SOLID-STATE PLASMA

By A. G. Chynoweth and S. J. Buchsbaum

Some twenty years ago Ruthemann[1] and Lang[2] shot a monoenergetic beam of electrons in the keV range through a thin foil of aluminum and measured the energy distribution of the emergent electrons. They noticed that while most of the beam penetrated the metal without an appreciable loss of energy, there was a distinct group of electrons which lost very nearly 15 eV. When a different metal was substituted for aluminum, the same phenomenon was observed except that the characteristic energy loss differed from metal to metal. The explanation of this effect was not long in coming.[3] Some of the electrons lost a certain definite amount of energy by exciting longitudinal plasma oscillations inside the metal at a frequency ω_p characteristic of the particular metal. This cost the electron a "quantum" of energy $\hbar\omega_p$, where $\hbar$ is Planck's constant; Pines[4] called this quantum the "plasmon". The experiment, and the Bohm and Pines[3] theory of it, marked the beginning of research into the properties of solid-state plasmas.

Today solid-state plasma is a label that embraces all phenomena that result from the *collective* response to external stimuli of electron clouds in solids. Here the continuum theory approach of gas plasmas becomes combined with the quantum and band-structure effects of solids. The resultant mixture is rich in novel physical phenomena which can be, and are, used to further our understanding of both fields.

Study of solid-state plasma has grown very rapidly in recent years, and the subject is now one of the most active frontiers in solid-state physics. A number of factors have contributed to this spurt of interest. Only recently have materials been prepared with sufficient purity to make a broad range of experiments possible and meaningful. Probably the most important stimulus, however, was the realization that under appropriate conditions electromagnetic waves, from audio frequencies through radio and microwave frequencies, could be transmitted in the form of slow waves right through the bulk of solid conductors.[5] Such waves and related phenomena attracted plasma physicists who were seeking convenient and inexpensive means of studying basic plasma physics, solid-state physicists who saw a new tool for the study of band structure of solids, and device physicists who sensed possible technological applications.

Generally speaking, the subject is at a stage where the solid-state physicist interested in understanding collective phenomena in solids draws quite heavily on the knowledge that the plasma physicist has built up. But the great variety of basic plasma parameters that is available, or potentially available in the solid, coupled with the quantum and band-structure effects peculiar to the solid, quickly removes the subject of plasmas in solids from the arena of pure plagiarism and provides it with a quality and a mission of its own. The subject is sufficiently rich and new that there is about it the excitement of pioneering; our knowledge of it is not yet so sophisticated that the vital element of surprise and discovery is missing.

What do solid-state plasmas offer in comparison with gas plasmas? In this article we attempt to answer this question by surveying some aspects of solid-state plasmas that are under scrutiny today. These concern primarily wave propagation, oscillations, instabilities, and related phenomena.

Other areas of research that are receiving a fair amount of attention (we shall not cover them at length in this article) concern experiments that are direct analogues of similar work in gaseous plasmas and in particular in thermonuclear plas-

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When electrons and holes display a collective response to external stimuli, they experience effects observed in gaseous plasmas and also those associated with band structure in solids. New, very pure materials have plasmas of interest to plasma physicists, students of solids, and makers of devices. Some effects predicted by theory are yet to be found, and the variety of plasma types available promise research riches for some time to come.

ma research. A good example is the helical instability[6] (sometimes called the oscillistor) which closely parallels the so-called Kadomtsev instability[7] observed in gas discharges. Another example is the work on the pinch effect in solids.[8] Even here lattice effects exist, and lead to novel phenomena such as electron-hole recombination and thermal pinching.[9] Recently, Ancker-Johnson[10] in a series of ingenious experiments has tried to exhibit plasma confinement and increased stability in various exotic magnetic bottles such as the "minimum-B" configuration of Ioffe[11], or the "maximum $\int dl/B$" toroidal configuration of Furth and Rosenbluth,[12] all in suitably shaped crystals of indium antimonide. "Minimum B" refers to a configuration in which the absolute value of the magnetic field is nonzero and increases in all directions from some point. A plasma sitting in such a magnetic well possesses exceptional hydromagnetic stability.[13] In a closed, that is, toroidal system, a "minimum-B" well is topologically impossible in vacuum. The next best thing is to ensure that a particle experience *on the average* a "minimum-B" configuration. Hence the "maximum $\int dl/B$" concept, where the path of integration is around the machine.

The analogues are interesting. It isn't clear, however, whether one can really scale machines which are meters in size and cost millions of dollars to build and operate, to something that can be perched on a dime (see *Physics Today*, October 1965, p. 95). The problem, of course, is the scaling of mean free paths: in gas plasmas it is huge; in solids, tiny. We must stress that solid-state plasmas and gas plasmas do not really resemble each other. The differences between the two are more varied and more numerous than their similarities. And certainly the motivation for research in the two fields and the problems being studied today are widely different.

Before he can do experiments, the plasma physicist must first produce his plasma. More often than not this is accomplished by violent means with the result that the gaseous plasma, being far from thermal equilibrium with its laboratory environment, breaks up as a consequence of one or more of a myriad of possible instabilities that allow it to escape. Thus, the central problem in gas-plasma research today is how to tame all the known (as well as the unknown) instabilities.

In solids—more specifically in metals, semimetals, and semiconductors—nature has provided us with a nearly free gas of charged particles which possesses many of the attributes of a classical gaseous plasma. The gas differs from an ordinary laboratory gaseous plasma in one very important respect. It is absolutely stable. Here, therefore, the problem is not how to get and contain a plasma, but given the plasma what to do with it. For example, how does one throw it out of thermal equilibrium and produce instabilities that can be put to use? The generation of instabilities and the study of propagation of waves in solid-state plasma accounts for a major portion of present-day research activities in the field.

