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Granular Co/Ag multilayers with crystalline coherence

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Abstract

We have made Co/Ag multilayers with ten repeats on MgO (1 0 0) single-crystal substrates at room temperature by magnetron sputtering from independent sources and keeping the Ag layers as thick as 40 Å. The analysis of the X-ray diffraction indicates a coherent structure of Ag layers with a lattice parameter 2.355 Å close to the bulk FCC (1 1 1) spacing and Co layers with 2.13 Å spacing corresponding to HCP (1 0 0) planes. Other experiments show the granular in-plane morphology and a large interfacial disorder. These Co layers develop in-plane magnetization and electrical magneto-transport whose properties are thickness dependent.

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1. Introduction

The interest in Co/Ag multilayers dates back to the nineties [1–3]. Co and Ag are immiscible and a FCC (1 1 1) superlattice would be an ideal system to show electron channeling because of superlattice effects [1]. However, this system has not been epitaxially achieved so far and, if the Co layers are very thin (<5–10 Å), the multilayer is a magnetic granular system, of which electrical transport and magnetization have become a basic and applied topic by themselves [2].

2. Experiments and discussion

We have made Co/Ag multilayers with ten repeats on MgO (1 0 0) unheated substrates in a magnetron sputtering system. Base-pressure is in the 10^{-8} mbar range. Two independent circular DC guns are operated at an Ar pressure of 8×10^{-3} mbar and the growth rates are 1.4 and 2.1 Å/s for cobalt and silver, respectively, as calibrated from the thickness of single layers with X-ray reflectivity. A sequential process is used with the substrates placed on a rotary holder. The X-ray reflectivity and diffraction experiments on every sample have been done in a Philips diffractmeter with a graphite monochromator. Contact-mode atomic force microscopy (AFM) has been used to study the surface morphology. Magnetization was recorded down to 4 K and high-fields in the film plane with a SQUID magnetometer. Electrical magnetotransport is studied in lithographically etched Hall bars with a 9 T commercial cryostat.

We have prepared a series of samples with different Co layer thickness (0–40 Å) and Ag thickness fixed at 40 Å. The deposition always started with cobalt and ended with a silver layer that avoids oxidation. As long as the cobalt layers are continuous and thinner than the Ag layers, the multilayer is a superlattice with Ag (1 1 1) texture and crystalline coherence along the growth direction. A similar structural quality has been achieved by other groups on *c*-axis sapphire or Si substrates [3].

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Low angle X-ray scans show multilayer reflections up to third order and finite size peaks that indicate acceptable layering. Modulation lengths and interface roughness are obtained from simulations of the $I(\theta)$ curves using the SUPREX code [4]. The estimate roughness is 6 ± 2 Å.

AFM images of a Co(15 Å)/Ag(40 Å) multilayer give an estimate of the average mound diameter 42 ± 13 nm and a roughness rms of 1–4 nm over areas $1\times1\,\mu m^2$.

High-angle X-ray diffraction from the film only arises at angles around $2\theta=38°$. Fig. 1 shows the scans of the representative Co(15 Å)/Ag(40 Å) and Co(40 Å)/Ag(40 Å) multilayers. One or two broad satellites are clearly observed in this range, and no other reflections apart from these. The intensity curves have been fitted with the SUPREX code [4] using a structure model of cobalt layers of 2.13 ± 0.03 Å lattice spacing and silver layers of 2.355 ± 0.005 Å spacing plus a line broadening that arises from both the interface roughness and the thickness fluctuations. The calculated $I(\theta)$ curves are included in Fig. 1. We should remark that such spacings are also valid for other Co thickness. The coherent structure can basically correspond to a periodic layering of HCP (1 0 0) cobalt and FCC (1 1 1) silver planes. The inset of Fig. 1 shows the dependence of the main reflection center on the cobalt nominal thickness. A rapid upturn occurs below about 7 Å, pointing to the critical thickness for which coalescence takes place [2].

Magnetization loops along the in-plane $H||$ MgO (1 0 0) axis at constant temperature are nearly square and the coercive fields do not change much down to liquid nitrogen temperatures. The calculated cobalt moment density is shown in Fig. 2 with solid squares referred to the left side

