LOW-TEMPERATURE MAGNETISM

Magnetotransport properties of Er/Sc artificial multilayer structures

Yu. N. Chiang,[a] O. G. Shevchenko, and R. N. Kolenov

B. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, pr. Lenina 47, Kharkov 61103, Ukraine
(Submitted January 17, 2005; revised manuscript received April 13, 2005)
Fiz. Nizk. Temp. **31**, 1117–1124 (October 2005)

Comparative studies of the transport properties—resistance, magnetoresistance, and Hall effect—of Er/Sc multilayer structures and erbium films prepared by the same deposition technology are carried out for the first time. Those properties of the structures are modified substantially in comparison with those of elemental erbium. The magnetoresistance of the samples is "giant," although it cannot compete in absolute magnitude with the values for superlattices based on d ferromagnetic materials. In the region of helium temperatures the Hall coefficient in the multilayer systems is more than an order of magnitude greater than at room temperature. It follows from the data for the Hall coefficient and magnetoresistance in that temperature region that the zero-field magnetization of the f structure is greater than the magnetization of the bulk f material in the ferromagnetic state. The conductance of the Er/Sc multilayer structure at $T > 20$ K is lower than at helium temperatures. The features mentioned are described in terms of a temperature-induced rearrangement of the magnetic ordering of the erbium layers in the Er/Sc structures. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2128073]

Despite many years of effort there is still no complete understanding of how the concept of an exchange interaction due to correlation of the electron spins is compatible with the behavior of the kinetic characteristics of metals, which basically conforms to a description in terms of the simple approximations of band theory. However, progress in the technology of epitaxial film growth,[1] primarily films of transition d metals and rare-earth magnetic materials, have permitted a close approach to the experimental study of this problem, in particular, to the investigation of the role of exchange interaction mechanisms in establishing some magnetic structure or other and the manifestation of such an interaction, if it occurs, in the character of the electronic conductivity. Studies of multilayer systems with magnetic layers alternating with spacer layers of various nonmagnetic materials, metallic or nonmetallic,[2,3] grown by the aforementioned technology have revealed the novel possibility of artificially varying the magnetic characteristics of systems and observing the unusual, often contradictory, relationship of these characteristics to the behavior of the electron transport. For example, in multilayer systems of the FM/NM/FM type, where the ferromagnetic (FM) material is a transition d metal, a "giant" negative magnetoresistance is observed (up to 150% in Fe/Cr structures),[4–6] which is explained as a manifestation of an oscillatory exchange coupling through the nonmagnetic (NM) spacers. At the same time, a magnetoresistance (MR) of the same sign and of comparable magnitude ($\approx 20\%$) has been observed in a nonlayered magnetically inhomogeneous material,[7] and in multilayers in which the magnetic phases are rare-earth f metals (for which, unlike d metals, the magnetism and transport can be reasonably attributed to different groups of charge carriers) a positive MR$\approx$30% has been observed.[8] In studying the features of the transport properties of magnetic systems it is customary to rely on the well-tried concept of spin-dependent scattering of conduction electrons in the theory of the Ruderman–Kittel–Kasuya–Yosida (RKKY) indirect exchange interaction,[9–11] the experimental justification of which continues to be extremely topical, especially for rare-earth ferromagnets.

The fact that there are no reasons for the appearance of direct magnetic coupling between atoms in rare-earth metals makes them interesting objects for studying the nature of the magnetic ordering as such and, in particular, as constituents of multilayer superlattices. At the same time, there have been very few studies of superlattices based on rare earths, and those have been mainly devoted to their magnetic properties without reference to their transport characteristics (exceptions are Refs. 8 and 12, for systems with Dy, Gd, and Nd).

In this paper we present the results of the first investigation of the magnetotransport properties of Er/Sc multilayer structures in combination with the results for Er prepared by the same deposition technology as the multilayers by the method of magnetron sputtering in an Ar atmosphere.

