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Magnetism SiC/Si hybrid structures that are synthesized by the vacancy mechanism of coordinated substitution of atoms

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We have investigated magnetic properties of the SiC/Si hybrid structures grown on surfaces of the *n*- and *p*-types of silicon by the vacancy mechanism of coordinated substitution of atoms (VMCSA). Magnetization of the samples was measured in SQUID installations at the temperatures 5, 100 and 350 K at the external magnetic field strengths from -25 to 25 kOe and by a Faraday method in the „Faraday Balance“ installation at the room temperature in the fields from -11 to 11 kOe. Magnetization field dependences obtained in the experiment were analyzed to show high efficiency of joint use of these methods for interpretation of the obtained results. We managed to find and explain origination of a magnetization paramagnetic component by formation of a superparamagnetic state of vacancies in silicon carbide. We have found oscillations that are periodic by the reverse field and identilled as the De Haas—Van Alphen effect as well as Aharonov—Bohm oscillations that are caused by capturing magnetic-flux quanta to hybrid structure defects.

Keywords: magnetization, superparamagnetism, De Haas—Van Alphen, Aharonov—Bohm oscillations, silicon carbide over silicon, silicon vacancies, nanostructures.

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1. Introduction

The prospects of development of modern instrumentation mean involve creating new low-dimensional semiconductor structures not only on silicon and silicon carbide, but also based on hybrid structures of these materials, which in their properties and applicabilities in nanoelectronics can have properties that exceed properties of the previously-known materials based on silicon carbide [1–4].

In this study, we report about investigation of the magnetic properties of the low-dimensional hybrid silicon-carbide-over-silicon samples grown on the surfaces of the *n*- and *p*-types of silicon by the vacancy mechanism of coordinated substitution of atoms (VMCSA) [5], which was based on measurement of their magnetization. When growing the SiC/Si hybrid structure by VMCSA, the silicon vacancies are created at the beginning of SiC synthesis not in silicon carbide itself, but in an upper layer of the silicon substrate [5]. Only after that, the upper part of silicon with the vacancies is transformed into an epitaxial layer of silicon carbide due to a chemical reaction of silicon with carbon monoxide [5]. At the same time, a part of the silicon vacancies that are initially formed in silicon, are transformed into silicon vacancies that are now in silicon carbide. In this synthesis method, the concentration of the silicon vacancies in the SiC layer can be up to about $10^{20}-10^{21}\,\mathrm{cm}^{-3}$, which can not be achieved when creating the silicon vacancies in SiC by other methods.

Investigation of magnetism of the SiC/Si hybrid structures made it possible, in particular, to experimentally confirm previously obtained results of quantum-chemical calculations performed by a density functional method [6], whereas joint use of two independent experimental methods of measurements of magnetic characteristics of the samples, namely the superconducting quantum interference device (SQUID) and the Faraday method (Faraday Balance), demonstrated reliability of the obtained results and made it possible to provide their correct interpretation.

2. Experimental methods and discussion of results

The measurements were carried out in installations using the superconducting quantum interference device (SQUID) and the Faraday method (Faraday Balance). On the one hand, the joint use of these methods allowed extending, in the performed studies, temperature intervals and ranges of external magnetic fields, in which the samples were placed, supplementing each other. On the other hand, within the intervals of values of the parameters „temperature“ and „magnetic field“ which are realized in both the methods, it allowed clearly demonstrating reliability of the obtained results.

The magnetic characteristics of the sample were studied using the superconducting quantum interference device Quantum Design MPMS XL SQUID. The measurements were carried out in the SQUID installation within the interval of the external direct and reverse polarity magnetic fields up to 25 kOe with a variable step of magnetic field change at the temperatures 5, 100 and 350 K for the sample that was produced on the *n*-type substrate and at 5 K on the *p*-type substrate. During the measurements, the planed of the studied sample was oriented perpendicular to a direction of the external magnetic field. Figure 1 shows the field dependences of magnetization of the SiC/Si hybrid structure grown by the vacancy mechanism of self-coordinated substitution of atoms on the substrates of crystals of *n*-type silicon and *p*-type silicon.

The performed study of the temperature dependence of the SiC/Si structure on the *n*-type substrate (Figure 2) allowed identifying a contribution by orientation magnetism to resultant magnetization of the sample in the high fields [7] as well as a respective value of diamagnetic susceptibility of the studied structure.

