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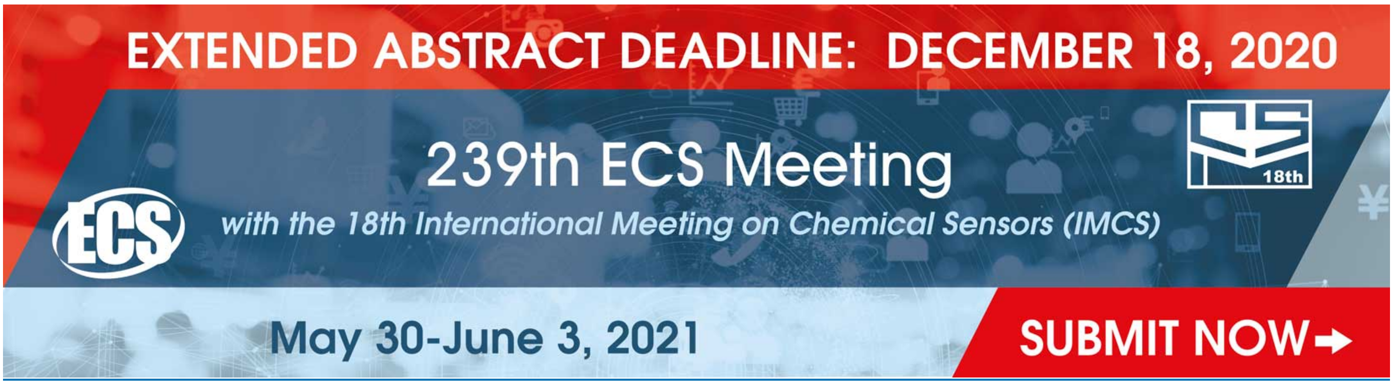

Hopping conduction in single crystals of the diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ (x=0.005)

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Abstract. Single crystals of the diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) were obtained by modified Bridgman method. According to the results of the X-ray powder diffractometry, the material was single-phased and isomorphic and corresponded to the pure Zn_3As_2 ($x = 0.0$). The research of the electroconductivity and the magnetoresistance was carried out at the temperature range from 10 to 300 K. It was found out that the electroconductivity in the temperature range 11 ÷ 19 K corresponded to the mechanism of the Mott type variable-range hopping conductivity. The microparameters, characterizing electroconductivity $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) at the temperature range of 11 ÷ 19 K, were defined.

1. Introduction

Zn_3As_2 is a semiconductor of group II_2V_5p-type conductivity, at the room temperature it has the width of the band gap$E_g \approx 1$ eV, tetragonal crystal structure and belongs to the space group $I4_1cd$ (it is so called α-phase Cd_3As_2)[1]. Solid solutions on the basis of Zn_3As_2, where a part of atoms As is changed by Mn, belong to the class of diluted magnetic semiconductors which can be applied in the heterostructures of spintroninc devices as injectors of spin-polarized charge carriers. As it is known, for a successful integration of magnetic material with nonmagnetic semiconductors in a microelectronic device, it is necessary for them to have comparable resistance values. In this case magnetic semiconductors have an indisputable advantage over metals [2]. Solid solutions of the diluted magnetic semiconductor $(Zn_{1-x}Mn_x)_3As_2$ were researched in a range of works [3-9]. We know only one work dedicated to the study of magnetic properties of a new diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ [10], and the reference to this material in a review [11] with the reference to the work [10]. In the work [10] the single crystals $(Zn_{1-x}Fe_x)_3As_2$ were synthesized at the range of compositions $0.005 \leq x \leq 0.04$. By X-ray phase analysis it was found out that solid solutions $(Zn_{1-x}Fe_x)_3As_2$ remained homogeneous till the composition $x = 0.015$. In the diffractograms for $x \geq 0.02$ there was fixed the appearance of the second phase, identified as Fe_2As. The parameters of the crystal lattice of $(Zn_{1-x}Fe_x)_3As_2$ did not change considerably at the growth of x up to 0.02. The magnetic properties were researched by the SQUID magnetometer, the presence of the spin glass phase was ascertained, and the freezing temperatures of magnetic moments $T_f < 50$ K were determined.

