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Field dependences of the magnetization of the hybrid SiC/Si structure grown by the vacancy method of coordinated substitution of atoms

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ABSTRACT

The measurement data and a general approach to the analysis of the field dependencies of magnetization of the hybrid SiC/Si structure grown by the vacancy method of coordinated substitution of atoms (VMCSA) are presented. The experimental results can be interpreted as a set of additive contributions to the magnetization of the sample. The analysis of the field dependences of magnetization allowed us to identify a presence of paramagnetic impurities in the sample under study and an inclusion that demonstrates characteristic features of ferromagnetic ordering. It is shown than the value of the specific diamagnetic mass susceptibility of the main SiC/Si substance determined from experimental data cannot be described by the simple additive contribution of silicon and silicon carbide.

KEYWORDS

silicon carbide • VMCSA, hybrid structure • SQUID • external magnetic field • magnetization • diamagnetism impurity ferromagnetism

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Introduction

Silicon carbide is a promising material for the development of semiconductor electronic and nanoelectronics devices [1–5], having advantages over devices based on pure silicon [6–12]. SiC thin films can become the basis for integrated circuits, complementing or replacing silicon [13]. In this regard, the study of the physical characteristics and properties of silicon carbide [14–20], grown by the developed original methods, is of particular interest. The presented research involved a sample of the hybrid SiC/Si structure grown at temperature 1360 °C by the vacancy method of coordinated substitution of atoms on the surface of n-type monocrystalline silicon (111).

The vacancy method of coordinated substitution of atoms (VMCSA) [21] is a natural development of the method of coordinated substitution of atoms (MCSA), first proposed and generalized in a series of articles and reviews [22–26], and the process of SiC/Si structures formation by this method differs significantly from the characteristic processes of SiC growth on Si surfaces provided by classical methods [27–30].

The use of the MCSA and VMCSA for growing hybrid structures makes it possible to create materials with bright magnetic [31,32] and other physical properties [33–35] and features [36,37]. The discovered superconductivity of silicon carbide structures at ultra-low temperatures [38,39], in particular, motivated the presented experimental work, devoted to the study and analysis of the field dependences of the magnetization of the hybrid SiC/Si structure grown by VMCSA, measured at various temperatures.

Materials and Methods

To study the magnetic properties of the sample, a superconducting quantum interferometer [40,41] Quantum Design MPMS XL SQUID of the M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences was used.

The measurements of the magnetization field dependences of the studied *hybrid SiC/Si structure* sample were carried out in the SQUID experimental setup [42] in the range of external magnetic fields up to 25 kOe both direct and reverse polarity with different magnetic field variation at temperatures of 5, 100 and 350 K. During the measurement process, the surface of the SiC/Si structure was oriented perpendicular to the direction of the external magnetic field.

Results and Discussion

To interpret the experimental data shown in Fig. 1, the so-called mechanical mixture model of the main substances of the studied structure, namely silicon carbide and silicon, containing impurities in concentrations much lower than the main chemical elements that form the structure under study, was used. The analysis showed that the measured field dependences can be described assuming the presence of ferromagnetic inclusions in the sample and, at the same time, paramagnetic impurities, contribution of which to the measured magnetization should obey the Curie law.

Thus, we proceeded from the idea that the measured dependences for the hybrid SiC/Si structure represents the total contribution of the spontaneous magnetization of ferromagnetic inclusions, the orientational paramagnetism [43] of impurity ions, increasing as the temperature decreases, and the diamagnetism of the hybrid SiC/Si structure itself.

Within the framework of the proposed model, the magnetization of the studied structure can be represented as:

$$M = fM_f + pM_p + dM_{SiC/Si} = f\chi_f H + \chi_{pd} H, \quad (1)$$

where

$$\chi_{pd} = p\chi_d + d\chi_{SiC/Si} = \frac{pC}{T} + (1 - p - f)\chi_{SiC/Si}, \quad (2)$$

f and p correspond to the fraction (by mass) of the ferromagnetic and paramagnetic components ($f, p \ll 1$), C is the Curie constant for paramagnetic impurities in the sample under study, and χ_f, χ_p and $\chi_{SiC/Si}$ are the corresponding specific ferro-, para- and diamagnetic susceptibilities.

