THz Emission and Detection by Quantum Faraday Effect in Silicon Nanosandwich-Structures

Nikolay T. Bagraev[1], Leonid E. Klyachkin[1], Anna M. Malyrenko[1], Andrew L. Chernev[2], Vyacheslav S. Chromov[1], N.I. Rul'[1], Anton K. Emelyanov[2], Michael V. Dubina[3]
[1]Ioffe Institute, St Petersburg, 194021, Russia
[2]St Petersburg Academic University, St Petersburg, 194021, Russia
[3]Pavlov First Saint Petersburg State Medical University, St Petersburg, 197022, Russia

Abstract: We demonstrate a novel approach to the problem of THz emission and detection by the quantum Faraday effect that manifests itself in the conductance of topological edge channels of silicon nanosandwich-structures containing DNA oligonucleotides.

Keywords: quantum Faraday effect, silicon nanosandwich, THz emission, DNA detection.

I. INTRODUCTION

Among prospective paths of the THz emitters and detectors development there is a conception that is highly motivated by the technological progress of topological edge channels in nanostructures. Energy parameters of such objects can be modified in a wide range compared to those of bulk materials.
In this work we study the potential opportunities of the THz emitters and detectors caused by the edge channels of a silicon nanosandwich structure (SNS). The THz emission is suggested to be applied to identify the DNA oligonucleotides deposited inside the SNS edge channels.

II. METHODS

Silicon nanosandwich-structures are based on an ultra-narrow, 2 nm, high-mobility p-type quantum well, Si-QW, confined by the delta barriers heavily doped with boron (5×10^{21} cm^{-3}) prepared within the frameworks of a Hall bar geometry on the n-type Si (100) surface after the preliminary oxidation and subsequent short-time diffusion of boron by the CVD method (Fig. 1a). Boron atoms have been shown to form trigonal dipole (B^+ - B^-) centers due to the negative-*U* reaction: $2B^o \rightarrow B^+ + B^-$, which are able to create the chains confining the edge channels that mainly provide the in-plane conductance of SNS (Figs. 1b,c and d) [1, 2]. According to experimental data provided by the studies of quantum Hall effect as well as de Haas-Van Alphen oscillations, each edge channel consists of the sequence of pixels, $S = 16.6$ μm $\times$ 2 nm, containing single holes (Figs. 1d and e) [1]. In such systems composite bosons and fermions appeared to be revealed even in weak magnetic fields by capturing of the flux quantum on the pixel containing a single hole.

Thus the experimental observation of the quantum Faraday effect becomes to be possible by varying the external magnetic field that induces step-by- step capture of single flux quanta. It should be noticed that the magnetic field value required for a single flux quantum formation in the device structure studied is equal to $H_0 = 1240$ Oe. Specifically, $\Phi_0 = H_0 \times S$, where S is the surface area of a single pixel. In addition to the above noted, the magnetization of the delta-barriers by the exchange interaction between single holes and dipole boron centers gives rise to the Landau quantization of single holes energy spectrum (Fig. 2). Moreover, the change of magnetic flux equal to the value of $\Phi_0=h/e$ provides the

