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Nano-electromagnets based on hybrid SiC/Si nanostructures

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Possible ways of obtaining electromagnets using electromagnetic induction on the surface of silicon carbide nanostructures containing silicon vacancies and grown on the surface of monocrystalline silicon by the method of coordinated atomic substitution are considered. The electrical characteristics of boron structures made within the framework of the Hall geometry are investigated, depending on the magnitude of the longitudinal source−drain current, during the transmission of which a magnetic field perpendicular to the plane of the structure is induced. This field determines the characteristics of non-dissipative transport of single carriers in the edge channels of the nanostructure, which are analyzed using the results of conductivity measurements depending on the magnitude of the magnetic current through the area of the edge channel.

Keywords: nanomagnets, magnetic susceptibility, silicon carbide on silicon, silicon vacancies, nanostructures.

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1. Introduction

Presently, developing and producing nanomagnets and various devices based thereon becomes an urgent problem [1,2]. A state of this field of science and engineering is analyzed to show that there are almost no developments based semiconductor nanostructures that contain low-dimensional nanomagnets. Besides, when developing the nanomagnets in combination with the low-dimensional structures, it is required to provide for conditions for nondissipative transport of single carriers, which seems to be a quite difficult task, since incorporation of an additional number of scatterers and various barriers prevents implementation of constructive quantum interference [3].

One of the effective ways of suppressing electron-electron interaction and, thereby, implementation of conditions for formation of spin interference contours inside quasi-two-dimensional and quasi-one-dimensional structures is to use shells that consist of chains of dipole centers with negative correlation energy (negative-U) [4,5]. At the same time, it is possible to separate edge channels limited by chains of negative-U centers into portions that contain single carriers, thereby implementing a variety of interference contours for observing macroscopic quantum effects [6]. It should be noted that nondissipative transport is ensured by constant interaction of the single carriers with the dipole negative-U centers of the shell. This constant energy exchange is replenishment of nondissipative transport, since carrier tunneling through the negative-U dipole centers $(D^+ + D^- + h \Rightarrow D^0 + (D^0 + h) \Rightarrow h + 2D^0)$ is accompanied by escape of the carrier and subsequent reduction of the dipole centers $(2D^0 \Rightarrow D^+ + D^-)$ [7,8]. Nowadays, the above-described principle of implementation of nondissipative transport of the single carries has been realized on several types of semiconductor nanostructures with edge channels, namely, in ultra-narrow quantum wells on the surface of single-crystal silicon [4,5], whose edge channels are limited with the chains of the negative-U dipole boron centers as well as on the surface of the CdB_xF_{2-x} heterojunctions [9,10].

Another possibility of suppressing electron-electron interaction is provided by silicon vacancies V_{Si} in SiC grown by means of a method of coordinated substitution of atoms [11]. The method of coordinated substitution of atoms is based on a reaction of interaction of gaseous carbon monoxide (CO) with a surface of single-crystal silicon at a certain temperature, pressure and flow rate of CO. One of the silicon atoms is removed as a result of this reaction, volatilizing with the SiO molecule, and the other, which is in the Si crystal lattice combines with carbon CO. In doing so, a vacancy is formed in the silicon cell. A distinctive feature of this reaction, which allows growing highly-refined silicon carbide layers on the silicon surface is that it proceeds in three stages separated by time, unlike the reactions used in classical method of growing of Sic on Si.

The first stage of the reaction includes formation of vacancies instead of a part of the Si atoms and arrangement of carbon atoms nearby in interstitial sites in Si. The vacancy compresses the lattice, while, on the contrary, carbon in the interstitial site expands it. The calculations [11,12] show that if these defects are in the plane (111) along the direction $\langle 1\bar{1}0 \rangle$, then they are elastically attracted to each other, thereby resulting in reduction of total elastic energy of the system. A subsurface area of silicon has an assembly of interconnected point defects that are in the study [11] referred to as dilatative dipoles similar to electric dipoles. If there is no attraction between the carbon atom and the silicon vacancy, then elastic stresses would occur in a silicon crystal, thereby resulting in cracking of the SiC layer. The dilatative dipoles are formed uniformly across the entire surface of a substrate. In the Si crystal cell, each fourth Si atom is substituted with the vacancy, while the carbon atom is arranged nearby in the interstitial site.

