Microwave Field Dependence of Drift Mobility in Germanium

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At lattice temperatures between 80 and 300°K, electrons and holes in germanium have been heated by microwaves, with an extension to high microwave fields of the technique developed by Morgan. The microwave frequency was 34.67 kMc/sec. The effect of carrier densities between 10^{13} and 10^{16}/cm^3 has been investigated. At large microwave fields E (up to about 10^4 volts/cm in amplitude) the mobility μ, relative to the mobility μ_0 at zero field, is proportional to $E^{-\gamma}$; the exponent γ is smaller for purer samples. These microwave measurements agree with previous dc field measurements. At small values of E, $(\mu_0-\mu)/\mu_0E^2\equiv\alpha$ is field independent. The variation of α with lattice temperature T has been measured. In the range of pure lattice scattering, $\alpha(T)\propto\mu_0{}^2T^x$; $\exp x=(n/n_0)^{0.67}$ where $n_0=1.7\times10^{14}$ cm^{-3} for electrons and 1.0×10^{14} cm^{-3} for holes. This dependence on carrier density suggests that carrier-carrier interaction plays an important role in the carrier-phonon scattering mechanism.

INTRODUCTION

THE mechanism of interaction of carriers with lattice vibrations in semiconductors is not yet fully understood. This is mainly due to experimental difficulties and a corresponding lack of reliable data. In the initial experiments on hot electrons by Ryder and Shockley[1,2] and by Ryder[3] with n- and p-type Ge and Si, relatively impure material was used. They measured drift velocities v_d at dc fields E up to about 10^4 volts/cm for 2.8 ohm cm n-type and 0.9 ohm cm p-type germanium at 77, 193, and 298°K. The data were considered to be characteristic of pure lattice scattering although, at least at 77°K and not too high field intensities, impurity scattering should be important in the germanium used. The reported measurements of $v_d(E)$ indicate that the mobility, $\mu=v_d/E$, is independent of E (Ohm's law valid) at low fields, proportional to $E^{-0.5}$ in an intermediate region, and proportional to E^{-1} at high field intensities. The dependence on E^{-1} means that the drift velocity saturates at high field intensities.

Recently Mendelson and Bray[4] reported measurements with p-type germanium at 78°K and 195°K. The published curve was obtained with a sample which was 3.3 ohm cm at 77°K and, therefore, probably intrinsic at room temperature. An ohmic region below 10 volts/cm was followed at higher fields by a gradual decrease in mobility. Above 500 volts/cm, $\mu\propto E^{-0.8}$ up to 10^4 volts/cm. All samples were reported to show the same $E^{-0.8}$ behavior for fields larger than 10^3 volts/cm irrespective of their purity. The different behaviors at small field intensities were supposed to be due to impurity scattering.

With 2 ohm cm n-type germanium at room temperature, Gunn[5] observed a saturation in drift velocity between 4.5×10^3 and 9×10^3 volts/cm, with a gradual variation of the slope between this region and the ohmic region. With a more refined technique[6] he was able to measure relative deviations, $(\mu-\mu_0)/\mu_0$, of μ from the ohmic mobility μ_0 in the low-field region where $(\mu-\mu_0)/\mu_0\propto E^2$; he used samples of about 4 and 0.1 ohm cm room temperature resistivity. Arthur, Gibson, and Granville[7] obtained data in the same region by detecting with microwaves the change in resistivity upon application of the dc field; they used a 4.5 ohm cm n-type sample. At high field intensities, above 4.5×10^3 volts/cm, they observed saturation of the drift velocity with a 5 ohm cm n-type sample. The saturation value was in agreement with that of Ryder,[3] namely 6.5×10^6 cm/sec. The method of detecting a change in conductivity by microwave absorption is based on measurements of Gibson[8] with 8-mm waves. Gibson found that for 40 ohm cm germanium at room temperature the microwave attenuation is proportional to the conductivity, in agreement with theory if the relaxation time is smaller than 4×10^{-12} sec. Gibson and Granville[9] used the same principle of microwave absorption to measure the high-field drift velocity of minority carriers injected by light. A saturation at 4×10^3 volts/cm was found for electrons. No saturation was found for holes. Unfortunately the experimental accuracy was not very high.

