Silicon Nanowire Field-Effect Transistor Biosensors with Bowtie Antenna

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Abstract — **In this study, we fabricated high-quality, 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 excitation in different solutions. A two-level signal (TLS) that is useful for biosensing was successfully activated by light excitation. The TLS demonstrates a linear dependence of its amplitude in relation to intensity. 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 enhanced.**

I. 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 signals (TLSs) [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 on the surface of a SiN_X membrane to fabricate a nanopore in dielectric layer through surface plasmon resonance induced by laser irradiation [7]. 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 excited by small varying intensities of light to influence the properties of the underlying dielectric layer in the NW LGAA FET (Fig. 1A). 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.

II. Results and Discussion

The electrical field redistribution between two triangular components of the antenna was modeled using Ansys Lumerical FDTD software. The results of calculations for distances of 60 nm and 40 nm between two parts of the antenna are shown in Fig. 1B and Fig. 1C, respectively. The optical simulation data indicate that the maximum value of the electrical field, E, exhibits an inverse proportional relationship with the distance between the two components of the antenna. The maximum intensity of the electrical field induced by the plane wave of 100 V/m was approximately 25 kV/m for a distance of 60 nm and 31 kV/m for a distance of 40 nm. The latter corresponded to the investigated LGAA NW FET samples with a fabricated antenna. A scanning electron microscope (SEM) image of the NW cross section, obtained after application of the focused ion beam (FIB) cut technique, is presented in Fig. 1D, illustrating the GAA feature of the NW channel.

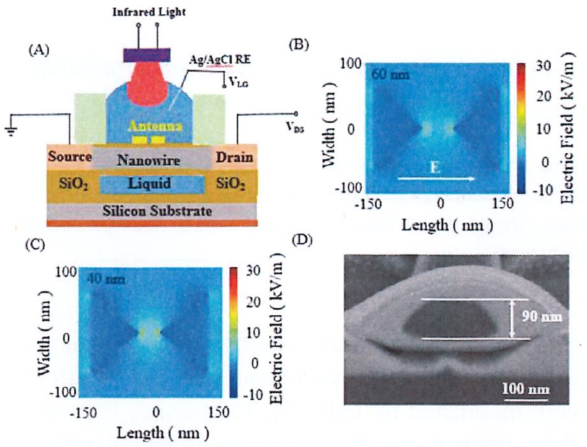

Figure 1. (A) Schematic presentation of a LGAA NW FET with a gold bowtie antenna under 940 nm LED excitation. (B) and (C) The results of modeling electric field distribution in relation to the longitudinal axis of a bowtie antenna under LED excitation for antennas with distances between two gold components of 60 nm and 40 nm, respectively. (D) SEM image of an NW cross section obtained using the FIB cut technique.

Figure 2 shows the amplitude of the TLS, which was recorded under 940 nm LED illumination utilizing an in-house noise measurement system at a constant VLG of 0.5 V and a VDS of 10 mV.

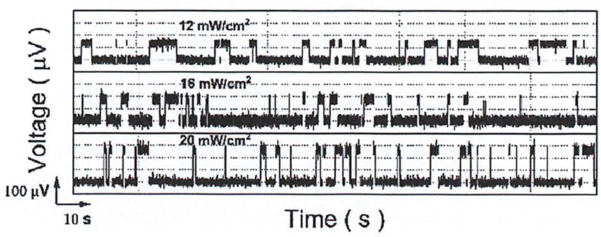

Figure 2. The TLS was measured for LGAA NW FETs with a nanowire that was 2 μm in length and 200 nm in width under different intensities of a 940 nm LED.

The amplitude of TLS increases with infrared intensity ranging from 4 mW/cm^2 to 20 mW/cm^2. The initiation of TLS in the PBS solution with pH = 7.4 only occurred under light excitation. It is crucial to emphasize the correlation between this initial condition of light excitation and the TLS in the sample with an antenna. Moreover, the results of studies in different $MgCl_2$ solutions show that the TLS approach allows the sensitivity in biosensors to be enhanced by at least 230% compared to the standard approach utilizing a shift in threshold voltage.

III. Conclusions

In summary, our findings based on the simulations and transport characteristics of fabricated LGAA NW FET biosensors demonstrate the significant role of a bowtie antenna under various 940 nm LED excitations. 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 and analyzed using the histogram method. 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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