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S. Gardelis
Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, P.O. Box 1527, Vassilika Vouton, 711 10 Heraklion, Crete, Greece and Department of Materials Science and Technology, University of Crete, P.O. Box 2208, 710 03 Heraklion, Crete, Greece

J. Androulakis
Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, P.O. Box 1527, Vassilika Vouton, 711 10 Heraklion, Crete, Greece

J. Giapintzakis[a]
Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, P.O. Box 1527, Vassilika Vouton, 711 10 Heraklion, Crete, Greece and Department of Materials Science and Technology, University of Crete, P.O. Box 2208, 710 03 Heraklion, Crete, Greece

O. Monnereau
MADIREL, Ctr St Jerome, F-13397 Marseille 20, France

P. D. Buckle
QinetiQ Ltd., Malvern Technology Ctr., Malvern WR14 3PS, Worcestershire, United Kingdom

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We report the growth of single-phase, stoichiometric polycrystalline thin films of the half-Heusler ferromagnet NiMnSb, predicted to be half-metallic, on single crystal InSb (100) substrates heated at 200 °C by pulsed laser deposition. The films exhibit saturation magnetization of 4 μ_B/formula unit at 5 K and coercive fields of 2 Oe at 300 K indicative of their good structural quality. At low temperatures ($T<200$ K) the system behaves like a Heisenberg ferromagnet as expected for a half-metal, while at $T>200$ K it behaves like an itinerant ferromagnet. The resistivity of the film at 5 K is 6 $\mu\Omega$ cm. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1807026]

Establishing efficient spin injection from a ferromagnetic metal into a semiconductor is presently one of the main issues in spintronics that has captured the interest of experimentalists and theorists alike.[1] The driving force behind this interest has been the realization of a spin field-effect transistor (SFET) proposed by Datta and Das.[2] For this device to operate as envisioned, the injection of spin-polarized carriers from a ferromagnet into a two-dimensional electron gas (2DEG) structure based on a narrow-gap semiconductor (NGS) is required. The aim is to exploit the high mobility and spin–orbit interaction exhibited by a NGS. The manipulation of the latter effect via a gate voltage will allow the control of the spin direction. Recent theoretical studies have attributed the observed low efficiency of the spin-injection from a 3*d* ferromagnetic metal into a semiconductor[3] to a conductivity mismatch between the two materials.[4] On the other hand, it has been proposed that using ferromagnets which exhibit 100% spin polarization, should enhance the spin-injection efficiency.[4]

In this context we have grown thin films of NiMnSb, a ferromagnetic ternary alloy with the C_{1b} half-Heusler structure, on InSb. NiMnSb has been chosen because band structure calculations predict[5] it to exhibit 100% spin polarization at the Fermi level. Other important reasons for choosing NiMnSb as a spin injector are (a) its similarity with the zinc blende structure which makes it compatible with the semiconductors commonly used in microelectronics industry and (b) its high Curie temperature (730 K). We have used InSb substrates because the ultimate goal of the European project FENIKS that we are participating in is to employ an InSb-based 2DEG system in fabricating a SFET similar to that proposed by Datta and Das.

In a previous study we reported the low-temperature growth of polycrystalline NiMnSb films onto Si (111) substrates using pulsed laser deposition (PLD).[6] Those films, however, exhibited a relatively low saturation magnetization of 3.5 μ_B at 5 K and a residual resistivity of 48 $\mu\Omega$ cm, indicating the presence of significant amount of structural disorder.

In this letter we report our efforts to grow single-phase, stoichiometric polycrystalline NiMnSb thin films on single crystal InSb (100) substrates heated at 200 °C by PLD. The need for the low temperature depositions is associated with the structural damage that InSb-based structures suffer when heated to temperatures above 250 °C. There are only a few reports on the deposition of high quality thin films at moderate temperatures (230–300 °C) using methods of growth other than PLD.[7–11] The films exhibit saturation magnetization of 4 μ_B/formula unit at 5 K consistent with the expected half-metallic behavior. In addition, the low coercive field of 2 Oe at room temperature and the low resistivity of 6 $\mu\Omega$ cm at 5 K exhibited by these films constitute strong evidence for their good quality.