Figure 1 shows a diagram of the arrangement and nominal thicknesses of the deposited layers in the structures studied. The number of Er/Sc bilayers in each structure is also indicated. Mica was used as the substrates for the multistructures, while the polycrystalline Er sample, 920 Å thick, was deposited on sitall (pyroceramic). In sample No. 2 the bilayers in the growth direction c consisted of one Sc monolayer and three Er monolayers. Sample No. 3 contained two blocks—an upper block of 19 bilayers (two monolayers of Sc and five monolayers of Er) and a lower block of 20 bilayers (two monolayers of Sc and three monolayers of Er). The total volume of Er in the systems studied was not less than twice that of Sc, so that it was possible to compare the

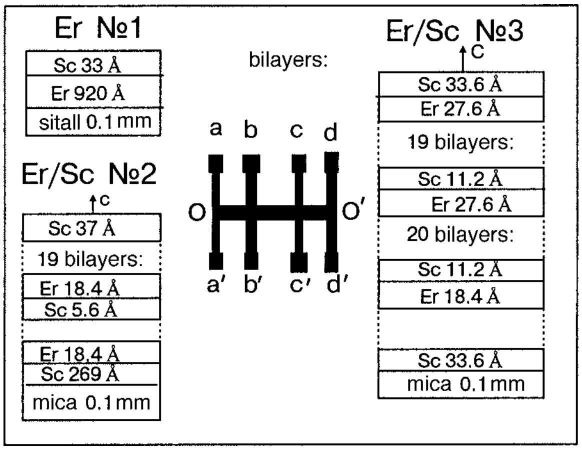

FIG. 1. Arrangement and thickness of the layers in the structures investigated.

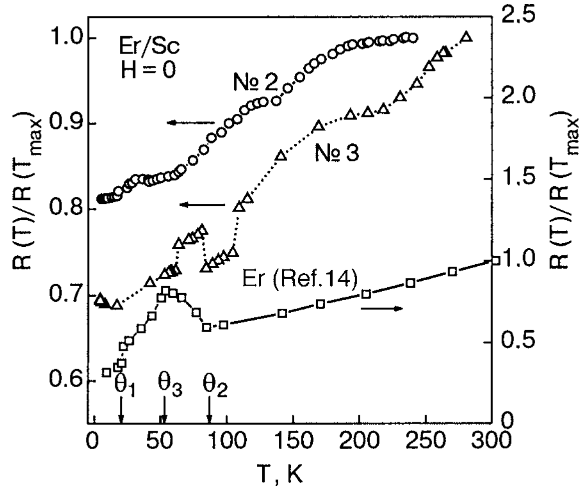

FIG. 2. Temperature dependence of the resistance of the O–O' region of samples Nos. 2 and 3, relative to the resistance at $T=240$ K (No. 2) and 280 K (No. 3). The arrows indicate the characteristic temperatures of the magnetic phase transitions in elemental Er: $\theta_1 \approx 20$ K; $\theta_2 \approx 84$ K; $\theta_3 \approx 54$ K.

transport properties of bulk erbium (sample No. 1) and the systems with discrete layers of nonmagnetic scandium intercalated in the matrix of magnetic erbium (samples Nos. 2 and 3).

The samples were deposited in the branched configuration shown in Fig. 1 for measurements of the resistance and Hall emf in the region O–O' by the standard 4-probe technique. A dc measuring current I from 10^{-2} to 1 mA was passed in the film plane along O–O'. Electrical connection to the samples was achieved by clamping plates of platinum foil to contact areas *a-d*, *a′-d′*.

It is known that the lattice constants of Er and Sc differ by 6% along the *c* axis and by 8% along the *a* axis, which obviously precludes obtaining superlattices with a single-crystal character over the whole volume of the sample, although in the samples studied the layers of magnetic Er and nonmagnetic Sc form a quasiperiodic structure. The values of the room-temperature resistivity ρ_{Er} and ρ_{Sc} obtained for a parallel connection scheme turned out, in the case of sample No. 2, to be comparable to the known values for polycrystalline materials[13] ($\simeq 100\ \mu\Omega\cdot$cm and $\simeq 60\ \mu\Omega\cdot$cm, respectively), while for sample No. 3 they were several times smaller ($\leqslant 20\ \mu\Omega\cdot$cm and $\simeq 10\ \mu\Omega\cdot$cm, respectively), as for very pure materials.[14] The resistivity ρ_{Er} estimated from the measurements for sample No. 1 was close to the value indicated above for the high-resistivity sample No. 2. Since the growth of these artificial superlattices can be regarded as the insertion of a foreign material (Sc) into an initially homogeneous material (Er), and the creation of such a defect structure generally speaking cannot in itself *improve* the conductivity of the system, the difference in the conductance of two samples obtained by the same technology already points to causes other than simple scattering on defects for the change in character of the transport in the structures studied, even in zero magnetic field.

