NANO LETTERS

2007
Vol. 7, No. 1
194−198

Low-Frequency Noise in Nanoscale Ballistic Transistors

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Received September 10, 2006; Revised Manuscript Received October 27, 2006

ABSTRACT

Low-frequency "1/*f*" noise is a major issue for nanoscale devices such at carbon nanotube transistors. We show that nanoscale ballistic transistors give voltage-dependent sensitivity to the intrinsic potential fluctuations from nearby charge traps. A distinctive dependence on gate voltage is predicted, without reference to the number of carriers. This dependence is confirmed by comparison with recent measurements of nanotube transistors. Possible ways of decreasing the noise are discussed.

Current trends in field-effect transistors (FETs) point clearly toward nanoscale and even ballistic devices. Carbon nanotube (CNT) transistors can already operate in the ballistic regime,[1] and the ubiquitous silicon MOS-FET is shrinking in this direction. However, as devices grow smaller, low-frequency electrical noise is expected to pose an increasing problem. Noise with approximately $1/f$ dependence on frequency f appears unavoidable, and its relative magnitude tends to scale inversely with system size.[2−4] Recently, several studies have reported extremely strong low-frequency noise in CNT-FETs.[5−8]

While $1/f$ noise has been studied extensively in many systems,[2−4] these have all been characterized by diffusive transport. Empirically, $1/f$ noise has been reported to scale as $1/N_c$ with the number N_c of carriers (electrons or holes) in a device or material.[2] Recent work confirms this behavior for long diffusive CNT-FETs.[8] This $1/N_c$ scaling has been reasonably attributed to the incoherent scattering in diffusive transport.[2,4] However, even the definition of N_c is unclear in many systems, and the microscopic understanding of the $1/N_c$ behavior remains unclear.[4] In any case, it is essential to understand how the noise characteristics change as we move toward nanoscale ballistic devices, and CNT-FETs are the best available test system.

Here we consider the noise in a *nanoscale ballistic* FET, and in particular a CNT-FET. We show that the current response to gate oxide charge fluctuations is greatly enhanced in the crucial subthreshold regime where the devices turn on and off. This voltage-dependent sensitivity to the intrinsic fluctuations is well approximated by a specific simple form. Comparison with recent measurements of Lin et al.[7] for "quasi-ballistic" CNT-FETs indicates that the predicted behavior is seen experimentally. Thus, for ballistic devices, it is possible to address important aspects of the noise in terms of well-understood device physics. The analysis provides insight into the source and scaling of the noise in CNT-FETs and has relevance for nanoscale FETs in general.

If the device is short compared to the inelastic (electron−phonon) scattering length, then it is described by a transmission factor for each quantum channel, rather than by a diffusive resistance. We refer to such transport as "ballistic", even if the transmission factor is $\ll 1$. Because CNTs have very long inelastic scattering lengths at low bias,[9] CNT-FETs can achieve this ballistic limit far more readily than Si devices.

It is well known that gate oxides contain "charge traps" with fluctuating charge state. The charge-state switching is thermally activated, with a range of activation energies,[6] leading automatically to a $1/f$ frequency spectrum.[3] The question to be addressed is how these fluctuations affect the current. This question has been discussed extensively,[2,4] but until now always in the context of diffusive devices.

For ballistic CNT-FETs, noise arises from modulation of the quantum transmission by the $1/f$ electrostatic fluctuations from charge traps in the gate oxide. The subthreshold noise can originate in either the contact or the channel, depending on the specific device type, and examples of both types are treated here. We find that for a ballistic device, the number of carriers N_c never appears in the analysis, and the predicted behavior is different than the familiar $1/N_c$ scaling.

Most CNT-FETs operate as Schottky barrier (SB) FETs, so we consider these devices first. In an ideal SB-FET, the current is limited primarily by a Schottky barrier at the contact. The gate voltage induces an electric field at the contact, which turns on the current by thinning the barrier and so allowing tunneling.[10−12] CNTs are particularly favorable for SB-FETs, because the very thin channel (1−2 nm) allows a very large field at the contact.[12]

10.1021/nl062141q CCC: $37.00
Published on Web 12/13/2006

The transmissivity of the Schottky barrier is a function of the electric field at the contact.[11,12] This field is proportional to the gate voltage V_g but also depends on oxide thickness and geometry. We can roughly scale out these factors to distinguish effects of device geometry from other factors, saying that the field is $\approx V_g/S_g$ at the contact, where the effects of device geometry are captured in a parameter S_g that is proportional to the subthreshold slope.[12] The fluctuating charges in the oxide induce an additional field $\gamma F(t)$, where F is a dimensionless noise function with approximately $1/f$ power spectrum and average value zero, and γ reflects the oxide quality (e.g., number of charge traps and their proximity to the contact).

