Anomalous Nernst-Ettingshausen effect in diluted magnetic semiconductors

Y Kuznetsov1,2, M Dorokhin1, A. Kudrin1,2, M Ved1, V Lesnikov1
1. Physical Technical Research Institute of Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603950 Russia
2. Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603950 Russia
yurakz94@list.ru

Abstract. The magnetic field dependences of the Hall and Nernst-Ettingshausen effects in (In,Fe)Sb, (Ga,Fe)Sb, (Ga,Mn)As diluted magnetic semiconductors were investigated. The samples were fabricated on a semi-insulating GaAs substrates by pulsed laser deposition in vacuum. The manifestation of the anomalous Nernst-Ettingshausen effect along with the anomalous Hall effect in manganese-containing structures was shown experimentally. It is demonstrated that the difference in the magnetic field dependences of the Hall and Nernst-Ettingshausen effects in systems with Mn and Fe is due to the different nature of ferromagnetism.

1. Introduction
One of the main directions of future electronics development is spintronics. To implement electronic devices, which use of spin degree of freedom, diluted magnetic semiconductors (DMS) with a Curie temperature close to room temperature are required. One of the main methods for studying the magnetic properties of the DMS near the Curie point is the analysis of the magnetic field dependence of the anomalous Hall effect (AHE) [1,2]. However, the nonlinear nature of the magnetic field dependence of the Hall effect (HE) is not sufficient indicate the intrinsic ferromagnetism of the studied structure. In particular, distortions of the linear Hall effect can be caused by internal magnetic fields generated by the agglomerates of magnetic impurities [3,4]. Additional research methods are the effects based on a complex of thermoelectric and thermomagnetic phenomena [5,6]. These methods, in combination with HE, can reliably determine the nature of carrier scattering, and, as a result, more accurately calculate the magnetic transport parameters of structures.

2. Anomalous Nernst-Ettingshausen effect
The Nernst-Ettingshausen effect (NE) arises when a temperature gradient is created in the structure along with simultaneous placing it in an external magnetic field, The effect consists in the phenomenon of generation of a transverse potential difference. The nature of the Nernst-Ettingshausen and Hall effects is similar, with the difference in driving force for free charge carriers. Unlike the Hall effect, the in NE effect it is not the applied electric field, but the temperature gradient. The fundamental peculiarity of the NE effect is the fact that the carriers with different signs move in the same direction, therefore, the sign of the resulting potential difference does not indicate the dominant contribution of electrons or holes to the conduction processes. On the other hand it gives information about the dominant contribution of the of scattering center type [5]. In the case of a ferromagnetic structure, the scattering of free charge carriers becomes spin-dependent, which leads to a distortion of
the magnetic field dependence of the NE voltage — an anomalous Nernst-Ettingshausen (ANE) effect [7].

One can draw analogies between the ANE effect and the Anomalous Hall effect (AHE), and as a result write the system of equations:

\[ U_{NE} = Q_0 B \Delta T + Q_M M(B) \Delta T, \]
\[ U_H = R_0 BI + R_M M(B) I, \]

where \( Q_0, R_0 \) are the constants of the ordinary HE and NE effect respectively, \( B \) is the external magnetic field, \( M(B) \) is the magnetic field dependence of the magnetization, \( I \) is the current transmitted through the structure, \( \Delta T \) is the temperature gradient, \( Q_M, R_M \) are the anomalous HE and NE constants respectively.

While the necessary condition for the manifestation of AHE effect is the very fact of spin-dependent scattering of free charge carriers, in the case of ANE effect this condition is not sufficient. For the anomalous thermomagnetic effect manifestation, it is necessary to manifest a difference in spin-dependent scattering of free charge carriers moving from the “hot” side of the structure to the “cold” one and vice versa. In other words, spin-dependent scattering should strongly depend on the velocity of free charge carriers. A strong dependence is the one for which the amplitude of anomalous thermomagnetic effect exceeds the thermal fluctuations by the order of magnitude, otherwise the phenomenon cannot be confirmed experimentally. To describe the interaction of carriers with various scattering centers, let us consider the Hamiltonian of the «free charge carrier – semiconductor» system:

\[ \hat{H} = \hat{H}_{no\, spin} + J \sum_i \bar{S}_i \cdot \bar{S}_j \delta(\bar{r}_i - \bar{R}_j) + \hat{A}(\vec{v}), \]

where \( \hat{H}_{no\, spin} = -\frac{\hbar^2 k^2}{2m^*} + V(\vec{r}) \) are terms describing all spin-independent interactions, \( \hbar \) is Planck's constant, \( k \) are wave vector, \( m^* \) is effective mass, \( J \) is integral of overlapping wave functions, \( \bar{S}_i \) is spin \( i \)-th particle, \( \bar{r}_i \) are coordinate \( i \)-th particle, \( \bar{R}_j \) are coordinates of \( j \)-scattering center, \( \hat{A}(\vec{v}) \) are a term describing all types of spin-dependent interaction, which depend on the velocity of free charge carriers [9].

