INFLUENCE OF MAGNETIC FIELD ON ELECTRIC CHARGE TRANSPORT IN HOLMIUM THIN FILMS AT LOW TEMPERATURES

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Abstract. *High precision electrical resistance measurements were performed in the low temperature range from 4,2 K up to room temperature on a holmium bulk sample, and on holmium thin films in magnetic field. The X-ray diffraction of Ho films confirmed their preferential crystal orientation and revealed diffraction peaks originating from the h.c.p. structure of Ho and those from inessential holmium dihydrid content. The T_N value of these films decreased with decreasing film thickness. Magnetic field applied parallel to the thin film plane caused an increasing suppression of the T_N value up to 5 K with increasing flux density value up to 5 T.*

Keywords

Holmium thin films, electrical resistance, low temperatures, Néel temperature, X- ray diffraction.

1. Introduction

Magnetic and transport properties of magnetic metallic 3d and 4f films exhibit a considerable renascence since the discovery of the spin polarized transport in multilayered ferromagnetic/nonmagnetic structures. Observation of a new magnetic phenomena such as the giant magnetoresistance are attractive for technical applications. The intense activity in this area is driven, in part, by needs of magnetic recording and other applications [1]. Sophisticated thin-film deposition techniques transformed the discovery of the spin polarized transport (GMR) in a billion-dollar business within a decade of its discovery.

Size effects may produce relevant modifications in the known magnetic phases of RE elements because of the nonuniform magnetic structure induced by the lower coordination near the surface. It has been shown, that the reduced coordination near surfaces may favor the nucleation of the helifan phase [2].

The intricate world of rare earth thin films is connected with the reactivity of the lanthanides. They are excellent getters for hydrogen and they can absorb $(OH)^-$ radicals causing problems in interpretation of the studied properties (see e.g. [3], [4]).

We concentrated in this paper to Ho thin films. Being paramagnetic at room temperature, holmium orders antiferromagnetically below the Néel temperature T_N = 130 K into the basal-plane spiral. At T_C = 20 K the spiral changes to a cone-shaped structure [5]. As for Ho films, thickness effects on magnetism, on magnetic ordering temperatures, on magnetoelastic stresses and electric charge transport anomalies were studied in the last time [6], [7], [8], [9].

We report on the influence of film thickness and magnetic field on the electrical resistance and on magnetic phase transitions in Ho thin films and we support interpretation of the observed resistance anomalies providing the experimental evidence by the X-ray diffraction.

2. Experimental

Holmium thin films were prepared by evaporation in vacuum at ~ 10^{-7} Pa onto glass substrates. The conventional four-point dc arrangement was used to measure the electrical resistance of bulk Ho and thin film samples in the temperature range from 4,2 K up to room temperature using a digital Keithley programmable

current source K 220 and a Keithley digital nanovoltmeter K181. The resistance was measured in zero magnetic field and in magnetic field parallel to the direction of electrical current below 150 K with magnetic flux density up to 5 T.

The temperature of the bulk and thin film samples in the helium cryostat was measured using calibrated Ge (from 4,2 K to 80 K) and Pt (from 80 K to room temperature) thermometers.

Film thickness was measured using the optical Tolansky method.

The 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 (λ = 0,17902 nm).

3. Results and Discussion

The electrical resistance of the holmium bulk sample was investigated as a reference in the temperature range from 4,2 K up to room temperature. The results of this investigation are illustrated in Fig. 1 as the R/R_0 *vs.* T dependence (R_0 being the resistance value at 4,2 K and R its value at the temperature T). The residual resistance ratio value (*RRR*-ratio of the resistance value at room temperature to that at 4,2 K) of this Ho bulk sample was *RRR*=18,8. The "knee-like" resistance anomaly, clearly seen near ~130 K in Fig. 1, is typical for the magnetic phase transition from the paramagnetic state to the antiferromagnetic one with the spiral structure.

