Optically Controlled Nanoscale FET Toward Advanced Biosensing Applications

Mykhailo Petrychuk
IBI-3 and HNF
Forschungszentrum Jülich
Jülich, Germany
m.petrychuk@fz-juelich.de

Akira Fujiwara
NTT Basic Research Laboratories
Nippon Telegraph and Telephone (NTT)
Atsugi Kanagawa, Japan
akira.fujiwara@ntt.com

Denys Pustovyi
IBI-3
Forschungszentrum Jülich
Jülich, Germany
d.pustovyi@fz-juelich.de

Yongqiang Zhang
IBI-3
Forschungszentrum Jülich
Jülich, Germany
y.zhang@fz-juelich.de

Hanlin Long
IBI-3
Forschungszentrum Jülich
Jülich, Germany
h.long@fz-juelich.de

Svetlana Vitusevich*
IBI-3
Forschungszentrum Jülich
Jülich, Germany
*s.vitusevich@fz-juelich.de

***Abstract*—Sensitivity enhancement is an important aspect of the development of ultrasensitive biosensors. Single-trap phenomena observed in liquid-gated nanostructures provide a new opportunity to enhance the sensitivity of nanoscale biosensors. The impact of light excitation on properties of a unique nanowire (NW) field-effect transistor (FET) structures utilizing single trap phenomena are studied. We revealed that parameters of single trap and interface phenomena in NW FET can be effectively tuned in a controlled way using optical excitation. Under the influence of optical radiation, the population of discrete levels is redistributed, which allows to control of their energy characteristics and, as a result, establishes the optimal sensitive regimes. A model of the potential profile description for carriers in NW structure is discussed to describe the mechanisms of capture dynamics in fabricated NW FETs and to control sensitivity in advanced biosensors.**

Keywords—single trap phenomena, nanowire transistors, optical excitation, fine tuning effect

I. INTRODUCTION

Sensitivity enhancement is an important aspect for the development of ultrasensitive biosensors. Single-trap phenomena observed in liquid-gated nanostructures provide a new opportunity to enhance the sensitivity of nanoscale biosensors. In small-area transistors, quantum effects [1] and the trapping/detrapping of charge carriers to/from a single trap located in the gate oxide near the Si/SiO_2 interface leads to the discrete switching of the transistor drain current, known as single-trap phenomena (STP), resulting in random telegraph signals (RTS).

Utilizing the STP approach, liquid-gated (LG) nanowire (NW) field-effect transistor (FET) biosensors have recently been proposed for ultimate biosensing with enhanced sensitivity [2-9]. The parameters of two-level RTS noise, which can be considered as a digital signal reflecting the sensitivity of biosensors, are required to understand the interplay between the single-trap phenomena and optimal operation regimes of biosensors. RTS parameters depend significantly on the voltage applied to the liquid gate, V_{LG}. The optimal voltage for the operation of the LG FET as an amplifier is usually not the same as the optimal voltage for RTS noise. In addition, fine-tuning the RTS noise parameters by changing the V_{LG} voltage may result in leakage current due to electrochemical reactions in the electrolyte. Therefore, the RTS process must be fine-tuned without changing the V_{LG}. Other external sources that influence the noise parameters must be identified. In this respect, optical irradiation is very promising as it is flexible in wavelengths. It should be noted that optical control of single trap phenomena for biosensing applications has not been reported in the literature.

The aim of our work is to clarify the effect of optical radiation on the kinetics of generation–recombination processes occurring at single traps in the gate dielectric of nanoscale FET structures. We demonstrate fine tuning carrier concentration and interface phenomena in NW FETs in a controlled manner using optical excitation. The impact of light excitation on the properties of a unique NW transistors utilizing single-trap phenomena was studied. Under the influence of optical radiation, the population of carriers on discrete levels is redistributed, which allows their energy characteristics to be controlled, and, as a result, establishes optimal sensitive regimes.