NiMnSb films were grown by the conventional PLD method onto heated single crystal InSb (100) substrates (T_s =200 °C) in vacuum. Details regarding the deposition of the films have been described elsewhere.[6] We have investigated the reproducibility of our results by producing several thin films of different thicknesses between 100 and 680 nm. The thickness of the films was measured accurately with an

[a]Electronic mail: giapintz@iesl.forth.gr

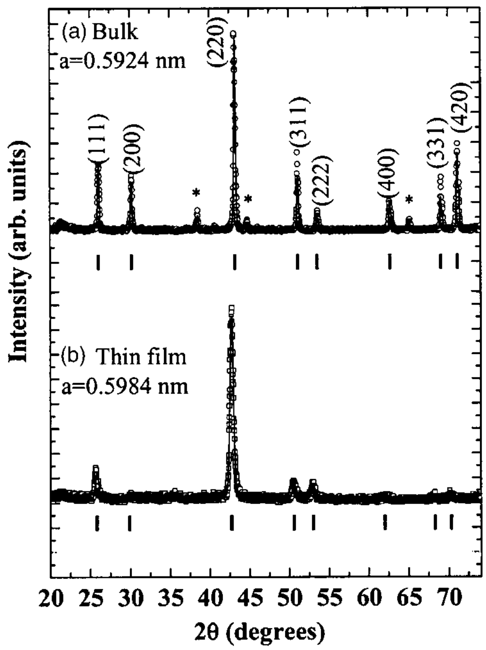

FIG. 1. X-ray diffraction pattern for (a) the NiMnSb target and (b) the NiMnSb thin film (t=590 nm). The open symbols correspond to the experimental data points. The solid lines are a least-squares fit (Ref. 14) of the observed diffraction profile based on the space group C_{1b} of NiMnSb (cubic—$F\bar{4}3m$). The vertical bar marks shown below the diffraction patterns define the position of the Bragg reflections determined after the multicycle self-consistent refinement of the spectra that involves simultaneous manipulation of several structural parameters. The asterisks on spectrum (a) denote Bragg reflections of the aluminum sample holder used to collect powder diffraction data of the target.

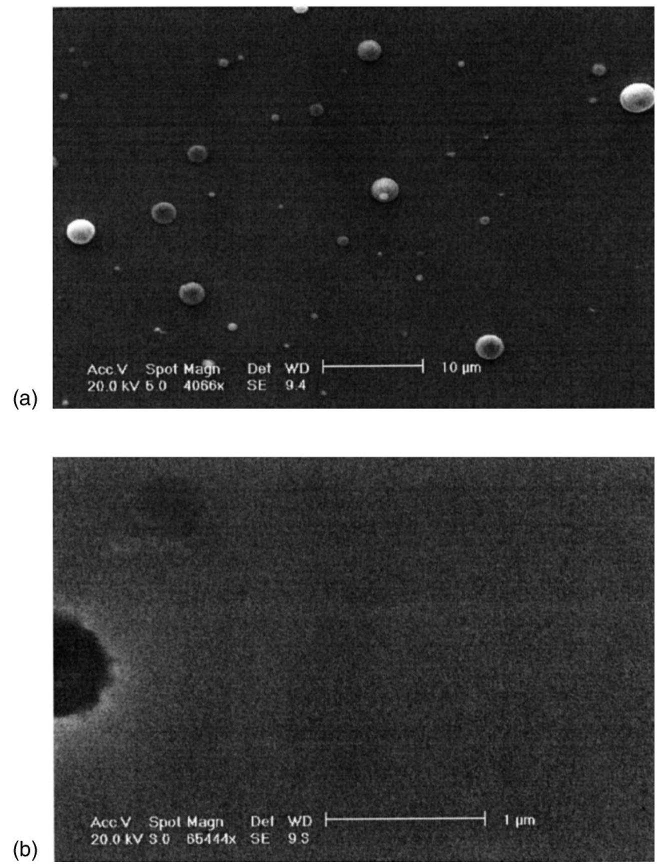

FIG. 2. (a) Scanning electron micrograph showing droplets. (b) The same film at higher magnification.

alpha-step profilometer. Here we report on a thin film of thickness 590 nm, which reflects the typical observed behavior.

