Electrical Properties of Ferromagnetic Ni$_2$MnGa and Co$_2$CrGa Heusler Alloys

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Abstract—The electrical properties of ferromagnetic Ni$_2$MnGa and Co$_2$CrGa Heusler alloys are measured in the temperature range 4–900 K. The effect of the energy gap near the Fermi level in the electronic spectrum on the behavior of electrical resistivity and absolute differential thermopower is discussed.

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INTRODUCTION

Ferromagnetic Heusler alloys (structure L2$_1$ and formula X$_2$YZ, where X and Y are transition metals and Z is a group III–V element of the periodic table) can be conventionally divided into two subclasses having different characters of the electronic band structure near the Fermi level with energy $E_F$. Some of them are called semimetallic ferromagnets (SMFs) and have an energy gap at $E_F$ in the electronic spectrum of one of the subbands, which have different directions of the spins of conduction electrons with respect to the spontaneous magnetization vector [1]. The energy gap depth and width in different SMFs can be strongly different. In particular, a Co$_2$CrGa alloy in the magnetically ordered state has an energy gap of the limiting depth exactly at $E_F$ in its electronic spectrum for electrons with spins directed opposite to the magnetization vector: the gap depth is 0.1–0.5 eV [2, 3].

The second subclass of the ferromagnetic Heusler alloys does not have a pronounced “gap” specific feature in their electronic spectra near $E_F$. Ni$_2$MnGa is a representative of these alloys. This was shown in one of the first works dealing with an ab initio calculation of the electronic band structure of the Ni$_2$MnGa alloy in both the ferromagnetic and paramagnetic states [4]. Obviously, the specific features of the electronic band structure should manifest themselves in the behavior of the electrical properties and result in a radical difference in this behavior for the discussed subclasses of Heusler alloys.

ELECTRICAL RESISTIVITY

Electrical resistivity $\rho(T)$ of the Ni$_2$MnGa alloy was studied in a number of works with allowance for its band structure [5–8]. Apart from residual resistivity $\rho_0 \sim 10 \mu\Omega$ cm determined at $T \rightarrow 0$ K, this alloy exhibits the most significant magnetic ($\rho_m$) and phonon ($\rho_{ph}$) contributions. Figure 1a shows the general view of the $\rho(T)$ dependence for the Ni$_2$MnGa alloy and the main additive components of the electrical resistivity. We determined contribution $\rho_{ph}(T)$ using the tabulated Bloch–Grüneisen function [9],

$$\rho_{ph} = B \left( \frac{T}{\theta_D} \right)^5 \int_0^1 \frac{x^5 dx}{(e^x - 1)(1 - e^{-x})}.$$  \hspace{1cm} (1)

In Eq. (1), the Debye temperature ($\theta_D = 319$ K) was chosen according to the results of measuring the low-temperature specific heat [10], and coefficient $B$ was chosen with allowance for the slope of the experimental linear dependence $\rho(T)$ at $T > \theta_D$, $T_C$. Component $\rho_m(T)$ was calculated as the difference between the measured values of $\rho(T)$ and phonon contribution $\rho_{ph}(T)$ calculated by Eq. (1). It is seen that $\rho_m(T)$ increases gradually with temperature and levels off sharply at about the Curie point ($T_C \sim 390$ K). The structural transformations that occur in this alloy at $T < T_C$ (from the austenite B2 phase into the L2$_1$ martensite phase followed by the transition into long-period 5M and 7M structures [11]) weakly affect the behavior of $\rho(T)$.

It is known [9] that the phonon contribution to the electrical resistivity at low temperatures ($T \ll \theta_D$, $T_C$) is described by the simple power expression

$$\rho_{ph}(T) = cT^5.$$ \hspace{1cm} (2)

As a result, we can determine the residual sum of the low-temperature contributions ($\rho_0 + \rho_m$), which is shown in Fig. 2a. Following [8], we can describe this

1 In this case, the contribution to $\rho(T)$ caused by electron–electron scattering is not taken into account because of its relative smallness.
sum with the expression characteristic of ferromagnetic metals [12],

$$\rho = \rho_0 + aT + bT^2. \quad (3)$$

The values of residual resistivity $\rho_0$ and coefficients $a$, $b$, and $c$ calculated by this formula are given in the table.

Coefficient $b$ in Eq. (3) is usually related to electron–electron scattering, which becomes substantial at low temperatures. However, the value of coefficient $b$ in the alloys under study is more than an order of magnitude higher than its values that are usually detected in transition metals (see [13] and the tabulated data). In principle, the quadratic temperature dependence of the electrical resistivity can be caused by electron–magnon scattering, as was established for ferromagnetic transition metals (see, e.g., [14]).

The nature of the component linear in temperature in Eq. (3) was considered in many theoretical and experimental works [12]. It is unusual in our case that coefficient $a$ in Eq. (3) has a negative sign. This is possible if it is induced by the scattering of conduction electrons by spin waves. In this case, the value and sign of coefficient $a$ depend on the type of dispersion law for conduction electrons. The weak effect of an applied magnetic field on the $\rho(T)$ dependence of the Ni$_2$MnGa alloy at low temperatures also indicates that the values of coefficients $a$ and $b$ in Eq. (3) are mainly determined by the parameters of the electronic band structure near the Fermi surface [8].

The table below shows the coefficients calculated with Eqs. (2) and (3) for the Heusler alloys under study.

<table>
<thead>
<tr>
<th>Alloys</th>
<th>$\rho_0$, $\mu\Omega\text{ cm}$</th>
<th>$a \times 10^3$, $\mu\Omega\text{ cm/ K}$</th>
<th>$b \times 10^4$, $\mu\Omega\text{ cm/ K}^2$</th>
<th>$c \times 10^{10}$, $\mu\Omega\text{ cm/ K}^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni$_2$MnGa</td>
<td>12</td>
<td>$-3.7$</td>
<td>3.5</td>
<td>15.4</td>
</tr>
<tr>
<td>Co$_2$CrGa</td>
<td>128</td>
<td>$-43$</td>
<td>9</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Fig. 1.** Electrical resistivity of Heusler alloys (a) Ni$_2$MnGa and (b) Co$_2$CrGa: (dashed line) temperature dependence of magnetic component $\rho_m(T)$ and (dotted line) phonon contribution $\rho_{ph}(T)$.

**Fig. 2.** Magnetic component of electrical resistivity at low temperatures in Heusler alloys (a) Ni$_2$MnGa and (b) Co$_2$CrGa: (solid lines) processing of the experimental data with Eq. (3).