Procurement of plasma

As we have said, a gaseous plasma must first be produced (generally by breakdown of a gas) before it can be studied or used. Many solid-state plasmas are made by avalanche breakdown but for most purposes of present-day research a plasma made up of electrons and/or holes already exists in semiconductors, semimetals, and metals. This variety of types gives solid-state plasmas a range of parameters not possible in a gas. For example, strict equality between the densities of *mobile* positive and negative charges is no longer necessary. Such equality does exist in semimetals, intrinsic semiconductors, and certain metals, but many other metals and degenerate semiconductors have plasmas made up of an electron gas neutralized by a fixed ion matrix. The latter can affect the plasma properties only through its vibrations (phonons). Semiconductors also offer variety: extrinsic semiconductors present either an electron or positive-hole gas depending on whether they are n type or p type; unbalanced plasmas with unequal densities of mobile positive and negative charges can be obtained by controlling the relative amounts of intrinsic and extrinsic conductivity (doping can also be used to unbalance the carrier densities in semimetals). Alternatively, the densities and the ratio of electron-to-hole concentrations in semiconductors can be controlled by injection techniques of various sorts. The most commonly used is bulk breakdown, but injecting contacts (as in p-i-n structures), electron bombardment, and light can also be used to generate electron-hole plasmas.

Unfortunately not every gas of charged particles is a plasma. For such a gas to exhibit plasma-like properties it must satisfy a number of requirements. The most important has to do with shielding. In a true plasma the Coulomb field of a charged particle (say, an electron) is shielded by other charged particles in its immediate vicinity. The shielding length—the so-called Debye length in classical plasmas obeying Boltzmann statistics and the so called Fermi-Thomas length in plasmas obeying Fermi-Dirac statistics—must be larger than the interparticle separation in order that it have a physical meaning. The condition that the shielding length exceed the interparticle separation is tantamount to the condition that the kinetic energy (kT for a Boltzmann plasma and the Fermi energy E_F for a degenerate plasma) exceed the potential energy at the average interparticle separation. For plasmas obeying Boltzmann statistics this implies a hot, dilute gas, and gaseous plasmas, being hot and dilute, satisfy the condition extremely well. Not so for solids. Even under most favorable circumstances, the shielding condition is barely satisfied in most solid-state plasmas obeying Boltzmann statistics. The condition is better satisfied when the lattice dielectric constant is large, as it is for most semiconductors, since a large dielectric constant reduces the potential energy. In a degenerate plasma the shielding condition is, of course, independent of temperature and depends only on charge carrier density, N, effective mass, m^*, and static dielectric constant, ϵ. The condition is

$$(\tfrac{1}{2})\ (3\pi/2)^{3/2}\,(\epsilon m_0/m^*)^{3/2}\,(a_0^3N)^{\frac{1}{2}}>1,$$

where a_0 is the Bohr radius. In metals, where $\epsilon \simeq 1$ and $m^* \simeq m_0$ (m_0 is the free electron mass), the condition just fails. This implies that in metals the electron gas is more like a fluid, the potential energy being greater than the kinetic energy, so that electron-electron interactions are strong. Yet these effects, known as Fermi-liquid effects, have so far played a relatively unimportant role as far as *gross* plasma properties are concerned, the largest effect being a small change in the effective mass of the carriers. Other aspects of Fermi-liquid effects such as their influence on cyclotron-resonance line shapes have been treated theoretically[14, 15] but remain to be explored experimentally.

Degenerate semiconductors and semimetals are often much better plasmas than are metals, not because N is large, but because m^* is small and ϵ is large. For example, in bismuth, where $\epsilon \simeq 100$ and $m^* \simeq 0.01\ m_0$, $(\epsilon m_0/m^*)^{3/2}$ is $\sim 10^6$ which more than makes up for the fact that the carrier density in bismuth is only about 2×10^{17} cm^{-3}.

Basic parameters

Before reviewing solid-state plasma research we will compare the range of some basic parameters (such as charge density, mean free path, velocity distribution, and mobile-charge mass) of gaseous and solid-state plasmas.

A major feature of solid-state plasmas is the range of charge densities available from less than 10^{13} per cm^3 in pure semiconductors to 10^{22} per cm^3 in metals. This means that the plasma frequency $[\omega_p = (4\pi Ne^2/m^*)^{\frac{1}{2}}]$ varies from microwave frequencies to frequencies in the ultraviolet. Furthermore, the density in semiconductors can be varied nearly at will by varying the donor or acceptor concentration. In contrast, it is difficult to exceed charge densities of the order of 10^{14} per cm^3 in gas plasmas. As we shall see, the high densities achievable in solid-state plasmas allow propagation of waves whose velocities are so small that even at audio frequencies the wavelengths are small compared with crystal dimensions.

Mean free paths of electrons in gaseous plasmas range from a fraction of a millimeter to many meters with corresponding relatively long mean free times. In solids it is rare to find collision times, τ, longer than 10^{-10} sec or mean free paths longer than 10^{-2} to 10^{-1} cm, although recently mean free paths in magnesium were found to be a few cms ($\tau \simeq 10^{-7}$ sec)![16] Such feats require extraordinary crystal purity that cannot yet be achieved in most materials; the crystal must also be without strains and at liquid-helium temperatures to reduce phonon scattering.

