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Magnetoresistance of Ge-Si Whiskers in the Vicinity to Metal–Insulator Transition

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The magnetoresistance of Ge_xSi_{1-x} ($x = 0.002 ¸ 0.11$) whiskers with an acceptor concentration ($N_a = 3 \cdot 10^{18} ¸ 2 \cdot 10^{19}$ cm^{-3}) near the metal-insulator transition (MIT) was studied at low temperatures (4.2 - 77 K) in magnetic fields up to 14 T. It is shown that at 4.2 K the magnetoresistance of the Ge-Si whiskers on the dielectric side of the MIT is quadratic, while the magnetoresistance of the crystals on the metal side of the MIT has an exponential dependence on the magnetic field. In the samples in the immediate vicinity to the MIT on the dielectric side, negative magnetoresistance was detected, whereas in metal samples with a high germanium content ($x = 11$ at.%) an anomalous positive magnetoresistance occurs. The resulting anomalous dependences are respectively explained by the conductivity with respect to the delocalized A^+ states of the upper Hubbard band and the increase in the electron-electron interaction in Ge-Si whiskers at increasing germanium content.

Key words: magnetoresistance, whiskers, Ge-Si solid solutions, metal-insulator transition.

Introduction

Analysis of magnetoresistance character is one of the methods, which allows investigating conductance mechanism in solids, which determines their further application [1]. Carrier transport in Ge-Si solid solutions, in particular in quantum dot arrays was studied in the work [2]. Magnetic-field dependences of the conductivity associated with hopping transport of holes over a 2D array of Ge/Si(001) quantum dots [3]. There are many works [4-6] devoted to theoretical and experimental studies of whisker magnetoresistance in Si and Ge. The authors of [7] investigated magnetoresistance in Si whiskers at temperature 4.2 K. Magnetoresistance of Ge-Si whiskers was comprehensibly investigated in [8] depending on level of crystal doping, strain as well as Ge composition up to 5 at.%. However, mechanism of carrier transport is not enough investigated at the range of cryogenic temperatures in Ge-Si whiskers with greater Ge content.

The aim of this work is studies of magnetoresistance in Ge-Si whiskers with germanium compositions up to 11 at. % at cryogenic temperatures in the field of metal-insulator transition.

I. Experimental results

The whiskers were grown by method of chemical transport reactions in a sealed bromide system with use of B and Au dopants [9]. The temperature of the source zone was 1370 K, and the crystallization zone – (1070 ¸ 1150) K. The composition of Ge-Si solid solution was controlled in the whiskers by microprobe analysis: germanium content was 1 ¸ 11 at. %. The crystals for investigations were selected with acceptor-impurity concentration closed to critical concentration of the metal-insulator transition (MIT) ($N_c = 8.3 \cdot 10^{18}$ cm^{-3}). Whisker magnetoresistance was measured at temperature 4.2 K in the range of magnetic field 0 ¸ 14 T. The investigations reveal that magnetoresistance dependences $\Delta R_B/R$ as functions of magnetic field B are very different for the samples with different impurity concentration ($N_a = 3 \cdot 10^{18} ¸ 2 \cdot 10^{19}$ cm^{-3}).

For the samples with impurity concentration about $N_a = 3 \cdot 10^{18}$ cm^{-3} whisker magnetoresistance practically does not depend on the magnetic field in all investigated range.