The second stage of the reaction starts when a transition layer gets a certain thickness. At this stage, the carbon atoms are embedded into a silicon matrix, combining with other silicon atoms. The silicon vacancy and the carbon atom are combined as a result of this process in a coordinated way, i. e. in such a way that the new chemical bonds Si−C are formed simultaneously and in accordance with collapse of old bonds Si−Si. This process occurs simultaneously across the entire surface of the substrate. In doing so, all the carbon atoms are at a time shifted towards the silicon vacancies. The studies generalized in the review [11] have shown that at this stage of synthesis the SiC layer is formed and it is saturated with incompletely-reacted silicon vacancies. In doing so, large shrinkage pores and areas of silicon, which are in a state of transition from silicon to cubic silicon carbide are formed in the silicon substrate under the SiC layer. These areas are referred in the study [12] to as „pre-carbide silicon".

In the third, final stage, when the SiC layer is formed on Si (for the time of synthesis exceeding 5 min), access of CO to deeper Si layers is prevented by the formed SiC layer. In doing so, the still entrapped SiO gas that is still left in the shrinkage pores and dissolved in Si results in deceleration of the SiC formation reaction. At this stage, during shrinkage and structure layer transformation the CO gas „drawn" deep into Si. The CO gas arrives into internal voids in silicon that have been formed during shrinkage and fills these voids. As a result, the pores start intensively forming under the SiC layer in the Si matrix. At this stage of synthesis the density of fine pores increases in a step-like manner. At this moment the elastic compressive deformations become zero, because of vacancy swelling of the material. At this stage of synthesis, the SiC layer originates tensile deformations that compensate the initial compressive deformations. By the 40-th minute of synthesis all the deformations in the SiC layer are fully relieved.

A detailed description of the changes occurring during formation of the SiC/Si structure and the associated significant changes in a number of physical properties of SiC/Si hybrid heterostructures can be found in the studies [11,12]. They can be briefly described as follows:

− in the SiC films grown both on the Si (111) substrates of the *p*-type and the *n*-type, only compressive elastic deformations are formed during synthesis;

− the elastic deformations in the SiC film significantly depend on the SiC synthesis time, having a maximum value at the beginning of synthesis (the 1-st minute of synthesis) and completely relaxing by the 40-th minute of synthesis;

− significant changes are undergone in the optical properties of the films, in particular, there are significant changes in the photoluminescence and ellipsometric spectra and their magnetic properties change, too [13].

It is found in the study [12] that even negatively-charged V_{Si} are quite strongly attracted to each other along the direction $\langle 10\bar{1}\rangle$, forming vacancy threads $Si-V_{Si}-Si-V_{Si}-\ldots$ in the three equivalent directions $\langle 10\bar{1}\rangle$. Attraction is caused by relaxation of C−C carbon bonds that unavoidably originated when the silicon vacancies V_{Si} interact [12]. Pure SiC has no C−C bonds. The initial state of the vacancy thread with the zero magnetic moment is metastable. Tunneling of the electron from one C atom to another with simultaneous spin flip (and origination of the magnetic moment) results in significant reduction of the system energy by relaxation of the C−C bond [12]. The similar processes of tunneling with spin flip and of relaxation of the C−C bonds also occur when the vacancy threads are attracted either to the SiC surface or any interface [13], but at the boundaries the electron is tunneled from the C atom to the Si atom. The tunneling processes $2C^0 \Rightarrow C^+ + C^-$ and $C^0 + Si^0 \Rightarrow C^+ + Si^-$ are totally similar to carrier tunneling through the negative-U dipole centers $2D^0 \Rightarrow D^+ + D^-$, which makes SiC grown by coordinated substitution of atoms a finished material for nondissipative transport of the single charge carriers. In doing so, field dependences of magnetization were measured to detect the Aharonov–Bohm effect and the De Haas–Van Alphen effect when $T = 300$ K due to suppression of electron-electron interaction as a result of formation of the negative-U shells of the edge channels [13–15]. It should be noted that a value of negative correlation energy in the SiC/Si samples, which is 0.132 eV [15], provides conditions for origination of quantum interference when $T = 300$ K. An important factor that confirms identification of quantum interference when $T = 300$ K is recording of a diamagnetic response and the respective magnetization hysteresis in weak magnetic fields [14]. Thus, using the technology of producing the chains of the negative-U dipole centers, which limit the edge channels in the SiC/Si structures, it is possible to realize the conditions of quantum interference at the high temperatures up to the room one.

The studies [13,14] have implemented various interference contours for observing the macroscopic quantum effects when T=300 K on the SiC/Si samples grown by coordinated substitution of atoms. As a result, it was found that varying technological parameters could produce the various interference contours inside the edge channels of the nanostructures with sizes that allowed realizing magnetization regions that are different in area.

