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Hot Electrons in Indium Antimonide

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Pulsed measurements of the Hall voltage in high-purity *n*-type InSb at 77°K allow calculation of the electron drift velocity as a function of the applied electric field. Drift velocities as large as 9×10^7 cm/sec are observed. The behavior for moderate electric fields (below the threshold for electron-hole pair production) is in good agreement with a theory assuming scattering by polar optical modes. The large drift velocities indicate a large velocity-space anisotropy for the electrons, with a ratio of drift to "thermal" velocity as high as 1.5. It is suggested that an observed anomaly in the drift velocity behavior, i.e., a sharp *drop* in value at the highest electric fields, is related to possible generation of high-frequency oscillations through the mechanism of the two-stream instability.

INTRODUCTION

When sufficiently high electric fields are applied to semiconductors, the average energy of the carriers is raised above kT_L, where T_L is the lattice temperature. The energetic carriers are described as "hot",[1,2] although temperature may not be an appropriate variable since their distribution may or may not be Maxwellian in form. Indium antimonide is of considerable interest in this respect, because its high electron mobility allows the production of hot carriers with rather low electric fields; for the same reason, one might expect to be able to induce large anisotropies of the electron distribution in high electric fields.

Earlier studies in indium antimonide at this Laboratory[3,4] and elsewhere[5–9] have shown the general features of the electronic behavior in moderately pure material for lattice temperatures in the range 77 to 300°K. Reported herein are results at 77°K in high-mobility material which indicate large electron energies in the direction of the electric field. When coupled with earlier estimates of the average energy transverse to the electric field,[10] it is noted that the anisotropy of the distribution function of the energetic electrons is large enough to expect generation of "acoustic" plasma oscillations.[11] Observations of the electron drift velocity as a function of the electric field show anomalous behavior, which may be due to the occurrence of such oscillations.

EXPERIMENTAL DETAILS

Measurements of the conductivity and Hall effect were made at 77°K with apparatus previously described.[10] Pulsed electric fields of duration 0.3 μsec, repetition rate 1 cps were used. All crystals were single but unoriented and had electron mobilities in the range $(6.2 \text{ to } 7.5)\times10^5$ cm²/V-sec at 77°K. Electron concentrations were in the range $(1 \text{ to } 6)\times10^{13}$ cm^{-3}, and only crystals with a variation of about 5% or less in carrier concentration along the length were used.

Samples were attached to a sapphire block with Araldite and cut with an ultrasonic tool into a bridge shape. Results obtained with two of the samples, representative of the set of measurements, are given in Table I. The electron density n is calculated from the expression $n=(R_He)^{-1}$, where R_H is the Hall coefficient and e the electronic charge. To ensure the proper application of this expression, the value of R_H measured for large magnetic fields (in excess of 1000 Oe) was used.

TABLE I. Properties of InSb crystals.

Property	Sample 1	Sample 10
Dimensions of section studied (cm)	$0.253\times0.0356\times0.0450$	$0.255\times0.0160\times0.0425$
Conductivity σ at 77°K (mho/cm)	4.81	7.15
Mobility at 77°K (cm²/V-sec)	690 000	750 000
Electron concentration at 77°K (cm^{-3})	4.7×10^{13}	6×10^{13}
Percent variation in concentration along length	2	5

Figure 1 shows the behavior of the mobility, $R_H\sigma$, as a function of the magnetic field, for low electric fields, i.e., less than 0.01 V/cm. The conventional large decrease in conductivity is observed. Measurements of the dependence of drift velocity on electric field were made in magnetic fields of 260 and 400 Oe, where it is expected that the effect of the field is to decrease the mobility (due to the magnetoresistance) but not to change greatly the form of dependence of velocity on electric field.