In the experiments reported so far, the mobility as a function of dc field intensity was measured. The reason why nearly all experiments were performed with about 1 ohm cm material is due to the following facts:

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[4] K. S. Mendelson and R. Bray, Proc. Phys. Soc. (London) **B70**, 899 (1957), Bull. Am. Phys. Soc. Ser. II, **2**, 153 (1957).
[5] J. B. Gunn, J. Electronics **2**, 87 (1956).
[6] J. B. Gunn, in *Progress in Semiconductors*, edited by A. F. Gibson (John Wiley & Sons, Inc., New York, 1957), Vol. 2, pp. 211–247.
[7] Arthur, Gibson, and Granville, J. Electronics **2**, 145 (1957).
[8] A. F. Gibson, Proc. Phys. Soc. (London) **B69**, 488 (1956).
[9] A. F. Gibson and J. W. Granville, J. Electronics **2**, 259 (1956).

Purer samples have a higher resistivity, and it is difficult to obtain ohmic, noninjecting contacts at the high field intensities of several thousand volts/cm. This problem does not exist with samples of low resistivity. However, currents and the consequent Joule heat become excessive at high field intensities, although in all measurements the currents are pulsed at about 50 cps with pulse widths between 0.1 and 2 μsec. Gunn applied 2×10^{-9}-sec pulses, mainly in order to avoid surface breakdown at high field intensities. Especially with high-resistivity material, surface breakdown is a serious problem.

The use of large microwave fields instead of large dc fields has several advantages. For example, microwave fields can be applied without electrodes by placing the sample in a wave guide. In this manner all annoying electrode effects are eliminated. The method is especially applicable to pure high-resistivity material, the investigation of which is of particular interest for studying lattice scattering. If the method of Arthur, Gibson, and Granville[7] is reversed, i.e., if the change in conductivity induced by the microwave field is measured by means of a small dc field across the sample, the region where $(\mu-\mu_0)/\mu_0 \propto E^2$ is valid may be explored with good accuracy. This method has been proposed by Morgan[10] and data on 20 ohm cm n-type germanium in the low-field region have been reported.[11,12]

In this paper similar experiments on both n- and p-type germanium are described. Also measurements with n- and p-type germanium samples have been made using microwave fields up to 10^4 volts/cm in amplitude. The data are compared with those obtained with dc fields.

Figure 1 is a block diagram of the microwave circuit. Both the magnetron and the klystron were operated at a frequency of 34.67 kMc/sec. This was frequently checked with a frequency meter not shown in Fig. 1. Both generators were pulsed, the magnetron with 0.176-μsec pulses at 50 cps repetition rate and the klystron with 100% 1000-cps square-wave modulation. Either one of the generators could be connected with the main wave-guide system through a wave-guide switch. The microwave power was attenuated to the desired power level by using a calibrated variable high-power attenuator (Microwave Associates No. 723) connected to the magnetron, and a similar low-power attenuator connected to the klystron. A pressurized gyrator-isolator served to prevent reflected waves from entering the generators. The wave guide was shorted at the end and operated as a tuned cavity using an $E-H$ plane tuner. The standing wave maximum and ratio were measured with a slotted section and a bolometer connected to a Hewlett-Packard 415B standing wave meter. The meter was tuned to 1000 cps for the 1000-cps modulation and to 500 cps for the 50-cps modulation. This arrangement has been calibrated with a calorimeter and, in the case of 1000-cps modulation, with an absolute-reading power bridge.