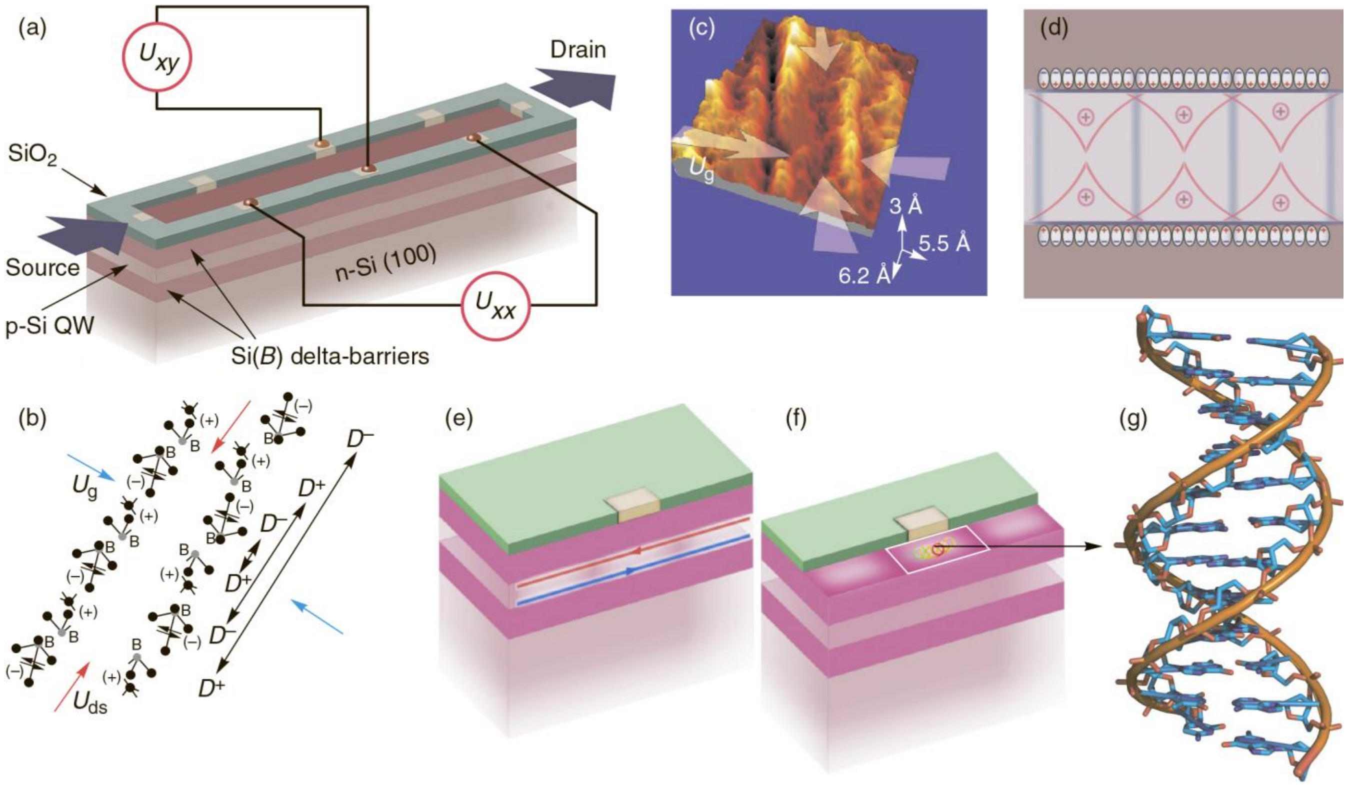


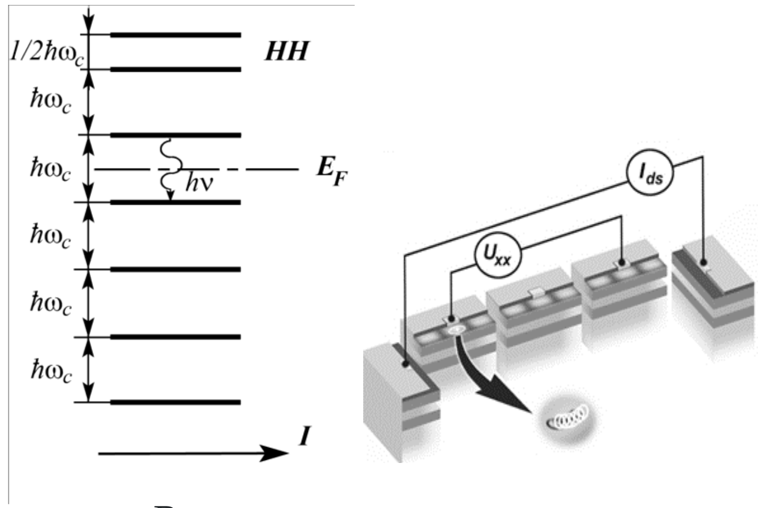
Fig. 1. Scheme of the silicon nanosandwich. (a) The silicon nanosandwich representing the ultra-narrow p-type silicon quantum well confined by delta barriers heavily doped with boron on the n-type Si (100) wafer. (b) The reconstructed trigonal dipole boron centers that result from the negative-U reaction, $2B^o \rightarrow B^+ + B^-$. (c) STM image of the upper delta barrier heavily doped with boron that demonstrates the chains of dipole boron centers oriented along the [011] axis. (d) Diagram showing the wave packs of holes in the edge channels of the dipole boron centers in the delta barriers. (e) Image of the contact region showing the edge channels scheme. (f,g) Scheme of an oligonucleotide molecule placed on the edge channels confined by the dipole boron centers.

formation of the Landau energy gap for heavy holes in silicon nanosandwich that corresponds to the frequency value equal to 2.8 THz that appears to related to the resonant modes of several well-known oligonucleotides [2].

To increase the selective THz line emission, the corresponding system of microcavities is introduced into the Si-QW plane [1]. Such devices allow for the creation of THz spectra that are similar to the self-resonant modes of oligonucleotides. Thus, the excitation of the self-resonant modes of the oligonucleotides deposited in the Si-QW plane becomes possible and provides feedback that gives rise to the changes in the conductance of the edge channels.

