FERROMAGNETIC RESONANCE IN COBALT SINGLE CRYSTALS

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The temperature dependence of ferromagnetic resonance curves is measured on disc-shaped hexagonal cobalt single-crystal samples of various crystallographic orientations. The measurements were carried out at temperatures between room temperature and 250°C. The domain structure at 20 and 75° was also studied. It is demonstrated that information about the domain structure can be derived from ferromagnetic resonance curves at temperatures at which visual observations are difficult.

INTRODUCTION

IT has been established experimentally that ferromagnetic resonance can be observed not only in the state of magnetic saturation of the sample, but also in the presence of domain structure. This permits a judgment on the basis of the resonance curves about the presence of domain structure in the investigated sample.[1,2] Of great interest are similar investigations of ferromagnets in which the resonance curves vary to a marked extent with temperature, as is the case for example in crystals of hexagonal cobalt. In this case the study of the behavior of the resonance peak corresponding to the single-domain state with increasing temperature can give information about the behavior of the domain structure in that temperature region where visual observation is difficult.

The goal of this paper was the study of the temperature dependence of the resonance fields in cobalt and the comparison of the resonance peaks with the form of the domain structure. In this connection the ferromagnetic resonance curves of monocrystalline samples of cobalt of various orientations were measured at a frequency of 36 900 MHz in the temperature interval from room temperature to 250°C. In this temperature interval cobalt is magnetically uniaxial, and the direction of easy magnetization coincides with the hexagonal axis. With increasing temperature the anisotropy field $H_a = (2K_1 + 4K_2)/I_s$ decreases by almost an order of magnitude, whereas the saturation magnetization I_s changes very little in this temperature interval.[3] Since the resonance field H_{res} depends on H_a, it is to be expected that in this interval the resonance frequencies of the magnetization vector will depend strongly on temperature. In addition, the angular dependence of the resonance curves was studied in the prism plane at room temperature.

SAMPLES AND EXPERIMENTAL METHOD

Disc-shaped samples with a definite crystallographic orientation were cut in an electric-spark apparatus from single crystals prepared from the melt. The orientations of the discs were determined by x-rays. Two groups of samples were prepared for the measurements. In the first group of samples the surface contained the hexagonal axis; in the second the surface was perpendicular to it (i.e., the surface was the basal plane). The surfaces of the discs were carefully polished on fine abrasive cloth and then polished electrolytically.

The resonance curves were measured at a frequency of 36 900 MHz. A cylindrical transmission cavity operating in the H_{112} mode was used. The samples were affixed to the bottom of the cavity in such a manner that the surface was parallel to the cavity bottom. This allowed measurement of the resonance curves on samples of the first group in different orientations of the dc magnetic field relative to the hexagonal axis. The cavity with sample was placed between the poles of an electromagnet. The dc and hf magnetic fields were mutually perpendicular and were in the plane of the sample. The resonance curves were measured point-by-point, the cavity being tuned up at each point. A heater was placed around the cavity for the high-temperature measurements. The domain structure was observed by means of powder figures at 20 and 75°C.

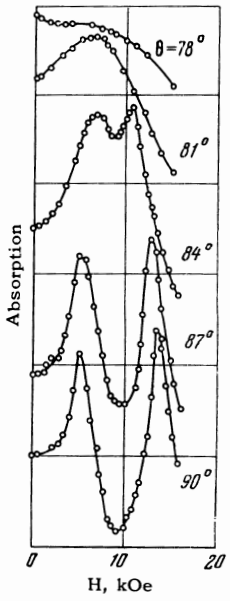


FIG. 1. Angular dependence of the resonance curves of cobalt at 20°C. θ is the angle between the direction of the external dc magnetic field and the hexagonal axis of the crystal.

