M. R. Oliver
J. O. Dimmock
T. B. Reed

Temperature and Magnetic Field Dependence of the Conductivity of EuO*

Abstract: The conductivity of EuO has been measured as a function of temperature from 30 to 300°K in magnetic fields up to 50 kG. The zero-field resistivity exhibits a sharp elbow at about 50°K, and increases as much as 10^8 between 50 and 70°K to a broad maximum between 75 and 80°K. In an applied magnetic field, the broad maximum is rapidly decreased and the elbow is shifted to higher temperatures. These data are interpreted in terms of a transfer of electrons between a conduction band and an electron trap. In the model the energy separation between the band and trap level depends on the magnetic energy of the crystal and is thus a strong function of temperature and magnetic field. At low temperatures the trap level is assumed to be above the conduction band edge such that the electrons lie in the band. As the temperature is increased the energy of the band edge increases such that it crosses the trap level at about 50°K. The large increase in resistivity with increasing temperature and the effects due to the magnetic field are explained by the transfer of electrons from the energy band into the trap states.

Studies have been made on the temperature and magnetic field dependence of the resistivity of EuS and EuSe in order to determine the conduction mechanisms in the Eu-chalcogenides.[1,2] For lightly doped samples a large peak in the resistivity and a large negative magnetoresistance was observed in the vicinity of the Curie point. Our studies were initiated in order to investigate these effects in EuO.

The resistivity measurements were made using the van der Pauw technique. The conducting samples were not intentionally doped, and mass spectrographic analysis showed trivalent rare earth impurity concentrations in the range from 0 to 100 ppm. Annealing studies, to be reported later, have shown, however, that the conductivity can be greatly enhanced or suppressed by heating in excess Eu or in vacuum respectively, indicating that the conductivity may be due in part to deviations from stoichiometry. Results of thermogravimetric analyses, however, have shown that the deviations from stoichiometry are less than one percent and probably less than 0.2 percent. The Curie points of similar samples were determined, by means of a moving coil magnetometer, to be within one degree of 69.5°K.

The resistivity curves of several representative samples are shown in Fig. 1. The curves exhibit a general pattern.

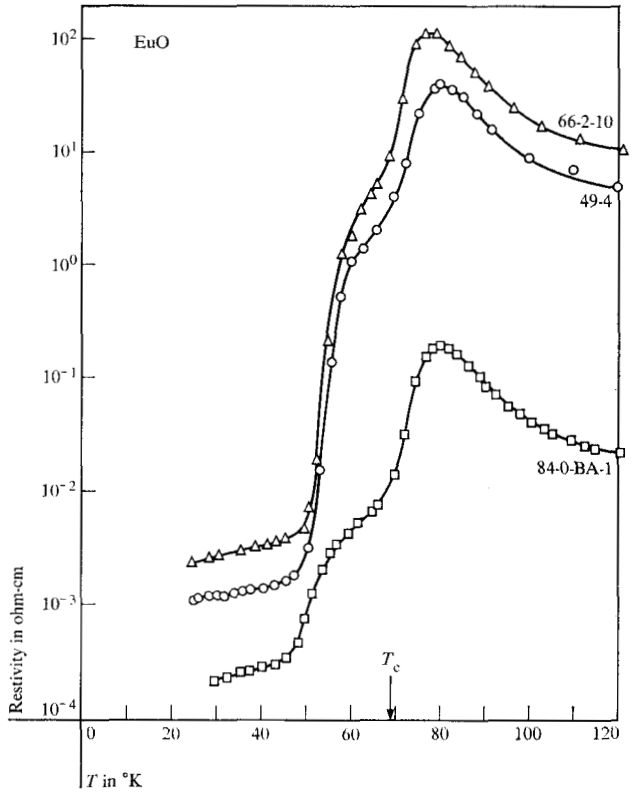

Figure 1 Resistivity vs temperature of three moderately conducting EuO samples.

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The authors are located at the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts 02173.

At low temperatures the resistivity rises slowly, but at about 50°K a sharp elbow occurs in the curve and above this temperature the resistivity rises more sharply. In some samples this rise has exceeded 10^8. A broad peak is observed around 75 to 80°K, and the resistivity decreases gradually above this peak. There is also some structure to the curve between 60°K and the peak.

Previous infrared absorption measurements[3] have shown that in conducting samples the absorption coefficient for $\lambda \geq 2.5\mu$ is proportional to λ^2 as would be expected for absorption by carriers in a conduction band. This relationship has now been established in the temperature range from 20 to 300°K indicating the presence of band conductivity throughout this range, rather than impurity conductivity as has been proposed previously.[4] When both conductivity and optical absorption results are used, for the same sample, the electron concentration and the relaxation time can be determined assuming a fixed value for the effective mass. The results for one particular sample are shown in Fig. 2 assuming $m^*/m_0 = 1$. In this sample, the free-carrier absorption was too small above 54°K to be determined accurately. These results indicate that the sharp change in resistivity that commences around 50°K is primarily due to changes in carrier concentration. Whereas previous models[4] for the temperature and magnetic field dependence of the conductivity in the Eu chalcogenides have ascribed the effects to changes in mobility, we find that the dominant effects in EuO at temperatures below T_c are due to changes in carrier concentration.

The above analysis depends on the validity of the Drude model for free-carrier absorption, which assumes an energy independent scattering factor. Although the observed λ^2 dependence of the free-carrier absorption indicates that the Drude model is satisfied in the infrared, using a scattering time derived from infrared absorption in connection with dc conductivity is somewhat questionable. It is, however, unlikely that the energy variation of the scattering factor could exhibit a sufficiently strong temperature and magnetic field dependence to significantly affect our conclusions. Nevertheless, Hall coefficient measurements as a function of temperature would be very helpful in corroborating our model. Unfortunately, however, due to low mobilities, we have been unable to obtain Hall coefficient measurements throughout the temperature range of interest.

