Letters to the Editor

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New Magnetic Anisotropy

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A NEW type of magnetic anisotropy has been discovered which is best described as an exchange anisotropy. This anisotropy is the result of an interaction between an antiferromagnetic material and a ferromagnetic material.

A material that exhibits this exchange anisotropy is fine particles of cobalt with a cobaltous oxide shell. The material is made by electrodeposition of cobalt into mercury. The fine particles of cobalt (~200 A) are then surface oxidized to form cobaltous oxide. The resultant particles have a core of cobalt and a shell of cobaltous oxide.

Above the Néel temperature (paramagnetic state), these fine particles of oxide-coated cobalt have magnetic properties as expected for pure cobalt particles. Below the Néel temperature of the cobaltous oxide, there exists an interaction between the spins of the ferromagnetic cobalt and the antiferromagnetic oxide.

In order to best observe the exchange anisotropy of a randomly-oriented compact of fine particles, the material is cooled from the paramagnetic state of the oxide to the antiferromagnetic state in a saturating magnetic field. Since the Néel temperature of cobaltous oxide is 293°K, the material was cooled from 300°K to 77°K in a magnetic field.

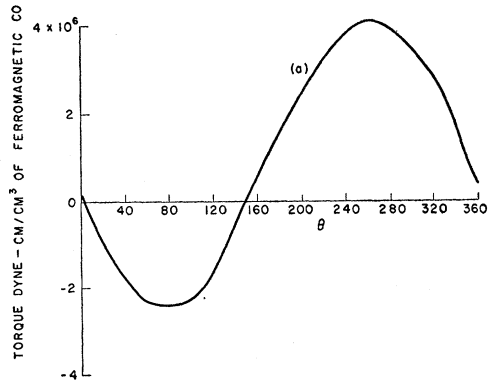

FIG. 1. Torque curve taken at 77°K on fine oxide-coated particles of cobalt, cooled in a saturating magnetic field from 300°K.

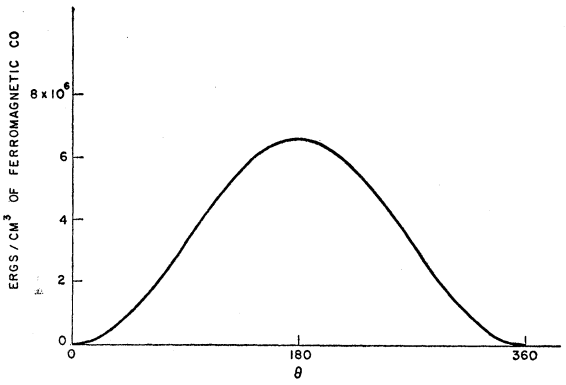

FIG. 2. Energy of rotation of a disk of fine oxide-coated particles of cobalt in a saturating magnetic field.

The exchange anisotropy is a unidirectional anisotropy in that it produces one easy direction of magnetization. As a result, the torque curve is proportional to $\sin\theta$ and not $\sin 2\theta$ as in materials of uniaxial anisotropy such as pure cobalt. A torque curve taken on the material is shown in Fig. 1 and the energy as a function of angle is shown in Fig. 2. It is apparent that the only stable position is at $\theta=0$, and therefore, the material has unidirectional anisotropy. An anisotropy constant of 5×10^6 ergs/cm³ has been calculated from the torque curves.

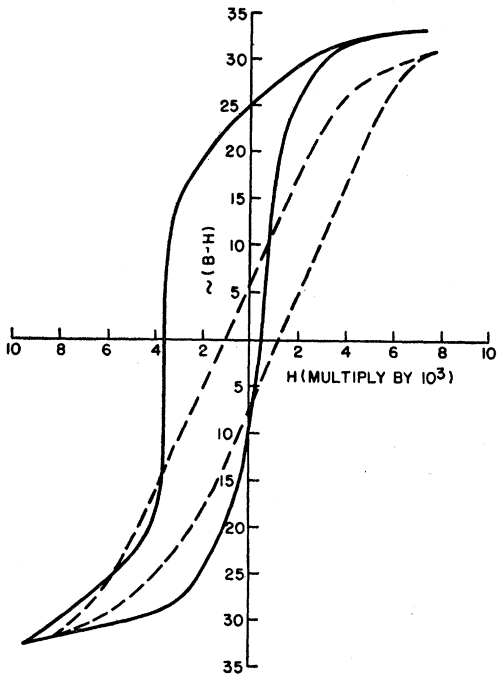

FIG. 3. Hysteresis loops of fine oxide-coated particles of cobalt taken at 77°K. The dashed lines show the hysteresis loop when the material is cooled in the absence of a magnetic field. The solid lines show the hysteresis loop when the material is cooled in a saturating magnetic field.

