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Dresselhaus G, Kip A F & Kittel C. Cyclotron resonance of electrons and holes in silicon and germanium crystals. *Phys. Rev.* 98:368-84, 1955.
[Department of Physics, University of California, Berkeley, CA]

The results of cyclotron resonance experiments on carriers in silicon and germanium single crystals near 4K are presented. A description is given of the light modulation technique that gives good signal-to-noise ratios. The sign of the charge carrier is determined by experiments with circularly polarized microwave radiation. The symmetry-allowed analytic form of the energy surfaces near the conduction and valence band edges is presented and the effective mass parameters are evaluated from the experimental observations. [The *SCI*® indicates that this paper has been cited in over 625 publications since 1955.]

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"This classic paper established the validity of theoretical models for electronic states in periodic solids for quantitative explanations of observed behavior. The research program that led to this experiment resulted from advances at Bell Laboratories in materials synthesis associated with semiconductor device technology that made possible the preparation of the semiconductors Si and Ge with extremely high purity and perfection. The experimental techniques, materials, and theoretical understanding were all developed in various research laboratories, and it remained for the Berkeley group led by C. Kittel to put it all together.

"Since Berkeley was at the forefront in the development of the cyclotron through the pioneering work of E.O. Lawrence,[1] it is appropriate to mention the fact that the magnet that we used in our first cyclotron resonance experiments in semiconductors had served Lawrence as a prototype magnet for his early cyclotron models.

"Similar experiments at Bell were carried out on doped materials near the temperature of maximum carrier mobility,[2] but the Berkeley group showed that, at this temperature, the carrier concentration is so high that plasma resonance effects modify and interfere with cyclotron resonance, and for this reason the Bell experiment was unsuccessful. Shockley's calculations had indicated that the experiment should be carried out at N_2 temperatures in order to have enough thermally activated carriers to see cyclotron resonance while eliminating the carrier scattering events due to lattice vibrations.[3] All the successful experiments at Berkeley were carried out in the liquid He temperature region. The carrier concentration was increased to give an observable signal by either avalanche breakdown on resonance or by optical excitation of carriers across the band gap.

"The first experimental observation of cyclotron resonance in Ge was very exciting. A.F. Kip was at the controls of the spectrometer while Kittel and I, along with other members of the research group, were offering lots of advice and encouragement in the background. The experimental results were unambiguous but indicated a significantly different model from that which was generally accepted at the time.

"I looked into some of the possible analytic forms for the electronic dispersion relations for E(k) that the valence band (holes) could satisfy and derived a simple analytic expression that represented an advance in sophistication in band theory.

"We announced our discovery in a short letter communication[4] in *Physical Review*. The experiment was sufficiently simple so that other groups immediately started reporting similar observations. This competition stimulated us to work tirelessly to complete the initial phase of our work. We knew at the time we wrote the paper that this was an important piece of work, and Kittel insisted that the quality of the presentation reflect the importance of the work.

"Subsequently, the Buckley Prize of the American Physical Society was awarded in 1957 to C. Kittel for work related to the first observation of cyclotron resonance. Both Kip and Kittel are now retired, but their classic work as well as the students whom they trained have resulted in significant advances in our knowledge of solid-state physics. For a recent publication in this field, see reference 5."

1. **Alvarez L W.** The early days of accelerator mass spectroscopy. *Phys. Today* 35:25-32, 1982.
2. **Fletcher R C, Yager W A & Merritt F R.** Observation of quantum effects in cyclotron resonance. *Phys. Rev.* 100:747-8, 1955.
3. **Shockley W.** *Electrons and holes in semiconductors*. New York: Van Nostrand, 1950. 558 p.
4. **Dresselhaus G, Kip A F & Kittel C.** Observation of cyclotron resonance in germanium crystals. *Phys. Rev.* 92:827, 1953. (Cited 95 times since 1955.)
5. **Kittel C.** *Introduction to solid state physics*. New York: Wiley, 1976. 599 p.