Noise in Single-Trap Punctual Nanobiosensors

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***Abstract*—Punctual nanobiosensors based on the trapping/detrapping of a single electron in a defect near the channel of a nanotransistor have been proposed for ultimate scaling and high sensitivity [1]. Unlike the usual nanotransistor-based biosensors, where the threshold voltage shift is the signal and voltage fluctuations are the noise, the signal in these devices is a trap occupancy probability. The fluctuations of this parameter become the noise. Therefore, the signal-to-noise (S/N) ratio needs to be quantitatively studied theoretically in order to compare the performance of sensors and to optimize experimental conditions. Here we show that under optimized conditions for the background noise amplitude and the averaging filter the S/N ratio can be substantially increased, above the level expected for devices monitoring threshold voltage shift.**

Keywords—Nanowire sensors, single trap, low-frequency noise, signal-to-noise ratio.

I. INTRODUCTION

A transfer of a single charge carrier between a process-induced defect (e.g. a single trap) located in a gate dielectric layer and a conductive channel of a nanotransistor results in a two-level discretized fluctuation signal known as random telegraph signal (RTS) noise [1]. Usually, such RTS fluctuations in nanoscale devices are treated as a noise source that degrades nanodevice performance. However, due to the discrete nature of the phenomenon and the possibility of monitoring its response with surface potential, RTS noise provides a significant opportunity for practical applications including biosensing [1-3]. In particular, monitoring the time constants of a single trap can be used as a new way to sense pH or biomolecules interacting with a nanotransistor. Such an approach permits a substantial increase in sensitivity in comparison to standard approaches that use the threshold voltage or drain current shift as the signal. However, as the signal-to-noise (S/N) ratio is a key parameter for any sensor, it should also be carefully introduced and investigated for nanotransistor sensors exploiting single-trap phenomena. This would allow sensor performance to be compared and experimental conditions to be optimized. In the case of transistor-based sensors, the S/N ratio is usually defined as the ratio of threshold voltage or drain current shift against low-frequency noise. This noise mainly originates from electron trapping/detrapping events [4, 5]. Therefore, it is now well accepted that the S/N ratio for transistor-based sensors can be optimized by modifying device dimensions, the quality of device fabrication, and the nature of noise sources [5-7]. However, nanoscale transistors statistically have a single trap, and when sensing based on single-trap phenomena is exploited (see Fig. 1), RTS is the signal and not a noise source. Therefore, the investigation of the nature of the noise is of fundamental importance in this particular case where the biosensor becomes a single and punctual single-electron trap.

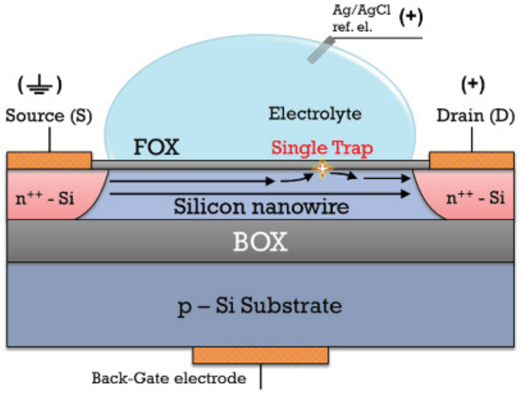

Fig. 1. Schematic representation of a nanotransistor with a punctual defect.

In this work, we demonstrate that for punctual nanobiosensors exploiting single-trap phenomena, noise can be defined as a fluctuation of trap occupancy probability (g-factor) affecting the distribution of RTS time constants. Moreover, in this study we present a method enabling us to calculate g-factor noise. In this respect, an S/N ratio was carefully introduced for the RTS-based biosensing approach. Furthermore, we show that under optimized conditions for the background noise amplitude (dielectric polarization noise) and an averaging window filter time lapse, the S/N ratio can indeed be substantially increased in comparison to sensors whose working principle is based on monitoring changes in threshold voltage or drain current.

