Magnetic and Transport Properties of Epitaxial Co_2MnSi Films

W. H. Wang[1], X. B. Ren[1], G. H. Wu[2], M. Przybylski[3,4], J. Barthel[3], and J. Kirschner[3]

[1]National Institute for Materials Science, Tsukuba, Ibaraki 305-8565, Japan
[2]State Key Lab. for Magnetism, Institute of Physics, Chinese Academy of Science, Beijing 100080, China
[3]Max-Planck-Institut für Mikrostrukturphysik, 06120 Halle, Germany
[4]Solid State Physics Department, Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, 30-059 Krakow, Poland

We report on magnetic and magnetotransport properties of single-crystalline Co_2MnSi films grown by using conventional pulsed laser deposition (PLD) method on moderately heated semiconductor GaAs(001) substrates. The films exhibit the expected high Curie temperature and a strong in-plane uniaxial magnetic anisotropy with the easy axis of magnetization along the [1–10] direction. A saturation magnetization of 950 emu/cm^3 was measured at 5 K. The temperature dependence of the resistivity shows metallic behavior down to low temperatures. At 5 K, a rather large negative magnetoresistance (MR) of 1.26% has also been observed.

***Index Terms*—Half metal, Heusler alloys, magnetic properties.**

I. Introduction

HALF-METALLIC ferromagnets have been proposed as ideal candidates for spin injection devices because they have been predicted to exhibit 100% spin polarization at the Fermi level. Notable among the half-metallic candidates are a number of Heusler alloys [1]. They have crystal structures and lattice parameters similar to many semiconductors, and thus could be easily epitaxially grown on top of them. In addition, they exhibit high spin polarization at the Fermil level and high Curie temperatures. These properties make them particularly attractive as injectors and detectors of spin polarized current. So far, a number of Heusler alloys have been grown epitaxially on semiconductor substrates including Ni_2MnGa [2], Co_2MnGe [3], Ni_2MnGe [4], and NiMnSb [5] on GaAs(001), and Ni_2MnIn [6] on InAs(001). It was found that substrate temperature has a dramatic effect on interface reactions, crystal quality, magnetic properties, and chemical atomic ordering. The Co_2MnSi Heusler alloy is an especially promising candidate due to the fact that it is predicted to have a large minority spin band gap of ~ 0.4 eV [7] and moreover it has the highest Curie temperature of 985 K among the known Heusler alloys. Recently, several groups [8], [9] have studied the properties of polycrystalline Co_2MnSi films and they have already been tested in TMR- and GMR-thin film heterostuctures [10]. In this contribution, we will present the study of magnetic and magnetotransport properties of single-crystalline Co_2MnSi thin films in order to elucidate their potential for future applications in the field of spin electronics.

II. Experiment

The Co_2MnSi films studied in this work were grown by conventional PLD method onto heated semiconductor GaAs(001) substrates in a multichamber UHV-system. Typically low-energy electron diffraction (LEED) pattern of a 60-Å-thick Co_2MnSi film is shown in Fig. 1, confirming epitaxial growth of the single-crystalline film. Detailed growth and spin polarization studies are published elsewhere [11]. Measurements of magnetic properties and electrical resistivity were performed in a superconducting quantum interference device (SQUID) magnetometer. While many samples of different thickness were fabricated, in this work we concentrate on the magnetic and transport properties of a 60-Å-thick Co_2MnSi film, which has been most thoroughly characterized.

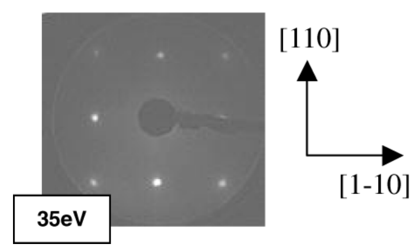

Fig. 1. LEED pattern a 60-Å-thick Co_2MnSi film deposited at 450 K.