Most solid-state plasmas (except those produced by breakdown or by generation of electron-hole pairs by light or bombardment) are in equilibrium with the host lattice. In relatively dilute semiconductor plasmas, the electrons and holes will then have a Maxwell-Boltzmann distribution corresponding to the ambient temperature. In more heavily doped (degenerate) semiconductors and in metals and semimetals, the distribution is Fermi-Dirac and the important velocities are Fermi velocities rather than thermal ones. In either case the random velocity, v_R, is of the order of 10^7 to 10^8 cm/sec. If a small electric field is applied, it introduces a drift velocity v_D superimposed on v_R and the total velocity distribution can then be approximated by a displaced Maxwellian (or Fermi-Dirac) distribution. Large electric fields give correspondingly large v_D, but it is difficult (if not

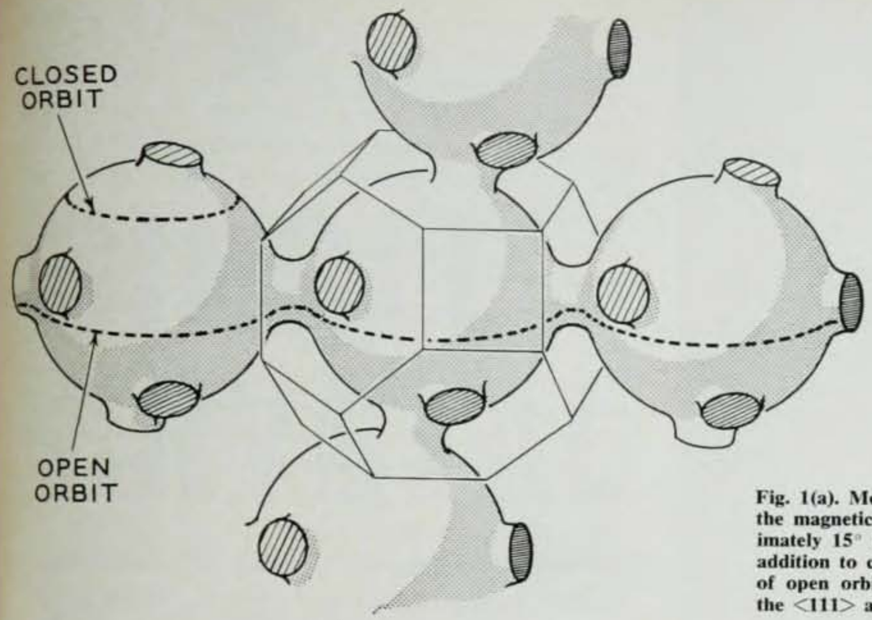

Fig. 1(a). Model of the Fermi surface of silver. When the magnetic field is in the (111) plane and is approximately 15° from the <1̄1̄0> direction, there exists in addition to closed, nearly circular orbits a single band of open orbits whose average direction is parallel to the <111> axis as shown.

impossible) to make v_D larger than v_R. Thus streaming and beam effects, so important in gas plasmas, are relatively unimportant in solid-state plasmas.

A feature of solids that often makes for considerable complications in plasma behavior is the dependence of carrier mass on crystallographic orientation. While this adds mathematical and, sometimes, additional physical complexities, it also makes solid-state plasmas a hunting ground for learning more about the crystal band structure. We mention one example: in many metals (copper, silver, lead, and others) the band structure is such that open cyclotron orbits can exist for certain orientations of magnetic field with respect to crystallographic axes. The presence of such open orbits can drastically modify the nature of wave motion in such metals.[17] (See Fig. 1.) This aspect of plasmas is still in its infancy. For many purposes and especially for qualitative understanding, it is often enough to assume that the masses are isotropic.

Another difference between gas and solid-state plasmas concerns the size of the masses of the mobile charges. In solids the electron has an effective mass, m^*, resulting from the periodic potential of the host lattice, which varies from material to material and can range from a few times the mass of a free electron, m_0, to about one hundredth of this value. Likewise, the positive holes can have masses in about the same range. As a consequence many of the gas-plasma phenomena in which the heavy positive ions are regarded as substantially fixed no longer apply directly to the solid. In particular, the plasma frequency, ω_p, and the cyclotron frequency, ω_c, for holes are often comparable with those for the electrons, which is far from true (for ions) in gases. Also, because very often m^* is much smaller than m_0, the cyclotron frequency can be made very large with relatively modest magnetic fields.

Thus we see that . . . the cylotron energy $\hbar\omega_c$ can be relatively large at modest magnetic fields. In particular it can be made of the order of or greater than kT, or $\hbar\omega_p$, or E_F even though these energies may be in the infrared. Under these

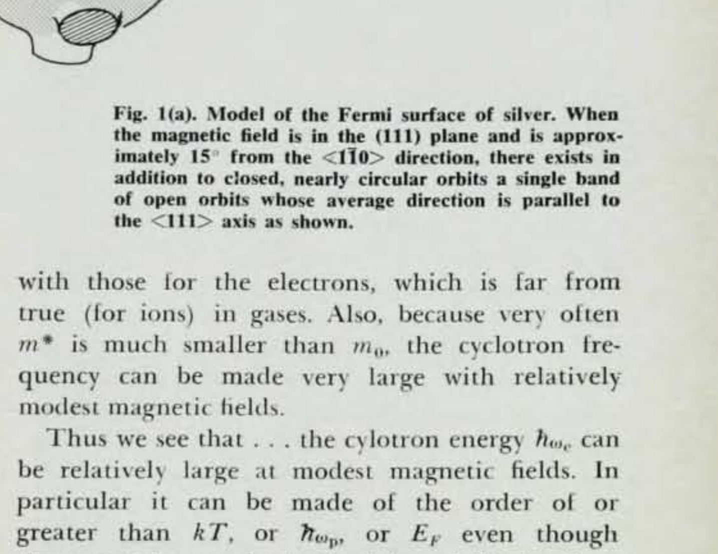

Fig. 1(b). The effect of open orbits on helicon wave propagation in silver. For curve B the magnetic field is so oriented that no open orbits exist. The linear relation between the magnetic field and frequency (at constant wavenumber) is the tell-tale mark of a helicon wave. In A the field has been rotated to the direction that yields open orbits as in Fig. 1a. Here $\omega \propto B^2$ is representative of a collisionally damped Alfvén wave (after C. C. Grimes et al[17]).

conditions strong quantum effects can be expected and, indeed, many of these have already been observed in bismuth by Hebel and Wolff[18] and by Williams and Smith.[19] The quantum effects in bismuth also exhibit features that can be related to the nonparabolic native of the energy bands.

