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Electrical and Thermal Properties of the GaSb–$FeGa_{1.3}$ Eutectic

M. I. Aliev*, A. A. Khalilova*, D. G. Arsaly*, R. N. Ragimov*, and M. Tanogly**

** Institute of Physics, Academy of Sciences of Azerbaijan, pr. Javida 33, Baku, AZ1143 Azerbaijan*

*** Izmir Institute of Technology, IYTE Campus, Gulbahce koyu Urla, Izmir, 35437 Turkey*

e-mail: rashad@physics.ab.az

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Abstract—The electrical conductivity, thermoelectric power, Hall coefficient, and thermal conductivity of the GaSb–$FeGa_{1.3}$ eutectic were measured in a wide temperature range at different relationships between the directions of the electric current, heat flux, magnetic field, and needlelike metallic inclusions. The results are interpreted in terms of electronic and phonon processes. The metallic inclusions are shown to have a significant effect on the transport properties of the eutectic.

INTRODUCTION

Semiconductor–metal eutectic alloys in which the metallic phase has the form of needlelike inclusions embedded in the semiconductor matrix are convenient model systems for studies of inhomogeneous semiconductors. Such composites offer the advantage of combining semiconducting and metallic properties, which can be controlled by external influences such as electric and magnetic fields, illumination, temperature, pressure, and doping. This opens up a wide variety of practical applications for these materials. Eutectic alloys based on III–V compounds are widely used in the production of galvanomagnetic, thermomagnetic, and photothermomagnetic transducers and strain gages [1–6].

Transport phenomena in eutectics containing evenly dispersed, aligned metallic needlelike inclusions have been studied extensively [1–14].

InSb-based eutectic alloys are the best studied among the eutectics formed by III–V semiconductors and metals.

In this paper, we report the electrical and thermal properties of GaSb–$FeGa_{1.3}$ eutectic alloys between 80 and 500 K.

EXPERIMENTAL

GaSb was prepared by melting equiatomic amounts of Ga and Sb, followed by horizontal zone refining. The hole concentration in the resultant ingot was about 1.7×10^{17} cm^{-3}. The eutectic alloy was prepared from an appropriate mixture (7.9 wt % FeGa) by the vertical Bridgman process at a solidification rate of 1 mm/min. The directionalized eutectic contained second-phase inclusions in the form of needles 1 μm in diameter and 20–100 μm in length, aligned in the solidification direction. The needle density was 3.3×10^4 mm^{-2}. The crystals were *p*-type, with a 300-K hole concentration of 1.2×10^{18} cm^{-3}.

Microstructures were examined under an MIM-8M optical microscope at a 200× magnification (Fig. 1).

Thermal analysis was carried out using a Paulik–Paulik–Erdey system. The melting onset and end-point temperatures were found to be 963 and 1003 K. The heat of fusion was 32.4 J/g, and the entropy of fusion was 6.17 kJ/(K mol) (accuracy of ±2–3%).

The Hall coefficient R_H, electrical conductivity σ, and thermoelectric power α were determined by the compensation method. The measurement accuracy was 5, 2, and 2%, respectively. Thermal conductivity was measured by an absolute steady-state technique with an accuracy of 5%. Thermal diffusivity was measured with an accuracy of 7% using pulsed radiation heating and the setup described in [15].

RESULTS AND DISCUSSION

The temperature dependences of σ and R_H are shown in Fig. 2 for different relationships between the directions of the current (*I*), magnetic field (*B*), and

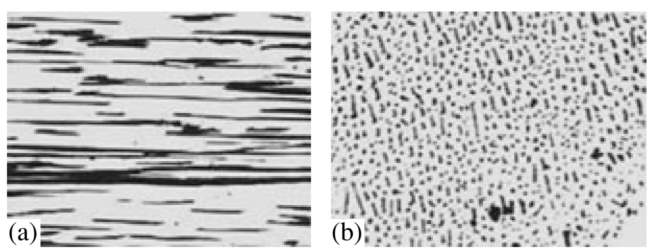

Fig. 1. Arrangement of needles in the GaSb–$FeGa_{1.3}$ eutectic (a) along and (b) across the solidification direction.