II. EXPERIMENTAL DETAILS

NW FET structures are designed for use as sensitive elements of sensors with extended gate for biochemical reactions. Several samples with a polysilicon gate were investigated. To study the influence of optical radiation on RTS fluctuations we used nanoscale transistors, schematically shown in Fig.1. The changes in the time constants of the capture and emission of free charge carriers per single trap were studied by recording current changes through the channel of silicon FET structures at different optical intensities. The structures under investigation were FETs with 40×50 nm channel dimensions (n+-i-n+ type of channel conductivity). The light source is selected to excite the structures with photon energy of 1.3eV using an infrared light emitting diode (LED) – λ = 0.95 μm. The IR383 LED from EVERLIGHT (Taiwan) was used in this work. The radiation intensity was determined by calculation using the datasheet information and taking into account the linear dependence of the radiation intensity on the current through the LED. The radiation intensity was regulated by the change in current and the distance between the LED and a FET. It should be noted that the transparent polysilicon gate is not an obstacle for using the transistor as a biosensor, since an extended gate can be applied. The noise properties and drain current fluctuations of

NW-FET devices are studied under external optical excitation and without it in different regimes defined by drain-source biases, V_{DS}, and gate voltages, V_{GS}, to understand the single trap characteristics.

III. Results and discussion

At nanoscale size of NW FET, the influence of single trap on current in the structure becomes significant. For the dielectric layer on the semiconductor surface near the Si/SiO_2 interface (at a distance of 0–2 nm) there is a single trap that randomly captures or emits an electron from the conducting channel. The change in the electric field around the trap then modulates the current in the channel, which manifests itself in the form of two-level voltage fluctuations. The capture time τ_c and the emission time τ_e are random variables; their average values τ_c and τ_e are referred to as capture and emission time constants, respectively:

$$\tau_c = \langle t_c \rangle, \qquad \tau_e = \langle t_e \rangle. \qquad (1)$$

These two quantities, as well as their ratio $R = \tau_e/\tau_c$, are used as informative parameters for estimating the sensitivity of biosensors. Unlike potentiometric sensors, where the change in the charge of molecules on the surface of the dielectric of the FET structure affects the amount of current in the channel, the value of the time constants τ_c and τ_e changes in the method based on the stochastic characteristics of RTS noise. This allows a significant increase in the sensitivity of sensors and the possibility of overcoming the thermal limit for increasing sensitivity, since new time characteristics and their dependence on the potential of the dielectric surface can be analyzed.

The values τ_c and τ_e in the equilibrium state can be controlled by the concentration of free electrons in the conduction band (n-silicon) or holes in the valence band (p-silicon) according to the laws (for electrons):

$$\tau_c = \frac{1}{C_n n_s} \exp\frac{\Delta E}{kT}, \quad \tau_e = \frac{1}{C_n N_c} \exp\frac{E_T}{kT}, \qquad (2)$$

where C_n is the electron capture coefficient $C_n = \sigma_n v_{th}$, σ_n is the capture cross section of electrons, v_{th} is the thermal velocity, n_s is the effective volume concentration of electrons at the Si/SiO_2 interface, N_c is the effective density of states at the bottom of the conduction band, E_T is the energy between the trap level and the bottom of the conduction band, and ΔE is the Coulomb blockade energy.

The $E_T, N_c, \Delta E, E_T$ values do not change during irradiation. The value of n_s changes slightly, since silicon is an indirect bandgap semiconductor and demonstrates a weak photoeffect. In the equilibrium state, the electron energy is determined by the lattice temperature, but in the non-equilibrium state, during irradiation, the electron energy increases by the photon energy $h\nu$, and the corresponding value of the electron energy should be considered. We therefore see that even when using the simplest formulas (2), it is possible to draw a conclusion about the reason for the dependence of τ_c and the independence of τ_e from irradiation. It should be noted that we took into account the probability of photon capture, which give the corresponding dependence of τ_c on the intensity of irradiation.

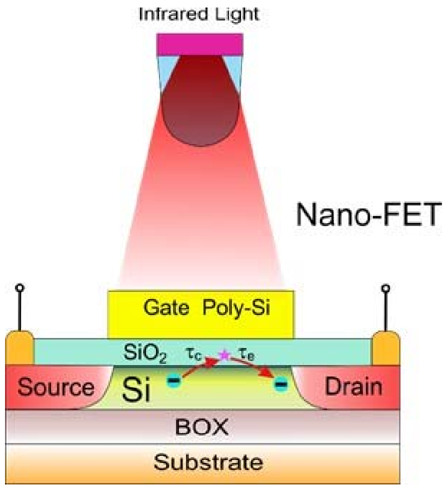

Fig 1. Schematic presentation of nano-FET under study of external IR optical excitation.

