Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp479-480

Combining Stochastic Resonance and Single-Trap Phenomena for Noise Suppression Beyond the Thermal Limit with Nanotransistor Biosensors

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Abstract

Signals coming from the target bio-objects are usually extremely small to be detected, therefore the physical mechanisms and effects leading to the amplification of weak signals as well as the reduction of noise level have to be thoroughly investigated. Recently, single-trap phenomena in liquid-gated nanotransistors have been proposed to enhance the performance of nanoscale transistor-based biosensors in terms of sensitivity.[1] Here, we combine theory and experiments to study the noise suppression offered by single-trap phenomena in an approach similar to the stochastic resonance effect found in biological systems. A good agreement between the proposed analytical model and experimental results has been achieved.

1. Introduction

In recent years, the application of nanotransistor-based devices evidenced remarkable progress in different areas including biosensing. In particular, such nanotransistor biosensors that are very similar to mass-production state-of-the-art semiconductor transistors enable faster, more compact, and more accurate biological[1,2] and chemical detection.[3,4] However, the performance and sensitivity of such devices are still limited by the intrinsic noise of the transducers' elements. Therefore, new transducer principles as well as novel device architectures have to be designed and developed. In this respect, the stochastic resonance effect is one of the effective approaches as it can boost the performance of a sensor device by adding white noise to the system. The phenomenon has been observed in a variety of systems and effectively used in many different applications including signal processing, control systems, and network designs.[5,6]

In nanoscale transistors, a single trap statistically capturing and emitting a charge carrier leads to random-telegraph signal (RTS) noise which determines a noise level of a nanoscale device. Usually, RTS is treated as a parasitic effect, but only recently it has been considered as a signal and proposed for ultimate scaling and high sensitivity.[1] From a more general perspective, RTS noise can be treated as a white noise below a cut-off frequency, f_0 (see Fig.1a). Therefore, single-trap phenomena can be considered as stochastic resonance (SR) effect when a white noise added to a signal enables better sensitivity and performance. Below, we theoretically demonstrate as well as experimentally prove that the exploitation of the trapping/detrapping of a single charge carrier in a single defect allows suppression of the transistor-related noise by orders of magnitude that is even below the level expected for the trap-free devices.

2. Results and Discussion

Unlike usual nanotransistor-based biosensor where a shift the threshold voltage is a signal and voltage fluctuations are the noise, the signal in devices exploiting single-trap phenomena is a trap occupancy probability (g-factor) defined as

$$g = \frac{\tau_e}{\tau_e + \tau_c} \qquad (1)$$

where τ_e is the emission time of a charge from the trap and τ_c is the capture time in the trap (see RTS time trace in Fig.1a).

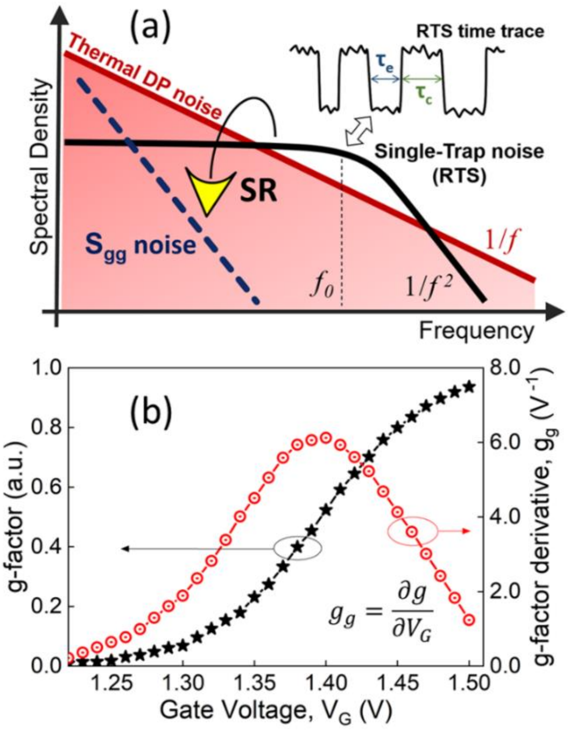

Fig.1. (a) Schematic representation of the stochastic resonance noise reduction mechanism for biosensors exploiting single-trap phenomena. (b) Trap occupancy probability and its derivative as a function of gate voltage calculated for numerically simulated RTS noise time traces.