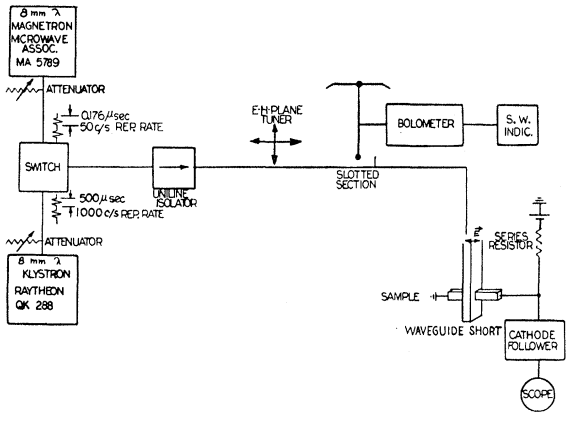

FIG. 1. Block diagram of the experimental arrangement.

The sample, in the form of a rectangular bar about 10 mm $\times$1 mm $\times$0.2 mm, was etched with $CP4$ and than was placed in the waveguide at the position of a standing-wave maximum, $\frac{3}{4}$ of a wavelength from the shorted end. The sample was parallel to the electric field vector, the mode excited being the TE_{10}-mode. Through low-resistance, nonrectifying soldered end contacts, a small dc current was passed through the sample. The modulated microwave field caused a modulation of the drift velocity and consequently of the dc current. The 1000-cps modulation of the current was amplified with a Tektronics 121 preamplifier and read on a Hewlett-Packard 415B meter. The 50-cps modulation signal required no amplification and was therefore picked up by a cathode follower and displayed on a calibrated oscilloscope. The ratio of the pulse height Δj to the dc current j_0, which flowed in the absence of microwaves, was measured as a function of microwave power P absorbed by the sample; P was measured with the standing-wave meter. The microwave field amplitude E_1 is related to the resistivity ρ and the volume V of the part of the sample inside the waveguide by $E_1=(2P\rho/V)^{\frac{1}{2}}$.

In order to obtain $\mu(E)/\mu_0$ from the measured values of $\Delta j/j_0$, one has to take into account that $j/j_0=1+\Delta j/j_0$ is an average over one period of the microwave field $E_1\cos\omega t$:

$$j/j_0=\int_{-\pi}^{\pi}\frac{v_d(E_0+E_1\cos\omega t)d(\omega t)}{2\pi\mu_0E_0}. \qquad (1)$$

μ_0E_0 is the drift velocity when the small dc field E_0 alone is present, and it is proportional to j_0. The unknown function $v_d(E)/\mu_0$ is obtained from the known data on j/j_0 by solving the integral equation (1). This is simplified by the fact that $E_0\ll E_1$. In the case of small microwave field intensities where $(\mu-\mu_0)/\mu_0=-\alpha E^2$, the solution of (1) can be put into the form

[10] T. N. Morgan, Bull. Am. Phys. Soc. Ser. II, **2**, 265 (1957).
[11] T. N. Morgan, J. Phys. Chem. Solids **8**, 245 (1959).
[12] T. N. Morgan, Bull. Am. Phys. Soc. Ser. II, **3**, 13 (1958).

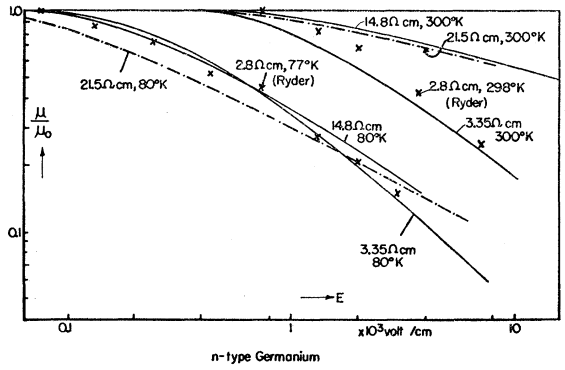

FIG. 2. High-microwave-field dependence of mobility for n-type germanium. Crosses represent dc data indicated by the work of Ryder.[3]

$\alpha=-2\Delta j/3j_0E_1^2$ (see Morgan[11]). For the case of large microwave field intensities, the equation has been solved numerically.