The mechanisms of the formation of RTS fluctuations in metal oxide semiconductor (MOS) structures are described as the random processes of either the capture or the emission of a free current carrier to a single trap in a sub-gate dielectric near the dielectric/semiconductor interface, leading to the modulation of channel conductivity.

As a result, corresponding current fluctuations in the channel can be registered. At a fairly low concentration of defects at the interface (~ 10^{12} cm^{-2}), the distance between adjacent active traps is greater than the Debye radius, meaning that there is no electrostatic correlation between them. As a result, there is also no correlation between the capture/emission processes of adjacent traps. The duration of the fronts of RTS pulses is therefore only determined by the capacitance of the measuring system. However, in several cases, such a correlation is possible due to the presence of a parallel conduction channel, which is electrostatically connected to the main channel. We have recently observed such a phenomenon in high-electron-mobility transistor (HEMT) structures based on GaN/AlGaN [10]. A similar effect may occur due to the drift of slow-moving charge carriers in the parallel channel under the action of the longitudinal electric field as a reaction to the spatial fluctuations of the field in the main channel. It should be noted that this effect is accompanied by a significant increase not only in the RTS noise, but also in the level 1/*f*-noise, i.e. the noise of such structures is extremely sensitive to the situation in the parallel channel.

In practice, it is convenient to use dimensionless value $R = \tau_e/\tau_c$ (*R* factor). The sensitivity of the time constants τ_c and τ_e, as well as the factor *R*, to optical irradiation with a wavelength of 0.95 μm are determined for nanoscale FETs with *n*-channel of small sizes: width equal to 40 nm, length equal to 50 nm. RTS fluctuations with extremely low frequencies (units and tenths of Hz) were detected in practically all samples. In some cases, exposure leads not only to changes in the parameters of RTS fluctuations but also to the appearance of new RTS components. Fig. 2 shows the typical dependences of the capture time constants: τ_c and emission τ_e on the current in the channel of the nanoscale FET structure with a polysilicon gate.

The RTS noise behavior is described below. Based on Eq. (2), it is possible to analyze the dependences of the time constants τ_c and τ_e on the gate voltage. However, the influence of optical radiation with different wavelengths is required for the fine-tuning subject of digital RTS signal parameters. It should be noted that the dependences presented in Fig. 2 are slightly different, from dependences for the situation where the trap is in the neutral channel area and $\neq f(I_{DS})$, and in particular, the value τ_e is not constant when the current changes. This indicates that the trap center is not in the neutral region of the channel, but in the region of space charge of the small nanoscale FET structure.

Detailed studies of this sample revealed a high sensitivity of the parameters of RTS fluctuations to the intensity of irradiation with an infrared wavelength of 0.95 μm. Fig.3 shows the dependences of time constants on the intensity of irradiation. It should be emphasized that such samples do not show hysteresis phenomena or degradation under the influence of irradiation. Fig. 3 shows that the threshold radiation power that results in the influence on characteristic time constant is equal $\sim 2 \times 10^{-3} \mathrm{mW/cm^2}$. The values of the time constants at the minimum values of the irradiation power are slightly different from the values obtained after a cycle of measurements at the same power (large symbols). At the same time, the latter coincide well in magnitude with the initial values represented by the horizontal sections of the graphs. This can be explained by the small recharging of slow centers in the dielectric. Strong characteristic time constant dependence on optical excitation is registered for irradiation power range from $2 \times 10^{-3} \mathrm{mW/cm^2}$ to $7 \times 10^{-1} \mathrm{mW/cm^2}$. The results are very promising for the development of tunable by light two-level signal applications.

