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Magnetism of the hybrid SiC/Si structure grown on silicon surface

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ABSTRACT
A low-dimensional hybrid structure of silicon carbide grown on silicon by the vacancy method of coordinated substitution of atoms based on the measurements of its magnetic characteristics – magnetic susceptibility and magnetization is studied. The measurements were carried out on the Quantum Design MPMS XL SQUID (superconducting quantum interferometer), M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences, Ekaterinburg, and Faraday Balance (Faraday method), Peter the Great St. Petersburg Polytechnic University, St. Petersburg. The results of magnetization field dependences measurement, carried out by two experimental setups, clearly confirm the reliability of the obtained results.

KEYWORDS
hybrid structure • silicon carbide • VMCSA • magnetic properties • superconducting quantum interferometer Faraday method • magnetization

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Introduction

Silicon carbide is of an interest to researchers because it possesses a wide range of qualities that determine the possibilities of its practical application [1–5]. Currently, the technology of obtaining both bulk crystals and thin SiC layers [6–8] is actively developing, which obviously requires the involvement of a wide range of experimental research methods, the results of which can be used as a basis for modeling its physical properties [9–15].

A fundamentally new method for monocrystalline silicon carbide (SiC) on silicon (Si) growth called the method of coordinated substitution of atoms (MCSA) was discovered [16,17]. The SiC growth by the MCSA method is carried out due to the interaction of a gaseous carbon (CO) with the Si surface at temperatures exceeding 1000 °C. The interaction reaction proceeds in several stages, which distinguishes it from the reactions used in classical method of growing SiC on Si [18,19]. The MCSA method was significantly improved in [20,21], resulting in the development of a new method, namely, the vacancy method of coordinated substitution of atoms (VMCSA).

In the present work, we demonstrate the results of the study of magnetic properties of a SiC structure grown by VMCSA technology on a silicon surface. The choice of magnetic research methods is justified by their high informativeness, which is provided, first of all, by measuring field and temperature dependences of static magnetic susceptibility and magnetization in wide range of magnetic fields and temperatures. Here we discuss the results of measuring the field dependences of the investigated structure, mainly at room temperature.

Materials and Methods

On a Faraday Balance setup based on the MGD 312 FG spectrometer, measurements were performed at room temperature in the range of magnetic fields up to 11 kOe, where the magnetic field was varied in steps of 5 Oe, by the Faraday method in automatic mode. The Faraday method is used to measure the magnetic characteristics of material samples, the linear dimensions of which do not exceed 3 mm, in an inhomogeneous magnetic field, the gradient of which is created by pole pieces of a special shape. The obtained field dependence of the sample magnetization is a sequence of measurement results recorded when the system reaches thermodynamically equilibrium states. The force of interaction of the sample with the magnetic field was measured using Microbalance MTB 10-8 high-precision scales with an accuracy of 10^{-7} g, which determined the error of measuring the magnetic susceptibility of a sample weighing up to 100 mg as 10^{-8} cm^3/g.

The relationship between the force acting on the sample in a magnetic field, the field characteristics, and the static magnetic susceptibility of the sample is given by a well-known equation:

$$F(H,T) = m \cdot \chi \cdot H \cdot dH/dz, \quad (1)$$

where χ is the specific static magnetic susceptibility having the inverse density dimension, H is the external magnetic field strength, dH/dz is the magnetic field gradient along the vertical axis z, and m is the mass of the sample measured on laboratory scales with the 10^{-5} g accuracy.

When analyzing the array of obtained data, the magnetic susceptibility or magnetization of the sample was considered to have changed if their determining force of interaction with the external magnetic field differed from the previous value by at least 10^{-7} g, after which the results of measurements were discussed and interpreted. Thus, the Faraday Balance setup makes it possible to measure the magnetic characteristics of low-dimensional structures at high temperatures, generally speaking, at room temperature and above, in weak magnetic fields.

