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Oscillations of the transport properties in Ni/Co superlattices

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Abstract

The transport and galvanomagnetic properties (resistivity, anisotropic magnetoresistivity and extraordinary Hall effect) of MBE grown Ni/Co superlattices oscillate as functions of the Ni and/or Co layer thicknesses, with a period of ~ 20 Å. These oscillations are a true superlattice effect, since they disappear when the number of bilayers in the superlattice is decreased.

Although metallic multilayers have recently attracted much attention, especially since the discovery of giant magnetoresistance in Fe/Cr multilayers [1], only a small number of true superlattice effects have been experimentally observed. These are the appearance of superlattice Bragg peaks in X-ray diffraction [2], the collective behavior of magnons in magnetic/non-magnetic superlattices [3], and the opening of superlattice gaps in the electronic band structure [4]. Until now, no superlattice effect has been observed in the transport properties. In particular, for all metallic multilayers, the resistivity ρ increases smoothly while decreasing the modulation wavelength, Λ, and for some range of thickness, $\rho \propto \Lambda^{-1}$, implying that in this range the electron mean free path is limited by the layer thickness, thus impeding the observation of superlattice effects [5–7].

We report here the observation of a true superlattice effect in the transport properties of Ni/Co superlattices: oscillations in the magnetotransport as functions of the Ni and/or Co layers thicknesses. Since the oscillations disappear when the number of bilayers is reduced, this behaviour is obviously related to the superlattice structure of the samples.

$(Ni_{dNi}/Co_{dCo})_N$ superlattices were grown by Molecular Beam Epitaxy on single-crystal sapphire substrates ($Al_2O_3(11\bar{2}0)$). The structure of the multilayers was characterized in-situ with electron spectroscopy (LEED, RHEED and AES) and ex-situ with X-ray diffraction [8]. The results show that the multilayers grow epitaxially, both Ni and Co in the fcc structure, with the (111) direction normal to the film surface and a perpendicular structural coherence length of the order of the whole superlattice thickness (~ 1000 Å), and lattice matched in the plane of the film [8]. There are four different types of in-plane domains, each one with a definite epitaxial relationship with the sapphire substrate, and whose in-plane size ranges between 100 and 200 Å. In summary, the multilayers are quasi single-crystalline, i.e. single crystals in the growth direction, but with four different types of in-plane domains [8].

The transport properties were measured at $T = 4.2$ K on photolithographically patterned samples. Fig. 1 shows the resistivity (ρ_0), anisotropic magnetoresistance ($\Delta\rho$), ordinary Hall coefficient (R_0), and spontaneous Hall coefficient (R_S), as a function of the modulation wavelength (Λ), for a series of superlattices of the form

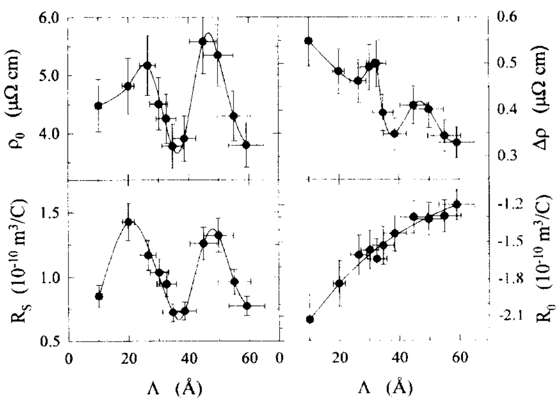

Fig. 1. Resistivity (ρ_0), anisotropic magnetoresistivity ($\Delta\rho$), ordinary Hall effect (R_0) and extraordinary Hall effect (R_S) as functions of the modulation wavelength Λ for a series of Ni/Co superlattices of the form $(Ni_{0.4\Lambda}/Co_{0.6\Lambda})_N$. Lines are guides to the eye.

