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Magnetic properties of edge channels of silicon nanosandwich structures with deposited DNA oligonucleotides

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Measurements of the field dependences of the static magnetic susceptibility demonstrate de Haas-Van Alphen and Aharonov-Bohm oscillations at high temperatures and low magnetic fields in silicon nanosandwich structures (SNS). In the case of the deposition of DNA oligonucleotides into the edge channels of the SNS, a change in the oscillation period is observed. The possibilities of using the obtained data to identify the properties of DNA oligonucleotides are discussed.

Keywords: THz radiation, DNA identification, de Haas-Van Alphen, Aharonov-Bohm.

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Introduction

Study of DNA oligonucleotide properties and search for new structure identification methods are most essential task of modern science. It is believed that personalized medicine concept will be implemented when the cost of human genome sequencing becomes suffciently low to afford wide implementation [1,2]. In this case most of modern genetic data analysis methods are based on genome sequencing which , in turn, depends on the development of technical methods of detecting oligonucleotide increase per nucleotide [1,2]. However, it should be noted that sequencing is a polynucleotide technology for oligonucleotide identification and analysis, while oligonucleotide sequence properties may be identified as a whole [3,4]. For this, we need to study oligonucleotide molecule properties, which may include dielectric and magnetic properties of DNA.

It was shown before that being based on the comparison of experimental conductivity data [1], nucleotide composition and oligonucleotide length play a fundamental role in formation of dielectric properties of these biomolecules, thus, electrical characteristics of 1 oligonucleotide–1 pixel were studied: SNS edge conductivity channels which constitute capacitance and inductance sequences are associated with deposited biomolecules. Oligonucleotide applied to the SNS surface, in turn, contribute to total capacitance and inductance which allows to rely on identification and determination of their dielectric constants in volt-ampere characteristic study. But since the electric properties interact with magnetic properties, it is interesting to know whether oligonucleotides may be studied by a contactless method using their magnetic properties. This research is focused on this problem — it does not claim to get full oligonucleotide sequencing, but it can provide the information on the presence of oligonucleotide (quantitative information) and serves as a follow-up of oligonucleotide dielectric properties study.

Thus, a silicon nanosandwich (SiNS) sample was use herein to study magnetic properties of DNA oligonucleotides. The investigations of edge channel properties in SiNS detected macroscopic quantum phenomena at high temperatures such as De Haas–van Alphen and Shubnikov–de Haas, quantum Hall effect, quantum conductivity ladder [5]. The obtained data demonstrate that the SiNS edge channels are composed of pixels containing single carriers in conditions of high suppression of electron-electro interaction. Pixel sequence in SiNS may be presented as a system of microresonator which capture magnetic flux quanta and, thus, form composite bosons on single carriers [6]. Therefore, electrical, optical and magnetic properties of edge channels in SiNS depend on the pixel area which determines the characteristics of Faraday effect which is of quantum type in single magnetic flux quanta capture conditions. Thus, the change in effective pixel area, in particular, during DNA oligonucleotide deposition in them, shall cause the change in quantum Faraday effect parameters and, therefore, to the change in recorded macroscopic quantum effects which, in turn, may be a basis for oligonucleotide properties identification [3,7].

1. Experimental procedure

SiNS is a p-type ultra narrow silicone quantum well limited by two delta barriers, heavily boron-doped ($5 \cdot 10^{21}\,\mathrm{cm}^{-3}$) on *n*- silicone (100) surface (Figure 3,5,7). With such superhigh concentration, boron atoms in δ-barriers form trigonal dipole centers ($\mathrm{B}^+ - \mathrm{B}^-$) due to negative-$U$ reaction: $2\mathrm{B}^0 -> \mathrm{B}^+ + \mathrm{B}^-$, whose crystallographic oriented sequences form edge channels responsible for conductivity in p-Si$-$QW. p-Si$-$QW edge channels in longitudinal current conditions are efficient THz- and GHz-radiation sources due to the presence of negative-U dipole boron centers [3,8]. This allows to emit SiNS in THz-band. It shall be noted here that all THz-radiation sources on Earth are artificial. Moreover, these are equipment of huge sizes. However, SiNS is a compact device capable of emitting and detecting in THz-band. Such nanostructure with Hall geometry is a basis for comparative study of DNA oligonucleotide properties [3,7].

oligonucleotide molecules were precisely deposited on δ-barrier over SiNS edge channels using a microdispenser and container-type microfluid system made from polydimethylsiloxane and placed on the SiNS surface [7]. Its volume included $0.5\,\mu$l of solution and prevented evaporation during operation. Single-strand oligonucleotide molecules were synthesized in a oligonucleotide synthesizer by amidophosphite method, purified by electrophoresis method in polyacrylamide gel and extracted in 0.3 molar sodium acetate solution. The following oligonucleotide sequences were studied:

