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Electron Transport and Magneto-optical Properties of Magnetic Shape-memory Ni_2MnGa Alloy

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Abstract

The physical properties, including magneto-optical and transport ones, of Ni_2MnGa alloy in the martensitic and austenitic states were investigated. The dependence of the temperature coefficient of resistivity on temperature shows kinks at the structural and ferro-para magnetic transitions. Electron-magnon and electron-phonon scattering are analyzed to be the dominant scattering mechanisms of the Ni_2MnGa alloy in the martensitic and austenitic states, respectively. The experimental real parts of the off-diagonal components of the dielectric function present two sharp peaks, one at 1.9 eV and the other at 3.2 eV, and a broad shoulder at 3.5 eV; all are identified by the band-structure calculations. These peak positions are coincident with those in the corresponding optical-conductivity spectrum, which is thought to originate from the single-spin state in Ni_2MnGa alloy.

1. Introduction

Ni_2MnGa Heusler alloys have been developed because of their wide applications [1]. The resistivity measurement was employed to investigate the structural and magnetic transition because of its simplicity and efficiency. Vasil'ev *et al.* observed a clear jump at the martensitic transition and a slope change at the ferromagnetic-paramagnetic transition from the resistivity measurement for $Ni_{2-x}Mn_{1+x}Ga$ alloys [2]. The $Ni_{2+x}Mn_{1-x}Ga$ alloys showed a distinct jump at the martensitic transition and a discontinuous slope change at the premartensitic transition [3]. However, the transport properties of Ni_2MnGa alloy in different structures are not well understood yet. In this work, we report the transport and magneto-optical (MO) properties of Ni_2MnGa Heusler alloy in the martensitic and austenitic states. The influence of structural and ferro-paramagnetic transitions on the transport and MO properties is also discussed.

2. Experimental

The stoichiometric Ni2MnGa alloy was prepared by melting high-purity (99.99 wt%) Ni, Mn and Ga pieces in an arc furnace with a water-cooled Cu hearth. The subsequent homogenization of the ingot was achieved by a vacuum annealing at 1273 K for 5 h. The resistivity measurement was done in a temperature range from 4.2 to 400 K by using a four-probe method. The MO equatorial-Kerr effect (EKE) of Ni_2MnGa alloy was measured at room temperature (RT) by using the dynamical method with p-plane polarized light in a spectral range of 1.1 - 4 eV and a saturated AC magnetic field of 900 Oe. The angles of incidence φ were equal to 66° and 75°.

3. Results and Discussion

The temperature dependences of resistance and temperature coefficient of resistivity (TCR) of Ni_2MnGa alloy are shown in Fig. 1. The TCR reveals an abrupt change at TS and steeply decreases to zero as temperature passes through T_C. The martensite-austenite transition from the tetragonal to the cubic $L2_1$ structure was observed for Ni_2MnGa alloy at 220 K [4]. T_C is the ferro-paramagnetic transition temperature.

Table 1 Fitting parameters for the martensite and austenite states of Ni_2MnGa alloy.

	$A[\Omega]$	$B[K^{-5}]$	$C[K^{-2}]$	$D\ [K^{-1.5}]$	Θ_D [K]
Martensite	0.00060	6.61×10^{-17}	6.67×10^{-9}	1.17×10^{-7}	624.6
Austenite	0.00081	8.08×10^{-16}	6.08×10^{-12}	6.52×10^{-10}	296.1

The usual expression for the temperature dependence of resistivity of metals and alloys can be described by $\rho(T) = \rho_0 + \rho_i(T)$, where ρ_0 is the temperature independent residual resistivity. The ideal resistivity includes the electron-phonon, electron-electron and electron-magnon (for magnetic materials) scatterings. The temperature dependence of the electron-phonon scattering can be written, similarly to the Bloch-Grüneisen law [5], as

$$\rho_{B-G} = \frac{1}{2}\rho_0 \frac{\pi\beta_1\tau}{\hbar(p_F\mu_l)^4}(k_B T)^5 \int_0^{\frac{\Theta_D}{T}} \frac{x^5\,dx}{(e^x-1)(1-e^{-x})} \tag{1}$$