The corresponding dependence of the R factor is shown in Fig. 4. Starting from power $P = 2 \cdot 10^{-3}$ mW/cm^2, a power dependence $R(P) \sim P^{1.3}$ is observed. One can see that the sensitivity of dimensionless R-factor reflecting change of RTS fluctuations parameters to infrared light increases as $R \sim P^{1.3}$ in a wide range of irradiation power. It should be noted that the efficiency of absorption of an electromagnetic wave by an electron or a hole captured by a trap depends significantly on the irradiation power.

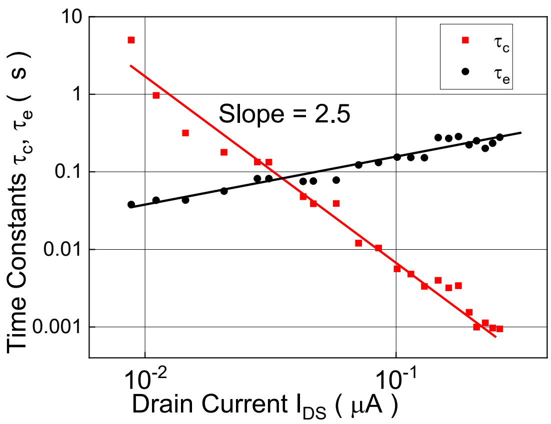

Fig. 2. Dependences of the capture time τ_c and emission τ_e constants on the current in the channel of the nanoscale FET structure with a polysilicon gate that is 40 nm in width and 50 nm in length when irradiated with light with a wavelength of 0.95 μm and a power of 0.1 mW/cm^2. The current was changed by changing the V_{GS}.

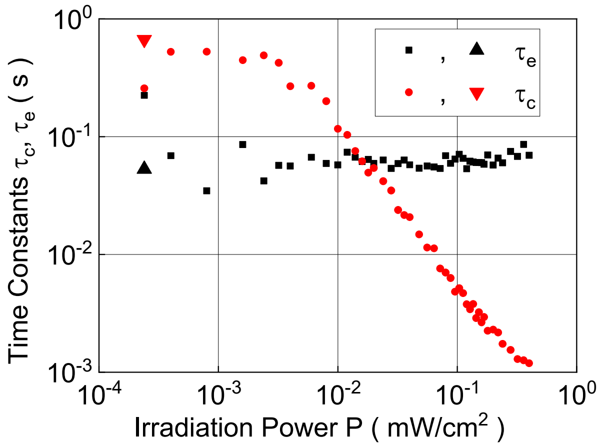

Fig. 3. Dependences of the capture time τ_c and emission τ_e constants in the channel of a nanoscale FET structure with a polysilicon gate 40 nm width and 50 nm length when irradiated with light with a wavelength of 0.95 μm vs the irradiation power, V_{GS}=0, I=43 nA. Enlarged triangular symbols correspond to repeated measurements in the absence of exposure to light.

Usually the light absorption of an electromagnetic wave has a maximum below which the energy of the photon is insufficient to activate the trap and above which a third particle is necessary, the phonon, the energy of which corresponds to the excess energy. As is already known, three-particle processes are less likely than two-particle processes, which occur when the trap activation energy and photon energy coincide. By selecting electromagnetic radiation with an appropriate wavelength, in our case of 950 nm, it is thus possible to effectively influence the parameters of RTS fluctuations with the light of low intensity, as well as to choose a trap with the appropriate activation energy, i.e. to ensure the selectivity of RTS fluctuations.

Fig. 5 shows the sequence of changes in the active trap as the intensity of IR irradiation increases. In the absence of irradiation, only one very low-frequency trap is active, which generates RTS-1 fluctuations (blue lines).

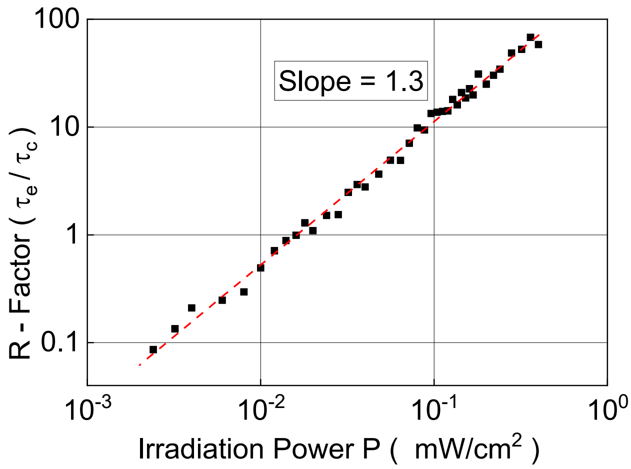

Fig. 4. Dependence of the R factor in the channel of the nanoscale FET structure with a polysilicon gate 40 nm in width and 50 nm in length when irradiated with light with a wavelength of 0.95 μm as a function of the irradiation power, V_{GS}=0, I=43 nA.