100 bases

5'-gcgctggctgcgggcggtgagctgagctcgcccccggggagctgtggcc ggcgcccctgccggttccctgagcagcggacgttcatgctgggagggcggcg-3'

and 50 bases

5'-gcgctggctgcgggcggtgagctgagctcgcccccgggga gctgtggccg-3'.

oligonucleotide molecule concentrations were chosen such that not more than one oligonucleotide molecule falls on each microresonator whose width is 2 nm, and length is defined by two-dimensional hole density, $3 \cdot 10^{13}\,\mathrm{m}^{-2}$ (Hall measurements [5]), and their values are 0.22 and $0.98\,\mu$g/μl, respectively. These concentrations were selected to satisfy the ratios with the number of holes in the edge channels. For comparative analysis, SiNS without oligonucleotides were also studied, since , as it has been shown herein, buffer solution does not introduce significant changes reflected on SiNS current-voltage curve.

Field dependences of SiNS magnetic susceptibility n two options were recorded herein: 1) with oligonucleotide applied to SiNS edge channels and 2) without oligonucleotide. Both experiments were carried out at room temperature and the results were obtained by Faraday method using MGD 312 FG unit in automatic mode [5,9].

The Faraday method is based on the measurement of interaction force between the material and external magnetic field whose inductance modulus varies with the sample „height"Ȧccording the Faraday method, the relationship between the static magnetic susceptibility and measured force — „magnetic weight" — is defined as follows [9]:

$$\chi(T, B) = \frac{F_0(T, B)}{mB\,dB/dz}. \quad (1)$$

Inductance gradient dB/dz of the external magnetic field is provided by a special form of pole magnet tips, and BdB/dz has the same value throughout the volume occupied by the sample.

For measurement, the sample is placed in a quartz cup which is connected to the scales by a hanger made of the same material. Force $F_0(T, B)$ shall be calculated as a difference of interaction force with magnetic field of the sample placed into the cup and a force applied to an empty cup in the same external conditions.

The setup was calibrated using a reference sample for which a magnetic-pure indium phosphide monocrystal was used with susceptibility $\chi = -313 \cdot 10^{-9}\,\mathrm{cm}^3$/g. And high sensitivity 10^{-9}–10^{-10} CGS, of MGD 312 FG balance spectrometer ensured high stability of BdB/dz calibration.

2. Experiment and results obtained

As a result of the measurements, field dependences of static magnetic susceptibility of SiNS were recorded in two cases: without oligonucleotide (Figgure $1, a-c$) and with oligonucleotide on the SiNS surface KHC (Figure $1, d$–f).

In the first case, powerful diamagnetism was detected in weak magnetic field followed by the corresponding oscillations as a result of Meissner effects which are caused by exchange interaction between single holes and dipole boron centers with negative correlation energy in barriers which limit the edge channel [5,9,10]. This conclusion is confirmed by limit diamagnetic magnetic susceptibility $1/4\pi$ in a weak magnetic field [9,10]. Moreover, De Haas$-$van Alphen and Aharonov–Bohm oscillations were observed whose period is interrelated with the pixel length containing single holes (Figure $1, a-c$). And two types of De Haas$-$van Alphen oscillations were recorded (respectively, in magnetic field ranges $0-300$ and $0-1240$ Oe (Figure $1, a, b$). Based on the pixel sizes containing single holes, a conclusion can be made that carriers responsible for occurrence of De Haas$-$van Alphen oscillations are pairs of holes because the following relation is satisfied $\Delta B \cdot S = \Phi_0$, where $\Delta B = 300$ Oe — is the De Haas$-$van Alphen oscillation period, S — corresponds to the area of two pixels, $\Phi_0 = h/2e$ — magnetic flux quantum, if pairs of holes or electrons serve as carriers. Thus , in weak magnetic fields, macroscopic quantum effects occur in carrier coupling conditions in adjacent channels. In this case, Aharonov–Bohm oscillation period shall also correspond to 300 Oe, i. e. to full population of pair of pixels with magnetic flux quantum $\Delta B \cdot S = \Phi_0$. Actually, such Aharonov–Bohm oscillations occur in macroscopic quantum process conditions in pairs of pixels (Figure $1, b$), but they are quickly attenuated as a result of separation of a pair of carriers with the increase in magnetic field above 300 Oe. In this case, De Haas$-$van Alphen and AB oscillations are caused by size quantization processes in pixels containing single holes: $\Delta B \cdot S = \Phi_0$, where ΔB — oscillation period, S — single pixel area, $\Phi_0 = h/e$ — magnetic flux quantum, if single holes or electron serve as a carrier, i.e. the recorded oscillation periods corresponding to 1240 Oe confirm that

