Anomalous Nernst-Ettingshausen effect in $\delta<$Mn$>$GaAs/InGaAs ferromagnetic semiconductor heterostructures

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Abstract. In the present work, the magnetic properties of GaAs with a ferromagnetic delta layer of manganese were studied using the Nernst-Ettingshausen effect. It is shown that at temperatures below the Curie point the dependence of the Nernst-Ettingshausen voltage on the magnitude of the external magnetic field is nonlinear, which is known as the anomalous Nernst-Ettingshausen effect. In the present study, it is established that the nonlinear dependence becomes linear above the Curie temperature.

1. Introduction
Diluted magnetic semiconductors (DMS), such as (A$_3$Mn)B$_5$, are promising materials for the creation of spintronic devices. However, a major obstacle to implementing DMS is a typically low value of the Curie temperature that determines low operating temperatures for DMS-based devices [1]. To increase the value of the Curie temperature, it is of great importance to analyze the ferromagnetic ordering mechanisms and to define the factors that influence ferromagnetism. In this paper, we investigate the magnetic properties of a ferromagnetic semiconductor heterostructure containing a $\delta<$Mn$>$ layer in a GaAs matrix using the Nernst-Ettingshausen effect. The latter measurements have proven to be a good tool to analyze the magnetic properties at the ferromagnetic-to-paramagnetic transition point [2]. In particular, the presence of the anomalous Nernst-Ettingshausen effect at temperatures below the Curie point is shown. The results of the measurements are discussed with the assumption of spin-dependent scattering in the magnetized ferromagnetic $\delta<$Mn$>$ layer.

2. The anomalous Nernst-Ettingshausen effect
The Nernst-Ettingshausen effect (NE) is based on the same principle as the Hall effect: the separation of carriers moving from one end of the sample to the other by an external magnetic field [2]. However, unlike the Hall effect, the carrier motion in NE is triggered via the application of a temperature gradient at the ends of the investigated structure (see figure 1).

Figure 1. Schematic of the Nernst-Ettingshausen effect measurements. $v_e$ is the electron velocity, $v_h$ is the hole velocity, $U_{NE}$ is the transverse Nernst-Ettingshausen voltage, and $U_{NEL}$ is the longitudinal Nernst-Ettingshausen voltage.
To analyze the anomalous NE effect, one can use similar formulas as for the Hall effect. In ferromagnetic samples, the dependence of the Hall voltage on the magnetic field is nonlinear, which is explained by spin-dependent scattering of carriers [3]. The formalism used in discussing the Hall effect is also valid for the NE effect. In particular, an analogous expression can be used to determine the NE electric field, according to [2]:

$$ E = S \nabla T - Q_0 [B \nabla T] - Q_s [M \nabla T], $$

(1)

where $S$ is the Seebeck coefficient (which characterizes the thermo-voltage emerging due to the asymmetry of contacts relative to the heat flux and the direction of the external magnetic field), $\nabla T$ is the temperature gradient in the structure under study, $Q_0$ is the Nernst-Ettingshausen constant, $B$ is the external magnetic field, $Q_s$ is the anomalous Nernst-Ettingshausen constant, and $M$ is the magnetization of the sample.

3. Experimental method

The investigations were made within an epitaxial ferromagnetic multilayer film grown on a semi-insulating GaAs (100) substrate. First, a sequence of layers consisting of a GaAs epitaxial layer, a 10-nm In$_x$Ga$_{1-x}$As quantum well ($x \approx 0.16$), and a 3-nm GaAs layer was grown by metal-organic vapor phase epitaxy at 650 °C. At the next stage, the growth temperature was decreased and a δ<$\text{Mn}$> layer followed by a 4-nm GaAs cap layer were grown by the pulsed laser deposition technique. The details of the growth process were described elsewhere [4]. The schematic view of the structures is depicted in figure 2.

![Figure 2. Schematic view of the structure under study.](image)

To measure the Hall Nernst-Ettingshausen effects, four Ohmic contacts were formed on the surface of the sample in such a way that one pair of contacts was located along the heat flux (D and C) and the other was across it (A and B, see figure 3). The sample was attached to a dielectric plate with low thermal conductivity. A resistor was installed on the surface of the sample, which played the role of a heater. The thermal contact between the resistor and the surface of the sample was ensured by a heat conducting paste which also provided the electrical isolation of the resistor and the sample. The opposite side of the structure rested against a massive metal radiator, which was used for removing heat. The space between the face of the sample and the metal radiator was filled with a thermal paste to create a thermal contact and provide dielectric insulation. The entire system was mounted on a closed-cycle cryostat holder such that the metal radiator was in good thermal contact with the holder, i.e. with one end of the sample, whereas the sample substrate was thermally isolated from the holder. The holder temperature was varied within the range of 10 - 300 K. The sample was placed between the poles of an electromagnet, so that a constant magnetic field was applied perpendicular to the sample surface.