The *U-I* characteristics of the silicon nanosandwich prepared within the frameworks of the Hall geometry were measured under the stabilization of a drain-source current to define the resonant frequencies of the oligonucleotides (Fig. 1a).

The oligonucleotides were precisely deposited onto the delta barrier above the edge channels of the silicon nanosandwich with a micropipette and microfluidic system (Fig. 1e, 1f and 1g). The concentration was selected to provide no more than one oligonucleotide per microcavity. The container-type microfluidic system was constructed using polydimethylsiloxane. It is placed on the silicon nanosandwich surface and holds the 0.5 ml drop of solution, preventing it from evaporating. Each



$$\omega_c = \frac{eB}{m^*} \qquad H = \frac{I}{2R}$$

$$\Phi_0 = \frac{h}{e}$$

$$\hbar\omega_c \square \frac{e}{\Delta I} \square \frac{\hbar}{2} \qquad I \square \frac{dE}{d\Phi} = \frac{eU}{\Phi_0} = \frac{e^2}{h}U$$

Fig. 2. The Landau quantization of holes in SNS as a function of the drain-source current which is created by the Faraday effect that is induced by the exchange ordered dipole boron centers confining the edge channels. The transitions between filled and empty states of the Landau levels near the Fermi level appear to result in the generation and detection of the THz emission.

solution drop was deposited on the surface of the silicon nanosandwich using a Proline plus Biohit 0.1-3 µl micropipette. Single-stranded oligonucleotides were synthesized using Applied Biosystems synthesizing equipment, purified with polyacrylamide gel electrophoresis, and extracted in a 0.3 M sodium acetate solution. The investigated sequences were 100 bp 5'-gcgctggctgcgggcggtgagctgagctcgcccccggggagctgtggccggcgcccctgccggttccctgagcagcggacgttcatgctgggagg gcggcg-3' and 50 bp 5'-gcgctggctgcgggcggtgagctgagctcgcccccggggagctgtggccg-3'. The concentrations were 0.22 and 0.98 µg/µl, respectively. These concentrations were chosen to fit the concentration of holes in the edge channels.

The U_{xx}-I_{ds} and U_{xy}-I_{ds} measurement circuit consists of a DC source (Keithley 6221), the U_{xx} and U_{xy} nanovoltmeters (Keithley 2182A), and the earthed metal capsule containing the chip holder. The system is synchronized using the National Instruments Lab View software package. The range of the driving DC drain-source current is (-50 – 50 µA), and the interval between the measured points is 100 nA. Each point was measured 10 times at a 1 ms interval.

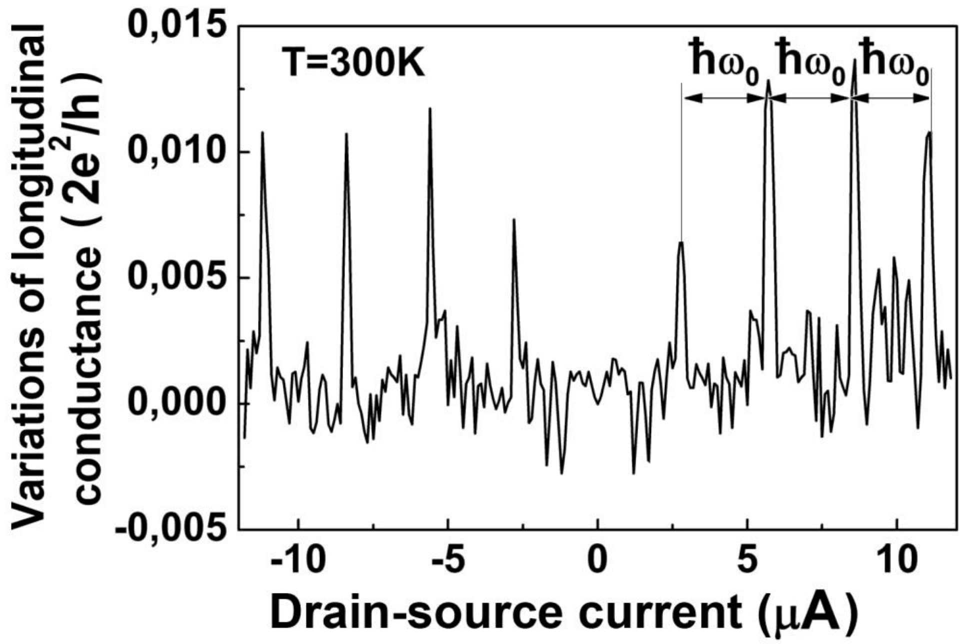


Fig. 3. Quantum Faraday effect revealed by the oscillations of the longitudinal conductance as a function of the drain-source current value, with the period that defines the conditions of the THz generation.