Another manifestation of this unidirectional anisotropy is a displaced hysteresis loop which occurs when the specimen is cooled in a magnetic field. An example of the displaced hysteresis loop of another specimen is shown as the solid curve in Fig. 3, where the loop displacement is 1600 oersteds. The dashed curve of Fig. 3 shows that the macroscopic hysteresis loop is symmetrical when cooled in the absence of a magnetic field. It is apparent that both the coercive force and the residual flux density become asymmetrical along the axis of magnetization. In the case that the exchange anisotropy is along the same axis as the applied field the material acts as though the effective field (H') is

$$H'=H_a-K_x/I_s,$$

where H_a is the applied field and K_x is the exchange anisotropy constant. The displacement of the hysteresis loop was not changed even in fields of 70 000 oersteds.

Another unusual property of this material is a rotational hysteresis that is substantially independent of the applied field at high fields. The rotational hysteresis was measured to be 5.7×10^6 ergs/cm^3, whereas the rotational hysteresis of pure cobalt particles at the same very high fields was essentially zero. This interaction between the ferromagnetic cobalt and the antiferromagnetic cobaltous oxide allows a measure of the lower limit of the anisotropy of an antiferromagnetic material.

Annealing of Germanium Supersaturated with Nickel

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VAN DER MAESEN and Brenkman[1] reported on the solid solubility of nickel in germanium as a function of temperature, in the range of 700°–920°C. The solubility is determined from resistivity measurements, assuming that each nickel atom gives one acceptor level with an activation energy of 0.23 ev above the valence band. They find that the solubility shows a retrograde character: the solubility being maximum at about 900°C and very low at temperatures below 500°C. Thus, a sample of germanium, saturated with nickel by diffusion at 800°C will be supersaturated at any temperature below 800°C. In agreement herewith, van der Maesen and Brenkman found that prolonged heating of such a supersaturated sample at 500°C restores the original resistivity. Here we report on experiments carried out to determine how the change in density of the nickel acceptor levels takes place during the annealing of such a supersaturated sample.

The sample is prepared as follows: A rectangular bar is cut out of a germanium crystal, containing about 7×10^{12} acceptors per cm^3. The bar is covered electrolytically with nickel and heated at 800°C, long enough to obtain by diffusion a homogeneous distribution of nickel atoms throughout the bulk of the sample. The

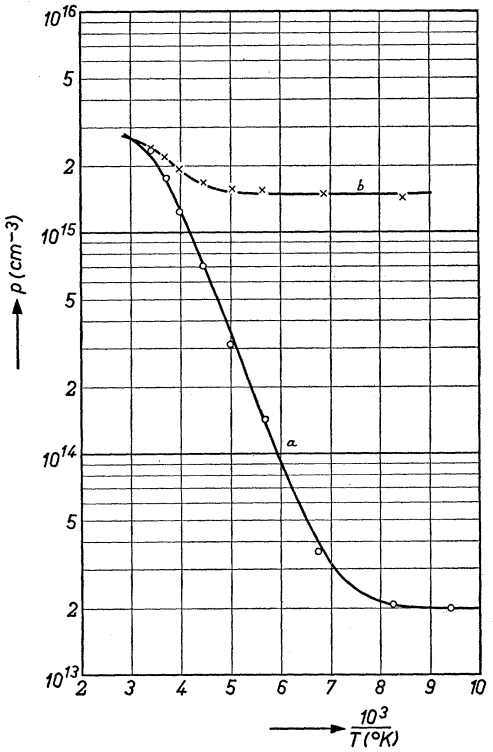

FIG. 1. Hole density as a function of the reciprocal absolute temperature. Curve a: sample saturated with nickel at 800°C. Curve b: after annealing for 6 hours at 430°C.

cooling to room temperature, after the saturation with nickel, is done by a quench, in order to avoid annealing during the cooling as much as possible.

By measuring the Hall effect of such a sample, the concentration of free holes in the valence band is determined as a function of temperature. The result is given in Fig. 1, curve a. The decrease in hole density is due to the change in occupation of the 0.23-ev acceptor level. In the horizontal part of the curve all these levels are empty and the density of the holes which are still present is equal to the density of acceptors which are still fully ionized at these temperatures. The activation energy of these levels will, accordingly, be much smaller than 0.23 ev. Curve b is found after annealing the sample 6 hours at 430°C. Comparison of this curve with curve a, shows in the first place that the hole density at room temperature decreased only slightly, corresponding to a low rate of restoration of the original resistivity. Secondly, in spite of this, the density of the 0.23-ev levels decreased by at least a factor of two, this decrease being compensated by the appearance of new acceptor