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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (26 April 1995)

A scientific session of The Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 26 April 1995 at the P L Kapitza Institute of Physics Problems. The following papers were presented at the session:

(1) **Antipov E V** (Institute of Radioelectronics, Russian Academy of Sciences, Moscow) "Superconducting complex copper oxides";

(2) **Gusev S A, Nozdrin Yu N, Rozenshtein D B, Tetel'man M G, Fraerman A A** (Institute of Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod) "Magnetic reorientational transition in multilayer Co/Pd structures".

A brief summary of the second paper is given below.

PACS numbers: 75.70.Cn; 75.50.Rr; 75.30.Kz

Magnetic reorientational transition in multilayer Co/Pd structures

S A Gusev, Yu N Nozdrin, D B Rozenshtein, M G Tetel'man, A A Fraerman

We shall present the results of an investigation of thermodynamics of multilayer structures consisting of ultrathin magnetic films separated by nonmagnetic spacers. The interest in ultrathin magnetic films is due to their quasi-two-dimensional properties such as an anomalously low Curie temperature, surface anisotropy, and others. One of these properties is a spin reorientational transition induced by temperature variation. This reorientational transition has been predicted for two-dimensional magnetic materials [1, 2]. The phase diagram, in which the anisotropy of a two-dimensional Heisenberg magnetic material is plotted against temperature (Fig. 1), shows that for some values of the initial (at $T = 0$) anisotropy a transition to a paramagnetic state is preceded by a transition from a uniaxial to a planar phase at a temperature T_r.

This spin reorientational transition had been observed experimentally for some ferromagnetic films [3 – 5]. Another class of objects in which quasi-two-dimensional properties can appear are multilayer structures, which are interesting because of their potential practical applications. In particular, the Co/Pd system is a promising material for superdense thermomagneto-optical data storage [6]. An increase in the data storage density requires perpendicular (to the surface) orientation of the magnetic moment in the carrier medium. However, such orientation is unfavourable from the energy point of view because of the appearance of demagnetising fields. Therefore, it is necessary to create in this carrier medium an anisotropy exceeding the demagnetising field. In multilayer Co/Pd structures this anisotropy does exist and it is due to the properties of the interfaces between the layers (interface anisotropy) [7]. The effective anisotropy, which includes the interface and magnetic-dipole contributions, is inversely proportional to the Co film thickness and is positive (of the easy-axis type), as found experimentally for films less than 1 nm thick [8]. A strong magneto-optical effect is governed by the sum of the contributions of the separate films across the skin layer thickness. An important feature of the Co/Pd structure is a considerable lowering of the Curie temperature, which makes it possible to use low-power lasers for thermal data storage. This lowering of the Curie temperature is attributed to the two-dimensional nature of the magnetic order in these systems [9]. In spite of a large number of the reported experimental investigations of the properties of Co/Pd multilayer structures, there has been as yet no investigation of the reorientational transition in this system.

We investigated the temperature dependence of the effective magnetic anisotropy of Co/Pd magnetic multilayer structures with the aim of determining whether a

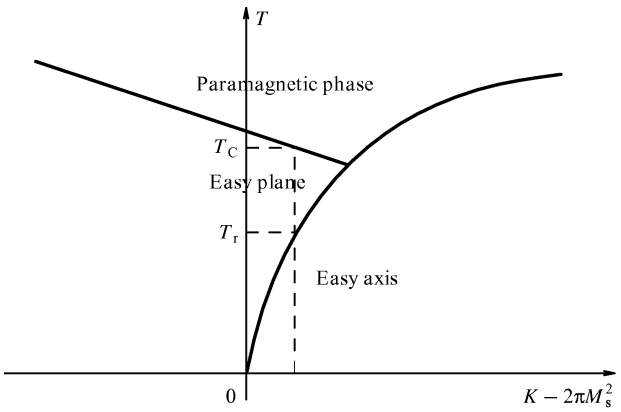

Figure 1. Phase diagram, taken from Ref. [1], in which temperature is plotted against the anisotropy of a two-dimensional Heisenberg magnet. Here, T_r is the temperature of the reorientational transition, T_C is the Curie temperature, K is the anisotropy constant, and M_s is the saturation value of the magnetic moment.

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reorientational transiton of this kind occurred in such structures. This was done by preparing a batch of samples with a fixed Pd layer thickness ($\sim$3 nm) and with the Co layer thicknesses varying in the range 0.5 – 3 nm. The total thickness of a structure was $\sim$100 nm. These structures were grown by the method of magnetron sputtering in an Ar atmosphere on smooth (surface roughness $\sim$0.4 nm) silicon substrates by alternate deposition of Co and Pd films. The residual gas pressure in the growth chamber did not exceed 10^{-4} Pa before this deposition procedure. In the course of deposition, the Ar pressure rose to 0.5 Pa. The sputtering was carried out with the aid of magnetron sources of 60 – 80 W power, which ensured that the film growth rate was 0.1 – 0.2 nm s^{-1}.

