14th Czech and Slovak Conference on Magnetism, Košice, Slovakia, July 6–9, 2010

Electrical Resistance Anomalies in Holmium Thin Films below 20 K in Magnetic Field

J. Dudáš[a], S. Gabáni[b], V. Kavečanský[b], I. Gościańska[c] and J. Bagi[d]

[a]Dep. of Theoretical Electrotechnics and Electrical Measurement
TU, Park Komenského 3, SK-043 89 Košice, Slovakia

[b]Institute of Experimental Physics, SAS, SK-043 53 Košice, Slovakia

[c]Institute of Physics, A. Mickiewicz University, PL-61-614 Poznań, Poland

[d]Húskova 61, 041 11 Košice, Slovakia

Electrical resistance (R) of Ho thin films evaporated in vacuum $\approx 10^{-7}$ Pa was studied in a temperature range from 2 K up to 300 K and in magnetic field up to 9 T. Measurements showed resistance anomalies below 20 K — minima of R value in 36 nm and 215 nm thin films and resistivity maximum at 3.58 K in 215 nm Ho film. Increasing value of the magnetic field, applied perpendicular to film surface up to 5 T, caused increasing suppression of the R minima in these films with subsequent disappearance of them in fields above 5 T. Maximum of R value in 215 nm thin film at 3.58 K decreased with increasing flux density up to 5 T and it was suppressed at fields above 5 T. X-ray diffraction of these films revealed two phases composition consisting of the hexagonal Ho and of cubic HoH_2. The preferential crystal orientation of both phases was detected.

PACS numbers: 73.61.At, 75.70.Ak, 68.55.Nq

1. Introduction

Rare earth (RE) metallic thin films are attractive because of the wealth of their physical properties, the variety of magnetic structures including, and because of their potential in the technical applications [1]. But the intricate world of RE thin films connected with their reactivity as excellent getters for hydrogen, causes problems in interpretation of the studied properties. Study of electrical and magnetic properties revealed resistance anomalies of Ho and Tm films at low temperatures. Two of them at ≈ 20 K and at ≈ 120 K in Ho films are connected with magnetic structure changes, but the resistance minima observed below 20 K in Ho and Tm films were not connected with magnetic structure [2].

This paper is devoted to study of the R vs. T anomalies of Ho films below 20 K by means of the phase composition study and by the study of magnetic field influence on the electrical resistance.

2. Experimental

The investigated Ho films were prepared by evaporation onto glass substrates in vacuum at $\approx 10^{-7}$ Pa. The AC electrical resistance measurements were carried out between 2 and 300 K and in the magnetic field up to 9 T oriented perpendicular to the film surface. Four point contact method was realized by silver wires and paste on the surface of Ho films. Commercial PPMS-Quantum Design equipment was used for resistance measurements. Film thickness was measured using the optical Tolansky method. Crystal structure of Ho films was investigated by means of the X-ray diffractometry (in the Bragg–Brentano focusing geometry) with Co $K_{\alpha_{12}}$ β-filtered radiation ($\lambda = 0.17902$ nm).

3. Results and discussion

The R vs. T dependences of thin Ho films were investigated in the temperature range from 2 K up to 300 K and in magnetic field up to 9 T. The R vs. T dependence below 20 K is illustrated in Fig. 1 for 36 nm thin film. The shallow resistance minimum in zero magnetic field is clearly seen at $T = 8.62$ K. Minimum depth taken as $\Delta R = R_{4.2} - R_{\min}$ attains the value of 0.26 Ω in zero field. Increasing magnetic field up to 5 T caused increasing suppression of the resistance minimum with subsequent dissappearance of it in fields above 5 T. This is clearly seen in Fig. 2.

