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Silicon nanowire field-effect transistor biosensors with bowtie antenna ☆

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ABSTRACT

In this study, we fabricated high-quality, liquid gate-all-around silicon nanowire (NW) field-effect transistor (FET) biosensors with a gold bowtie antenna using a silicon-on-insulator (SOI) wafer. The electrical and noise properties of these novel NW FETs were investigated under 940 nm light-emitting diode (LED) optical excitation in different solutions. A two-level signal (TLS) that is useful for biosensing was successfully activated at the light excitation only. The detection of repeatable fluctuations in current, manifested as minor peaks in the I–V curves under infrared illumination, confirms the activation of a TLS in the biosensors. The TLS demonstrates a linear dependence of its amplitude in relation to intensity. Moreover, we performed TLS studies in $MgCl_2$ solutions of different concentrations. The results indicate that the FET devices incorporating a gold antenna have considerable potential for the excitation of TLS, thus allowing the sensitivity of the biosensors to be about 300 % enhanced.

1. Introduction

To develop a high-performance, liquid gate-all-around (LGAA) FET biosensor, a stronger emphasis on the fabrication technology and measurement methodology is essential [1]. In particular, the development of optically controlled device structures allows for the more flexible tuning of their properties. Optical radiation induces a redistribution in the population of discrete energy levels, thus enabling the generation of two-level signal (TLS) [2,3]. It should be emphasized that TLSs play a critical role in different digital signal applications, including biological detection. Kutovyi et al. reported that in comparison to the standard approach based on current change due to a threshold voltage shift, the novel approach based on the utilization of single-trap phenomena with TLSs resulted in a 300 % improvement in sensitivity [4].

Petrychuk et al. demonstrated that the TLS phenomenon can be controlled in nanotransistors with a polysilicon gate when subjected to infrared light excitation [5]. Furthermore, the biosensitivity in liquid-gated devices can be enhanced, as the parameters of single-trap and interface phenomena can be effectively modulated by light [6]. This assists in establishing optimal sensitivity regimes. Pud et al. utilized a gold bowtie antenna [7] on the surface of a SiN_x membrane to fabricate a nanopore in dielectric layer through utilization of surface plasmon resonance [8] induced by laser irradiation. We hypothesized that the gold bowtie antenna could be used to influence the properties of the dielectric layer without destroying it but instead activating the TLS.

In this work, we fabricated a gold bowtie antenna and excited it by small varying intensities of light to influence the properties of the underlying dielectric layer in the NW LGAA FET (Fig. 1 (A)). The successful activation of the TLS phenomenon was achieved by regulating the intensity of the light source without destroying the dielectric layer. According to the results of the electrical experiments, the I–V curves exhibited a shift corresponding to an increase in the intensity of the LED. This alteration in current is identified as the photocurrent. In the noise spectra, a distinct Lorentzian-shaped noise component was observed exclusively when the LGAA NW FET was excited by the LED. The results revealed that the gold antenna exhibits considerable potential for applications in generating the TLS, which is useful for enhancing the sensitivity of biosensors.

2. Results and discussions

High quality liquid-gate controlled NW FETs were fabricated based

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on SOI wafer with 50 nm undoped silicon layer using CMOS compatible technology [9]. On the top of each nanowire channel a gold bowtie antenna (Fig. 1A) was formed, using electron beam lithography (EBL) patterning. The thickness of patterned gold layer was 40 nm on the surface of 20 nm dielectric SiO_2 layer. The electrical field redistribution between two triangular components of the antenna was modeled using Ansys Lumerical FDTD software for several distances between two parts of the antenna. The results of calculations for distance of 40 nm between two parts of the antenna, corresponding to fabricated antenna, studied in this work, are shown in Fig. 1 (B). It should be noted that 40 nm-distance samples were selected as high-quality samples with the smallest distance obtained after EBL patterning. The optical simulation data show that the maximum value of the electrical field, E, is formed at the sharp edges of two parts of the antenna. The maximum intensity of the electrical field induced by the plane wave of 100 V/m was approximately 30 kV/m for the distance of 40 nm. The latter corresponded to the investigated LGAA NW FET samples.