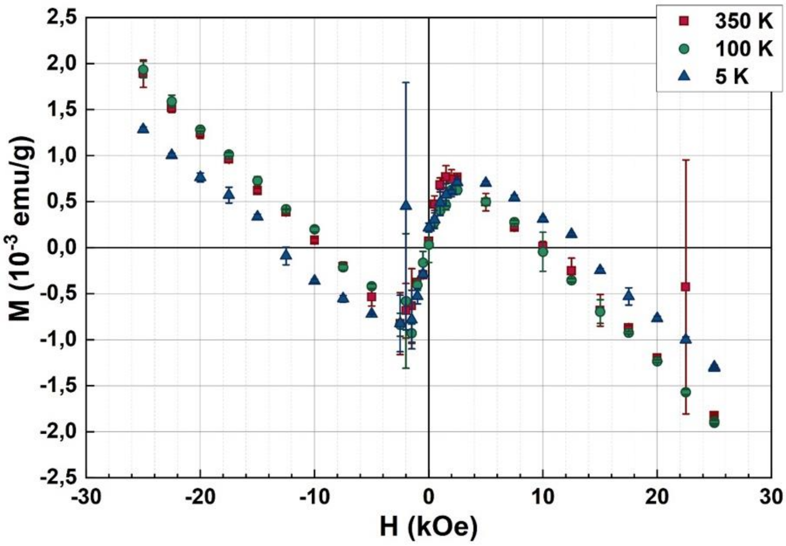

Fig. 1. Field dependences of the magnetization of the hybrid SiC/Si structure grown by the vacancy method of coordinated substitution of atoms at temperatures of 5, 100 and 350 K, respectively

In the region of strong magnetic fields determined from the condition $H > NM_s$, where M_s is the saturation magnetization of the ferromagnetic component, and N is the effective value of the demagnetizing factor, Eq. (1) for ferromagnetic component saturation can be rewritten as:

$$M = fM_s + \chi_{pd}H = fM_s + \left(\frac{pC}{T} + d\chi_{SiC/Si}\right)H, \quad (3)$$

which allows the analysis of the field dependencies using linear approximation. For the studied sample of the hybrid SiC/Si structure, the linear approximation was carried out in the fields with the strength higher than 15 kOe for the dependence measured at 5 K, and for the field dependences measured at 100 and 350 K in the external magnetic fields that exceeds 10 kOe. The results of the analysis of the field dependencies shown in Fig. 1 for the region of strong magnetic fields are given in Table 1.

Table 1. Properties of the sample under study in the region of strong magnetic fields

Temperature	Saturation magnetization, $f \cdot M_s$, 10^{-3} emu/g		Total para- and diamagnetic contributions to the magnetic susceptibility, χ_{pd}, 10^{-9} cm^3/g	
	For opposite orientations of the external magnetic field		For opposite orientations of the external magnetic field	
5 K	1.33 ± 0.03	-1.07 ± 0.07	-105.3 ± 1.3	-93 ± 3
100 K	1.24 ± 0.04	-1.02 ± 0.03	-125.0 ± 1.9	-115.6 ± 2.3
350 K	1.32 ± 0.03	-1.08 ± 0.04	-126.2 ± 1.5	-115.5 ± 2.6

Impurity paramagnetism weakens with increasing temperature, which allows us to separate the paramagnetic contribution of the impurities and the diamagnetic contribution of the main component SiC/Si on the field dependences in the region of strong magnetic fields by means of the linearization of the form:

$$T\chi_{pd} = pC + d\chi_{SiC/Si} \cdot T. \quad (4)$$

The results of processing the dependence shown in Fig. 2 using Eq. (4) are given in Table 2.

Table 2. Paramagnetic and diamagnetic contribution properties for the hybrid SiC/Si sample

Magnetic field region	Orientational paramagnetism, $p \cdot C$, 10^{-9} K·cm^3/g	Diamagnetism of the main substance, $d \cdot \chi_{SiC/Si}$, 10^{-9} cm^3/g
Direct magnetic field	105.2 ± 1.7	-126.33 ± 0.22
Reversed magnetic field	117 ± 5	-116.4 ± 0.4
Average value	110.6 ± 1.1	-121.28 ± 0.12