The quadratic dependence of magnetoresistance as function of magnetic field corresponds to the insulating side of the MIT for Ge-Si solid solution whiskers at low germanium content range ($x = 0.22 ¸ 3$ at. %). The

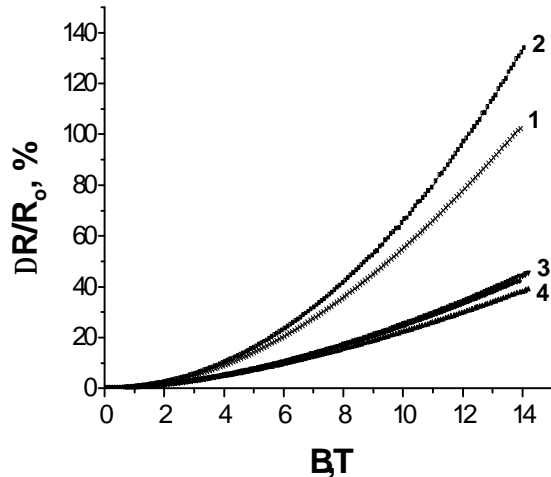**Fig. 1**. Magnetoresistance dependences of Ge_xSi_{1-x} (x = 0.01) whiskers as function of magnetic field. The whiskers ($N_a = 6 \cdot 10^{18}$ cm^{-3}), deformed by different substrates: 1 - copper; 2 - aluminium; 3 - quartz; 4 - free.
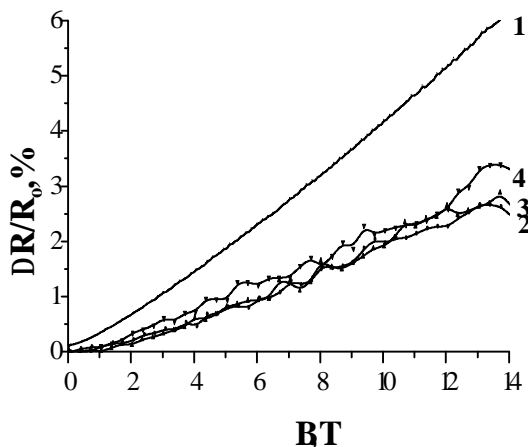

Fig. 2. Magnetoresistance dependences of Ge_xSi_{1-x} (x = 0.01) whiskers as function of magnetic field. The whiskers ($N_a = 1.5 \cdot 10^{19}$ cm^{-3}), deformed by different substrates: 1 - free; 2 - copper; 3 - aluminium; 4 – quartz.

dependences were found to be in the samples with acceptor-impurity concentration $N_a = 5 \cdot 10^{18}$cm^{-3}, $N_a = 6 \cdot 10^{18}$cm^{-3} and $N_a = 7 \cdot 10^{18}$cm^{-3} (see Fig. 1).

The exponential law of magnetoresistance field dependences $\Delta R_B/R \sim \exp(B^n)$ is found for the whisker with acceptor-impurity concentration $N_a > N_c$ ($N_a = 1 \cdot 10^{19} - 1.5 \cdot 10^{19}$ cm^{-3}) (Fig. 2). Boron density in these samples corresponds to the metallic side of the MIT. The dependences are found in the whiskers with low germanium content only up to 1 at. %.

The so-called "anomalous" positive magnetoresistance (PMR) was observed at very high germanium composition (x = 11 at. %) in the whisker with the impurity concentration ($N_a = 2 \cdot 10^{19}$ cm^{-3}). In fact

the magnetoresistance is small and does not depend on the field over the range 0.2 to 1.4 T (Fig. 3). The similar effect was found in [10] for p-type Ge samples from the metallic side of the MIT. The PMR mechanism may be related to changing a density of states at the Fermi level under magnetic field according to the model described in [10].

The negative magnetoresistance (NMR) is revealed for the whisker with the impurity concentration very closed to the critical one of the MIT $N_a \approx N_c$ from its insulating side ($N_a = 8 \cdot 10^{18}$ cm^{-3}) at the intermediate level of germanium composition (x = 4.15 at. %) (Fig. 3). This sample has the Mott $\rho(T)$ dependence. Its magnetoresistance is negative over the range of magnetic field from 0 to 1.4 T and it is weakly dependent upon the mutual orientation of a current and field. The same effect was observed in [7] for p-type Si whiskers from the insulating side of the MIT.

