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Evidence of a Phase Shift in Acoustic Cyclotron Resonance*

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In this paper we report the first observation of a phase shift, similar to that observed in the Azbel-Kaner–type cyclotron resonance, obtained in acoustic-cyclotron-resonance experiments using high-purity single crystals of gallium. No satisfactory explanation of the effect can be given by the introduction of a finite value of $\omega\tau$ into the existing theories (contrary to the Azbel-Kaner–resonance case), since this treatment yields a shift an order of magnitude smaller than the experimentally observed shift.

Acoustic cyclotron resonance (ACR) in metals was theoretically proposed many years ago.[1-5] Two different types of experimental conditions can be used to observe this resonance: Either the wave vector $\vec{q}$ of the ultrasonic wave is perpendicular to the magnetic field $\vec{H}$ (normal geometry) or $\vec{q}$ and $\vec{H}$ are not perpendicular (condition for Doppler-shifted acoustic cyclotron resonance). In the following we will only be interested in the normal geometry with which, so far, very few experimental data have been taken.[6,7] The main reason is that a condition required to observe ACR is $\omega\tau \gg 1$ (ω is the ultrasonic frequency and τ the collision time of the electrons involved in the effect; τ is related to the mean free path l and the Fermi velocity v_F by the relation $l = v_F \tau$). In most metals τ is rarely larger than 10^{-10}–10^{-11} sec and the required frequency should be of the order of 10^{10} Hz. Ultrasonic experiments in metals at those frequencies are difficult to achieve. In spite of these difficulties ACR has the theoretical advantage over the classical Azbel-Kaner–type cyclotron resonance (AKCR) in that the interaction takes place in the bulk of the metal and not within the skin depth, near the surface. In order to improve on $\omega\tau$ the choice of the metal is limited to a very pure one (until the difficulties of propagating high-frequency ultrasonic waves in metals are overcome). So far only gallium has shown a sufficiently long collision time to allow ACR in the range of 10^8 Hz.

We have investigated ACR in high-purity single crystals of gallium and in this paper we report the first observation of a phase shift of the resonant fields similar to that observed in AKCR. The measurements were made using an ultrasonic pulse-echo technique.

The samples were cylinders of 10-mm diameter and 5- or 10-mm length, grown from 99.99999% pure gallium. The axes of the cylinders were aligned to within 1° with one of the main crystallographic axes *a*, *b* or *c*. The ultrasonic waves, of frequency 300 MHz, were created by an *X*-cut quartz crystal bonded on one face of the cylinders. The wave vector $\vec{q}$ of the ultrasonic wave was thus aligned with one of the crystallographic axes. The magnetic field, which was kept perpendicular to $\vec{q}$, was created by a pair of Helmholtz coils; its value was determined to better than 1 Oe. In order to increase the collision time the temperature of the sample was lowered to 1.3 °K.

The field dependence of the ultrasonic attenuation was studied by recording the amplitude of a selected echo as a function of the applied magnetic field. Such a recording is shown in Fig. 1. A typical set of geometric and cyclotron-resonance oscillations can be observed. Each minimum of amplitude corresponds to a maximum of the attenuation. In general two types of oscillations are superimposed: one due to geometric resonance and one due to ACR. Obviously it is necessary to identify the two types; it is also important to separate the different periods of oscillations of the same type. Superposition of two resonances, either belonging to the same type or not, can produce in some cases displacements of the maxima of attenuation.[8,9]

Acoustic-cyclotron-resonance oscillations occur

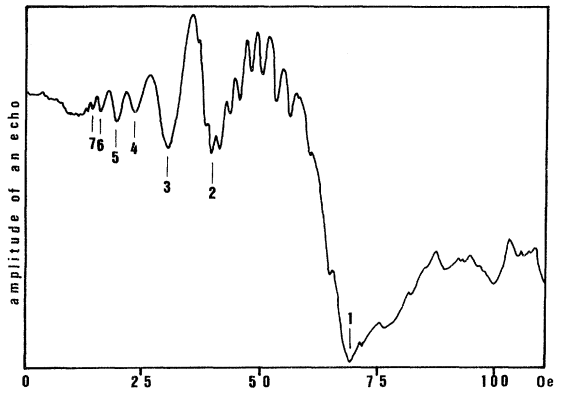

FIG. 1. Magnetic field dependence of the amplitude of an echo for a propagation along the c axis. The frequency is 300 MHz and the temperature 1.3 °K. The cyclotron oscillations are labeled by their harmonic number.

when $\omega \approx \omega_c$ while geometric resonance is expected when $\omega \ll \omega_c$. The cyclotron frequency ω_c is equal to eH/m^*c, where m^* is the effective mass. This implies that ACR oscillations appear for lower fields than geometric-resonance oscillations. Moreover, the condition allowing the observation of ACR is $\omega\tau \gg 1$. It is much more restrictive than that required to observe geometric resonance which is $ql \gg 1$. Thus a variation of temperature (acting on τ) or frequency has much larger effect on $\omega\tau$ (which is, in our experiments, only slightly larger than unity) than on ql which is very large anyhow.

Taking into account these two remarks, the ACR oscillations have been rather easily identified. In Fig. 1, geometric oscillations are superimposed on the fundamental ACR oscillation and only one ACR set of oscillations can be observed.

