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LONGITUDINAL MAGNETORESISTANCE OF PURE SINGLE-CRYSTAL COPPER

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The longitudinal magnetoresistance was measured along the [100] direction of a pure single crystal of copper. The temperature dependence of the saturation ratio, $\rho(B = \text{sat.})/\rho(B = 0)$, is given between 4 and 35°K. A limit is placed on the diffusion approximation for small-angle electron scattering and it is suggested that the assumption of a relaxation time or of a mean free path parallel to the velocity is not valid for some types of impurity or low-temperature phonon scattering.

The longitudinal magnetoresistance of metals has been proposed as a means of determining the effective mean-free-path variations upon the Fermi surface.¹ Both Pippard¹ and Klemens and Jackson² have formulated expressions for the saturation ratio of the longitudinal magnetoresistance for isotropic scattering and, under the diffusion approximation, for very small angle scattering of electrons.^{1,2} Comparison of the saturation ratios for known scattering mechanisms or for known scattering angles yields information regarding the regions of validity of these approximations.

We have measured the longitudinal magnetoresistance between 4 and 35°K along the [100] direction of a pure single crystal of copper whose residual resistance ratio, $\rho_{273^\circ\text{K}}/\rho_{4^\circ\text{K}}$, is 41 800. The effective electrical purity of the specimen was increased by an oxidation-annealing treatment³ of a single crystal grown from selected 99.9999% pure copper. After removal of the spark-planing surface damage,⁴ the sample was 2 mm × 2 mm × 3 cm and was oriented along the [100] crystal axis to within 0.1 deg. Voltage probes, soldered on the surfaces, were precisely located and confined by 0.1-mm holes in a protective coating of varnish. The voltages were measured using a system with an imprecision of 50 pV. Orientation in the magnetic field was ac-

complished by observation of the magnetoresistance signals.

The temperature dependence of the saturation ratio, $\rho(B = \text{sat.})/\rho(B = 0)$, is shown in Fig. 1. The curve shows the change in ratio from nearly total impurity scattering of the electrons at 4°K to nearly total phonon scattering of the electrons at 35°K. Also indicated is the percentage of phonon scattering determined from a plot of resistivity versus temperature. The low-temperature zero-field measurements were corrected for size effect using the equation of Nordheim^{5,6} and a measured $\alpha\rho_B l_B$ on the same piece of copper.⁷

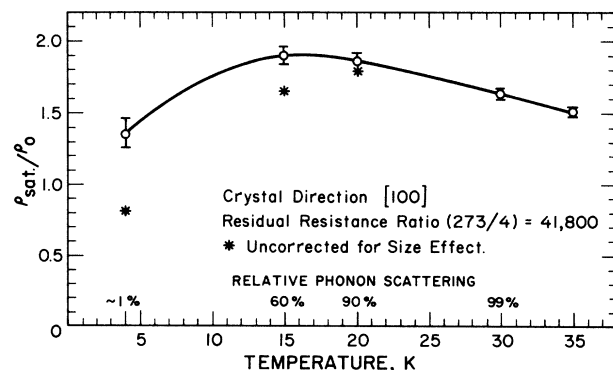


FIG. 1. Longitudinal magnetoresistance saturation ratio for copper.

The uncertainty of this correction, which is indicated in Fig. 1, introduces the largest error.

There has been widespread application of the anisotropy of a relaxation time to explain experimental data, with varied success.⁸⁻¹¹ Therefore, using Pippard's theory, one of the authors calculated saturation longitudinal magnetoresistance ratios for copper.¹² Calculations of saturation ratios from Pippard's formula, which assumes that a relaxation time for isotropic scattering exists at all points on the Fermi surface and that the mean free path is parallel to the velocity, can be performed using a detailed Fermi surface geometry and specified different variations of the mean free path. For those calculations a self-consistent Fermi surface model was developed, partially from the work of Roaf¹³ for the intermediate regions, but also from others for the neck edge and neck regions.^{14,15} This model differs radically from the sphere with caps that was used by Pippard and by Klemens and Jackson in their simple tutorial examples.

In many different calculations the mean free paths were varied in regions around the [100] directions and/or the necks with their relative values ranging from 0.2 to 2.0 times a normalized average value. Included was a distribution suggested by Taylor's¹⁶ calculation. These variations resulted in changes of only ± 0.2 in the saturation ratio of 1.98 (for a [100] orientation) calculated for a constant mean free path. At 4°K, where the scattering is essentially all from impurities, and at the higher temperatures, where the average scattering angle from phonons is large, a nearly isotropic scattering approximation would be expected to be valid; yet here the values for the saturation ratio are well below the calculated values for even extreme variations of the mean free path. There has been some indication that dislocation scattering has a disproportionately large effect on longitudinal magnetoresistance,² but a correction for this would yield an even higher predicted value. Therefore, it is suggested that the assumption of a relaxation time or of a mean free path parallel to the velocity is not valid for some types of impurity or low-temperature phonon scattering.