In the high fields, the behavior of the obtained dependences of magnetization of the SiC/Si structures is identical on both the substrates (Figure 1). An exception is an obvious difference of the magnetic properties in the fields of less than 4 kOe. Therefore, in relatively low fields that do not exceed 4 kOe magnetization of the samples of the studied structures was measured at the room temperature in the installation Faraday Balance, which has higher sensitivity and informativity within the said interval of the magnetic fields [8].

The installation Faraday Balance based on the MGD 3 12 FG spectrometer was used to measure at the room temperature within a technically available interval of the magnetic fields up to 11 kOe, in which the magnetic field was changed with a step of 1 Oe in a region of the low fields up to 1.1 kOe and with a step of 5 Oe in a region of the strong fields, by the Faraday method in an automatic mode. The measurement method used — the Faraday method — is applied for measuring the magnetic characteristics of the material samples, whose linear sizes do not exceed 3 mm, in a inhomogeneous magnetic field, whose gradient is created by specially-formed pole tips [9]. The obtained field dependence of magnetization of the sample is a sequence of measurement results, which are obtained during quasi-continuous variation of the external magnetic field when the sample has thermodynamically-balanced states. A force of interaction of the sample with the magnetic field was measured using a high-accuracy scale microbalance 10^{-8} with accuracy of 10^{-7} g, thereby determining an error of measurement of magnetic susceptibility of the sample of the mass of up to 100 mg as 10^{-8} cm^3/g.

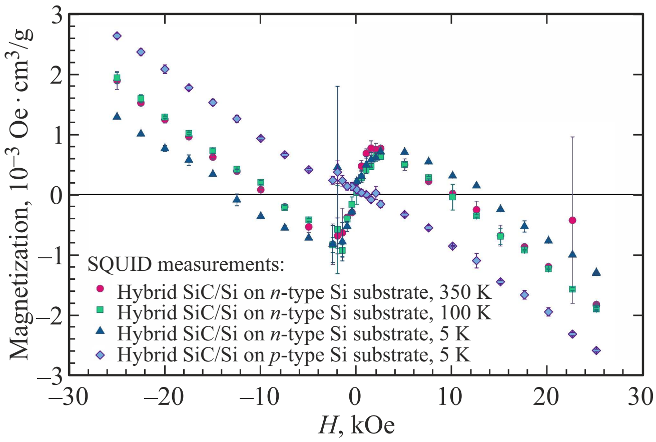

Figure 1. Field dependences of the SiC/Si hybrid structures grown on silicon of a various doping type, which are obtained in the superconducting quantum interference device.

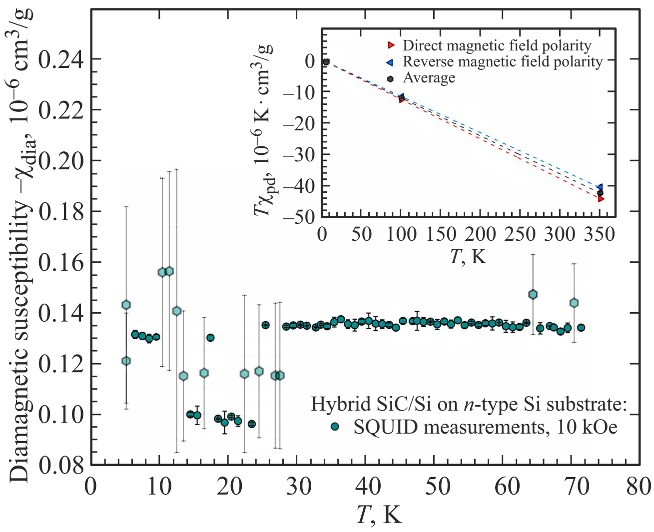

Figure 2. Temperature dependence of magnetic susceptibility of the SiC/Si hybrid structure grown on *n*-type silicon.

A relation between the force acting on the sample in the magnetic field, the field characteristics and static magnetic susceptibility of the sample is defined by a well-known expression

$$F = m\chi H \frac{dH}{dz},$$

where χ — the specific static magnetic susceptibility having a dimension of reciprocal density, H — the strength of the external magnetic field, dH/dz — the magnetic field gradient, z — the vertical axis, m — the mass of the sample measured by means of a laboratory scale with accuracy of 10^{-5} g.

