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Transport Properties of CdTe

C. Canali, M. Martini, and G. Ottaviani
Istituto di Fisica dell'Universita, Modena, Italy

and

K. R. Zanio
Hughes Research Laboratories, Malibu, California 90265
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The drift-velocity characteristic for electrons in CdTe has been measured by the transient-charge technique from 77 to 370 °K and for electric fields up to 70 kV/cm. Over this temperature range a negative differential mobility was found. The measured peak drift velocity increases from 1.25×10^7 cm/sec at 370 °C to 2.5×10^7 cm/sec at 77 °K and is characteristic of intrinsic material. The threshold field decreases from 16 kV/cm at 370 °C to 11 kV/cm at 77 °K. At lower temperatures (< 220 °K) and at low electric fields ($< 10^4$ kV/cm) the drift velocity varies from sample to sample increasing with increasing trapping time, and is presumably associated with scattering by ionized centers. An increase of the electron trapping time from 4 nsec at an electric field at 2 kV/cm to 45 nsec at an electric field of 30 kV/cm has also been measured at room temperature.

I. INTRODUCTION

CdTe has been the object of recent studies because of its potential use as a material for room-temperature γ-ray detectors,[1,2] Gunn-effect devices,[3,4] electro-optical modulators,[5] and as infrared windows. The charge-transport process is directly related to the performance of devices for the first two applications. More refined measurement of transport phenomena should provide additional information about material inhomogeneities which are relevant to and degrade the performance of devices considered for all four applications. Preliminary measurements of the drift-velocity characteristic for electrons at room temperature have already been reported[6] and compare favorably with an approximate theoretical treatment.[7] In this paper we present a more extensive measurement of the electron-velocity–field characteristic in the temperature range from 77 to 370 °K and in the electric field range from 1 to 70 kV/cm. Some preliminary theoretical calculations[8] performed by using a Monte Carlo technique[9,10] also permit us to obtain a good fit at 300 °K and are useful for a better understanding of our results. In the course of this experiment we also have been able to observe an increase in the trapping time[11] τ^* of the electrons with an increase in the electric field. These results are of special interest for the use of CdTe as an γ-ray detector since an increase in the charge collection efficiency can be obtained by increasing the electric field beyond the threshold value.

This paper is divided in the following manner. Section II describes the method of measuring the drift velocity and trapping time from waveform analysis in semi-insulating material. The experimental arrangement is described in Sec. III. The drift-velocity results are presented in Sec. IV and discussed in Sec. V. A comparison between the drift-velocity results in CdTe and GaAs is made in Sec. VI. Section VII describes the variation of the electron trapping time with the electric field. Since the latter study required more accurate measurement of the energy to form an electron-hole pair such measurements were made and the results are also reported there.

II. MEASUREMENT OF THE DRIFT VELOCITY AND TRAPPING TIME

Since this topic has been recently treated in several papers,[12-14] we will recall here only its principal features. A sheet of electron-hole pairs is formed near one thin contact of a wafer of semi-insulating material by ionizing radiation, whose range is much less than the sample thickness. When a bias voltage V is applied to the sample, the charge pulse is primarily due to the motion of only one carrier. From Ramo's theorem[15] the charge Δq induced by a charge q travelling a distance Δx of the total crystal thickness W is given by

$$\Delta q = q\Delta x/W \quad . \tag{1}$$

If it is assumed that the electric field is uniform and trapping is not present, the transient current is given by

$$I(t) = Q/T_R, \quad t \leqslant T_R \tag{2a}$$

$$I(t) = 0, \qquad t > T_R \tag{2b}$$

where Q is the total charge generated by the ionizing radiation and T_R is the carrier transit time defined

as the sample width divided by the carrier drift velocity (i.e., $T_R = W/v_d$).

For the case of trapping but no detrapping the transient current is given by

$$I(t) = (Q/T_R)\, e^{-t/\tau^+}, \quad t \leq T_R \tag{3a}$$

$$I(t) = 0, \quad t > T_R \tag{3b}$$

where τ^+ is the carrier mean-free drift time or trapping time which is defined by the reciprocal of the density of trapping centers N_T, the capture cross section of the trapping center σ, and the thermal velocity of the carrier v_{th}, i.e., $\tau^+ = 1/N_T \sigma v_{th}$. In order that the current waveform is exponential it is necessary that the density of trapping centers be uniform.