At fixed drain bias, the current through the device (the drain current I_d) is a function primarily of the electric field at the contact, $I_d = I_d(V_g/S_g + \gamma F)$. Thus the fluctuations in the current are equivalent to those of an ideal device having noise in the applied gate voltage. The effective noisy gate voltage is $V_g + \gamma S_g F\,(t)$. Then, to first order in the noise

$$I_d = I_0(V_g) + \gamma S_g \frac{dI_d}{dV_g} F(t) \tag{1}$$

where I_0 is the time-average current. The value of this expression lies in the fact that dI_d/dV_g can be measured directly.

Current noise with $1/f^\nu$ character (with $\nu \approx 1$) is conventionally described by a parameter A, implicitly defined from the current "power spectrum" S_I by

$$S_I = A I_0^{\,2} f^{-\nu} \tag{2}$$

Then from eqs 1 and 2

$$A = \gamma^2 S_g^{\,2}\left(\frac{d\ln I_d}{dV_g}\right)^2 \tag{3}$$

$$= \gamma^2 \left(\frac{d\ln I_d}{d(V_g/S_g)}\right)^2 \tag{4}$$

The coefficient γ describes the intrinsic electrostatic fluctuations at the contact. These fluctuations are reflected in the output current with a factor $S_g^2\,(d\ln I_d/dV_g)^2$ The voltage dependence of the noise comes from the term $d\ln I_d/dV_g$, which is largest in the subthrehold regime where the device turns on. (The second form, eq 4, is included simply to show that a change in dI_d/dV_g due to oxide thickness or such does not correspondingly change the noise, since $dI_d/d(V_g/S_g)$ remains nearly unchanged.[12])

Note that the greater simplicity of the ballistic case allows us to actually derive the noise characteristics directly from a natural and accepted microscopic model and known device physics. It is well understood that charge traps exhibit $1/f$ behavior,[3] and we simply calculate their effect on current. Of course, several approximations are made in the derivation. If the traps are not too close, it is well justified to treat the electric field as weak and similar in form to that induced by the gate. Also, we neglect the dependence of trap characteristics on the gate and drain voltages.[6] Aside from a factor of 2, the result (eqs 3 and 4) is the same at low bias whether both contacts are identical, or one is ohmic.

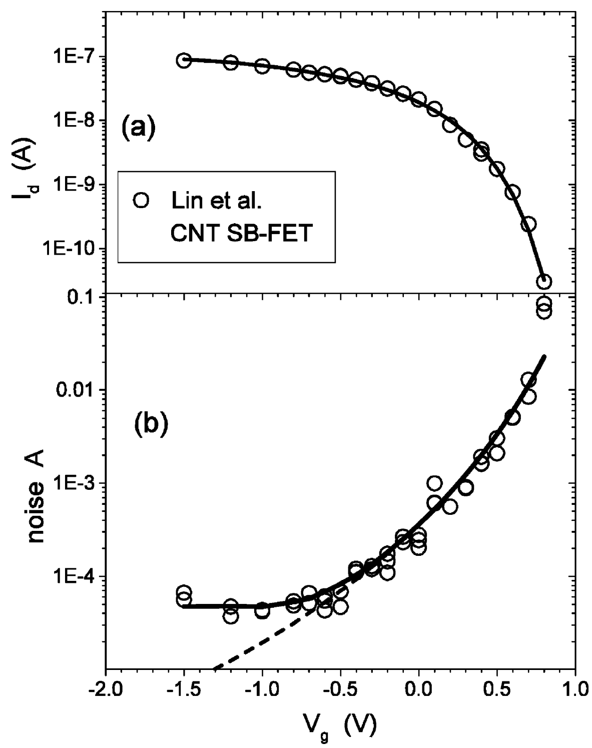

Figure 1. Comparison of theory with experiment (Lin et al.[7]) for noise in a CNT SB-FET. (a) Circles are measured current I_d vs V_g. Solid line is a smooth fit to allow differentiation. (b) Circles are measured noise A vs V_g. Dashed curve is eq 3, the predicted noise for a ballistic SB-FET; the coefficient giving the overall magnitude (a vertical shift on this log scale) is the only adjustable parameter. Solid curve is same prediction including additional scattering (modeled as a series resistor), eq 5, with the one additional parameter chosen to fit the noise in the high-current regime.