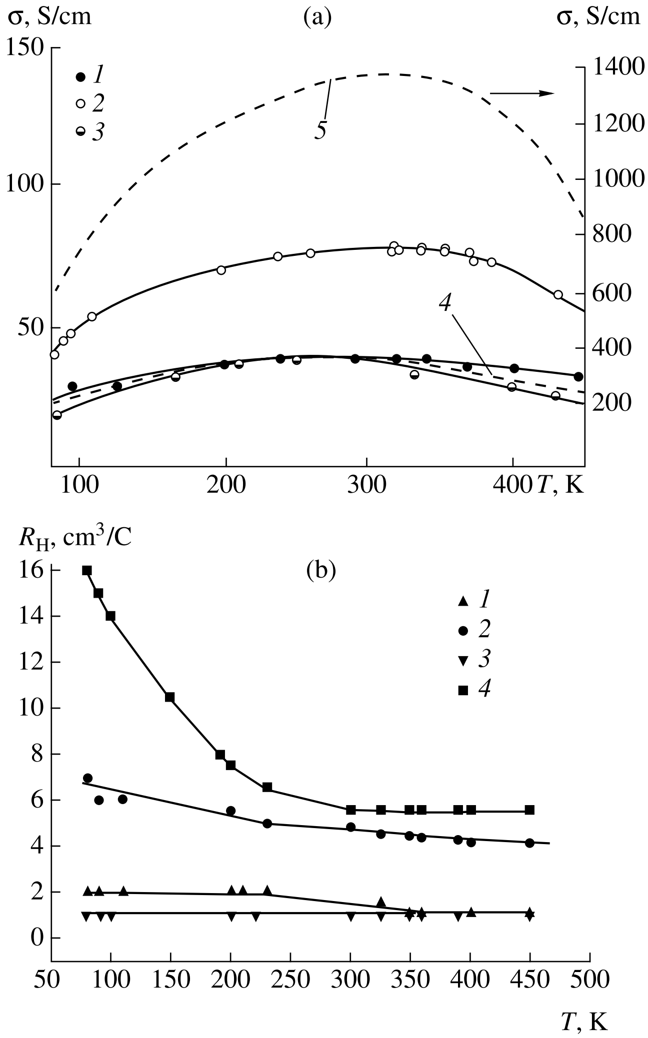

Fig. 2. (a) Temperature dependences of electrical conductivity for (*1*, *2*) $GaSb–FeGa_{1.3}$ ($I \parallel x$ and $I \perp x$, respectively) and GaSb ($p = 2 \times 10^{18}$ cm^{-3}); (*4*, *5*) calculations for GaSb and $FeGa_{1.3}$, respectively. (b) Temperature dependences of the Hall coefficient for (*1*) GaSb and (*2–4*) $GaSb–FeGa_{1.3}$ at (*2*) $I \perp x \parallel B$, (*3*) $I \parallel x \perp B$, and (*4*) $I \perp x \perp B$.

solidification (x). For $I \perp x$, the $\sigma(T)$ curve is similar to that for GaSb with the corresponding hole concentration. The electrical conductivity for $I \parallel x$ is higher owing to the percolative transport along the needles. The short-circuiting of the voltage drop along the sample length by metallic inclusions for $I \parallel x \perp B$ and the short-circuiting of the Hall voltage for $I \perp x \perp B$ reduce the Hall coefficient. With the metallic needles normal to the current and parallel to the magnetic field ($I \perp x \parallel B$), we obtained the largest Hall coefficient, and the $R_H(T)$ curve was similar to that of the matrix.

Various models and relations have been proposed for assessing the effective parameters of eutectics [16]. Such relations include, for the most part, parameters of the matrix and inclusions and the volume fraction of the metallic phase. According to Leonov *et al.* [8], the eutectic structure can be represented by two conductors connected in parallel for $I \parallel x$ and by a combination of parallel and series conductors for $I \perp x$. The electrical conductivity of the material is then given by

$$\sigma_{\parallel} = \sigma_1 \frac{1}{1+c} + \sigma_2 \frac{c}{1+c}, \tag{1}$$

$$\sigma_{\perp} = \frac{(\sigma_1 - \sigma_2)\left(1 - \sqrt{\frac{c}{1+c}}\right) + \sigma_1 \sqrt{\frac{1+c}{c}}}{1 + \frac{\sigma_2}{\sigma_1}\left(\sqrt{\frac{1+c}{c}} - 1\right)}, \tag{2}$$

where σ_1 and σ_2 are the electrical conductivities of the matrix and inclusions, and c is the volume fraction of the inclusions.

For lack of data for $FeGa_{1.3}$, the generalized conductivity of the $GaSb–FeGa_{1.3}$ eutectic could not be calculated, and we solved the inverse problem: jointly solving Eqs. (1) and (2) for the unknown electrical conductivities of the matrix and inclusions and substituting the $GaSb/FeGa_{1.3}$ volume ratio and experimental data on conductivity at different directions of the electric field and needles ($\sigma_{\parallel}$ and $\sigma_{\perp}$), we found the conductivities of the eutectic components. Good agreement between the calculated and experimental conductivities of the matrix (Fig. 2a, curves *3*, *4*) validates this approach to determining the σ of metallic inclusions. The calculated electrical conductivity of $FeGa_{1.3}$ inclusions is one order of magnitude higher than the σ of the GaSb matrix.