OBSERVATIONS

Because of the high electron mobility, even at 260 Oe, $\omega_c\tau$ or the product $R_H\sigma H$, is almost 2. ω_c is the cyclotron frequency, eH/m^*c, and τ is the scattering time. Thus observations at this field are not truly low-magnetic-field measurements, in the sense normally used in transport theory. However, the observations at mag-

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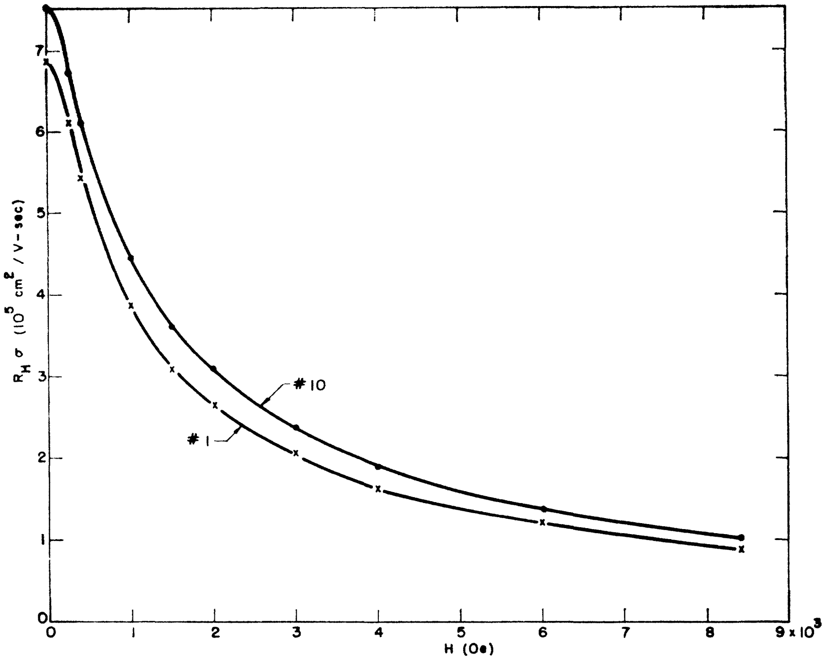

FIG. 1. Magnetic field dependence of electron mobility.

netic fields greater than 100 Oe do not show the pulse-shape changes associated with self-pinching.[10] It should then be possible to compare the observations with the theory for hot electrons in the absence of a magnetic field.[12] At smaller magnetic fields there is evidence for self-pinching, and these measurements can be used only in the lower electric field region prior to the occurrence of such effects.

In the strongest electric fields there are oscillations which appear in both the longitudinal and transverse electric fields, of maximum amplitude about five percent and of observed frequency in the 10–40 Mc/sec range. The presence of low-frequency instabilities and oscillations (low with respect to plasma or cyclotron frequency) has been noted in earlier studies,[9,10,13–15] and the assignment of the appropriate modes are not continued here. Some of these oscillations may be related to the instabilities discussed by Pines and Schrieffer.[11]

Measurements in a transverse magnetic field of 260 Oe are shown in Fig. 2. It is seen that for electric fields less than 200 V/cm the Hall coefficient is independent of field and the current density shows a less-than-linear dependence on the field, indicative of a decreasing mobility. At 200 V/cm the behavior portends either the injection of a large density of holes (and electrons) or the production of electron-hole pairs by impact ionization. The observed shapes of the two curves (the "bump" in both j and R_H which is also present in the $j-E$ curve when $H=0$) bear some resemblance to the observations[13] in p-type InSb in which injection occurred first, followed by impact ionization at higher electric fields. The slow rise of j in the field range 200 to 300 V/cm may be due to this effect.