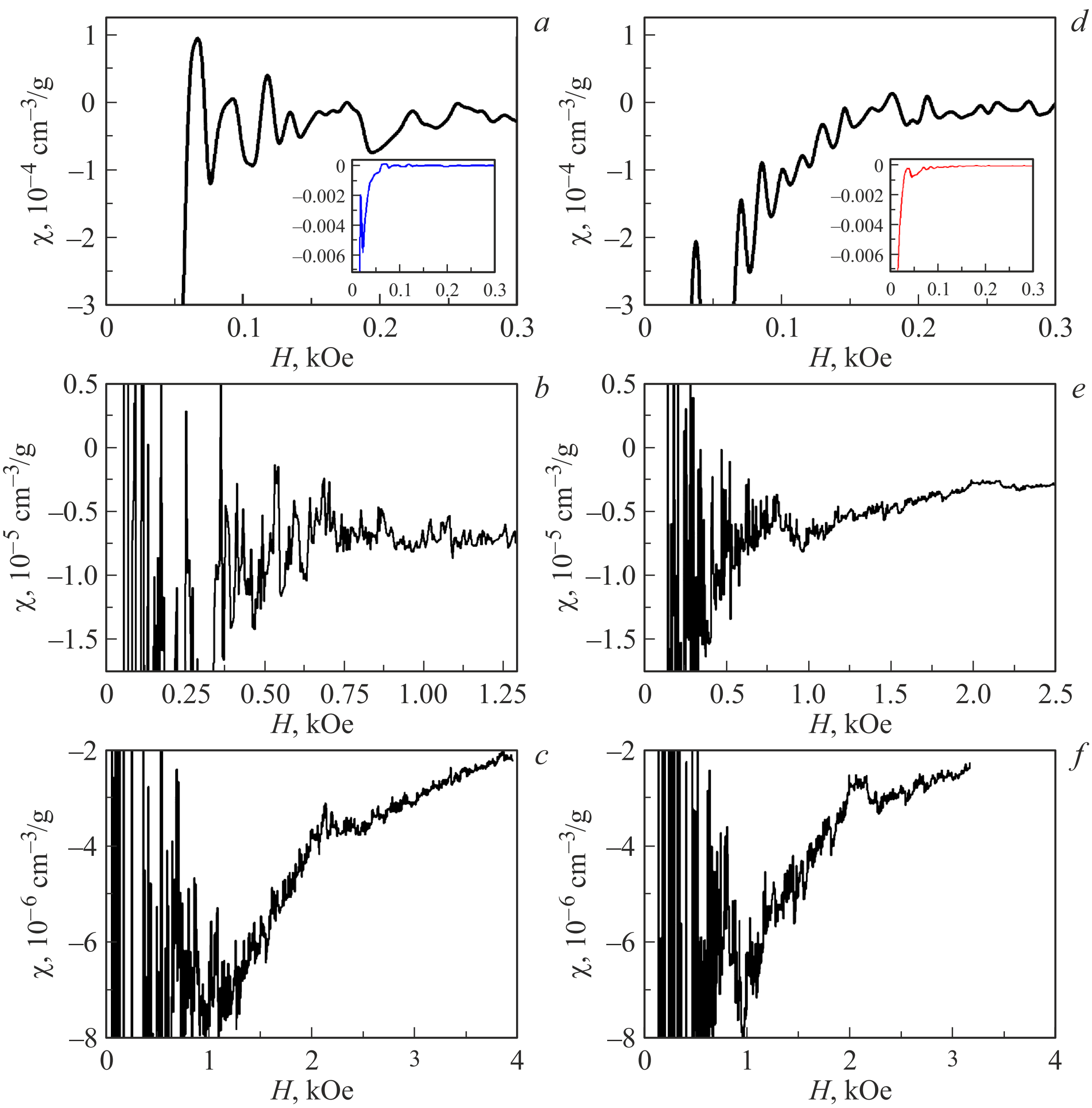

Figure 1. Field dependences od static magnetic susceptibility of silicon nanosandwiches without (*a–c*) and with (*d–f*) DNA oligonucleotides on surface, demonstrating De Haas–van Alphen and Aharonov–Bohm oscillations in magnetic field: *a, d* — 0 to 300; *b* — 0 to 1250; *c, f* — 0 to 4000; *e* — 0 to 2500 Oe. DNA oligonucleotide deposition on the SNS surface causes changes in size quantization. The details show statistical magnetic susceptibility behavior in weak magnetic field range which demonstrates limit diamagnetic values due to the presence of dipole boron centers with negative correlation energy in SiNS edge channels.

occurrence of De Haas–van Alphen and Aharonov–Bohm oscillations in strong magnetic fields was caused by size quantization of single holes in the SiNS edge channels.