To measure thermomagnetic effects, it is necessary to create a temperature gradient in the sample. This can be achieved by passing an electric current through the resistor F-E. To control the temperature at the sample ends, we have used A-B contacts as a detector. For this reason, the temperature dependence of the resistance between A-B contacts was recorded (figure 4). In the operating regime, the temperature of the A-B region of the sample was considered as the average
temperature \( T_{av} \) and its value was estimated from the \( R(T) \) dependence shown in figure 3. The temperature of the cold end \( T_{cold} \), provided there is good thermal contact, can be equated to the temperature of the holder. The temperature of the hot end \( T_{hot} \) thus can be calculated by the formula:

\[
T_{hot} = 2T_{av} - T_{cold}
\]  

(2)

![Figure 3. Schematic view of mounting the sample on the holder. The heat flow propagates along the structure. 1 – carrier holder, 2 – sample, 3 – layer of dielectric thermal paste, 4 – resistor heater, 5 - contact areas, 6 – radiator.](image)

The value of the Seebeck voltage was measured by connecting a voltmeter to the contacts C-D. Measurements of the voltage at the contacts A-B allowed us to investigate the transverse Nernst-Ettingshausen effect. We emphasize that the NE voltage was several orders of magnitude lower than the one used to determine the A-B contact resistance. Thus, the NE effect did not affect the measurements of the resistance and the \( T_{av} \). The measurements of the voltages and currents were carried out using a Keithley 2401 universal measuring instrument.

![Figure 4. Dependence of the resistance between A-B contacts on the temperature of the cold end.](image)

4. Results of the experiment

Figure 4 illustrates the temperature dependence of the resistance for the studied structure. From the dependence obtained, it can be seen that at temperatures around 15 K the resistance reaches tens of GΩ, which does not allow us to carry out the Hall effect measurements. However, since the dependence is strongly nonlinear, the resistance at temperatures about 50 K is 1 MΩ.

Unlike the Hall effect, the measurements of the Nernst-Ettingshausen effect could be performed and the results are shown in figure 5. In the low temperature region (figure 5 (a)), \( T_{cold} = 16 \) K, \( T_{av} = 64.4 \) K, \( T_{hot} = 112.8 \) K, a nonlinear dependence of the NE voltage on the magnetic field was observed. When the holder temperature (i.e. the cold end temperature) was increased up to 25 K and
further to 50 K, the dependence of the NE voltage on the magnetic field became linear, so it could be fitted by a linear function (see figure 5 (b) and figure 5 (c), respectively).

![Graphs](a) (b) (c)

**Figure 5.** Experimentally obtained curves of the transverse Nernst-Ettingshausen voltage as a function of the external magnetic field: (a) – the anomalous Nernst-Ettingshausen effect \((T = 17.00 \text{ K})\); (b), (c) – the ordinary (linear) Nernst- Ettingshausen effect \((b) – T=25 \text{ K}; \ (c) – T = 50 \text{ K})\).

The linear magnetic field dependence of the NE voltage is typical for the Nernst-Ettingshausen effect and can be attributed to different trajectories of carriers moving from the cold end to the hot end of the sample and vice-versa. Thus, the excess charge is accumulated in the left part of the sample and the electric field can be measured between contacts A and B [4]. A nonlinear \(U(H)\) dependence, i.e. the anomalous Nernst-Ettingshausen effect, is usually attributed to spin-dependent scattering of carriers in magnetized ferromagnetic samples [2]. An interesting fact is that the average temperature of the sample is much higher than the Curie point, hence no abnormality should arise. Although both the average temperature and the temperature of the hot end are above the Curie point, the temperature of the cold end remains below the Curie point. So, one can assume that the anomalies of the NE effect are due to spin-dependent scattering in the cold region of the sample that remains below the Curie point.

The result obtained gives us a tool to measure ferromagnetic properties of highly resistive samples for which the measurements of the anomalous Hall effect are rather complicated and not always realizable. The application of a temperature gradient creates thermally generated carriers that participate in the conductivity and the formation of thermomagnetic voltages. Moreover, the analysis performed at the ferromagnetic-to-paramagnetic transition point can supply some new information on the ferromagnetic ordering in diluted magnetic semiconductors.

5. Conclusions

The measurements of the anomalous Nernst-Ettingshausen effect were performed on a ferromagnetic \(\delta\langle\text{Mn}\rangle/\text{GaAs/InGaAs}\) sample. It has been shown that the anomalous Nernst-Ettingshausen effect can be observed whenever the cold end of the sample is kept below the Curie point, although the average temperature is way above the Curie point. This gives one a powerful tool for studying ferromagnetism in samples that are highly resistive below the Curie point.

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