We define $H_c = m^* c\,\omega/e$ and we will systematically use the reduced values of magnetic fields relative to H_c. The resonance condition can be expressed as $H_c/H_n = n$. Since the experimental variable oscillates in $1/H$, it is more convenient to measure $\Delta(1/H) = e/m^*\,c\omega$ and to use this relation to calculate the effective mass m^*. This method was used to draw a map of effective masses in the ab, bc, and ca planes.[10]

A plot of reciprocal reduced-resonance fields against harmonic number n, $H_c/H_n = f(n)$, should be a straight line passing through the origin and having slope 1. In the case of a propagation along the a or b axes, we often noticed that this line did not pass through the origin. Along these axes the periods were determined using only a very small number of oscillations so that the uncertainty was of the order of the shift of the line from the origin. However, on the many recordings which were taken the shift was sytematically found on the same side of the origin. In the case of a propagation along the c axis, a branch of effective masses has been determined much more accurately in a large angular range (40° to 75° from the a axis). Each period has been measured using six or seven oscillations. The ACR oscillations shown on Fig. 1 correspond to this branch, and the associated $H_c/H_n = f(n)$ line is plotted on Fig. 2. It can be clearly seen that this line does not pass through the origin and that there is a phase shift $\Delta\phi$. This shift of the resonant fields has been observed for all the periods of this branch of effective masses. The uncertainty on this measurement is about ten times smaller than the shift.

The possibility of experimental error due to a slight misalignement of the experimental setup can be easily eliminated. If we assume that the angle between $\vec{q}$ and $\vec{H}$ is $(\frac{1}{2}\pi - \alpha)$ instead of $\frac{1}{2}\pi$, there is a Doppler shift of the frequency seen by the electrons, which is $\omega_{\text{eff}} = \omega(1 \pm \alpha v_H/v_s)$, where v_s is the sound velocity and v_H the velocity of the electrons in the direction of the magnetic field. The resonance condition is now $\omega_{\text{eff}} = n\omega_c$, which leads to

$$H_c/H_n = n\,(1 \pm \alpha v_H/v_s)^{-1}.$$

We can see that this misalignment would only produce a slight change of the measured effective mass but no phase shift.

Such a phase shift has already been observed in AKCR experiments[11] and has been explained by a finite value of $\omega\tau$. It must be noticed that the phase shift observed in Ref. 11 was of the order of 0.12 whereas in our experiments it reached 0.4.

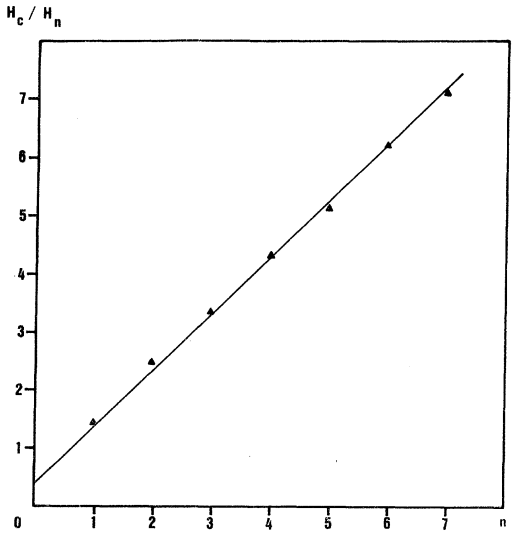

FIG. 2. Reciprocal reduced-resonance fields as a function of harmonic number n for the cyclotron oscillations referred to in Fig. 1. $\Delta\phi = 0.4 \pm 0.05$.

A straightforward numerical calculation based on the existing theory of ACR,[3] done with a finite value of $\omega\tau$, does not explain this effect. It leads to a phase shift an order of magnitude smaller than the experimentally observed one.

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Some Numerical Corrections to the Lattice Thermal Resistivity Due to Dislocations*

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Dislocation densities estimated from the increase of the lattice thermal resistivity in cold-worked alloy samples have been found to exceed measured values by a factor of 6. Some of the factors which may have contributed to the discrepancy are examined. This examination leads to some numerical corrections of the expression for the lattice thermal resistivity which substantially reduce the discrepancy.

I. INTRODUCTION

The reduction in the lattice thermal conductivity of alloys due to dislocations can be used to estimate dislocation densities in cold-worked specimens, if the scattering of phonons by dislocations is known. A comparison of the dislocation density calculated from the observed increase in thermal resistivity with dislocation densities of the same specimen derived by other means is thus essentially a test of the theory of phonon scattering by dislocations.[1-3] The thermal resistivity has been compared with dislocation counts from electron micrographs[4] and with the stored energy of dislocations,[5] and thus with an indirect measure of dislocation densities. In both instances the dislocation densities deduced from the lattice thermal resistivity were higher by a factor of 6 and 9, respectively. This would indicate that the theory underestimates the scattering of phonons. It is the purpose of the present paper to examine some of the factors which may have contributed to these discrepancies. These factors are (a) a confusion in the literature between two measures of dislocation density (previously discussed by Schoek[6]), (b) the fact that scattering differs for screw and edge dislocations, and an appropriate average should be used for random arrays which are assumed, (c) in the comparison with stored energy the theoretical value of the energy referred to an edge dislocation, while the value for phonon scattering was that of a screw dislocation, and (d) impurity atmospheres may have enhanced the scattering in the case of brass. This examination leads to some numerical corrections of the expression for the lattice thermal resistivity which substantially reduce the discrepancy.

II. REVISIONS IN EXPRESSION FOR THERMAL RESISTIVITY

The original expression for the thermal resistivity due to dislocations was a rough estimate obtained by multiplying the thermal resistivity due to a screw dislocation perpendicular to the temperature gradient by a geometrical factor of 0.55, to obtain the thermal resistivity of a randomly oriented dislocation, and then by the density of dislocations N_d.