The NiMnSb targets used for the PLD deposition were prepared by arc-melting and postannealing treatment.[12,13] The structure of the films and the targets was determined by x-ray diffractometry (XRD) using a Rigaku (RINT-2000) diffractometer equipped with a thin-film attachment. The stoichiometry of the films was determined by energy dispersive x-ray (EDX) measurements in a PHILIPS XL 30 scanning electron microscope. dc magnetization measurements in the temperature range $5 \leqslant T \leqslant 300$ K were carried out in a commercial Oxford extraction magnetometer. The electrical resistivity of the films was measured using the standard four-probe ac method.

It is evident from Fig. 1 that the film is polycrystalline and there is no trace of a second phase both in the film and the target within the resolution of the x-ray diffractometer. Both the film and the target structures were successfully refined within the $F\bar{4}3m$ space group.[14] Direct comparison of the XRD spectra for the bulk and the film indicates a high degree of (220) texturing in the film. It is noteworthy that (220) is the most intense peak of the bulk XRD spectrum. A high degree of (220) texturing has also been observed by us in NiMnSb films grown on Si (100) and becomes more intense as the thickness of the films is increased. The extracted lattice parameter for the film is 0.5984(1) nm, compared to 0.5924(1) nm for the target.

Figure 2 shows scanning electron micrographs of the film obtained at different magnifications. As can be seen there are small droplets on the otherwise smooth surface of the film. EDX measurements on the NiMnSb film show that its stoichiometry is 1:1:1, same as that of the PLD target. Similar chemical composition measurements on a number of droplets show that they also are stoichiometric (1:1:1).

Figure 3 shows the applied magnetic field dependence of magnetization, $M(H)$, at 5 K and room temperature. The magnetic field was applied parallel to the plane of the film; it is known that the easy axis of magnetization lies within the plane because of the thin film shape anisotropy. A saturation magnetization, M_s, of 4.0 ± 0.06 μ_B/f.u. was obtained at 5 K, consistent with the expected half-metallic nature of the film.

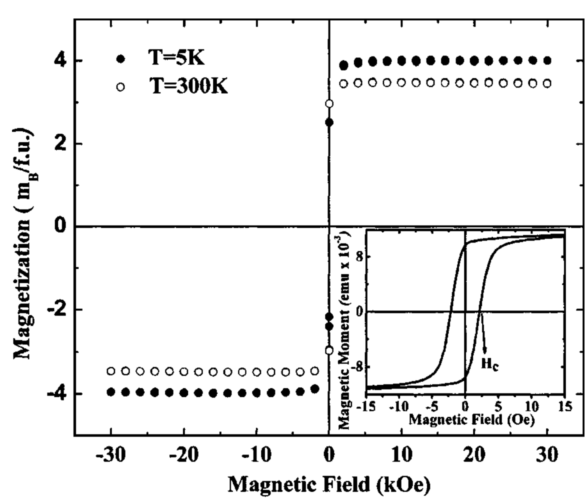

FIG. 3. Magnetization curves for the NiMnSb film at 5 and 300 K. Inset: Hysteresis loop showing a coercive field, H_c, of 2 Oe.

