27 October 1961, Volume 134, Number 3487

SCIENCE

CURRENT PROBLEMS IN RESEARCH

Cyclotron Resonance

This phenomenon has proved to be a powerful tool for the study of the electronic energy bands in solids.

Benjamin Lax

Resonance phenomena in solids have been extensively investigated since World War II, due primarily to the development of microwave techniques which were a by-product of the accelerated radar effort in America and in England. Magnetic resonance, which involves the interaction of the magnetic dipole of the electron or the nucleus, has until recently been the most popular resonance phenomenon investigated, but electrical resonance, better known as cyclotron resonance, although much older, has now come into its own. Cyclotron resonance was first encountered by ionospheric physicists some thirty-odd years ago and more recently has been investigated in ionized gases, and also with free electrons. However, it is in solids that cyclotron resonance has demonstrated its tremendous potentialities as a tool for basic investigations. The initial experiments in semiconductors represented a dramatic demonstration of some of the fundamental predictions of quantum mechanics as applied to solids. These early results constitute an experimental proof of the existence of energy bands and the effective mass of an electron in a solid.

When a free electron is allowed to move in the presence of a magnetic field, it executes a helical path axially about the direction of the magnetic field (Fig. 1, left) with a component of the velocity (that is unaffected) parallel to the magnetic field and a rotational component transverse to the magnetic field (Fig. 1, right) whose cyclotron frequency ν_c is given by the well-known expression

$$\nu_c = \frac{1}{2\pi}\frac{eH}{m_0 c} = 2.8 \times 10^6 H \text{ (gauss) Mcy/sec} \quad (1)$$

In this equation e is the charge of the electron, m_0 is its mass, c is the velocity of light, and H is the magnetic field. If an alternating electric field is oriented perpendicular to the magnetic field and is superimposed on the system, a small oscillatory component is added to the rotational motion of the electron. However, if the frequency of the alternating field is made equal to the cyclotron frequency—that is, if $\nu_c = \nu$, then the motion in the transverse plane will no longer be oscillatory but will become an ever-expanding spiral in which the electric field will be in phase with the rotation just as in the dees (*1*) of a cyclotron, so that the electron will absorb energy resonantly at every cycle.

Of course in a practical system, such as a gas or a solid, this cannot continue indefinitely, since the electron must either collide with a neutral atom or, in a solid, with impurities and imperfections in the crystal. If there are no such impurities or imperfections, the limiting time between collisions is determined by the thermal vibrations of the lattice, which represent a deviation from a perfect crystal and can "scatter" the electron and thereby limit its free time or collision time, τ. The magnitude of τ increases as the temperature of the crystal is lowered, since the amplitude of the vibrations are decreased. The occurrence of collisions gives rise to a well-defined absorption peak at the cyclotron frequency which is found by varying or tuning the magnetic field above and below the value corresponding to cyclotron resonance.

Resonance in Gases

Such an experiment was first carried out in the ionosphere about 35 years ago (*2*) by propagating waves at radio frequencies of the order of 1.5 megacycles corresponding to the cyclotron resonance of the electron in the earth's magnetic field. Subsequently, these experiments were performed in the laboratory at higher frequencies, in ionized media contained in glass tubes in the presence of external magnetic fields of the order of several hundred gauss (*3*). Perhaps the most definitive experiment was that carried out in a copper microwave cavity at microwave frequencies (3000 megacycles), in which the resonance phenomenon was observed by determining the minimum in the threshold microwave electric field required for ionizing the gas at low pressures (*4*). In addition, the breakdown was controlled by diffusion of the ionized particles to the wall. When both of these phenomena were taken into account theoretically, the comparison between the experimental and theoretical curves provided excellent confirmation of the analysis, as shown in Fig. 2. The mini-

The author is head of the Solid State Division, Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, and director of the M.I.T. National Magnet Laboratory.

mum in the breakdown corresponds to the resonance condition $\nu = \nu_c$, since at this value of the magnetic field the energy transfer between the alternating electromagnetic field and the electron is a maximum and the field required to ionize the gas is therefore minimized.

In the last decade the intensified activity in plasma research has revived interest in cyclotron resonance of positive ions in a gaseous medium. The objective in this case is to permit an efficient energy exchange between a radio-frequency source and the positive ions in order to heat up the fully ionized gas to energies sufficiently large to initiate a thermonuclear reaction. Although this scheme has not succeeded, a number of interesting experiments involving the resonance of charged nuclei have been performed. Since the nucleus is much heavier than the electron, the resonance equation, which states that the frequency is inversely proportional to the mass, gives for the proton a frequency

$$\nu = 1.5\, H \text{ (gauss) kcy/sec} \qquad (2)$$

where the frequency, ν, is in kilocycles per second and the magnetic field is in gauss. Thus, for fields of the order of 10,000 to 20,000 gauss, which are obtainable in large coils, the corresponding frequency is from 15 to 30 megacycles per second.

In a fully ionized plasma, at low pressures of the order of 1 micron of mercury, the electron density is approximately 10^{13} per cubic centimeter. Normally there is a cutoff or critical frequency associated with such a plasma, due to the electrons, whose frequency ν_p is given by the relation

$$\nu_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m_o}} \qquad (3)$$

where N is the electron concentration per cubic centimeter, e is the electric charge, and m is the electron mass. Below this critical frequency the radio wave is reflected by the plasma. The value for the frequency is given by

$$\nu_p \approx 9 \times 10^3\, N^{\frac{1}{2}} \text{ cy/sec} \qquad (4)$$

Consequently the cutoff frequency for an electron concentration of 10^{13} per cubic centimeter corresponds to approximately 3×10^{10} cycles per second —well into the microwave region. The depth of penetration, δ_p, of the electromagnetic field into the plasma is of the order of the wavelength at this frequency—namely, 1 centimeter. This is much too small for effective heating of ions in a large volume of gas, since only the surface of the plasma is affected. Fortunately, however, the use of a high magnetic field can serve to decrease the effective plasma frequency of the electrons and, in accordance with the following relation, increase the penetration depth δ into the plasma, so that

$$\delta = \delta_p\, (\nu_c)^{\frac{1}{2}}/\nu \qquad (5)$$

where ν_c is the cyclotron frequency of the electron and ν is the radio frequency of the electromagnetic wave of