The first term of expression (2) describes the kinetic interaction of free charge carriers and scattering centers (impurity, phonons, etc.). This interaction does not depend on the spin of the particle and is the cause of the ordinary Hall and Nernst-Ettighausen effects. Analyzing both these phenomena together, one can conclude about the transport parameters of free charge carriers (mobility, concentration), as well as about the type and nature of scattering centers (scattering factor, Hall factor, etc.).

The second term is the reason for only AHE, since this expression does not depend on the speed of free charge carriers, but depends only on the relative position of the carrier and the spin-dependent scattering center. The presence of AHE only indicates the fact of spin-dependent scattering, but does not characterize its exact form.

The manifestation of ANE effect requires the presence of the third term in expression (2) in order to ensure the difference between the spin-dependent scattering of carriers moving with different speeds. The similarity, but at the same time, the difference in the nature of the AHE and ANE effect, allows one to obtain information on the nature of the ferromagnetism in investigated structures. The latter is the main task in the development and diagnostics of the DMS structures in order to practically implement it in spintronics devices [10-12].

**3. Studied structures**

In [13], the presence of ANE effect in epitaxial layers of gallium arsenide with embedded ultra-thin layers of (Ga,Mn)As was demonstrated. Such structures manifest ferromagnetic properties up to temperatures of 30 K, which complicates their implementation in spintronics devices. A detailed study of such structures was presented in [14,15]. It was shown that magnetism is mediated by free charge carriers, which explains the presence of nonlinearity in the magnetic field dependence of the NE voltage. Similar studies were carried out on manganese silicide structures [16], in which same mechanisms of ferromagnetism were assumed.
Semiconductor structures based on \(A_3B_5\) doped with atoms of transition elements (Mn and Fe) are of great interest to researchers from the point of view of combining ferromagnetic and semiconductor properties in one system. For example, in [17, 18] the presence of ferromagnetism in the GaMnAs system was demonstrated in the temperature range up to 120 K. The trend in recent years is the fabrication of \(A_3B_5\) semiconductors doped with iron atoms, due to a higher Curie temperature. For example, the presence of ferromagnetism at room temperature in InFeSb and GaFeSb systems was shown in [19, 20]. In [20], the different nature of ferromagnetism in (III,Mn)V and (III,Fe)V structures was discussed. It was assumed that in the layers doped with iron, the mechanism of ferromagnetic ordering is not associated with free charge carriers. This is one of the most significant differences between this material and systems containing Mn-doped layers. This difference should be manifested in the magnetic field dependences of the NE effect, study of which is the main goal of this paper.

The investigated structures were thin (~ 40 nm) layers of GaMnAs, GaFeSb, and InFeSb grown on a substrate of semi-insulating gallium arsenide by pulsed laser deposition in vacuum [17–20]. Sputtering targets was GaAs, InSb, GaSb, Fe, and Mn plates. The concentration of the impurity element \(Y_{Fe}\) and \(Y_{Mn}\) was determined from the ratios:

\[
Y_{Fe} = \frac{t_{Fe}}{(t_{GaSb} + t_{Fe})}, \tag{3}
\]

\[
Y_{Mn} = \frac{t_{Mn}}{(t_{GaAs} + t_{Mn})}, \tag{4}
\]

where \(t_{Fe(Mn)}\) are sputtering time of an iron (manganese) target, \(t_{GaSb}\) are gallium (indium) antimonide target sputtering time, \(t_{GaAs}\) are gallium arsenide target sputtering time.

The concentration of iron was varied in the range 0.04–0.17, manganese: in the range 0.13–0.23. The temperature of the substrate during sputtering was 350 °C. The list of structures is given in table 1.

**Table 1. List of studied structures.**

| Designation | Structure | \(Y_{Fe(Mn)}\) | Feature |
|-------------|-----------|----------------|---------|
| Structure 1 | GaMnAs    | 0.23           | The presence of magnetic MnAs clusters |
| Structure 2 | GaMnAs    | 0.13           | Uniform distribution of impurities |
| Structure 3 | InFeSb    | 0.17           | The presence of magnetic Fe clusters |
| Structure 4 | InFeSb    | 0.04           | Uniform distribution of impurities |
| Structure 5 | GaFeSb    | 0.04           | Uniform distribution of impurities |

4. **Experimental technique**

To study AHE and ANE effect, 6 ohmic contacts were formed on the surface of structures. Samples were mounted on the holder (Figure 1).

![Figure 1](image-url)

**Figure 1.** Scheme: a – mountings of the structures under study, b – resistivity measurements, c – HE, d – thermoelectric effect, e – NE.

The sample was installed from one side on a flat resistor-heater. The opposite side was fixed between two massive radiators necessary for heat removal and corresponding formation of a temperature gradient inside the structure.
To study the HE, it is necessary to pass current through the A-F contacts, and using the contacts B-E to measure the resulting voltage. To detect the NE, it is necessary to pass the current through the resistor-heater and measure the voltage between C-D the contacts. Layer resistance was measured according to the standard four-probe scheme shown in Figure 1b. The presence of thermal contact and the created temperature gradient can be controlled due to the Seebeck effect, by measuring the emerging voltage between contacts A-E or B-F (see Figure 1d). The holder was installed in a Janis CCS-300S / 202 closed-loop helium cryostat. Measurements were carried out over a wide temperature range (10-300) K.