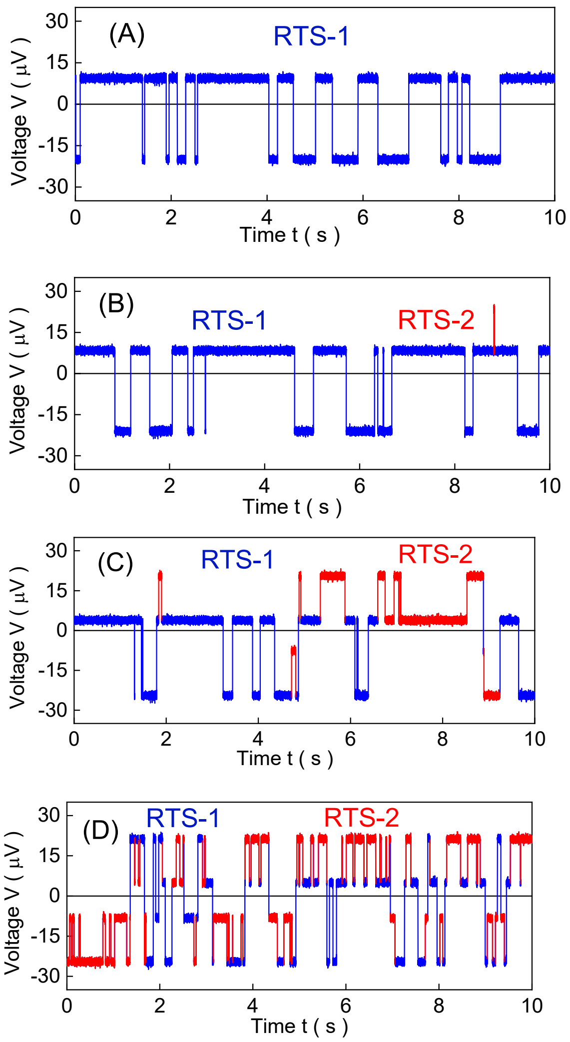

Fig. 5. Time traces of the fluctuation process measured for nanoscale FET. RTS-1 (blue lines) and RTS-2 (red lines) at a different power of irradiation: (A) P = 0, (B) P = 0.08 mW/cm^2, (C) P = 0.40 mW/cm^2, (D) P = 20 mW/cm^2 IR irradiation, λ=0.95 µm. The nanoscale FET structure has a polysilicon gate 40 nm in width and 50 nm in length, V_{GS}=0.6V, I=270 nA

Under the influence of irradiation, another trap becomes active, which results in the generation of RTS-2 fluctuations (red lines). As the intensity of irradiation increases, the frequency of RTS pulses also increases (the time constant τ_c decreases). RTS fluctuations can be well separated in amplitude. The results demonstrate that an additional trap can be initiated by light with relatively shorter time constants compared to the characteristic times measured for a trap in dark. A model of the potential profile description for carriers in NW structure is discussed to describe the mechanisms of capture dynamics in fabricated NW FETs and to control sensitivity in advanced biosensors.