When analyzing an array of the obtained data, magnetic susceptibility or magnetization was considered as changed, if a force of interaction of the sample with the external magnetic field, which determined them, differed from the previous value by at least 10^{-7} g, and after that the measurement results were discussed and interpreted.

Thus, the Faraday Balance installation allows measuring the magnetic characteristics of the low-dimensional structures at the high temperatures, generally speaking, at the room temperature and above, in the low magnetic fields.

The obtained dependences have been analyzed by us based on a concept of additive contributions by the components of the SiC/Si hybrid structure, first of all, the silicon substrate, the SiC layer grown on its surface as well as a transition region between them.

The SQUID-measured field dependence of magnetization of the SiC/Si hybrid structure grown on the *n*-type-silicon substrate clearly demonstrates a paramagnetic component, which is manifested within the interval of strength of the external magnetic field from 0 to ~ 4 kOe and saturated, against the background of sample diamagnetism that almost linearly increases with the field (Figure 1).

It was assumed based on the performed measurements that this effect was caused by presence of an uncontrolled ferromagnetic impurity in the sample [7]. In order to check this hypothesis, the field dependence of sample magnetization was measured using the Faraday Balance installation. The Faraday method used for the measurements presupposes measurement of a „magnetic weight" of the sample that is placed in a quartz cup and loosely suspended in a space between electromagnet poles. In its idea, the Faraday method is used for investigating low-magnetic samples, since materials that contain ferromagnetic impurities will deviate towards one of the magnetic poles and demonstrate a tendency to „sticking", revealing strongly pronounced specific features on the field dependence of magnetization. It did not take place in our experiment (Figure 3). Besides, even low impurity ferromagnetism could have been identified by presence of hysteresis. However, no magnetic hysteresis was observed on the obtained dependence. Therefore, the observed effect required another explanation.

The discussed paramagnetic contribution observed on the field dependences of magnetization of the SiC/Si hybrid structure formed on the substrate of *n*-type-conductivity silicon, which are measured in the installations SQUID and Faraday Balance, seems to be attributed to an assembly of weakly interacting structure defects that have anomalously high magnetic moments and are formed by exchange-related silicon vacancies in SiC. I.e., when the substrate material is pre-annealed at the temperature 1300–1400 °C, vacancies are formed in silicon, wherein a part of them is transformed into silicon vacancies in SiC, which have magnetic moments. Using the density functional method, it was shown in the study [6] by the authors that it was energetically expedient to form assemblies of clusters formed by silicon vacancies in the silicon-carbide-over-silicon layer, which was confirmed in our experiment.

Thus, the additive paramagnetic contribution to magnetization of the sample can be interpreted as superparamagnetism [10] of the studied hybrid structure.

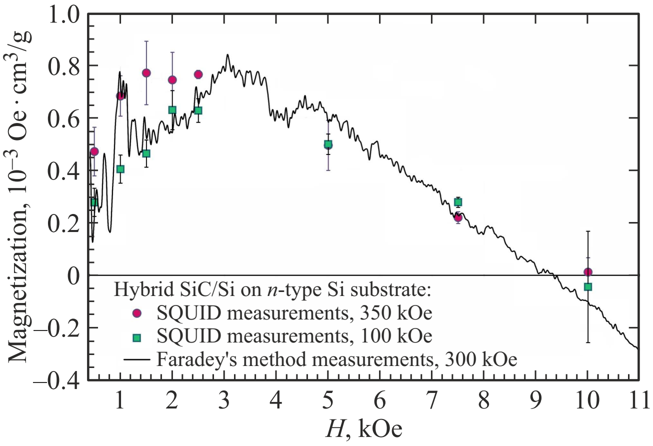

Figure 3. Field dependence of magnetization of the SiC/Si hybrid structure grown on the surface of *n*-type silicon, which is obtained by the Faraday method at the temperature of 300 K, as compared to results of measurements in the SQUID installation.