Measurements were made between room temperature and 80°K. For the low-temperature measurements the sample holder was clamped to a surrounding brass pot which could be dipped into liquid nitrogen. In this manner liquid nitrogen was kept outside the wave guide. The condensation of moisture was prevented by firmly covering the pot and inserting a mica shield between the wave-guide flanges which connect the sample holder to the rest of the wave-guide system. A thermally insulating piece of wave guide made from stainless steel tubing was inserted between the cold sample holder and the main wave guide so that the temperature of the sample holder was practically that of the sample. The temperature was measured with a copper-constantan thermocouple attached to the wave guide in the vicinity of the sample. Measurements with low microwave fields were made as the sample was gradually warmed up. At high microwave field intensities the temperature was kept constant during a run, either at 80°K or 300°K.

RESULTS

Figures 2 and 3 show the experimental results for $\mu(E)/\mu_0$ obtained at high field intensities from 3 n-type and 2 p-type samples at 80°K and 300°K. The samples are labeled by their room-temperature resistivity. For comparison Ryder's experimental points,[3] transformed into $\mu(E)/\mu_0$ and the curve published by Mendelson and Bray[4] have also been plotted. Ryder's points on 2.8 ohm cm n-type Ge are in good agreement with our curve on 3.35 ohm cm n-type Ge both at 80°K and at 300°K. The same applies to a comparison of Ryder's data on 0.9 ohm cm p-type Ge with our data on 1.42 ohm cm p-type Ge. The agreement of Mendelson and Bray's curve on pure p-type Ge with our curve on 12.4 ohm cm p-type Ge at 80°K is extremely good. However, this is somewhat accidental since their sample had a resistivity of 3.3 ohm cm at 77°K and probably was intrinsic (47 ohm cm) at room temperature, in this respect being different from our sample. Figures 2 and 3 show $\mu(E)/\mu_0$ also for 14.8 ohm cm and 21.5 ohm cm Ge at 80°K and 300°K and for 12.4 ohm cm p-type Ge at 300°K.

By comparing the curves for samples of different resistivities the following features are noticed. At low field intensities $(\mu_0-\mu)/\mu_0$ is larger for purer material. For high fields the opposite is true in most cases; here the mobility μ found in dc fields has been reported to follow a power law $\mu\propto E^{-\gamma}$. In Figs. 2 and 3 a log-log plot of μ *vs* E has been made in order to display the dependence on γ. For example at 80°K the slope γ is 1.0 for 1.42 ohm cm p-type Ge (this means saturation of the drift velocity) and 0.89 for 12.4 ohm cm p-type Ge. It is 0.9 for 3.35 ohm cm n-type Ge, 0.68 for 14.8 ohm cm n-type Ge, and 0.55 for 21.5 ohm cm n-type Ge. Apparently γ is smaller for purer samples. Although at first sight one would expect different results with dc and 35-kMc/sec ac fields, no frequency dependence seems to be involved as the good agreement between Ryder's dc data and the ac data presented here shows. This point will be discussed later.

At room temperature higher fields are necessary to obtain changes in mobility. It seems that at 10^4 volts/cm a constant slope is not yet reached. The smallest slope of 0.25 at 10^4 volts/cm is obtained with the high-resistivity n-type samples, whereas the 12.4 ohm cm p-type sample at this field intensity gives a slope of 0.38.

Recently Gunn[13] has published drift velocities of electrons in Ge at 77°K with high dc field intensities which are in qualitative agreement with the data presented here. The same dependence on resistivity has been found in the range of medium field intensities.