To investigate the features, observed in transfer I–V curves under the influence of light, we performed studies of LGAA NW FETs using varying intensities of a 940 nm LED. Fig. 2 (A) presents the current–voltage (I–V) characteristics of the LGAA NW FETs with an antenna, measured under increasing intensities of infrared excitation. In these studies, a small drain-source voltage, $V_{DS,}$ of −10 mV was applied for studies of I–V characteristics for biosensors in 1 mM PBS solutions at different light intensities. The magnitude of the photogenerated current exhibits a gradual increase with the enhancement of the light source's intensity, resulting in a well-correlated shift of the I–V curves. The modeling was performed to support this phenomenon: In the context of a gold antenna, a notably strong potential gradient is established within the structure. The nanostructure, incorporating a gold antenna, generates a photovoltaic effect (Fig. 2) that induces potential redistribution upon the intensity of the light. Fig. 2 (B) presents the photogenerated current values derived from the data in Fig. 2 (A), measured at zero V_{LG}. The photogenerated current exhibits a linear relationship with light intensity. Minor peaks were identified in the I–V curves during the infrared treatment, indicating fluctuations in the current (Fig. 2 (A)). The data indicate that the frequency of current fluctuations increases considerably with the enhancement of the 940 nm LED intensity. The initial hypothesis that TLS can be excited using antenna is confirmed through subsequent analyses of noise spectra and time trace experiments.

To examine the relationship between the influence of the antenna fabricated on the surface of the nanowires and the dynamics induced by light in the gate SiO_2 layer contacting with the PBS solution in LGAA NW FETs, noise spectra were measured using home-made noise experimental setup [10] under varying intensities of 940 nm LED excitation in a 1 mM PBS solution at pH = 7.4. Fig. 3(A) shows the typical power spectral density (S_V) of the drain voltage for a LGAA NW FET device with a 2 μm nanowire length and a 200 nm width. The measurements were conducted at constant voltages: $V_{LG} = -0.3$ V and $V_{DS} = -10$ mV, under varying intensities of infrared treatment. The measured noise spectra support the previous hypotheses concerning the behavior of the I–V characteristics. The Lorentzian peak is observed under the condition of excitation with a 20 mW/cm^2 intensity, as depicted in Fig. 3 (A), which corroborates our findings. The findings reflect that, under conditions of light excitation, the LGAA NW FET devices with a bowtie antenna assists in activation of the TLS at the Si/SiO_2 interface, resulting in the manifestation of modulation phenomenon.

Fig. 3 (B) illustrates the dependence of S_V multiplied by frequency, f, plotted as a function of f. The Lorentzian component becomes more pronounced in such a plot in noise spectra and can be analyzed as a function of illumination. The shape of noise spectra appears to be substantially influenced by light excitation. As the intensity of light increases, the noise spectra exhibit the development of Lorentzian-shaped features, ultimately achieving a perfect Lorentzian shape when the intensity of the 940 nm LED reaches 20 mW/cm^2.

Fig. 4 shows the TLS, which was recorded under 940 nm LED illumination utilizing an in-house noise measurement system at a constant V_{LG} of −0.5 V and a V_{DS} of −10 mV. The initiation of TLS in the PBS solution with pH = 7.4 only occurred under light excitation of gold bowtie antenna.

The amplitude of TLS increases with infrared intensity ranging from 12 mW/cm^2 to 20 mW/cm^2.

Analysis of time traces demonstrates very good correlation with registered Lorentzian components in the noise spectra. It is crucial to emphasize the correlation between this initial condition of light excitation and the TLS in the sample with the antenna. The increase in TLS amplitude correlates with the growth of photocurrent and exhibits a linear relationship with infrared intensities. It is important to note that the TLS in our NW FETs is observed exclusively under the light excitement and disappeared upon the light switching off. The fact reflects that TLS is activated at the Si/SiO_2 interface due to influence by light in the region with the antenna of the LGAA FET device exclusively under infrared light due to plasmonic effect [8]. Moreover, our results of studies in different $MgCl_2$ solutions show that the TLS approach allows the sensitivity in biosensors to be enhanced by about 300 % (Fig. 5) compared to the standard approach utilizing a shift in threshold voltage [11] resulting in I_D change obtained at definite V_{LG}.

Upon infrared excitation, the gold antenna effectively activates a TLS in proximity to the Si/SiO_2 interface, which is revealed in the time trace measurements for different $MgCl_2$ solutions and analyzed using the statistical histogram method. The data show that the slope for linear fit of red points increases by 3 times compared to the slope obtained for blue points. This fact reflects the enhancement [12] up to 300 % of the biosensor sensitivity.