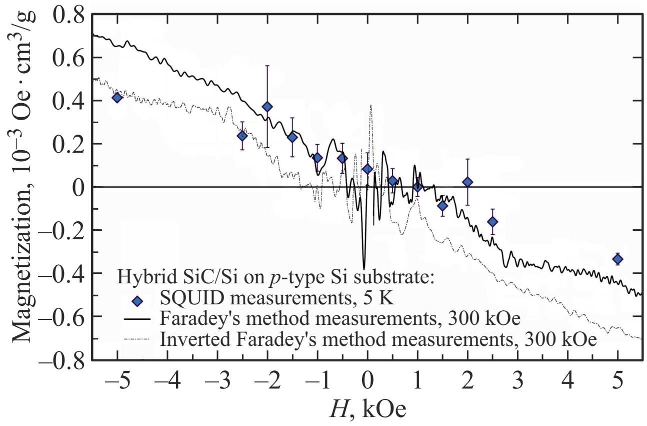

Figure 4. Field dependence of magnetization of the SiC/Si hybrid structure grown on the surface of *p*-type silicon, which is obtained by the Faraday method at the temperature of 300 K, as compared to results of measurements in the SQUID installation.

It should be noted for substantiation of the proposed model that both the requirements of experimental confirmation of the superparamagnetic state are fulfilled in the studied system: first of all, there is no hysteresis on the magnetization curve, and secondly, no divergence of the magnetization curves in the coordinates MH/T, which are measured in the SQUID installation at the different temperatures. The latter indicates negligibly weak interaction between the clusters of the exchange-related vacancies.

It is impossible to reliably identify the discussed specific feature on the curves of the field dependence of magnetization of the SiC/Si hybrid structure grown on the *p*-type substrate (Figure 4).

A separate research is needed for a mechanism of ordering of the magnetic moments of the silicon vacancies included in the clusters. At the same time, the obtained results make it possilbe to assume that formation of a magnetic order in the discussed structure defects may be attributed to indirect exchange via charge carriers [11]. This conclusion correlates well with results of measurement of a concentration of the charge carriers [6], since the discussed effect is almost unobserved in the structure grown on the *p*-type substrate, where the concentration of the carriers is by an order less than in the donor-doped silicon substrate.

Here, first of all, we pay attention to experimentally-observed oscillations of magnetization, which are periodic by the reverse field (Figure 5), against the background of a basic curve of magnetization of the studied hybrid structure, which is going to a diamagnetic region. This specific feature was interpreted by us as a macroscopic De Haas–Van Alphen quantum effect caused by variation of population of the Landau levels in the external magnetic field [12]. According to the results of the experiment, the value of the first critical field (the filling factor $\nu = 1$) is within the interval (3.39 ± 0.05) kOe.

Improvements to a signal recorder of the Faraday Balance installation made it possible to resolve the observed spectrum of the field dependence of magnetization and to identify the De Haas–Van Alphen oscillations in the SiC/Si hybrid structure with the filling factor $\nu > 20$ at the room temperature (Figure 5) in the magnetic field of strength $H \leq 150$ Oe, which may allow determining characteristics