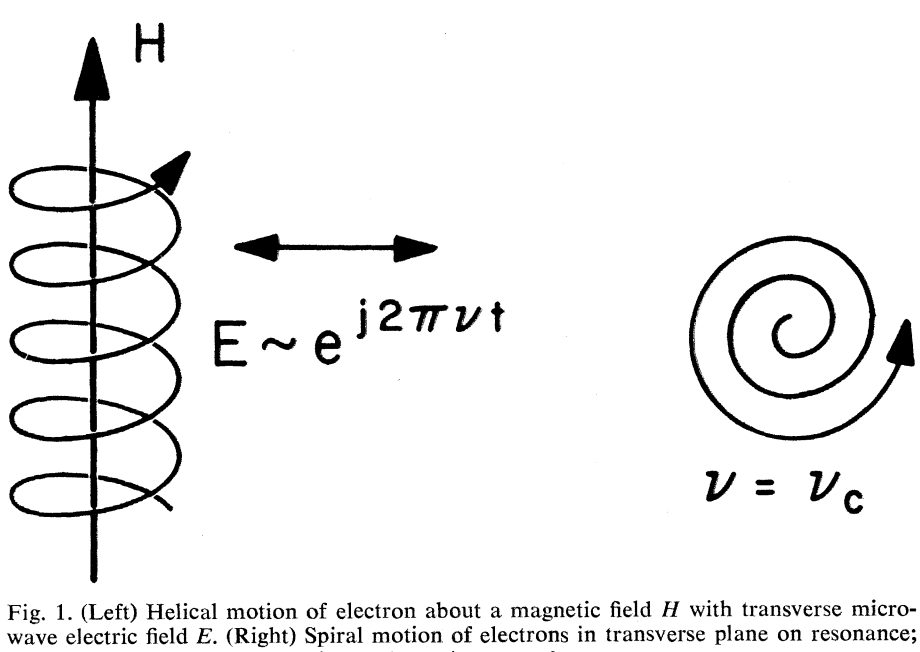


Fig. 1. (Left) Helical motion of electron about a magnetic field H with transverse microwave electric field E. (Right) Spiral motion of electrons in transverse plane on resonance; that is, cyclotron frequency ν_c is equal to microwave frequency ν.

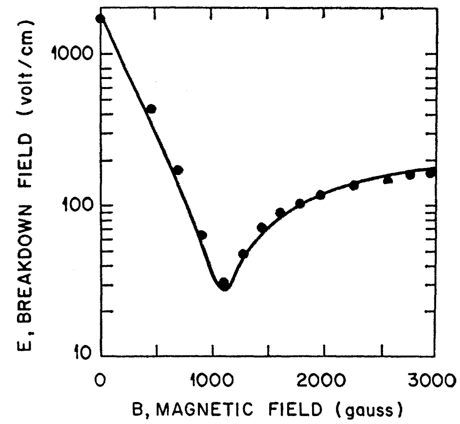


Fig. 2. Ionizing field for breakdown of helium gas at 1 millimeter pressure in a cylindrical microwave cavity at 3000 Mcy/sec. Solid line, theoretical curve; points, experimental data. [After B. Lax, W. P. Allis, and S. C. Brown (*4*)]

the resonance of the ions. The former, for 20,000 gauss, corresponds to a frequency of 5.6×10^{10} cycles per second, and therefore the penetration depth is increased in excess of 1 meter, so that the radio-frequency energy can now permeate the entire plasma, which might be several feet in diameter in a practical experiment.

In carrying out such an experiment, the technique requires that the ionized gas contained in a large discharge tube be surrounded by a coil which is energized by a high-frequency generator. As the ions absorb energy resonantly, the load on the generator becomes noticeable and can be measured in terms of the power output into the plasma. One contributing reason for the failure to energize the plasma to the desired ion energies by cyclotron resonance heating is that the ion acquires greater and greater energy and a so-called runaway condition ensues which makes the ion cloud much more highly conducting, until the conductivity of the gas becomes comparable to that of a metal. Under these conditions, once again the electromagnetic radiation of the radio frequency fails to penetrate the entire plasma, and the process becomes essentially self-limiting. Nevertheless, from a scientific point of view the observation of cyclotron resonance of ions or a mixture of ions can be successfully accomplished and has been observed in the experimental Stellarator at Princeton (*5*), as shown in Fig. 3. This curve demonstrates the resonance absorption of hydrogen and helium ions as the magnetic field is varied for fixed radio frequencies.

Resonance in Solids

Cyclotron resonance experiments in solids are performed in an entirely different manner and provide very different types of information. In the first place, if we are to carry out these experiments at microwave frequencies, as previously stated, it is necessary that the mean free time, τ, between any scattering events due to impurities, imperfections, or vibrations of the lattice be reduced in such a way that the product of the angular frequency ω equals $2\pi\nu$ and the relaxation time is greater than unity—that is, $\omega\tau > 1$. This means that the electron describes more than a radian of its arc during one cycle of the alternating field before it is scattered. When this condition is fulfilled, then the absorption as a function of the magnetic field has a well-defined maximum or resonance peak, which becomes sharper as the product $\omega\tau$ increases. This is indicated in Fig. 4. In order to achieve the above condition, it was found necessary to purify the material to an extremely high degree and to grow crystals of extreme perfection, in which the imperfections could not be detected by modern metallurgical techniques under the most powerful electron microscope.

In 1953, when this experiment was contemplated, the only two materials that possessed these remarkable qualities of perfection were germanium and silicon. The foreign chemical impurities were reduced to less than 1 part in a billion by chemical refining and the development of zone refining, which further segregated and removed the impurities. Although the resultant single crystals were mechanically perfect, nevertheless, it was necessary to immerse the crystal in liquid helium in order to reduce the vibrations of the atomic lattice, so that the scattering of the electron due to this effect would be sufficiently low to permit observation of a well-defined resonance.

