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# High-field Nonohmic Behavior of the p-type Ferromagnetic Semiconductor $Ag_xCd_{1-x}Cr_2Se_4$*

**Abstract:** The high-field longitudinal magnetoresistance of the ferromagnetic (polycrystalline) p-type semiconductor $Ag_xCd_{1-x}Cr_2Se_4$ has been measured as a function of temperature and applied magnetic and electric fields. It is suggested that the observed "anomalies" may be related to the possible spin wave-carrier wave interactions in these materials.

## Introduction

The basic magnetic and semiconducting characteristics of the ferromagnetic chalcogenide spinels have been the subject of a considerable amount of recent research.[1–3] The n-type semiconductor $In_xCd_{1-x}Cr_2Se_4$ has received much attention because it shows many striking peculiarities. In this paper, however, we consider the electrical behavior of the p-type ferromagnetic semiconductor $Ag_xCd_{1-x}Cr_2Se_4$, where $x = 0.01$, which also shows some interesting "anomalies" in large applied fields.

To understand the physical characteristics of a ferromagnetic semiconductor, we must consider the additional interactions in these systems, i.e., the interactions between the ferromagnetic subsystem of the "bound" electrons and the paramagnetic subsystem of the free carriers occupying a band. These interactions can be decomposed into three components: (1) the interaction of the streaming carriers with the electromagnetic field of the spin waves, (2) the interaction of the spin magnetic moment of the free carriers with the spin waves and (3) the exchange interaction between the free carriers and the localized spinning electrons. In a given magnetic conductor, all of these may be important in various degrees. Since, in general, the calculations from first principles in such systems are quite complicated, we must be guided by a combination of experimental results and simplified theoretical models.

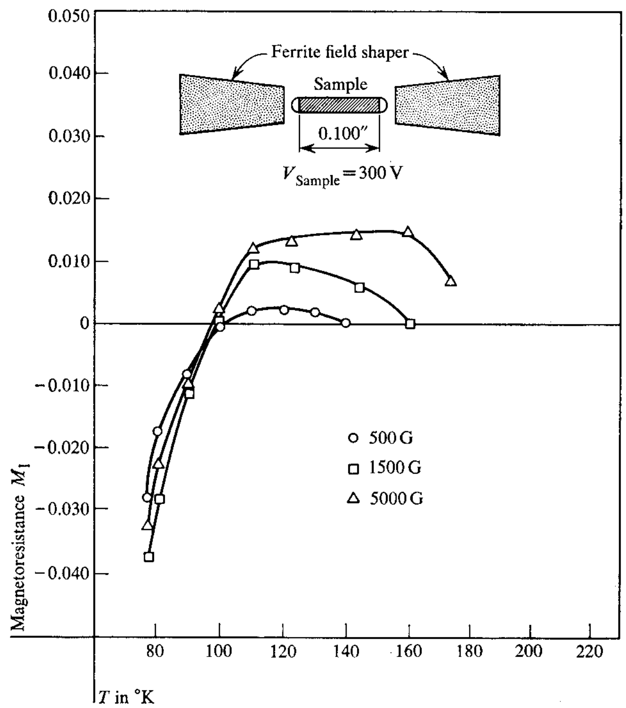


**Figure 1** Longitudinal magnetoresistance as a function of temperature in a constant dc electric field, with magnetic field strength as a parameter.

## Experimental results

The high-field magnetoresistance coefficients ($M_l$ for $B_0 \parallel I$ and $M_t$ for $B_0 \perp I$) of polycrystalline $CdCr_2Se_4$ doped with 1%Ag have been measured as functions of temperature, magnetic field and electric field. We have used samples of various sizes and shapes. The samples used in the experiments leading to the results presented in Figs. 1, 2 and 3 were slabs of the dimensions 0.010″ × 0.040″ × 0.100″ (or 0.200″).

The measurements presented in Fig. 1 were carried out in a shaped magnetic field so that the internal field within

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* This work was partially supported by the Air Force Office of Scientific Research under Grant No. AFOSR-69-1700.

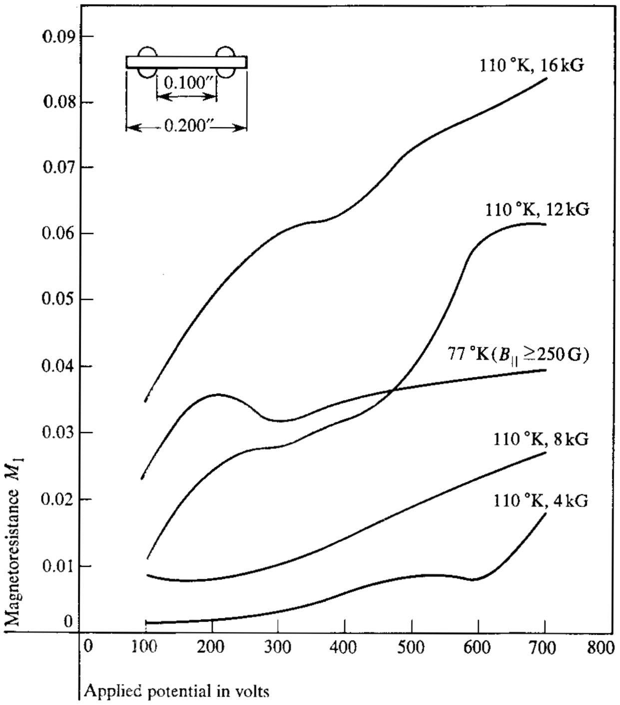


**Figure 2** Longitudinal magnetoresistance as a function of applied voltage at 110°K, with magnetic field strength as a parameter.