III. Result and Disscussion

Fig. 2 shows two representative hysteresis loops for the 60-Å-thick Co_2MnSi film measured at 5 K by SQUID. Qualitatively, the loops are very similar to the MOKE loops measured. A strong in-plane uniaxial magnetic anisotropy is detected in agreement with what was suggested from our previous MOKE observations [11]. Interestingly, the two $\langle 110 \rangle$ directions, while both relatively easy, are not equivalent. As it is shown in Fig. 2, along the easier of the two axes, labeled [1–10], one measures the expected square hysteresis loop. When the magnetic field H is applied along the [110] direction, the resultant hysteresis loop is no longer square but shows a double-step behavior. It should be noted that these data look quite similar to those observed by Ambrose *et al.* [3] and Pechan *et al.* [12] in Co_2MnGe and Co_2MnGa on GaAs, respectively. This behavior may

Digital Object Identifier 10.1109/TMAG.2005.854833

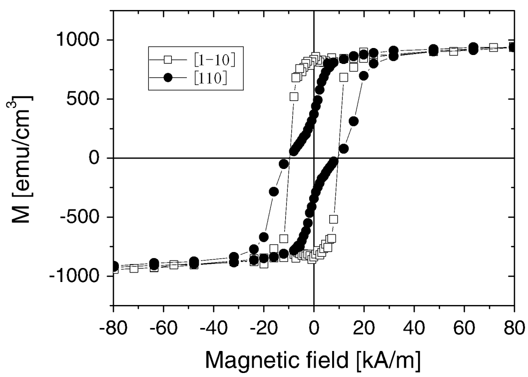

Fig. 2. Magnetic hysteresis loops measured at 5 K for the 60-Å-thick Co_2MnSi film with the magnetic field applied in the film plane along the [1–10] and [110] directions, respectively.

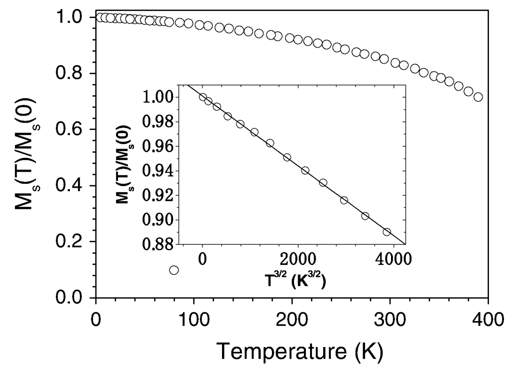

Fig. 3. Temperature dependence of the saturation magnetization for the 60-Å-thick Co_2MnSi film measured with the field applied in plane along the [1–10] easy axis. Magnetization is normalized to its value at 0 K which is obtained from the fit. The solid line in the inset is a linear fit of the magnetization versus $T^{3/2}$, demonstrating that the $M(T) = M(0)(1 - b \times T^{3/2})$ dependence of magnetization is valid for $T < 250$ K.

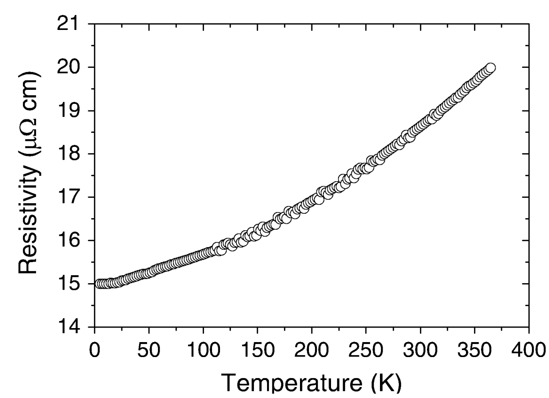

Fig. 4. Temperature dependence of resistivity for the 60-Å-thick Co_2MnSi film. The direction of current is along the [1–10] easy axis.

originate from the superposition of (i) the in-plane uniaxial magnetic anisotropy imposed by the substrate symmetry with easy axis of magnetization along the [1–10] direction with (ii) the four-fold symmetry of the film preferring magnetization equivalently along the two $\langle 110 \rangle$ in-plane directions. Details concerning magnetization reversal for varying film thickness and at different temperatures measured by MOKE are published elsewhere [11]. At 5 K, the saturation magnetization for 60-Å thick and thinner Co_2MnSi films was measured to be 5.1 and 4.95 μ_B per formula unit, respectively. These values fit well to the predicted theoretical integral value for Co_2MnSi of 5.0 μ_B per formula unit. However, spin and orbital magnetic moments we obtained separately for Co and Mn from sum rule analysis of XMCD measurements differ from that predicted theoretically for bulk defect-free Co_2MnSi (the moment of Co is increased roughly by 15%, the moment of Mn is decreased by 10%) [11]. These discrepancies can be attributed to a partial chemical disorder (swapping mechanism) in the Co_2MnSi films. However, if one adds the Co and Mn moments obtained by XMCD analysis and calculate the moment per formula unit, the result is ~ 5 μ_B in agreement with SQUID result.