The period and the thickness of these structures were determined by low-angle x-ray diffraction at the wavelength 0.154 nm. The period was found from the positions of the Bragg maxima. The concentrations of the separate elements were found by quantitative analysis based on the characteristic x-ray luminescence and carried out with the aid of a Link Analytical analyser, in combination with a JEM20000EXII electron microscope. The crystal structure of these multilayer samples was investigated by electron diffraction and transmission electron microscopy. All the samples were polycrystalline and the average grain size was 10 – 20 nm. In this way we obtained full information on the structure of the samples and the thickness of the films of which they were composed.

The magnetic properties were investigated by measuring the Hall resistance in the temperature range 4.2 – 400 K and by recording the ferromagnetic resonance (FMR) at temperatures 77 and 300 K. Fig. 2 shows typical hysteresis loops determined at various temperatures. At low temperatures the magnetisation loop was almost rectangular. The perpendicular magnetic moment in a sample magnetised to saturation was not affected by the magnetic field until the field reached the value $-H_a$. When temperature was increased, the field H_a decreased and it vanished at T_r. At temperatures $T > T_r$, the perpendicular magnetic moment was unstable in zero field, resulting in a considerable reduction in the residual magnetisation compared with the saturation value. (Here, H_a is the anisotropy field.) The temperature dependences of this anisotropy field, determined for samples with different thicknesses of the Co films, are presented in Fig. 3 [10]. Reversal of the sign of the anisotropy at T_r corresponded to reorientation of the magnetisation from the direction perpendicular to the films (at temperatures less than T_r) to the plane of the films (at higher temperatures). An increase in the thickness of the Co films reduced the temperature T_r.

Direct measurements of the effective anisotropy field were made by the FMR method in conjunction with a PS100.X ESR spectrometer operating at 9.45 GHz. Fig. 4 gives the angular dependences of the resonance field obtained for a sample in which the Co and Pd films were, respectively, 1 and 3.1 nm thick. The measurements were carried out at 77 and 300 K. The angle was measured from the plane films in a sample. The curve determined at 77 K represented the easy-axis magnetic anisotropy, whereas the curve recorded at 300 K corresponded to the easy-plane anisotropy. Therefore, a reorientational

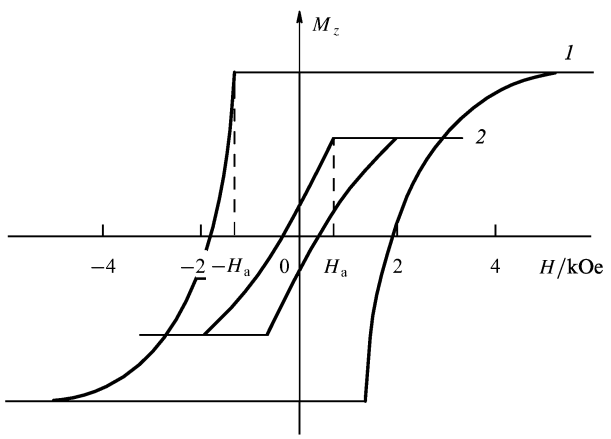

Figure 2. Hysteresis loops obtained for a sample consisting of 30 [0.5 nm Co/1.5 nm Pd] pairs, determined by the Hall method at 4.2 K ($T < T_r$, curve *1*) and 6 K ($T > T_r$, curve *2*). Here, H_a is the anisotropy field.

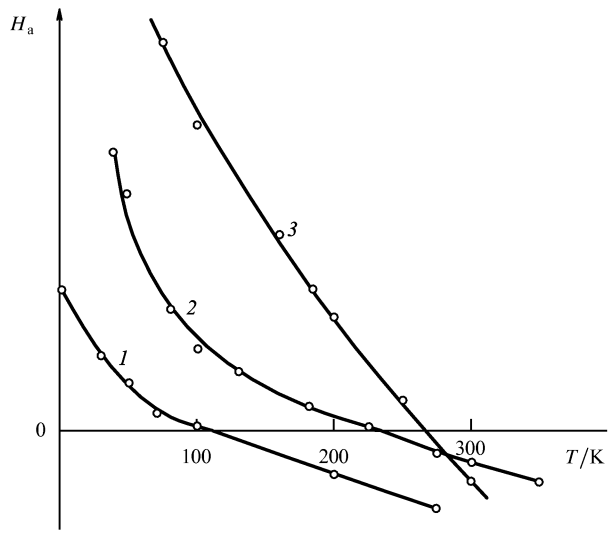

Figure 3. Temperature dependences of the anisotropy field of several samples, measured by the Hall method: (*1*) 30 [0.7 nm Co/2 nm Pd] pairs; (*2*) 30 [0.5 nm Co/1.5 nm Pd] pairs; (*3*) 30 [0.4 nm Co/1.4 nm Pd] pairs.