Figure 3 shows the temperature dependences of thermal conductivity λ and thermoelectric power α for the $GaSb–FeGa_{1.3}$ eutectic, with the heat flux (W) parallel and normal to the needles. The thermal conductivity is seen to be anisotropic and to decrease with increasing temperature. The $\lambda_{\parallel}/\lambda_{\perp}$ ratio attains 1.3 at 80 K and approaches unity at higher temperatures. The thermoelectric power of the eutectic is also anisotropic. The short-circuiting at $W \parallel x$ reduces α. For $W \perp x$, $\alpha_{\perp}$ rises as the temperature decreases to below 200 K. The increase in thermoelectric power with decreasing temperature may be associated with the effect of phonon drag on hole mobility, just as in homogeneous GaSb [17]. It is well known that this effect is due to the long-wavelength acoustic phonons with $q \le 2k$, where q and k are the wave vectors of phonons and charge carriers at the Fermi level, respectively. Note that, at comparable carrier concentrations, the low-temperature increase in the thermoelectric power of the eutectic is smaller in comparison with p-GaSb (Fig. 3b, curves *1*, *2*).

The carrier thermal conductivity of $GaSb–FeGa_{1.3}$, evaluated from the Wiedemann–Franz law, is as low as $0.04\lambda_{total}$, and the effect of phonon drag is insignificant in comparison with the phonon contribution.

By analogy with the generalized conductivity of heterogeneous systems containing cylindrical inclusions [18], the thermal conductivity as a function of the heat flow direction can be written in the form

$$\lambda_{\parallel} = \lambda_1\left[1 + \frac{c}{\frac{\lambda_1}{\lambda_2 - \lambda_1}}\right];$$
$$\lambda_{\perp} = \lambda_1\left(1 + \frac{c}{\frac{1-c}{2} + \frac{\lambda_1}{\lambda_2 - \lambda_1}}\right), \quad (3)$$

where subscripts 1 and 2 refer to the semiconducting and metallic phases, respectively, and c is the volume fraction of metallic inclusions. Since c is small, the effect of inclusions on thermal conductivity is insignificant.

In spite of the small contribution from the inclusions to the heat transport in the $GaSb–FeGa_{1.3}$ eutectic, they have a strong effect on phonon scattering. During the synthesis of $GaSb–FeGa_{1.3}$, the GaSb matrix takes up Fe atoms, which then effectively scatter short-wavelength phonons. The thermal resistance due to phonon scattering by impurities, evaluated by the Klemens formula [19], is 0.4 cm K/W at 300 K and 0.23 cm K/W at 80 K (in calculations, we used the parameters of GaSb and took into account only the density changes around defects). At a strong scattering of short-wavelength phonons, the thermal conductivity is dominated by long-wavelength phonons. The mean phonon free path $l = 3\lambda/(Cv)$ (where C is heat capacity and v is the sound velocity) is 0.1 μm at 80 K and 0.04 μm at 300 K. At the same time, the mean free path of long-wavelength phonons, evaluated using the Landau–Rumer–Simmons formula [20] for the relaxation time,

$$\tau^{-1} = (2\pi/\rho)(2\pi V/(kT))^4 q$$

(where ρ is density and q is the phonon wave vector) is 1.1 μm at 80 K and 4.1×10^{-2} μm at 300 K. Therefore, at low temperatures, the mean free path of long-wavelength acoustic phonons is comparable to the diameter of the metallic needles (d = 1 μm). It seems likely that the observed anisotropy in thermal conductivity is associated with the scattering of long-wavelength phonons from semiconductor–metal interfaces at $W \perp x$. The weaker phonon drag in the eutectic alloy compared to GaSb with a comparable hole concentration is probably also related to the scattering of long-wavelength phonons from interfaces. Thus, we are led to conclude that, varying the solidification rate during the preparation of composites, one can ensure conditions for the scattering of phonons with a particular wavelength, which offers the possibility of controlling the thermal conductivity of the material.

