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MAGNETISM AND FERROELECTRICITY

Anomalous Temperature Dependence of the Magnetoresistance in Co/Cu Multilayers

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Abstract—An anomalous temperature dependence of magnetoresistance (MR) of Co/Cu multilayer films with a ~3 Å thick magnetic layer has been established experimentally. The temperature of the MR maximum T_{max} is shown to coincide with the Néel temperature. The variation of T_{max} with the Cu layer thickness follows an oscillatory pattern. © *2000 MAIK "Nauka/Interperiodica".*

Multilayer films with alternating ferromagnetic and nonmagnetic layers have been among the most intensely studied magnetic systems in recent years. The mounting interest in magnetic multilayers stems primarily from the application potential of these systems (in particular, the possibility of using them in magnetic information storage devices). At the same time, such structures represent a good model system for studying fundamental physical relations.

We have studied magnetic and magnetoresistance properties of Co/Cu multilayer films with ultrathin (about 3 Å-thick) Co layers. As was shown earlier [1, 2], this thickness of a magnetic layer is a limit at which magnetic ordering is still possible. We studied the temperature dependences of the magnetoresistance of Co/Cu multilayered films. All the samples were prepared by magnetron sputtering with the successive deposition of Co and Cu layers on glass substrates at room temperature in an argon environment. Each sample was made up of 120 Co/Cu bilayers. The Co layer thickness and the Cu modulation period of the multilayer system were calculated from x-ray fluorescence data. All the samples had a polycrystalline structure.

The temperature dependence of the MR was studied by the technique described in [2]; a dc current I was passed through the sample whose magnetization was reversed by a varying magnetic field $H = H_a\cos(\omega t)$ normal to the film plane with a frequency $f = \omega/2\pi$ = 37 Hz. The magnetization M generated in this way is proportional to H within a broad range of fields, and the domain structure of the sample does not affect the value of being MR measured. It was shown earlier that $\Delta R \sim M^2$ [2], and therefore,

$$\Delta R \sim H_a^2\cos^2(\omega t) = \frac{1}{2}H_a^2(1+\cos(2\omega t)).$$

Since the current through the sample is constant, an ac voltage of frequency $2f$ = 74 Hz is induced across the sample with an amplitude proportional to the MR: $U_a = \Delta RI/2$, where $\Delta R = R_0 - R_{min}$, R_0 being the sample resistance in zero field, and R_{min}, in a field H_a. The voltage was amplified by a selective amplifier. The temperature dependence of R_0 was measured separately. The magnetoresistance was determined from the relation $MR = \Delta R/R_0$. The investigation was carried out in the 77–300 K temperature range under heating and in magnetic fields of up to 500 kOe.

We found that the temperature dependences of the magnetoresistance of films with ultrathin Co layers behave anomalously; namely, each curve exhibits a clearly pronounced maximum (a magnetoresistance peak) below room temperature (Fig. 1). The absence of

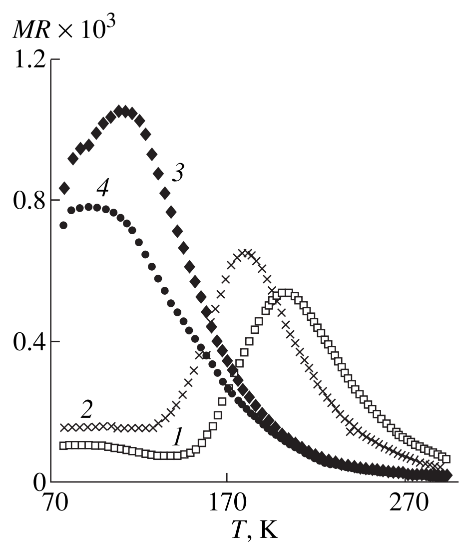

Fig. 1. Typical temperature dependences of the MR of Co/Cu multilayer films obtained for various thicknesses of the Cu layer in a field of 500 Oe. d_{Cu} (Å): (*1*) 14, (*2*) 15, (*3*) 18.5, and (*4*) 21.5.

an MR peak for some samples is apparently due to a shift in the temperature T_{max} of the peak towards a region below 77 K.

This method of magnetoresistance determination was proposed by us [2] to estimate the Curie temperature Θ_C directly from magnetoresistance measurements. The magnetoresistance curve for Co/Cu multilayer films contains a linear segment at temperatures above T_{max}. Within this region, the $M \sim (\Theta_C - T)^{1/2}$ relation holds, because $\Delta R \sim M^2$ [3]. Extrapolation of the linear segment makes it possible to determine the Curie temperature Θ_C of the film for a given applied magnetic field H (Fig. 2). Knowing the dependence of Θ_C on H, one can determine the zero-field value of Θ_C.