Waves in magnetized plasmas

A major spur to solid-state plasma research has been the variety of phenomena associated with the propagation of nearly transverse electromagnetic waves through a plasma in a magnetic field. Without the field the plasma is highly opaque to an electromagnetic wave whose frequency is smaller than the plasma frequency. A static magnetic field changes the situation dramatically. Now there are a number of new frequencies in the problem; the electron and hole cyclotron frequenies, ω_{ce} and ω_{ch}, as well as various combination, or hybrid, frequencies;[20] $(\omega_p^2+\omega_c^2)^{1/2}$, $(\omega_{ce}\omega_{ch})^{1/2}$, etc. Another new quantity is the angle that the direction of wave propagation makes with the magnetic field. Thus the general problem of wave propagation in plasmas is fairly involved. We refer the interested reader to a number of texts on the subject.[21] Here we shall discuss the low-frequency regime, $\omega \ll \omega_c$, because it is the one most actively pursued experimentally in solid-state plasma today and is the easiest to understand physically.

When a static magnetic field is perturbed by a time-varying disturbance with a frequency much smaller than the cyclotron frequencies of the carriers, the carrier motion about magnetic-field lines remains adiabatic. That is, if a line of force moves at right angles to itself, the charged particles are constrained to move with it like beads on a moving string. The model of waves on a charged string parallel to a magnetic field proves quite adequate for description of the low-frequency waves in a plasma. Let us consider such a string stretched to a tension T with linear mass density ρ and charge per unit length σ. Its equation of motion is

$$\rho\frac{\partial^2 \mathrm{y}}{\partial t^2} = T\frac{\partial^2 \mathrm{y}}{\partial z^2} + \frac{\sigma}{c}\frac{\partial \mathrm{y}}{\partial t} \times \mathrm{B}. \qquad (1)$$

Here y is the transverse vector displacement of the string, and z the length along the string. There exist two limiting conditions in the solution of Eq. 1. When the charge density σ and therefore the Lorentz force acting on the string are negligibly small, a linearly polarized wave of the form $\mathrm{y} = \mathbf{Y}_0 \exp[i\ (\omega t - kz)]$ can propagate along the string where ω and k are related by

$$\omega/\mathrm{k} = (T/\rho)^{1/2}. \qquad (2)$$

This situation obtains in a compensated plasma, that is, one in which the electron and hole densities are strictly equal ($N_e = N_h = N$). There are then just as many positively charged beads on the string as there are negatively charged beads and σ is zero. Replacing T by $B^2/4\pi$ and ρ by the value $N(m_e^* + m_h^*)$, Eq. 2 becomes $\omega = V_a k$ where $V_a = \{B^2/[4\pi N\ (m_e^* + m_h^*)]\}^{1/2}$ is the Alfvén speed (after Hannes Alfvén who first discovered these low frequency magnetohydrodynamic waves in his study of sun spots[22]). Such magnetohydrodynamic waves propagate quite well in compensated solid-state plasmas. They have been studied extensively in bismuth[23] and have been observed in antimony[24] and graphite.[25] The condition that the frequency of these waves be much smaller than the cyclotron frequency is not very restrictive in solid-state plasmas because all carriers have small masses. Typically, Alfvén waves are studied at microwave frequencies. It is necessary to use as high a frequency as possible because, unless $\omega\tau > 1$, the wave is heavily damped by collisions. Alfvén waves are slow, not because the masses are large (as in a gas) but because the carrier densities are large. In bismuth $V_a \simeq 10^4\ B$ cm/sec where B is in gauss. The speed V_a is different along different crystallographic directions because the effective masses in bismuth are highly anisotropic. Williams[23] used this fact to determine accurate values of the heavy masses in bismuth. Unlike waves on strings Alfvén waves can propagate at any angle with respect to the magnetic field.

The second limit of Eq. 1 occurs when σ is finite and ω is so low that the inertia term $\rho\partial^2\mathrm{y}/\partial t^2$ is negligible compared to the Lorenz term $\sigma\partial\mathrm{y}/\partial t \times \mathbf{B}$. Then the waves on the string are circularly polarized and for $\mathbf{B}$ parallel to the string we have the dispersion relation

$$k^2 = \pm\ \sigma\mathrm{B}\omega/Tc. \qquad (3)$$

Such waves (which Aigrain[26] called helicons because of their circular polarization) can propagate in uncompensated plasma where $N_e \neq N_h$. In single-component plasmas, where $N_h = 0$, say, σ becomes $N_e e$ and the dispersion relation for helicon wave propagation is

$$k^2 = \pm \frac{4\pi N_e \omega e}{cB} = \pm \frac{\omega^2 \omega_p^2}{c^2 \omega\omega_0} \qquad (4)$$

Only one sense of circular polarization (the one that rotates with the carriers) gives a propagating wave. Helicon waves have the welcome property that their damping is small if $\omega_c\tau >> 1$, irrespective of the value of $\omega\tau$. They can therefore

