Temperature dependence of 1/f noise mechanisms in silicon nanowire biochemical field effect transistors

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The 1/f noise of silicon nanowire biochemical field effect transistors is fully characterized from weak to strong inversion in the temperature range 100–300 K. At 300 K, our devices follow the correlated Δn - $\Delta\mu$ model. As the temperature is lowered, the correlated mobility fluctuations become insignificant and the low frequency noise is best modeled by the Δn -model. For some devices, evidence of random telegraph signals is observed at low temperatures, indicating that fewer traps are active and that the 1/f noise due to number fluctuations is further resolved to fewer fluctuators, resulting in a Lorentzian spectrum. © 2010 American Institute of Physics. [doi:10.1063/1.3526382]

Silicon nanowire (NW) field effect transistors (FETs) with exposed channels have shown great sensitivity when used as chemical and biological sensors (bioFETs).^{1–3} However, top-down fabricated devices have often exhibited degraded electrical performance, due to the exposed silicon surfaces and interface traps/defects at those surfaces. Due to the device geometry, traditional capacitance-voltage measurements for estimating interface trap densities become impractical. Instead, we rely on low frequency noise (LFN) measurements which provide a nondestructive and highly sensitive method of probing surface states.⁴ Reports of LFN noise of nanowire devices usually focus on operation in the linear regime (strong inversion or accumulation).^{5–7} However, the highest sensitivity of nanowire bioFETs is in the subthreshold regime.⁸ Reports that characterize the noise from subthreshold to linear regimes usually conclude that the LFN follows the correlated number-mobility (Δn - $\Delta\mu$) fluctuation model,^{9–11} whereas some reports^{12,13} model the noise in the different regimes separately. To fully characterize the 1/f noise of our Si NWs, we carried out measurements from weak to strong inversion at low drain bias and at different temperatures (100–300 K). We observe a change in the noise mechanism as the temperature is lowered, from the Δn - $\Delta\mu$ correlated model to the Δn model. At certain gate voltages, the 1/f spectra evolve into Lorentzian spectra, indicative of random telegraph signal (RTS) noise.

The silicon NW FETs were fabricated from silicon-on-insulator (Soitec) as outlined previously.¹⁴ Devices were nominally 100 nm wide, with lengths varying from 1 to 10 μm . The NW channels were defined by a wet orientation dependent etch using tetramethylammonium hydroxide, which we have shown yields better electrical characteristics and lower noise figures (e.g., Hooge parameter) compared to dry etching techniques.¹⁴ The devices are used in the back-gated configuration, where the gate voltage (V_g) is applied to the handle layer of the SOI wafer. The source-drain bias was kept constant at 0.1 V and the drain current (I_d) was fed into a current preamplifier (SRS 570) setup as a band-pass filter with cutoff frequencies at 0.03 and 1 kHz. The noise data was recorded using a DAQ card at 1000 samples/s and the spectral power density estimated using Welch's modified pe-

riodogram method¹⁵ implemented in MATLAB. The temperature dependent measurements were carried out in a Janis Instruments variable temperature cryostat.

A typical measurement of the normalized noise power spectra for various gate voltages, from weak to strong inversion is shown in Fig. 1. The spectra are clearly $1/f^\beta$ with $0.8 < \beta < 1.2$ as determined from a least-squares fit. For low gate bias voltages, the 1/f noise is small and becomes comparable to the noise floor at relatively low frequencies. The normalized drain current noise, S_{I_d}/I_d^2 at $f=1$ Hz (noise amplitude A), is extracted and plotted against I_d in Fig. 2. In the subthreshold region at 300 K, it is observed that S_{I_d}/I_d^2 is proportional to $(g_m/I_d)^2$, where g_m is the transconductance extracted from the I_d - V_g curve. Since the correlation does not hold as well in the strong inversion region, we conclude that the 1/f noise of our devices follows the Δn - $\Delta\mu$ correlated model. For measurements at 100 K, the S_{I_d}/I_d^2 versus I_d plot indicates a change in the dominant 1/f noise generating mechanism, since S_{I_d}/I_d^2 is now proportional to $(g_m/I_d)^2$ even in strong inversion. The enhanced correlation between S_{I_d}/I_d^2 and $(g_m/I_d)^2$ indicates that at low temperature the correlated mobility fluctuations are suppressed and carrier number fluctuations dominate the LFN.¹⁶

The transition from the Δn - $\Delta\mu$ correlated model to a purely Δn model is a gradual transition as seen from the

FIG. 1. (Color online) Typical noise spectra measured for a device biased at different gate voltages (22–40 V) from subthreshold to strong inversion. The exponents of the $1/f^\beta$ spectra all lie in the range $0.8 < \beta < 1.2$. The flattening of the noise spectra is due to background noise from the measurement setup.