In this paper we report about the research of electroconductivity and magnetoresistance in a single crystal of the solid solution of the new diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$), which was carried out for the first time.

2. Results and discussion

The research of the temperature dependence of single crystals of the solid soution of the new diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) resistance was done by six-probe method. The samples were in the form of parallelipiped 2x2x5 mm, copper contacts were attached to the samples by silver conductive paste. The temperature range of measurements was from 10 to 300 K with the step of 2 K. The temperature dependence of the magnetoresistance was measured in the magnetic field of 1 T. In order to change the sample's temeparture we used the closed cycle cryostat of the model Janis CCS-350S, equipped with a thermostat and a helium compressor, 8200 Compressor, and a thermocontroller 331 of the brand Lake Shore.

Figure 1 shows the experimentally mesured dependence of the resistivity on the temperature,$\rho(T)$, of the single crystal $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) in the zero magnetic field and in the magnetic field $B = 1$ T. The behaviour of the resistivity dependence on the tmperature $\rho(T)$ $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) has a complicated character both in the zero magnetic field and in the magnetic field $B = 1$ T. At all the temperature range from 10 to 300 K there is a positive magnetoresistance. In the low-temperature area the dependence $\rho(T)$ has an activation character from 10 to 40 K in the zero magnetic field and from 10 to 30 K in the field $B = 1$ T. The further temperature increase leads to the growth of the resisitivity, which corresponds to the presence of metallic conductivity in the impurity band due to Mott transition [12].

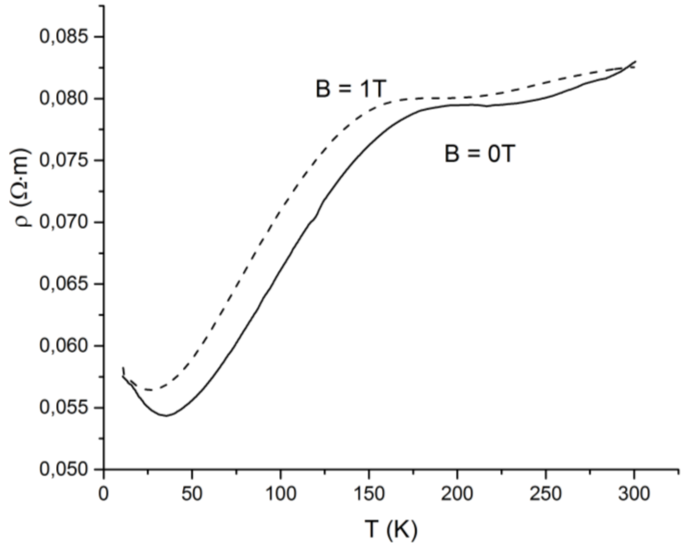

Figure 1. The dependence of ρ on T for the single crystal $(Zn_{1-x}Fe_x)_3As_2$ (x = 0.005).

The resistivity of the semiconductor at the thermal activation follows the law [13]:

$$\rho(T) = \rho_0 \exp\left\lfloor E_A \cdot (kT)^{-1} \right\rfloor, \tag{1}$$

where k is Boltzmann constant; E_A is the activation energy; ρ_0 is the preexponential factor.

On the other hand, the hopping conduction in three-dimensional (3D) alloyed semiconductors can be assigned by the universal equation [14], describing the implementation of the hopping conduction with the help of different mechanisms

$$\rho(T) = DT^m \exp(T_0/T)^p, \tag{2}$$

where D is the constant; T_0 is a characteristic temperature, depending on the implemented hopping conduction mechanism, which is mathematically described by the parameter quantity p ($m = p$). The parameter p can get the following, most probable for the semiconductors alloyed by the shallow impurity, quantities: at $p = 1$ there is a nearest-neighbor hopping (NNH) conductivity; at $p = 1/4$ there is Mott variable-range hopping conductivity (Mott VRH); at $p = 1/2$ there is Shklovsky-Efros (SE) type VRH [15].

