

Signal-to-Noise Ratio in Carbon Nanotube Electro-mechanical Piezoresistive Sensors

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Noise measurements of SGS-CNFET #2

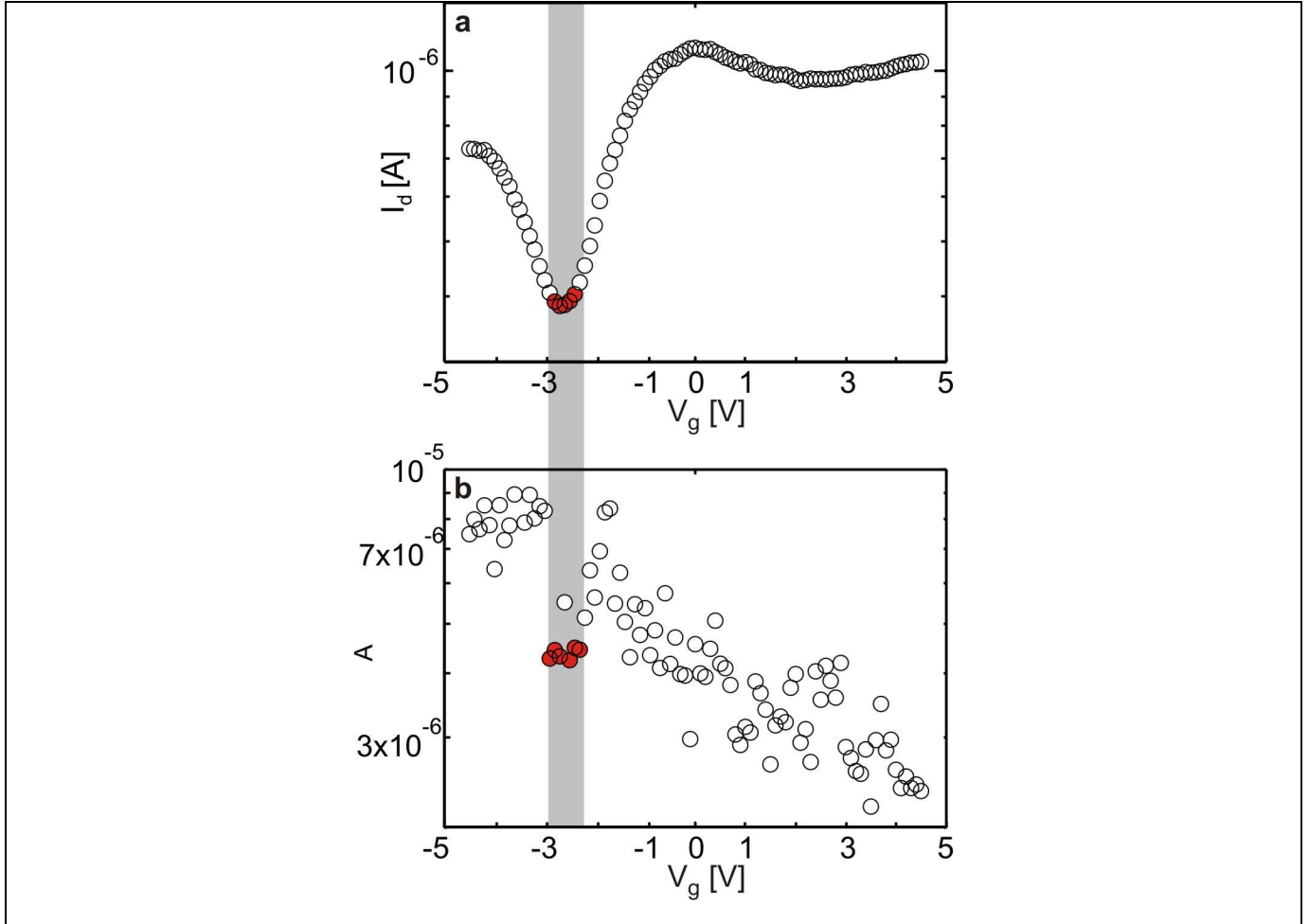


Figure S1: Low frequency $1/f$ noise of SGS-CNFET #2 (a) Gate characteristic of SGS-CNFET #2 measured from $V_g = -4.5$ V to $+4.5$ V. (b) Extracted low frequency noise amplitudes $A(V_g)$. A is minimum in the device on-state and at I_{\min} and largest at maximum transconductance.