Figure 2 shows the temperature behavior of the resistance relative to its value at room temperature for samples Nos. 2 and 3. The character of the anomalies of this behavior in the structures studied and the temperature regions where they are manifested correlate with the known features of the temperature dependence of the resistance of elemental erbium. It has been established that such features are due to a rearrangement of the magnetic structure of erbium, i.e., to transitions from the paramagnetic state to an antiferromagnetic state (temperature θ_2) and further to a ferromagnetic state (at θ_1) as the temperature is lowered.[14–18] The temperature θ_3 corresponds to a rearrangement of the structure in the antiferromagnetic region from a sinusoidal to a cycloidal phase.[16,17]

The connection between the changes in character of the transport and the changes of the magnetic structure should be manifested most clearly when an external magnetic field, even a very weak one, is applied, since the magnetic energy required for the formation of a nonzero magnetization is low, and in certain materials there is even a partial spontaneous magnetization in the absence of external field. Figures 3–8 show the results of measurements of the MR and Hall effect in our samples at fields up to 7 kOe.

Figure 3 shows a three-dimensional projection of the temperature dependence of the transverse MR of erbium (sample No. 1), i.e., the relative change of the resistance

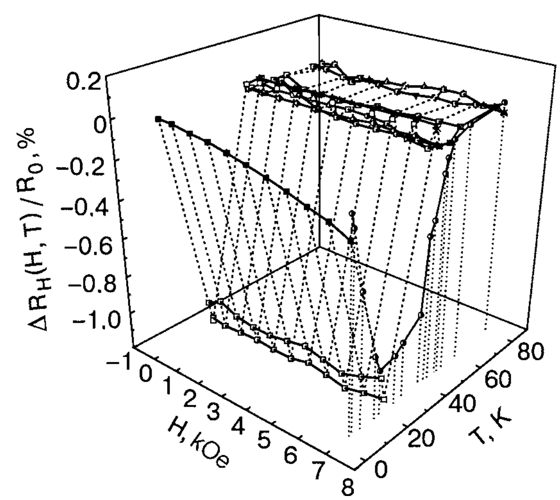

FIG. 3. Temperature-field curves of the magnetoresistance of the erbium film.

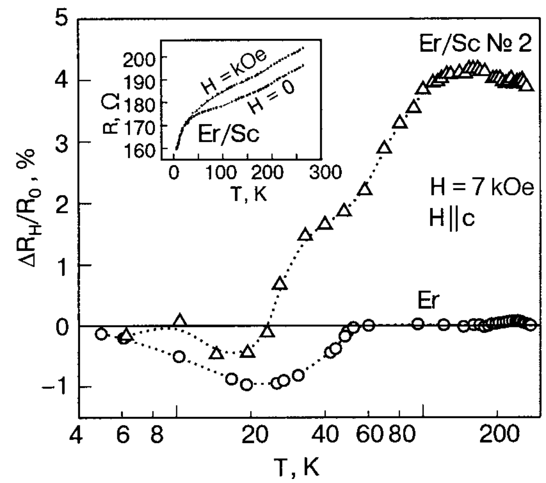

FIG. 4. Temperature dependence of the magnetoresistance of erbium and of an Er/Sc multilayer system. The inset shows the resistance of the system as a function of temperature in the absence of magnetic field and in a field of 7 kOe.