In the small-field range where $(\mu_0-\mu)\propto E^2$, measurements have been made during a gradual warmup of the sample from 80°K to 300°K. In Figs. 4 and 5 the quantity $\alpha=(\mu_0-\mu)/\mu_0E^2$ has been plotted as a function

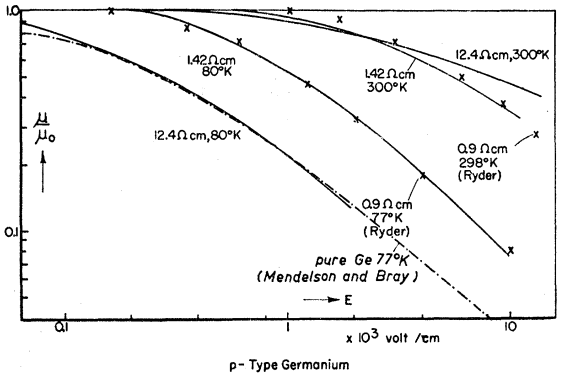

FIG. 3. High-microwave-field dependence of mobility for p-type germanium. Crosses represent dc data indicated by the work of Ryder.[3] The dot-dashed curve represents dc measurements by Mendelson and Bray.[4]

[13] J. B. Gunn, J. Phys. Chem. Solids 8, 239 (1959).

of absolute temperature T for n-type and p-type germanium. The curve for 21.5 ohm cm n-type germanium was taken from Morgan[11] (Fig. 2, labeled as 20 ohm cm, 35 kMc). If the curves in Fig. 4 for the 3.35 ohm cm, 14.8 ohm cm, and 21.5 ohm cm samples are compared with each other either at 80°K or 300°K, the same general behavior is apparent as has been discussed for the range of small field intensities in Fig. 2. The same applies to a comparison of the curves characteristic for 1.42 and 12.4 ohm cm p-type Ge (Figs. 3 and 5).

In addition to these measurements, similar ones have been made with n-type samples of 0.13 ohm cm, 3.5 ohm cm, and 47 ohm cm room-temperature resistivity and with p-type samples of 0.12 ohm cm, 23.5 ohm cm, and 47 ohm cm room-temperature resistivity. The 47 ohm cm samples are intrinsic at room temperature, the n-type sample having a maximum resistivity of 77 ohm cm at 260°K and the p-type sample having 57 ohm cm at 270°K. Unfortunately the microwave power absorbed by these high-resistivity samples was relatively small, with the result of a large standing-wave ratio due to reflections from the wave-guide short. Therefore these data are not too reliable and have been represented by dashed curves. The same applies to the 0.1 ohm cm samples, although for another reason. Here the microwave power absorbed by the samples was relatively large with the result that the penetration depth of the field ("skin depth") was smaller than the sample thickness and the field was far from being homogeneous. In addition, the standing wave ratio was extremely large and measurements were not very accurate.

For all samples in the range of pure lattice scattering

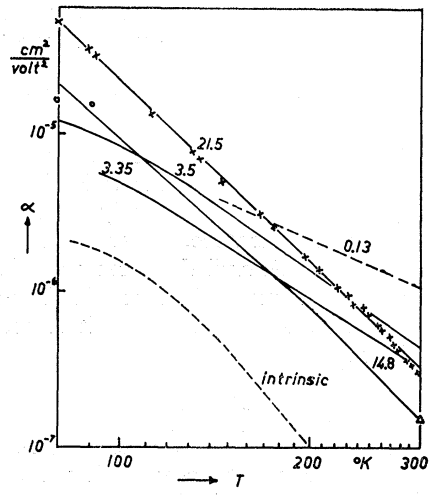

FIG. 4. Relative mobility changes produced by weak microwave fields in n-type germanium, as a function of absolute temperature. The numbers at the curves are room-temperature resistivities of samples, in ohm cm. The circles represent Gunn's dc data,[6] the triangle a dc value indicated by the work of Arthur, Gibson, and Granville.[7] For the sake of clarity, experimental points are plotted for one curve only.