5. Results and discussions

During the studies, the magnetic field dependences of the NE effect and HE for GaMnAs structure were obtained. The results are shown in Figure 2. The measurement temperature was 100 K. The temperature gradient created in the structure was 10 K. The object of study was a structure with MnAs clusters (Structure 1) (Figure 2a), and a structure in which the impurity element is uniformly distributed over the volume (Structure 2). The presence of clusters was revealed by transmission electron microscopy.

In Figure 2a, one can clearly see the hysteresis loop, both on the magnetic field dependence of the HE and the NE effect. The effects are explained by the action of the additional Lorentz force on the charge carriers. The Lorentz force is associated with the magnetic field of the magnetized MnAs clusters. The magnitude of the Lorentz force depends on the speed of charge carriers, this explains the presence of the anomalous component in the NE effect.

Structure 2, without MnAs clusters, also exhibits ferromagnetic properties — nonlinearity is observed in the magnetic field dependences of the HE and NE effect; however, no hysteresis is observed. This indicates the smallness of the coercive fields. It is important to note a smaller size of effects compared to the corresponding values on a structure with clusters, which indicates the absence of the contribution of the Lorentz force and the effect of spin-dependent scattering in the structure on the HE and NE effect. The presence of ANE effect in the structure is associated with the difference in spin-dependent scattering of carriers moving from the «cold» end to the «hot» one and vice versa. Since such carriers are characterized by different speeds, the magnitude of the spin-dependent scattering in ANE effect depends on the speed of the carriers. This is indirect evidence of the Ruderman-Kittel-Kasua–Iosides (RKKY) mechanism for ferromagnetic ordering in such structures.

![Figure 2](image)

**Figure 2.** Magnetic field dependences of the HE and NE effect of the GaMnAs structure: a – Structure 1 (with MnAs clusters), b – Structure 2 (without MnAs clusters).

Similar studies were carried out on the InFeSb structure. Two structures were also considered: Structure 3 with Fe clusters and Structure 4 without clusters. Since these layers have a high Curie temperature, measurements were carried out at room temperature. The experimental results are shown in Figure 3.
Figure 3. Magnetic field dependences of the HE and NE effect of the InFeSb structure: a - Structure 3 (with Fe clusters), b - Structure 4 (without Fe clusters).

Structure 3 is characterized by the presence of a hysteresis loop in the magnetic field dependence of the HE and NE effect. This is associated with similar reasons as for GaMnAs structure 1. The latter confirms once again the assumption about the influence of the magnetic field of magnetized clusters on carrier transport. In structure 4, the magnetic field dependence of the NE effect has a strictly linear form, despite the presence of AHE. A linear NE effect was observed over the entire temperature range (10–300) K at which measurements were performed and at various iron concentrations, provided that there were no Fe phases in the films. The explanation for the absence of ANE effect is associated with the absence of interactions that would be described by the term $\hat{A}(\vec{u})$ from (2), that is, depending on the speed of free charge carriers. As shown in [20], the magnetic properties of such systems are independent of free charge carrier concentration, which means that the RKKY mechanism is not the cause of magnetism. Carrier spins probably interact with magnetic centers; however, this interaction weakly depends on the velocity of charge carriers. This issue remains relevant and requires additional research.

Similar results were obtained in structure 5 containing GaFeSb layers (see Figure 4):

Figure 4. Magnetic-field dependences of the HE and NE effect of the GaFeSb structure.

In this structure, as in structure with InFeSb layer, while the magnetic field dependence of the HE is nonlinear, the magnetic field dependence of the NE effect is strictly linear. The amplification of the HE amplitude is explained by an increase in the layer resistance of the studied structure. In the same time a nearly 10-fold decrease in the Nernst-Ettingshausen effect amplitude indicates a decrease in the scattering difference between “hot” and “cold” charge carriers. The nature of the magnetism in this system, similarly to structure with InFeSb layer, is not related to free charge carriers. Thus, it was shown that the analysis of the total mutual behavior of the magnetic field dependences of the HE and the NE effect allows us to evaluate not only the presence of spin-dependent scattering, but also to additionally diagnose the mechanisms of its implementation.
6. Conclusions
The fundamental reasons of ANE effect manifestation were considered. Using the GaMnAs diluted magnetic semiconductor an example of coupling between ANE effect and carrier mediated ferromagnetism have been shown. Using structures with the InFeSb and GaFeSb layers as an example, it was shown that the presence of Anomalous Hall effect is not a sufficient condition for the Anomalous Nernst-Ettingshausen effect. This emphasizes a different nature of the phenomena. It was assumed that the absence of ANE effect in the (III,Fe)V structures can be explained by the difference in the mechanism for ferromagnetic ordering for (III,Mn)V and (III,Fe)V system.

Acknowledgments
This work was supported by a grants from the President of the Russian Federation (MD-1708.2019.2), as well as by the RFBR projects (20-38-70063, 20-32-90032). The structures for the study were obtained at the expense of the Russian Science Foundation (project 18-79-10088).

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