The use of liquid helium, however, created another problem, but this was not too difficult to overcome. Semiconductors at these temperatures lose their electronic conductivity and for all practical purposes become insulators. This occurs because the electrons are no longer free to wander throughout the crystal but become trapped by the residual impurities ($10^{13}/cm^3$), since the binding energy due to the Coulomb attraction of the impurity is greater than the energy of the thermal vibrations of the lattice at these low temperatures. This situation is actually not a disadvantage, since it makes it possible to control the number of free conducting electrons that are introduced into the crystal for resonance. If the concentration of free electrons is too great, the microwave field cannot penetrate the semiconductor material because it behaves essentially like a metal, which reflects the electromagnetic energy. Two methods have been used to reionize the weakly bound electrons. The first involved the use of microwave energy of the order of milliwatts, which was sufficiently high to ionize 10^8 to 10^{10} electrons per cubic centimeter by an avalanche process similar to that in a fluorescent lamp, but of course at a much lower power level. The other technique was to use infrared and optical radiation of sufficiently high energy to break the weak electrical bond of the electron to the impurity, or the stronger bond to the crystal itself, in order to create conducting electrons.

Such experiments in the two classic materials, germanium and silicon, turned out to be successful beyond expectation. One of the first demonstrations that was made was a direct proof of the existence of "holes" in semiconductors. A hole is an electric carrier which has an effective positive charge opposite to that of the electron. It is created in a semiconductor by the removal of an electron from the chemical bond; the semiconductor is then in a conducting state and a positive charge is left behind at the broken bond. However, since an electron in a neighboring atom which is bound to the crystal can readily jump

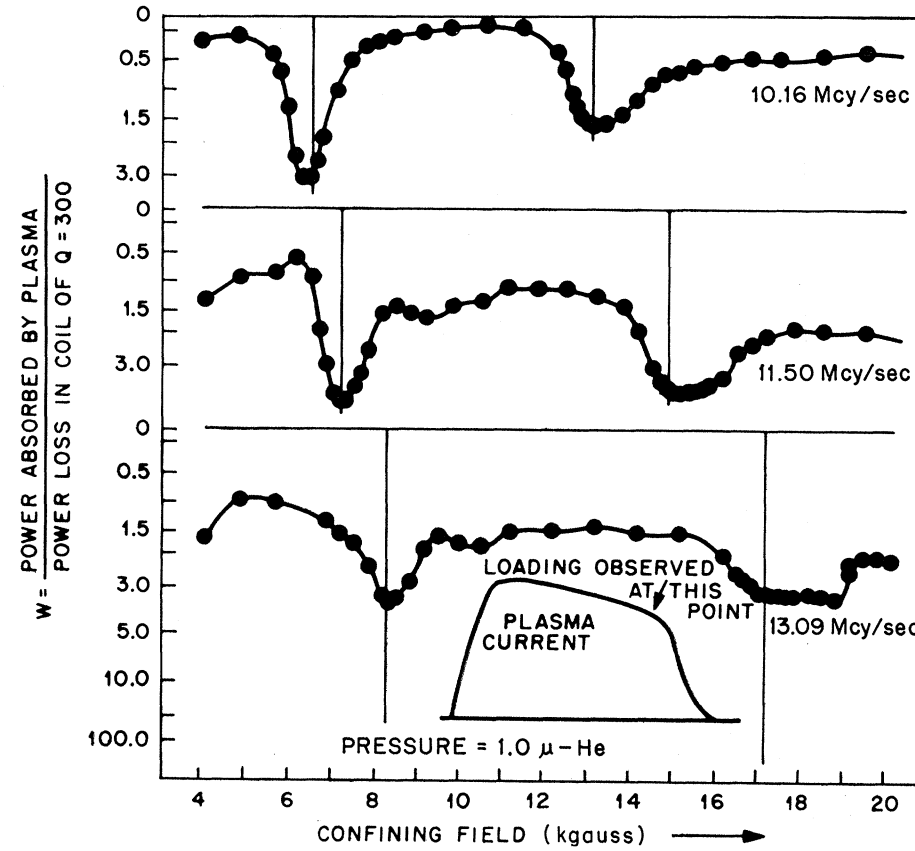


Fig. 3. Ion cyclotron resonance plasma loading plotted against confining field for various frequencies. Vertical lines are drawn for cyclotron field values for H^+ and He^{++} ions. Insert shows plasma current plotted against time and indicates time for which loading points were taken. [After T. H. Stix and R. W. Palladino (5)]

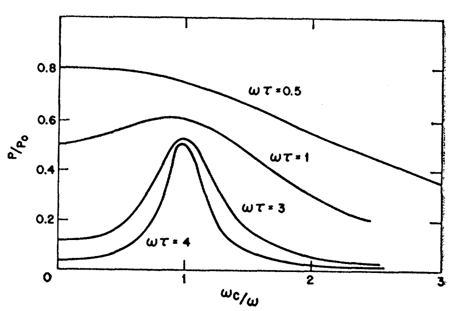
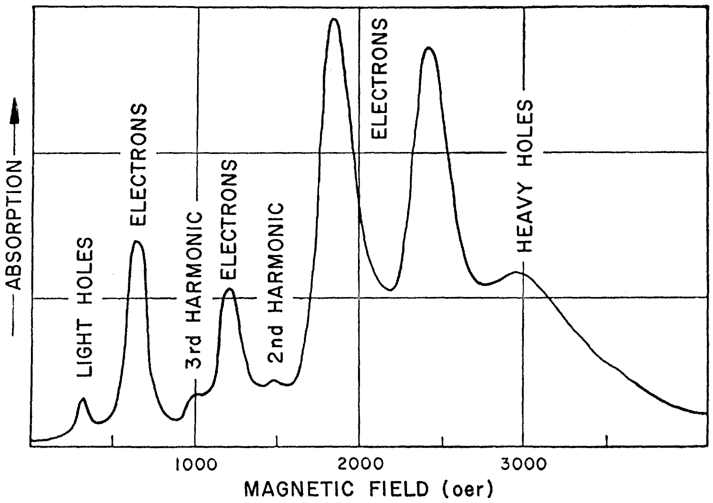


Fig. 4. Microwave power absorption P as a function of magnetic field or ν_c/ν, where ν_c is the cyclotron frequency of Eq. 1, P_0 is the absorption at zero magnetic field, τ, is the relaxation or collision time, and ω equals $2\pi\nu$, the angular frequency of the microwave field.