Investigation of the R vs. T dependence of 215 nm thin Ho revealed two resistance anomalies in zero magnetic field below 20 K — a shallow resistance minimum at 16.19 K and a resistance maximum at 3.58 K. The depth of this minimum $\Delta R = R_{4.2} - R_{\mathrm{m}}$ attains the value of 0.99 Ω in zero field. Increasing suppression of the resistance minimum with increasing magnetic field up to 4 T was observed. The resistance minimum disappeared in fields above 4 T, which is illustrated in Fig. 2. Increasing

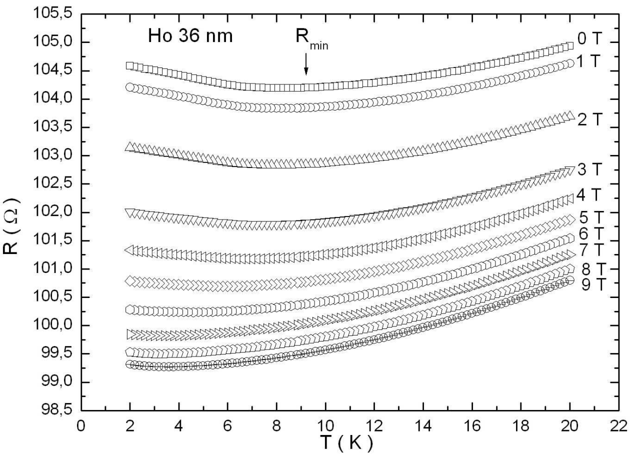

Fig. 1. The R vs. T dependence of 36 nm thin Ho film in the temperature range from 2 K up to 20 K in magnetic field with magnetic flux density up to 9 T.

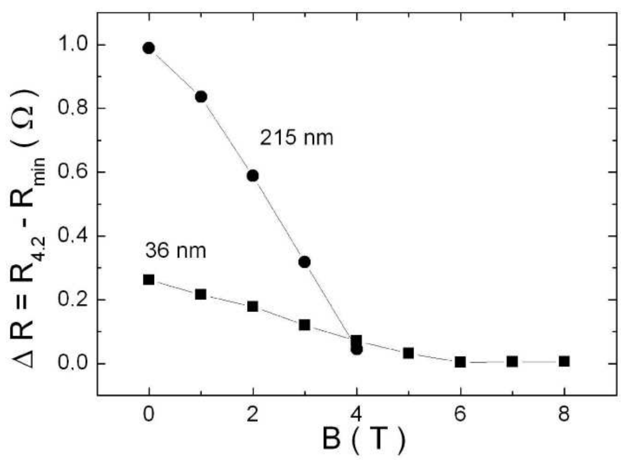

Fig. 2. The resistance minimum depth $\Delta R = R_{4.2} - R_{\min}$ vs. B curves for 36 nm and 215 nm thin holmium films.

magnetic field caused suppression of the resistance maximum value and its disappearance in fields above 4 T.

The X-ray diffraction (XRD) of these films revealed two phases composition consisting of the hexagonal Ho (space group $P6_3/mmc$) and of cubic holmium dihydride HoH_2 ($Fm3m$). The result of this investigation is illustrated in Fig. 3 for 215 nm Ho film. Analysis of the X-ray diffraction pattern for 215 nm thin Ho film revealed that the dominant phase in the sample is HoH_2 ($a = 0.51663(2)$ nm) and minority one the hexagonal Ho phase ($a = 0.3612(2)$ and $c = 5.6663(9)$ nm). Both phases show a preferred orientation. This two-phase composition was also detected in 36 nm thin Ho film.

The resistance is caused by various scattering mechanisms of conduction electrons which limitate the electron mean free path. These mechanisms are temperature dependent as electron–phonon and electron–spin scattering

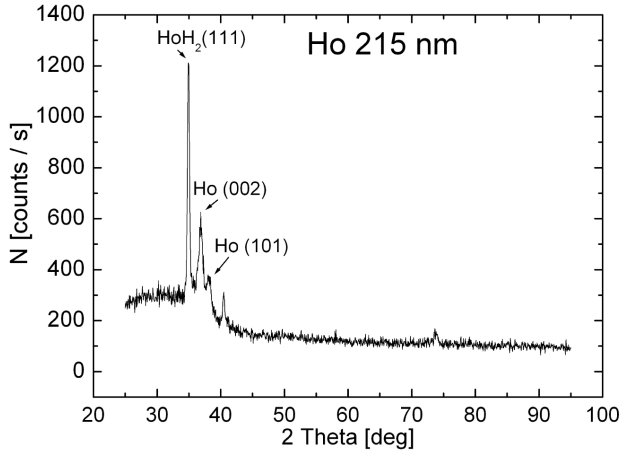

Fig. 3. The X-ray diffractogram of 215 nm thin holmium film.