So, we could find out the NMR and the "anomalous" PMR as connected with increasing of germanium content from 4.15 to 11 at. % in some investigated samples at uniaxial compression applied.

II. Discussion

The quadratic dependence of whisker magnetoresistance as function of magnetic field is known [5] to correspond to band conductance, or localized state conductance in the upper Habbard band with the activation energy ε_2. An observation of quadratic field dependences of magnetoresistance in the samples (Fig. 1) indicates that their conductance occurs by localized states in the upper Habbard band.

Weak magnetoresistance of the whiskers with low impurity concentration $N_a = 3 \cdot 10^{18}$cm^{-3} at 4.2 K is likely connected with fact that kT is rather small to provide the conductance by the upper Habbard band. A quadratic field dependence of magnetoresistance in the samples is expected to occur at higher temperatures (10 – 20 K).

The exponential field dependence of magnetoresistance corresponds to conductance in the lower Habbard band with the activation energy ε_3 for insulating samples or to conductance with strong electron correlation in the metallic samples.

We have not found an exponential field dependence of magnetoresistance for the whiskers from insulating side of the MIT. But, it should be noted, that at cryogenic temperatures the transition from conductance with the activation energy ε_3 to conductance with the activation energy ε_2, as rule, takes place. So, at 4.2 K mix conductance mechanism with the activation energies (ε_2 and ε_3) in the whiskers occurs. In our opinion, it can lead to decrease of magnetoresistance absolute value.

The above consideration can be illustrated by the following examples.   Only free sample has hopping conductance with activation energy ε_2, while the mix conductance mechanism is found for deformed samples (ε_2 i ε_3). Thus, magnetoresistance of free sample decreases at deformation from 70 % to 53 %. The mix conductance mechanism is found for both free and quartz
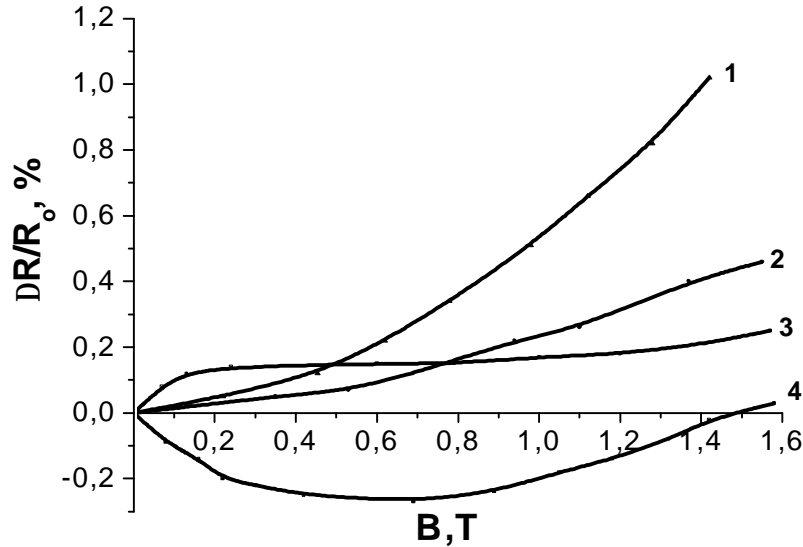
Fig. 3. Magnetoresistance dependences of Ge_xSi_{1-x} whiskers as function of magnetic field: 1 - $N_a = 5 \cdot 10^{18}$ cm^{-3}, (x = 0.22 at. % of Ge); 2 - $N_a = 2 \cdot 10^{18}$ cm^{-3}, (x = 11 at. % of Ge); 3 - $N_a = 1 \cdot 10^{19}$ cm^{-3}, (x = 0.5 at. % of Ge); 4 - $N_a = 8 \cdot 10^{18}$ cm^{-3}, (x = 4.15 at. % of Ge).

deformed samples (Fig. 1); copper and aluminium substrates provides conductance with the activation energy ε_2 in the given temperature range. In result, magnetoresistance of samples deformed by aluminium and copper substrates (140 % and 110 % respectively) are higher than that for free sample (30 %) (Fig. 1).

