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A silicon nanowire ion-sensitive field-effect transistor with elementary charge sensitivity

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We investigate the mechanisms responsible for the low-frequency noise in liquid-gated nanoscale silicon nanowire field-effect transistors (SiNW-FETs) and show that the charge-noise level is lower than elementary charge. Our measurements also show that ionic strength of the surrounding electrolyte has a minimal effect on the overall noise. Dielectric polarization noise seems to be at the origin of the $1/f$ noise in our devices. The estimated spectral density of charge noise $S_q = 1.6 \times 10^{-2} e/\text{Hz}^{1/2}$ at 10 Hz opens the door to metrological studies with these SiNW-FETs for the electrical detection of a small number of molecules. © 2011 American Institute of Physics. [doi:10.1063/1.3535958]

Semiconductor nanowire transistors are of great interest for future high performance¹⁻³ or low power electronics⁴ and chemical sensors applications.⁵⁻⁸ Evaluation of electrical noise is of prime interest to determine the performance limits of these devices. In particular, small transistors can reach elementary charge sensitivity provided a very low noise level. This was first reached at very low temperature, and has led to considerable progress in solid-state physics including quantum-bit devices, counting statistics, and spintronics. The high quality of Si/SiO₂ interface has allowed reaching elementary charge sensitivity, even at room temperature and has led to the fabrication of single-electron memories⁴ or other single-charge based devices. From a fundamental view point, the room-temperature elementary charge sensitivity opens the door to metrological studies that can only be done at room temperature such as electrical detection of ions or bio- and other functional molecules. However, it often requests an electrolytic environment and until now, liquid-gated transistors with elementary charge sensitivity have not been demonstrated. Low-frequency noise in liquid-gated FETs often called ion-sensitive or chemical FETs (ISFETs or CHEMFETs) was studied in conventional large size FETs (Ref. 9) and more recently in carbon-nanotube¹⁰ ISFETs. In both cases trapping-detrapping of many charges in the close channel proximity is the limiting low-frequency noise source. Here, we show that these two limiting noise sources disappear using a 50 nm long Si nanowire covered with high quality thermal oxide.

A schematic view of the device is shown in Fig. 1(a). A droplet of de-ionized (DI) water with NaCl salt is inserted in a 0.86 mm² microbath made with a 300- μm -thick polymerized SU8 resist, Shipley©. Optical microscope image of the device (top view) is shown in Fig. 1(b). An atomic force microscope image of the SiNW is shown in Fig. 1(c). Large undoped silicon-on-insulator channels are locally constricted and oxidized for the formation of an upper oxide with a thickness of 40 nm. Then, we implanted phosphorous ions outside the constriction, 8 μm away from it, using a resist mask to form highly doped source and drain regions. The output drain current characteristics are determined by the

constricted channel which width W and length L after the oxidation are 15 and 50 nm, respectively.¹² Such a small wire channel makes this SiNW-FET useful as a high-charge-sensitivity electrometer with single-electron resolution at room temperature.^{4,13} Different possible sources of noise related to ISFETs are represented in Fig. 1(d). A platinum microelectrode is used to bias the droplet at voltage V_g with SiNWs source electrode grounded. Since at the bias used in this study, the leakage current is negligible (<100 fA) due to insulation with 40 nm of SiO₂ below the liquid, the electrochemical potential is in equilibrium. We have confirmed that an Ag/AgCl reference electrode in the microdroplet measures the V_g potential applied on the Pt microelectrode, except an offset, that has been calibrated (Fig. 2, inset).¹¹ Electrical measurements were performed at room tempera-