The proposed concept of producing the nanomagnets inside the edge channels of the SiC/Si hybrid structures grown by coordinated substitution of atoms is demonstrated in the present study by exemplifying electrical measurements of the magnetic field values by means of electromagnetic induction in conditions of variation of source−drain current (I_{ds}).

2. Methods

As noted above, an advantage of the structures considered in the present study is that quantum interference in the single-carrier system makes it possible to produce the nanomagnets almost for any range of the magnetic field. Moreover, using the planar technology makes it possible to produce multilayer structures, whose depth can comprise local $p-n$ junctions, various loops of structural and impurity, point-like and extended defects, thereby allowing implementing generation of the magnetic field when transmitting both a longitudinal and a transverse current. Upper layers of such nanostructures can have the above-described properties of the negative-U systems, whose framework makes it possible to implement quantum transport of the carriers, which is affected by the magnetic fields generated deep in the structures. Thus, it is now possible to model the influence of the external magnetic field on quantum transport in the edge channels without leaving a studied object.

Static magnetic susceptibility of the SiC/Si hybrid structures used in the present study was measured to show that irrespective of their synthesis time all these structures were diamagnetics ($\chi < 0$). Along with the magnetic measurements, both the SiC layer and the SiC/Si phase interface were structurally studied [13,14]. The high-resolution transmission electron microscopy method was used to show that maximum values of diamagnetism of the hybrid structure corresponded to formation of a transition layer on the SiC/Si interface. It was shown by means of the structure studies that this transition layer consisted of twinned ordered layers arranged parallel to the interface boundary in the plane (111) with a period of 0.252 nm with a triple periodicity, i.e. with an interval of 0.756 nm [13]. The quantum-mechanical calculations have shown that these twinned ordered layers contain ordered assemblies of the silicon vacancies. The electrical characteristics of the SiC/Si hybrid structures and their temperature properties were studied to show that arrays of the silicon vacancies had properties of the chains that consisted of the negative-U centers. Unlike the dipole negative-U boron centers in the silicon nanostructures, which are characterized by negative correlation energy of 0.044 eV, the vacancy negative-U centers in SiC/Si exhibit a much higher value of self-compensation energy — 0.132 eV, thereby determining their significant thermal stability and greater capabilities of practical use [15].

Figure 1 shows a topology of the studied structures formed within the framework of the Hall geometry. The SiC/Si hybrid structures are ultra-narrow quantum wells of p-type of conductance on the surface of n-type single-crystal silicon. Thus, the produced structures contain superfine $p-n$ junctions, which make it possible to control a value of spin-orbit interaction, thereby determining the topological properties. It is especially true for implementation of nondissipative transport of the single carries in the edge channels of the quantum well.

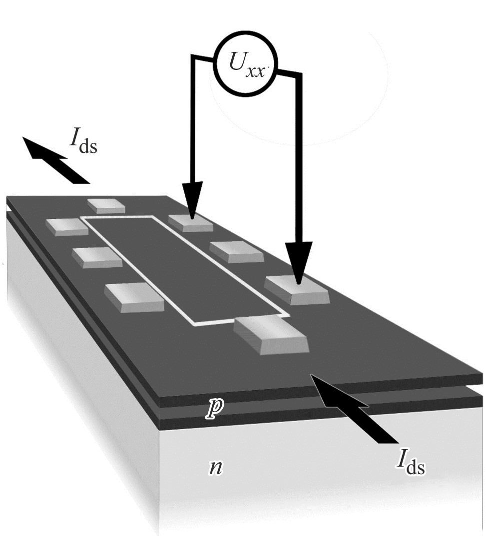

Figure 1. Experimental structure in the Hall geometry.