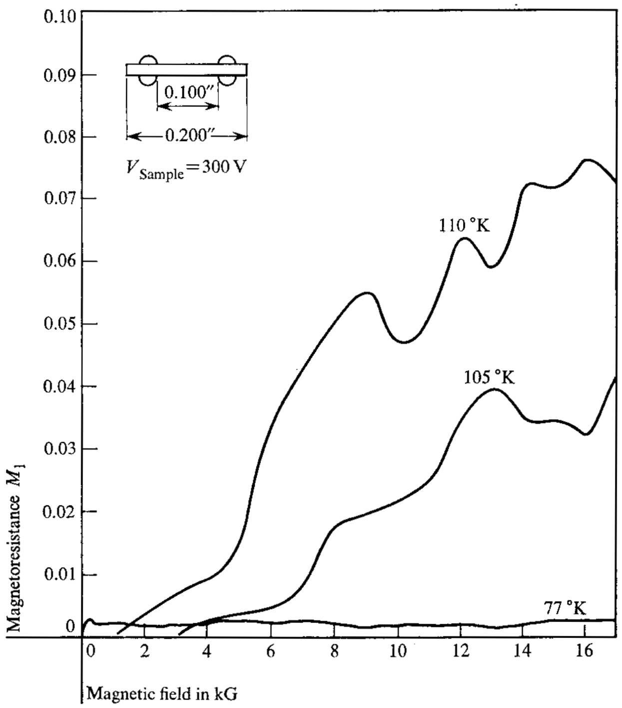


**Figure 3** Longitudinal magnetoresistance as a function of magnetic field strength at constant voltage, with temperature as a parameter.

the sample would be reasonably uniform. In some samples, such as the ones used in obtaining the results presented in Figs. 2 and 3, the contacts were recessed from the ends so that the internal magnetic field was reasonably constant in the region of current flow. Similar measurements, carried out in a uniform external magnetic field (resulting, of course, in a nonuniform internal field within the magnetic sample), exhibit the same kind of overall behavior but with some fine structure. This is especially true at temperatures above approximately 100°K, where the material is definitely a p-type semiconductor.[1]

We now briefly discuss the overall characteristics of the results presented in Figs. 1 through 3, and suggest a simple model which seems to account for this behavior, at least in a qualitative manner. The discussion is confined to the results obtained in a parallel magnetic field and to the temperature region where the material is definitely p-type.

## Discussion

One of the salient characteristics of the results is that the longitudinal magnetoresistance coefficient,

$$M_l = [\rho(B_{\parallel}) - \rho(B = 0)]/\rho(B = 0),$$

is zero at high temperatures where there is no magnetic ordering (see Fig. 1). This is to be expected for an isotropic semiconductor. However, when the magnetic ordering starts setting in, $M_l$ becomes finite and positive and remains so down to $T \approx 100$ to 77°K, depending on the sample and the shape of the magnetic field. Figure 2 shows that $M_l$ increases with increasing dc electric field applied to the sample. With the voltage held constant, $M_l$ increases with increasing magnetic field strength, as indicated in Fig. 3.

The study of the basic semiconducting characteristics indicates that the Ag-doped $CdCr_2Se_4$ is a p-type semiconductor[1,4] (down to $T \approx 100$°K in polycrystalline form) of reasonably high mobility ($\mu_p \approx 400$ to 1000 $cm^2$/V-sec at $T_c = 130$°K in polycrystalline samples). It seems reasonable to assume that in this material the holes occupy a single broad valence band. The band splitting due to the exchange interactions between the holes and the localized electrons seems to be very small. On the other hand, it has been suggested[5,6] that in the "high" mobility ferromagnetic semiconductors, one may expect "strong" interactions between the collective excitations of the spin system (spin waves) and the collective excitations of the free-carrier systems (carrier waves, such as helicon waves). As a result of these interactions, the drifting carriers can lose energy to the spin system, which in turn loses that energy to the lattice. For instance, as a consequence of the active spin wave-helicon wave interactions in the p-type material, one obtains a longitudinal magnetoresistance coefficient which qualitatively exhibits many of the characteristics of the experimental results.

The detailed calculations based on this spin wave-carrier wave interaction model and measurements in single crystal samples are in progress and will be reported later.

### Acknowledgments

The magnetic semiconductor samples were supplied by the magnetics group at the RCA Laboratories. The measurements were made in collaboration with E. E. Thomas at the RCA Laboratories. The author expresses his thanks to P. J. Wojtowicz, P. K. Baltzer, H. Pinch and E. E. Thomas.

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*Received October 28, 1969*