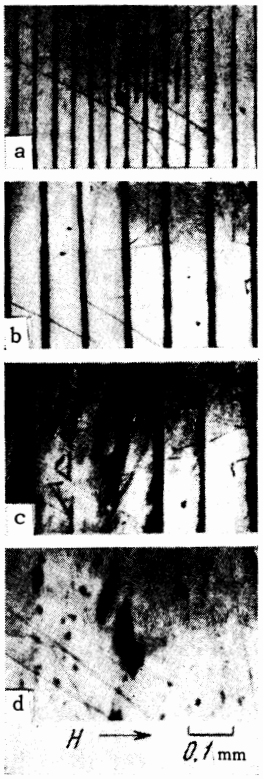


FIG. 2. Change of the domain structure in the prism plane of the cobalt crystal in fields: a–0, b–2500, c–5500, d–10 000 Oe.

ANGULAR DEPENDENCE OF THE RESONANCE CURVES

The angular dependence of the resonance curves was studied on samples of the first group, and their domain structure was observed. Figure 1 shows the resonance curves of a sample 7 mm in diameter and 0.1 mm thick, measured at different orientations of the dc magnetic field H relative to the hexagonal axis (absorption of energy from the hf field is plotted on the ordinate axis in relative units). It is seen from the figure that there are two resonance peaks on the absorption curve for $\theta = 90°$: one at a field $H'_{res} = 5300$ Oe, the other at $H''_{res} = 13\,900$ Oe. Two resonance peaks on the absorption curves are also observed when the angle between the easy axis of magnetization and the field H is decreased, when θ equals 87 and 84°. At $\theta = 81°$ a single maximum is observed on the curve of resonant absorption, and at $\theta = 78°$ the resonance peak becomes difficult to distinguish.

Figure 2 shows photographs of the domain structure for the same sample. The field H is applied perpendicular to the hexagonal axis, i.e., the easy magnetization axis. Powder deposits are seen on the surface of the sample in the absence of field (H = 0, Fig. 2a), indicating 180-degree boundaries between domains with antiparallel orientation of the magnetization (the arrows indicate the direction of magnetization I_s in the domains). When the field H is turned on and gradually increased the powder deposit on some of the boundaries (every other one) becomes more dense; on the others it decreases and after a certain value of the field is attained, completely disappears, although the boundaries between the domains still exist.[1)] Thus, in a field H = 2500 Oe (Fig. 2b) we see wider bands than at H = 0. The growth of magnetization in the direction of the external field occurs as a result of the rotation of the magnetization vectors within the domains. In a field H = 5500 Oe domain structure is still visible on the surface of the sample, and in a field H = 10 000 Oe saturation is observed (Fig. 2d). Thus, from the photographs of Fig. 2 it is clear that if the field H is applied perpendicular to the hexagonal axis, the sample is magnetized to saturation in the field $H''_{res} = 13\,900$ Oe, whereas in the field $H'_{res} = 5300$ Oe there is domain structure in the sample.

Figure 3 shows the angular dependence of the resonance field for this same sample. On the graph are plotted points representing the values of the resonance fields obtained by measurement in the direction of hard magnetization and at a deviation of 9° on either side of this direction. From the figure it is seen that the magnitude of the resonance fields near the direction of hard magnetization ($\theta = 90 \pm 3°$) depends weakly on orientation. If at $\theta = 90°$, the field $H''_{res} = 13\,900$ Oe, then at $\theta = 87°$ we find $H''_{res} = 13\,500$ Oe the resonance field changes by only 400 Oe following a change in angle

[1)] The behavior of such a domain structure in a field and the effect of the disappearance of the deposits on the boundaries is discussed in [4,5].

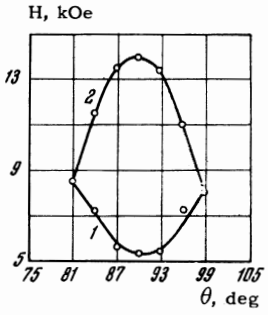


FIG. 3. Angular dependence of the resonance fields of cobalt for the multidomain state (curve 1) and for the state of magnetic saturation (curve 2).