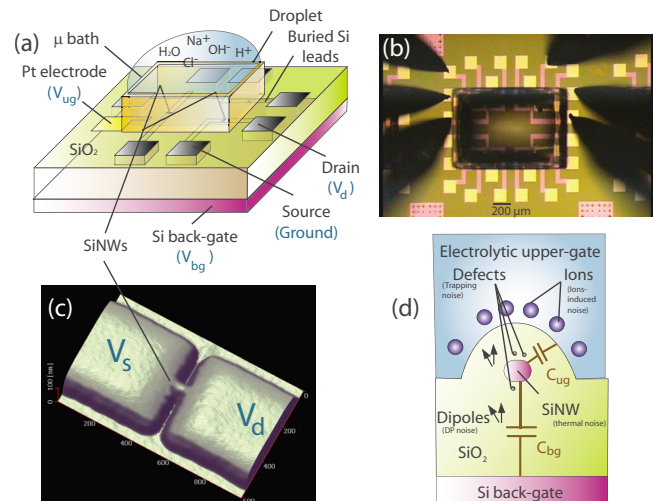


FIG. 1. (Color online) (a) Three-dimensional schematic view of the device. The Si substrate can act as a back-gate biased at V_{bg} . SiNW source is grounded ($V_s = 0$ V) and drain is biased at V_d . A microbath is fabricated with polymerized SU8 resist, Shipley©. Droplet voltage is fixed using a platinum electrode inserted in the microbath (voltage V_g). SiNWs and contact leads are surrounded by SiO₂. (b) Optical image of the experimental setup. Needles bias the device from outside the microbath which is necessary to avoid any leakage current and pollution of the droplet. (c) AFM image of the SiNW. (d) Schematic cut view of the SiNW that explains the different sources of noise: ions induced noise, dielectric polarization noise, trapping noise, and thermal noise.

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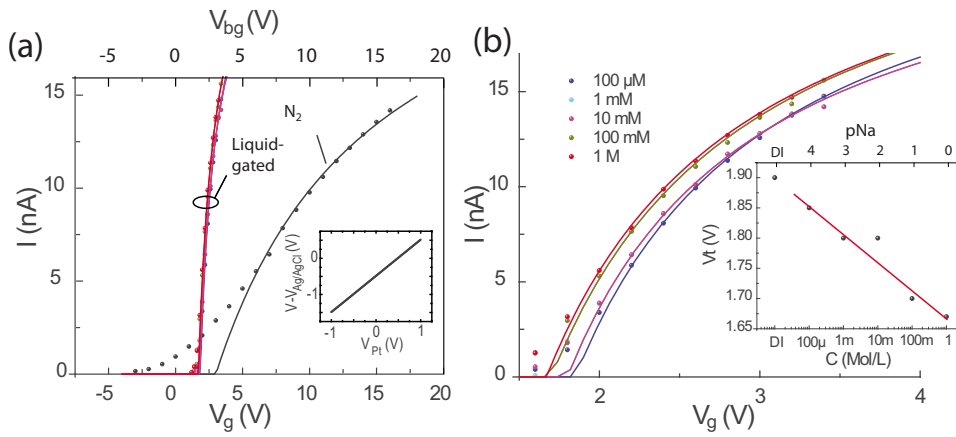


FIG. 2. (Color online) (a) $I-V_{bg}$ curve for the reference sample (no electrolyte: N_2) and $I-V_g$ curves (liquid-gated) with different NaCl concentrations. Since $I-V_g$ curves for different NaCl concentrations are tight, a zoom is shown in (b). (a) Inset: calibration of our Pt electrode at $[NaCl]=0.1M$ with an Ag/AgCl reference electrode. The offset is 0.503 V. (b) Inset: threshold voltage is shifted according to Nernst law on pNa . DI in the scale bar means DI water (no NaCl).

ture in a glove box with a controlled N_2 atmosphere (<1 ppm of O_2 and H_2O). The pH of the DI water used is about 6.2 and it barely change with Na^+ concentration.

Figure 2(a) shows the output current versus back-gate voltage ($I-V_{bg}$) reference curve (no droplet, device under a dry N_2 atmosphere) and the output current versus liquid top gate ($I-V_g$) curves for biased droplets of DI water with NaCl, selected as an archetype salt, at different ionic strengths (from 10^{-4} to $1M$). Fits (solid lines) are obtained with the classical metal-oxide-semiconductor equations in the linear regime with a transverse field-dependent mobility, which allows us to extract the threshold voltage.¹¹ Figure 2(b) is a zoom of Fig. 2(a) at low gate voltages to focus on biased droplet at different ionic strengths. The threshold voltage V_{th} follows an average decrease of about 60 mV/dec versus ($pNa=\log[Na^+]$) with some dispersion [Fig. 2(b), inset]. Similar tendency is observed for other measured devices.¹¹ As proposed initially by Bergveld,¹⁴ ISFETs are sensitive to Nernst potential that depends on the concentration of ions having affinity with the gate insulator surface. As a consequence, increasing the concentration of such ions can shift

the threshold voltage of the liquid-gated SiNW-FET up to 59 mV/dec. For nanowire ISFETs, sensitivity to pH has been previously shown.⁷ Here we show that other ions such as Na^+ can be sensed with such devices. Capacitance, mobility, and subthreshold swing $S \approx 350$ mV/dec barely depends on ionic strength. This is mainly because the dielectric constant of H_2O is much larger than that of SiO_2 and therefore the electrolytic double layer capacitance does not affect the gate capacitance.