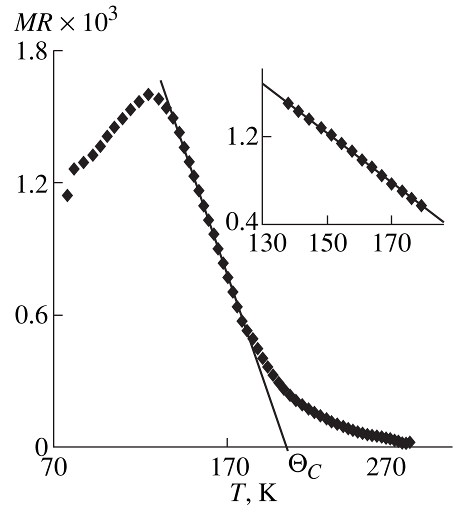

Fig. 2. Determination of the Curie temperature Θ_C (for the sample with d_{Cu} = 16 Å).

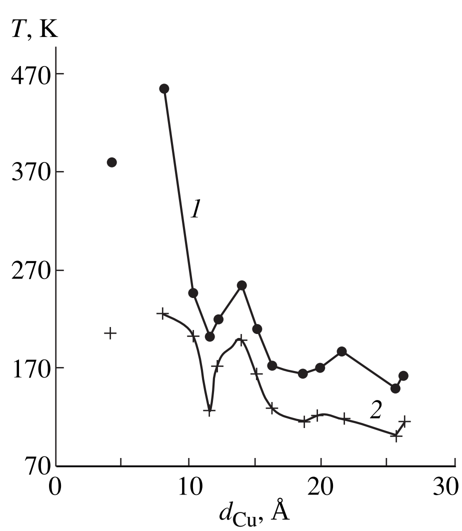

Fig. 3. Dependences of the Curie temperature Θ_C (*1*) and T_{max} (*2*) on d_{Cu}.

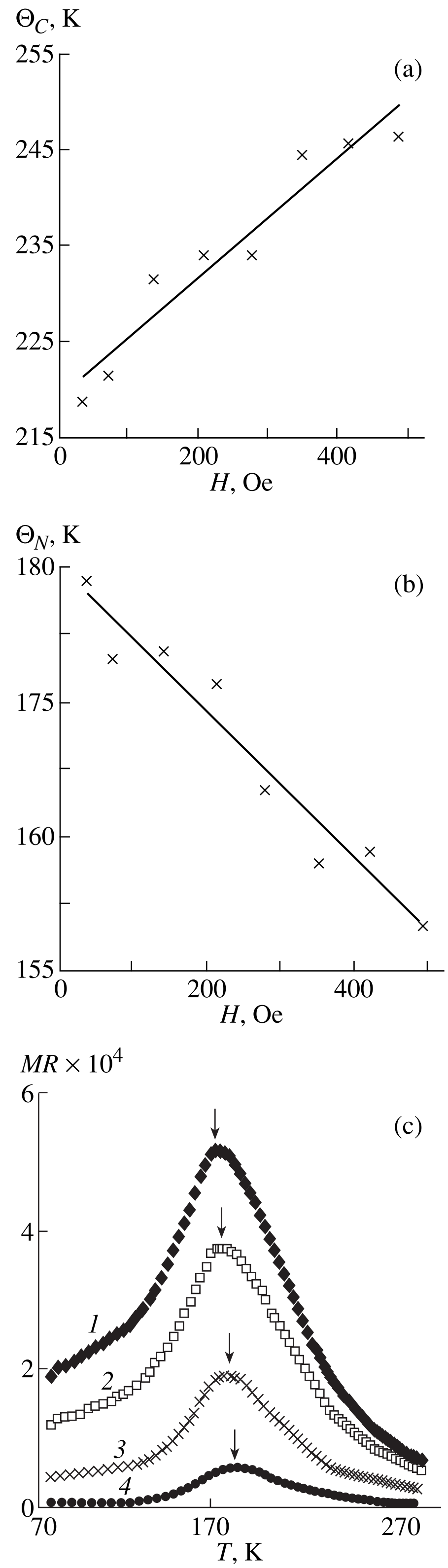

Fig. 4. Dependences of the Curie (a) and Néel (b) temperatures on the applied magnetic field H obtained for the sample with d_{Cu} = 12 Å; and (c) magnetoresistance curves measured in different fields. The arrows identify the MR peak. H (Oe): (*1*) 490, (*2*) 420, (*3*) 280, and (*4*) 140.