The temperature dependence of resistivity, resulting from the scattering by electron-phonon-vibrating impurities, is described as [6]

$$\rho_{VIS} = \rho_0\left[2\left(\frac{\mu_l}{\mu_t}\right)\beta_t - \left(1-\frac{\pi^2}{16}\right)\beta_l\right]\frac{4\pi^2 k_B^2}{3E_F p_F \mu_l} T^2 \int_0^{\frac{\Theta_D}{T}} \frac{e^x(x-1)+1}{\left(e^x-1\right)^2}\,x\,dx. \tag{2}$$

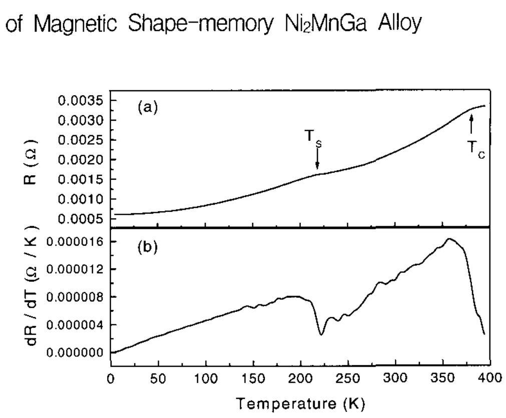

Fig. 1. Temperature dependences of (a) the resistance and (b) the TCR of Ni_2MnGa alloy.

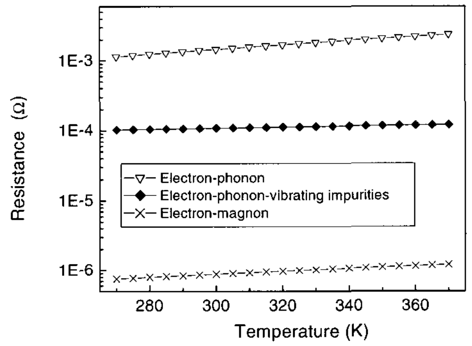

Fig. 2. Contributions of different scattering mechanisms on the resistance of Ni_2MnGa alloy in the martensitic state.

Here, τ is elastic transport time, μ_l and μ_t are sound velocity of the longitudinal and transverse phonon, β_l and β_t are constants of electron coupling with the longitudinal and transverse phonons, E_F and are p_F the Fermi energy and momentum, respectively. Θ_D is the Debye temperature. It follows from Eqs. (1) and (2) that at low temperature the resistivity is proportional to T^5 for the pure electron-phonon scattering, and is proportional to T^2 for case of the electron scattering by the vibrating impurities. Electron-magnon scattering gives rise to a temperature exponent α =1.5 in dilute ferromagnetic alloys [6]. The following function was employed to carry out analyses of the experimental data. There are five parameters in this fitting procedure: A, B, C, D and Θ_D. The resultant fitting parameters are presented in Table 1.

$$R = A + BT^5F_1(T) + CT^2F_2(T) + DT^{\frac{3}{2}},$$

where A is the residual resistance, and

$$F_1(T) = \int_0^{\frac{\Theta_D}{T}} \frac{x^5dx}{\left(e^x-1\right)\left(1-e^{-x}\right)},$$

$$F_2(T) = \int_0^{\frac{\Theta_D}{T}} \frac{e^x(x-1)+1}{\left(e^x-1\right)^2}xdx.$$

The fitting and experimental results agree well with each other. The contributions of different scattering mechanisms on the resistance of Ni2MnGa alloy in the martensite state are shown in Fig. 2. The electron-magnon scattering is dominant when temperature is lower than 75 K. The contributions of electron-magnon and electron-phonon scatterings increase with temperature. When temperature reaches about 220 K, those two kinds of mechanism give almost the same contribution to the resistance. On the other hand, the contribution of electron-phonon-vibrating impurities scattering is relatively low and slowly increases with temperature. Thus, the electron-magnon is the dominant mechanism in the martensite when temperature is low.

