Cyclotron Resonance in Magnesium in the Field-Normal Geometry*

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Data are presented for cyclotron-resonance signals in magnesium with the magnetic field oriented perpendicular to the specimen surface. The characteristics of these signals strongly suggest that they must arise from charge carriers on trajectories that lie entirely within the skin depth.

Starting with the work of Galt and his co-workers,[1,2] there have been many observations of cyclotron-resonance signals in metals with the magnetic field $\vec{H}$ oriented perpendicular to the surface of the specimen. However, in contrast to the situation for $\vec{H}$ parallel to the specimen surface (the Azbel'-Kaner geometry), there is little agreement on the precise mechanism responsible for these signals. Galt, Merritt, and Klauder[3] have attempted to explain the field-normal signals in cadmium by higher-order terms in the surface-impedance expression given by Dingle,[4] coupled with delicate "interference" effects from different charge carriers. Naberezhnykh and Dan'shin,[5] again invoking higher-order terms in Dingle's surface-impedance expression, have concluded that the cadmium field-normal signals arise from electrons that have, within their cyclotron period, an extremal displacement along the magnetic field. The only reasonably rigorous theory is that by Miller and Haering[6] for the case of a single, isotropic charge carrier. This theory predicts no resonance at all near the classical cyclotron-resonance field, but rather one Doppler shifted to a much higher magnetic field strength.

The purpose of this Letter is to present data for cyclotron-resonance signals in magnesium observed with $\vec{H}$ perpendicular to the specimen surface. These data shed considerable light on the nature of such signals and strongly suggest that they must arise from charge carriers on trajectories that lie entirely within the microwave skin depth at the surface of the specimen. The strength of these signals is quite comparable to that of the signals observed with $\vec{H}$ parallel to the surface. Subharmonic resonances are present as in the case of the Azbel'-Kaner geometry. However, their relative strengths and the dependence of this strength on the polarization of the oscillating electric field are appropriate to trajectories that lie entirely in the skin depth.

The reflection microwave spectrometer used for this investigation was essentially identical to that employed by Zych and Eck[7] for their Azbel'-Kaner cyclotron-resonance study of the Fermi surface of Mg. The detected signal is proportional, for low magnetic field modulation amplitude, to dR/dH, the field derivative of the surface resistance. $\vec{E}_{rf}$, the oscillating electric field at the surface of the specimen, was linearly polarized and could be oriented along any crystallographic direction in the specimen surface by rotating the movable half of the resonant cavity. The Mg single crystals were grown directly from the vapor phase and had residual resistance ratios $[\rho(300°K)/\rho(4.2°K)]$ in excess of 10^5. All measurements were carried out at a frequency of 22.9 GHz and a temperature of 2°K. The reader is referred to Ref. 7 for details of the spectrometer and sample preparation.

Figure 1 shows recorder traces of signals ob-

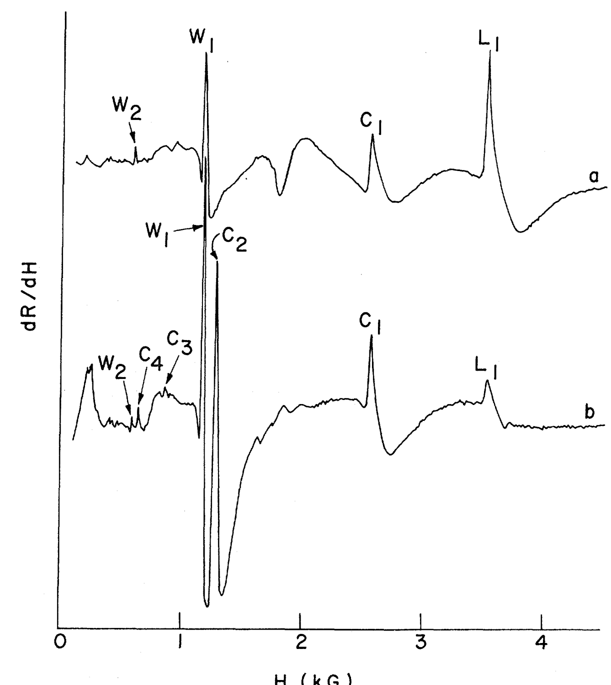

FIG. 1. Cyclotron-resonance signals in Mg for $\vec{H}$ perpendicular to the surface of a $\{11\bar{2}0\}$ specimen. For trace *a* $\vec{E}_{rf}$ is parallel to $\langle 0001\rangle$, and for *b* parallel to $\langle 10\bar{1}0\rangle$.