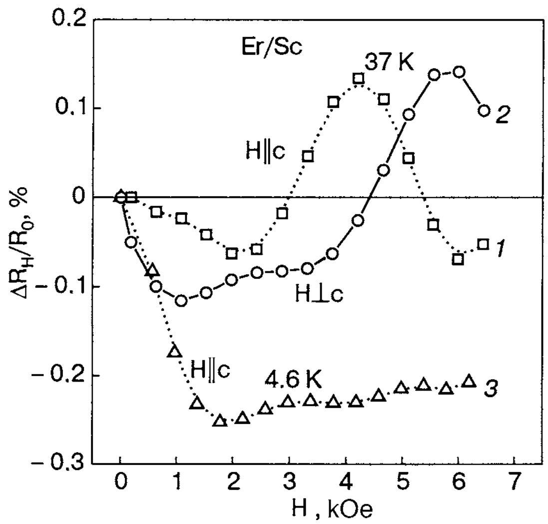

FIG. 6. Transverse (curves *1,3*) and longitudinal (curve *2*) MR of the Er/Sc system versus magnetic field at temperatures above and below θ_1.

$\Delta R_H(H,T)/R_0(T)=(R_H(T)-R_0(T))/R_0(T)$, for external magnetic fields varying from 500 Oe to 7 kOe and temperatures from 4.6 to 80 K in comparison to the resistance at zero field (in the geometry $\mathbf{H}\|\mathbf{c}$). It is seen immediately that the change of the MR first, is intimately related to the characteristic temperatures of magnetic ordering in erbium (indicated in Fig. 2), and, second, in the region below θ_3 it is negative, corresponding to an increase of the conductance. In the temperature region 10–50 K the MR undergoes a strong change at fields of only about 1 kOe $[(\Delta R/R(T=23.5\text{ K})\ \approx -1\%]$, after which it varies weakly with magnetic field. We note that this accords with the small value given in Ref. 19 for the magnetization saturation field corresponding the to ferromagnetic ordering of erbium.

Figure 4 shows the temperature dependence of the MR of erbium over a wider temperature interval—from helium to room temperatures—for a field value of 7 kOe; the character of this curve is typical for other fields in the interval 0.4–7 kOe. From a comparison of this curve with the temperature behavior of the MR of a multilayer sample, also shown in the figure, it follows that the character of this behavior in the Er/Sc structures is substantially different: the MR is positive and decreases with decreasing temperature from a value of +4% at 300 K down to 0 at ≈23.5 K, where it changes sign. The values of the parameter $\omega\tau$, which determines the efficiency of the magnetic field, did not exceed 10^{-4}–10^{-3} in the whole range of temperatures and fields both in the case of erbium and for multilayer structures. Such values correspond to the low-field regime, in which the variation of the usual MR $(\Delta\rho_{xx}/\rho_0)$ cannot exceed a fraction of a percent. Thus we can consider the value of the positive MR of the Er/Sc structure observed in the interval 50–250 K to be "giant." Attempts to explain the appearance of a positive MR, e.g., by the possibility that the degree of specularity of the reflection at the interfaces is decreased by a transverse magnetic field, as was proposed in Ref. 8, are unfounded, especially in our case, when the MR does not increase with decreasing temperature, as in the Dy/Sc superlattice,[8] but rather decreases. We shall show that there are no other reasons for such unusual behavior of the MR

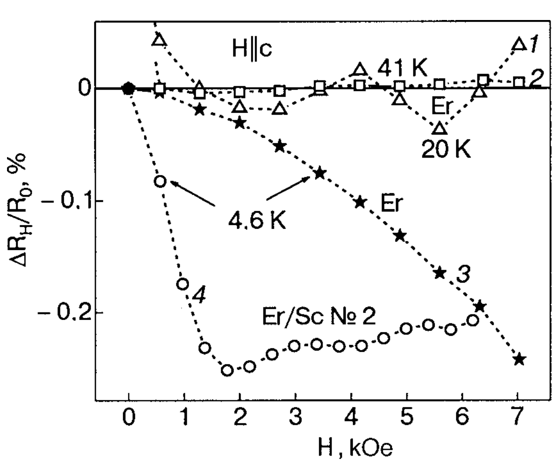

FIG. 5. Transverse magnetoresistance of erbium and of an Er/Sc system versus the magnetic field: *1,2,3*—MR of erbium at 20, 41, and 4.6 K, respectively; *4*—MR of the Er/Sc system at 4.6 K. Curves *1* and *2* are displaced along the vertical by +1%.