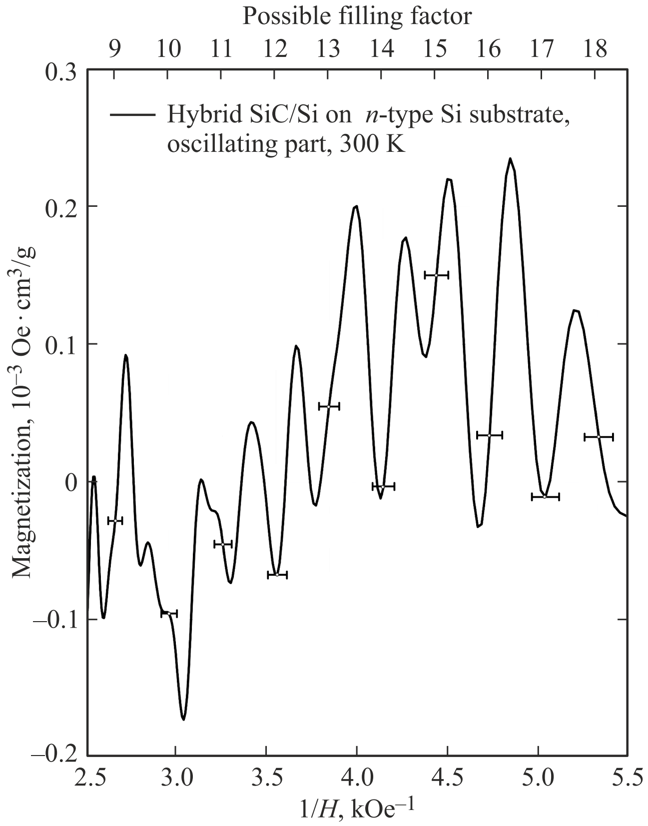

Figure 5. De Haas–Van Alphen oscillations that are detected in the SiC/Si hybrid structure grown on the surface of *n*-type silicon.

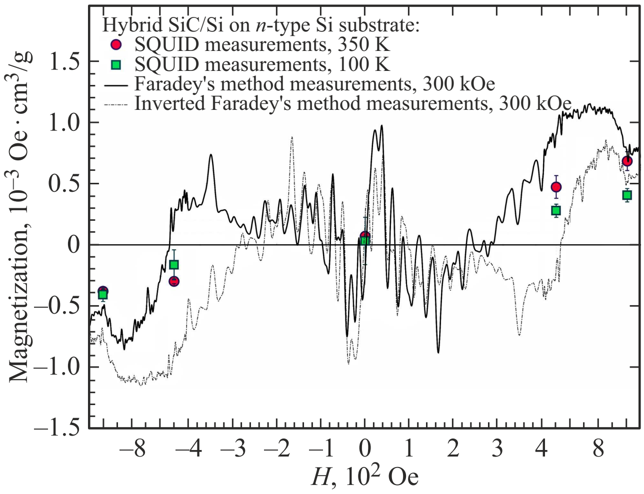

Figure 6. Field dependence of magnetization of the SIC/SI hybrid structure grown on the surface of *n*-type silicon, in the region of low fields.

of the charge carriers in the future. Shoenberg [13] has demonstrated that description of the De Haas–Van Alphen effect in two-dimensional structures shall involve discussion of not only oscillations characteristics, but of a basic component relative to which the magnetic moment oscillates. In due time, A. M. Kosevich and I. M. Lifshitz [14,15] did not calculate the basic component in the De Haas–Van Alphen effect, assuming that it shall be determined by an experiment. In our experiment (Figure 6), as the filling factor ($\nu \sim 10$–20) is reduced, the basic curve goes away into the diamagnetic region, and then the oscillations continue relative to a curve that is composed by superposition of the diamagnetic component of the hybrid structure and by paramagnetism caused by the superparamagnetic effect. In addition to the described De Haas-Van Alphen effect, one should mention magnetization oscillations that are periodic by the magnetic field (Figure 6). This phenomenon seems to be caused by the Aharonov–Bohm effect that demonstrates capturing the magnetic-flux quanta to the low-dimensional structure defects. We have already discussed analysis of origination of the Aharonov–Bohm oscillations in similar media in the studies [16,17]. Therefore, we will not turn to it again in order to avoid overloading of the material presented herein.

In addition to the above-said, based on results of measurements in the Faraday Balance installation that is designed to record specific features manifested in the magnetization curve in the fields of less than 4 kOe, we have analyzed a contribution to magnetization of the SiC/Si hybrid structure by the SiC nanolayer.

3. Conclusion

It is shown as a result of performed investigation that the SiC/Si hybrid structures grown on the surfaces of the *n*- and *p*-types of silicon by the vacancy mechanism of coordinated substitution of atoms (VMCSA) are diamagnetics.

The silicon vacancies in SiC, which are initially formed in silicon during heat treatment of the used substrates, make the additive paramagnetic contribution to magnetization of the structure.

The exchange-related vacancies form the assemblies of the clusters that are distributed in the nanoscale SiC layer on *n*-type silicon, thereby implementing the superparamagnetic contribution to magnetization of the studied system.

The Landau levels are formed in the SiC nanolayer, whose population varies in the external magnetic field to demonstrate the De Haas–Van Alphen effect in the two-dimensional structure.

Capturing the magnetic-flux quanta to the low-dimensional structure defects results in origination of the Aharonov–Bohm oscillations.

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Conflict of interest

The authors declare that they have no conflict of interest.

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