We can test this simple prediction directly against experiment. Lin et al.[7] reported measurements of current and noise vs V_g for a CNT-FET with a 600 nm channel in a back-gated geometry. They characterized the device as a "quasi-ballistic" SB-FET. (In that work, the current data were fitted with a ballistic model, and the noise data were interpreted in terms of a $1/N_c$ scaling. However, all explanations of $1/N_c$ scaling have been based on the diffusive character of the transport.[2,4])

A comparison between theory and experiment is shown in Figure 1. The measured current is fitted with a smooth function in Figure 1a. From this, the noise is calculated using eq 3. The only unknown factor is the overall magnitude, $\gamma^2 S_g^2$. Given the measured current, the dependence of noise on V_g (i.e., the slope in Figure 1b) is *predicted with no adjustable parameters.* As seen in Figure 1b (dashed line), the prediction is in striking agreement with experiment over 2 orders of magnitude in noise and 2 orders of magnitude in current in the crucial subthreshold regime, where noise is most problematic in devices. The fitted value of γS_g is 7 meV.

The prediction describes the measured noise less well in the "on" regime, where the current saturates. This is not surprising, since our analysis neglected any scattering in the channel, assuming that the SB was the sole factor limiting current. This is a good approximation when transmission through the SB is exponentially small. However, oxide charge fluctuations should also cause fluctuations in the transmissivity of the channel, even in a device that is perfectly ballistic (in the sense of having no inelastic scattering). In the "on" regime, the SB becomes more transparent, so scattering in the channel can no longer be neglected relative to the SB.

For a ballistic device, we can consider the contact and channel as two transmissivities in series. Expanding to linear order in the transmission (which is typically $\ll 1$ in CNT SB-FETs), and in V_d (so the device is linear), the effect of the channel is equivalent to adding a classical noisy resistance in series. (The correspondence between transmission and resistance is given by the usual Landauer formula.)

We therefore treat the channel as a classical resistor in series, with resistance R_c and noise A_c. This treatment should then also apply to a device where the channel is not ballistic. In either case the noisy series resistance will have some dependence on V_g, but we assume that any such dependence is weak compared to that of the SB, over the regime of interest. (Thus the analysis does not apply to very long devices, where the resistance and noise are dominated by the channel.[8])

Including this series resistor, the noise is

$$A = \frac{(\delta R_c)^2 + (\delta R_{SB})^2}{(R_c + R_{SB})^2}$$

where R_{SB} is the resistance of the Schottky barrier alone, δR_{SB} represents the fluctuation of R_{SB}, and R_c and δR_c are the classical series resistor and its fluctuation. The "ideal" SB-FET noise calculated with eq 3 corresponds to $A_{SB} = (\delta R_{SB})^2/(R_c + R_{SB})^2$ since the measured current already includes all resistances in the device. The total noise is then

$$\begin{aligned} A &= A_{SB} + A_c\left(\frac{R_c}{R_{tot}}\right)^2 \\ &= \gamma^2 S_g^{\,2}\left(\frac{\mathrm{d}\ln I_d}{\mathrm{d}V_g}\right)^2 + \alpha_c I_d^{\,2} \qquad (5) \end{aligned}$$

where $\alpha_c = A_c(R_c/V_d)^2$ and $A_c = (\delta R_c)^2/R_c^2$ is the noise parameter of the classical resistor alone.

Returning to the measured data in Figure 1b, we keep the original parameter $\gamma^2 S_g^2$ fixed. Including the one new parameter α_c, eq 5 fits the data well over the entire range. Moreover, this analysis allows us to separate two distinct contributions to the noise. In the crucial subthreshold regime, the noise in a ballistic CNT SB-FET comes almost entirely from the contact. However, the noise does not reflect any fluctuation of the contact itself, but only of the electric field at the contact. On the other hand, in the "on" state of the device, the noise may be dominated by the channel. We expect that, if the channel length is reduced, R_c and α_c will be reduced. Then the noise in the "on" state will be decreased, and the range of validity of eq 3 will extend to larger I_d.