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FIG. 2. (Color online) Normalized drain current noise amplitude at $f=1$ Hz (A) is plotted against drain current (I_d). Measurements at room temperature 300 K compared to the $(g_m/I_d)^2$ curve clearly indicate that the device follows the correlated Δn - $\Delta \mu$ noise model. For measurements carried out at 100 K, the noise amplitude is consistent with a carrier number fluctuation noise (Δn noise) model as indicated by the change in slope (compared to 300 K data) in the strong inversion region.

change in slope in strong inversion in Fig. 3(a). The data for $T=250$ K and $T=100$ K have been scaled to make the change in slope clearer, since the noise is subthreshold increases with decreasing temperature. Even though only the data for $T=100$ K is shown, the measurements carried out at $T=200$ K are proportional and show the same trend as the $T=100$ K data. This means that the transition happens over a small temperature range, between 200 and 300 K. For the carrier number fluctuation model, including correlated mobility fluctuations, the gate-referred noise is given by¹⁷

FIG. 3. (Color online) (a) The data show the gradual change of the slope in the strong inversion regime as temperature is lowered at $T=300$, 250, and 100 K, respectively. The data points for 250 and 100 K have been scaled for easier visualization of the change. (b) The data are fitted using the correlated Δn - $\Delta \mu$ noise model, confirming the change in the noise generating mechanism as the temperature decreases. The Coulomb scattering coefficient, α , is also extracted from linear fits to the data at 250 and 300 K. The fit to the data at 100 K clearly indicates that the correlated model is no longer valid at that temperature.

FIG. 4. (Color online) Evolution of the normalized noise power spectral density from room temperature (300 K) to 120 K for certain devices. At certain gate voltages and at low temperature (120 K), only a few traps are active and contribute to the noise spectrum, which consequently changes from a $1/f$ spectrum (with the dotted line representing a $1/f$ least-squares fit) to a Lorentzian superimposed on a $1/f$ trend at low frequencies (with the solid line representing a least-squares fit yielding a corner frequency of 25 Hz).

$$\sqrt{S_{v_g}} = \sqrt{S_{V_{FB}}} [1 + \alpha \mu_0 C_{ox} (V_g - V_t)], \quad (1)$$

where α is the Coulombic scattering coefficient, μ_0 is the low-field mobility, C_{ox} is the oxide capacitance per unit area, and $S_{V_{FB}}$ is the flatband-voltage noise spectral density due to fluctuations in the interface charge. The flatband-voltage noise can be modeled as¹⁸

$$S_{V_{FB}} = \frac{\lambda k T q^2 N_{ot}}{W L C_{ox}^2 f}, \quad (2)$$

where λ is the tunnel attenuation distance, N_{ot} is the oxide trap density, and W is the effective channel width. For negligible correlated mobility fluctuations we expect S_{v_g} to be equal to the flatband-voltage noise density, but for appreciable values of α and large number of carriers (i.e., operating in strong inversion), we expect a linear relationship between $\sqrt{(S_{v_g})}$ and V_g . We therefore investigate how well the data in Fig. 3(a) fits the correlated Δn - $\Delta \mu$ model as temperature is lowered. For the measurement at 300 K in Fig. 3(b), the data confirm what we expect, with $\sqrt{(S_{v_g})}$ directly proportional to V_g . As the temperature is lowered to 250 K, the linear relationship becomes hard to resolve due to the scatter in the data points, but a linear least-squares fit gives an estimate of the dependence. For 100 K, the absolute noise magnitude is much larger as expected from previous observations and the direct proportionality between $\sqrt{(S_{v_g})}$ and V_g vanishes. Instead, the gate-referred noise increases as gate voltage is decreased. In this regime, the correlated mobility fluctuations have been completely suppressed and what we observe is the gate voltage dependence of the carrier number fluctuation noise, or in other words the gate voltage dependence of the interface trap density. The calculated slopes correspond to $\alpha C_{ox} \mu_0 \sqrt{(S_{V_{FB}})}$. Both the mobility and the flatband-voltage noise density have slight temperature dependence from 300 K down to 250 K. Accounting for this, it is determined that the scattering coefficient α decreases as the temperature is lowered, from 1.9×10^4 V s/C (at 300 K) to 96 V s/C (at 250 K).

For devices where a large number of trapping/detrapping events are involved, the superposition of multiple Lorentzian

spectra (signature of a two level random telegraph signal) results in $1/f$ -type spectra.¹⁹ However, for certain combinations of gate bias and temperature, only a few traps are involved in the carrier number fluctuation and we are able to decompose the $1/f$ spectra into its constituent Lorentzian components.^{20,21} Figure 4 explicitly shows the evolution of the $1/f$ spectrum at room temperature to a Lorentzian curve superimposed on a $1/f$ spectrum, as temperature is lowered to 120 K. The primary effect of the decrease in temperature is to reduce the number of traps which are thermally accessible, resulting in a noise spectrum originating from a few fluctuators only. $1/f$ noise is still present for frequency values much less than 25 Hz, but the roll-off at approximately 25 Hz and the subsequent $1/f^2$ dependence clearly indicates the superimposed RTS power spectra.