II. RESULTS AND DISCUSSION

RTS is generated numerically using master equations with the additional consideration of background noise components (dielectric polarization noise and thermal noise). The capture and emission rates were defined using the following formulas:

$$R_c = R_0 \exp\left[-\frac{q}{kT}\,\gamma\,(E_{trap} - \alpha V_g)\right] \quad (1)$$

$$R_e = R_0 \exp\left[\frac{q}{kT}\,(1-\gamma)\,(E_{trap} - \alpha V_g)\right] \quad (2)$$

where q is the elementary charge, T is an absolute temperature, k is the Boltzmann constant, γ is the charge transfer coefficient, E_{trap} is the energy of the trap, V_g is the gate voltage applied, and α is the ratio between the trap depth d_{trap} and the dielectric thickness t_{ox} . For simulation purposes, the following values were used $T = 300\ K,\ E_{trap} = 100\ meV,\ d_{trap} = 2\ nm,\ t_{ox} = 20\ nm$, thus $\alpha = 0.1$. The charge transfer coefficient γ was set to 1 for all simulation results presented in this study, so that the emission rate does not depend on the gate voltage applied. The prefactor R_0 was set to a constant value of 100.

RTS timetraces generated for different liquid-gate voltages are presented in Fig. 2A. The averaged capture and emission times characterizing the RTS process are plotted in Fig. 2B against the applied liquid-gate voltage and reflect the typical behavior of capture (τ_c) and emission (τ_e) times for nanowire FET devices [2, 8].

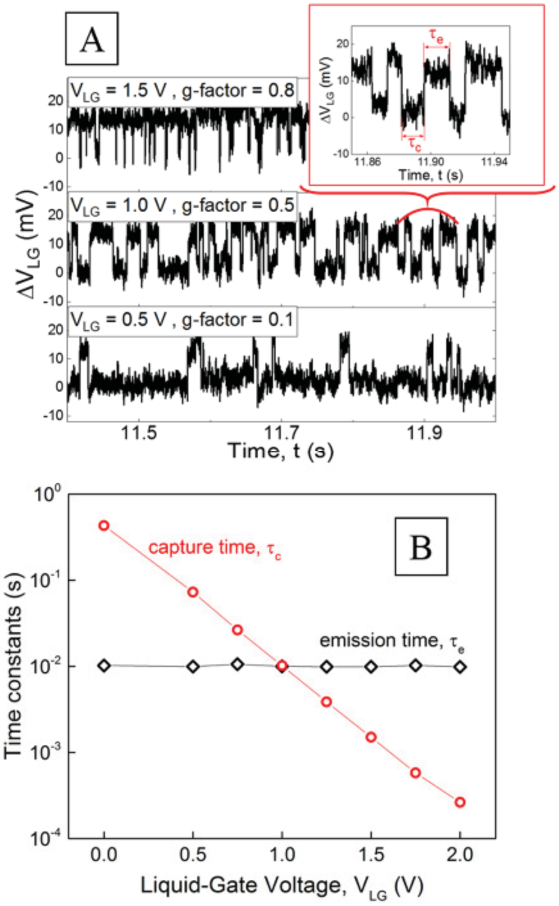

Fig. 2. (A) RTS timetraces generated numerically at different liquid-gate voltages. (B) Capture and emission time constants plotted as function of liquid-gate voltage applied.

Fig. 3A shows a distribution of time in the emission (up) and capture (down) states at a given gate voltage V_{LG} = 1V, which corresponds to the case when the trap level coincides with the Fermi level. As can be seen in Fig. 3A, exponential decay distributions are obtained for both capture and emission time constants. Fig. 3B represents a trap occupancy probability g calculated using the following formula:

$$g = \frac{<\tau_e>}{<\tau_e> + <\tau_c>} \quad (3)$$

where $<\tau_e>$ and $<\tau_c>$ are average emission and capture time constants, respectively.