The same treatment may be applied to a more conventional channel-limited CNT-FET,[1] if the transport is ballistic. In the subthreshold regime, the channel represents a barrier too thick for any tunneling, and current arises from thermionic emission over the top of this barrier. The fluctuating charge traps give a potential that varies both with time and with position along the tube. If the length scale of the fluctuations is long (as for a charge not too near the CNT), then tunneling remains unimportant, and transport is limited by the maximum potential along the channel. If this maximum exhibits $1/f$ fluctuations, then the analysis carriers over, but γ now represents the fluctuation of the maximum potential along the channel. This picture is highly simplified, but it suggests that in the subthreshold regime the effect of potential fluctuations along the tube can still be described by an effective fluctuation of V_g.

In CNT-FETs, it is difficult to achieve a strictly channel-limited regime in practice, except in tubes much too long to be ballistic. The resistance from the Schottky barrier at the contact is always substantial, except in tubes where the band gap is smaller than desired for room-temperature devices.[1] To study the channel-limited case, ref 7 applied a strong bias to the back gate. This reduces the contact resistance, and effectively converts the nanotube into a doped wire. The current is modulated by a separate Al gate 40 nm wide. This provides a good test of the generality of eqs 3 and 5.

The experimental results are compared with our model in Figure 2. As before, the dashed line shows the fit with eq 3, where the only adjustable parameter is the overall magnitude of the noise. The prediction describes the data well in the subthreshold regime. The fitted value of γS_g is 12 meV.

As the device turns on, the transmissivity is no longer determined primarily by the highest barrier in the channel. The contacts, as well as the rest of the channel, may be important sources of resistance and noise in this regime. Again, we can approximate this as a noisy resistance in series. Then, as for the SB-FET, eq 5 fits the data well over the entire range. By analogy with Figure 1, we expect that reducing the voltage on the back gate should increase both the resistance and the noisiness of the contacts, reducing the current and increasing the noise of the FET. This is exactly what is seen experimentally.[7]

The channel-limited case also provides in principle a clean test for distinguishing between the prediction here and the more familiar $1/N_c$ scaling. In the subthreshold regime, N_c depends exponentially on V_g, and so does current I_d, whether the device is ballistic or diffusive. Thus if the noise scales as $1/N_c$, it varies exponentially with V_g, but if it obeys eq 3, the noise approaches a constant value.

Discrepancies between predicted and measured behavior could originate from limitations in either the model or the experiment. Therefore, to have a convincing test, it is important that the ballistic character of the device be

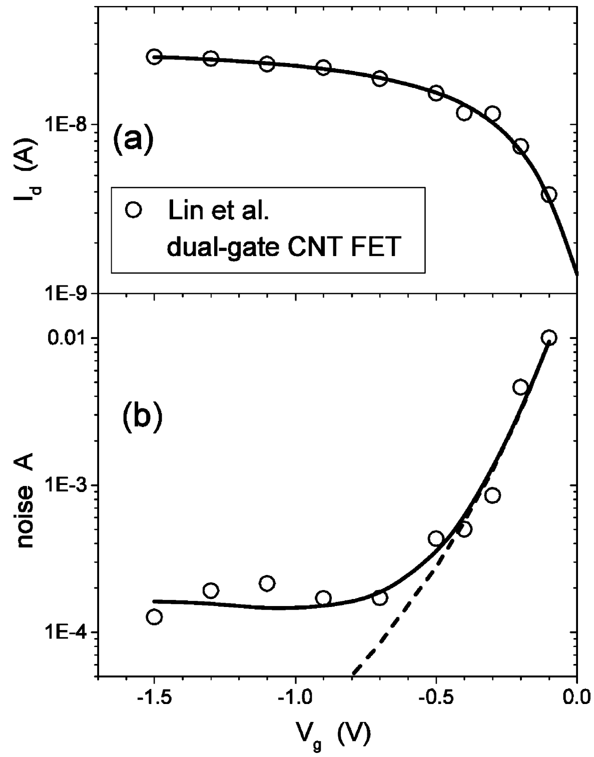

Figure 2. Comparison of theory with experiment (Lin et al.[7]) for noise in a channel-switched CNT FET, where the SB contacts are biased by independent gates at a fixed voltage of −2.5 V to reduce their resistance. (a) Circles are measured current I_d vs V_g. Solid line is smooth fit to allow differentiation. (b) Circles are measured noise A vs V_g. Dashed and solid curves are eqs 3 and eq 5, as in Figure 1.