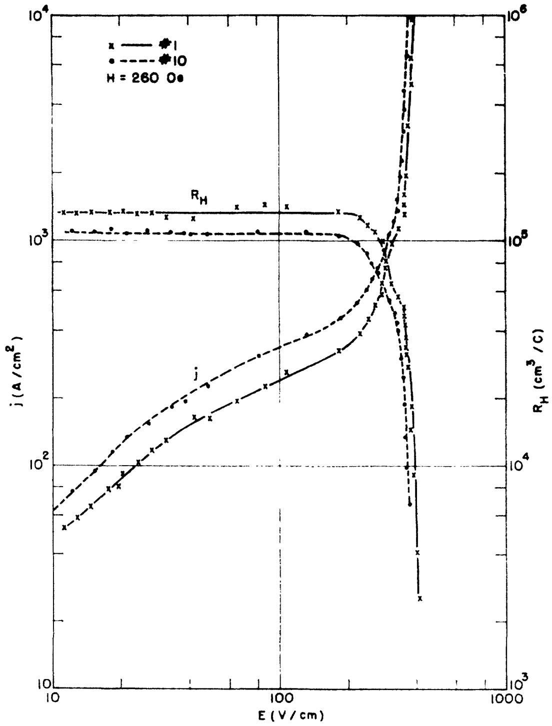

FIG. 2. Current density and Hall coefficient as function of electric field, in a magnetic field of 260 Oe.

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[13] B. Ancker-Johnson, R. W. Cohen, and M. Glicksman, Phys. Rev. **124**, 1745 (1961).

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Injection here is not as strongly affected by the magnetic field as was the case in *p*-type material, since the injected carriers are holes. Their mobility is small enough so that they will not be immediately swept to the surface for the magnetic fields used; the mobility of holes in this material is about 10 000 cm^2/V-sec. It was also noted that the voltage pulse showed a slow decaying shape in this electric-field region, with a time constant corresponding approximately to that calculated from the hole drift mobility and the voltage probe spacing. These effects disappeared as the electric field was increased into the known impact ionization region.

The product R_Hj is plotted as a function of the electric field in Fig. 3. R_H should be equal to $1/ne$ (certainly even more so at higher magnetic fields) unless a very peculiar electron distribution function occurs, i.e., one with great departure from monotonic, Maxwellian shape. The current density, j, will be approximately equal to nev, where v is the electron drift velocity, as long as the holes play a minor role in the conduction, which is the case over the whole range considered. Thus, this plot should represent the behavior of the drift velocity of the electrons as a function of the applied electric field.

In Fig. 3, the upper solid straight line, with its dashed extrapolation, is the measured low-field behavior, and it is seen that the mobility v/E begins to decrease for fields in the vicinity of 15 V/cm. Anomalous behavior sets in just prior to and in the impact ionization region, where the velocity rises sharply and then falls even more sharply as the electric field is further increased. Similar behavior is observed at 400 Oe and is plotted in Fig. 4.

In these two figures it should also be noted that the differences between the two samples observed at low electric fields decreases as the carriers are heated, and for fields above 50 V/cm, the data for the two samples of different low-field mobilities coincide. This is expected, since the small difference in mobility at the low electric fields, presumably due to some difference in ionized impurity concentration, should disappear for the higher velocity carriers, which are much less scattered by the impurities.

THEORY

These data may be compared with calculations employing a theory for hot electrons in a polar semiconductor developed by Stratton.[12] Equations (2.17) and (2.18) of Stratton's paper are used:

$$(E/E_0)^2=(2/3\pi)N_0^2\gamma^2 \exp\gamma[\exp(\gamma_0-\gamma)-1]K_0(\gamma/2)$$
$$\times\{[\exp(\gamma_0-\gamma)-1]K_0(\gamma/2)$$
$$+[\exp(\gamma_0-\gamma)+1]K_1(\gamma/2)\},$$

$$\frac{m^*v^2}{k\theta}=\frac{3}{\gamma}\left[1+\frac{\exp(\gamma_0-\gamma)+1}{\exp(\gamma_0-\gamma)-1}\frac{K_1(\gamma/2)}{K_0(\gamma/2)}\right]^{-1},$$

where

$$eE_0=(\epsilon_\infty^{-1}-\epsilon^{-1})m^*e^2k\theta/\hbar^2;$$
$$\gamma\equiv\theta/T;\quad \gamma_0\equiv\theta/T_0;\quad N_0=(\exp\gamma_0-1)^{-1}$$

and $k\theta$ is the optical phonon energy, T_0 the lattice temperature, T the electron temperature, and the functions K_0 and K_1 are the usual modified Bessel functions of the second kind. ϵ and ϵ_∞ are the static and high-frequency dielectric constants, respectively.