IV. CONCLUSIONS

It was revealed that the parameters of RTS fluctuations can be effectively tuned by optical excitation. Moreover the parameters can be tuned by infrared radiation without changing external voltages. It was shown that the appropriate trap can be selected, which allows for the small responses from biochemical reactions in the liquid to be increased when detecting RTS fluctuations. In the experiments performed, a change in dimensionless R factor by 3 orders of magnitude was obtained when the intensity of optical radiation changed from 0.002 mW/cm^2 to 0.4 mW/cm^2. The obtained results can also be applied to different areas, including for example reducing the noise of optical matrix photodetectors with a high resolution and biosensing applications. Thus, this work opens prospects for the development of a new generation of biosensors, utilizing quantum effects in low-dimensional transistors and single-trap phenomena. The use of single-trap phenomena as a sensing technique involving traps with statistically repeatable signal change can be considered as an approach to overcome the signal-to-noise limitation and to get detection of biological signal in a very short time.

ACKNOWLEDGMENT

M.P. is very grateful for partial support of Helmholtz Fond for research grant and Dr.W.Albrecht, Helmholtz Nano Facility (HNF) of Forschungszentrum Jülich for support of research grant as well as for research grant received from the Philipp Schwartz Initiative of the Alexander von Humboldt Foundation. YZ and HL are very grateful for a research grant received from the China Scholarship Council (CSC).

REFERENCES

[1] M. Petrychuk, I. Zadorozhnyi, Y. Kutovyi, S. Karg, H. Riel and S. Vitusevich. "Noise spectroscopy to study the 1D electron transport properties in InAs nanowires. Nanotechnology",vol.. 30, pp.305001-1-9 (2019).

[2] S. Pud,J. Li,V. Sibiliev, M. Petrychuk,V. Kovalenko, A. Offenhäusser, S. Vitusevich. „Liquid and Back Gate Coupling Effect: Toward Biosensing with Lowest Detection Limit ". Nano Letters. ,vol.14,pp-578-584 (2014).

[3] S. Pud, F. Gasparyan,M. Petrychuk,J. Li,A. Offenhäusser, S. A. Vitusevich. "Single trap dynamics in electrolyte-gated Si-nanowire field effect transistors". Journal of Appl. Phys,vol.. 115, pp. 233705-1-11 (2014).

[4] .J. Li, S. Pud, M. Petrychuk, A.Offenhäusser, S.Vitusevich. "Sensitivity Enhancement of Si Nanowire Field Effect Transistor Biosensors Using Single Trap Phenomena" Nano Letters. ,vol.14, pp.3504-3509 (2014).

[5] Y. Kutovyi, I. Zadorozhnyi, V. Handziuk, H. Hlukhova, N. Boichuk, M. Petrychuk, S. Vitusevich . "Liquid-Gated Two-Layer Silicon Nanowire FETs: Evidence of Controlling Single-Trap Dynamic Processes" Nano Letters. Vol.18, pp.7305-7313 (2018).

[6] Y. Kutovyi, I. Zadorozhnyi,H. Hlukhova,V. Handziuk,M. Petrychuk,A. Ivanchuk,S. Vitusevich. Origin of noise in liquid-gated Si nanowire troponin biosensors. Nanotechnology.,vol. 29,pp.175202-1-11 (2018).

[7] Y. Kutovyi,I. Zadorozhnyi,V. Handziuk, H. Hlukhova, N. Boichuk, M. Petrychuk, S. Vitusevich. "Temperature-Dependent Noise and Transport in Silicon Two-Layer Nanowire FETs" Phys. Status Solidi,vol. B. 156, pp.1800636-1-6.(2019)

[8] Y. Kutovyi, V. Piatnytsia, N. Boichuk, I. Zadorozhnyi, Jie Li, M. Petrychuk, S. Vitusevich . "Boosting the Performance of Liquid-Gated Nanotransistor Biosensors Using Single-Trap Phenomena" . Adv. Electron. Mater. ,vol.7, pp. 2000858-1-10 (2021)

[9] Y.Kutovyi, H.Hlukhova, N.Boichuk, M.Menger, A.Offenhaeusser, S.Vitusevich, "Amyloid-beta peptide detection via aptamer-functionalized nanowire sensors exploiting single-trap phenomena". Biosensors and bioelectronics. ,vol. 154, pp.112053-1-8 (2020)

[10] M.Petrychuk, S.Vitusevich. "Transformation in low-frequency noise spectra in GaN HEMT in non-equilibrium conditions".. Physica Status Solidi (a) Applications and Materials Science.,vol.220,pp. 2200619 -1-5, (2022),.