3. Results and discussion

Figure 2 shows a current-voltage characteristic (I-V curve) of the above-described structure under the conditions of variation of source−drain pulling current. As said above, the studied structure is bilayered. Just below the ultra-narrow quantum well of the p-type with the edge channels limited by the chains of the negative-U dipole vacancy centers, there is the superfine p^+-n junction, along which source−drain current flows. Due to interaction of the silicon vacancies, various loops are formed on the SiC/Si interface, which extend in the three equivalent directions $\langle 10\bar{1}\rangle$ and form triangular, tetragonal and hexagonal closed loops. The C and Si atoms near the threads, which emit and absorb the tunneling electrons due to release of elastic energy of the C−C bonds [12] act like the negative-U centers [13]. During transmission of source−drain current, these loops that consist of intrinsic defects can be regarded as current coils, which are responsible for generation of the internal magnetic field and control transport of the single carriers in the edge channels of the quantum well arranged above the p^+-n junction. It is generation of the magnetic field in the quantum well of the p-type, to which origination of specific features in the recorded I-V curve is related (Figure 2). In this case, variation of pulling current (ΔI_{ds}) stimulates origination of the magnetic field within the framework of electromagnetic induction, which is reflected in respective formation of a magnetic flux in a system of the interference contours between various contacts of an instrumentation structure. Thus, the magnetic field that originates during transmission of current I_{ds}; $H = \Delta I_{ds}/2r_0$, where H — the generated magnetic field when varying source−drain current (ΔI_{ds}), r_0 — the effective radius of the current coil. In case of the interference contour formed between the contacts XX, $r_0 = (S/\pi)^{1/2}$, where $S = ld$ — the area of the interference contour ($l = 2$ mm — the distance between

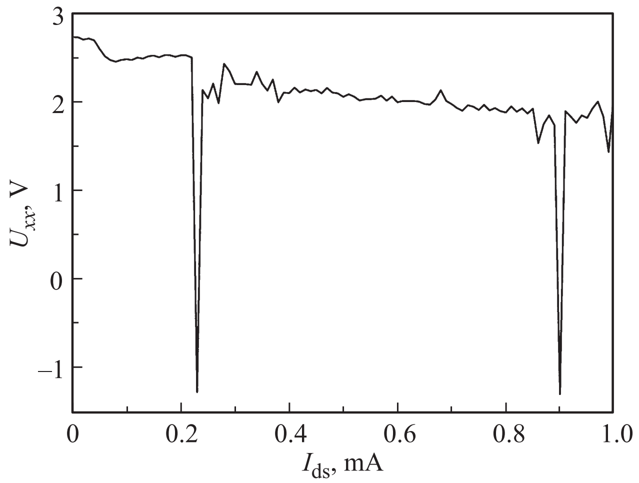

Figure 2. Variation of the value of voltage U_{xx} in a dependence on the value of stabilized source−drain current, I_{ds}. $T = 300$ K.

the contacts XX, d — the width of the interference contour, which can be determined from a relationship for H). Taking into account the structure parameter, $d = 4.2$ nm and, respectively, $S = 8.4 \cdot 10^{-12}\,\mathrm{m}^2$. Whence, it is possible to determine a value of generation current (I_{gen})

$$I_{gen} = \frac{U_{xx}}{R} = \frac{U_{xx}n}{h/e^2} = \frac{U_{xx}ne^2}{h}, \qquad (1)$$

where h/e^2 — quantum resistance of a region of the edge channel (pixel), which contains the single carrier; U_{xx} — EMF between the contacts XX, which is induced by the magnetic field; $n = 400$ — the number of pixels of the edge channel between the contacts XX [5].

Using the relationship for electromagnetic induction, it is possible to determine the value of the magnetic field induced inside the studied structure

$$eU_{xx} = I_{gen}B_{gen}S \qquad (2)$$

whence $B_{gen} = 1.23 \cdot 10^{-6}$ T. It should be noted that almost good coincidence of the value of variation of generated EMF when varying the captured magnetic flux between the contacts XX, $\Delta\Phi = B_{gen}S$, indicates implementation of the conditions of quantum interference of the single carriers. I.e., it is enough to know geometric sizes of the spin contours in order to select a value of the used range of the magnetic fields for implementation of the conditions of quantum interference in the edge channels of the nanostructures in the negative-U shells. In doing so, the magnetic field of the electro-nanomagnets can be controlled by means of a classic relationship for electromagnetic induction in case of using the semiconductor nanostructures with the edge channels limited by the chains of the negative-U dipole centers.

4. Conclusion

It is shown that the internal magnetic field induced during transmission of source−drain current in the SiC/Si hybrid structures with the edge channels limited by the vacancy threads with the negative-U centers makes it possible to determine the value of the external magnetic field responsible for its origination, thereby controlling the characteristics of the electro-nanomagnets. At the same time, the value of the induced internal magnetic field can be determined both using a ferromagnetic probe and by electrical measurements of the value of the arising EMF. The proposed technique of using the chains of the negative-U dipole centers, which limit the edge channels of the SiC/Si nanostructures in the Hall geometry, allows crating electro-nanomagnets for the wide range of the magnetic fields.

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Conflict of interest

The authors declare that they have no conflict of interest.

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