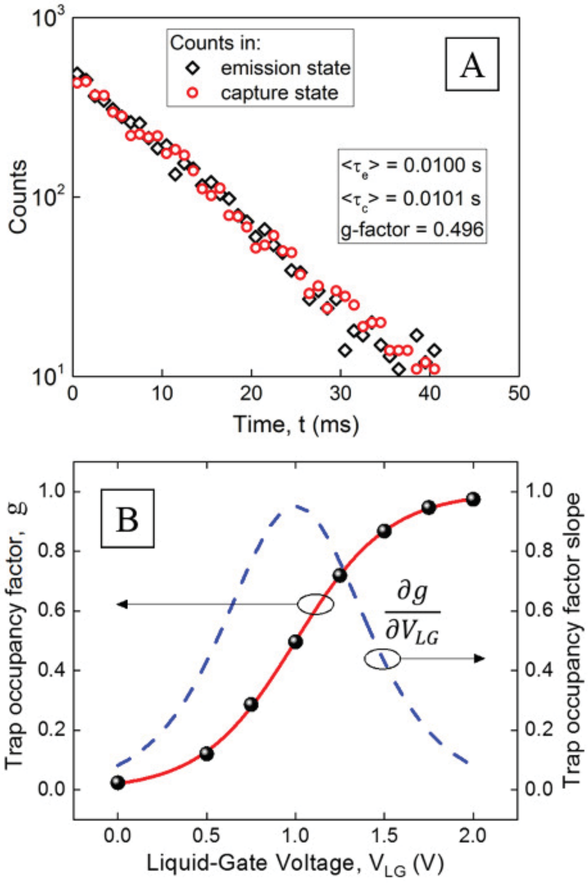

Fig. 3. (A) Histograms of capture and emission events at V_{LG} = 1 V plotted on a semi-logarithmic scale and confirming that both time constants obey the exponential distribution.

As can be seen from Fig. 3B, the trap occupancy factor g follows a widened Fermi-type distribution (due to the partial potential drop at the trap level). At low V_{LG}, the trap is unoccupied and at high voltages, it is fully occupied.

We assume that g is the signal and that its fluctuation is the noise. We expect that the sources of g-factor fluctuations have the same origin as in any nanotransistor including flicker noise and thermal noise. However, the impact of these noise sources on trap occupancy fluctuations has to be estimated. Therefore, we suggest converting RTS voltage fluctuations into fluctuations of the trap occupancy factor. More precisely, we calculate g-factor probability over a given time window T and then by sliding the window along the generated timetrace one can obtain timetrace with the trap occupancy factor fluctuations. Typical g-factor fluctuations calculated for different time windows are presented in Fig. 4A. It should be noted that g-factor fluctuations decrease with increasing T while keeping the value of g unchanged (here g = 0.5 is obtained at V_{LG} = 1 V).

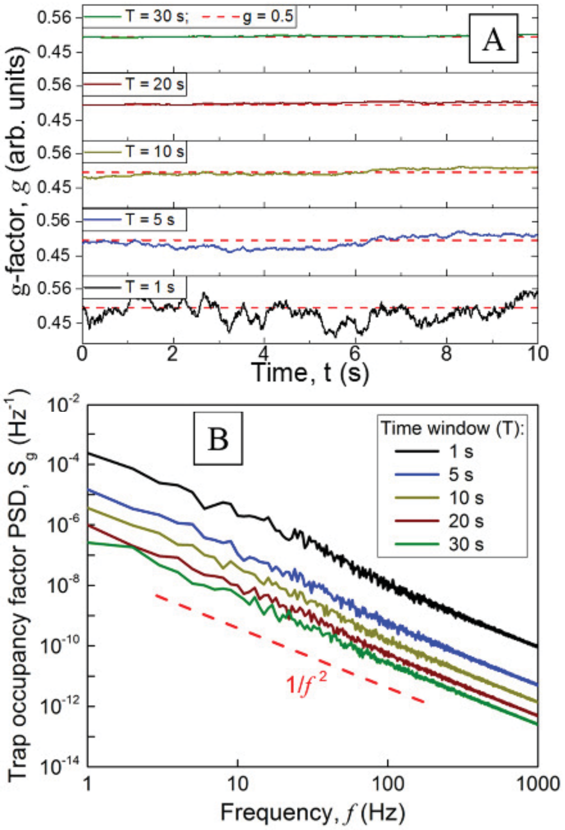

Fig. 4. (A) Trap occupany factor timetraces calculated for different time windows T at $V_{LG} = 1$V. (B) g-factor PSD obtained for timetraces in (A).