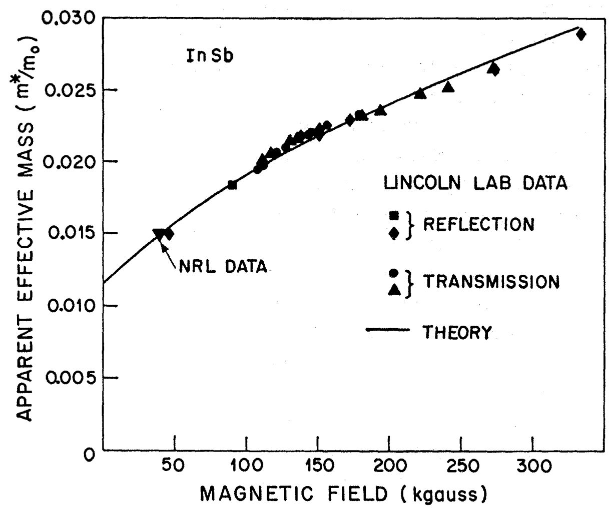


Fig. 5 (left). Cyclotron resonance trace in germanium at 4°K and 23,000 Mcy/sec. The orientation of the magnetic field was selected to show the eight resonances observed in germanium [after R. N. Dexter, H. J. Zeiger, and B. Lax (*36*)]. Fig. 6 (right). Variation of apparent effective mass with magnetic field in indium antimonide at room temperature [after B. Lax, J. G. Mavroides, H. J. Zeiger, and R. J. Keyes].

into the vacancy left by the first electron, the positive charge moves in a direction opposite to that of the jumping electron. Thus, in the presence of an electric field, this electrical vacancy, or hole, behaves as a positive charge.

The existence of this hole was demonstrated in two different ways by groups at Berkeley and at the Lincoln Laboratory (*6*), respectively, who had pioneered in these resonance experiments in semiconductors. The Berkeley group (*7*) used circularly polarized radiation in which the radio-frequency electric field rotated in a plane perpendicular to the magnetic field in a counterclockwise direction. Now, if an electron is assumed to rotate in a clockwise direction, resonance can only be observed if the circular polarization is in the same sense. Similarly, for a hole which rotates in the counterclockwise direction, it is the polarization in the counterclockwise sense that gives resonance absorption. The Lincoln group (*8*) resorted to techniques developed by the transistor people, who in essence demonstrated by this device the existence of the two kinds of carriers—holes and electrons. They took germanium, which had an excess of impurities with a valence of either five or three. In the case of an impurity with a valence of five, an excess electron is trapped at low temperatures, whereas for the impurity with a valence of three, a hole is trapped at the impurity Coulomb center. Upon ionization by the microwave field, these semiconductors conduct by electrons or holes, respectively, depending upon the valency of the impurity. The experiments were then repeated, but this time with excitation by infrared and optical wavelengths to demonstrate the existence of holes and electrons. By means of appropriate filters it was possible to filter out wavelengths at the higher energies, corresponding to optical radiation, and to permit only infrared radiation of low energy to strike the crystal. Thus in *n*-type and in *p*-type germanium, the infrared preferentially excited the electrons and the holes, respectively. However, when a quartz rod was used to transmit the energy of an incandescent source, the infrared light was filtered out and the "white light" at the optical frequency irradiated the crystal and was of sufficient energy to remove the electrons from their normal chemical bond, thereby simultaneously creating hole-electron pairs so that resonance lines of both carriers were observed, as shown in Fig. 5.

Figure 5 clearly illustrates a remarkable experimental manifestation of the consequences of quantum mechanics as applied to solids. Not only does it show the existence of the hole, which is a direct consequence of this theory, but it shows multiple resonances of both holes and electrons, which can only be explained by the quantum theory of energy bands. Before these experimental results were obtained, Shockley (*9*) had hypothesized the possible existence of such multiply degenerate energy bands, which would give rise to many resonance peaks. This was dramatically demonstrated by the discovery of the anisotropy of the resonances by the Lincoln group—a finding which, although differing in detail from these theoretical predictions, nevertheless agrees in principle. When the crystal was rotated in the magnetic field it was observed that the resonance peaks occurred at different values of the magnetic field, and in certain high-symmetry directions of the crystal only a single resonance peak for the electrons was observed. The detailed interpretation of these results elucidated the electronic band structure of germanium and silicon and set off a chain reaction of theoretical and experimental work which accounted for the electrical, magnetic, and optical properties of these materials.

Infrared Resonance

The important consequences of the cyclotron-resonance results in germanium and silicon prompted a vigorous effort to apply the microwave techniques to other semiconductors. Partial success was achieved in indium antimonide, and the mass of the electron was measured (*10*). This was found to be 0.013 m_0, where m_0 is the mass of the free electron. No definitive new data in semiconductors were obtained until 1959 when a number of II-VI compounds (*11*) such as cadmium sulfide, cadmium arsenide, and zinc arsenide, were obtained in sufficiently pure form to provide well-resolved spectra (*12*).

However, in the meantime, in order

to overcome the difficulties posed by the relatively impure semiconductors, it became apparent that cyclotron resonance at higher frequencies would be the solution. The logic in this is evident from the required relation $\omega\tau > 1$. Since τ is determined by the impurities in most materials, with a value of the order of $\tau \approx 10^{-12}$ sec, the frequency ν dictated by the above relation is $\nu \approx 6 \times 10^{12}$, which corresponds to a wavelength of 50 microns in the far infrared. From the fundamental resonance equation it becomes evident that if the frequency is increased by several orders of magnitude, the magnetic field required for resonance increases in proportion. Even for a small electron mass, as in indium antimonide, the field required at these wavelengths is approximately 50,000 gauss. Indeed, the Naval Research Laboratory group which first observed infrared cyclotron resonance in indium antimonide at 40 microns used a large solenoid with a field of this order of magnitude (*13*). Shortly thereafter the group at Lincoln Laboratory (*14*) performed a similar experiment at shorter wavelengths (from 10 to 20 microns), using pulsed magnetic fields as large as 300,000 gauss. The fields were obtained by discharging a large condenser bank through a small but rugged solenoid. The effective masses (deduced according to Eq. 1 from the data, which were recorded on a Polaroid film) showed a decided dependence on magnetic field.

The theoretical interpretation of this experiment, as indicated in Fig. 6 by the solid curve, truly represents a sequence of triumphs for the quantum theory of solids. Not only does it give a unique confirmation of the theoretically predicted form of the energy bands (*15*), but it requires a quantum mechanical model for cyclotron resonance in terms of quantized magnetic levels with a superimposed fine structure due to an anomalous electron spin, which splits the magnetic levels. The magnitude of the electron spin was also accounted for theoretically in terms of the quantum treatment of the energy bands and was shown to be 25 times that of the normal electron (*16*).