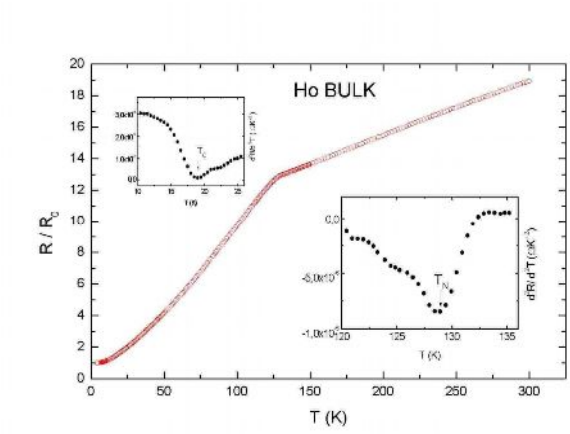

Fig. 1: Temperature dependence of the resistance ratio R/R_0 of Ho bulk sample in the temperature range from 4,2 K to 300 K. The inserts show the second temperature derivative of resistance near the Néel temperature T_N (right bottom) and near the Curie temperature T_C (left upper corner).

If the operative scattering mechanisms of the conduction electrons are independent, contributions to the electrical resistance of magnetic metals are represented by the well-known formulae [10].

$$R_{(T)} = R_0 + R_{ee}(T) + R_{eph}(T) + R_{ems}(T), \qquad (1)$$

where R_0 is residual resistance caused by chemical and physical impurities, R_{ee} (T) represents electron-electron scattering contribution, R_{eph} (T) denotes scattering on thermal vibrations of the crystal lattice and R_{ems} (T) represents scattering of electrons by magnetic spins. As the R_0 contribution is temperature independent and R_{ee} (T) is significant only below ~ 10 K, the temperature dependence of the resistance of magnetic metals is caused by electron-phonon and electron-spin contributions. The temperature dependence of R_{eph} (T) contribution is represented by known Bloch-Grüneisen formula predicting well-known linear increase of R_{eph} (T) with temperature at high temperatures and T^5 law for low temperatures. The spin contribution R_{ems} (T) manifests the influence of magnetic spins on resistance, its value is temperature dependent below the magnetic phase transition temperature and constant above it [10]. Thus, the magnetic phase transitions are manifested as extrems of the R vs. T data and could be obtained by numerical processing of experimental data.

Numerical analysis of the experimental R vs. T data of our Ho bulk sample yielded a deep minimum in the dR^2/dT^2 *vs.* T curve (illustrated in the right bottom insert in Fig. 1.) corresponding to the Néel temperature T_N = 128,94 K. Numerical analysis of the experimental data below ~ 25 K yielded the other minimum in the dR^2/dT^2 *vs.* T curve (illustrated in the left upper insert) corresponding to the Curie temperature T_C = 19 K. This value is in reasonably agreement with the value of T_C = 20 K obtained by neutron measurements [5].

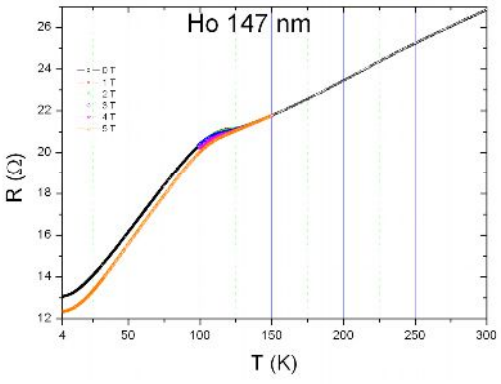

Fig. 2: The R vs. T dependence of 147 nm Ho thin films in temperature range from 4,2 K to 300 K and in magnetic fields up to 5 T.

The electrical resistance of holmium films was investigated in the temperature range from 4,2 K up to room temperature in a thickness range from 36 nm to 215 nm in zero magnetic film and in magnetic field up to 5 T below 150 K. The results of these measurements are

illustrated in Fig. 2 as the temperature dependence of the resistance for the 147 nm thin Ho film.

