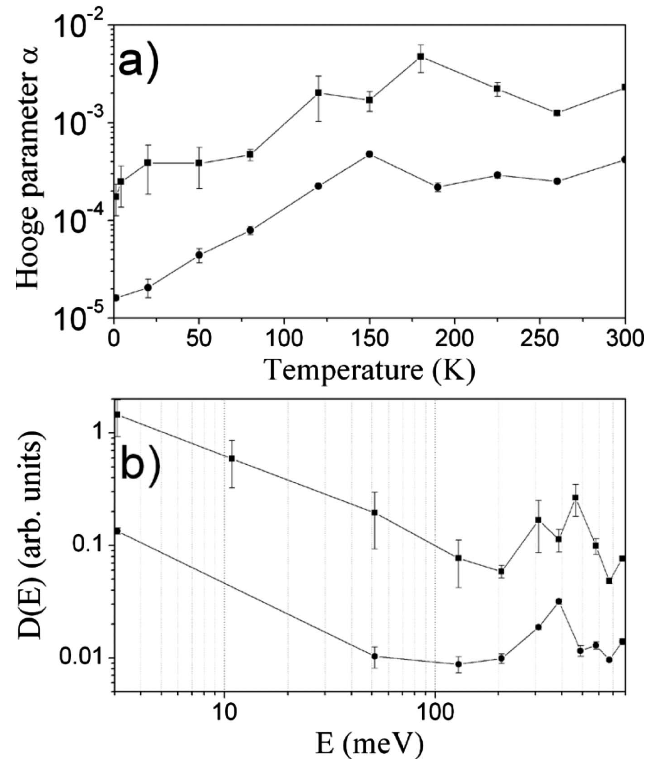

FIG. 3. (a) Temperature dependence of the Hooge parameter $\alpha(T)$ for both CNT devices. The data points are calculated using the slope from $\langle 1/A\rangle$ vs V_g, as shown in Fig. 2. The significant upward trend between 1.2 K and about 150 K is seen in both samples. (b) Distribution of activation energies of the fluctuators $D(E)$ responsible for $1/f$ noise, calculated as described in the text. Filled squares and circles correspond to device 1 and device 2, respectively, in both (a) and (b).

First, we discuss the peak in $D(E)$ at $E\sim 0.4$ eV. We argue that this feature, i.e., the broad peak that ranges from ~ 0.2 to 0.6 eV, is responsible for the majority of the room-temperature noise, as follows. The low-energy behavior of $D(E)\sim 1/E$ corresponds to an approximately temperature-independent Hooge parameter [see Eq. (2)]. Thus, the rise of the Hooge parameter by a factor of ~ 20 from low temperature to room temperature is due entirely to the broad peak in $D(E)$ around 0.4 eV. The characteristic energy scale allows us to rule out some possibilities for the source of the noise. The energy scale is comparable to the band gap (~ 0.5 and ~ 0.37 eV for devices 1 and 2, respectively) and, therefore, we can rule out electronic excitations (e.g., defect ionization, etc.) within the CNT itself as the major noise source; such mechanisms should have characteristic energies less than or equal to half the band gap. As discussed above, we also rule out carrier number fluctuations due to the motion of charged defects in the dielectric. Structural fluctuations of defects in

the CNT lattice itself are also ruled out, as they have very high characteristic energies ($\sim$10 eV for Stone-Wales defect formation).[23,24]

Unfortunately, the characteristic energy $\sim$0.4 eV does not provide enough information to completely pinpoint what is causing the noise. However, the fact that the noise magnitude is comparable to conventional metal-oxide-semiconductor field-effect transistors suggests that the noise may, in fact, result from similar processes in CNT-FETs, i.e., motion of, or change in charge state of, charged defects in the dielectric or at the dielectric/CNT (or dielectric/vacuum) interface.[10,12] Still, other processes, such as binding and unbinding of strongly physisorbed species, cannot be ruled out; the binding energies for CO_2 and H_2O, for example, lie in this range.[25] Though our measurements are carried out in helium gas with an extremely low partial pressure of atmospheric components, it is possible that previously adsorbed water is still present on the SiO_2 surface and could be responsible for the noise, though this would contradict the observation of *increased* room-temperature noise for CNT devices baked in ultrahigh vacuum versus ambient.[10]

In conclusion, we have measured the Hooge parameter $\alpha(T)$ at temperatures between 1.2 and 300 K. The room-temperature value $\alpha(T=300\text{ K})\sim 10^{-3}$ we observe is comparable to $\alpha(T=300\text{ K})$ found in traditional FETs, indicating that CNT-FETs are not afflicted by inherently large noise at room temperature. We use $\alpha(T)$ to estimate the distribution of activation energies of the fluctuators $D(E)$ responsible for the noise; $D(E)$ shows two features: a rise at low energy with no characteristic energy scale, and a broad peak at energy of order 0.4 eV. The latter feature is responsible for the room-temperature noise. We rule out electronic excitations and structural fluctuations within the CNT itself as the source of this feature. We conclude that fluctuations within, or at the surface of, the amorphous dielectric are likely responsible for the room-temperature $1/f$ noise in CNT-FETs on SiO_2, though some physisorbed species (e.g., H_2O and CO_2) have similar binding energies[25] and could be responsible for the room-temperature noise.

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