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Magnetic susceptibility and magnetoresistance of neutron-irradiated doped SI whiskers

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ABSTRACT

The effect of $8.6 \cdot 10^{17}$ n/cm^2 fast neutron irradiation on the magnetic susceptibility and magnetoresistance of Si whiskers with impurity concentration near metal–insulator transition (MIT) has been studied. Neutron irradiated specimens with boron concentration away of MIT are mainly diamagnetic with a small amount of paramagnetic centers originated from dangling bonds on the whisker surface. It has been established that at temperatures near 4.2 K, a significant contribution to the conductivity is made by light charge carriers of low concentration but with high mobility. The as grown whiskers with impurity concentration correspondent to MIT showed hysteresis loops in magnetization at temperature of liquid helium. Besides hysteresis loops in magnetoresistance was observed for whiskers under compression stress at low temperature up to 7 K. The possible reason of the effect can be magnetic interaction between impurities centers in subsurface region of the whisker with the orbital moment of dangle bounds in the whisker core–shell interstices.

1. Introduction

Quasiferromagnetism of silicon crystals is mainly originated from their doping with magnetic impurities [1–5]. But at the last time a discussion is continuing concerning a possibility of ferromagnetism without magnetic impurities. For example Dubroca et al. observed ferromagnetism in neutron irradiated Si crystals [6]. The possible reason of ferromagnetism is an appearance of paramagnetic defects during the sample irradiation. Neutron-inducted ferromagnetism in Si crystals was reported by Sounder more than 30 years ago [7], where magnetic susceptibility and Hall measurement were mentioned. The authors of Ref. [8] have speculated about the possibility of ferromagnetism in grown by chemical vapor deposition (CVD) method Si crystals based on EPR investigations but did not present magnetic hysteresis loops. Other group of authors doubting Dubroca results have fulfilled a set of experiments on neutron irradiated Si and established an absence of magnetic hysteresis loops in all specimens [9]. This implies that neutron-inducted ferromagnetism is still controversial. Also is a next open question about the quasiferromagnetism in Si crystals without magnetic impurities.

The aim of the present paper is a study of Si whiskers with boron impurity concentration in the vicinity to metal–insulator transition (MIT) both neutron irradiated and as grown by CVD techniques. The results showed that neutron irradiated specimens with boron concentration away of MIT are mainly diamagnetic with a small amount of paramagnetic centers originated from dangling bonds on the whisker surface. The as grown whiskers with impurity concentration correspondent to MIT showed hysteresis loops both in magnetization and magnetoresistance at temperature of liquid helium. The observed electric and magnetic behavior can be explained by hopping conductance and magnetization resulting from the whisker structure.

2. Experiment

Si whiskers were grown by the chemical transport reaction method in a sealed bromide tube [10]. In quartz tube the following materials were loaded: silicon – growth materials; gold – initiator of growth; boron – doping impurity and bromine – transport agent. Temperature of evaporation zone and temperature of crystallization zone were 1000 °C and 700–800 °C, respectively.

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The investigated whiskers have diameters ranging from 100 nm to 40 μm. Boron content in Si whiskers was controlled by microprobe analysis and consisted of 0.01–0.05. For control of the whisker contamination Auger spectroscopy and mass spectral analysis was used. The results of the analysis indicate in the presence of *B* impurities with concentration ranging from 10^{17} cm^{-3} to 10^{19} cm^{-3} as well as in an absent of any others impurities in the whiskers with concentration exceeding 10^{14} cm^{-3}.

Strained and free-standing whiskers were under investigation. The compression strain was applied to the whisker due to their mounting at copper substrate and cooling to low temperatures. Due to different coefficient of thermal expansion of silicon and copper the compression of Si whiskers occurs. Our previous calculations of uniaxial compression [11] have shown that value of stain is practically constant and equal to 4×10^{-3} rel.u. in temperature range 4.2–40 K.

Low temperature investigations of Si whisker magnetoresistance were conducted in temperature range 4.2–300 K at magnetic field up to 14 T. The magnetic field was applied in transverse direction to current movement, thus the transverse magnetoresistance was measured. The samples have been cooled down to 4.2 K in the helium cryostat. A special inset with the bifilar winding heater has been used to heat-up samples to the room temperature. The stabilized electrical current of 1–100 μA depending on the resistance of the sample being studied has been generated by the Keithley 224 current source. The Keithley 2000 and Keithley 2010 digital voltmeters with the simultaneous automatic registration via the parallel port of PC, the vizualization and saving the data arrays into files have been used to measure the voltage at the potential contacts of samples, the output of thermocouple and of the magnetic field sensor with the accuracy of up to 1×10^{-6} V. The Bitter-magnet based setup has been used to study the effect of strong magnetic fields on the samples. The induction of the magnet was 14 T, deflection time 1.75 T/min and 3.5 T/min at 4.2 K and higher temperature range respectively.

Magnetic susceptibility (MS) of whiskers was measured by the Faraday method [12] in magnetic fields 0.3–4.0 kOe at temperature range 4.2–300 K. Before measurement a samples were formed from the whiskers in such a way. The whiskers were packed in cylindrical glass tubes with 3 mm in diameter and were filled with beeswax. After that glass tube was removed from the samples. Experimental results show that magnetic susceptibility of beeswax is in order of magnitude less that MS of the whiskers. Nevertheless every time a correction of data on magnetic contribution of beeswax was made. The measurement error does not exceed 5%.