Two important assumptions are involved in Stratton's theory. The first is that the electron distribution function at high electric fields is still dominated by electron-electron collisions, so that its functional form is that of a displaced Maxwellian. This may be of marginal validity for the crystals studied, with $n\approx5\times10^{13}$ cm^{-3}, since the

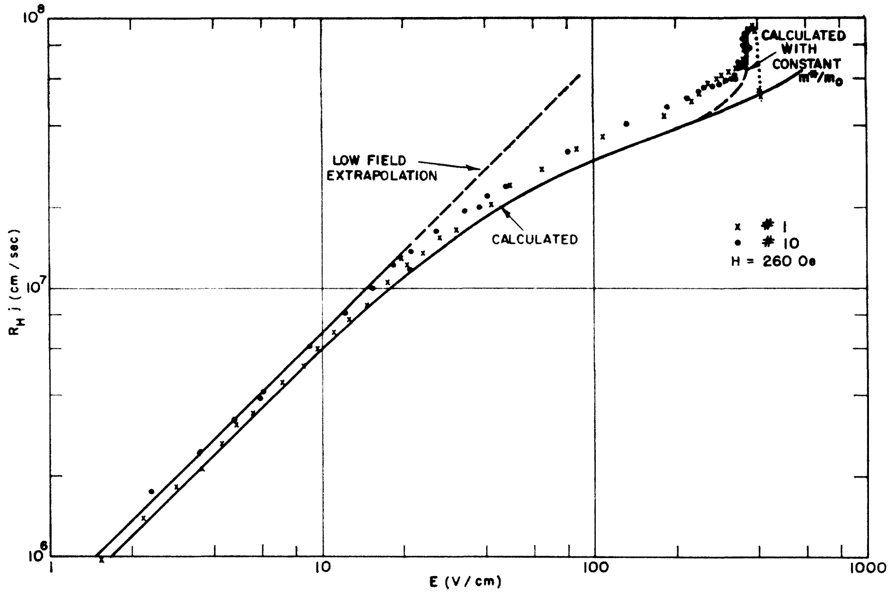

FIG. 3. Observed and calculated values of drift velocity ($=R_Hj$) as function of electric field, in a magnetic field of 260 Oe.

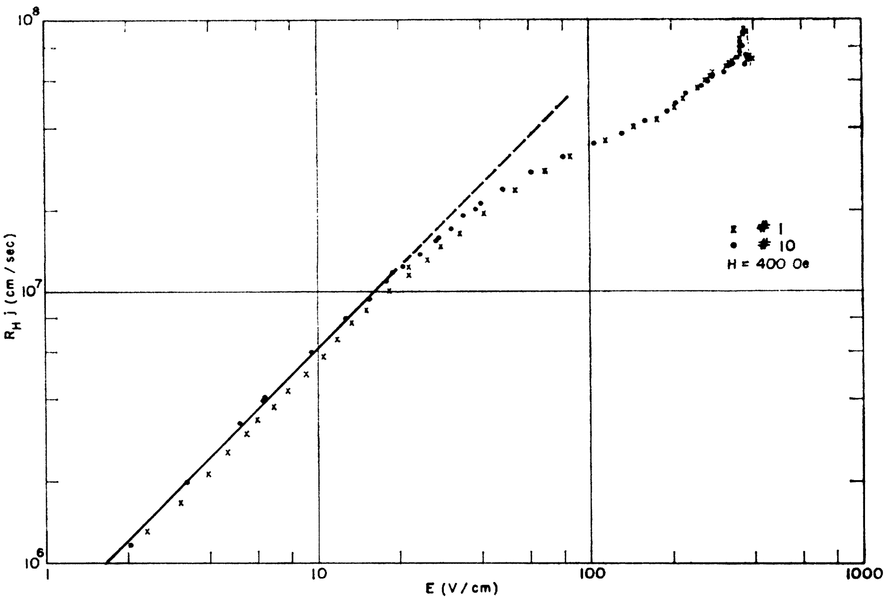

FIG. 4. Observed values of drift velocity ($=R_H j$) as function of electric field, in a magnetic field of 400 Oe.

density at which interelectronic collisions control the energy distribution is considerably higher than 5×10^{14} cm^{-3}, and the density at which the interelectronic collisions control the momentum distribution (a smaller value at low temperature) is about 2×10^{13} cm^{-3}.