3. Conclusion

In summary, our findings based on the comparison of simulation data

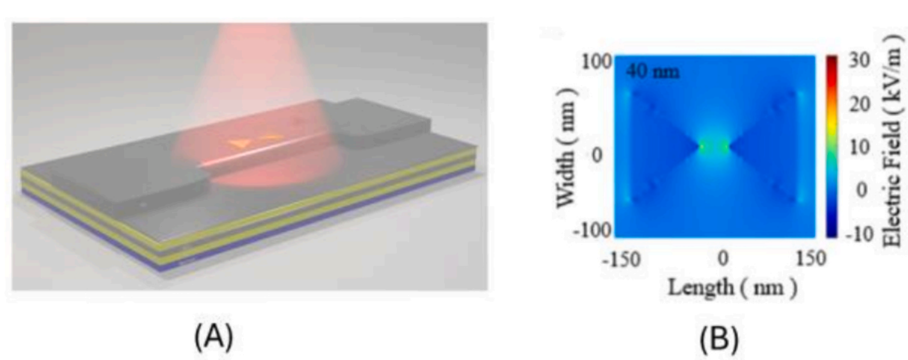

Fig. 1. (A) Schematic presentation of a LGAA NW FET with a gold bowtie antenna under 940 nm LED excitation. (B) Modeling of the electric field distribution in relation to the longitudinal axis of a bowtie antenna under LED excitation for antennas with distances between two gold parts of 40 nm.

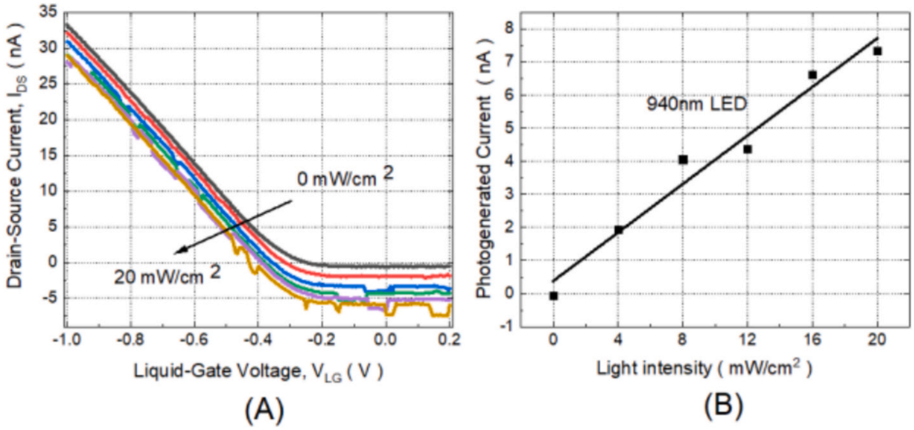

Fig. 2. (A) The transfer characteristics of a 200-nm-wide and 2-µm-long nanowire in LGAA NW FET devices with a gold bowtie antenna, were measured at $V_{DS} = -10$ mV in 1 mM phosphate-buffered saline (PBS) at pH 7.4 under varying intensities of 940 nm LED excitation (mW/cm^2): 0,4,8,12,16,20; (B) The photogenerated current extracted from Fig. 2 (A) data, demonstrates a linear relationship with the intensities of the 940 nm infrared LED. The black line represents a linear fit for the registered photogenerated current at $V_{LG} = 0$.