Distinct noise spectra of SGS-CNFET #1

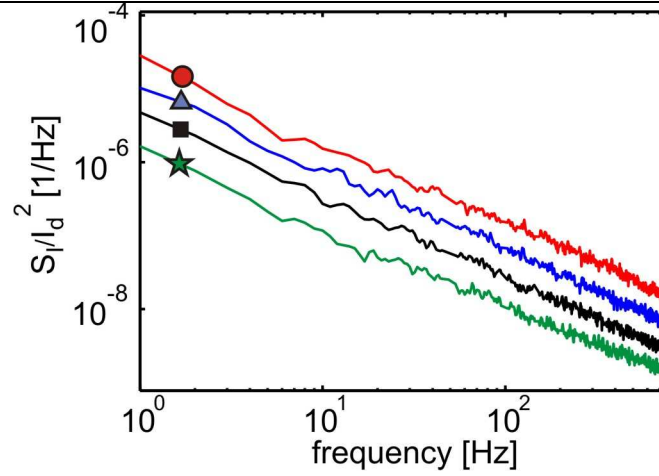


Figure S2: Four noise spectra in the frequency range $f \in [1, 800]$ Hz recorded at different V_g . The

spectra belong to the subthreshold region of this SGS-CNFET (black square, blue triangle, red circle) and to the on-state of the SGS-CNFET (green star) (as marked in Figure 3a in the main text). The low frequency noise spectrum measured at the minimum current (black square) is clearly below the noise spectra in the region where the device transconductance, g_m , is large (blue triangle, red circle).

Noise measurements of SGS-CNFETs under strain

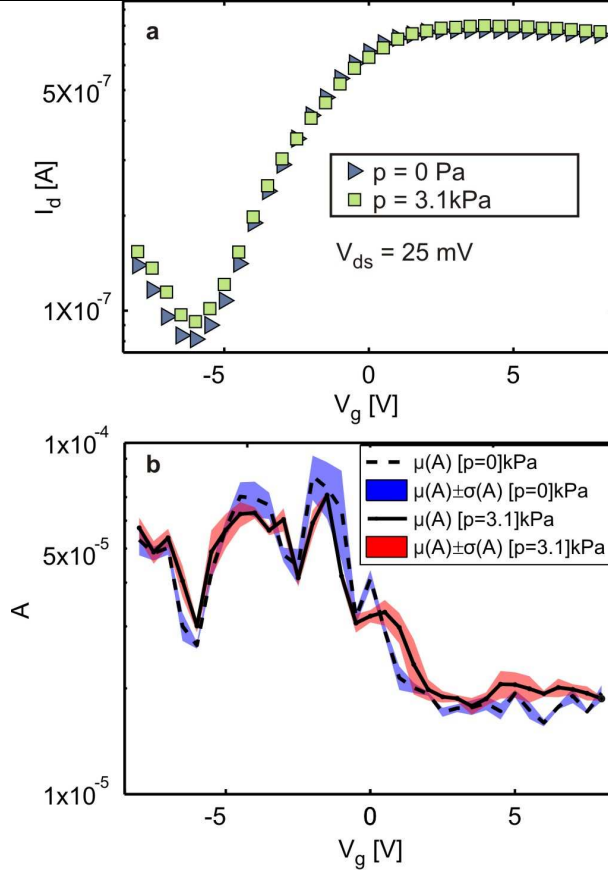


Figure S3: Low frequency noise measured with and without strain applied to the CNFET. (a) I_d - V_g characteristics at $p = 0$ Pa and $p = 3.1$ kPa. I_d is increased under pressure around I_{\min} (i.e. $GF < 0$). (b) Summary of six $A(V_g)$ measurement runs out of which three runs are recorded at $p = 0$ Pa and three at $p = 3.1$ kPa. Black lines indicate mean values of $A(V_g)$ (over three measurements) and the outer line of the blue and red shaded areas are standard deviations. Quantitative similar $A(V_g)$ results with and without strain indicate negligible sensitivity of low frequency noise in SGS-CNFETs to small strain.