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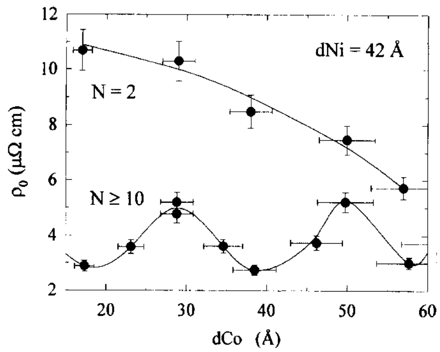

Fig. 2. Resistivity (ρ_0) as a function of the Co layer thickness (d_{Co}) for two series of Ni/Co superlattices of the form $(Ni_{42}/Co_{d_{Co}})_N$, one where the total thickness is ~1000 Å ($N \geq 10$) and the other one with $N = 2$. Lines are guides to the eye.

$(Ni_{0.4\Lambda}/Co_{0.6\Lambda})_N$, that is, with the same relative concentration of Ni and Co.

The results show that ρ_0, $\Delta\rho$ and R_S exhibit an oscillatory behavior, with changes in the resistivity sometimes as large as 100%, much larger than the measurements uncertainty. It is important to note that no correlation was found between the transport results and any structural parameter (other than the layers thicknesses) that may indicate that these changes could be due to some uncontrolled structural disorder.

Similar oscillations were also observed as functions of the Co and Ni layer thickness, for two other series of samples of the form $(Ni_{42}/Co_{dCo})_N$ and $(Ni_{dNi}/Co_{18})_N$. In all cases, the oscillation period ranges between 12 and 20 Å.

To check whether this behavior is a *true* superlattice effect, another series of samples was grown, with $d_{Ni} = 42$ Å, but with the number of bilayers periods reduced to $N = 2$. Fig. 2 shows the results for this case, together with the results for $N \geq 10$. The oscillations disappear when the number of bilayers is reduced, indicating that the oscillations are due to the superlattice structure of the samples.

Since the ordinary Hall effect, R_0, does not follow the same oscillatory behavior as ρ_0, $\Delta\rho$ and R_S (Fig. 1), these oscillations may not be due to periodic variations in the total number of carriers, but rather to periodic changes in the density of states at the Fermi level $N(E_F)$ or in the scattering strength.

A possible reason for this oscillatory behavior of $N(E_F)$ with layer thicknesses could be the opening of superlattice band gaps in the electronic band structure (superlattice 'minigaps'). If the superlattice periodicity is such that the Fermi level lies inside one of these 'minigaps', this could noticeably alter the density of states at the Fermi level, thus modifying the electronic and transport properties of the superlattice. The main requirement for the existence of such superlattice 'minigaps' is the existence of extended electronic states throughout the superlattice thickness. As mentioned above, these Ni/Co superlattices are single-crystalline in the growth direction and lattice matched in the plane, and therefore are favorable candidates for the existence of such extended states.

Another feasible explanation relies on the existence of localized electronic levels at the interfaces. Disorder at the Co/Ni interfaces (roughness, interdiffusion) could turn the superlattice structure into a quasiperiodic system. The energy of these localized states depends on modulation wavelength, crossing the Fermi level at periodic intervals, and thus also producing an oscillatory variation in $N(E_F)$.

In summary, we have found a new superlattice effect in Ni/Co multilayers, namely, the oscillation of the transport properties as a function of the Ni and/or Co layer thicknesses.

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References

[1] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P.E. Etienne, G. Creuzet, A. Friedrich and J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472.
[2] I.K. Schuller, Phys. Rev. Lett. 44 (1980) 1597.
[3] M. Grimsditch, M.R. Khan, A. Kueny and I.K. Schuller, Phys. Rev. Lett. 51 (1983) 498.
[4] T. Miller and T.C. Chiang, Phys. Rev. Lett. 68 (1992) 3339.
[5] M. Gurvitch, Phys. Rev. B 34 (1986) 540.
[6] G. Reiss, K. Kapfberger, G. Meier, J. Vancea and H. Hoffmann, J. Phys.: Condens. Matter 1 (1989) 1275.
[7] Y. Inoue, K. Mae, N. Kyuno, T. Kaneko and R. Yamamoto, J. Magn. Magn. Mater. 126 (1993) 475.
[8] J.M. Gallego, S. Kim, T.J. Moran, D. Lederman and I.K. Schuller, Phys. Rev. B 51 (1995) 2550.