The R vs. T curve of this film exhibits a change of the resistance anomaly from a small "hump-backed" anomaly near the Neel temperature value in zero magnetic field to a "knee-like" anomaly in magnetic field of 5 T. Similar R vs. T dependences were observed in other Ho films. The R vs. T dependences in narrower temperature range near T_N in magnetic fields up to 5 T of three films with thickness of 98, 147 and 196 nm are illustrated in Fig. 3, Fig. 4 and Fig. 5. The observed R vs. T dependences of Ho films under influence of magnetic field are result of superposition of two temperature dependent conduction electron scattering mechanisms. The electron–phonon interaction was mentioned above. The spin scattering is influenced by the decrease of the turn angle between adjancent magnetic spins.

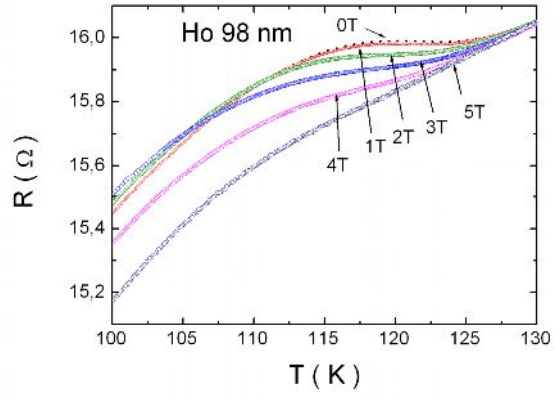

Fig. 3: Influence of magnetic field on the *R vs. T* anomaly in 98 nm thin Ho film near T_N and in fields with increasing flux density from 1 T up to 5 T.

The majority of the hcp crystallites of Ho is oriented with their basal plane parallel to the substrate. In lower fields oriented in the basal plane the helix is slightly distorted.

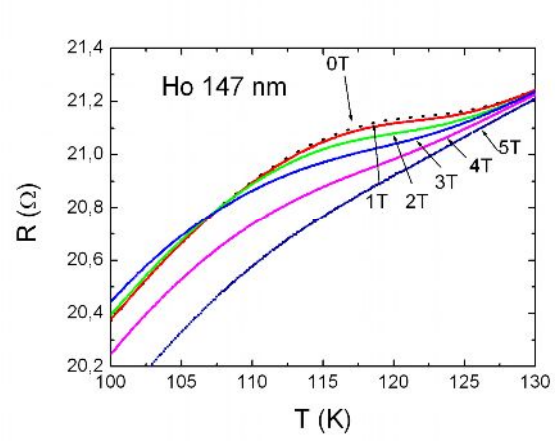

Fig. 4: The *R vs. T* anomalies in 147 nm thin Ho film near T_N and in fields with increasing flux density from 1 T up to 5 T.

Helifan phase appears, spins are more oriented in the direction of the applied field and spin scattering of the conduction electrons is lower. Upon further increase of the applied field the fan phase covers the whole film [11], thus the spin contribution to resistance decreases with increasing magnetic field.

We have observed the decrease of the T_N value with decreasing film thickness, e.g. from T_N =126,90 K (196 nm) to T_N =121,70 K (98 nm). Reduced magnetic ordering temperatures compared to those of bulk samples have been observed in other RE metal thin films like Dy, Sm, Tm (see e.g. [4]) as well as in ferromagnetic films.

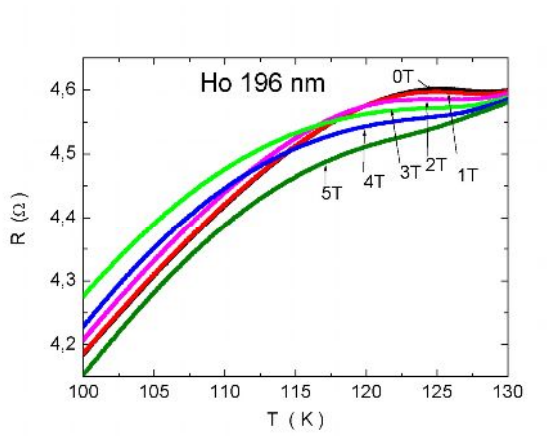

Fig. 5: The *R vs. T* anomalies in 196 nm thin Ho film near T_N and in fields with increasing flux density from 1 T up to 5 T.