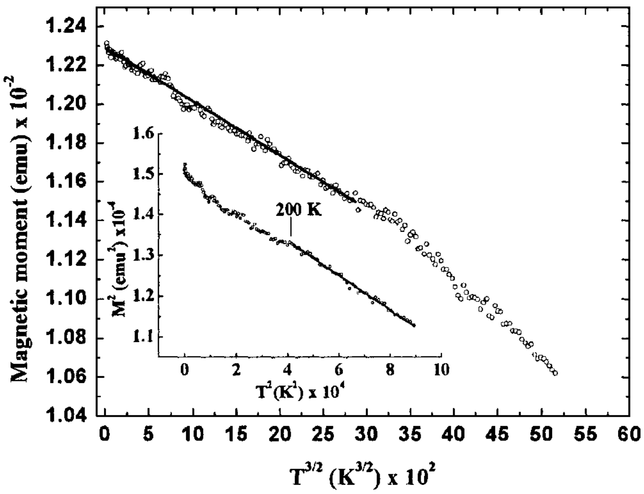

FIG. 4. Temperature dependence of the magnetic moment for the NiMnSb film. The open circles are the experimental data. The solid line in the main figure is the fitted *Bloch* $T^{3/2}$ *law* for the temperature range $5\text{ K} \leqslant T \leqslant 200\text{ K}$. Inset: The solid line is a fit which shows that for temperatures higher than 200 K, M^2 is a linear function of T^2.

The magnetization was calculated by measuring accurately the mass of the deposited film using a thermogravimetric balance. The inset of Fig. 3 depicts a room-temperature hysteresis loop. The coercive field, H_c, deduced from the $M(H)$ loop is 2 Oe almost bulk-like (for bulk NiMnSb: $H_c < 1$ Oe). The low value of H_c is of great importance in the use of these films in spintronics as it defines the operating field range of active devices.

Figure 4 shows the temperature dependence of the saturation magnetization, $M_s(T)$, for the film obtained at a magnetic field of 10 kOe. The magnetization curve up to 200 K can be fitted well, as shown by the solid line in Fig. 4(a), to the Bloch law:

$$M_s = M_s(0)(1 - AT^{3/2}),$$

where $M_s(0)$ is the extrapolated saturation magnetization at 0 K, and $A = 2 \times 10^{-5}\text{ K}^{-3/2}$. This is consistent with the fact that this law is expected to hold up to $T_c/3$ (for NiMnSb, $T_c = 730$ K). Hence, the system behaves like a Heisenberg ferromagnet at low temperatures. This behavior is expected for half-metals and accounts for the fact that the Mn spin magnetic moment is well localized due to the exclusion of the spin-down electrons at Mn sites.[15] Using the value of A that resulted from the fitting of the experimental data, we estimate the spin wave stiffness coefficient D in a similar way as in Refs. 13, 16, and 17. We find $D = 170$ meV Å^2. This value for D is of the same order of magnitude as that of the bulk NiMnSb[13,16,17] and other prototypical half-metallic systems such as doped manganites.[18] For temperatures above 200 K (see inset of Fig. 3), we find that M_s^2 is proportional to T^2, as also found in the case of the target,[13] which is the classical behavior for itinerant ferromagnets. At these temperatures it is expected that both spin bands contribute to transport and individual spin reversals can occur, i.e., Stoner excitations modify the temperature dependence of the magnetization. This is in agreement with theoretical calculations, which predict that terms such as T^2 and $T^{4/3}$ contribute to the magnetization due to spin fluctuations in itinerant ferromagnets.[19]

Finally, the resistivity of the film at 5 K was measured to be $6 \pm 0.2\ \mu\Omega$ cm, slightly lower than that of the target ($8.6\ \mu\Omega$ cm),[13] indicating that the film is of good quality with low disorder. At room temperature the resistivity was $20 \pm 0.2\ \mu\Omega$ cm. The residual resistivity ratio $[\text{RRR} \equiv \rho(300\text{ K})/\rho(5\text{ K})]$ is ~ 3. This relatively low RRR value is most likely due to the presence of the grain boundaries in the polycrystalline film, which may not affect the saturation magnetization but could significantly increase the residual resistivity of the sample. More detailed analysis of the transport measurements, which suggest that the contact between NiMnSb and InSb is ohmic and thus suitable for spin injection,[20,21] will be reported elsewhere.[22]

In conclusion we have studied the structural, compositional, magnetic and electrical properties of NiMnSb polycrystalline thin films grown onto moderately heated single crystal InSb substrates by PLD. The films were single-phase and stoichiometric, and exhibited a rather high degree of (220) texturing. The measured magnetic and electrical properties indicate that the films are of high quality and exhibit signatures expected for half-metallic systems.

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