Without delving into the mathematics, one can construct a physical picture of cyclotron resonance which describes the essence of the theoretical treatment involved in obtaining the solid curve of Fig. 6. It can be shown from the quantum theory that when an electron finds itself in a magnetic field, the energy levels associated with this electron are quantized in energy, as indicated in Fig. 7, where each discrete magnetic level is designated by a number, from zero on up. The energy $\mathcal{E}_n$ of these levels in a simple parabolic band, where the energy $\mathcal{E}$ and momentum p have the relationship

$$\mathcal{E} = p^2/2m^*, \quad (6)$$

is given by the relation

$$\mathcal{E}_n = (n + \frac{1}{2})\ h\nu_c \quad (7)$$

where h is Planck's constant and m* is the effective mass. In this case these are equally spaced energy levels with properties analogous to a harmonic oscillator, except that the energy spacing corresponds to the cyclotron frequency.

For indium antimonide the situation, as mentioned previously, is a little bit more complicated because the energy-momentum relation is not parabolic, but the curvature decreases as a function of energy, as shown in Fig. 7. Hence, the quantum theory tells us that the energy-level spacings become closer for higher energy or increasing values of the quantum number n. In addition, the energy level is split by the electron spin; this is largely due to its anomalous character and is also indicated in the figure. In terms of the language of the quantum theory, cyclotron resonance corresponds to absorption of an infrared photon in which the electron is taken from state zero to state unity with the spin conserved as indicated. Thus, in terms of the two transitions shown in the diagram, each with the proper statistical weighting, the theoretical curve of Fig. 6 was obtained (*17*). Such cyclotron resonance experiments have been carried out in such materials as indium antimonide with more modest fields and longer wavelengths (of the order of 100 microns) and also in indium phosphorus, indium arsenide, and other, similar intermetallic semiconductors with small effective masses (*18*).

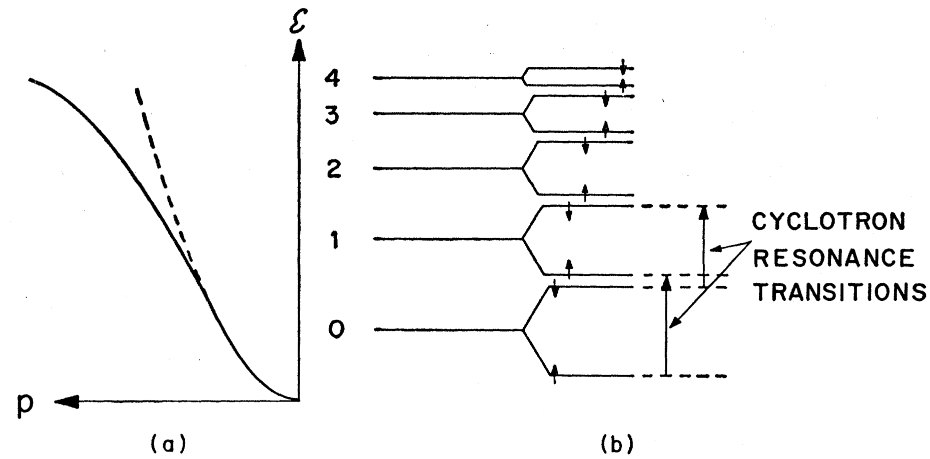


Fig. 7. Nonparabolic electron energy band in indium antimonide. (*a*) Energy $\mathcal{E}$ plotted against momentum *p*. For comparison the $\mathcal{E}$-*p* relationship for a parabolic band is also indicated (dashed line). (*b*) Nonuniformly spaced magnetic level structure for conduction band with spin splitting (arrows indicate spin up, spin down).

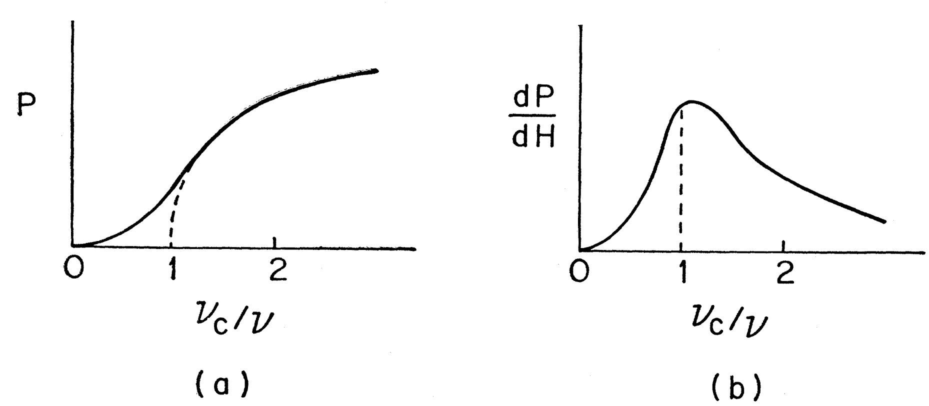


Fig. 8. Nonresonant cyclotron absorption in a metal.

Resonance in Metals

Early in the game those of us who were interested in cyclotron resonance in solids contemplated the possibility of carrying out experiments in metals similar to the experiments in semiconductors. Relatively simple theoretical analysis indicated that this type of resonance was not possible at microwave frequencies, although some of the metals considered could be obtained in sufficiently pure crystalline form. The obstacle to observing resonance absorption at microwave frequencies was created by the existence of the high electron concentration found in these metals. Metals which are nearly perfect reflectors at infrared and optical frequencies are also good reflectors at microwave frequencies. However, it was shown theoretically that a small amount of energy is nevertheless absorbed in a thin layer of the metal surface within a depth known as the "skin depth" (*19*). Furthermore, this absorption is nonresonantly dependent upon magnetic fields, as shown in Fig. 8. This type of nonresonant cyclotron-resonance absorption phenomenon was first observed in bismuth by the groups at Bell Telephone Laboratories (*20*) and at Lincoln Laboratory (*21*). The latter group demonstrated that it was possible to deduce the cyclotron resonance from such data by taking the derivative as a function of magnetic field, as shown in Fig 7*b*. Subsequently, the Bell Telephone group, using this technique, obtained very striking and significant results in graphite (*22*), which are shown in Fig. 9. The data, in addition to the fundamental adsorption associated with both holes and electrons in this material, also exhibited harmonic absorption. The interpretation of the results of this experiment played an important role in the development of the quantum theoretical model of the energy bands in this material (*23*). Similar and more extensive studies on bismuth and bismuth antimony alloys resulted in a more accurate determination of the effective mass tensor (*24*) of electrons and holes in these metals (*25*). In interpreting the results of the nonresonant absorption, the Bell Telephone group utilized the extrapolation of the high-field-resonance portion of Fig. 8*a*, as indicated by the dotted line, in order to identify the cyclotron resonance value of the magnetic field as the intercept at zero power. Nonresonant absorption has also been observed and studied in antimony, whose properties are very similar to those of bismuth (*26*).