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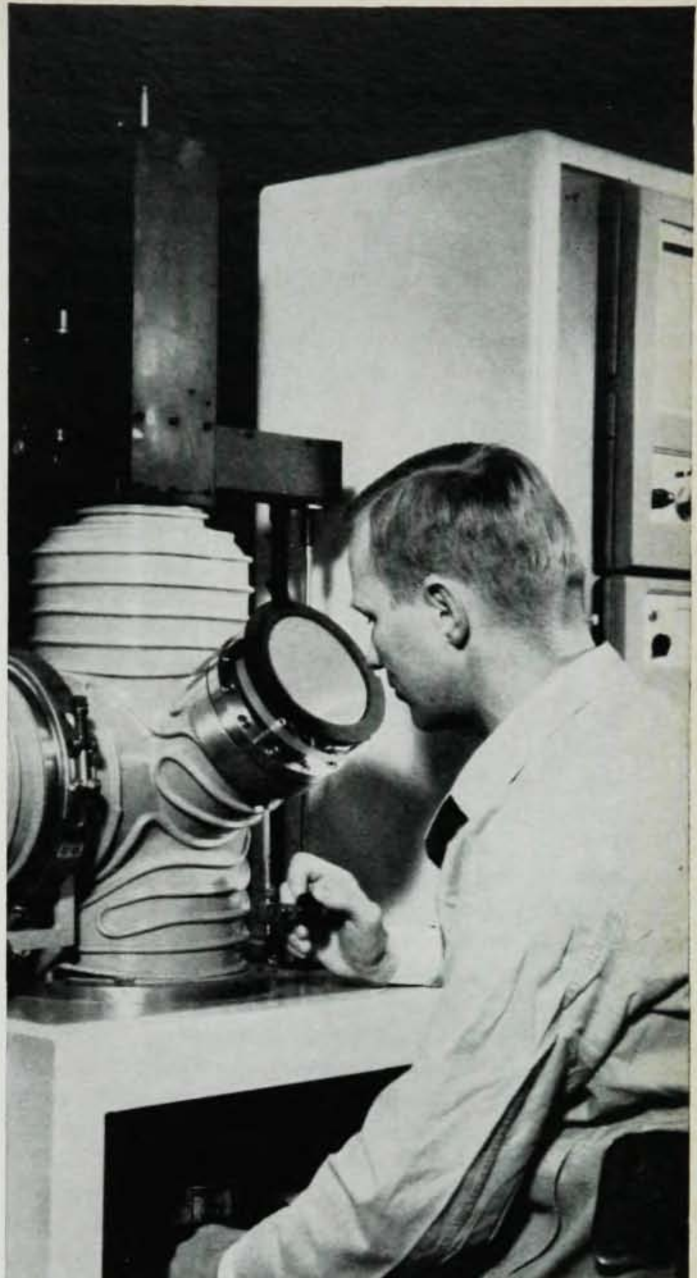

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Cambridge, Massachusetts • Zurich, Switzerland be studied at very low, even audio, frequencies. It was at such audio frequencies (~30 cps!) that Bowers[27] first observed these waves in a cylindrical piece of sodium. At about the same time Libchaber and Veilex[27] were propagating helicon waves through indium antimonide at 10 kMc/sec! Since then helicon waves have been observed and studied in many uncompensated metals and in many semiconductors. From Eq. 4 we see that the helicon waves, unlike Alfvén waves, are dispersive, their phase velocity $V_h = \omega/k = c(\omega\omega_c/\omega_t^2)^{1/2}$ being a function of frequency.

Measurement of the wave velocity obviously provides direct information about the carrier density (for helicon waves) or carrier mass density (for Alfvén waves) of the material. In this way it has been shown, for example, that in metals such as potassium and sodium, there is indeed one electron per atom to within one or two percent, a precision not achievable by other means. In some materials, such as lead telluride, the lattice dielectric constant ϵ is large and helicon wave-velocity measurements can be used to arrive at values of ϵ by extrapolation. Values of several hundred have been measured by such means in lead telluride;[28] such high values are believed to be due to the effects of plasma-phonon coupling. A fruitful use of these waves in fundamental solid-state studies is for exploring Fermi surfaces. The simple dispersion relations given above hold only when there is a local relation between current and field of the wave. They have to be modified when the wavelength of the wave becomes comparable with the radius of the cyclotron orbit, i.e., when $k \sim (\omega_c/v_F)$, where v_F is the Fermi velocity. Because the carrier has a nonzero component of velocity v_z $(v_z \leq v_F)$ along the magnetic field, it experiences a wave at the Doppler-shifted frequency $\omega \pm kv_z$, and can undergo cyclotron resonance when $\omega + kv_z = \omega_c$ even though $\omega << \omega_c$. Such resonance first sets in at the limiting point $kv_F = \omega_c$. For helicon waves, as we saw, $k^2 \propto \omega/\omega_c$, so that the magnetic field at resonance is proportional to the cube root of the frequency. Such relationship has been first observed in a beautiful experiment by Taylor.[29] It turns out that the constant of proportionality depends only on the Fermi momentum of the carriers. Stern[30] has discussed the use of the method for measuring curvatures of limiting points of Fermi surfaces whose shape is not spherical. Cyclotron damping of Alfvén waves (in bismuth) was first reported by Kirsch and Miller.[29]

There are other phenomena associated with the waves in solid-state plasmas which have been predicted but not yet observed. One of them is Landau damping.[31] If a helicon wave propagates at an angle to the magnetic field, there exists a longitudinal component to the electric field. This can result in additional damping of the wave by those carriers whose velocity matches the phase velocity of the wave. These carriers then experience a static electric field and thereby readily exchange energy with the wave in a way similar to that in the acoustoelectric effect.