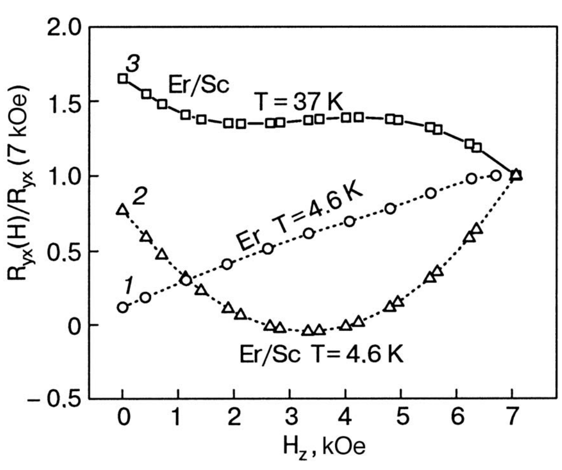

FIG. 7. Hall resistance of erbium (*1*) and of the Er/Sc multilayer structure (*2,3*) as a function of magnetic field in comparison with its value for H =7 kOe.

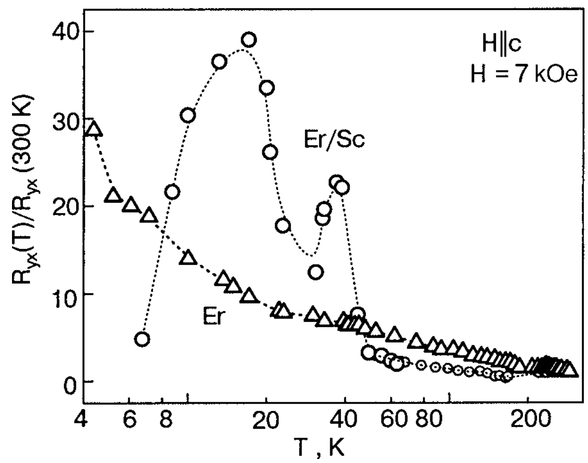

FIG. 8. Temperature dependence of the Hall resistance of the Er film and of an Er/Sc structure.

except for changes of the magnetic structure of the Er/Sc multilayer system in comparison with the magnetic structure of bulk erbium.

Despite the fact that the influence of magnetic field on the behavior of the transport properties of the systems under study is substantially weaker than the influence of temperature, which brings about a rearrangement of the magnetic structure, such a rearrangement should be reflected most fully in the character of the field dependences, and that is what our experiment shows.

Figure 5 shows the dependence of the MR on the magnetic field H for Er at 41, 20, and 4.6 K and for the Er/Sc structure at 4.6 K, and Fig. 6 shows the dependence on H of the transverse MR of the structure at temperatures of 37 and 4.6 K and of the longitudinal MR of the structure at $T=37$ K (curves *1*, *2* in Fig. 6). Furthermore, at helium temperatures 4.2–4.6 K the dependence of the MR of the system on H has a inflection point at around 1.5 kOe (curve *4* in Fig. 5), which is absent on the curve for erbium (curve *3*). This last curve also shows no tendency toward saturation, as does the dependence of the Hall coefficient of Er in the whole field interval investigated at these same temperatures (Fig. 7, curve *1*). In other words, the inflection point on the field curve MR(H) for the multilayer structure arises at a lower field than the field of complete saturation of the magnetic moment in the erbium layers.[19] A similar situation was encountered, in particular, in a study of the Co/Au system, where anomalies in the behavior of the MR were also observed at fields much less than the saturation field.[20]

It is natural to suppose that this disagreement may be due to the spin-dependent nature of the scattering of conduction electrons by magnetically ordered layers. In that case the contribution to the resistance from scattering by a pair of magnetic layers separated by a nonmagnetic spacer becomes dependent on the mutual orientation (parallel or antiparallel) of the magnetization vectors at the boundaries of the spacer.[4,21,22] In particular, under otherwise equal conditions for all the interfaces and under the usual assumption that the orientation of the spin of a conduction electron antiparallel to the moment of the magnetic layer [the so-called "minority" (↓) orientation] corresponds to more efficient electron scattering than the parallel ["majority" (↑)] orientation, the value of the conductivity and the corresponding sign of the MR in the multilayer structure will depend on the ratio of the number of pairs of boundaries (the number of nonmagnetic layers) with the same or with a different mutual orientation of the moments of the adjacent magnetic layers.