3. PART A: magnetic investigation of neutron irradiated Si whiskers

Irradiation with the fast neutron effect dose $8.6 \cdot 10^{17}$ n/cm^2 on magnetic and magnetoresistive properties of Si has been studied. The irradiation was carried out using the Pressurized water reactor of the Institute for Nuclear Researches of the National Academy of Sciences of Ukraine. The whisker with the diameter of 30–40 μm, the length of 2–3 mm and of *p*-type conductivity with the resistivity close to $\rho = 0.02$–0.2 Ohm cm were selected for the experiment.

After irradiation, the magnetic susceptibility in the magnetic fields 0.3–4.0 kOe at the ambient temperature was measured.

Fig. 1 shows the magnetic susceptibility dependences on the value of magnetic field for initial samples with boron concentration of about 10^{17} cm^{-3} (curve 1) and neutron irradiated Si whiskers (curve 2). To compare the neutron irradiation effect on the magnetic susceptibility, Fig. 2 presents the same dependence for bulk samples of monocrystalline Cz–Si, grown in the direction

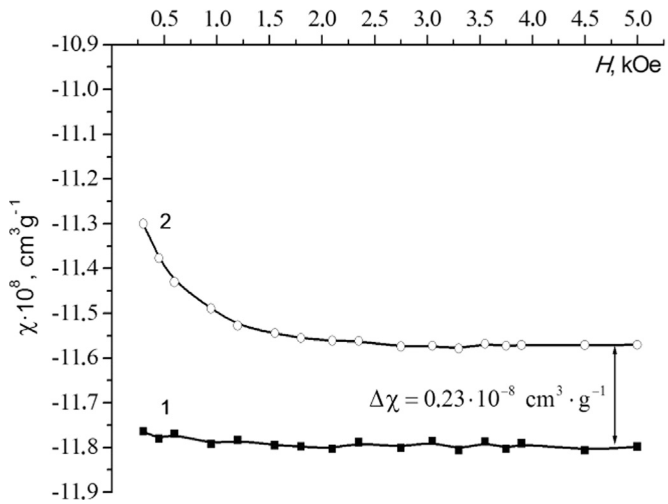

Fig. 1. Magnetic susceptibility versus magnetic field for Si whiskers (d=30–40 μm): 1 – initial sample, 2 – neutron irradiated simple with the dose of $8.6 \cdot 10^{17}$ n/cm^2.

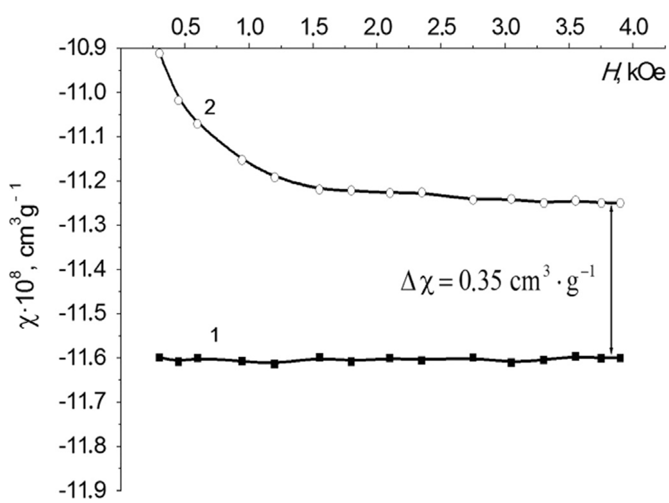

Fig. 2. Field dependence of the magnetic susceptibility for the monocrystalline Cz–Si sample: 1 – initial sample, 2 – neutron irradiated simple with the dose $8.6 \cdot 10^{17}$ n/cm^2.

⟨100⟩ with the dissolved oxygen concentration $(7–8) \cdot 10^{17}$ cm^{-3} and resistivity ~10 Ohm cm.

Comparing Figs. 1 and 2, one can see that the neutron irradiation effect is more essential in the monocrystalline silicon samples. In particular, the change in the magnetic susceptibility in Cz–Si is $\Delta\chi = 0.35 \cdot 10^{-8}$ cm^3 g^{-1}, whereas in Si whiskers it is $\Delta\chi = 0.23 \cdot 10^{-8}$ cm^3 g^{-1}. One can assume that they are more resistive to neutron irradiation.

The rise of non-linearity, depending on the magnetic susceptibility, with the magnetic field value for Si whiskers after neutron irradiation demonstrates formation of some clusters in addition to dispersed paramagnetic centers in crystals, which behave like Langevin paramagnetism of atoms possessing a magnetic moment $10^3 \ldots 10^5$ times higher than the magnetic moment of individual atoms. As it is known, neutron irradiation causes formation not only of a variety of point defects in the material but also formation of the so-called regions of disorder, which, apparently, can serve as centers responsible for creation of magnetic nanoclusters.

To analyze the experimental dependences of magnetic susceptibility on the magnetic field value $\chi(H)$ (Figs. 1 and 2, curves 2), we use the theoretical model, which is described in detail in [13]: