Large magnetoresistance with low saturation fields in magnetic/magnetic superlattices

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Ni/Co multilayers grown by molecular beam epitaxy are found to exhibit a magnetoresistance $\Delta R/R$ at liquid helium temperature as large as 8.2%, with saturation fields $\Delta H \approx 22$ Oe and a sensitivity $(\Delta R/R)/(2\Delta H) \approx 0.19\%$ Oe^{-1}. The highest room temperature sensitivity obtained to date in this system is 0.18% Oe^{-1} and at 4.2 K is 0.29% Oe^{-1}. This demonstrates that high values of the sensitivity can be achieved in multilayers in which both components are ferromagnetic. The magnetoresistance and saturation field can be tuned by the superlattice and growth parameters.

Since the discovery of giant magnetoresistance (GMR) in Fe/Cr multilayers,[1] a large variety of magnetic/normal multilayer (ML)[2,3] and granular ferromagnetic-nonmagnetic systems[4,5] have shown anomalously large magnetoresistance (MR) values when compared to *ordinary* ferromagnetic materials.[6] The GMR effect has attracted much attention both from a fundamental point of view and for its possible applications in magnetic sensor technology. Magnetoresistive applications, however, require a high sensitivity, i.e., a large change in the MR with magnetic field,[7] which is not realized in GMR systems due to the large fields required for sizeable changes in resistance. The development of new magnetoresistive materials which exhibit large MRs with small magnetic fields is therefore of great importance.

In this letter, we report large MRs with small saturation fields in Ni/Co (*ferromagnetic/ferromagnetic*) metallic multilayers. Depending on the growth conditions and superlattice parameters, this system shows a MR at $T=4.2$ K as high as 8.2%, with a sensitivity $[(\Delta R/R)(2\Delta H)]$ of 0.19% Oe^{-1}. The highest liquid helium and room temperature sensitivities measured to date are 0.29% and 0.18% Oe^{-1}, respectively. These compare favorably with values for other candidates used or proposed as magnetoresistive materials and opens up the search for new systems of potential use as magnetoresistive sensors.

$(\mathrm{Ni}_x\mathrm{Co}_y)_N$ multilayers, with x and y being the thicknesses in Å of the Ni and Co layers, respectively, and N the total number of bilayers, were grown by molecular beam epitaxy on sapphire $[\mathrm{Al_2O_3}(11\bar{2}0)]$ substrates. The base pressure was 2×10^{-10} Torr, and did not exceed 5×10^{-9} Torr during growth. Ni and Co were deposited at 150 °C, for a total thickness of ~1000 Å, using two independent electron guns and computer-controlled pneumatic shutters. The growth rate (~0.1 Å/s for Ni and ~0.05 Å/s for Co) was controlled using two calibrated electron impact emission spectroscopy sensors. Prior to the deposition of the multilayer, a 50 Å Co buffer layer was deposited at 350 °C. No aligning magnetic field was used during growth.

The structure of the multilayers was characterized *in situ* using Auger electron spectroscopy, low and high energy electron diffraction (LEED and RHEED, respectively), and *ex situ* using x-ray diffraction. The four lead MR measurements were carried out at $T=4.2$ K in magnetic fields up to 30 kOe on photolithographically patterned samples. The MR was measured in a variety of configurations, including: the magnetic field parallel to the film surface and parallel to the current (longitudinal, $\mathrm{MR}_\parallel$), the magnetic field parallel to the film surface and perpendicular to the current (transverse, MR_t), and the magnetic field perpendicular to the film surface and perpendicular to the current (perpendicular, $\mathrm{MR}_\perp$). The magnetization of the samples was measured with a superconducting quantum interference device magnetometer at $T=10$ K and in fields of up to 50 kOe parallel and perpendicular to the film surface. The conclusions presented here rely on measurements in more than 20 samples prepared over a period of one year.

Figure 1 shows high angle x-ray spectra for a set of Ni/Co multilayers with $x=42$ Å and $y(N)=6$ Å (19), 18 Å (16), 29 Å (13), and 59 Å (10). The peaks at $2\theta \sim 44.5°$ are the central Bragg peaks of the superlattices,[8] corresponding to a weighted average of Ni and Co, probably Ni(111) and either Co(0002) or Co(111), depending on whether Co grows in the hcp or fcc structure. The tail at the left-hand side of the spectrum is due to the $(11\bar{2}0)$ reflection of the sapphire substrate, and the peak at ~51.6° is due to a small quantity (<1%) of Ni(100). The other peaks shown in the spectra are satellite peaks due to the superlattice periodicity. A detailed quantitative analysis of these spectra is difficult to perform due to the low scattering contrast between Ni and Co. As a consequence, the parameters obtained from structural refinement[9] are not unique. Nevertheless, the fact that the fourth-order satellite peak is clearly observed in some of the multilayers despite this low contrast is a sign of little, if any, interdiffusion. This is in agreement with the Auger spectra taken during growth, which show that the high energy signal of either Ni (848 eV) or Co (775 eV) disappears almost completely when the overlayer thickness is higher than ~15 Å. The escape depth of these Auger electrons is ~10–12 Å,[10] so that an upper limit of 4–5 Å can be estimated for the thickness of the interdiffused region at the Ni-Co interface. The full width at half-maximum of the main superlattice x-ray peaks are ~0.12°. This corresponds to a crystalline coherence length, calculated from the Scherrer's equation, of ~1040 Å, which is approximately equal to the entire superlattice thickness.

The bulk lattice parameter for Ni is $d_{\mathrm{Ni}}(111)=2.034$ Å; for hcp Co, $d_{\mathrm{Co}}^{\mathrm{hcp}}(0002)=2.023$ Å; and for fcc Co, $d_{\mathrm{Co}}^{\mathrm{fcc}}(111)=2.046$ Å. With increasing Co thickness, the main

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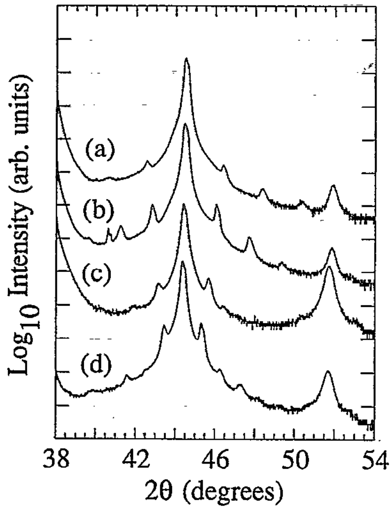

FIG. 1. High-angle x-ray diffraction spectra for a series of Ni_xCo_y multilayers with $x=42$ Å and $y=$(a) 6 Å, (b) 18 Å, (c) 29 Å, and (d) 59 Å.

peak shifts from a position corresponding to $d=2.035$ Å for $(Ni_{42}Co_6)_{19}$ to $d=2.041$ Å for $(Ni_{42}Co_{59})_{10}$, i.e., the peak shifts from the Ni position to the Co fcc position. This suggests that in these multilayers Co grows in the fcc structure. RHEED diffraction patterns taken during growth, and θ–2θ x-ray diffraction spectra with both in-plane and out-of-plane components of the scattering vector, confirm this finding. LEED patterns and grazing incidence x-ray diffraction indicate four in-plane domains, their epitaxial relationship being $Al_2O_3(\bar{1}10\bar{2})\|Ni/Co(11\bar{2})$ and $Al_2O_3(1\bar{1}00)\|Ni/Co(11\bar{2})$, and their respective twins.

Thus, the Ni/Co multilayers grow quasi-epitaxially on the sapphire substrate, with both Ni and Co growing in the fcc structure and the (111) direction of the multilayer parallel to the $(11\bar{2}0)$ direction of the substrate. Note that bulk fcc Co is also ferromagnetic with a magnetic moment ~2% larger than that of Co hcp,[11] although the moment may vary with strain.

Figure 2 shows the resistivity of a $(Ni_{42}Co_{29})_{13}$ multilayer as a function of applied magnetic field. When the magnetic field is parallel to the current [Fig. 2(a)], the maximum MR $[(\rho_{max}-\rho_{min})/\rho_{min}]$ is 8.20%. The most striking feature, however, is the sharpness of the peaks in the parallel geometry, $\Delta H \sim 22$ Oe, with a sensitivity of ~0.19% Oe^{-1}. The transverse MR of this sample [Fig. 2(b)] is only 0.79%, with $\Delta H=37$ Oe, while the perpendicular magnetoresistance [Fig. 2(c)] is 2.10%, with $\Delta H=7939$ Oe.

The MR shows a strong in-plane anisotropy. Thus, the highest sensitivity was measured in a $(Ni_{42}Co_{59})_{10}$ multilayer, in which $MR_{\|}=6.62\%$, with $\Delta H=18$ Oe, and $MR_t=2.59\%$, with $\Delta H=19$ Oe. However, when the magnetic field is in the plane of the film, at 70° with the direction of the current, the MR is 3.48%, with $\Delta H=6$ Oe, and the sensitivity is 0.29% Oe^{-1}. The highest room temperature sensitivity of ~0.18% Oe^{-1} was obtained for a $(Ni_{42}Co_{48})_{11}$ multilayer.