In addition, the calculations involve a perturbation expansion of the distribution function in the presence of the electric field, with the perturbation parameter essentially the ratio of drift energy to thermal energy, $m^*v^2/2kT$. Neglect of higher order terms can be important as this parameter approaches 1. The theory for indium antimonide at 77°K gives a "maximum" value for this ratio of 0.485. Although there is thus some question about the accuracy of the calculations for the complete range of fields used in the experiments, a comparison is useful for a check on the theory and some hoped-for check on other observations.

The electrons are scattered by the holes, ionized impurities, and acoustical phonons in addition to the polar optical modes considered by Stratton. The contribution to the mobility from these processes is small compared to that of the polar optical modes,[16] and their neglect in this treatment is reasonable.

Values of the electric field and the drift velocity as functions of the electron temperature were calculated using the following values for the parameters involved: $\theta=260$°K,[17] $\epsilon_\infty=15.7$,[18] $\epsilon=18.7$.[17] The effective mass of the electrons in InSb is a strong function of their energy, and the values calculated from the measurements of Palik, Picus, Teitler, and Wallis[19] and Lax, Mavroides, Zeiger, and Keyes,[20] with the latter adjusted for the lattice temperature dependence, were used to estimate an appropriate average value, $\bar{m}^*$, to substitute into the theory.

$$\bar{m}^*=\int_0^\infty \exp(-\mathcal{E}/kT)[m^*(\mathcal{E})]^{-1/2}\mathcal{E}^{1/2}d\mathcal{E}\Big/\int_0^\infty \exp(-\mathcal{E}/kT)[m^*(\mathcal{E})]^{-3/2}\mathcal{E}^{1/2}d\mathcal{E}.$$

Table II lists the values of this ratio. At higher temperatures this is less precise, because of the importance of contributions to the integrals from the large m^* values at large $\mathcal{E}$ values.

TABLE II. Values of the average effective mass.

Electron temperature (°K)	$\bar{m}^*/m_0$
77	0.0152
150	0.0162
300	0.0182
500	0.0205
750	0.0232
1000	0.0256
1300	0.0283

Results of these calculations are plotted in Fig. 5, in the form of the ratio of drift velocity to thermal velocity $v/(2kT/m^*)^{1/2}$, as a function of electric field, and the electron temperature as a function of electric field. The theory gives 5.95×10^5 cm^2/V-sec for the low-field mobility at 77°K. This is considerably lower than the

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measured values noted here and the lattice mobility of Putley[21] of 700 000 cm^2/V-sec obtained by extrapolating the higher temperature measurements made with his purest crystals. It is much smaller than the recent measured values of $(1-2)\times 10^6$ cm^2/V-sec reported by Vinogradova, Galavanov, and Nasledov.[22] However, the calculated value is quite sensitive to the values of indices of refraction and the optical phonon temperature.

It should be noted that the theory does not include the possibility of electron-hole pair production, although under certain conditions the theory does include breakdown. In InSb, pair production is observed to occur, in the absence of an external magnetic field, just beyond 200 V/cm; in the magnetic fields applied here, it apparently occurs for higher fields, close to 400 V/cm. The theory is thus not expected to be applicable to these regions.

DISCUSSION

The general behavior predicted by the theory is seen to be in good qualitative agreement with experiment for fields up to about 300 V/cm; the theoretical results are plotted in Fig. 3. It is beyond this region that the theory begins to predict a substantial rise in electron temperature, and the result of such a temperature rise is also to increase the effective mass. A dashed curve which is the result of calculations with a constant effective mass of $0.016m_0$ (and thus a temperature forced to stay at about 200°K) has been included in Fig. 3. It is seen that this dashed curve follows qualitatively the sharply rising drift velocity observed for electric fields of 300–350 V/cm. The subsequent drop in velocity does not appear in any theoretical curve which ignores both impact ionization and other possible new dissipative mechanisms.