A comparison of low frequency noise measured with and without strain applied to a SGS-CNFET is shown in Figure S3. The results are obtained from noise measurements on a CNFET that is contacted on a diaphragm with a radius $r = 350$ μm , therefore the applied pressure of $p = 3.1$ kPa is large enough to strain the CNFET moderately. In the experiment, the gate voltage dependent noise amplitude, A , is acquired six times. Three noise measurements are made at $p = 0$ Pa and three at $p = 3.1$ kPa. Figure S3a

shows typical I_d - V_g characteristics of the SGS-CNFET acquired simultaneously with the noise amplitude at $p = 0$ Pa (blue triangles) and $p = 3.1$ kPa (green squares). An increase of I_d around I_{min} is observed when the membrane is under pressure, which identifies the GF of the SGS-CNFET as negative. The noise amplitudes of the SGS-CNFET are shown in Figure S3 b. The black dashed and solid lines indicate mean value of A over the three corresponding measurements under $p = 0$ Pa and $p = 3.1$ kPa, respectively. The standard deviations are indicated by the outer line of the blue and red shaded areas. A qualitative comparison of the noise amplitudes versus V_g with and without applied strain to the CNFET yields very similar $A(V_g)$ characteristics. Quantitatively small differences are observed which are however minute compared to the overall V_g dependency of A and are as such expected not to significantly influence the SNR analysis performed thus far.

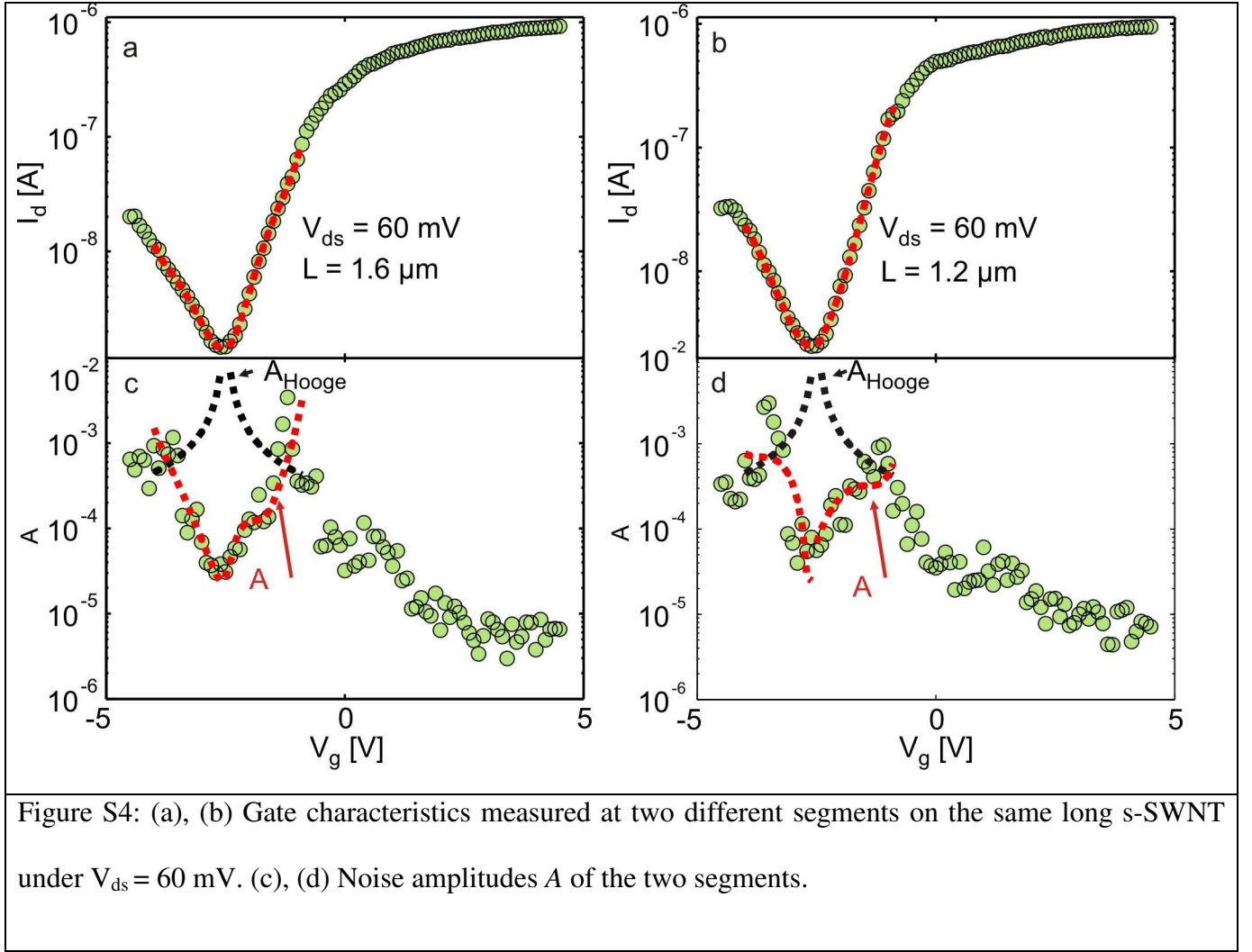


Figure S4: (a), (b) Gate characteristics measured at two different segments on the same long s-SWNT under $V_{ds} = 60$ mV. (c), (d) Noise amplitudes A of the two segments.

The gate characteristics shown in Figure S4a and S4b are from two different segments on the same SWNT with length $L_1 = 1.6 \mu\text{m}$ and $L_2 = 1.2 \mu\text{m}$, respectively. Asymmetric ambipolar gate characteristics are observed for both segments, with I_{\min} at $V_g = -2.5$ V, and with an on/off ratio $\sim 10^3$ under a bias $V_{ds} = 60$ mV. The n-type on-state is reached at $V_g = 0$ V whereas the p-type on-state is not reached for a gate voltage range and sweep direction from $V_g = -5$ V to 5 V. Both gate characteristics are very similar which leads to the conclusion that it is indeed the intrinsic characteristics of the SWNT that are being measured. The acquired noise amplitudes, $A_{1.6}$ and $A_{1.2}$, shown in Figure S4c and S4d are now compared, starting with the n-type on-state. Both noise amplitudes start around $A \sim 10^{-5}$ at $V_g = 5$ V which increases to around $A = 7 \cdot 10^{-5}$ at the onset of the subthreshold region $V_g = 0$ V. Then, A sharply

increases to $A \sim 10^{-2}$ - 10^{-3} when V_g is changed from $V_g = 0$ V towards V_g , where the gate characteristics features the maximum transconductance slope, g_m . From that point onwards A is reduced to $A = 2\text{-}4 \cdot 10^{-5}$ at I_{\min} , which is followed by an increase to $A = 10^{-3}$ at the maximum slope on the p-side of the CNFET characteristics. These results demonstrate, that qualitatively the noise amplitudes, $A_{1.6}$ and $A_{1.2}$, measured on the same SWNT at different segments exhibit the same V_g dependency. Quantitatively, both segments obtain the maxima and minima of the noise amplitude at the same absolute V_g . The exact magnitude of $A(V_g)$ exhibit small differences between the two segments. The differences are, however, smaller than the scattering of the data. Both segments shown in Figure S4c and S4d exhibit minima and maxima at the same V_g and at the same characteristic features of the I_d - V_g curve. This result is obtained when both segments are measured under the same sweep direction. Hysteresis, which is always present in CNFETs, moves the characteristic features on the V_g axis, when the I_d - V_g curve is measured in the opposite sweep direction. The size of the hysteresis is dependent on the sweep rate and on $V_{g\max}^{1-3}$. The sweep rate of noise measurements is very low, because it takes approximately 3-5 min to capture one spectrum at a single V_g value. Consequently, the hysteresis is very large.