Both Pippard and Klemens and Jackson have formulated expressions for the saturation ratio under the diffusion approximation, as would be expected for scattering by very low temperature phonons.^{1,2} They both determined that the ratio should be large, on the order of three to eight for the [100] direction. Because this is well

above any of our measured values, we can say that the diffusion approximation is not valid for any known dominant scattering angles present; that is, for scattering angles of about 0.05-0.1 rad.¹⁷ As the temperature and therefore the average scattering angle decreases, the experimental ratio rises as would be expected from an approach to the diffusion approximation. It is entirely possible that the ratio would rise to the values predicted by Pippard and Klemens and Jackson if impurity scattering did not become dominant.

Pippard and Klemens and Jackson have also calculated ratios assuming isotropic large-angle scattering. In this case they find a ratio of 1.3, compared with our measured value of 1.35 at 4°K and 1.5 at 35°K. However, they used a spherical Fermi surface, a model too simple to allow accurate calculations for copper. Therefore, the above agreement must be considered fortuitous.

It is part of our continuing study of the galvanomagnetic properties of metals to repeat these measurements on other orientations and on copper crystals grown with known impurities and thus obtain a transition from a known scattering mechanism to phonon scattering.

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ULTRAVIOLET MAGNETO-OPTICAL PROPERTIES OF RARE-EARTH ORTHOFERRITES*

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The first ultraviolet measurements of the complex polar Kerr effect (rotation and ellipticity) are reported between 1.8 and 5.5 eV for the rare-earth orthoferrites. The resonances observed are identified as charge transfer or charge-transfer-enhanced crystal-field transitions associated with octahedrally coordinated Fe³⁺ ions.

Since Dillon first observed large Faraday rotations associated with the visible absorption edge in rare-earth iron garnets,¹ there has been considerable interest in the optical properties of ferric oxide compounds.²⁻¹¹ Clogston discussed these phenomena in terms of electrical dipole allowed transitions, i.e., charge transfer and orbital promotion.² However, the strength of these transitions and the resulting opaqueness of these materials has prevented confirmation or elaboration of his theories.

Through the use of optical and magneto-optical (complex polar Kerr effect) reflection techniques, we have made the first observations of the ultraviolet spectra of bulk, single-crystal ferric oxide compounds.¹² We report here our results between 1.8 and 5.5 eV for europium orthoferrite, EuFeO₃. Measurements have also been made on rare-earth iron garnets, spinel ferrites, magnetoplumbite, nine additional rare-earth orthoferrites (RFeO₃, where R = Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu), and YFeO₃. By application of these same techniques to the garnet system Eu₃Fe_{5-x}Ga_xO₁₂ (0 ≤ x ≤ 1.9), we have distinguished between the contributions of octahedrally and tetrahedrally coordinated Fe³⁺ ions. Furthermore, applying the results presented in this paper, we have shown that charge-transfer transitions occurring at about 4 and 5 eV, associated with octahedral and tetrahedral Fe³⁺ sites, respectively, are responsible for the principal features of the uv magneto-optical spectra of all the materials investigated.¹³ To our knowledge there have been no previous measurements of the com-

plex polar Kerr effect in the ultraviolet.¹⁴

Measurements were made near normal incidence and at room temperature on growth faces of crystals magnetized to saturation. Detailed investigations show that the properties measured are characteristic of the bulk rather than just the surface.¹³ While the spectrometer will be described elsewhere,¹⁵ typical signal-to-noise ratios are indicated by the error bars of Fig. 1(a). Our data are in good agreement with the results of Jung who measured the polar Kerr rotation, φ, and the diagonal element of the complex dielectric tensor, ε₀, for ErFeO₃ in the visible range.⁸

The rare-earth orthoferrites, space group *D*_{2h}¹⁶-*Pbmm*, have a distorted perovskite structure with only one type of Fe³⁺ ion site, Fe³⁺ octahedrally coordinated with O²⁻ ions.¹⁶ Nearest-neighbor Fe³⁺ ions are antiferromagnetically aligned, but a slight canting of the Fe³⁺ spins by an angle α on the order of 8 mrad creates a weak ferromagnetic moment.¹⁷ This net ordering of the spin system gives rise through spin-orbit coupling to the observed magneto-optical effects. The rare earths are only weakly coupled to the Fe³⁺ ions and at room temperature their magnetization can be neglected.¹⁷

Considering only effects linear in the magnetization \vec{M} , the complex dielectric tensor is of the form

$$\begin{aligned}\epsilon_{xx} &= \epsilon_{yy} = \epsilon_0' + i\epsilon_0'', \\ \epsilon_{xy} &= -\epsilon_{yx} = i(\epsilon_1' + i\epsilon_1''),\end{aligned}$$