Giant quantum oscillations in helicon wave propagation have been predicted by Quinn and by Miller,[32] but have not yet been observed, although quantum oscillation of the de Haas–Van Alphen type have been seen in aluminum and tin.[33] Alfvén waves in antimony ought to couple

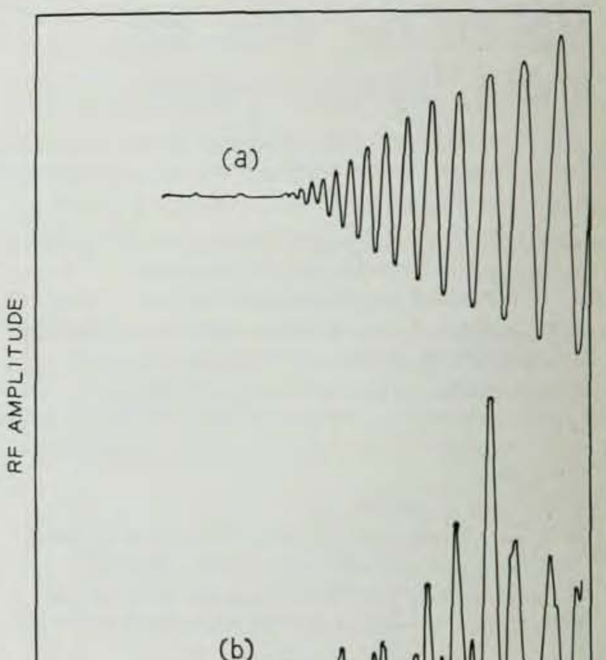


Fig. 2(a). Experimental curves showing the transmission of helicon waves through slabs of sodium (trace a) and potassium (trace b). The interference patterns are obtained by beating the transmitted signal with a reference signal of constant phase. The cut-off of transmission below about 50 kG in trace a and below 40 kG in trace b is caused by Doppler-shifted cyclotron resonance. For sodium, helicon-phonon coupling does not occur for B less than 100 kG for the frequency used (50 Mc/sec). In potassium such coupling occurs and is strongest at about 68 kG when f = 20 Mc/sec. Note the monotonic increase in the separation between successive maxima in a caused by the increase of helicon wave velocity with magnetic field. In b the beat pattern can be resolved into two series of peaks that correspond to the coupled branches of the helicon wavesound wave dispersion relation (after C. C. Grimes and S. J. Buchsbaum[35]).

strongly to plasma sound waves to form so-called magnetoacoustic waves whose speed is $(V_0^2 + U_s^2)^{\frac{1}{2}}$; U_s will be defined shortly. This too has so far eluded observation.

A very intriguing prospect is the use of helicon waves for the study of nuclear magnetic resonance in large, oriented single crystals of metal. To date NMR work in metals is limited to use of powder when rf fields are used. Not too many metallic systems are good candidates for such experiments, but Grimes[34] has found two or three (such as In or Al) where prospects are good, provided that large magnetic fields are available (100 kG is quite adequate).

Of all the properties of helicons and Alfvén waves perhaps the most important is the fact that they are *slow* electromagnetic waves. Moreover, their velocities can be controlled and varied over a considerable dynamic range. The velocity is reduced for both types of wave as the carrier density is increased. We already mentioned that in bismuth, Alfvén speeds are of the order 10^7 cm/sec for a field of about 1000 G. Helicon velocities can be made lower simply by lowering the frequency. In metals with $n \sim 10^{22}$ per cm^3 and at frequencies of a few cycles per second, phase velocities of the order of 10 cm/sec can be achieved. These low and controllable phase velocities allow studies of coupling between these waves and other waves in solids, such as sound waves (transverse phonons) and spin waves. Both effects have been studied experimentally by Grimes—the first in single-crystal potassium[35] (see Fig. 2) and the other in nickel.[36] The work on nickel confirmed the theoretical prediction of Stern and Callen[37] and led to a better determination of the low-temperature anisotropy energy in this ferromagnetic material.

While the transverse helicon and Alfvén waves have received most attention to date, there are other waves and oscillations known in gaseous plasmas which have their counterpart in solid-state plasmas. The best known of these (theoretically) are the electrostatic ($\nabla \times \mathbf{E} = 0$) plasma oscillation of Bohm and Pines. As we mentioned in the introduction, the study of such oscillations in the transmission of beams through metal foils is quite old although the most interesting work is recent.[38] Also recently ultraviolet radiation, which accompanies the excitation of plasmons in metals, has been studied.[38] In a two-component plasma, that is, one containing both electrons and holes, or two or more distinct mass electrons (as in many-valley semiconductors), there also exists an "acoustic" branch of plasma oscillations.[39] In this mode electrons and holes oscillate very nearly in phase) so that there is very little charge separation. For long wavelengths the dispersion relation has the form $\omega = kU_s$ where the plasma sound speed U_s is typically of the order of the Fermi velocities. Unfortunately, these modes are heavily Landau damped unless the Fermi velocities of the plasma components differ widely. Theoretical work has shown that the damping can be reduced by causing the two components to drift relative to each other.[39] Indeed, with sufficiently large drifts the mode becomes unstable as a result of the so-called two-stream instability. The mode could then be detected by Brillouin scattering of laser radiation from such oscillations.[40]