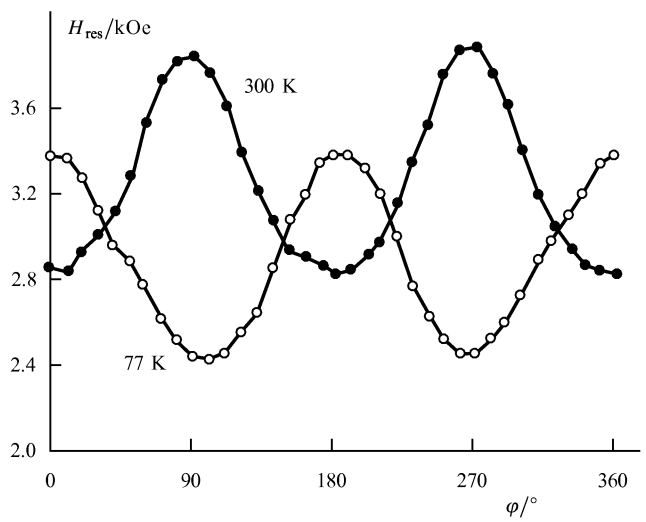

Figure 4. Angular dependences of the FMR field (H_{res}), determined for a sample with 30 [1 nm Co/3.1 nm Pd] pairs, at 77 and 300 K (φ is the angle between a static magnetic field and the plane of the sample).

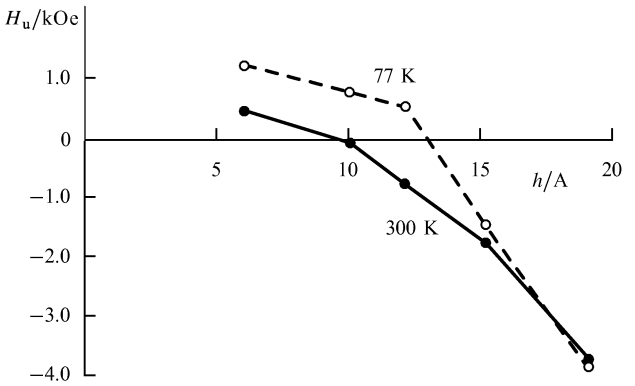

Figure 5. Dependences of the effective anisotropy field of a magnetic structure (H_u) on the thickness of Co films (h), measured at 77 and 300 K. The thickness of the Pd spacers was 3 nm.

transition took place at a tempera-ture 77 K $< T_r <$ 300 K. This effect was reversible, as checked by several cycles of measurements carried out at low and high temperatures.

The angular dependences of the FMR signal were analysed with the aid of formulas for a homogeneous resonance and the effective anisotropy fields were calculated. The dependences of the anisotropy fields of a multilayer structure on the thickness of the Co films, determined at 77 and 300 K, are presented in Fig. 5. The uniaxial anisotropy field increased on reduction in the Co film thickness, in accordance with the adopted model of the interface anisotropy of these systems. The anisotropy of the samples with thinner Co films was perpendicular to the film plane, whereas in the case of thicker Co films the multilayer structures had the easy-plane anisotropy. The sign of the anisotropy was a function of temperature: in the case of the samples with the Co film thicknesses 1.0 and 1.2 nm it was found that the easy-plane anisotropy was observed at room temperature and at 77 K the anisotropy was of the easy-axis type. Therefore, in the case of these samples a reorientational transition took place at 77 K $< T_r <$ 300 K [11].

The reorientational transition observed in multilayer structures was probably of the same nature as the transition in the individual films. However, this hypothesis applies only in the case of a weak coupling between the magnetic layers via nonmagnetic spacers.

The exchange coupling between the Co layers was estimated in the following experiment. A multilayer sample with a special structure was used: in this structure a unit cell consisted of two Co films of different thickness separated by Pd spacers (inset in Fig. 6). We could expect the magnetic properties of such a complex structure to be governed, under weak exchange conditions, by the properties of the two isolated subsystems of which this structure was composed. In particular, the difference between the values of the anisotropy in the subsystems (because of the different Co film thicknesses) should be detectable in FMR experiments. An FMR absorption curve should have two maxima corresponding to the two subsystems.