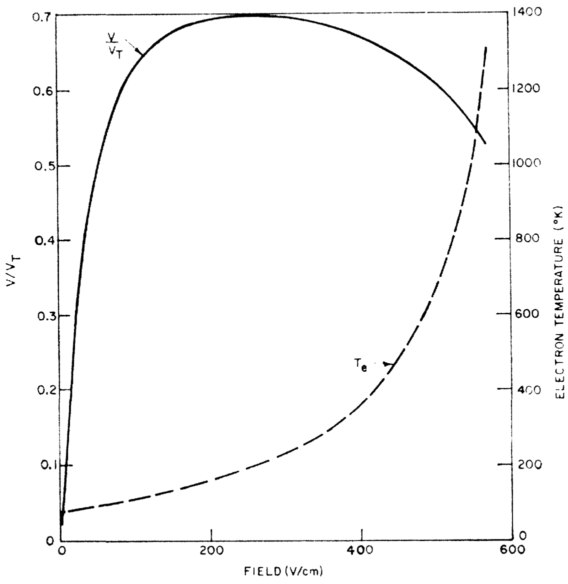

FIG. 5. Calculated values of drift velocity-thermal velocity ratio and electron temperature as a function of electric field, in InSb at 77°K, assuming scattering by polar modes alone.

It should be noted that the experiments were performed in a transverse magnetic field of 260 Oe, while the calculations neglect the effect of an external magnetic field. The comparison above, which shows such good qualitative agreement, leads to the conclusion that the effect of the magnetic field is not of fundamental importance at this intermediate field ($\omega_c\tau\approx 1$). Substantial changes in the behavior of the drift velocity do occur for stronger magnetic fields, and these will be the subject of another paper.[23]

In observations of pinching effects,[10] comparison with theory for the pinch-time yielded an expression for the threshold current[24] in abamperes:

$$I_c' = 3ck(T_e+T_h)/2ev,$$

where c is the velocity of light. For a drift velocity of 5.5×10^7 cm/sec and an I_c' of 0.1 abA, this expression gives $k(T_e+T_h)=0.037$ eV. As can be seen from Figs. 3 and 4, v is not affected much by the magnetic field at these electric fields (200 V/cm and higher). The velocity is also not "saturated," but increases and then decreases in the impact ionization region. Stratton's theory, which neglects pair production and other possible dissipative mechanisms, predicts a kT_e of 0.014 eV at 200 V/cm and 0.0224 eV at 325 V/cm. It is expected that the holes could be somewhat lower in energy,[11] although the large ratios of electron to hole temperature calculated by Pines and Schrieffer at 20°K lattice temperature are probably overestimates if extrapolated to 77°K, because of their neglect of electron-hole scattering and the presence of the light holes. It thus seems, *a priori*, reasonable to assume that the electron and hole temperatures will be close to equal. The temperature values calculated with Stratton's theory then bracket closely (0.028 to 0.045 eV for kT_e+kT_h in the range where 0.037 eV is deduced from pinching) the values estimated from pinching observations, even though Stratton's theory does not include the effects of pair production in limiting the temperature. However, the comparison is being made at the onset of such effects. At higher fields, the theory which neglects the additional dissipation does show a rapid increase in temperature, while the pinching observations would imply a rather constant temperature.

It is worth noting the rapid rise and sudden fall of the drift velocity for fields of 300–350 V/cm, which shows up at 260 and 400 Oe, but turns out to be much less prominent in stronger magnetic fields.[24] The rise may be related to that expected for hot carriers being scattered by polar optical modes,[12] although it is clear that an increasing effective mass with increasing tem-

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[22] K. I. Vinogradova, V. V. Galavanov, and D. N. Nasledov, Fiz. Tverd. Tela 4, 1673 (1962).

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perature tends to make the effect more gradual (Fig. 3). The falling velocity is an unusual effect. A few comments on possible sources for this are in order.