tained with $\vec{H}$ perpendicular to the surface of a $\{11\bar{2}0\}$ specimen. Trace a is for $\vec{E}_{rf}$ parallel to $\langle 0001\rangle$, and b for $\vec{E}_{rf}$ parallel to $\langle 10\bar{1}0\rangle$. The sharp resonance peaks in Fig. 1 are labeled with the letters L, C, and W with subscripts indicating the subharmonic number of the particular resonance. The L signals arise from electrons on the central orbit of the lens-shaped electron surface in the third band of Mg, the C signals from the central orbit on the "clam" (third- and fourth-band electron combination sheet of the Fermi surface), and the W signals from the orbit about the waist of the "monster" (second-band hole surface). The field strengths at which these peaks occur are identical within our precision of 0.5% to the field strengths observed for these peaks in the Azbel'-Kaner geometry, i.e., for $\vec{H}$ parallel to $\langle 11\bar{2}0\rangle$ and parallel to the surface of a $\{10\bar{1}0\}$ or $\{0001\}$ specimen. Figure 2 shows the shapes and orientations of the L, C, and W trajectories.[8] These were taken from Kimball, Stark, and Mueller's[9] pseudopotential band-structure calculation, which is known to give an excellent representation of the Fermi surface of Mg.

With $\vec{H}$ perpendicular to the surface of a $\{10\bar{1}0\}$ specimen and $\vec{E}_{rf}$ parallel to $\langle 0001\rangle$, we observe the L_1, L_3, and L_5 signals with strengths decreasing rapidly with increasing subharmonic number. There is even a hint in the data of the L_7 peak, but not a trace of the even subharmonic resonances. The L_3 signal is probably present in trace a of Fig. 1, but is obscured by the W_1 signal which occurs at the same field strength for $\vec{H}$ parallel to $\langle 11\bar{2}0\rangle$.

If it is granted that the signals we observe are due to electrons which execute their entire free paths between collisions in the presence of the oscillating electric field in the skin depth, most

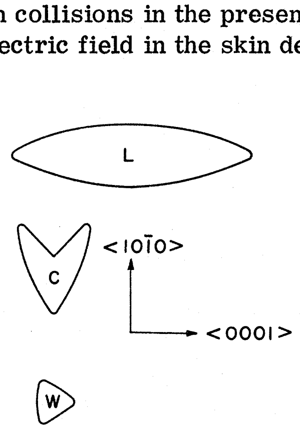

FIG. 2. Shape and orientation of the lens (L), clam (C), and monster-waist (W) trajectories in Mg for $\vec{H}$ parellel to $\langle 11\bar{2}0\rangle$.

of the qualitative features of our data are obvious consequences of the shapes of the trajectories shown in Fig. 2. The absence of even subharmonic signals for the lens is a result of the twofold rotational symmetry of the L trajectory. The re-entrant character of the C trajectory explains the strong even subharmonic signals for the clam when $\vec{E}_{rf}$ is parallel to $\langle 10\bar{1}0\rangle$ compared to their absence when $\vec{E}_{rf}$ is parallel to $\langle 0001\rangle$. Similarly, the dependence of the strengths of the L_1 and W_1 signals in Fig. 1 on the direction of $\vec{E}_{rf}$ is just what one would expect from the shapes and orientations of the L and W trajectories.

