Listening to Molecular Diffusion and Adsorption using Nanotube Field Effect Transistors

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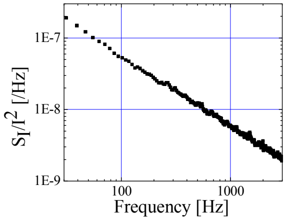
We have measured the 1/f noise in individual semiconducting carbon nanotubes (s-CNT) in a field-effect transistor configuration in ultra-high vacuum. The amplitude of the normalized current spectral noise density is independent of source-drain current, and inversely proportional to gate voltage, to channel length and therefore to carrier number, indicating the noise is due to mobility rather than number fluctuations. Hooge's constant for s-CNT is found to be (9.3±0.4)×10^{-3}. The magnitude of the 1/f noise is found to be highly environmentally-dependent and is substantially decreased by exposing the devices to air.

We are currently in process of understanding how electronic noise in nanotubes (which can be up to 5% of total current in gas sensing applications) is influenced by molecular diffusion and adsorption on carbon nanotubes. Such studies will be used to develop highly sensitive nanoscale chemical sensors with chemical specificity.

Why care about 1/f noise?

1/f noise: Hooge's Empirical Rule

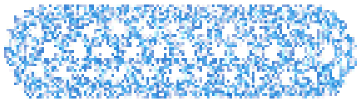


$$\frac{S_I}{I^2} = \frac{\alpha}{N} \times \frac{1}{f}$$

α = 0.002 for most materials
N : total number of carriers

F. N. Hooge, IEEE Tran. On Elect. Dev. 41 1926 (1994)

1/f Noise in Nanotubes



Many unanswered questions:

- Origin of 1/f noise: surface or bulk?
- Effects of dimensional confinement
- No FET measured: Gate dependence?
- Magnitude?

The amplitude of the 1/f noise usually follows the Hooge's empirical rule for most materials. Within this empirical rule, the noise amplitude is inversely proportional to the total number of carriers, N. Thus, the empirical rule has enormous consequences for nanoscale electronics in which N is vanishingly small.

The transistor configuration is useful in determining the direct dependence of the noise on N (linearly varied by the gate electrode). The quantitative understanding of the noise amplitude is crucial for nanoscale electrical engineering. Furthermore, determining effects of dimensional confinement and the origin of the 1/f noise has a fundamental significance. However, there are no previous measurements of noise in nanotube transistors.

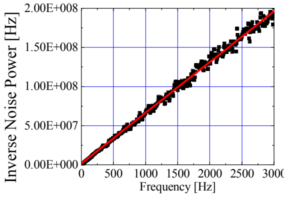
Our Devices

- Nanotubes grown using chemical vapor deposition
- Two probe configuration with channel lengths of 1.6 to 28 µm
- Contact resistance improved using H_2/Ar annealing at 400 °C

- Annealed at 200°C in UHV prior to measurements
- Measurements performed in UHV

Our experiment is performed in ultra high vacuum (UHV) at pressures of less than 5×10^{-10} torr.

Noise Characteristics of Nanotube Devices



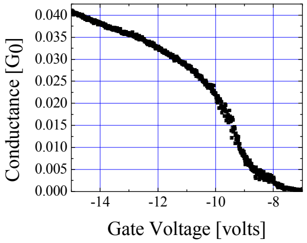
$$\frac{S_I}{I^2} = \frac{A}{f}$$

In the above figure, inverse of noise power is plotted to show that the noise spectrum is indeed 1/f. Strictly linear fit is applied to inverse noise power to obtain A.

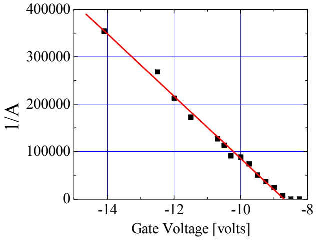
Gate Dependence of 1/A

$$\frac{1}{A} = \frac{N}{\alpha} = \frac{1}{\alpha}\frac{C_g}{e}\left|V_g - V_{th}\right| = D\left|V_g - V_{th}\right|$$

Transfer Curve



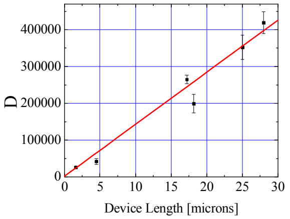
Dependence of 1/A on gate voltage



If Hooge's empirical rule applies to nanotube transistors, 1/A is expected to depend linearly on the applied gate voltage. This is indeed what we find. The figures above show the transfer curve and the dependence of 1/A on the gate voltage for a representative nanotube device. We denote the slope of the linear fit to 1/A as D.

Length Scaling of 1/f Noise

Dependence of the slope of 1/A on the device length



$$D = \frac{1}{\alpha}\frac{C_g}{e}$$

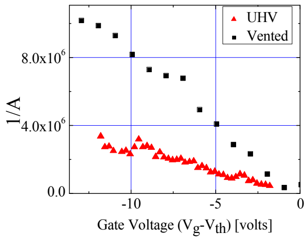
$$C_g = \frac{2\pi\varepsilon_0\varepsilon_{ave}L}{\ln\left(\frac{2z}{d}\right)}$$

- **α = (9.3±0.4)×10^{-3}**

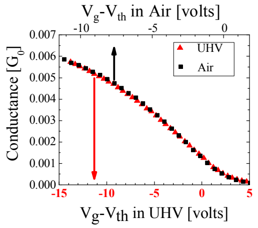
We find that D, which is the slope of the dependence of 1/A on the gate voltage, is linearly dependent on the device length. The above figure represents noise measurements performed on nanotube devices with 1.2~1.8nm diameter and 2~28µm in length. The gate capacitance is linearly-dependent on the length and weakly-dependent on the device diameter. Therefore, D is expected to be linear if the noise generating process is same for all of the devices measured. We determine universal α for nanotube devices by fitting the above formula for D to the data.

Effect of Exposure to Air

Change in Noise Spectra



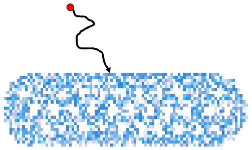
Change in Transfer Curve

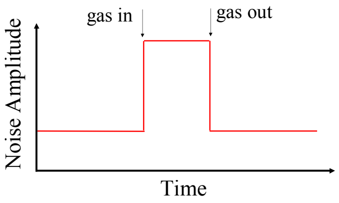


- Devices apparently **quieter in air by a factor of 2~4**
- Not fully accounted for by change in the device capacitance

Noise in nanotube devices decreases upon exposure to air. The mechanism for the apparent silencing of electronic noise in air is unclear. The change in device capacitance suggested by the change in the transfer curves shown above is not sufficient to fully account for this silencing effect.

Ongoing work: utilizing electronic noise to listen to molecular diffusion and adsorption





- Sensing with chemical specificity: correlate adsorbate with noise
- Monitoring nanoscale molecular activity: correlate molecular diffusion with noise

Electronic noise from adsorbates is expected to be dependent on molecular specific parameters such as the diffusion coefficient and the strength of chemical interaction. We aim to use molecule-specific noise as another detection channel along with other device characteristics such as transconductance and threshold voltages to develop nanoscale sensors with chemical specificity. We will also incorporate the nanotube FETs into flexible substrates to develop wearable nanoscale sensors.