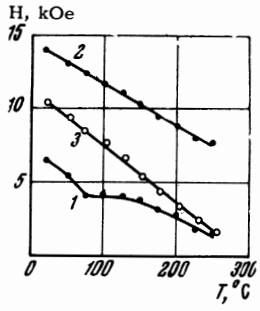


FIG. 5. Temperature dependence of the resonance fields for the multidomain state (curve 1) and for the the state of saturation (curve 2). Curve 3 is the temperature dependence of the anisotropy field of cobalt according to [3].

of 3°. With further decrease of the angle from 87 to 80°, the magnitude of the resonance field depends strongly on orientation. Thus, at $\theta = 84°$ the field $H''_{res} = 11\,500$ Oe, i.e., it changed by 2000 Oe in a rotation of 3°. At angles less than 78° the resonant absorption is so weakly expressed that it is impossible to determine the magnitude of the resonance field.

TEMPERATURE DEPENDENCE OF THE RESONANCE CURVES

1. The temperature dependence of the resonance curves was studied on samples of the first group in the temperature interval from room temperature to 250°C. In Fig. 4 are presented the resonance curves for different temperatures measured on a sample 7.25 mm in diameter and 0.23 mm thick. The field H was directed perpendicular to the hexagonal axis ($\theta = 90°$). It is seen from the figure that there are two resonance maxima on the resonance curve at room temperature. The first maximum is observed in the absence of domain structure ($H'_{res} = 6400$ Oe), and the second corresponds to the state of saturation ($H''_{res} = 13\,900$ Oe). As the temperature is increased, both maxima are shifted toward lower fields, the intensity of the second maximum scarcely changing. On the resonance curve for 250°C we see, as at room temperature, two maxima ($H'_{res} = 1600$ Oe, $H''_{res} = 7700$ Oe). The resonance peak at 7700 Oe at 250°C corresponds to saturation, whereas the resonance peak located at 1600 Oe is evidently associated with the presence of domain structure.

Figure 5 shows the temperature dependence of the resonance fields H'_{res} and H''_{res} for this sample. From the figure it is seen that with increasing temperature the resonance field H'_{res} (curve 1) decreases monotonically from 6400 Oe at room temperature to 1600 Oe at 250°C. The resonance field H''_{res} (curve 2) decreases from 13 900 Oe at 20°C to 7700 Oe at 250°C. Curve 3 represents the dependence of the anisotropy field H_a on temperature, calculated from the data of Barnier et al.[3] It is seen that the anisotropy field decreases approximately from 10 000 to 1500 Oe in going from room temperature to 250°C.

2. Figure 6 shows the resonance curves at various temperatures for a sample whose surface

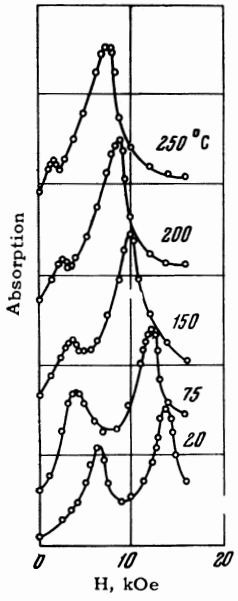
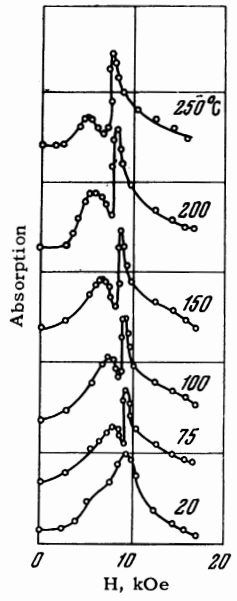


FIG. 4. Temperature dependence of the resonance curves in the direction of hard magnetization ($\theta = 90°$). The hexagonal axis lies in the plane of the disc.