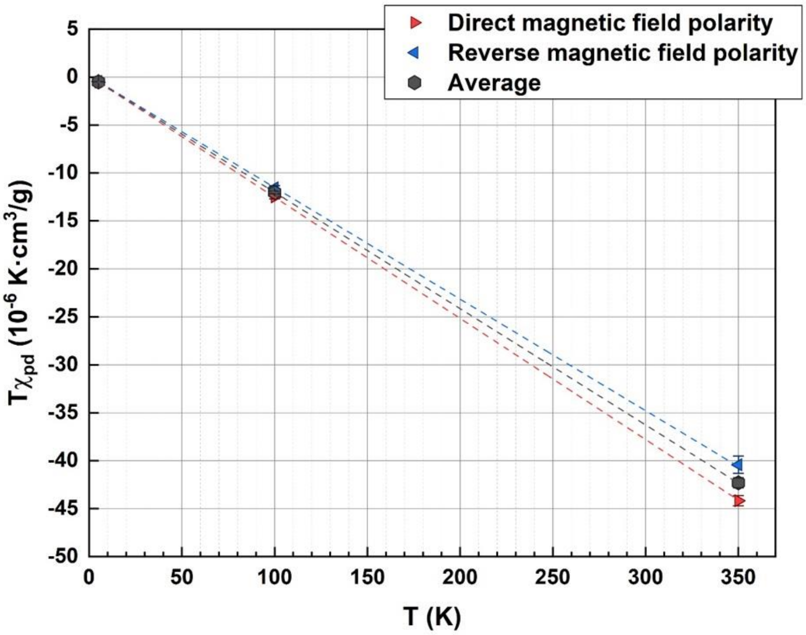

Fig. 2. Para- and diamagnetic contribution properties of the studied hybrid SiC/Si sample in the region of strong magnetic fields depending on temperature

It is obvious that the found specific diamagnetic susceptibility of the main SiC/Si component is less than the values $\chi_{Si} = -228 \cdot 10^{-9}\ \mathrm{cm^3/g}$ and $\chi_{SiC} = -265 \cdot 10^{-9}\ \mathrm{cm^3/g}$ for crystalline silicon [44,45] and silicon carbide [45,46] at room temperature, respectively, which makes it impossible to describe the diamagnetism of the hybrid structure under study by additive contribution of each component.

The experiment showed that in a weak external magnetic field the magnetization changes linearly. This observation indicates that the ferromagnetic inclusion found in the sample under study appears to saturate in relatively weak fields. Analysis of the experimental dependence in the region of weak magnetic fields corresponding to the condition $H < NM_s$, in the range from -1.5 to 1.5 kOe, allows us to identify the ferromagnetic contribution to the susceptibility of the studied sample and estimate the proportion of the ferromagnetic component as 10^{-3} wt. %.

The presented analysis made it possible to present the experimentally obtained magnetization field dependences of the hybrid SiC/Si structure as a set of contributions of various magnetic nature (Fig. 3).

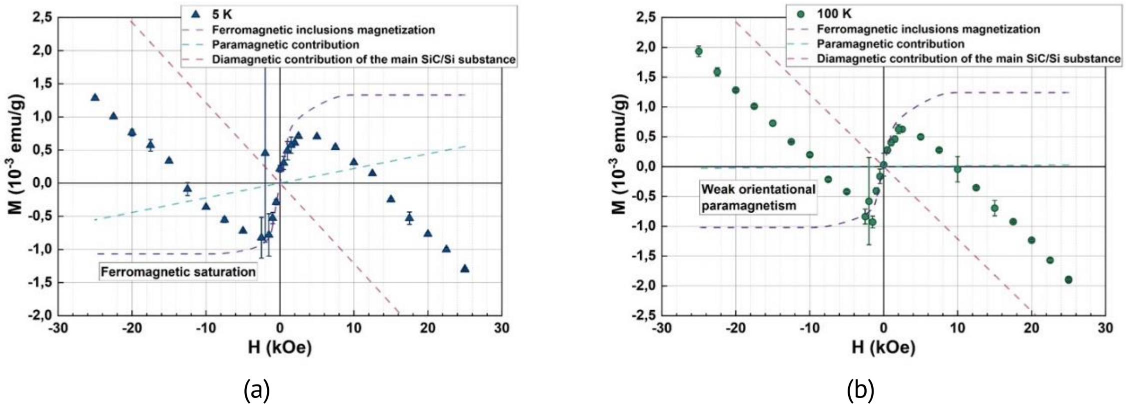

Fig. 3. The analysis of the field dependences of the hybrid SiC/Si structure measured at temperatures of (a) 5 and (b) 100 K performed within the framework of the proposed mechanical mixture model

Conclusions

The fields dependences of the magnetization of the hybrid SiC/Si structure grown by the vacancy method of coordinated substitution of atoms were measured on a superconducting quantum interferometer and studied.

The interpretation of the measured field dependences of magnetization within the framework of mechanical mixture model made it possible to identify a presence of paramagnetic impurities obeying Curie's law in the sample under study and a component that demonstrates characteristic features of ferromagnetic ordering, as well as to determine the value of the specific diamagnetic susceptibility of the main substance SiC/Si.

The field dependences of magnetization in relatively weak magnetic fields allow us to state with a certain degree of confidence that the observed ferromagnetic contribution is apparently due to the presence of a highly magnetic component in the sample under study, the weight fraction of which is significantly less than that of the main substance.

In addition, the measured value of the specific diamagnetic mass susceptibility of the main SiC/Si component cannot be described by the additive contribution of silicon and silicon carbide, requiring consideration of an additional paramagnetic contribution, which is, apparently, unable to reveal itself in the study of field dependences exclusively.

A joint analysis of both the field and temperature dependences of the magnetization of the studied structure may make it possible to clarify and supplement the proposed interpretation of the experimental results.

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