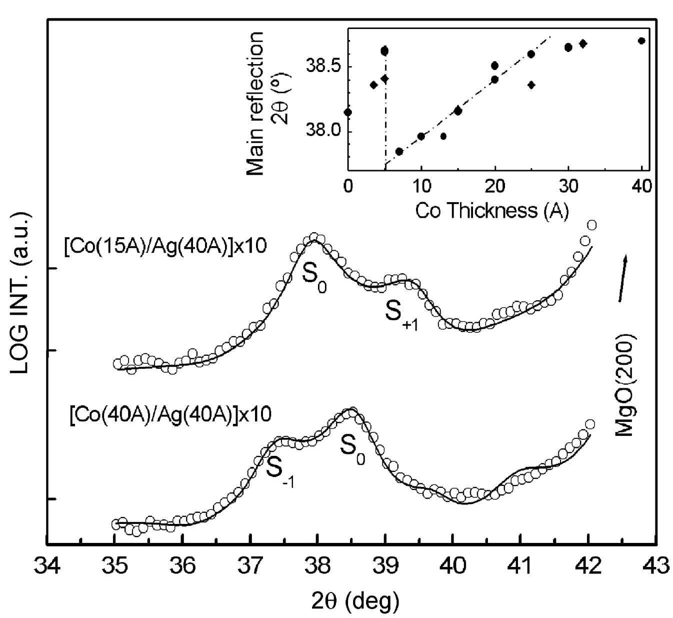

Fig. 1. High angle X-ray diffraction scans around the superlattice reflection for two representative multilayers: Co(35 Å)/Ag(40 Å)—upper curve—and Co(15 Å)/Ag(40 Å)—lower curve— together with the simulated intensities according to the model described in the text. Inset: 2θ angle of main reflection versus the cobalt thickness.

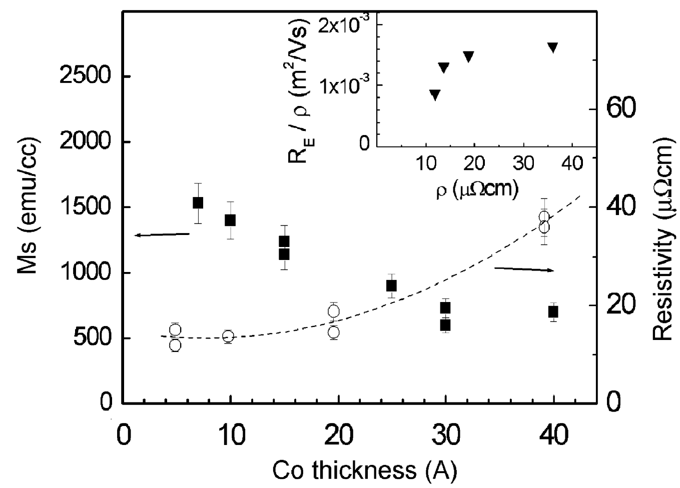

Fig. 2. Magnetic moment at 4 K (solid squares) at the in-plane saturation field in the series of Co/Ag(40 Å) samples. The open circles represent the electrical resistivity of the same series at zero field and 5 K (line is a guide to the eye) on the right axis. The inset shows the extraordinary Hall coefficient over resistivity as a function of resistivity.

scale. Maximum values are reached in multilayers of thin cobalt, whereas 40–50% as much is representative of the thick ones.

Besides, the multilayers have a higher electrical residual resistivity in case of thick cobalt layers (open dots in Fig. 2), which may arise in the interface roughness, but all samples have values larger than the values of bulk Ag or Co ($<1\,\mu\Omega$ cm). The Hall effect at 5 K proves the expected carrier density from the ordinary coefficient (nearly the same value as pure cobalt or pure silver) and shows the extraordinary component at low fields related to cobalt [5].

The behavior of R_E coefficient at 5 K is explored for a few significant samples with the plot of the inset, R_E/ρ as a function of ρ. Clearly the linear relation based on $R_E = A\rho + B\rho^2$ for isotropic metallic ferromagnets does not hold here at low resistivity values—low thickness—where the granular behavior must set in and a rapid variation can be observed [6].

3. Conclusions

Crystalline coherent Co(7–40 Å)/Ag(40 Å) multilayers have been successfully made on MgO (1 0 0) substrates by magnetron sputtering. The structural analysis indicates hcp(1 0 0)Co/fcc(1 1 1) Ag layering. For Co thickness below 7 Å, X-ray and ferromagnetic Hall data suggest granular behavior. Magnetization takes place collectively in the film plane. However, multilayers of thick Co layers have a reduced moment and large resistivity.

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References

[1] M.P. López-Sancho, L. Chico, M.C. Muñoz, Phys. Rev. B 59 (1999) 1232.
[2] E.A.M. van Alphen, W.J.M. de Jorge, Phys. Rev. B. 51 (1995) 8182.
[3] K. Sakai, T. Kingetsu, J. Cryst. Growth 126 (1993) 184;
T. Veres, M. Cai, R.W. Cochrane, S. Roorda, J. Appl. Phys. 87 (2000) 8504;
M. Angelakeris, et al., J. Magn. Magn. Mater. 165 (1997) 334.
[4] E. Fullerton, I.K. Schuller, H. Vanderstraeten, Y. Bruynseraede, Phys. Rev. B. 45 (1992) 9292.
[5] J. Kötzler, W. Gil, Phys. Rev. B 72 (2005) 060412.
[6] P. Xiong, G. Xiao, J.Q. Wang, J.Q. Xiao, J. Samuel Jiang, C.L. Chien, Phys. Rev. Lett. 69 (1992) 3220.