Note that using the traditional definition,[6] the longitudinal [Fig. 2(a)] MR is positive, while the transverse [Fig. 2(b)] and perpendicular [Fig. 2(c)] ones are both negative. In contrast, the GMR in magnetic/nonmagnetic multilayers and granular films is always negative. In this respect, our data are similar to those found in most homogeneous ferromagnetic metals.[12]

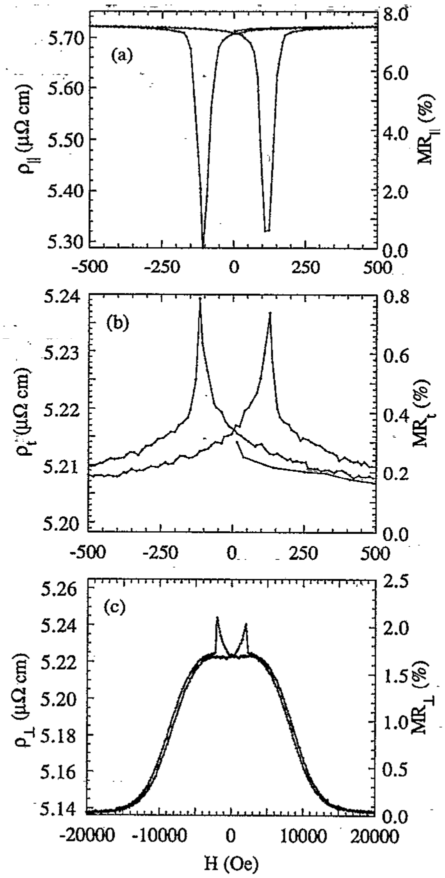

FIG. 2. Resistivity as a function of the applied magnetic field for a $(Ni_{42}Co_{29})_{13}$ multilayer. In (a) and (b) the magnetic field is parallel to the film surface and the current (a) parallel and (b) perpendicular to the field. In (c) the magnetic field is perpendicular both to the surface and to the current.

For comparison, we also measured the transport properties at 4 K of 1000-Å-thick Ni, Co, and $Ni_{0.43}Co_{0.57}$ films grown on the same substrate. The values for the longitudinal, transverse, and perpendicular MRs (sensitivities) are: 0.71% (0.0011% Oe^{-1}), 0.75% (0.0007% Oe^{-1}), and 0.49% (0.0002% Oe^{-1}) for Ni; 1.41% (0.006% Oe^{-1}), 1.88% (0.001% Oe^{-1}), and 3.0% (0.000 02% Oe^{-1}) for Co; and 6.32% (0.05% Oe^{-1}), 6.66% (0.04% Oe^{-1}), and 10.52% (0.0007% Oe^{-1}) for $Ni_{0.43}Co_{0.57}$. The highest sensitivities that have been measured to date are in $Ni_{80}Fe_{20}$/Cu multilayers (0.4% Oe^{-1}),[13] NiFeCo/Cu multilayers (0.4% Oe^{-1}),[14] and $Ni_{80}Fe_{20}$/Ag annealed multilayers (1.2% Oe^{-1}).[15] These values compare favorably with that of ~0.5% Oe^{-1} for permalloy,[16] the material commonly used as a magnetic sensor.

Figure 3 shows the in-plane and out-of-plane hysteresis loops of a $(Ni_{42}Co_{29})_{13}$ multilayer. All the Ni/Co multilayers exhibit an easy axis of magnetization in the plane of the film. The magnetic anisotropy, however, decreases with layer thicknesses. We note that a perpendicular magnetic anisot-

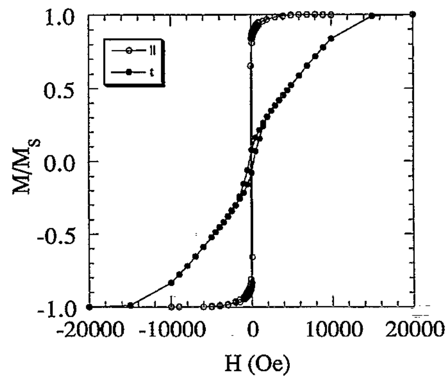

FIG. 3. Field dependence of the magnetization at $T=10$ K for a $(Ni_{42}Co_{29})_{13}$ multilayer.

ropy was previously found in $(Ni_4Co_2)_{20}$ multilayers.[17] A comparison with Fig. 2 shows that the longitudinal and transverse MR and the in-plane magnetization saturate at approximately the same field. The same is true for the perpendicular MR and the out-of-plane magnetization. This indicates a possible connection between the magnetic domain structure and the magnetotransport properties.

In summary, large MR values with high sensitivities were measured in Ni/Co multilayers, in which both components are ferromagnetic. This opens a new field in the current search for new materials useful in magnetic sensor technology.

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