Finally, the power spectral density (PSD) of the trap occupancy factor g (Fig. 4B) is calculated from g-factor timetraces shown in Fig. 4A. It should be emphasized that in the frequency domain, the g-factor PSD demonstrates a clear $1/f^2$ dependence in the frequency range 1 Hz – 1 kHz for the calculated time windows. As can be seen from Fig. 4B, the g-factor noise amplitude decreases with increasing time window T confirming the data in Fig. 4A. The result can be explained considering the fact that a larger time window T corresponds to a larger number of trapping/detrapping events occurring over time T, and therefore the trap occupancy factor can be estimated with higher accuracy for larger windows. It should be noted that such an approach for g-factor noise calculation is similar to the averaging filter in a stochastic process. Note that such noise suppression cannot be obtained by averaging drain-source voltage fluctuations.

In order to compare the signal-to-noise ratio obtained for the single-trap phenomena approach with the usual approaches, we introduced the input-referred trap occupancy factor noise S_{gg} in a similar manner to the way in which one can calculate the equivalent input-referred noise for voltage fluctuations S_{Vg} as defined by [8-11]:

$$S_{Vg}=S_I/g_m^2 \tag{4}$$

where S_I denotes the current noise and $g_m=\partial \mathrm{I}/\partial \mathrm{V_g}$ stands for the transconductance. Similarly, we define the input-referred trap occupancy factor noise S_{gg} as:

$$S_{gg}=S_g/g_g^2 \tag{5}$$

where S_g is g-factor noise and $g_g=\partial g/\partial \mathrm{V_g}$ stands for a trap occupancy derivative (slope) (Fig. 3B).

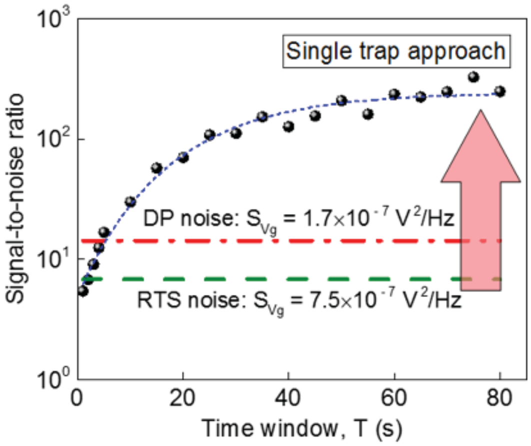

Fig. 5. S/N ratio estimated for different conditions. The dashed blue line represent an aid for the eye.

As a last step, we estimate an S/N ratio for nanobiosensors whose working principle is based on single-trap phenomena as follows:

$$S/N=(5.9mV)\ /\sqrt{S_{gg}} \tag{5}$$

where S_{gg} - is an input-referred trap occupancy factor noise at a given frequency and 5.9 mV is selected as a signal which corresponds to a threshold voltage shift of the liquid-gated nanosensor caused by 0.1 pH change in the gating solution. The S/N ratio calculated for different time windows T at S_{gg} taken at 10 Hz is shown in Fig. 5. As can be clearly seen, the S/N ratio strongly increases with increasing aggregation time T, showing that under optimized conditions it can indeed be substantially increased, even above the level expected for devices monitoring threshold voltage shift. This suggests that, as long as the RTS amplitude remains well above the other noise sources, the single-trap phenomena approach can be used as a noise filter when sufficiently large averaging windows are used.

III. CONCLUSIONS

In order to demonstrate the full potential of the single-trap approach for biosensing, we generated RTS noise numerically and proposed a method which permits the calculation of trap occupancy factor noise. Under these conditions, the S/N ratio was estimated for nanosensors exploiting RTS noise as a signal. We revealed that the S/N ratio can indeed be substantially increased. The results shed light on relevant parameters required to optimize nanobiosensors based on single-trap phenomena.

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