Magnetoresistive effect in Yb$_x$Mn$_{1-x}$S at small concentrations

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Abstract. The results of measurements of electrical resistivity without a field and in magnetic field of 0.8 T in the temperature range 100 K < T < 450 K for composition Yb$_x$Mn$_{1-x}$S with x = 0.05, 0.1 are presented. For the x = 0.05 the gigantic magnetoresistive effect at room temperature is found.

1. Introduction

The relationship of magnetic and electrical properties is an important factor for creating electronic devices that operate on new principles and open new directions, such as spintronics [1-3] and new materials of multiferroics [4-9].

The interaction of electrons with an elastic lattice can also manifest itself in the resistive properties of semiconductors [10-13]. A strong magnetoresistive effect was detected in the vicinity of the orbital ordering in the two-orbit Hubbard model with $\frac{1}{4}$ the electron filling function at the site [14]. The resistance detects a small maximum in the region of formation of the orbital ordering [15], the electron density of states at the Fermi level splits in the magnetic field, which leads to an increase in the resistance in the paramagnetic phase [16-17]. The formation of an orbital ordering is accompanied by lattice deformations and changes in the magnetic state [18-20]. In chalcogenide compounds with polymorphic transitions, negative magnetoresistance is associated with tunneling of electrons having the same spin orientation in the magnetic field [21-23].

Manganese sulfides have a NaCl-type crystal FCC lattice with a constant unit cell parameter $a = 0.5222$ nm (MnS). Ytterbium sulfides have a NaCl-type crystal FCC lattice with a constant lattice $a = 0.5693$ nm (YbS). When the critical pressure value $P = 8$ GPa is reached, the YbS lattice is compressed by 12 % [24]. It can be expected that when replacing of manganese cations with ytterbium ions, the pressure of nearest neighbors will lead to a change in the valence of ytterbium ions and to the formation of a metal bond. If the valence of the metal to be +3 and the sulfur to be −2, then each unit cell containing four formula units of YbS will have four electrons that do not participate in the Me-S bond. These electrons will take part in the Me-Me bond and be collectivized. The formation of chemical bonds between ytterbium and manganese ions induces rearrangement of the electronic structure in a solid solution and changes in the magnetic and transport properties [25].

The purpose of this work is to determine the optimal conditions for the occurrence of the magnetoresistive effect by temperature and concentration. To achieve this goal, the temperature dependences of the resistance in the magnetic field will be measured and a correlation with the elastic system will be established from the temperature dependences of the coefficient of thermal expansion of the lattice.
2. Experimental results and discussion

X-ray diffraction analysis was performed on the DRON-3 installation. X-ray images and the crystal structure of YbxMn1-xS compositions were studied at room temperatures on the polished side surfaces of parallelepipeds: in the initial state after their preparation, after measurements of electrical measurement up to 500 K. The reflexes, different from the FCC structure are not observed. The size of a unit cell in a solid solution of Yb3Mn1.8S increases linearly with the concentration.

Electrical resistivity measurements were carried out using a four-probe compensation method at a direct current in the temperature range of 80 K – 500 K. Temperature dependences of electrical resistance for solid solutions YbMn1-xS are shown in figure 1. The dependence of resistance on temperature has an activation form. They have a typical semiconductor type and do not differ qualitatively from the temperature dependence \( \rho(T) \) for MnS for compositions with \( x \leq 0.1 \). When heating a solid solution of Yb0.05Mn0.95S, the activation energy increases 1.7 times at \( T = 440 \) K. With increasing concentration the activation energy is decreased, and the temperature shifts to the low temperature range to \( T = 390 \) K for \( x = 0.1 \).

Replacement of manganese with ytterbium leads to an increase in the concentration of current carriers and a decrease in the activation energy. The absence of plateau in the temperature range 300 - 500 K of \( \rho(T) \) in the solid solution at magnetic field is observed. The energies of impurity states (\( E_i \)) are located below the bottom of the conduction band (\( E_c \)) by the value \( \Delta E = E_c - E_i \) and with increasing concentration, the energy interval decreases.

Figure 1. Temperature dependences of specific electrical resistivity for YbMn1.8S samples with \( x = 0.05 \) (a), \( x = 0.1 \) (b) measured without a field (1) and in a magnetic field \( H = 0.8 \) T (2).

The influence of the magnetic field on the electrical resistance was studied without a field and in a magnetic field \( H = 0.8 \) T. In a solid solution of YbMn1.8S, the resistance increases in the magnetic field \( H = 0.8 \) T in the range of 150 K < \( T < 450 \) K and the relative change in the specific electrical resistance at magnetic field reaches a maximum at \( T = 329 \) K. In the area of room temperatures, have a giant positive magnetoresistive effect with a change in the resistance value by an order of magnitude (figure 2a). The value of the activation energy does not change in the range of 150 K – 300 K, and the preexponential is decreased tenfold in the magnetic field.

In YbMn1.8S \( c x = 0.1 \), the activation energy of current carriers in the magnetic field decreases and the magnetoresistive coefficient changes sign from negative to positive at \( T = 260 \) K (figure 2b). The maximum value \( (\rho(H) - \rho(0)) / \rho(0) \) is observed at \( T = 360 \) K and the magnetoresistive effect disappears asymptotically at \( T = 500 \) K.
The formation of an orbital ordering [26, 27] of the glass state type [28, 29] can lead to a change in elastic characteristics, both static and dynamic, for example, a change in the impedance in a magnetic field [30]. Below the coefficient of thermal expansion of the lattice as a function of temperature is studded.

The thermal expansion coefficient was measured using a Netzsch dilatometer DIL-402C in the temperature range of 200 K – 750 K with a heating rate of 5 K/min. Fused quartz and corundum standards were used to calibrate and account for the thermal expansion of the measuring system. The results of strain studies ($\Delta L / L$) and thermal expansion coefficient ($\alpha(T)$) for samples Yb$_x$Mn$_{1-x}$S ($x = 0.05, 0.1$) are shown in figure 3. When heated, the coefficient of thermal expansion decreases and has a minimum at $T = 275$ K and a sharp jump in $\alpha(T)$ for the sample with $x = 0.1$. At this temperature, the permittivity and magnetic capacity have maximum values, and the magnetoresistive effect changes sign from negative to positive. Above $T > 480$ K, the slope in the temperature dependence $\alpha(T)$ ($d\alpha / dT = 0$ at $T = 480$ K) decreases and the magnetoresistance disappears. The increase in the coefficient of thermal expansion with temperature may be caused by the anharmonicity of lattice vibrations as a result of electron-phonon interaction, which induces an asymmetry of the crystal field on the ion.

3. Conclusion
Thus, a magnetoresistive effect was found for Yb$_x$Mn$_{1-x}$S with $x = 0.05$ and $x = 0.1$ at temperatures above room temperature and for $x = 0.05$ the magnetic capacity sign changes in the vicinity of 200 K. A decrease in the activation energy of the transition of electrons from the impurity level to the zone of
conductivity and mobility of charge carriers in a magnetic field was found. For a sample \( \text{Yb}_{0.05}\text{Mn}_{0.95}\text{S} \), the magnetoresistive effect is 900\% at room temperature. The change of the magnetoresistance sign from negative to positive when heated in the sample region for \( \text{Yb}_{0.1}\text{Mn}_{0.9}\text{S} \) is established. The critical temperature above which the magnetoresistance disappears is determined. The magnetoresistive effect is explained in the model of the orbital ordering of electrons. The change in the sign of magnetoresistance versus temperature is explained by the formation of magnetic and orbital ordering at different temperatures.

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