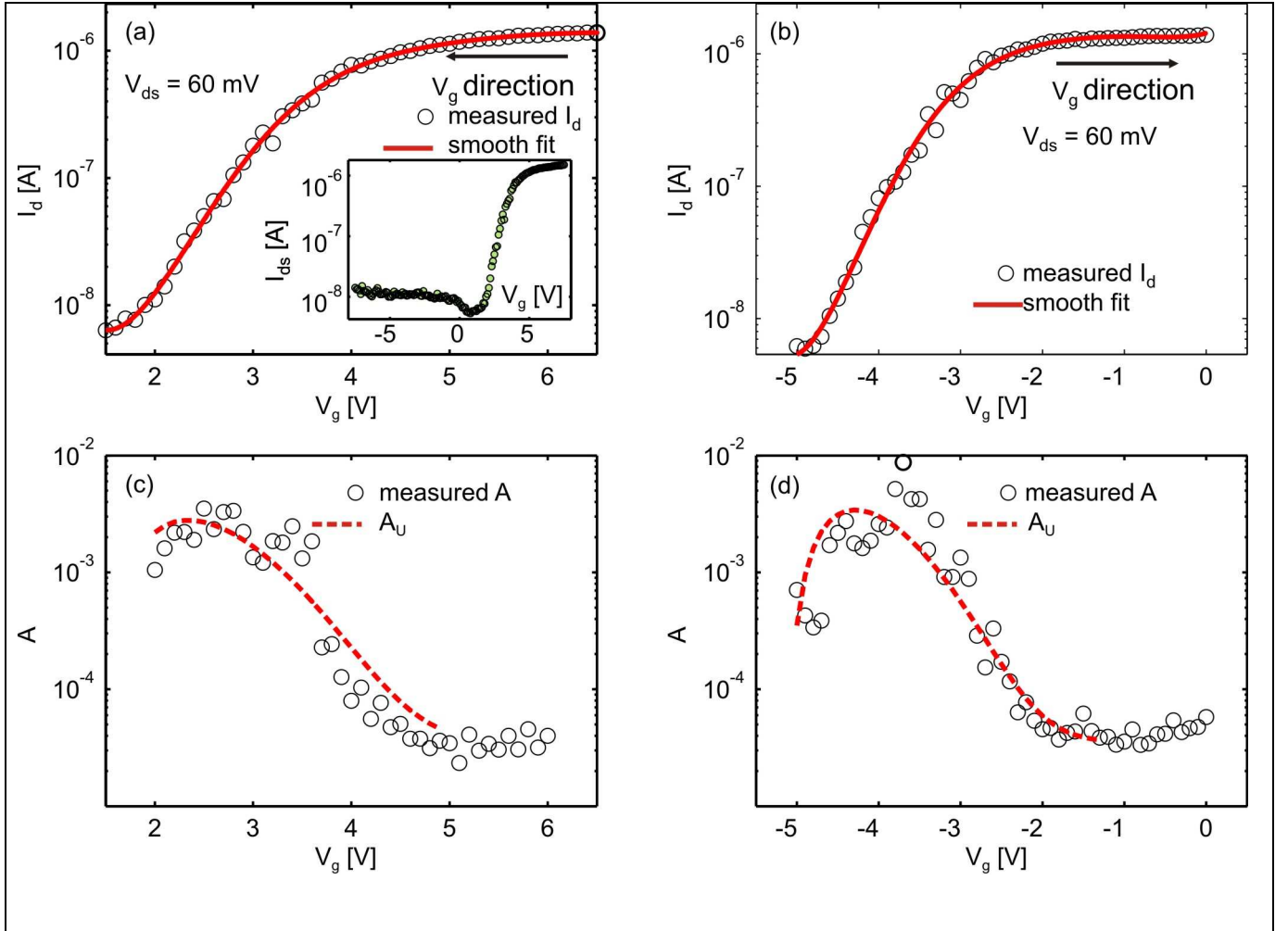


Figure S5: n-type branch of the gate characteristics and noise amplitudes of a s-SWNT measured under opposite gate sweep direction. (a) and (c) result for the sweep direction from $-V_{g\max}$ to $+V_{g\max}$. (b) and (d) results for the sweep direction $+V_{g\max}$ to $-V_{g\max}$. The inset in (a) depicts the full gate characteristic for $V_{g\max} = 7$ V.

Investigations of the influence of the sweep direction on the noise in CNFETs are shown in Figure S5. The ambipolar gate characteristics are measured under $V_{ds} = 60$ mV with $V_{g\max} = 7.5$ V and $SR = 2.2$ V/h. This yields a hysteresis, H , of the gate characteristics of $H = 6.6$ V. For simplicity and clarity only the n-type branch is considered in the analysis. The p-type branch behaves similarly. The full gate characteristic of the backward sweep is shown in the inset of Figure S5a. The extracted A values for both measurements are as follows: In the n-type on-state, $A = 3 \cdot 10^{-5}$, increasing by two orders of

magnitude to $A = 4\text{--}6 \cdot 10^{-3}$ at maximum g_m and decreasing to $A \sim 5 \cdot 10^{-4}$ at I_{\min} . Hence, the maximum and minimum of the noise amplitude values are obtained at the same characteristic features of the I_d - V_g curve, but at different absolute V_g values. The maximum noise amplitude of the upward sweep is at $V_g = -4$ V and of the downward sweep at $V_g = 2.5$ V. The indicated V_g values correspond to the values of maximum g_m .

References:

1. Kim, W.; Javey, A.; Vermesh, O.; Wang, O.; Li, Y. M.; Dai, H. J., *Nano Lett.* **2003**, 3 (2), 193-198.
2. Lee, J. S.; Ryu, S.; Yoo, K.; Choi, I. S.; Yun, W. S.; Kim, J., *J. Phys. Chem. C* **2007**, 111 (34), 12504-12507.
3. Robert-Peillard, A.; Rotkin, S. V., *IEEE Trans. Nanotechnol.* **2005**, 4 (2), 284-288.