When the carriers are thermally activated from the traps the current response is given by

$$I(t) = \frac{Q}{T_R} \times \left\{ \frac{\tau^+}{\tau^+ + \tau_D} + \left[\frac{\tau_D}{(\tau^+ + \tau_D)} \right] \exp\left[\frac{-t(\tau^+ + \tau_D)}{\tau^+ \tau_D} \right] \right\}$$

$$\text{for } \tau^+ \leq T_R . \tag{4}$$

Here τ_D is the detrapping time or the mean time that a carrier spends in a trap and is given by $1/\nu - e^{E_T/kT}$, where E_T is the activation energy of the trap and ν is a frequency factor which is slowly dependent on temperature. Throughout this discussion it is assumed diffusion effects are negligible and that there is only one type of trapping center which controls the trapping-detrapping process. For $t > T_R$ the equation cannot be written in a closed form and the appropriate series solutions have been developed.[12-14]

For accurate measurement of the drift velocity it is necessary that T_R be clearly defined. This requires that appreciable charge collection occurs, that is, the trapping time is at least comparable to the transit time. Figure 1 shows current transients with a CdTe device where the measurement of T_R from the pulse shape was (A) possible ($T_R/\tau^+ = 1.5$) and (B) impossible ($T_R/\tau^+ = 7$). The break at the trailing edge of the pulse indicates the arrival of electrons at the positive electrode. Because of the finite risetime of the system the waveform was not ideally vertical at $t = 0$ and $t = T_R$. Therefore to define T_R the pulse width was measured at the midpoint of the trailing edge of the transient after the break. In practice a break occurs only if the current $(Q/T_R)\exp(-T_R/\tau^+)$ is well above the noise level. In our case this was true for $T_R/\tau^+ \leq 2.5$. Figure 2 shows a series of current waveforms taken at room temperature with another CdTe sample for increasing electric fields [(A) 6 kV/cm, (B) 16 kV/cm, and (C) 32 kV/cm], where T_R is clearly defined. The transit time initially decreases and then increases when the threshold field (15 kV/cm) is exceeded. Since the trapping time was equal to or larger than the transit time in samples where the drift velocity was analyzed, the latter could be easily measured.

In order that the detrapping process does not severely degrade the break at T_R it is necessary that the trapped charge is released much later than the transit time, i.e., $\tau_D \gg T_R$. For this condition Eq. (4) is comparable to Eq. (3). Such a condition was satisfied in our measurements. For example, at room temperature $\tau_D \approx 1$ μsec and T_R was always less than 30 nsec. The value of τ_D presumably increased at lower temperature in accord with its definition but could not be accurately measured due to the reduced detrapping current. In many of our measurements it was unimportant to verify the condition $\tau_D \gg T_R$ as often nearly total charge collection occurred, i.e., $T_R/\tau^+ \ll 1$, and the contribution to the pulse from charge released by traps was negligible. Although a detailed analysis of the detrapping times is not necessary to define T_R, consideration of such measurements should be made so as to more correctly interpret the trailing edge of the pulse. The awareness of such tails due to detrapping is also necessary so as to correctly interpret diffusion effects.[16]

An alternative method of determining v_d is, in principle, to measure the initial amplitude of the current pulse [Eq. (3)]. Since excessive overshoot and ringing of the electronics degrades the accuracy of the measurement, the former method was used.

It should be noted that τ^+ can be measured from both waveforms in Fig. 1. When the value of τ^+ is large with respect to T_R an exponential behavior is not clearly observable (for example, as in Fig. 2, cases B and C) and it is impossible to measure τ^+ from the current waveform. Also deformations of the current waveform due to overshoot and ringing make it impossible to obtain a direct reliable measurement of τ^+ for any transient which lasts less than approximately 5 nsec. For these extreme conditions an alternative method[17,18] is necessary to determine τ^+. When Eq. (3) is integrated the pulse shape is given by

$$V = (Q/C)\,(\tau^+/T_R)\,[1 - e^{-t/\tau^+}], \quad t \leq T_R \tag{5a}$$

$$V = (Q/C)\,(\tau^+/T_R)\,[1 - e^{-T_R/\tau^+}], \quad t \geq T_R \tag{5b}$$

where C is the input capacitance of the amplifier. Once the v_d-vs-E curve is obtained for a sample, τ^+ can be calculated after measuring the amplitude of the fast component of the voltage pulse from the output of a charge (or voltage) sensitive amplifier for $t > T_R$. It is not necessary for the amplifier to