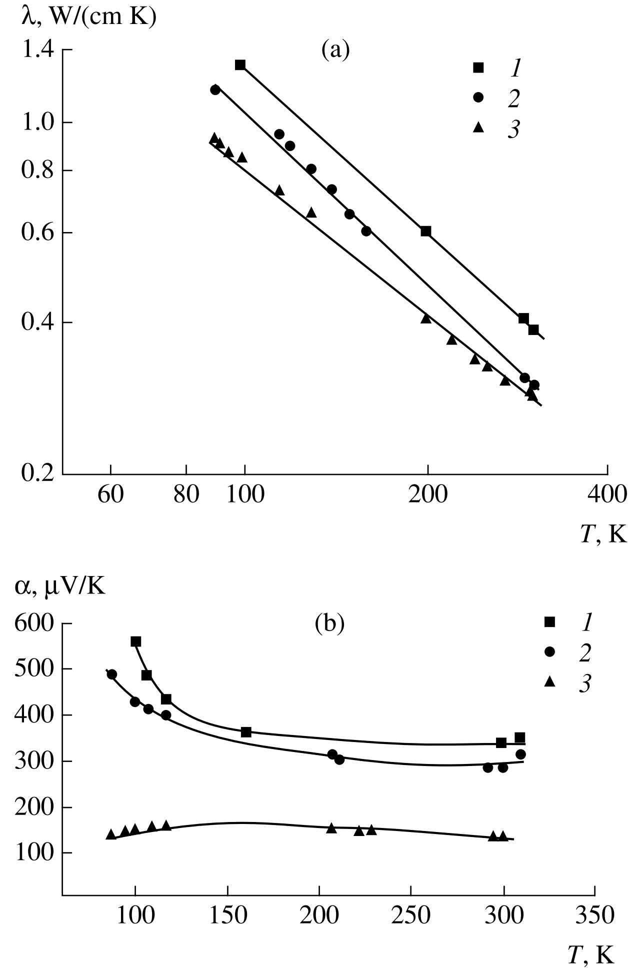

Fig. 3. (a) Temperature dependences of thermal conductivity for (*1*) GaSb ($p = 1.7 \times 10^{17}$ cm^{-3}) and (*2*, *3*) $GaSb–FeGa_{1.3}$ ($W \parallel x$ and $W \perp x$, respectively). (b) Temperature dependences of thermoelectric power for (*1*) GaSb ($p = 2 \times 10^{18}$ cm^{-3}) and (*2*, *3*) $GaSb–FeGa_{1.3}$ ($W \perp x$ and $W \parallel x$, respectively).

The metallic inclusions also have a significant effect on the temperature-dependent thermal diffusivity (a) of the eutectic (Fig. 4). At high temperatures, the thermal diffusivity of the $GaSb–FeGa_{1.3}$ alloy, as well as its λ, is isotropic. At $\Delta T \parallel x$, a has a minimum at $T = 505 \pm 5$ K, whose depth far exceeds the uncertainty in our measurements. Since $GaSb–FeGa_{1.3}$ is a ferromagnet [21], the minimum in $a(T)$ may be due to the ferromagnetic–paramagnetic phase transition. Clearly, the magnetic ordering occurs in the $FeGa_{1.3}$ inclusions, and the tran-

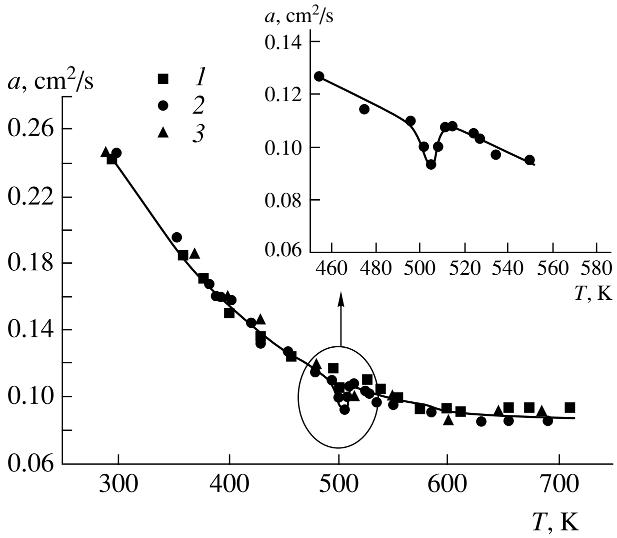

Fig. 4. Temperature dependences of thermal diffusivity for (*1*) GaSb ($p = 2 \times 10^{18}$ cm^{-3}) and (*2*, *3*) GaSb–$FeGa_{1.3}$ ($W \parallel x$ and $W \perp x$, respectively).

sition temperature $T = 505 \pm 5$ K is their Curie temperature.

CONCLUSIONS

The electrical conductivity, Hall coefficient, thermoelectric power, and thermal conductivity of the GaSb–$FeGa_{1.3}$ eutectic were studied at different relationships between the directions of the current, magnetic field, temperature gradient, and needlelike metallic inclusions. The transport properties of the alloy are shown to be anisotropic owing to the anisotropy of the inclusions.

The anisotropy in the thermal conductivity of the GaSb–$FeGa_{1.3}$ eutectic and the weaker phonon drag in comparison with GaSb are shown to be associated with the scattering of long-wavelength phonons from semiconductor–metal interfaces. The minimum in the thermal diffusivity at 505 ± 5 K at a heat flux parallel to the needles is attributable to the ferromagnetic–paramagnetic phase transition of the material.

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