We have measured the low frequency power spectrum current noise S_I following a protocol described elsewhere.^{11,15} Figure 3(a) shows S_I at $V_{bg}=12$ V for the reference (no electrolyte) device and Fig. 3(b) shows S_I at different gate voltages V_g for the biased droplet with $[NaCl]=10$ mM. We see in both cases that S_I scales as $1/f$ at low frequency and becomes constant (white noise) above a corner frequency which can be as low as 70 Hz due to the very low $1/f$ noise level in our SiNW transistor. $1/f$ noise amplitude increases first with V_g and then decreases, which is not the case for the thermal white noise at higher frequency as illustrated in Fig. 3(c). This is because S_I at 10 Hz scales

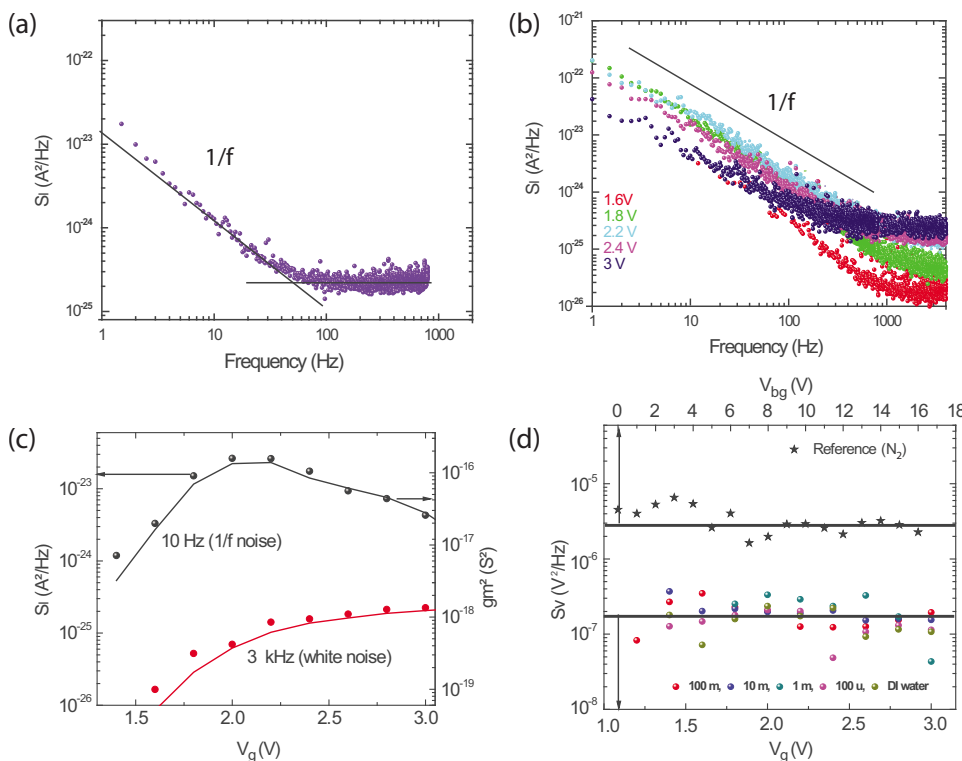


FIG. 3. (Color online) (a) Example of power spectrum current noise for the reference when $V_{bg}=12$ V. It follows $1/f$ law at low frequency and above a corner frequency the Johnson-Nyquist noise dominates. 50 Hz peaks from extrinsic noise have been removed (Ref. 11). (b) Liquid-gated power-spectra current noise for different V_{bg} (concentration of NaCl=10 mM). (c) Gate-voltage dependence of S_I at 10 Hz ($1/f$ noise) $\propto g_m^2$ and white noise at 3 kHz $\approx 4 kTI/V_d$. (d) $S_v=S_I/g_m^2$ at 10 Hz as a function of V_g for different ionic strengths and as a function of V_{bg} for reference. The decrease of S_v by about an order of magnitude when the SiNW is liquid-gated is in accordance with DP noise [Eq. (2)].

as g_m^2 and not I^2 , where $g_m = \partial I / \partial V_g$ is the transconductance [black line in Fig. 3(c)]. The noise at 3 kHz [red line in Fig. 3(c)] is well fitted with a SiNW thermal noise $S_I = 4 kTV_d/I$ where k is the Boltzman constant, T the temperature, V_d the drain voltage, and I the average drain current. Figure 3(d) shows the power spectrum voltage noise $S_v = S_I/g_m^2$ (i.e., the power spectrum noise referred to the input gate) at 10 Hz as a function of V_{bg} and V_g for the reference sample (no droplet) and the liquid-gated sample, respectively. We note that S_v is constant with gate voltage and there is an order of magnitude of difference in noise between the reference and liquid-gated sample. The behavior and origin of this $1/f$ noise will be discussed later.