confirmed experimentally. Similarly, for the Schottky barrier case, it is important to establish that the current is indeed controlled by the barrier and not the channel. A true SB-FET is most readily obtained for a narrow tube, where the band gap and barrier are large. Such tubes are also superior for comparison purposes, in reducing the problem of drain injection in the subthreshold regime for both types of devices.[13,14]

We now turn from the specific device characteristics, to consider some more general features of noise in nanoscale ballistic transistors in the light of these results.

Number of Channels: For a device having N_{ch} equivalent quantum channels, if the noise in different channels is uncorrelated, the total noise A is reduced by a factor of N_{ch} relative to a single such channel. A CNT at low bias has four channels—two spins in each of two degenerate bands. However, the analysis here suggests that, rather than being uncorrelated, these channels would be identically modulated by the fluctuating potential. Thus the noise should be the same as for any single channel alone. (However, if the fluctuating potential has a symmetry that affects different channels independently, then the noise would be reduced.)

Number of Carriers: In discussions of diffusive devices, the number of carriers N_c plays a central role.[2] This is logical if the scattering of different carriers is uncorrelated, giving $1/N_c$ scaling of the noise. However, the number of carriers never appears in our analysis of a ballistic device. All carriers in a channel see the same fluctuating barrier, so there is no addition of uncorrelated fluctuations to reduce the noise.[15]

Nanoscale Device Size: As the lateral dimension of the device shrinks, so does the number of channels. As the length of the device shrinks below the inelastic mean free path, the device becomes ballistic. Thus, sufficiently small devices will almost inevitably have noise described by the fluctuating transmissivity of a few ballistic quantum channels, as here.

Proximity of Fluctuating Charges: If the noise is due to fluctuating charges in the gate oxide, then obviously the closer these charges are to the channel, the larger is γ in eq 1, so the larger the noise. A device which is extremely narrow in both transverse directions, such as a CNT, is particularly susceptible—a single charge can be within ~2 nm of every point across a cross section of the device. Thus, under some conditions, a single fluctuating charge can cause large fractional changes in the current.[6,16]

In this respect, CNT-FETs may have a disadvantage compared with nanoscale Si FETs. At a Si−SiO_2 interface, each atom can have nearly its ideal bonding geometry,[17] so the density of charge traps can be extremely low at the interface. In contrast, the CNT is chemically inert, so immediately adjacent to the CNT is an unpassivated SiO_2 surface, which is more susceptible to formation of charge traps. In addition, exploratory CNT devices generally use oxides of relatively poor quality, compared with commercial Si MOS-FETs.

What is to be done? An effective strategy for noise reduction must take into account the particular properties of these novel nanoscale devices. (1) For a ballistic SB-FET, the dielectric constant of the gate oxide is not important for the device operation.[12] Therefore, one may choose the dielectric based on its noise properties (with particular attention to surface passivation) regardless of dielectric constant. Vacuum would be the ideal gate dielectric, if it could be made practical. (2) For a ballistic SB-FET, only charge fluctuations near the contact are important in the crucial subthreshold regime; so one should focus on controlling the noise sources in that region especially. (3) Because CNTs are so narrow, the device spacing and total capacitance are typically controlled by the size of the metal electrodes and their parasitic capacitance. Thus, one could in principle have N identical CNTs in parallel between a single source and drain electrode, sufficiently separated that their noise is virtually uncorrelated, without increasing the device spacing or capacitance. This would reduce the noise by a factor N. It would also increase the current by a factor of N, while leaving the (mainly parasitic) capacitance nearly unchanged, thereby increasing the switching speed of the device.

In conclusion, we find that the low-frequency noise in nanoscale ballistic transistors can be understood in terms of the basic device physics. This sheds light on the origin and scaling of the noise and on the steps needed to reduce the noise in future devices.

Acknowledgment. It is a pleasure to acknowledge Yu-Ming Lin for providing data of ref 7 prior to publication and Yu-Ming Lin and Stefan Heinze for valuable discussions.

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NL062141Q