and temperature independent (caused by chemical and physical impurities, film surface limits, rough surfaces, grain boundaries). We assume that the observed $R(T)$ anomalies in our Ho films below 20 K are caused by the HoH_{2+x} phase with various x content of H atoms. It is known that solubility of H in Ho is up to ≈ 0.03 (at.H/R) (α phase) and excess H atoms form the HoH_2 (β phase) where H atoms occupy ideally all available tetrahedral interstitial sites [3]. Excess H atoms play an essential role modifying the magnetic and transport properties of the system which can change the crystal-field symmetry and introduce new magnetic structures.

Neutron diffraction revealed modulated incommensurate antiferomagnetic structure below 6.3 K coexisting with commensurate antiferromagnetic one below 4 K [4]. Unusual resistivity minimum at 23 K was observed in dihydride HoH_{2+x} with $x = 0$ and was attributed to magnetic fluctuations or to gap opening between new magnetic superzones caused by incommensurate structure. Varying x concentration in low $x < 0.03$ region the R vs. T curves of HoH_{2+x} showed several local resistance maxima below 8 K and resistance minima near ≈ 10 K connected with the evolution of the magnetic transitions [3]. We assume that the resistivity maximum at 3.58 K and resistivity minimum at 16.19 K in our 215 nm thin film could be attributed to the conduction electron scattering on magnetic spins of HoH_{2+x} phase in low-x region.

The R vs. T curves of HoH_{2+x} sample with $x = 0.08$ showed a smooth decrease of resistance value with increasing temperature from 1.3 K to 8 K for $x = 0.08$ [3]. The smooth decrease of resistance value in the temperature interval from 2 K to 8.62 K and resistivity minimum at 8.62 K in our 36 nm Ho film supports the idea of higher than $x = 0.03$ concentration of H atoms in HoH_{2+x} phase of our film. We assume that the observed resistance minimum is caused by this HoH_{2+x} phase.

Applied magnetic field causes the reorientation of magnetic spins of magnetic phases. The increasing suppression of the resistance minima in 36 and 215 nm Ho films and that of resistance maximum in 215 nm film with increasing magnetic field, applied perpendicular to the film surface, was caused by increasing reorientation of magnetic spins of the ordered HoH_{2+x} phases in the direction of external magnetic field. Disappearance of the observed resistance anomalies in fields above 5 T suggests the idea that magnetic moments of HoH_{2+x} phases are oriented in the direction of magnetic field.

4. Conclusions

It follows from the investigation of Ho thin films in the temperature range below 20 K: (1) The X-ray diffraction of these Ho films revealed two phases composition consisting of the hexagonal Ho (space group $P6_3/mmc$) and of cubic holmium dihydride HoH_2. Both phases of studied films show significant preferred orientation. (2) Electrical resistance measurements revealed resistance minima at 8.62 K in 36 nm and at 16.19 K in 215 nm Ho thin films and resistance maximum at 16.19 K in 215 nm film which are caused by the HoH_{2+x} phase. (3) Increasing magnetic field caused suppression of resistance maximum and resistance minima in fields up to 5 T and their disappearance in fields above 5 T.

References

[1] P. Grünberg, *Acta Mater.* **48**, 239 (2000).

[2] J. Dudáš, M. Guzan, S. Gabáni, V. Kavečanský, K. Flachbart, M. Konč, I. Gościańska, *Czech. J. Phys.* **54**, Suppl. D, 253 (2004).

[3] J.N. Daou, P. Vajda, *Phys. Rev. B* **50**, 12 635 (1994).

[4] P. Vajda, G. André, O.J. Zogal, *Phys. Rev. B* **57**, 5830 (1998).