In this report, we have investigated the LFN behavior of NW FETs used for sensing applications. At room temperature the devices are shown to follow the correlated number-mobility fluctuation model with noise spectra that show a $1/f$ dependence even in subthreshold. As the temperature is lowered, we observe a suppression of the correlated mobility fluctuations, yielding a pure carrier number fluctuation noise. For even lower temperatures, the LFN noise is decomposed even further to a few carrier number fluctuators, which give rise to a Lorentzian power spectrum instead of $1/f$ spectra.

¹Y. Cui, Q. Q. Wei, H. K. Park, and C. M. Lieber, *Science* **293**, 1289 (2001).

²Z. Li, Y. Chen, X. Li, T. I. Kamins, K. Nauka, and R. S. Williams, *Nano Lett.* **4**, 245 (2004).

³E. Stern, J. F. Klemic, D. A. Routenberg, P. N. Wyrembak, D. B. Turner-Evans, A. D. Hamilton, D. A. LaVan, T. M. Fahmy, and M. A. Reed,

Nature (London) **445**, 519 (2007).

⁴C. A. Richter, H. D. Xiong, X. X. Zhu, W. Y. Wang, V. M. Stanford, W. K. Hong, T. Lee, D. E. Loannou, and Q. L. Li, *IEEE Trans. Electron Devices* **55**, 3086 (2008).

⁵W. Y. Wang, H. D. Xiong, M. D. Edelstein, D. Gundlach, J. S. Suehle, C. A. Richter, W. K. Hong, and T. Lee, *J. Appl. Phys.* **101**, 044313 (2007).

⁶M. R. Sakr and X. P. A. Gao, *Appl. Phys. Lett.* **93**, 203503 (2008).

⁷S. Y. Ju, P. C. Chen, C. W. Zhou, Y. G. Ha, A. Facchetti, T. J. Marks, S. K. Kim, S. Mohammadi, and D. B. Janes, *Appl. Phys. Lett.* **92**, 243120 (2008).

⁸X. P. A. Gao, G. F. Zheng, and C. M. Lieber, *Nano Lett.* **10**, 547 (2010).

⁹B. G. Min, S. P. Devireddy, Z. Celik-Butler, F. Wang, A. Zlotnicka, H. H. Tseng, and P. J. Tobin, *IEEE Trans. Electron Devices* **51**, 1679 (2004).

¹⁰J. Zhuge, R. S. Wang, R. Huang, Y. Tian, L. L. Zhang, D. W. Kim, D. Park, and Y. Y. Wang, *IEEE Electron Device Lett.* **30**, 57 (2009).

¹¹C. Q. Wei, Y. Z. Xiong, X. Zhou, N. Singh, S. C. Rustagi, G. Q. Lo, and D. L. Kwong, *IEEE Electron Device Lett.* **30**, 668 (2009).

¹²J. Rhayem, D. Rigaud, A. Eya'a, M. Valenza, and A. Hoffmann, *J. Appl. Phys.* **89**, 4192 (2001).

¹³C. Q. Wei, Y. Z. Xiong, and X. Zhou, *IEEE Trans. Electron Devices* **56**, 2800 (2009).

¹⁴N. K. Rajan, D. A. Routenberg, C. Jin, and M. A. Reed, *IEEE Electron Device Lett.* **31**, 615 (2010).

¹⁵P. D. Welch, *IEEE Trans. Audio Electroacoust.* **Au15**, 70 (1967).

¹⁶C. Q. Wei, Y. Jiang, Y. Z. Xiong, X. Zhou, N. Singh, S. C. Rustagi, G. Q. Lo, and D. L. Kwong, *IEEE Electron Device Lett.* **30**, 1081 (2009).

¹⁷G. Ghibaudo, O. Roux, C. Nguyenduc, F. Balestra, and J. Brini, *Phys. Status Solidi A* **124**, 571 (1991).

¹⁸R. Jayaraman and C. G. Sodini, *IEEE Trans. Electron Devices* **36**, 1773 (1989).

¹⁹M. J. Uren, D. J. Day, and M. J. Kirton, *Appl. Phys. Lett.* **47**, 1195 (1985).

²⁰J. Muller, S. von Molnar, Y. Ohno, and H. Ohno, *Phys. Rev. Lett.* **96**, 186601 (2006).

²¹H. D. Xiong, W. Y. Wang, Q. L. Li, C. A. Richter, J. S. Suehle, W. K. Hong, T. Lee, and D. M. Fleetwood, *Appl. Phys. Lett.* **91**, 053107 (2007).