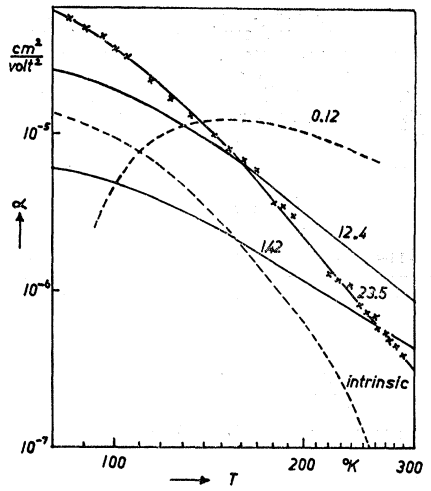

FIG. 5. Same as in Fig. 4 but for p-type germanium.

in the extrinsic region the $\alpha(T)$-curve is a straight line in the log-log plot. Here $\alpha(T)$ can be represented by a power law, as was found out by Morgan[11] with the 21.5 ohm cm n-type sample. According to the theory of acoustical phonon scattering, α should be

$$\alpha=\frac{3\pi}{64c^2}\mu_0^2\propto T^{-3}, \tag{2}$$

since the sound velocity c is practically temperature independent and μ_0 should be proportional to $T^{-1.5}$. Experimentally however, μ_0 was found to be proportional to $T^{-1.66}$ for n-type and to $T^{-2.33}$ for p-type Ge. If we take these values for μ_0 and write α in the form

$$\alpha(T)=\frac{3\pi}{64c^2}\mu_0^2(T/\theta)^x, \tag{3}$$

the behavior of α for each sample in the lattice scattering range can be represented by two constants x and θ. It is tempting to look for a relation between these constants and the resistivity ρ or the carrier concentration n which has been estimated from ρ. In fact it is obvious from Figs. 4 and 5 that the slope of the curves is steeper for samples with higher room-temperature resistivity. The following relation between x and n was found empirically:

$$\exp x=(n/n_0)^{0.67}, \tag{4}$$

with n_0 equal to $1.7\times10^{14}/\text{cm}^3$ for electrons and $1.0\times10^{14}/\text{cm}^3$ for holes. This relation is true only to a first approximation, since the experimental values scatter considerably around the curve representing Eq. (4). In Table I the experimental values of x and those calculated from Eq. (4) have been listed for the various samples.

It is of interest that the samples marked "intrinsic" are highly compensated and would not obey Eq. (4)

TABLE I. List of samples characterized by their resistivity and mobility at 300°K, type and carrier concentration in the extrinsic region, and experimental data on σ_{80}/σ_{300} and x, and values of x calculated from Eq. (4). σ_{80} is the conductivity at 80°K, σ_{300} is the conductivity at 300°K, extrapolated from the extrinsic region, and x is defined by Eq. (3). Mobilities are close to those reported by Prince.[a]

Resistivity at 300°K (ohm cm)	Type	Assumed mobility at 300°K (cm^2/volt sec)	Estimated carrier density (cm^{-3})	σ_{80}/σ_{300} (extrap.)	x exp.	x calc. from Eq. (4)
intrinsic	n	3800	1.2×10^{13}	5.56	+1.63	+1.78
21.5	n	3800	6.8×10^{13}	8.26	+0.53	+0.62
14.8	n	3800	1.0×10^{14}	6.97	+0.23	+0.34
3.5	n	3800	4.8×10^{14}	6.30	−0.52	−0.70
3.35	n	3800	5.2×10^{14}	6.12	−0.77	−0.75
0.13	n	3000	1.6×10^{16}	2.48	−1.62	−3.08
For comparison, $(300/80)^{1.66}=9.0$						
intrinsic	p	1800	4.0×10^{13}	7.82	+0.59	+0.62
23.5	p	1800	1.5×10^{14}	15.30	+0.34	−0.25
12.4	p	1800	2.8×10^{14}	9.73	−1.41	−0.69
1.42	p	1800	2.5×10^{15}	7.51	−2.13	−2.15
0.12	p	1550	3.4×10^{16}	2.19	−3.86	−3.92
For comparison, $(300/80)^{2.33}=21.8$						

