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MILLIMETER CYCLOTRON RESONANCE EXPERIMENTS IN DIAMOND

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Cyclotron resonance has been observed in several semiconducting diamonds at 70 kMc/sec and at helium temperatures. For magnetic fields below 33.5 kilo-oersteds, two strong lines have been observed having effective masses of $(0.70\pm 0.01)m_0$ and $(1.06\pm 0.04)m_0$ with little or no anisotropy. The experiments will be described in this Letter.

The 4-mm wave spectrometer system is similar to a 2-mm spectrometer described previously,[1] with the following exceptions. A three-port circulator[2] and a commercial 1N2792 crystal detector are used to observe the signal reflected from the microwave cavity which operates in the TM_{013} mode and has a loaded Q factor of about 1500. As previously, the samples are positioned in the high axial electric field of the cavity for cyclotron resonance. The static magnetic field is obtained from a commercial 12-inch electromagnet with a 9/16-inch pole face gap. The light modulation of carriers and detection system as described previously is used.

The diamond crystals which were investigated are of the IIb variety.[3] Resonance was observed in only a few of the samples, and there appears to be a qualitative agreement of crystal perfection as determined from x-ray data with the observed linewidths in the spectrum. Some samples having $\omega\tau$ less than unity exhibited the characteristic nonresonant microwave magnetoresistance. Figure 1 shows a typical experimental trace in one of the better samples.

The curve is a reproduction of a recorder trace of the absorption at 69.2 kMc/sec as a function of magnetic field. The data were obtained at an ~0.1-microwatt rf power level at 1.2°K with a low level of light excitation. Lines are observed at $0.70m_0$ and at $1.07m_0$ having linewidths given by $\omega\tau\approx 13$ and $\omega\tau\approx 7$, respectively. The recorder trace of absorption is taken as a linear function of magnet current but the magnetic field is linear only through the low-field line. The high-field line falsely appears to be asymmetrical and much broader than twice the low-field line, but this results from a progressive increase in nonlinearity of the magnetic field.

Absorption line intensities decrease upon moving the sample to a region of weaker rf electric field, thus indicating that cyclotron rather than paramagnetic resonance is observed. Detailed anisotropy measurements indicate that little or no anisotropy exists in either resonance within the limits of accuracy of the experiment. At 4.2°K, the spectrum below 33.5 kilo-oersteds is very similar with the exception of unresolved structure on the low-field side of the low-mass line. On occasion at relatively low rf level, both at 4.2°K and 1.2°K, a weak line at about $0.5m_0$ is observed which may be a "quantum effect" line.

An attempt to observe resonance in the conduction band by exciting carriers across the gap (5.5 ev) with a hydrogen arc has not been successful.

The carriers which are observed have been excited with a tungsten light source which does not visibly glow, thus suggesting that the resonances are due to carriers in the valence band since the

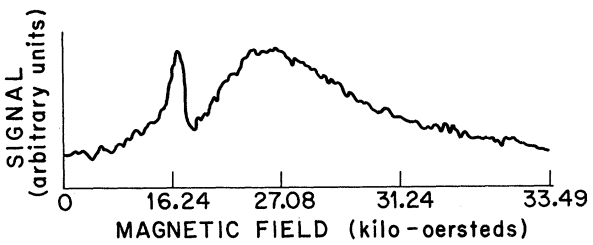

FIG. 1. Experimental trace of cyclotron resonance absorption in diamond at 69.2 kMc/sec and 1.2°K.

impurity levels in the IIb's lie a few tenths of a volt above the valence band.[4] An estimate of the spin-orbit splitting Δ of the order of 0.005 volt from atomic data suggests that possibly the constant-energy surfaces cannot be simply expressed by[5]

$$E(k)=Ak^2\pm[B^2k^4+C^2(k_x^2k_y^2+k_y^2k_z^2+k_z^2k_x^2)]^{1/2},$$

which is good for the valence band of germanium[6] and silicon,[7] but that higher order terms must be taken into account in the secular determinant for diamond. It has been suggested[8] that the low-mass line is due to the light hole, and that the high-mass line, being isotropic, is a spherical energy surface which goes with the split-off band, and that the heavy hole should be anisotropic and have a mass of $\sim 3m_0$. Further experiments are in progress to clarify the data.

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ELECTRIC-FIELD-INDUCED MODULATION OF THE ABSORPTION DUE TO INTERBAND TRANSITIONS OF FREE HOLES IN GERMANIUM

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Provided the structure of the valence band of Ge in the vicinity of $\vec{k}=0$ is independent of temperature, then the absorption due to direct interband transitions[1-3] depends on temperature only through the distribution function of the free holes. The distribution function is of prime importance in determining the absorption, and any agency which changes the energy distribution of holes in $\vec{k}$ space will produce a corresponding change in absorption. It is possible, therefore, to study the effect of a high electric field (E) on the distribution function in a direct manner. In principle, if the details of the band structure are known, it is possible to relate a photon energy with a range (because of warping) of $\vec{k}$ for both types of hole and hence to obtain the distribution function in $\vec{k}$ space of both light and heavy holes. Such a relationship is shown in Fig. 1 for transitions to the split-off band, for a band structure calculated as described below. The arrows indicate the value of k^2 at which the energy of the hole (light or heavy according to band) is $\frac{3}{2}kT$.

In practice the change in absorption was observed due to a change in distribution produced by the high field; such a differential method is inherently more sensitive than a method measuring the total absorption. In a subsidiary experiment performed for the purpose of comparison, the distribution function was changed in a known way by raising the lattice temperature a small amount and the change in absorption observed (to be referred to as the δT effect). The change in absorption can be calculated from Kane's[3] theory. Taking the spin-orbit splitting as 0.290 ev, and the other band-structure parameters as given by Kane—but modifying the energy dependence on $\vec{k}$ of the split-off band by 30%, as Kane suggests, crudely to allow for higher order perturbation terms not rigorously included—the change in absorption due to a 13.5% increase of temperature of a Maxwellian distribution at 93°K (Fig. 1, curve 1) and 293°K (Fig. 2, curve 1) has