Structures of this type were prepared by the technology described above. The Co film thicknesses were 0.7 and 1.5 nm and the thickness of the Pd spacer was 2.5 nm. In the angular x-ray diffraction spectrum, plotted in Fig. 6, the first and second Bragg maxima had the same amplitudes, corresponding to a sample with the complex structure shown in the inset in Fig. 6. The existence of two peaks in the FMR spectra (Fig. 7) and the dependences of their positions on the orientation of a static magnetic field indicated that the exchange across the Pd spacer was weak. At the very least we could say that the field of the exchange interaction across the Pd spacer did not exceed the difference between the anisotropy fields of the two subsystems ($\sim$1 kOe) [12]. Therefore, the interaction between the two cobalt films was much weaker than the exchange field in one Co film.

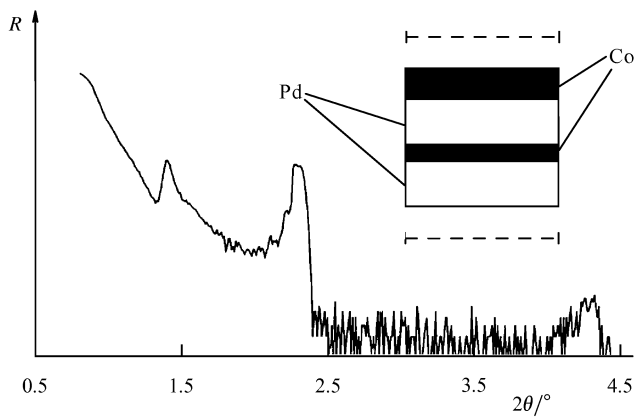

Figure 6. Spectrum of low-angle x-ray diffraction of a sample with a complex structure consisting of 30 [0.7 nm Co/2.5 nm Pd/1.5 nm Co/2.5 nm Pd] pairs. The inset shows a unit cell of this complex structure. Here, θ is the angle of incidence of x-rays.

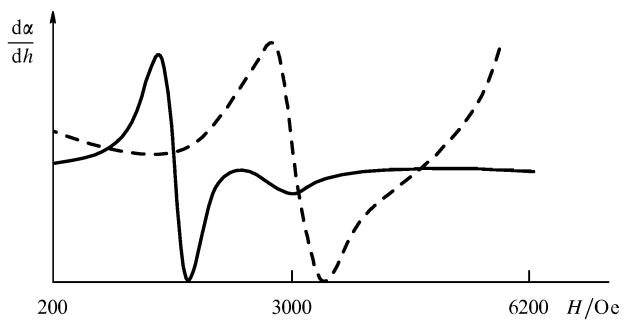

Figure 7. FMR absorption spectra of a sample with a complex structure, recorded in a magnetic field applied in the plane of the sample (continuous curve) and along the normal to the sample (dashed curve). H is the magnetising field and α is the absorption coefficient of microwave radiation (in relative units).

Our Hall and FMR measurements, carried out on a batch of Co/Pd multilayer structures at various temperatures, revealed that the effective anisotropy depended not only on the thickness of the Co films, but also on temperature. We could thus speak of the existence of a temperature-induced reorientational transition. Experiments in which we estimated the exchange coupling across the Co spacer indicated that the coupling was weak. This made it possible to regard a geometrically three-dimensional multilayer structure as quasi-two-dimensional and to suggest that the transition in such a structure was similar to that between isolated films.

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References

1. Tetel'man M G *Zh. Eksp. Teor. Fiz.* **98** 1003 (1990) [*Sov. Phys. JETP* **71** 558 (1990)]
2. Pescia D, Pokrovsky V L *Phys. Rev. Lett.* **65** 2599 (1990)
3. Pappas D P, Kamper K-P, Hopster H *Phys. Rev. Lett.* **64** 3179 (1990)
4. Allenspach R, Bischof A *Phys. Rev. Lett.* **69** 3385 (1992)
5. Kerkmann D, Pescia D, Allenspach R *Phys. Rev. Lett.* **68** 686 (1992)
6. Carcia P F, Meinhaldt A D, Suna A *Appl. Phys. Lett.* **47** 178 (1985)
7. Rozenshtein D B, Tetel'man M G, Fraerman A A *Poverkhnost'* **4** 15 (1993)
8. Engel B N, England C D, Van Leeuwen R A, et al. *Phys. Rev. Lett.* **67** 1910 (1991)
9. Bloemen P J H, SwuSste C H W, Poodt G J M, et al. *J. Appl. Phys.* **67** 4470 (1990)
10. Gusev S A, Nozdrin Yu N, Rosenshtein D B, et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **58** 35 (1993) [*JETP Lett.* **58** 36 (1993)]
11. Gusev S A, Fraerman A A, Rozenstein D B, et al. *Phys. Lett. A* **198** 437 (1995)
12. Sapozhnikov M V (Personal communication)