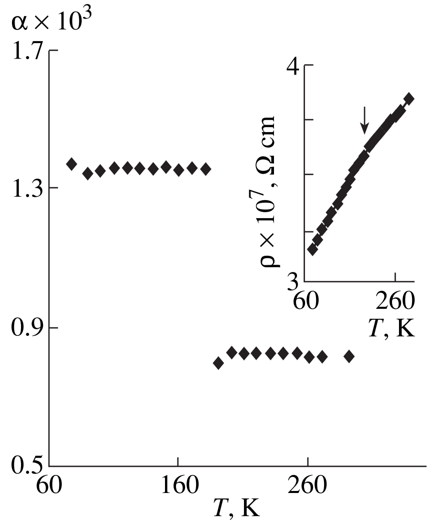

Fig. 5. Dependence of the temperature coefficient of resistivity α for a sample with d_{Cu} = 14 Å on temperature T. The inset shows the temperature behavior of the resistivity ρ. The arrow identifies T_{max} for this sample.

Thus, there exists a critical temperature T_{max} for multilayer Co/Cu films, at which the magnetoresistance is maximal. This temperature depends substantially on the thickness of the Cu nonmagnetic layer, and this dependence, as well as the dependence of Θ_C on d_{Cu}, exhibits an oscillatory character (Fig. 3).

The magnitude of the applied magnetic field also noticeably affects the measured values of Θ_C and T_{max}; namely, an increase of the field amplitude generally brings about a decrease of T_{max} and an increase of Θ_C (Fig. 4).

The interaction of magnetic atoms through a nonmagnetic layer in the multilayer films studied may be both ferromagnetic and antiferromagnetic [2]. The observed experimental results can be interpreted if we take into account the existence of antiferromagnetic coupling in these films.

It is known that the existence of a susceptibility maximum at the Néel point Θ_N is a feature of antiferromagnetic ordering [3]. The film structure can be represented in the following way: the Co magnetic layer consists of a large number of ferromagnetic spin clusters ordered antiferromagnetically or in a mixed manner, part of the clusters ordered ferromagnetically, and the remainder, antiferromagnetically. The magnetoresistance peak corresponds to the maximum in the film susceptibility at $T_{max} = \Theta_N$. Such a temperature dependence of susceptibility was theoretically considered by Landau in 1933 [4] for materials made up of ferromagnetically ordered layers.

This model finds confirmation in the character of Θ_C and Θ_N variation with an increasing external magnetic field. The magnetic field orients the spins in one direction, which favors the ferromagnetic and hinders the antiferromagnetic ordering. Therefore, the destruction of antiferromagnetic order in the presence of a field occurs at lower, and that of the ferromagnetic order, at higher temperatures.

Antiferromagnetic systems exhibit anomalies of nonmagnetic properties, for instance, the conductivity, at the Néel point. Figure 5 presents the dependence of the temperature coefficient of resistivity α on temperature (for a sample with d_{Cu} = 14 Å). Within the temperature interval from 180 to 190 K, α undergoes a jump. The Néel temperature Θ_N for a given sample, which is determined by extrapolating the T_{max} to a zero field, is ~180 K. This observation can be treated as an indirect confirmation of the proposed model.

The temperature dependences of magnetoresistance of the films with d_{Cu} varying from 8 to 12 Å have a more complex pattern and contain two or three peaks, which can be attributed to the more complex structure of these samples. Most likely, they represent a multi-phase system, with each phase having its own Curie and Néel temperatures.

Such temperature anomalies characterized by a magnetoresistance peak were observed earlier in Ni/Cu films with thicker magnetic layers (~15 Å) in an in-plane magnetic field [4, 5]. This effect, however, is less clearly pronounced in them with the MR varying smoothly, and the peak not observed in all samples. We believe that the anomalies in the temperature dependence of MR are due to a substantial increase in the magnetic anisotropy at lower (below T_{max}) temperatures.

Thus, we have experimentally discovered an anomalous peak in the magnetoresistance of Co/Cu multilayer films with ultrathin Co layers, which is due to the existence of an antiferromagnetic ordering and corresponds to the Néel point. The dependence of the position of the peak on d_{Cu} exhibits an oscillatory character.

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REFERENCES

1. E. S. Mushailov, V. K. Maltsev, I. A. Turpanov, and P. D. Kim, J. Magn. Magn. Mater. **138**, 207 (1994).
2. P. D. Kim, Y. H. Jeong, I. A. Turpanov, *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **64** (5), 341 (1996) [JETP Lett. **64**, 370 (1996)].
3. S. V. Vonsovskiĭ, *Magnetism* (Nauka, Moscow, 1971; Wiley, New York, 1974).
4. L. D. Landau, Phys. Z. Sowjetunion **4**, 675 (1933).
5. H. Kubota, M. Sato, and T. Miyazaki, J. Magn. Magn. Mater. **167** (1), 12 (1997).

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