OBSERVATION OF A RESISTANCE MINIMUM IN CADMIUM BY MAGNETO-ACOUSTIC MEASUREMENTS

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Received 16 September 1963

It has previously been shown that a detailed analysis of the high magnetic field attenuation of ultrasonic waves in a pure metal single crystal can give information concerning electron mean free path anisotropy [1]. In the course of measurements on two 99.999% pure cadmium crystals in which the electron mean free path is thermal phonon limited at 4.2°K, anomalous behaviour of the temperature variation of the mean free path has been observed. Upon further investigation it was found that the mean free path exhibited a clear maximum around 3°K. This maximum in the electronic mean free path is just what would be expected if the cadmium samples have a resistance minimum such as those reported widely in other materials over the past several years [2-6].

The present analysis is based on the free electron theory of metals and essentially involves finding the ultrasonic frequency at which the high field limiting attenuation is equal to the zero field attenuation. In zero field for compressional waves, it is found that the ultrasonic attenuation by the conduction electrons is [7]

$$\alpha_L(ql) = \frac{nm}{\rho v_s \tau}\left[\frac{q^2 l^2 \tan^{-1} ql}{3(ql - \tan^{-1} ql)} - 1\right], \qquad (1)$$

where n is the number of free electrons per unit volume, m is the electron mass, v_s the sound velocity, ρ the metal density, τ the electron relaxation time, q the magnitude of the sound wave vector ($q = 2\pi\nu/v_s$), ν is the sound frequency, and l the electron mean free path. In the limit $H \to \infty$, the compressional attenuation is given by [7]

$$\lim_{H\to\infty} \alpha_L(H) = \frac{nmvq^2 l}{15\rho v_s}. \qquad (2)$$

Experimentally, it is possible to determine the difference between eq. (1) and eq. (2) by comparing the attenuation in the high field limit with that in zero field. When the high field attenuation is equal to that in zero field, a numerical calculation shows that $ql = 6.8$. Thus, if the frequency at which $\alpha(H\to\infty) = \alpha(H=0)$ can be found, the electron mean free path can be determined. The mean free path measured is an average over that part of the Fermi surface being traversed. Different orbits on the Fermi surface can be selected by changing the configuration of sound and field directions.

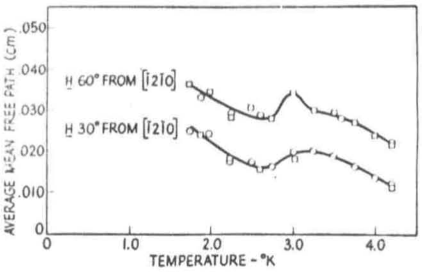

Fig. 1. The electronic mean free path in cadmium sample A as a function of temperature for two different magnetic field directions. The sound direction q is along [10$\bar{1}$0].

In the present study, the above analysis was carried out from 4.2°K to 1°K at magnetic fields up to 19 000 gauss. Fig. 1 shows results of the temperature variation of the mean free path obtained for sample A which is less pure than sample B. In the data of fig. 1, the propagation direction is along [10$\bar{1}$0] while the magnetic field directions correspond to H 30° from [$\bar{1}2\bar{1}0$] and H 60° from [$\bar{1}2\bar{1}0$]. A marked anisotropy of l is observed for different field directions and the temperature dependence clearly shows maxima and minima around 3°K. The position of the maximum is also found to be slightly different for different field and sound configurations.

For the particular sound and field configuration of fig. 1 the principal magneto-acoustic oscillations observed are those around the central ellipse in the third hole band of cadmium [8-10]. It is probable that orbits around this part of the Fermi surface are also responsible for the high field attenuation although other parts of the Fermi surface might well contribute. No thorough theoretical investigation of this problem has been carried out.

In order to further substantiate the occurrence of the mean free path maximum, the following methods were used:

1. Determination of the halfwidth and the height of the open orbit resonance phenomena [11].
2. Eddy current resistivity measurements [12].

It has been shown that the halfwidth and height of the open orbit resonance are directly related to ql [13]. It is found that the open orbit resonance has a Lorentz shape and that the height of the resonance is proportional to ql while the width is inversely proportional to ql. Measurements of the height and halfwidth of the open orbit resonance as a function of temperature were made for each direction * in sample A and only a very slight anomalous behaviour could be detected, probably because the changes in height and width were quite small. In the higher purity sample B, however, definite indications of maxima in both height and the reciprocal of the halfwidth are observed. These are shown in fig. 2 in which the quantities are plotted as a function of temperature. The eddy current resistivity measurements were made in the usual way [12] on sample B; and, although they are crude as compared to the other results, a definite indication of a resistance minimum occurs at about 3°K. The results are shown in fig. 2 where the resistivity relative to that at 4.2°K is plotted as a function of temperature. It should be noted in regard to fig. 2 that high field measurements on sample B give maxima around 2°K whereas the open orbit resonance and resistivity measurement show maxima at about 3°K.

The resistance minimum effect has been discussed theoretically in several papers [14-17]. The effect is apparently caused by the presence of certain ferromagnetic or paramagnetic impurities which introduce a temperature dependent term to the resistance. The present sample A was spectrographically analysed and the major impurities found to be iron and lead. From the spectrographic analysis it was estimated that the iron concentration was about 10-20 parts per million. It thus appears that for extremely pure crystals, ferromagnetic impurities of concentrations a few parts per million can have definite effects on the transport properties.

Investigations with a high purity zinc single crystal also yield results showing a maximum in the mean free path at about 3.5°K.

A full account of the temperature variation of the mean free path in cadmium and zinc will be published elsewhere. It is hoped that a correlation can be found between the mean free paths determined by the magneto-acoustic technique and those derived from zero field conductivity measurements.

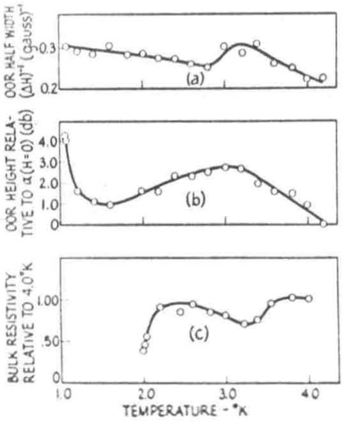

Fig. 2. a. The reciprocal of the halfwidth of the open orbit resonance in sample B for $q \parallel [10\bar{1}0]$, $H \parallel [\bar{1}2\bar{1}0]$.
b. The height of the open orbit resonance in sample B with respect to the zero field attenuation for the same configuration as that in (a).
c. Bulk resistivity of sample B as a function of temperature as measured by an eddy current technique.

I am indebted to J. R. Miller, J. R. Boyd and K. B. Ward Jr. for help with the measurements and wish to acknowledge helpful discussions with S. Rodriquez and J. C. Thomspon. This research was supported by the General Dynamics Corporation, the National Science Foundation and the Office of Naval Research.

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* The open orbit resonance in cadmium was reported earlier for the configuration q along $[\bar{1}2\bar{1}0]$ and H along $[10\bar{1}0]$. It has now been observed also for q along $[10\bar{1}0]$ and H along $[\bar{1}2\bar{1}0]$. The resonance is also seen for both configurations in zinc.