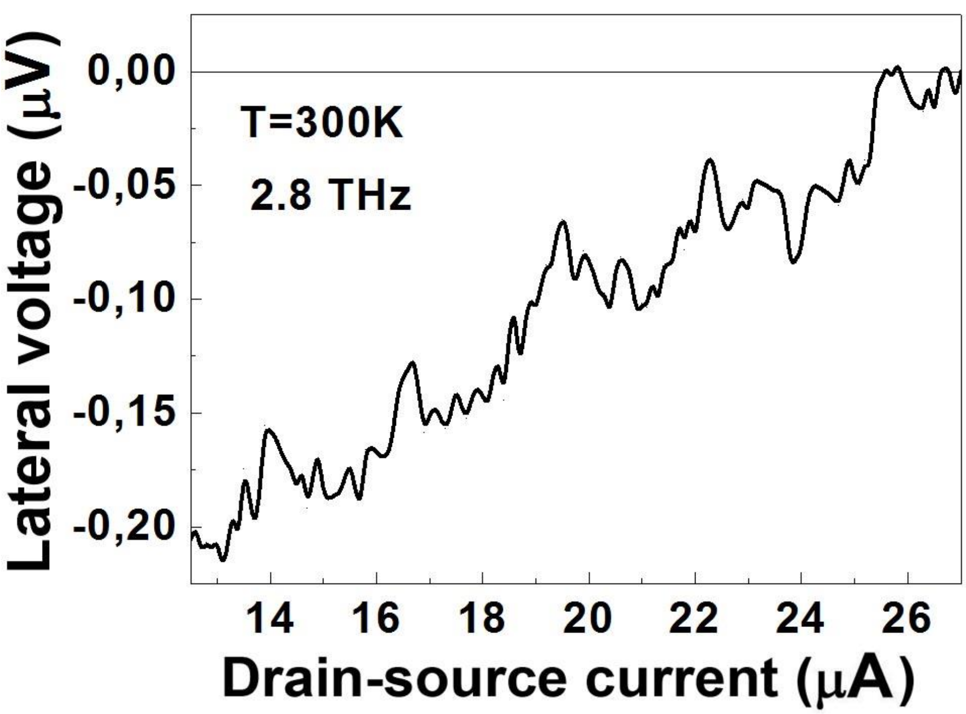


Fig. 4. Quantum Faraday effect revealed by the quantum staircase of the lateral voltage, *Uxy*, as a function of the drain-source current value, with the plateau and peak the period of which result from the conditions of the THz generation.

III. Results and discussion

Here we demonstrate that the quantum Faraday effect can be obtained in SNS with implementation of zero magnetic field by changing the drain-source current value. In this case magnetic moment appears in any pixel analogously to a current loop. In other words, the quantum spin Faraday effect is able to be realized. Thus, the Landau quantization manifests itself in relation to longitudinal conductance and lateral voltage as a function of the drain-source current in analogy to the formation of the Shubnikov-de-Haas oscillations and the quantum Hall resistance staircase [2]. Thus induced transitions between filled and empty states of the Landau levels near the Fermi level appear to result in the generation and detection of the THz emission (Fig. 2). For example, the oscillations of G_{xx} and quantum staircase of *Uxy* shown in Figs. 3 and 4 that appear to be due to the balance of generation provided by the SNS emission and detection of a reflected signal from an oligonucleotide on its surface [2], correspond to the frequency value equal to 2.8 THz.

IV. Conclusion

Finally, the study of the SNS current-voltage characteristics under the conditions of the quantum spin Faraday effect can be used as a method of the THz emission diagnostics. This THz diagnostics is demonstrated for the identification of the oligonucleotides deposited in the SNS edge channels by measuring the longitudinal conductance oscillations and the quantum staircase of the *Uxy* as a function of the drain-source current value. Thus, we propose a rapid technique for analyzing of the THz characteristics of various oligonucleotides using a SNS with microcavities inserted into the edge channels.

Acknowledgment

N.T. Bagraev, L.E. Klyachkin, and A. M. Malyarenko acknowledge the support of the Presidium of the Russian Academy of Sciences, program “Topical Problems of Low-Temperature Physics”, grant no. 10.4, project no. 10.17, the support of Ioffe l Institute, Russian Academy of Sciences and the support of the Department of Science and Higher Education of the St. Petersburg government. A.L. Chernev, A.K. Emel’yanov, and M.V. Dubina acknowledge the support of the Foundation for Assistance to Small Innovative Enterprises (FASIE); and the Department of Science and Higher Education of the St. Petersburg government.

The study was supported in part by the Ioffe Physical–Technical Institute, Russian Academy of Sciences, and St. Petersburg Academic University, Russian Academy of Sciences.

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