The sharpness of the resonance peaks in Fig. 1 indicates a long relaxation time (long time between collisions) for the electrons responsible for these signals. However, the weakness of the higher-order subharmonics of a given subharmonic series would argue for a short relaxation time if we were considering Azbel'-Kaner cyclotron-resonance signals. This apparent conflict can be resolved if we interpret the sharpness of a signal as a measure of the relaxation time of the electrons contributing to it and its strength as a measure of the number of these contributing electrons. It is reasonable to expect that the range of orbits about the central L, C, and W orbits which contribute to a given resonance peak would decrease fairly rapidly with increasing subharmonic number, since the increased time to traverse a subharmonic trajectory would allow electrons with even small drift velocities to spiral out of the skin depth or scatter at the surface.

As $\vec{H}$ is tilted from the normal to the specimen surface, there is no substantial change in the shape or the strength of the observed signals until $\vec{H}$ departs from the surface normal by approximately 2 or 3 deg. Beyond this range the signals weaken slowly and gradually form normal subharmonic series of the kind reported by Koch and Kip.[10] These latter signals are essentially Azbel'-Kaner in character, since, while the electrons responsible for them return repeatedly to the skin depth, they spend only a small fraction of each cycle of their motion in the skin depth. The persistence of the field-normal signals out to several degrees from the normal is attributed to the approximately cylindrical character of the central regions of the lens, clam, and monster waist. For a cylindrical section of the Fermi surface the real-space trajectory lies in a plane perpendicular to the axis of the cylinder for any angle between $\vec{H}$ and the cylinder axis.

All of the field-normal signals that we have observed tend to have the same line shape independent of the particular orbit on the Fermi surface which gives rise to the signal. When the signal is weak, as, for example, W_2 in Fig. 1, its dR/dH line shape closely resembles that predicted by Chambers[11] for the Azbel'-Kaner signals from regions of the Fermi surface where the cyclotron effective mass m^* is locally constant with varying k_H. For the stronger signals, such as L_1 and W_1 in trace a of Fig. 1, this line shape is distorted by the presence of a broad, deep minimum on the high-field side of the resonance. We speculate that the basic line shape for the field-normal signals is the Chambers constant-m^* line shape, and that the broad minimum on the high-field side of the stronger signals is associated with a wave propagation phenomenon of the type discussed by Walsh.[12] If one had to choose a line shape for the field-normal signals from among Chambers's three basic Azbel'-Kaner line shapes, it would be reasonable to pick the constant-m^* line shape, since little mass variation is to be expected over the band of orbits that contribute to a field-normal signal.

We wish to thank W. L. Gordon for several helpful discussions and W. M. Walsh, Jr., for his suggestion that wave propagation phenomena may play an important role in determining the line shape of our signals.

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Nonhydrogenic Exciton and Energy Gap of GaAs

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The free-exciton series $n = 1, 2, 3$ in high-purity GaAs has been observed in photoluminescence and photoconductivity. The $n = 1$ peak shifts upon changing the excitation level because of free-carrier screening. Anisotropy and exchange effects as well as two valence bands must be included to interpret the series spectrum of this Wannier-like exciton. New values are derived for the band gap at 1.6 K ($E_g = 1.5189 \pm 0.0001$ eV) and for the $n = 1$ excitonic binding energy [$E_X(1s) = 3.77 \pm 0.05$ meV].

Free-exciton states have been calculated by several authors for the Frenkel and Wannier cases.[1] These calculations do not apply directly to zinc-blende semiconductors because of their degenerate valence bands at Γ. Recently Baldereschi and Lipari[2] (BL) considered this degeneracy and also determined the effect of valence-band anisotropy upon the states of free excitons. Rohner[3] treated exchange interaction; earlier Abe[4] calculated numerically this energy for GaAs. In high-purity materials experimental tests for these calculations are still lacking.[5]

This Letter presents spectra of near-band-gap photoluminescence (PL) and photoconductivity (PC) of high-purity GaAs, including data at *very low* excitation levels. The $n = 1$ free-exciton emission is found to shift towards higher energies with increasing excitation intensity because of screening by free carriers.[6] We measure a definitive energy for the $n = 1$ state at vanishing