It shall be noted that the field dependences of magnetic susceptibility also answer the question how oligonucleotide „lied " on the edge channel. If it „lies" across, this has a significant effect, because the oligonucleotide size (14 nm) exceeds the pixels width (2 nm) by a factor of several times. If oligonucleotide „lies" transversely , this does not have any effect due to the length of the edge channel (8 μm). This is explained by the fact that in different biomolecule location options in the edge channel, pixel area, where magnetic flux quantum is captured, is changed and this, in turn, influences De Haas–van Alphen oscillations. Thus, correlation between oligonucleotide arrangement on SiNS (Figure 2) and field dependences of magnetic susceptibility (Figure 1) is observed.

Study of SiNS with deposited DNA oligonucleotides also shows De Haas–van Alphen and Aharonov–Bohm oscillations, but with other periods and amplitudes (Figure 1, *d–f*).

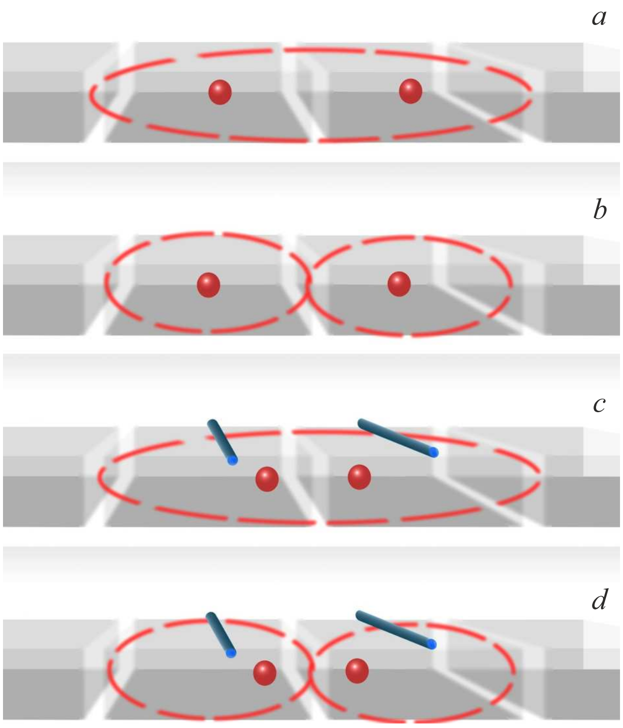

Figure 2. The edge channel in SNS in the absence of (a, b) and in the presence of (c, d) DNA oligonucleotide in pixel containing a single carrier; a, c — size quantization processes are caused by carrier coupling in adjacent pixels in a weak field; b, d — size quantization processes in carrier decoupling in a strong magnetic field.

First of all, note the increase in the period of the above oscillations in the presence of oligonucleotides in pixels. As mentioned above, when oligonucleotides where deposited on the SiNS surface, conditions were selected to ensure that one oligonucleotides corresponds to one hole. In this case, a single hole in a pixel and one oligonucleotide, i.e. the presence of oligonucleotides reduces effective area for the size quantization processes both in case of hole coupling in adjacent pixels and in case of decoupling (Figure 2).

The foregoing causes the increase in De Haas–van Alphen and Aharonov–Bohm oscillation period similarly to the case with the increase in two-dimensional carrier density [5]. According to the presented model of effective pixel area reduction where macroscopic, the increase in oscillation period may be may be explained due to the pair of carriers from 300 to 600 Oe in weak magnetic fields and single carriers from 1240 to 2500 Oe in strong magnetic fields with DNA oligonucleotides deposited on SiNS.

t should be noted that by means of further development of the method for determining De Haas–van Alphen and Aharonov–Bohm oscillation period in DNA oligonucleotide deposition conditions on SiNS, the change in the effective area may be defined more precisely for the size quantization processes in pixels and, thus, to use the obtained data in more detail for their identification.

Conclusion

The conducted study of field dependences of static magnetic susceptibility of silicon nanosandwiches (SiNS) shows that quantum interference in the SiNS edge channels occurs in the presence of both single carries and pairs whose relative contribution varies in the external magnetic field conditions and can be changed significantly when DNA oligonucleotides are deposited on the SiNS edge channels. The study of interrelation of magnetic, electric and optical properties of oligonucleotides deposited on the SiNS edge channels makes it possible to develop an identification technique.

For this, measurements are generally carried out at liquid helium temperatures, because in this case relaxation time is low which is required for quantum interference observation. But in our case, observations are performed at room temperature due to the SiNS properties, because the edge channel is surrounded by dipole centers with negative correlation energy which leads to the increased relaxation time.

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Conflict of interest

The authors declare that they have no conflict of interest.

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