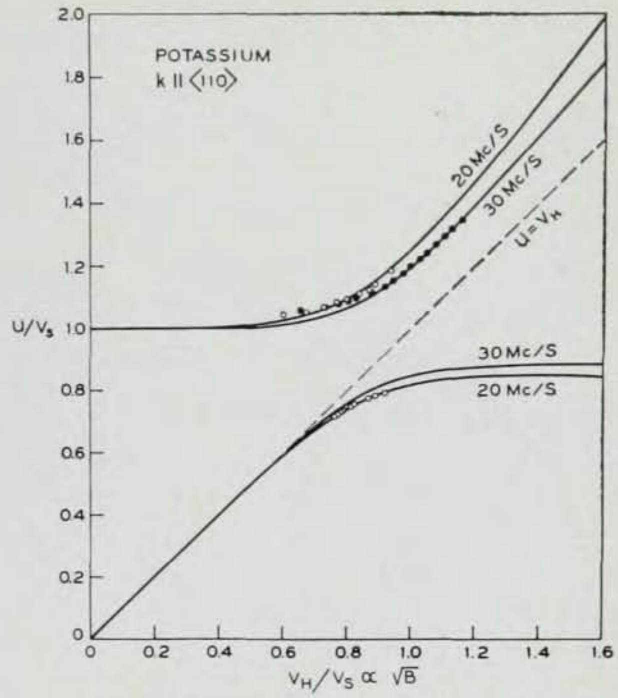


Fig. 2(b). Plot of phase velocities of the coupled helicon-phonon dispersion relation normalized to the sound velocity V_s as a function of magnetic field. Solid curves are theoretical and points are experimental (after C. C. Grimes and S. J. Buchsbaum[35]).

Technological aspects

The slow waves that can propagate in plasmas are of interest also to those who hope for some technological fall-out. In principle, slow waves can be used in passive devices such as delay lines and isolators. A 30-Mc/sec isolator which uses helicon waves has, in fact, been built by Gremillet[41] (and reportedly is used in Paris taxicab systems). Bowers[42] and his students built a magnetometer whose principle is based on the linear dependence of frequency on magnetic field in the helicon dispersion relation. But slow waves also invite applications in active devices where they are coupled

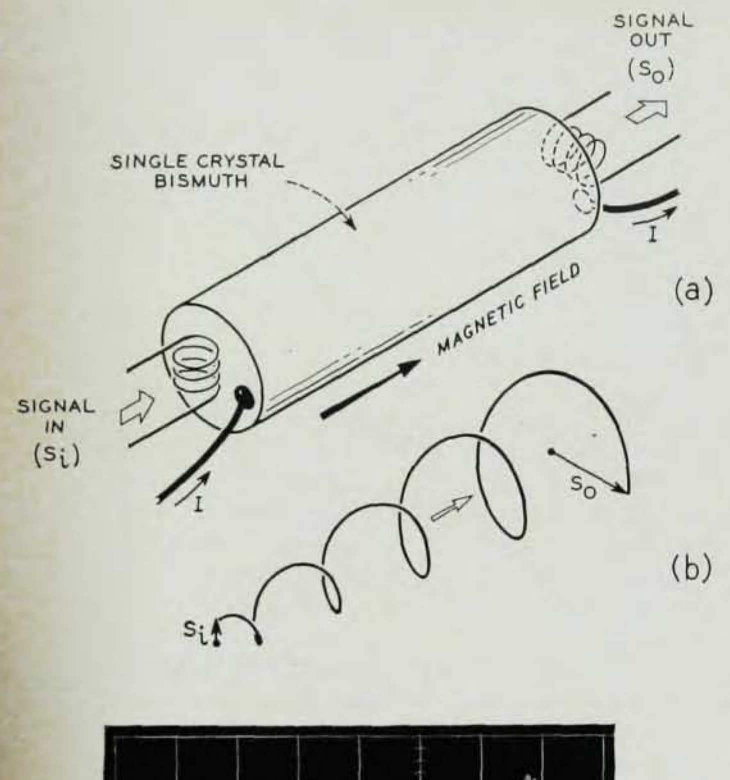
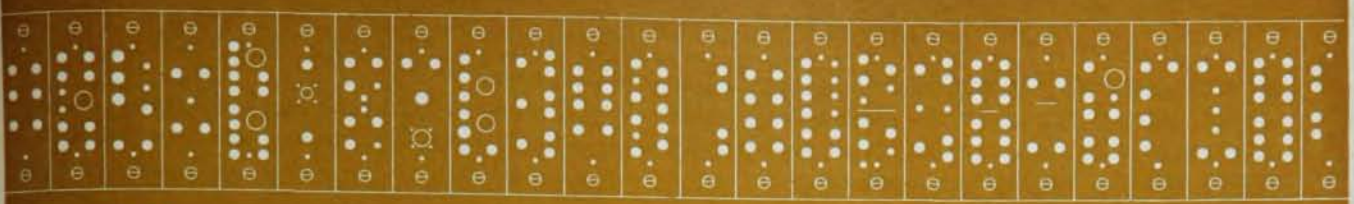


Fig. 3. Wave amplification in bismuth caused by dc current. (a) Schematic of a single crystal of bismuth, which forms a *solid-state plasma waveguide* within which the wave propagates. Shown also are the rf input and output coils. The actual geometry incorporates a heat sink that uses the large transverse magnetoresistance of bismuth and allows the crystal to carry a large dc current I. (b) Trace of the tip of the circularly polarized electric field of the amplified wave. (c) The output signal S_o as a function of current I. Growth is due to amplification of the wave. For currents somewhat larger than those shown, self-oscillations occur (after D. J. Bartelink[45]).

with electron streams rather analogously to travelling-wave tubes.