Following a careful and detailed calibration procedure reported elsewhere,¹⁶ we obtained, for this device, $C_g = 6.25$ aF for the upper gate capacitance (liquid-gated) and $C_{bg} = 0.66$ aF for the back-gate capacitance (reference sample). From S_v , we can estimate the charge noise at 10 Hz $Sq_{bg}^{1/2} = 7 \times 10^{-3}$ e/Hz^{1/2} for reference sample and $Sq_g^{1/2} = 1.6 \times 10^{-2}$ e/Hz^{1/2} for the liquid-gated configuration using

$$Sq_g^{1/2} = \frac{C_g}{q} S_{v_g}^{1/2}; \quad Sq_{bg}^{1/2} = \frac{C_{bg}}{q} S_{v_{bg}}^{1/2}. \quad (1)$$

This charge noise level is low enough to get elementary charge sensitivity at room temperature. As a comparison, at very low temperature, charge noise level of 10^{-3} e/Hz^{1/2} at 10 Hz for charge-sensitive electrometers is a standard value.¹⁷ Another easy way to confirm the elementary charge sensitivity is the observation of a discrete two levels fluctuation, the so called random telegraph signal, due to the trapping/detrapping of a single electron in a defect located in the oxide.¹¹

The $1/f$ noise in ISFETs could have several origins including trapping/detrapping of electrons by a huge number of oxide defects close to electrons in the channel, noise due to mobility fluctuations, ion-induced noise (Brownian motion of ions), or dielectric polarization (DP) noise,^{18,19} as illustrated in Fig. 1(d).

In the case of mobility noise, the power spectrum current noise S_I should scale with I^2 and not with g_m^2 as shown in Fig. 3(c) (black curve). Ion-induced noise is also negligible in our devices because S_v does not depend on ionic strength [Fig. 3(d)] and the measured white noise follows thermal noise of the SiNW [Johnson–Nyquist noise, Fig. 3(d), red curve]. DP noise is the only good candidate for the observed $1/f$ noise in our device.¹¹ Equation (2) is derived from the fluctuation-dissipation theorem which extends Johnson–Nyquist noise equation to complex impedances.^{18,20}

$$S_{v_g} = 4kT \operatorname{Re}(Z) = \frac{2kTtg\delta}{\pi C_g f}; \quad S_{v_{bg}} = \frac{2kTtg\delta}{\pi C_{bg} f}, \quad (2)$$

where $tg \delta = \varepsilon''/\varepsilon'$ is the dielectric loss tangent with ε' and ε'' the real and imaginary dielectric permittivities of the oxide, respectively. SiO₂ is considered as a low loss/flat loss dielectric.²¹ A standard value for high-quality thermally grown oxide²¹ is $tg \delta \approx 3.8 \times 10^{-3}$. Considering $C_g = 6.25$ aF and $C_{bg} = 0.66$ aF as discussed previously, we get using Eq. (2) and the S_{v_g} and $S_{v_{bg}}$ in Fig. 3(d), $tg \delta = 7.8 \times 10^{-3}$ for back oxide and 4.3×10^{-3} for front oxide, which are in the range of expected results.

This study is very useful to investigate the best structure for optimum ISFETs sensitivity. For example, let us consider

a single molecule detection, for instance a single redox event (single-charge detection), the associated current variation is $\Delta I = g_m \cdot \Gamma \cdot q / C_g$. Γ is a parameter to account for molecule screening effects.⁸ ($\Gamma = 1$, for no screening, < 1 otherwise). The signal to noise ratio in our ultralow noise SiNW-FET can be expressed as

$$\Delta I / S_I^{0.5} = \frac{\Gamma \cdot q \cdot (\pi f)^{0.5}}{(2kT \cdot tg \delta \cdot C_g)^{0.5}}. \quad (3)$$

The dielectric loss should be as low as possible. Therefore, native oxides or not optimized oxides should be avoided. Finally C_g should be as small as possible which implies nanometric dimensions for the SiNW.

To conclude, we have demonstrated that liquid-gated SiNW ISFETs can have an elementary charge sensitivity ($S_q = 1.6 \times 10^{-2}$ e/Hz^{1/2} at 10 Hz) making it a suitable device for single molecule detection with a signal to noise ratio larger than 50. Although the threshold voltage of this device is sensitive to NaCl concentration, we show that ion-induced noise is negligible in the device. Among the several possible sources of $1/f$ noise in this device, only the dielectric polarization noise gives a quantitative agreement with the experimental data. These results open the door to metrological studies with SiNW-FET for the electrical detection of a small number of molecules.

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