This reduction is due to relative increase of the internal stresses and impurities with decreasing film thickness and as the result of the intrinsic property of films.

Applied magnetic field caused a suppression of the T_N value-e.g. it decreased from 126,90 K (0 T) to 122,50 K (5 T) in 196 nm film and from 121,70 K (0 T) to 118,00 K (5 T) in 98 nm film.

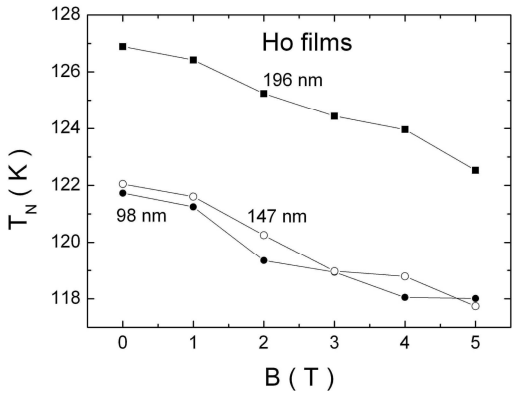

Fig. 6: The influence of magnetic flux density B on the Néel temperature value in ho films with thickness of 96, 147 and 196 nm.

We assume, the decrease of the T_N value in dc magnetic

field is connected with nonuniform distortion of helix [11] which could lead to the decrease of the total magnetic exchange energy. The influence of magnetic field on the T_N value is illustrated in Fig. 6.

The crystal structure was investigated in all Ho films. Diffraction patterns of films with thickness of 98, 147 and 196 nm are illustrated in Fig. 7. The analysis revealed the (002) preferred orientation of the Ho films as well as the presence of the second but minority phase of holmium dihydrid HoH_2 for the investigated samples.

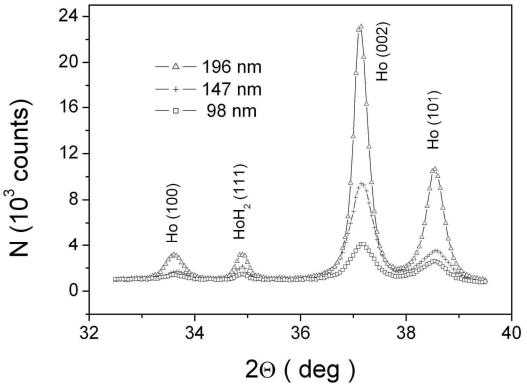

Fig. 7: The X-ray diffraction patterns of Ho films with thickness of 98, 147 and 196 nm.

It is known that rare earth metal thin films readily interact with hydrogen to form dihydrides with the fcc structure (see e.g. [3], [4]) and/or solid solution. Comparing the R vs. T curves of Ho films with those of Ho bulk we assume, the amount of HoH_2 did not influence the R vs. T curve qualitatively.

4. Conclusion

The following conclusions could be made from this study:

1. The R vs. T dependences of Ho films exhibit anomalies caused by magnetic structure similar to those observed in the Ho bulk sample.
2. The Néel temperature values decreased with decreasing film thickness.
3. Increasing magnetic field up to 5 T caused increasing suppression of the T_N value by about 5 K.
4. The X-ray diffraction studies of Ho thin films revealed the (002) textured hcp Ho phase as well as the presence of the second but minority phase of fcc holmium dihydrid.

Acknowledgements

The research was supported by the Slovak Scientific Grant Agency VEGA under Projects 1/3139/06, 2/0148/10, by the Slovak Research and Development Agency under the contract No. VVCE-0058-07, and US Steel Kosice sponsored liquid nitrogen.

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