Most likely this ratio cannot in principle be equal to unity, either by virtue of the smallness of the phase coherence length of the moments with respect to the thickness of the structure, as is apparently the case for our high-resistivity samples, or because of the presence of more than one period of the oscillatory exchange coupling,[23] if such a case is realized at all in systems with rare-earth magnetic metals.

We shall therefore assume that the negative sign of the MR of the Er/Sc structure and the inflection point on its H dependence in the region of helium temperatures reflect a change of the orientation of the moments of a number of magnetic layers of erbium at a rather low field in the direction toward establishment of a ferromagnetic orientation, which in the case of a spin-dependent character of the scattering of conduction electrons can lead to an increase of the conductance of the multilayer structure as a whole. Here the behavior of the Hall resistance with change in magnetic field and the presence of a minimum on the $R_{yx}(H)$ curve (Fig. 7) attests to the existence of a remanent magnetization M_0 of the system in zero field and, accordingly, of a magnetization component M_{0z} perpendicular to the film ($\| c$), which varies with temperature because of the temperature-dependent rearrangement of the magnetic structure, including in the region of helium temperatures. The data in Fig. 7 can be used to estimate the ratio of the remanent magnetizations of the multilayer system Er/Sc in the "quasiferromagnetic" and "quasiantiferromagnetic" temperature regimes from the values of the measured Hall voltage at $H=0$.

The measured Hall resistance for a magnetic system is customarily written in the form

$$R_H = R_{yx} = \frac{U_{yx}}{I_x} = \frac{1}{d}[R_0 H_z + R_s 4\pi M_z],$$

$$R_0 = \omega\tau\frac{\rho}{H_z}, \quad R_s = C_1\rho + C_2\rho^2, \tag{1}$$

where d is the thickness of the sample, R_0 and R_s are the normal and anomalous Hall constants, respectively, M_z is the transverse component of the magnetization, ρ is the resistivity, and C_1 and C_2 are constants. At low fields M_z depends linearly on the field, and one can therefore write $M_z=\chi_z H_z + C_3\chi_{0z}$ (χ_0 is the susceptibility in the absence of magnetic field). It follows from Fig. 2 that the variation of ρ for erbium in the interval from 4.2 to 37 K does not exceed 2%. Ultimately, the corresponding ratios of the Hall resistance at $H=0$ from curves *1* (37 K) and *2* (4.6 K) for the multilayer structure and curve *3* (4.6 K) for Er (Fig. 7), according to (1), is

$$\left.\frac{R_{H=0}(T>\theta_1)}{R_{H=0}(T<\theta_1)}\right|^{\mathrm{Er/Sc}} = \frac{\chi_0(T>\theta_1)}{\chi_0(T<\theta_1)} \simeq 2;$$

$$\left.\frac{R_{H=0}^{\mathrm{Er/Sc}}}{R_{H=0}^{\mathrm{Er}}}\right|_{T<\theta_1} = \left.\frac{\chi_0^{\mathrm{Er/Sc}}}{\chi_0^{\mathrm{Er}}}\right|_{T<\theta_1} = 6-14.$$

Thus our data indicate that the conductance of the Er/Sc system studied is extremely sensitive to rearrangement of the magnetic structure even at comparatively low magnetic fields of around 1 kOe, which is suggestive of incomplete ordering of the magnetic moments of the layer in all the temperature regions characteristic for the magnetic structures of elemental Er and of small values of the magnetic energy required for reorientation of the moments in the erbium layers in the multilayer samples. It is possible that this last circumstance explains the positive MR of the structure (up to 4% at 300 K; Fig. 4): in the paramagnetic region of uncorrelated erbium layers in the multilayer samples a magnetic field, by ordering the moments in the Er layers and turning on the contribution from scattering on the pair of interfaces of the nonmagnetic layer, with antiparallel (though asymmetric in value) moments of the Er layers adjacent to these interfaces, causes an increase of the resistance of the multilayer system as a whole. With decreasing temperature and the transition to a more ordered distribution of moments in the Er layers and at the interfaces, the conductance of the Er/Sc structure grows (see the inset in Fig. 4), and that leads to vanishing of the positive MR. That the observed temperature dependence of the MR is unrelated to the dependence on the parameter $\omega\tau$ attests both to the estimate of that parameter given above and the identical nature of the slopes of the $R(T)$ curves for $H=0$ and $H\neq 0$ (inset to Fig. 4).