The trap occupancy factor g and its derivative calculated for numerically simulated RTS noise are shown in Fig.1b as a function of gate voltage. As can be seen, the g-factor follows a widened Fermi-type distribution due to the partial potential drop at the trap level. Considering g as a signal, the fluctuations of this parameter becomes the noise. To calculate the g-factor noise, one can extract $g(t)$ over a given time window Θ directly from the RTS time trace. Then, by sliding the window along the trace one can obtain a new time trace with the trap occupancy factor fluctuations in time. The time-domain g-factor data can be further translated into a frequency spectrum resulting in the power spectral density, S_g. Finally, the equivalent input-referred noise caused by the variation of the occupancy factor can be calculated as

$$S_{gg} = \frac{S_g}{g_g^2} \qquad (2)$$

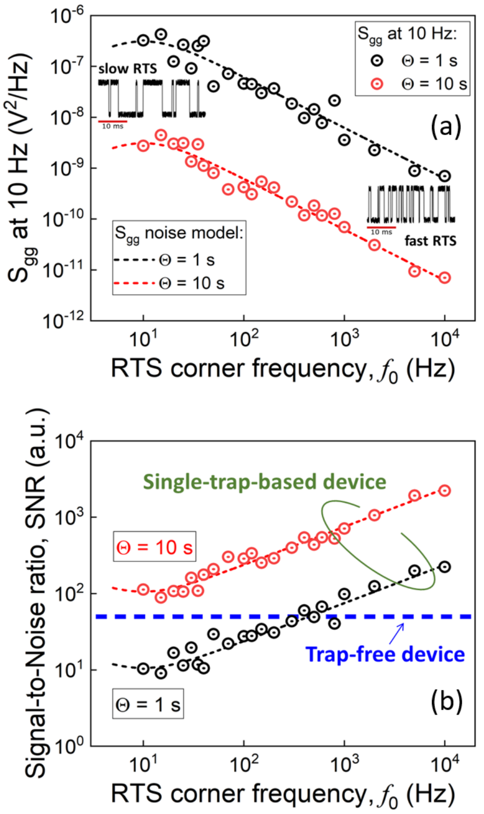

Fig.2. (a) Input-referred trap occupancy factor noise calculated for $\Theta = 1s$ and $\Theta = 10s$ and plotted as a function of the RTS corner frequency when $g = 0.5$. (b) The signal-to-noise ratio of 5.9 mV signal for the single-trap-based device estimated from (a). The horizontal dashed line represents the SNR level calculated for the trap-free device with DP voltage noise of 1.4×10^{-8} V^2/Hz at 10 Hz.

From an applied mathematics perspective and following a statistical analysis formalism the power spectral density of g can be derived as

$$S_g^{(\Theta)}(\omega) = \frac{2\gamma\left(1-\cos(\Theta\omega)\right)}{\Theta^2\omega^2(4\gamma^2+\omega^2)} \qquad (3)$$

where $\omega = 2\pi f$, γ is capture and emission rates at $g = 0.5$, and Θ is a duration of a sliding time window.

Fig.2a shows the input-referred trap occupancy factor noise at 10 Hz calculated for the time windows $\Theta = 1s$ and $\Theta = 10s$ and plotted as a function of the RTS corner frequency, f_0 when $g = 0.5$. The number of capture/emission events over time Θ is higher for the high-frequency RTS compared to the low-frequency RTS in the case of the same trap occupancy probability. Therefore, the g-factor can be evaluated with more accuracy for the fast RTS considering the same amount of time as for the slow (low-frequency) RTS process. For the sensors exploiting the g-factor as a signal, the signal-to-noise ratio (SNR) can be defined as:

$$SNR = \frac{\delta V}{\sqrt{\int_{f2}^{f1} S_{gg}\,df}} \qquad (4)$$

where δV is an input signal caused by the interaction of the analyte with the sensing surface of the biosensor. The SNR calculated for RTS noise with different corner frequencies at $g = 0.5$ and for different time windows is shown in Fig.2b. A larger number of transition events due to the higher RTS rate results in smaller S_{gg} noise and thus leads to an increase in SNR (see Fig.2b). Very interestingly, the SNR ratio can indeed substantially be increased under the optimized conditions even above the level expected for the trap-free devices monitoring the threshold voltage shift as a signal.

3. Conclusions

A discrete nature of single-phenomena can be exploited to suppress the noise level of nanotransistor-based biosensors in an approach analog to the stochastic resonance effect. An analytical model has been derived to account for this trend obtained from both numerical simulations and experiments. The results are important for the development of advanced RTS-based devices that could revolutionize the fields of biotechnology and personalized medicine.

Acknowledgements

The authors acknowledge the Seed Money funds for supporting a new international collaboration as part of the RTS-Biosensor project. This work was partially supported by the JSPS Core-to-Core Program (A. Advanced Research Networks). Y. Kutovyi greatly appreciates a research grant from the German Academic Exchange Service (DAAD). I. Madrid acknowledges the interdisciplinary research funds from CNRS for the BIOSTAT project.

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