It was Bok and Nozieres[43] who first pointed out that, in a two-component plasma, helicon and/or Alfvén waves can become unstable if the two components drift relative to each other at a velocity which exceeds a certain threshold value. Although the details of the Bok and Nozieres analysis were subsequently criticized,[44] there is no question that in the presence of a sufficiently large drift, helicon or Alfvén waves can become unstable. A myriad of such instabilities are known in gaseous plasmas. Some of these instabilities are of the convective type; that is, an initial perturbation grows as it propagates in space away from the source of perturbation (as opposed to absolute instabilities in which an initial disturbance grows in time without necessarily propagating in space). A convective instability can be used to build an amplifier. That such instabilities can be excited in the laboratory as well as on paper has been demonstrated by Bartelink[45] (see Fig. 3), who succeeded in amplifying a radiofrequency wave in bismuth. But he had to operate at liquid-helium temperatures and use current densities of thousands of amperes per square centimeter with all the attendant heating. This has hardly the makings of a competitive device. The need for such large drift currents arises from the fact that in the Bok-Nozieres scheme, as in all related schemes, the threshold drift velocity is of the order of the phase velocity of the wave which is being amplified. For a given frequency the phase velocity is low because the carrier density is high, and high carrier density means large currents. To reduce dissipation one needs (a) extremely high mobility materials and (b) a mechanism which amplifies at drift velocities much smaller than the phase velocity of the wave. Recently, Baraff and Buchsbaum[46] have proposed just such a mechanism. It involves the presence of surface waves which necessarily accompany the propagation of a helicon wave along any *finite* (in transverse dimensions) plasma slab or column. The properties of such surface waves at plasma-vacuum interfaces has received considerable attention.[47] The surface wave is necessary to match boundary conditions at the surface, which the helicon wave alone cannot quite do. Its presence is generally accompanied by additional loss. It turns out that when *two* solid-state plasma slabs of slightly different densities are butted against each other with the interface parallel to a magnetic field, a "surface" wave will also exist at the plasma-plasma interface. By causing the carriers to drift in one of the two media, the dielectric constant of that medium can be shimmed by Doppler shifting into exact equality with that of the adjacent medium. At this, the threshold drift velocity, the surface wave disappears since, to the wave, the two media now appear identical. At drift velocities larger



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than the threshold, the surface wave reappears but with its phase reversed. Baraff showed that the interaction of the surface wave (with its reversed phase) with the bulk helicon wave can lead to instability. By making the densities in the two media very nearly equal, the threshold drift velocity can be made as small as one pleases, although at the price of reduced gain. There is also the technological difficulty of making the density variations in each medium smaller than the difference in average density between the two media. That the device works remains to be demonstrated.

The topics discussed above generally represent a controlled approach to amplification and instabilities in drifted systems in that the investigations start with passive waves that are relatively well understood and the effect of the drift on the wave propagation is explored gradually. But it often happens in drift experiments that instabilities arise unexpectedly and the problem then is to find the responsible mechanism. There are many mechanisms that can give rise to instabilities, such as acoustoelectric effects, minority-carrier conductivity modulation, and various thermal effects, to name only a few. Many of these are basically low-frequency instabilities (i.e., up to tens of megacycles per second). The more interesting instabilities from the point of view of devices have microwave frequencies or higher. Only a few microwave instabilities in bulk semiconductor plasmas (as distinct from p-n junctions) have been reported so far. One, in gallium arsenide, has become known as the Gunn oscillator[48], after its discoverer. While various plasma effects were considered at one time as an explanation for the Gunn oscillator, recent work[49] has shown that it is basically a hot-electron effect in which, at sufficiently high electric fields, the heated electrons transfer rapidly to a state of lower mobility (i.e., transfer to higher-lying low-mobility valleys in the GaAs conduction band). A magnetic field is not involved in this instability.

Microwave emission has been observed from InSb crystals subjected to the combined effects of electric and magnetic fields, and this can be classed as a plasma phenomenon. Two distinct types of emission have so far been reported, occurring at low and high electric fields, respectively. The high-field emission[50] occurs with the crystal operated in avalanche breakdown and must be a property of an electron-hole plasma. On the other hand, the low-field emission[51] is purely an electron-stream effect; there is some evidence that it is related to the excitation of helicon waves by an unknown coupling mechanism.

Conclusions

We have attempted to survey present-day research in solid-state plasmas. In the space of this article it was impossible to review all aspects of the field, and our account is biased in that we have emphasized what is of particular interest to us.

Which way will research in solid-state plasmas go from here? It is always dangerous to predict, but let us try. Instabilities in plasmas will receive an increasing amount of attention, with attempts at establishing inhomogeneous (in real space) and/or anisotropic (in velocity space) distribution functions in spite of randomizing collisions. Such distributions may lead to instabilities that are already well-known from gas plasmas. Here, anisotropic scattering processes in many-valley en-

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ergy bands might be exploited, or laser radiation might be used to create nearly monoenergetic distributions, as proposed by Wolff[52]. Electron beams passing adjacent to solid-state plasma might be used—the latter providing, of course, the slow-wave structures necessary for the traveling-wave interaction.

Turning to fundamental studies of solids, the study of low-frequency waves is now passing the "looking for effects" stage and should begin to yield considerable new knowledge about the band structure of solids. However, many predicted phenomena remain to be found. Some of these we have mentioned. Others include helicon wave propagation in superconductors, the effect of magnetic breakdown on helicon and Alfvén waves, nonlinear phenomena in wave propagation, shocks and turbulence, plasma-phonon interaction especially in polar materials, plasma effects in cyclotron and spin resonance in metals when nonlocal effects are of importance. Finally, plasmas in solids and lasers are just begging to be wedded. Raman and Brillouin scattering from various plasma oscillations are yet to be observed.

As we indicated several times above, many of the more interesting plasma phenomena require long collision times. In other words, the purer the material the better. So, as with so many other aspects of solid state, the rate of progress often depends on the quality of available materials.

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