The quantity of the characteristic temperature T_0 in case of the implementation of one of VRH mechanisms can be presented as

$$T_{0M} = \frac{\beta_M}{kg(\mu)a^3}, \quad T_{0SE} = \frac{\beta_{SE} e^2}{\kappa ka}, \tag{3}$$

where $g(\mu)$ is the density of the localized states (DLS) near Fermi level; a is the charge carrier localization length; κ is a dielectric conductivity, $\beta_M = 21$, $\beta_{SE} = 2{,}8$ [14].

The implemented hopping conduction mechanism at low temperatures according to the equation (2) mathematically is considered to be the parameter quantity p, but, on the other hand, the power dependence T^m also influences considerably the hopping conduction mechanism. In connection with this it is suitable to rewrite the equation (2) at $B = 0$ and $B = 1$ tesla as:

$$\ln\left[E_a/(kT + m)\right] = \ln p + p \ln T_0 p + \ln\left(T^{-1}\right), \tag{4}$$

where $E_a \equiv d \ln \rho / d(kT)^{-1}$ is the local activation energy [14].

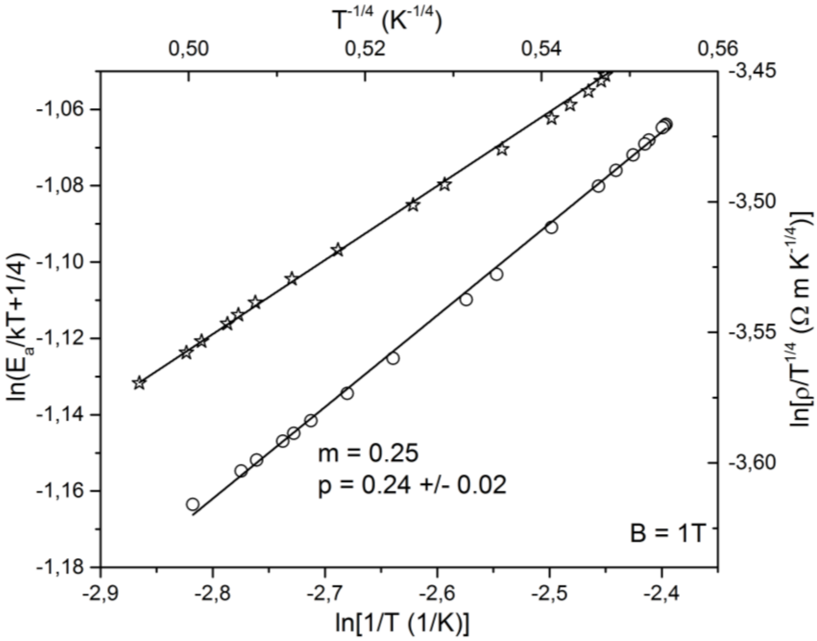

Figure 2. The dependences of $\ln(E_a/kT+1/4)$ on $\ln(1/T)$ (○) and $\ln(\rho/T^{1/4})$ on $T^{-1/4}$ (✫) at B = 1 tesla (temperature range 11 ÷ 19 K).

Thereby, for the definite conduction mechanism the left part of the equation (4) will be a linear function of $\ln(T^{-1})$, and p will be determined by the incline of the graph $\ln\left[E_A/(kT + m)\right]$ from $\ln(T^{-1})$ (Figure 2).

For the analysis of the hopping conduction type consider $m = ¼$ in the equation (4), we get $p \approx 1/4$, which corresponds to the Mott type VRH. Mott VRH occurs in case when DLS near Fermi level is a constant and finite [12].