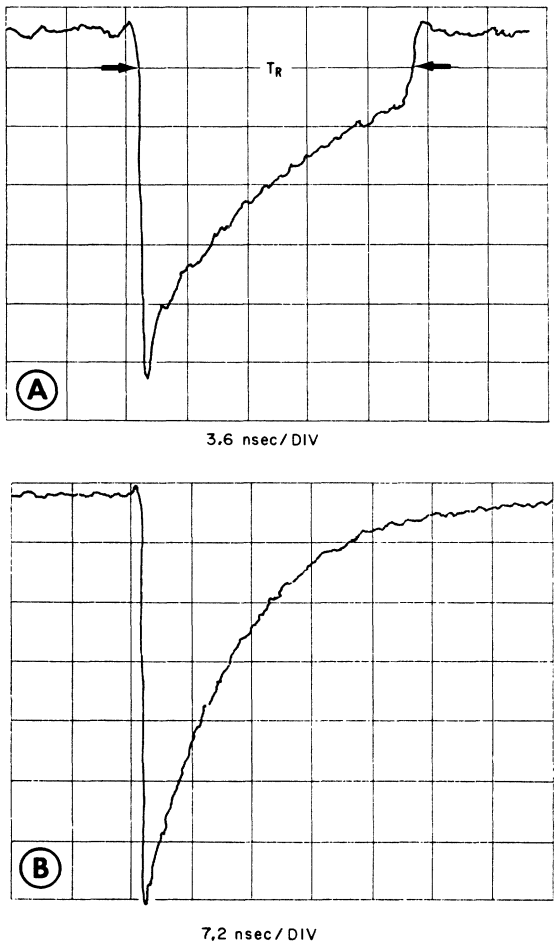

FIG. 1. Current waveform taken at room temperature for a sample of semi-insulating CdTe showing a case (A) where measurement of the electron transit time T_R is possible even in the presence of heavy trapping ($\tau^+ \approx 11$ nsec, $T_R = 16$ nsec). The sample thickness is 600 μm, the applied bias voltage is 230 V, and the horizontal sensitivity is 3.6 nsec/division. Current waveform (B) is at a lower electric field in the same sample where a direct measurement of T_R is not possible. The applied bias voltage is 50 V and the horizontal sensitivity is 7.2 nsec/division.

have a very short rise time, the only limitation on the rise time being that it has to be much smaller than τ_D. The accuracy in determining τ^+ for large values of τ^+/T_R strongly depends upon the accuracy in knowing Q. This requires a knowledge of both the energy of the ionizing radiation and the energy necessary to create an electron-hole pair. For this reason the energy to form an electron-hole pair was remeasured and alpha particles, whose energy is precisely known, were used as a source of ionizing radiation. These measurements have already been described in another paper.[19] When alpha particles were used to measure the amplitude of the voltage pulse the accuracy in determining τ^+/T_R, and therefore τ^+, is also limited by the plasma time. Since the electric field cannot immediately separate the dense column of electron-hole pairs produced by the alpha particles the apparent transit time is larger than the correct value determined when electrons are used as the source of ionization. When τ^+ was determined from the Hetch relationship corrections for the plasma time were made.[20]