[a] See reference 20.

if the impurity density rather than the carrier density would be taken for n. The impurity density can be estimated with the aid of the Brooks-Herring formula[14] from the ratio of the conductivity σ_{80} at 80°K to that at room temperature σ_{300}, the latter being extrapolated from the extrinsic region in the case of the high-resistivity samples; it is assumed here that no freeze-out of carriers occurs at 80°K, as is the case for not too impure germanium. The ratio σ_{80}/σ_{300} has been listed in Table I and can be compared with the values 9.0 for n-type and 21.8 for p-type germanium calculated for no impurity scattering. The high degree of compensation of the intrinsic samples is evident from their σ_{80}/σ_{300} values. Because of this compensation and its corresponding large ion density, the experimental x values are different from the calculated x values by a factor of about 2 if the impurity density is taken for n, but they agree quite well if n is the carrier density.

However, there is another reason for taking n to be the carrier density rather than the impurity density. In the range of dominant lattice scattering where Eq. (3) is valid, the slopes of the $\alpha(T)$ lines vary systematically with n as discussed before. If there were appreciable impurity scattering causing this effect, a corresponding variation of the slopes of the $\mu_0(T)$ curves should be observed if $\log\mu_0$ *vs* $\log T$ is represented by straight lines at high temperatures. However, for all samples under discussion, slopes of the $\mu_0(T)$ curves were 1.65 ± 0.07 in good agreement with Morin's value[15] of 1.66. The small deviations from the average value were within the experimental error. Therefore no evidence of impurity scattering in these samples can be found in the zero-field mobility data μ_0 from about 150°K up to room temperature. It could be possible that the impurities affect α much more than μ_0. A calculation has been made[16] for n-type germanium, assuming impurity densities small enough that for the average carrier energy the mean free path l for lattice scattering is small compared to that for ion scattering, l_{ion}. Then $\alpha\propto 1-c_\alpha l/l_{\text{ion}}$ and $\mu_0\propto 1-c_{\mu 0}l/l_{\text{ion}}$. The ratio $c_\alpha/c_{\mu 0}$ of the constants is about 4, depending somewhat on temperature. This shows that indeed impurity scattering affects α more than μ_0 but by far not enough to explain the experimental data plotted in Figs. 4 and 5. It is concluded therefore that impurity scattering is not the cause of the different $\alpha(T)$ slopes, and n in Eq. (4) represents the carrier density rather than the impurity density.

It may be interesting to look into the effect of impurities on both $\mu_0(T)$ and $\alpha(T)$ at low temperatures where impurity scattering is dominant. With the 0.12 ohm cm p-type sample, the conductivity and consequently $\mu_0(T)$ reach a maximum of 2.58 times the room-temperature values at 125°K. Below this temperature, impurity scattering is predominant as is indicated by a positive slope of $\mu_0(T)$. Here also $\alpha(T)$ bends down and changes sign at about 90°K as can be seen in Fig. 5. At 80°K, $\alpha=-2.3\times10^{-5}$ cm^2/volt^2. This means an increase in mobility with increasing field intensity. Such an effect was first observed by Ryder[3] using dc fields, and later investigated by Gunn[6] with an uncompensated sample containing 1.7×10^{16} donors/cm^3. He found $\alpha=-0.72\times10^{-5}$ cm^2/volt^2 at 77°K and $\alpha=-0.16\times10^{-5}$ cm^2/volt^2 at 90°K. This is somewhat smaller than our value although the number of donors was about the same. The difference may be due to the previously discussed experimental errors with samples of such a low resistivity in the present experimental arrangement.

The circles in Fig. 4 represent data obtained by Gunn[6] with dc fields with a sample whose donor density was $4\times10^{14}/cm^3$. The circles are somewhat above the α curve of the 3.5 ohm cm sample which has a comparable donor density. Unfortunately Gunn did not measure at room temperature. However, the work of Arthur, Gibson, and Granville[7] indicates a value with 4.5 ohm cm n-type germanium at 300°K which is represented in Fig. 4 by a triangle. It is somewhat below our 3.5 ohm cm curve.