From the dependence $\ln\left(\rho/T^{1/4}\right)$ on $T^{-1/4}$ for the sample $(Zn_{1-x}Fe_x)_3As_2$ (Figure 2) we get an extensive linear interval of low temperatures, this also allows assumption about VRH mechanism type. Quantities of T_{0M} at $B = 0$, $B = 1$ tesla can be found out from the linear sections of Figure 2 and are presented in Table 2. The activation energy E_A can be determined from the linear section of the dependence $\ln\rho$ on T^{-1} in the equation (1) at the temperature range from 11 K to 19 K, under condition that the coefficient ρ_0 faintly depends on T [14]. These values are presented in Table 1.

According to the data, obtained at $B = 0$ and in weak fields at $B = 1$ T, it is possible to find out different microscopic parameters [15].

Table 1. Coefficient ρ_0 and the activation energy E_A in $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$).

	ρ_0 (Ohm·m)	**E_A (meV)**
$B = 0$ T	1.54	0.249
$B = 1$ T	1.66	0.250

Table 2. The calculated quantities of T_{0M}, of the soft Coulomb gap in DLS near Fermi level Δ, tough gap δ, κ, a, W and g for the sample $(Zn_{1-x}Fe_x)_3As_2$ (x = 0.005).

	T_M, K	**g_μ, cm^{-3} meV^{-1}**	***r*, nm**	***a*, nm**	**κ**	**Δ, meV**	**W, meV**
$B = 0$ T	69	$2.65\cdot10^{+15}$	3.7	12	165	0.18	1.13
$B = 1$ T	25	$7.33\cdot10^{+15}$	2.9	12	180	0.04	0.53

In the sample $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$) the influence of Coulomb gap is minimal, Mott type conductivity is implemented at $B = 0$, $B = 1$ T. That is why DLS in the acceptor zone can be approximated by the rectangular form, the width of Coulomb gap in DLS of Fermi level is $W \approx kT_{VM}^{3/4}T_{0M}^{1/4}$ [12]. From the formula $g(\mu) \approx N_A/(2W)$ we get DLS for this type of conductivity $(g(\mu) \equiv g)$, and from the equation (3) we find *a*. The value κ will be got from the formula $E_A = F(K)e^2\kappa^{-1}N_A^{1/3}$ [12], where *F*(*K*) is some universal compensation function (*F*(*K*) = 0.43 [16]). Then from the formulas

$$\Delta \approx \frac{k}{2}\sqrt{T_{VM}T_{0M}}, \quad g_0 = \frac{3\kappa^3(\Delta-\delta)^2}{\pi e^6}, \quad g(\mu) = \frac{N_A}{2k\left(T_{VM}^3 T_{0M}\right)^{1/4}}, \tag{5}$$

we find the values Δ and *δ*. The calculated values Δ, *δ*, *κ*, *a*, *W* and *g* for the sample are presented in Table 2. The correlations between the values Δ and *W* are coordinated with the corresponding conduction mechanism at $B = 0$. The ratio $\Delta/W \sim 0{,}1$ is suitable for Mott VRH regime.

3. Conclusion

For the first time we researched the temperature dependence on electroconductivity and magnetoresistance of single crystals of the diluted magnetic semiconductor $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$), obtained by modified Bridgman method. According to the results of the X-ray powder diffractometry, the material was single-phased and isomorphic and corresponded to the pure Zn_3As_2 ($x = 0.0$). The research of the electroconductivity and the magnetoresistance was carried out at the temperature range from 10 to 300 K. In the low-temperature zone of the dependence *ρ(T)* there was an activation section from 10 to 40 K in the zero magnetic field and from 10 to 30 K in the field $B = 1$T. It was found out that the electroconductivity in the temperature range 11 ÷ 19 K corresponded to the mechanism of the Mott type variable-range hopping conductivity. The microparameters, characterizing electroconductivity $(Zn_{1-x}Fe_x)_3As_2$ ($x = 0.005$), were determined for the hopping conduction mechanism. With the growth of temperature the resistivity increases, which is characteristic of the metal conductivity, and we may presume that this is connected with the metallic conductivity appearance in the impurity zone as a result of Mott transition [12].

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