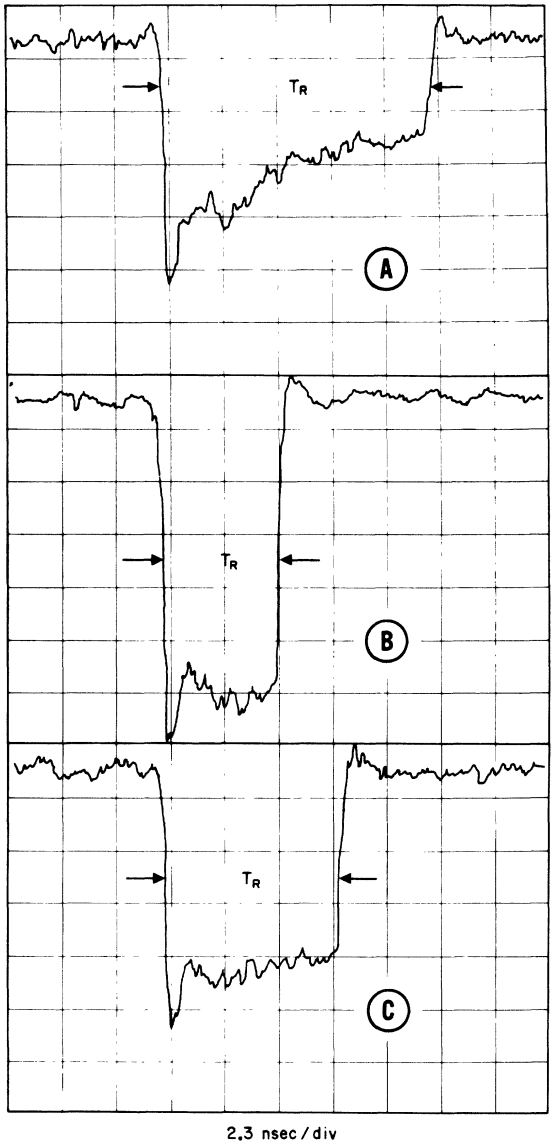

FIG. 2. Current waveforms at room temperature for a sample of semi-insulating CdTe ($W = 680$ μm and $\tau^+ = 10$ nsec) for three values of the electric field [(A) 6kV/cm; (B) 16 kV/cm; (C) 32 kV/cm] where a straightforward measurement of the electron transit time is possible. The transit time decreases and then increases as the threshold field (15 kV/cm) is exceeded. The horizontal sensitivity is 2.3 nsec/div.

III. EXPERIMENTAL ARRANGEMENT

The transient-charge technique is now a classical tool for studying transport phenomena in semiconductors[16,21–23] and does not require a lengthy description. In our experiment the artificial source of ionizing radiation was the Modena University pulsed electron accelerator[24] which delivers 0.1-nsec bunches containing up to 10^4, 40-keV electrons. The crystals of high resistivity ($\rho \approx 10^8$–10^9 Ω/cm) CdTe were grown at Hughes. The thickness of the samples varied from 0.45 to 1.20 mm. The contacts were obtained by evaporating gold on the finely polished surfaces. The area of the evaporation was about 10 mm^2 in all samples.

The measurement of v_d and τ^+ were made on 10 samples obtained from six different crystals. The experimental error in measuring the drift velocity was less than 5%. The spread among data obtained from samples with different values of τ^+ is also less than 5% at temperatures higher than 220 °K. The trapping time of the electrons varied from 3 to 100 nsec, where not specified, measured trapping times refer to low electric fields ($E < 5$ kV/cm) as τ^+ was found to be strongly dependent upon E at high electric fields. By means of the pretrigger pulse available from the pulsed-electron accelerator the bias voltage was pulsed, each pulse being 10 μsec long. This permitted reaching high electric fields (up to 70 kV/cm in several cases) and also avoided polarization effects at low temperatures.[25] The current pulses from the samples were sent directly to the input of the sampling oscilloscope by means of a 50-Ω coaxial cable. When it was necessary to improve the signal-to-noise ratio, the analogical output of the oscilloscope could be fed by an x-y plotter through an averaging computer (ND 801 Enhancetron). The total risetime of the system was about 0.35 nsec and was due essentially to stray inductances and capacitances. The small capacitance of the samples did not give a significant contribution to the risetime of the system.

IV. DRIFT-VELOCITY RESULTS

The experimental data on the electron drift velocity were obtained from waveforms typically similar to the ones shown in Fig. 1(a) or Fig. 2. As previously states, the detrapping process was too slow to appreciably influence the current waveforms at all the temperatures. An over-all picture of the measured electron drift velocities is shown in Fig. 3 where a smooth curve was drawn through the data points (cf. Fig. 5). These curves show the peak velocity to increase from 1.25×10^7 cm/sec at 370 °K to 2.5×10^7 cm/sec at 77 °K. The value of the electric field E_{th} corresponding to the maximum drift velocity and to the threshold field of the negative differential mobility decreases from 16 kV/cm at 370 °K to 11 kV/cm at 77 °K. The maximum initial negative differential mobility increases with the decreasing temperature (Fig. 4). From the lowest electric fields used ($E \simeq 5$ kV/cm) to E_{th} and at temperatures less than 370 °K, the drift velocity increases faster than a linear relation with E (i.e., superohmic behavior).