The causes of the negative MR in the Er film $(\Delta R/R)_{\max}\approx -1\%$ in a certain region of the nonferromagnetic state (Fig. 4) is apparently due to inhomogeneity of the structure of our film, in particular, to a specific distribution and interaction of local magnetic moments in a magnetic field.

The comparative data on the behavior of the conductance of the investigated Er/Sc structures and of a continuous erbium film in the absence and presence of magnetic field allows one to judge the following circumstances.

First, according to the Hall coefficient measurements the magnetization of a multilayer system in the absence of field is substantially nonzero and differs from the magnetization of a continuous erbium film under the same conditions; this must indicate that the very fact that interfaces are present plays a role in the change of the transport characteristics of the system in comparison with those of an nonlayered rare-earth material. Second, in certain temperature regions these changes are manifested anomalously, which indicates that they are related to both the type of magnetic structure of the f layers, which is temperature dependent, and to the character of the distribution of the directions of the moments of these layers in the system, which determines the value of the total magnetic moment of the system as a whole. This means, in particular, that in the case of a uniform distribution of moments in each individual magnetic layer a change of the total magnetic moment is possible only upon the establishment of a distribution of orientations of the moments of the magnetic f layers at the interfaces with the nonmagnetic layers of the multilayer system which does not average out.

In turn, because of the weak (or completely absent) direct exchange interaction of the $4f$ layers in rare-earth metals, the orientation of the moments at the interfaces can be reflected in the character of the conductance of the Er/Sc structure through a spin-dependent coupling with the conduction electrons of the nonmagnetic scandium spacers, whereas in elemental erbium such a coupling can be realized only through the f–s spin-orbit interaction at the ions. The idea of a spin-dependent mechanism of interaction of the magnetic layers of the system leads immediately to dependence of the scattering efficiency at the interface on the mutual orientation of the electron spin in the nonmagnetic layer and the moment in the f layer. Under otherwise equal conditions a large change of conductance is given by the antiparallel and not by the parallel orientation of the moments on opposite interfaces of the nonmagnetic layer: the value of the MR is larger in the antiferromagnetic region than in the ferromagnetic region.

The overall trend of the Hall resistance R_{yx} in the multilayer system with temperature in the ingerval 4.2–300 K (Fig. 8) demonstrates anomalously large changes of this characteristic in the region where the rearrangement of the magnetic structure from antiferromagnetic to ferromagnetic occurs. The character of these changes corresponds to second-order phase transitions.

Thus we have made the first comparative studies of the transport properties—the resistance, MR, and Hall effect—of Er/Sc multilayer structures and elemental erbium, prepared by the same deposition technology. The indicated properties of the multilayer systems are modified substantially in comparison with those same properties of elemental erbium. The MR becomes "giant," although in absolute magnitude it cannot compete with the values realized in superlattices based on the d ferromagnetic materials Fe and Co.

In the region of helium temperatures the Hall coefficient in the Er/Sc system reaches values more than an order of magnitude greater than the value at room temperature. It is found that the features of the transport and Hall coefficient in the investigated multilayer systems are correlated with the concepts of a temperature-dependent rearrangement of the magnetic ordering of the erbium layers and a spin-dependent mechanism of scattering of the conduction electrons.

Without invoking the magnetic measurements it is shown that the magnetization of the f structure in zero field is higher than the remanent magnetization of the f material in the ferromagnetic state, while the conductance of the Er/Sc structure in the proposed region of the antiferromagnetic state of the erbium layers is lower than the conductance in the ferromagnetic state of the same layers.

We are grateful to Prof. S. Oseroff (San Diego State University) for providing the rare-earth metal targets and to A. N. Stetsenko and V. V. Zorchenko (National Technical University "KPI") for preparing the Er films and Er/Sc multilayer systems.

[a)]E-mail: chiang@ilt.kharkov.ua

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Translated by Steve Torstveit