It is clear from a comparison of the observations with the calculations of Pines and Schrieffer[11] that the plasma may be able to sustain the generation and growth of plasma oscillations due to the anisotropic velocity distribution. The above measurements would indicate values of v_t (a thermal or transverse average velocity) of the order of $(6\text{–}8)\times 10^7$ cm/sec, and if these hold to the maximum v's observed, the ratio v/v_t could be as high as 1.5. This is adequate to induce the onset of oscillations, even with equal electron and hole temperatures. Whether such oscillations grow, depends on the relative magnitude of growth rate and dissipation. Since the calculated growth rates are of the order of 1/30 to 1/15 of the hole plasma frequency, ω_{ph},[11] it would be necessary to have $\omega_{ph}\tau$ larger than 15–30. In breakdown, ω_{ph} can be as large as 6.6×10^{12} sec^{-1} (a density of 2.5×10^{15} cm^{-3})while τ is probably of the order of 10^{-12} sec. The experimental $\omega_{ph}\tau$ would appear to be perhaps a factor of 2 lower, at 77°K, than the value deemed necessary by Pines and Schrieffer's calculations for two-stream instabilities. Nevertheless, the possibility of such instabilities occurring in the above observations remains strong, since the estimated losses may be off by the factor 2, and since the theory is uncertain to the extent that collisional losses were not included in the derivation of the dispersion relation or the calculation of growth rates.

A velocity which decreases with increasing field strength is unusual, and at first thought, unexpected. If, for some given field (and velocity) a new dissipative mechanism occurs, this mechanism normally requires that the velocity be above the threshold for its occurrence, i.e., as the mechanism becomes stronger it may keep the velocity from increasing, but a decrease in velocity would inhibit the occurrence of the dissipative mechanism, and the velocity would then be self-resistant to such a change. Under conditions where the threshold for this mechanism is not dependent on the electric field, one expects that the rate of increase of velocity with electric field would be at most reduced to zero. In the case of the two-stream instability, however, the onset of the instability depends on the relative magnitude of the growth constant and the other scattering dissipation terms, represented by τ. The threshold velocity for nonzero growth constant is the lowest velocity which sustains growth, and the growth constant increases as the velocity increases. In addition, the growth constant increases as the plasma frequency increases.[11] This is demonstrated in Fig. 6, which gives the results of a calculation of the growth constant for one of the Pines-Schrieffer cases (hole temperature assumed 0°K) for the same wavelength instability, but for two different plasma densities. To have growth, the growth constant needs to exceed the damping, $1/\tau$, and for the case shown it is clear that the threshold velocity for growth of plasma oscillations decreases as the plasma density increases. This condition holds for short wavelengths (comparable to the Debye length); at long wavelengths, where the growth constants are also very small, the growth constant is practically independent of plasma density, if the wavelength and relative densities of electrons and holes are unchanged.

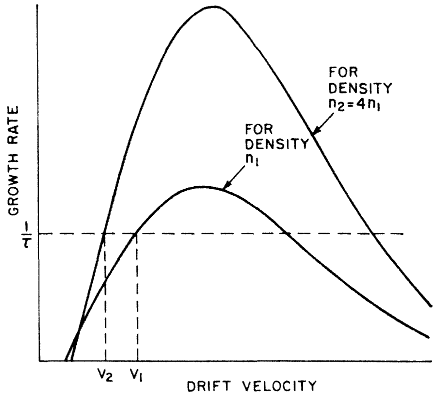

FIG. 6. Theoretical growth rate as a function of the electron drift velocity. v_1 and v_2 are the minimum drift velocities for the onset of plasma oscillations, for densities n_1, and $n_2=4n_1$, respectively.

In the breakdown conditions of the above observations, the plasma frequency is increasing very rapidly with increasing electric field. It is thus expected that the threshold velocity for net growth can *decrease* as the electric field is increased. The observed decrease in electron velocity with increasing electric field therefore provides additional evidence for the onset of instabilities due to the generation of plasma oscillations in this region of electric field strength. Experiments intended to observe the instabilities produced are planned.

ACKNOWLEDGMENTS

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