The joint use of experimental techniques applied in the study, firstly, made it possible to expand the temperature intervals and ranges of external magnetic fields in which the sample was placed, complementing each other. And, secondly, to evidentially consider and resolve the question of the reliability of the obtained results, based on the comparison of the obtained data in the intervals of magnetic fields and temperatures realized at both setups.

Results and Discussion

The interpretation of the experiments performed on SQUID (Fig. 1) via superconducting quantum interferometer [22,23] and by the Faraday method [24] on Faraday Balance setup can be based on the consideration of different additive contributions to the sample magnetization due to the composition and presence of defects in the grown hybrid structure. In addition, the magnetization curves exhibit oscillations that, when interpreted, can be grouped together to reveal general patterns characteristic of the nanostructures under study.

When analyzing the results of sample measurements on a superconducting quantum interferometer, it is necessary to take into account that the technique implemented at the SQUID setup does not allow, due to a large hardware error in relatively weak fields, less than 2 kOe, to reveal features in the magnetization behavior of the structure under study. At the same time, in magnetic fields up to 25 kOe at temperatures from 5 to 350 K the applied technique allows minimizing the instrument error and measuring with high accuracy the field dependences of magnetic characteristics of the studied samples.

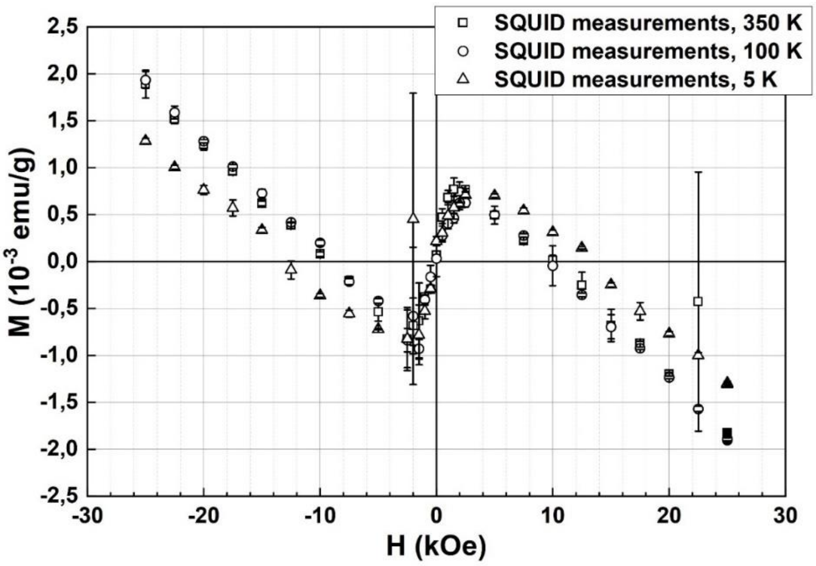

Fig. 1. Field dependences of the magnetization of the SiC/Si hybrid structure grown by the vacancy method of coordinated substitution of atoms measured on the Quantum Design MPMS XL SQUID at temperatures of 5, 100, and 350 K, respectively

High-field measurements performed at helium temperatures on SQUID, in particular, showed that the diamagnetism of SiC layers grown on the silicon crystal surface by VMCSA cannot be described solely by additive contributions of the substrate and the low-dimensional structure grown on it, but requires a different interpretation that takes into account the modification of the internal structure of the latter – structural transformations during the transition from bulk to low-dimensional crystals, and depends on the growth conditions.

Once again, we note that hybrid structures grown by VMCSA on the silicon surface and formally defined as low-dimensional silicon carbide layers, differs significantly [25–27] from SiC crystals due to specially realized growth conditions.

We will not dwell on the discussion of the studies conducted on the superconducting quantum interferometer, since we have devoted a separate publication to a detailed description of the experimental SQUID method [28], the processing of the data obtained during the measurement and their interpretation with respect to the structures under study.