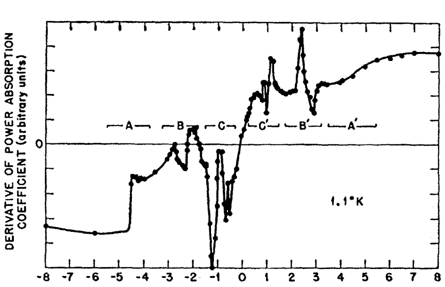


Fig. 9. Derivative of the power absorption plotted against magnetic field H for circularly polarized radiation at 24,000 Mcy/sec, at normal incidence on (001) plane of graphite at 1.1°K. [After J. K. Galt, W. A. Yager, and H. W. Dail, Jr.]

Following the initial work on nonresonant absorption in metals, another problem, known as the anomalous skin effect, received attention in these highly conducting materials at low temperatures. The term *anomalous skin* is associated with the finite but small penetration of microwave energy into the metal. This penetration is usually of the order of a few microns or less. At low temperatures in pure materials, it can be considerably smaller than the mean free path of the electron—smaller by one or two orders of magnitude. This gives rise to a very interesting behavior of the electron in the presence of a magnetic field as it moves on its trajectory in and out of this finite penetration depth.

The problem was formulated mathematically by two Russian theorists (*27*), who predicted that if the magnetic field were parallel to the surface of the metal, a new type of cyclotron resonance phenomenon could be observed. They showed that some electrons in their helical motion about the magnetic field would repeatedly come in and out of the skin, as shown in Fig. 10, and with an appropriate phase relation between the microwave electronic field such that a new cyclotron resonance condition could be satisfied. If the frequency of the microwave field is an integral multiple of the cyclotron frequency

$$\nu = n\nu_c \qquad (8)$$

then, corresponding to each value of the number n, there would be a resonance peak. Indeed they calculated theoretical curves, similar to that indicated in Fig. 11 (bottom), which showed this behavior. Within about a year a number

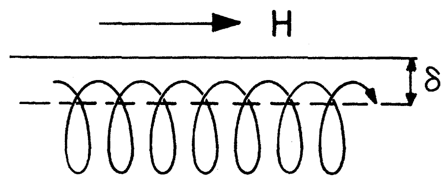


Fig. 10. Orbital motion of an electron in and out of the anomalous skin region δ of a metal (Azbel-Kane effect).

of experimentalists confirmed these predictions in a rough but convincing fashion in such materials as copper, bismuth, and tin (*28*). In due time, as the techniques were improved and pure materials were made available, such resonance absorption was more distinctly observed in greater detail and structure in a number of metals. One of the recent results obtained in copper is shown in Fig. 11 (top) and bears a remarkable resemblance to the theoretical curve. Other materials which have been investigated include antimony, zinc, lead, aluminum, cadmium, sodium, and potassium (*29*).

Discussion

With each passing year, more and more researchers have begun to undertake investigations of cyclotron resonance. At the moment, if one can hazard a guess, only a handful, perhaps a dozen groups, are engaged in investigating cyclotron resonance in plasmas throughout the world. The situation in solids is somewhat more encouraging; in the United States alone there are probably a dozen independent investi-

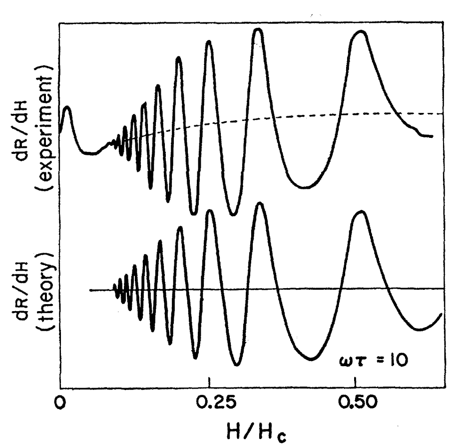


Fig. 11. (Top) Experimental curve of cyclotron resonance absorption in copper under anomalous skin conditions; (bottom) theoretical curve. [After A. F. Kip in *The Fermi Surface* (*37*)]

gators, and a somewhat smaller number are scattered in other countries, primarily in England, France, Holland, and Russia. In the case of semiconductors, the most recent advances involve the use of millimeter techniques as well as infrared radiation.

Perhaps one of the most exciting recent results in work with the millimeter spectrometer was the observation of the so-called quantum effects of holes in germanium (*30*), which are associated with the complex energy bands in this material—another instance of experimental confirmation of theoretical prediction based on the quantum theory (*31*). For example, if we compare the resonance spectrum at 2 millimeters, as shown in Fig. 12, to that at microwave frequencies, shown in Fig. 5, we find that there are, in addition to the normal electron and normal hole resonance, a large number of resonance peaks at intermediate magnetic fields which are accounted for by the theory. The interpretation of these new lines is analogous to that used in explaining the infrared absorption in indium antimonide, in which we talked in terms of electron transitions between discrete neighboring magnetic levels. In this case the magnetic-level structure is much more complex than before. Another important achievement of the millimeter techniques has been the recent observation of cyclotron resonance in diamond by the Lincoln group (*32*). The study of resonance in metals is also being advanced by the millimeter techniques, since the line structure is better resolved and more easily analyzed, particularly when the spectrum has several components and is anisotropic as well. The use of the higher frequencies permits better definition of the anisotropy plot of the resonances and should lead to further elucidation of the energy bands in metals. With the availability of higher magnetic fields, of the order of 100,000 gauss and more, it should be possible to extend these measurements, both for semiconductors and metal, into the submillimeter region and thus examine materials at higher resolution, and investigate materials not now amenable to investigation.