The contributions of different scattering mechanisms on the resistance of Ni2MnGa alloy in the austenite state are shown in Fig. 3. In the whole temperature range, the electron-phonon scattering gives the biggest effect.

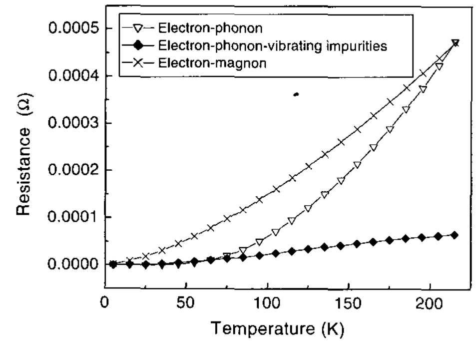

Fig. 3. Contributions of different scattering mechanisms on the resistance of Ni2MnGa alloy in the austenitic state.

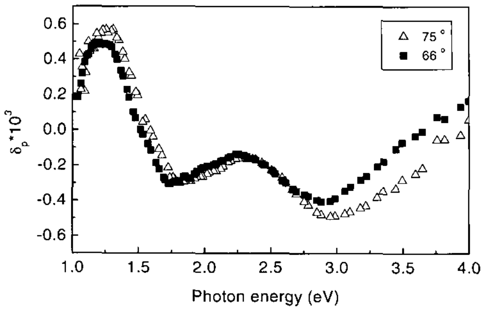

Fig. 4. Experimental EKE spectra for Ni2MnGa alloy in the austenitic state at φ = 66° and 75°.

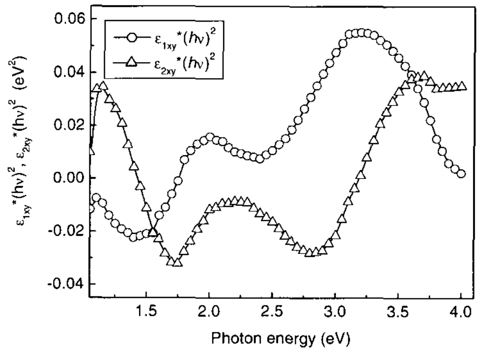

Fig. 5. Calculated off-diagonal components of the dielectric function, multiplied by (hv)^2, for Ni2MnGa alloy.

Fig. 4 is the EKE spectrum of Ni2MnGa alloy at RT. The off-diagonal components (ε_{xy}) of dielectric function (DF), multiplied by $(hv)^2$, were calculated from the EKE spectrum and shown in Fig. 5. The real part (ε_{1xy}) of off-diagonal components shows two peaks at about 1.9 and 3.2 eV. The similar peak positions to those in the corresponding optical-conductivity (OC) spectrum are observed. This indicates that the spin state is not changed according to an external magnetic field, which is thought to be caused by the single-spin state of this alloy. Investigations on Heusler alloys present that certain Heusler alloys are predicted to be 100% spin polarized at Fermi level, i.e., they exhibit half-metallic behavior, in other words, metallic for the majority-spin electrons and semiconducting for the minority-spin electrons. The theoretical calculation of density of states informs us that Ni2MnGa alloy in the austenitic and martensitic states is nearly fully spin-polarized. In the present study, the similarity between EKE and OC spectra may be attributed to this spin-polarized state. Our experimental result is coincident with the theoretical calculation.

4. Conclusions

The transport and MO properties of Ni_2MnGa alloy were measured for the martensitic and austenitic states. The temperature dependence of resistance shows a jump-like behavior at the martensitic and ferromagnetic transitions. The real part of off-diagonal components of the DF showed two peaks whose positions are coincident with those in the corresponding OC spectrum. This is thought to originate from the single-spin state in Ni_2MnGa alloy.

Acknowledgements

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