Freiser et al.[5] and Busch and Wachter[6] have shown that the energy of the optical absorption edge varies strongly with temperature, exhibiting a total increase of about 0.26 eV from $T = 0$ to about 2 T_c. Freiser et al.[5] have related this to the spin-spin correlation function in EuO, as determined by Argyle et al.[7] If we assume that the variation of the edge is due to a shift of the conduction band, we can account for the depopulation of the conduction band with increasing temperature by a transfer of carriers to a trap level whose energy is relatively independent of temperature and magnetic field and which crosses the bottom of the conduction band at 50°K. A similar model has been proposed for $CdCr_2Se_4$ by Lehmann.[8]

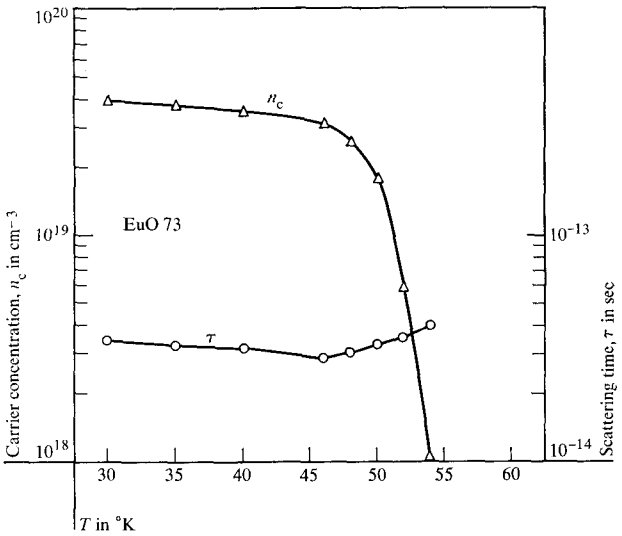

Figure 2 Carrier concentration and scattering time of an EuO sample, computed from optical absorption and conductivity measurements.

With these restrictions the model can be made to agree quantitatively with the data obtained on a large variety of samples. In each case, agreement is obtained assuming that the trap level - band edge crossing occurs at about 50°K, and, in the moderate conductivity range (10^{-1} ohm-cm $< \rho_{max} < 10^5$ ohm-cm), that the trap level density is approximately equal to the electron density. Figure 3 shows the resistivity vs temperature for an EuO sample at $H = 0$ and 48 kG. A theoretical curve based on the model is also shown for $H = 0$. The fit was obtained assuming the number of traps to be equal to the number of conduction electrons. The deviation between theory and experiment in the range between 75 and 80°K could be due to variations in mobility not accounted for in the model.

For slightly fewer electrons than traps, the Fermi level of the system remains tied to the trap level and the population of the conduction band is governed primarily by a Boltzmann factor, $\exp(-\Delta E/kT)$, where ΔE is the energy separation between the trap level and the bottom of the conduction band. For this case the resistivity curve will have a relatively broad peak near the temperature where $d(\Delta E/kT)/dT = 0$. Small variations in the ratio of electron density to trap state density about the value unity result in large variations in total resistivity change and can totally account for the variation between samples. Although the identity of the trap state has not been determined by these

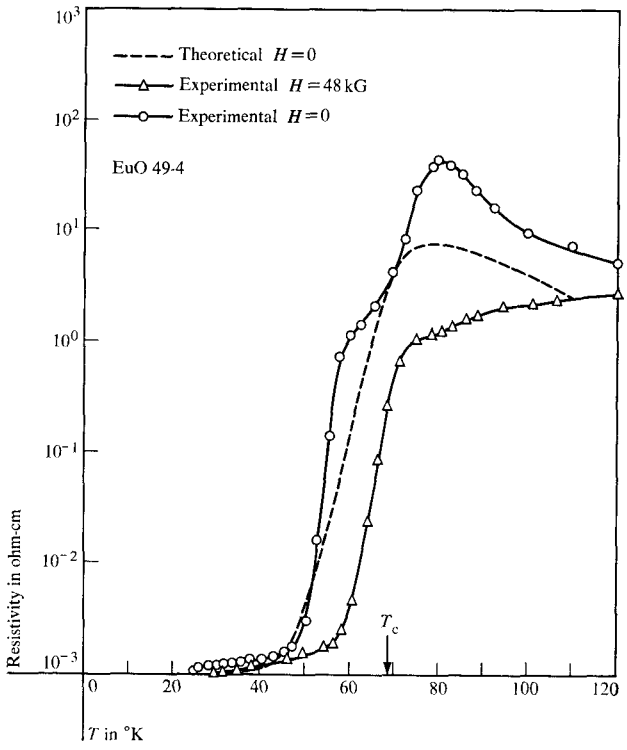

Figure 3 Resistivity vs temperature of an EuO sample with $H = 0$ and 48 kG. A theoretical curve (see text) is also shown for $H = 0$.

measurements, its apparent lack of dependence on temperature or magnetic field may indicate that it is nonmagnetic in character.

This model also accounts for the negative magnetoresistance of EuO. As Argyle and Miyata[9] have demonstrated, an applied magnetic field decreases the magnetic energy in the vicinity of the Curie point. In our model, this will lower the band edge and two effects will occur: 1) the elbow will move to a higher temperature, and 2) the ρ vs T slope will be more gradual. As seen in Fig. 3 the shift in the elbow is about 10°K for the 48 kG field. The calculated shift for an 18 kG field, the highest studied by Argyle and Miyata, is about 3°K. Our 48 kG results are consistent with a reasonable extrapolation from their data.

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