Moreover, from study of cyclotron resonance, devices are being designed that may play an important role in advancing scientific investigations in the difficult region of the electromagnetic spectrum known as the submillimeter and far-infrared regions, which span the

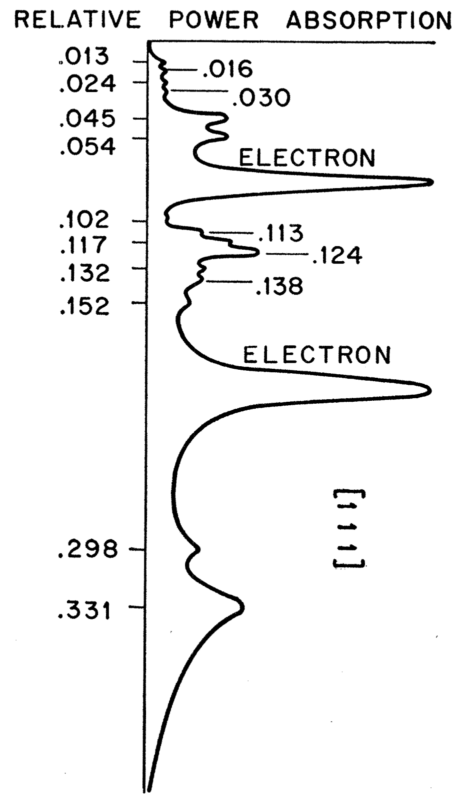


Fig. 12. Cyclotron resonance in germanium at 2 millimeters pressure (150,000 Mcy/sec), showing added structure due to quantum effects of holes. [After J. J. Stickler, C. J. Rauch, H. J. Zeiger, and G. S. Heller]

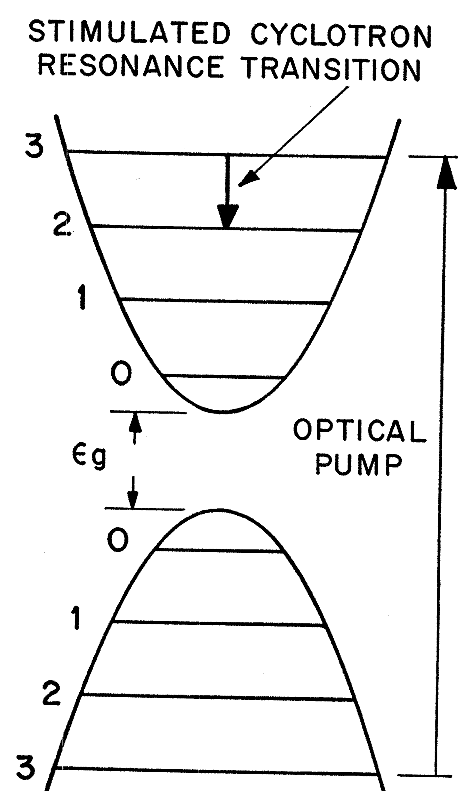


Fig. 13. Energy diagram and transitions illustrating the principle of operation of a cyclotron resonance maser.

wavelength range of 50 to 1000 microns. The first device, a cyclotron resonance photodetector, requires a relatively pure sample of indium antimonide, which is to be used at liquid-helium temperatures with a superconducting electromagnet capable of achieving 25,000 gauss in a small gap. The superconducting coils of this magnet, which consist of niobium wire, are energized by a small battery which can vary the magnetic field, so that cyclotron resonance absorption in the semiconductor can serve as a tunable photodetector at wavelengths from 60 microns on up, in the far-infrared to the millimeter region. This device is an extension of the original work done by the group at the Royal Radar Establishment on an indium antimonide submillimeter photodetector (*33*).

Perhaps the most exciting and difficult invention that is to use the phenomena discussed in this article is the cyclotron resonance maser (*34*). Theoretical analysis indicates that such a device should be feasible and would utilize, in addition to cyclotron resonance, another newly observed phenomenon, known as the oscillatory magnetoabsorption in semiconductors (*35*). When a magnetic field is superimposed on a semiconductor, magnetic levels are created not only for the electrons but for the holes as well. Therefore, on the energy diagram shown in Fig. 13, the levels become quantized both in the conduction band and in the valence band, which are separated by a forbidden region in energy space corresponding to the energy gap $\mathcal{E}_g$ associated with the semiconductor. Now, if an infrared or optical photon irradiates the semiconductor and its energy is greater than that of the energy gap ($h\nu > \mathcal{E}_g$), then it is possible to excite an electron from a magnetic level in the valence band to one with the corresponding quantum number in the conduction band, which is normally empty of electrons. This means that the population of level 3 becomes much greater than that of level 2, creating an abnormal situation designated as an inverted population. This type of inversion has been put to use in other types of masers by placing the sample in a resonant structure, which in this instance would be an interferometer resonant to the cyclotron frequency, which corresponds to the energy separation of levels 2 and 3 in the conduction band. Under these circumstances, a random photon at this resonance frequency, which is always present, can induce an electron to jump down from level 3 to level 2, the loss of energy creating another photon of the same energy which, in turn, induces a second electron to do the same, and so on. This avalanche process can go on indefinitely and can be maintained to give a coherent oscillation at these wavelengths if the energy balance between the optical pump and the losses in the system is appropriately achieved. Numerical estimates indicate that this is now possible if the optical pump is the output of an optical maser, which is now available, and if one uses large magnetic fields of the order of 100,000 gauss, which are also on hand. With the variety of materials and sources now contemplated, it appears that highly monochromatic sources in the energy-starved region of the far-infrared and submillimeter wavelengths may be possible. Furthermore, these sources would be tunable and would provide energy and resolution many times greater than any now obtainable.

In conclusion, it is evident that cyclotron resonance has proved to be a very useful and powerful tool for fundamental investigations in solids and may yet prove to have equally important application in the design of practical devices for exploiting plasmas and for providing much-needed infrared sources and detectors. Undoubtedly a number of unexpected and significant new developments other than those discussed here lie before us in this fast-moving and exciting field of resonance research.

References and Notes

1. The dees of a cyclotron are the semicircular electrodes across which the accelerating alternating high voltage is applied.

A. H. Taylor and E. O. Hulburt, *Phys. Rev.* **27**, 189 (1926).

3. E. W. B. Gill, *Nature* **140**, 1061 (1937); I. S. Townsend and E. W. B. Gill, *Phil. Mag.* **26**, 290 (1938); A. E. Brown, *ibid.* **29**, 302 (1940).