Below 220 °K and for electric fields less than E_{th} there is a well-defined difference in the drift velocities from sample to sample which appeared to be correlated with τ^+; this difference increased with decreasing values of the temperature and the electric field. Figure 5 shows this effect at the lowest temperature (77 °K) with low ($\tau^+ \approx 10$ nsec) and high ($\tau^+ \approx 100$ nsec) trapping time samples. The same effect is further illustrated in Fig. 6 where

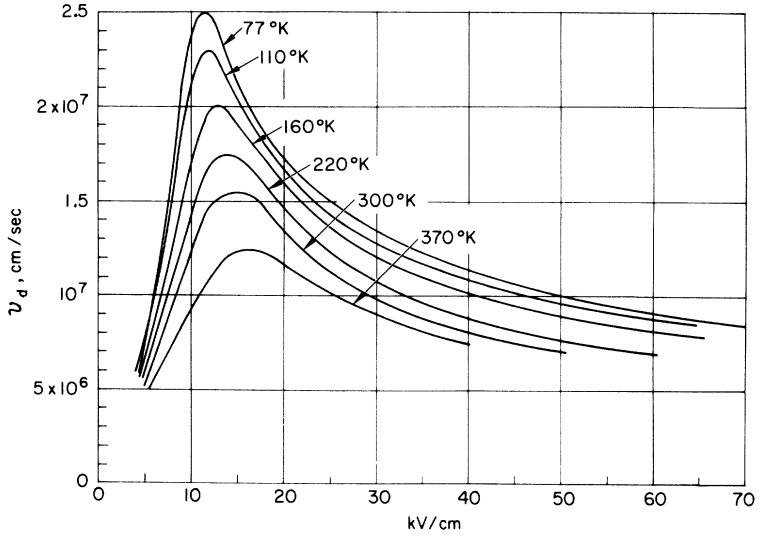

FIG. 3. Electron drift velocities in CdTe as a function of the electric field in the temperature range between 77 and 370 °K. The values shown here are the highest measured at every temperature (see Fig. 5) and correspond to samples with high τ^+ values.

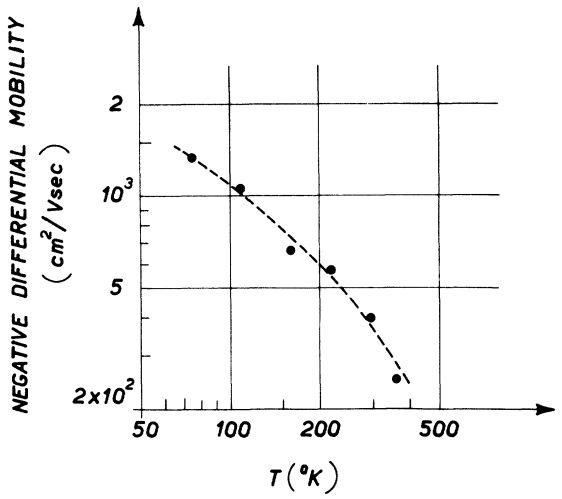

FIG. 4. Initial negative differential mobility in CdTe as a function of temperature.

the mobilities for high and low τ^+ samples are plotted as a function of the temperature for two different electric fields. The circles ($\tau^+ \approx 100$ nsec) and squares ($\tau^+ \approx 10$ nsec) correspond to an electric field of 2 kV/cm. The triangles correspond to data taken at 10 kV/cm with high and low τ^+ samples. In the same figure, the Hall-mobility measured by other workers[26] on low-resistivity material is reported for comparison. It should be noted that both Figs. 5 and 6 show that the difference in the drift velocity measured on samples made with material with different values of τ^+ disappears for $E > 10$ kV/cm.

The values of the drift velocity reported in Fig. 3 are the highest obtained at every temperature and correspond to samples with high τ^+ values. For example, the curve corresponding to the circles in Fig. 5 is reported in Fig. 3.

V. DISCUSSION OF THE DRIFT-VELOCITY RESULTS

One general feature of the drift-velocity characteristic in Fig. 3 which is consistent with optical phonon scattering is that v_d increases with decreasing temperature. In order to simplify the discussion of the other features we divide this section into two subsections: the first relevant to that portion of the curves lying to the left of the threshold field E_{th}, and the second relevant to that portion of the curves lying to the right of E_{th}.