Effects of electron correlation are likely to occur in metallic whiskers, in which exponential dependences of magnetoresistance are found. Our results show that electron correlation increases with a rise of Ge content in the whiskers. So, for the whiskers anomal PMR is observed (Fig. 3).

An existence of NMR is typical for samples with impurity concentration in the vicinity to critical concentration of the MIT. We have found NMR in the whiskers from insulating side of the MIT (Fig. 3). In such samples NMR is known to occur due to carrier conductance by delocalized states of upper Habbard band [11]. Activation energy of this conductance $\varepsilon_2 = 1.5$ meV was determined from temperature dependence of conductance at 4.2 K in the samples. In the whiskers with lower doping level ε_2 value rises at a decrease of impurity concentration. So, in the whiskers with $\varepsilon_2 = 4.5$ meV an appearance of NMR is expected to observe at higher temperatures (7 – 20 K).

Conclusions

The magnetoresistance and hopping conductance were investigated at cryogenic temperatures in Ge-Si whisker samples with various acceptor-impurity concentration ($N_a = 3 \cdot 10^{18}$ ¸ $2 \cdot 10^{19}$ cm^{-3}) and Ge content (x = 0.2 ¸ 11 at. %). Whisker magnetoresistance in Ge-Si solid solution with carrier concentration $N \le N_a$ is described by the quadratic dependence upon magnetic field and it practically corresponds to localized state conductance in the A^+ upper Habbard band with the activation energy ε_2 at temperature 4.2 K. The hopping conductance with the activation energies ε_2 and ε_3 is found in deformed samples, which leads to decrease of magnetoresistance absolute value. The negative magnetoresistance was found for the whisker sample with the impurity concentration very closed to the critical concentration of the MIT $N_a \approx N_c$ from its insulating side at the intermediate level of germanium composition (x = 4.15 at. %). NMR is not found for the crystals with low level of germanium composition at temperature 4.2 K. Obviously, the delocalized state conductance in the A^- upper Habbard band and existence of NMR should be expected in the range of higher temperatures about 7 ¸ 20 K. The "anomalous" positive magnetoresistance was observed at very high germanium content (x = 11 at. %) in the whisker with the impurity concentration ($N_a = 2 \cdot 10^{19}$ cm^{-3}). The exponential dependence of magnetoresistance as function of magnetic field is found for the whiskers with impurity concentration $N > N_a$.

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Магнітоопір ниткоподібних кристалів Ge-Si в області переходу метал-діелектрик

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Магнітоопір ниткоподібних кристалів (НК) Ge_xSi_{1-x} (x = 0,002 ͦ 0,11) з концентрацією акцепторів ($N_a = 3 \cdot 10^{18}$ ͦ $2 \cdot 10^{19}$ см⁻³) поблизу переходу метал-діелектрик (ПМД) вивчали за низьких температур (4,2 - 77 К) в магнітних полях до 14 Т. Показано, що при 4,2 К магнітоопір ниткоподібних кристалів Ge-Si з діелектричного боку переходу є квадратичним, тоді як магнітоопір кристалів з металевого боку переходу має експоненціальну залежність від магнітного поля. У зразках у безпосередній близькості до ПМД з діелектричного боку виявлено від'ємний магнітоопір, тоді як у зразках з металевого боку переходу з високим вмістом германію (x = 11 ат.%) спостерігається аномальний позитивний магнітоопір. Отримані аномальні залежності, відповідно, пояснюються провідністю по делокалізованих станах A^+ верхньої зони Хаббарда та збільшенням електрон-електронної взаємодії в НК Ge-Si при збільшенні вмісту германію.

Ключові слова: магнітоопір, ниткоподібні кристали, тверді розчини Ge-Si, перехід метал-діелектрик.