B. Lax, W. P. Allis, S. C. Brown, *J. Appl. Phys.* **21**, 1297 (1950).

T. H. Stix and R. W. Palladino, *Phys. Fluids* **1**, 446 (1958).

6. The Lincoln Laboratory is operated with support from the U.S. Army, Navy, and Air Force.

G. Dresselhaus, A. F. Kip, C. Kittel, *Phys. Rev.* **92**, 827 (1953); **95**, 368 (1955).

8. B. Lax, H. J. Zeiger, R. N. Dexter, E. S. Rosenblum, *ibid.* **93**, 1418 (1945); R. N. Dexter, H. J. Zeiger, B. Lax, *ibid.* **95**, 557 (1954); B. Lax, H. J. Zeiger, R. N. Dexter, *Physica* **20**, 818 (1954).

W. Shockley, *Phys. Rev.* **90**, 491 (1953).

G. Dresselhaus, A. F. Kip, C. Kittel, G. Wagoner, *ibid.* **90**, 491 (1953).

11. These are semiconductors in the form of binary compounds between elements from the second and sixth columns of the periodic table.

R. N. Dexter, *J. Phys. Chem. Solids* **8**, 494 (195 M. J. Stevenson, *Phys. Rev. Letters* **3**, 464 (1959).

E. Burstein, G. S. Picus, H. A. Gebbie, *Phys. Rev.* **103**, 825 (1956).

R. J. Keyes, S. Zwerdling, S. Foner, H. H. Kolm, B. Lax, *ibid.* **104**, 1804 (1956).

E. O. Kane, *J. Phys. Chem. Solids* **1**, 249 (1957).

L. M. Roth, B. Lax, S. Zwerdling, *Phys. Rev.* **114**, 90 (1959).

B. Lax, J. G. Mavroides, H. J. Zeiger, R. J. Keyes, *ibid.* **122**, 31 (1961).

E. D. Palik, G. S. Picus, J. Teitler, R. F. Wallis, *ibid.* **122**, 475 (1961).

G. Dresselhaus, A. F. Kip, C. Kittel, *ibid.* **100**, 618 (1955).

J. K. Galt, W. A. Yager, F. R. Merritt, B. B. Celtin, H. W. Dail, Jr., *ibid.* **100**, 748 (1955).

R. N. Dexter and B. Lax, *ibid.* **100**, 1216 (1955).

J. K. Galt, W. A. Yager, H. W. Dail, Jr., *ibid.* **103**, 1586 (1956).

B. Lax and H. J. Zeiger, *ibid.* **105**, 1466 (1957 J. W. McClure, *ibid.* **108**, 612 (195 P. Nozieres, *ibid.* **109**, 1510 (1958).

24. Because of the crystalline structure, in many solids the effective mass is different for different directions of motion of the electron or hole—that is, the effective mass is a tensor quantity.

J. K. Galt, W. A. Yager, F. R. Merritt, B. B. Cetlin, A. D. Brailsford, *Phys. Rev.* **114**, 1396 (1959).

26. W. R. Datars and R. N. Dexter, *Bull. Am. Phys. Soc.* **2**, 345 (1957).

27. M. I. Azbel and E. A. Kaner, *Soviet Phys. JETP* **3**, 772 (1956); **5**, 730 (1957).

A. F. Kip, D. N. Langenberg, B. Rosenblum, G. Wagoner, *Phys. Rev.* **108**, 494 (1957);

J. E. Aubrey and R. G. Chambers, *J. Phys. Chem. Solids* **3**, 128 (195 D. N. Langenberg and T. W. Moore, *Phys. Rev. Letters* **3**, 328 (1959).

J. K. Galt, F. R. Merritt, W. A. Yager, H. W. Dail, Jr., *Phys. Rev. Letters* **2**, 292 (1959); P. A. Bezuglyi and A. A. Galkin, *Soviet Physics JETP* **1**, 163 (195 D. N. Langenberg and T. W. Moore, *Phys. Rev. Letters* **3**, 137 (195 E. Fawcett, *ibid.* **3**, 139 (1959);

J. K. Galt, F. R. Merritt, P. H. Schmidt *ibid.* **6**, 458 (1961); A. F. Kip, in preparation.

R. C. Fletcher, W. A. Yager, F. R. Merritt, *Phys. Rev.* **100**, 747 (1955); J. J. Stickler *et al.*, *Bull. Am. Phys. Soc.* **6**, 115 (1961).

J. M. Luttinger and W. Kohn, *Phys. Rev.* **97**, 869 (1955).

C. J. Rauch, *Phys. Rev. Letters* **7**, 83 (1961).

E. H. Putley, *Proc. Phys. Soc. (London)* **76**, 802 (1960).

34. B. Lax, Proc. Quantum Electronics Conference, Berkeley, Calif., March 1961.

35. B. Lax and S. Zwerdling, *Progr. in Semiconductors* **5** (1960).

R. N. Dexter, H. J. Zeiger, B. Lax, *Phys. Rev.* **104**, 637 (1956).

37. A. F. Kip, *The Fermi Surface*, W. A. Harrison and M. B. Webb, Eds. (Wiley, New York, 1960), p. 146.

Who Participates in Local Politics and Why

The better-off citizen is more active, but so is the citizen who encounters social and economic barriers.

Robert A. Dahl

Why do individuals vary in the amount of influence they exert on local political decisions?

To influence another person, one needs resources or inducements. However, some persons use more of their resources on politics than others do. If we put to one side the question of variations in the efficiency or skill with which different persons use their resources for political purposes, then influence over local decisions should increase with the amount of resources one uses.

Considerations such as these have led to radically different theories about the structure of influence in local politics. According to one kind of theory, some important resources seem to be distributed rather evenly among the great body of citizens. Nearly everyone can vote, information about local affairs is accessible, problems of local policy are close to the experience of the average man, citizens can easily get in touch with their officials, and so on. Hence, it is said, influence over local decisions is likely to be distributed rather evenly among citizens. According to another theory, however, certain important resources are distributed very unevenly in almost every modern American town and city—chiefly wealth, income, social standing, control over jobs, and control over the mass media. In these respects, it is said, the American community is highly stratified. Hence, it is argued, influence over local decisions is likely to be distributed very unevenly; citizens who are best off with respect to wealth, income, social standing, and so on will