Saturation magnetization as a function of temperature was measured over the range 5–360 K. The sample was first cooled down to 5 K and then warmed up while a constant magnetic field of 1 kOe was applied parallel to the [1–10] easy axis. The saturation magnetization M versus T is plotted in Fig. 3. Obviously, there is no difference to the temperature dependence of Kerr rotation measured at saturation for the films of a similar thickness [11]. The temperature dependence of the magnetization in saturation could be described, within a reasonable limit and in the low-temperature range (5–250 K), by the Bloch formula: $M(T) = M(0)(1 - bT^{3/2})$, where M(0) and the spin-wave parameter b depend on the film thickness [11]. As it is shown in the inset of Fig. 3, fitting the data to this formula yields the best fit for a b value of $2.84 \pm 0.21 \times 10^{-5}$ $K^{-3/2}$. This is in agreement to the b value of $2.50 \pm 0.32 \times 10^{-5}$ $K^{-3/2}$ which we found fitting the temperature dependence of the Kerr rotation at saturation measured for a film of almost the same thickness [11]. Above 250 K, we found the best fit to the $M(T) = M(0)(1 - bT^{\alpha})$ power law with an α parameter varying between 1.9 and 2.2 depending on the film thickness. This kind of a progressive change of the character of the magnetism from localized moments (Heisenberg type) and collective spin excitations at low temperatures (the magnetization varies as $T^{3/2}$) to itinerant at high temperatures (the magnetization varies more as T^2) was previously observed for NiMnSb [13] and Ni_2FeGa [14]. The transition was interpreted as a result of individual Stoner excitations forbidden at low temperatures due to the half metal gap between the Fermi energy and the bottom of the spin-down band of NiMnSb [13].

The temperature dependence of resistivity (ρ) for the 60-Å-thick Co_2MnSi film is shown in Fig. 4. The first striking aspect of the data is that the zero temperature resistivity (ρ_0) is quite small (~ 15 $\mu\Omega$ cm), while the overall variation with temperature is weak. In the case of the well-defined single-crystalline Co_2MnSi grown by the Czochralski method [15], a very low ρ_0 value of ~ 7 $\mu\Omega$ cm has been measured. This indicates that the contribution to resistivity from lattice defects and other forms of atomic disorder is small. We understand this relatively small residual resistivity as further evidence for the high quality single-crystalline structure of our PLD grown Co_2MnSi films. The second striking result is the fact that at low temperatures, below ~ 20 K, the resistivity of the Co_2MnSi film is nearly independent of temperature, which has been observed by Singh [9] for polycrystalline Co_2MnSi films grown by RF sputtering on sapphire a-plane substrates.

In order to gain insight into the transport properties, magnetoresistance (MR) was also measured with H applied in the film plane along the [1–10] and [110] directions, respectively. Detailed MR studies will be published elsewhere [15]. As a characteristic feature of the Co_2MnSi film we found a rather large negative MR of 1.26% at 5 K very similar to other Heusler alloy films. A rather large isotropic negative MR is found as a characteristic feature of all Co-based Heuser alloy films. Interestingly, in our PLD Co_2MnSi films, a small anisotropic MR is observed at low fields, i.e., below 20 kA/m, due to the large in-plane uniaxial anisotropy. The MR value also showed temperature dependence as the MR decreases to about 0.9% when temperature increases up to 300 K.

IV. Conclusion

In conclusion, we have studied the magnetic and magnetotransport properties of single-crystalline Co_2MnSi films grown on GaAs(001). The films exhibit a strong in-plane uniaxial magnetic anisotropy with the easy axis of magnetization along the [1–10] direction. The saturation magnetization for the 60 Å thick Co_2MnSi film was measured to be $5.1\mu_B$ per formula unit. This value perfectly fits to both the XMCD and the predicted theoretical integral value for Co_2MnSi of 5 μ_B per formula unit. The temperature dependence of the resistivity shows metallic behavior down to low temperatures. At 5 K, a rather large negative magnetoresistance of 1.26% has also been observed.

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Manuscript received February 6, 2005.