FIG. 6. Temperature dependence of the resonance fields of a monocrystal of cobalt whose surface coincides with the basal plane.



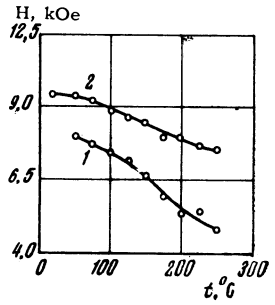


FIG. 7. Temperature dependence of the resonance fields obtained in the basal plane of cobalt for the multi-domain state (curve 1) and for the state of saturation (curve 2).

coincides with the basal plane (diameter 5 mm, thickness 0.33 mm). On the room-temperature (T = 20°C) curve we see two resonance maxima that are so close to each other that it is difficult to distinguish them. When the sample is heated to 75°C the resonance peaks separate. In the interval 50—75°C the second maximum appears at a field of about 8000 Oe. Upon further increase in temperature two maxima are observed on the absorption curves for the entire interval up to 250°C. From the curves in Fig. 7, which gives the temperature dependence of the resonance field for this sample, it is seen that with increasing temperature the magnitude of the resonance field H'_{res} (curve 1) decreases to 4900 Oe, and H''_{res} (curve 2) to 7500 Oe.

Figure 8 shows photographs of the domain structure for this same sample at 75°C. In the absence of field (Fig. 8a) we see a structure of little "stars" on the surface of the sample. In a field H = 8000 Oe, which corresponds closely to the field H'_{res} at this temperature, we see on the surface a domain structure in the form of bands perpendicular to the direction of H. In a field of about 9000 Oe saturation was observed. Thus, the first peak on the resonance curve for 75°C corresponds to a multi-domain state, the second, to the state of saturation. With increasing temperature both peaks shift smoothly to lower fields; hence it is natural to assume that even at 250°C the first resonance peak corresponds to a multi-domain state, even though domain structure has never been successfully observed visually in the basal plane at this temperature.[6]

From the above results it follows that in cobalt at a frequency of 36 900 MHz, in that temperature interval where the easy direction coincides with the hexagonal axis (up to 250°C), and at an orientation of the dc magnetic field along the hard direction (or close to it), oscillations of the magnetization vectors are excited both in the multi-domain state and in the state of saturation. The obtained

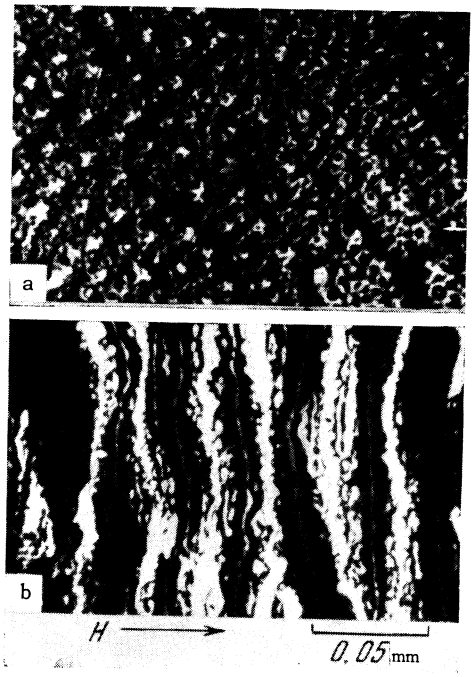


FIG. 8. Domain structure in the basal plane of a crystal of cobalt at 75°C in fields: a—0, b—8000 Oe.

dependence of the resonance fields H'_{res} and H''_{res} on temperature (Figs. 5 and 7) shows that the resonance fields decrease in going from room temperature to 250°C, although not as rapidly as the anisotropy field in this same temperature interval.

In conclusion, the authors thank V. G. Maĭkov for preparing the crystals and L. M. Magat for orienting the crystals by x-rays.

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