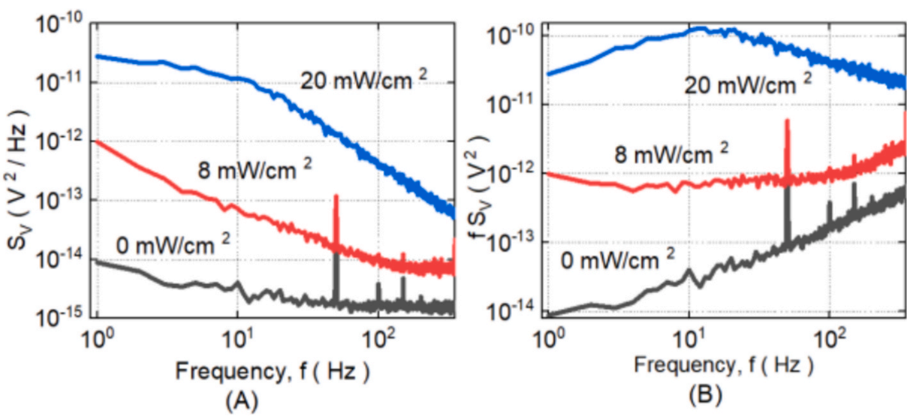

Fig. 3. (A)The voltage spectral density was measured for a nanowire with dimensions of 2 µm in length and 200 nm in width, subjected to varying intensities of a 940 nm LED. This measurement was conducted under a constant gate voltage (V_{LG}) of −0.3 V and a drain-source voltage (V_{DS}) of −10 mV in a PBS solution. (B) The normalized noise spectral density at constant V_{DS} and V_{LG}, revealing pronounced Lorentzian noise components under light excitation of 20 mW/ cm^2.

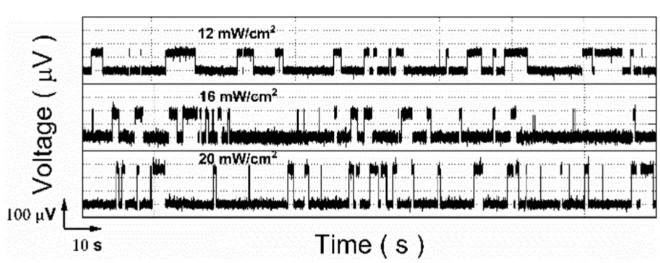

Fig. 4. The TLS, measured for LGAA NW FETs with a nanowire that was 2 µm in length and 200 nm in width under different intensities of a 940 nm LED.

and transport characteristics of fabricated LGAA NW FET biosensors demonstrate the significant role of a bowtie antenna under 940 nm LED excitation of different intensity. In terms of electrical performance, it was observed that under light treatment, the I–V curves of the LGAA transistor exhibit a shift relative to the reference line recorded without optical excitation in a 1 mM PBS solution. The study also identified the photocurrent when the gate voltage was set to zero and revealed minor peaks in the I–V characteristics. This fact suggests that TLS current fluctuations are induced by the light. The analysis of the Lorentzian components within the voltage spectral density has confirmed the excitation of TLS in LGAA NW FET biosensors with an antenna under

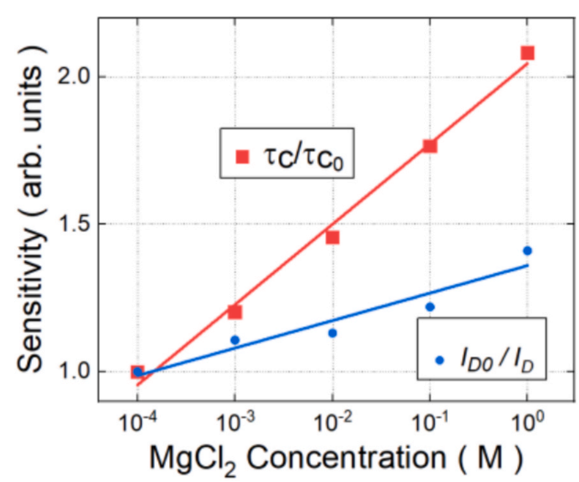

Fig. 5. Extracted characteristic time constant as a function of $MgCl_2$ concentration normalized to starting time constant (obtained for 10^{-4}M $MgCl_2$ solution) under influence of 940 nm LED excitation shown in comparison to standard change in drain current, I_D, (because of threshold voltage shift) with increasing $MgCl_2$ concentration plotted as normalized I_{D0} (obtained at starting small $MgCl_2$ concentration) to I_D. The following physiologically relevant $MgCl_2$ concentrations (M): 10^{-4}, 10^{-3}, 10^{-2},10^{-1}, 10^{0} are studied.

infrared light treatment. The data obtained open up prospects for the use of LGAA FETs with bowtie antenna in different applications, including biosensor technologies.

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CRediT authorship contribution statement

Yongqiang Zhang: Investigation. **Kai Li:** Investigation. **Nazarii Boichuk:** Investigation. **Denys Pustovyi:** Investigation. **Valeriia Chekubasheva:** Investigation. **Hanlin Long:** Investigation. **Mykhailo Petrychuk:** Investigation. **Svetlana Vitusevich:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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