DISCUSSION

The experimental data show that with respect to microwave carrier heating there are differences between samples of various resistivities both at large and small field intensities. This is not a feature of the special microwave arrangement but applies to dc experiments too, as can be seen by comparing Ryder's data[3] for

[14] Discussed by P. P. Debye and E. M. Conwell, Phys. Rev. **93**, 693 (1954).

[15] F. J. Morin, Phys. Rev. **93**, 62 (1954).

[16] K. Seeger (to be published).

p-type germanium at 77°K with those of Mendelson and Bray[4] for a sample of different purity. The differences exist even at temperatures where impurity influence on zero-field mobility is negligible. In addition, it seems that it is only in the range of pure lattice scattering that mobility changes can be represented by Eq. (3). A dependence on carrier concentration was found as indicated by Eq. (4). This suggests that electron-electron scattering dominates the part of electron-phonon scattering which is not low-energy acoustical phonon scattering, as proposed by Morgan.[11] Recently Gunn[13] has expressed the same idea. They assumed excess energy gained from the field by low-energy electrons to be transferred by electron-electron scattering to the few high-energy electrons able to emit optical phonons. The rate of energy loss should then increase by an amount dependent on electron density. No detailed theory has been published yet. Qualitatively, however, this idea seems to be supported by the experimental data.

For high field intensities an influence of crystal orientation on carrier heating has been predicted by Gold[17] and found experimentally.[18] An influence of dislocations was found by Gibson.[19] These influences have been neglected in this investigation. The scattering of the data may partly be due to the different crystal orientations and dislocations of the samples.

The zero-field drift mobilities μ_0 of the samples have not been measured. For an estimate of the carrier density n, values of μ_0 have been assumed which are characteristic of perfect crystals.[20] They are listed in Table I. The actual values may be somewhat smaller than these. The error introduced in n may account for the deviations of the calculated x values from the measured ones.

In general the carrier heating will depend on the frequency of the exciting field. If ω is the microwave angular frequency and τ the carrier relaxation time, this dependence is negligible in the case $\omega\tau \ll 1$. At low temperature, τ becomes long enough so that this is no longer true. Morgan[11] has calculated that with electrons in germanium, for microwave frequencies above about 50 kMc/sec this is the case at room temperature, and for about 5 kMc/sec at liquid nitrogen temperature. For the frequency of 35 kMc/sec used in the experiments of this paper, the critical temperature would be about 200°K for electrons and about 100°K for holes. Impurities reduce this temperature. The application of high fields has the same effect due to the reduction of the relaxation time with increasing carrier energy. Therefore the high-field mobilities for all samples should be independent of the microwave frequency. This is confirmed by the good agreement between the data obtained with microwaves, and those obtained by Ryder[3] with dc fields.

With the high-resistivity samples of 0.2-mm thickness, surface effects could occur. However, the samples were etched with *CP*4 and therefore in a condition where the ambient atmosphere had a minimum of influence. Furthermore, microwave field intensities of the order of 10^4 volts/cm could be applied without trouble, whereas with dc fields of this intensity very often surface breakdown occurs. Therefore it seems unlikely that surface effects would obscure the interpretation of the data obtained with microwave fields.

CONCLUSION

The experiments show that, in germanium, mobility changes due to the application of both strong and weak fields depend on the carrier density. Ryder's data[3] are characteristic for rather impure germanium. It seems to be desirable for theoretical considerations to take carrier-carrier interaction into account in the way Morgan[11] and Gunn[13] proposed recently. This theory is supported qualitatively by most of the experimental data presented in this paper. Apparently there is no dependence of mobility on microwave frequency for most of the samples, at least at high field intensities and above 200°K. This is confirmed by the good agreement of the data with those obtained with dc fields.

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