The results obtained in the experiment at the Faraday Balance setup are displayed in Fig. 2, which also shows the field dependences of the magnetization of the low-dimensional structure of the silicon-silicon carbide hybrid grown by the vacancy method of coordinated substitution of atoms measured at the SQUID setup. The above dependences clearly demonstrate the possibilities and advantages of both methods.

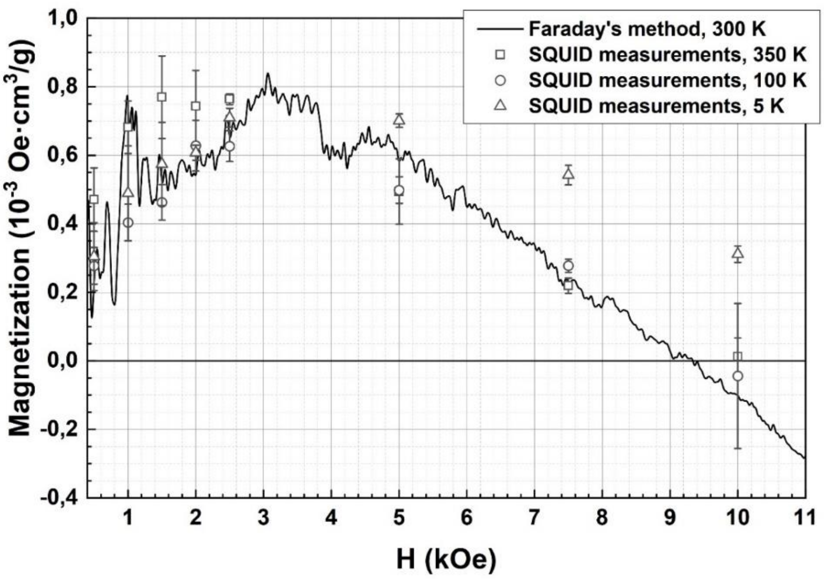

Fig. 2. Field dependence of the magnetization of the SiC/Si hybrid structure grown on the silicon surface obtained by the Faraday method at 300 K (solid curve) in comparison with the results of measurements at the SQUID setup

The analysis of the obtained results shows that in fields less than 2 kOe at room temperature the field dependence of magnetization obtained by the Faraday method is the most informative. Thus, measurements at room temperature in weak magnetic fields at the Faraday Balance at quasi-continuous variation of the external magnetic field (in the range up to 1.5 kOe with a step of 1 Oe) demonstrate oscillations of magnetization, which are combined into groups and, apparently, can be interpreted as a macroscopic quantum de Haas – van Alphen effect [29–31], related to the most direct methods of measuring the charge carriers effective mass [32], and the Aharonov-Bohm effect [33,34], the periodicity of oscillations in which may contain information about charge carriers, the detailed analysis of which we assume to carry out in a separate publication.

Conclusions

The field dependences of the magnetization of the SiC/Si hybrid structure grown by the vacancy method of coordinated substitution of atoms, obtained by two complementary experimental methods have been studied.

The correlation of results of measurements carried out at room temperature in the range of external magnetic field strength up to 11 kOe, realized by two experimental setups, clearly confirm the reliability of the obtained results.

In conclusion, it should be noted that the development and creation of VMCSA technology made it possible to grow hybrid structures based on silicon carbide, exhibiting magnetic properties due not only to a decrease in dimensionality, but, first of all, to the technology of their growth, which was established in this study.

CRediT authorship contribution statement

Vladimir V. Romanov : writing – review & editing, writing – original draft, investigation; **Nikolai I. Rul'** : investigation, writing – review & editing; **Vitaliy E. Gasumyants** : writing – review & editing; **Ivan D. Venevtsev** : data curation; **Konstantin B. Taranets** : data curation; **Aleksandr V. Korolev** : investigation; **Sergey A. Kukushkin** : conceptualization; **Andrey V. Osipov** : conceptualization; **Nikolay T. Bagraev** : conceptualization.

Conflict of interest

The authors declare that they have no conflict of interest.

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