A. Electric Fields < E_{th}

All the curves of Fig. 3 but the one at 370 °K show a region of superohmic behavior for $E < E_{th}$. This behavior is possibly due to scattering by both polar optical phonons and ionized centers. It should be noted that at the two highest temperatures, scattering by ionized centers is unimportant and the theory can predict (see later) the observed behavior taking into account only polar optical mode and intervalley scattering. As the temperature is lowered the impurity scattering becomes more and more important. In fact for sufficiently low electric

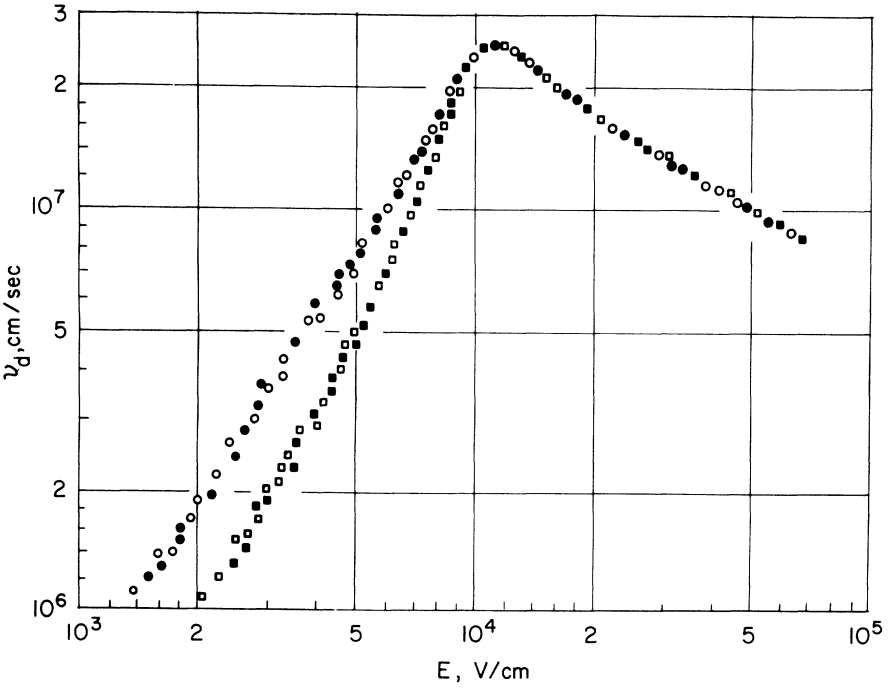

FIG. 5. Electron drift velocity at 77 °K. The circles correspond to high τ^+ samples ($\tau^+ \approx 100$ nsec), while the squares correspond to low τ^+ samples ($\tau^+ = 10$ nsec). Open and closed data points correspond to different samples taken from the same boule.

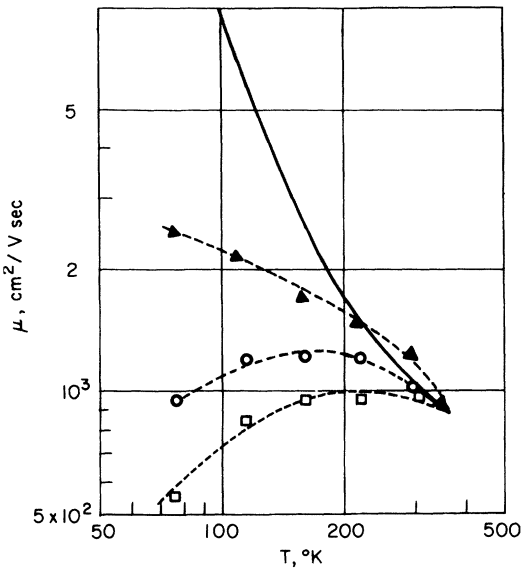

FIG. 6. Electron drift mobility as a function of temperature: □, $E = 2$ kV/cm, $\tau^+ \simeq 10$ nsec; ○, $E = 2$ kV/cm, $\tau^+ \simeq 100$ nsec; ▲ $E = 10$ kV/cm. At 10 kV/cm the data are identical for both the low and high τ^+ samples. Hall mobility measured in low-resitivity samples by B. Segall, M. R. Lorenz, and R. E. Halsted [Phys. Rev. 129, 2471 (1963)] are indicated by the solid lines.

fields and at low temperature, v_d actually decreases with the temperature. This phenomenon is apparent in Fig. 3 at 77 °K. Further evidence of scattering by ionized centers is presented in Fig. 5 where drift velocity varies between samples taken from different boules. At 77 °K the polar optical-mode scattering is expected to give a subohmic behavior[27] and a value of the low-field mobility much higher than the one shown in Fig. 6. The correlation between the mobility and τ^+ is significant under this aspect. As expected a larger τ^+ is correlated with a high mobility and presumably a lower concentration of ionized scattering centers.

B. Electric Fields > E_{th}

When the electric field is increased beyond a critical value the optical phonons are not any more able to dissipate all the energy of the electrons (it should be remembered that scattering by ionized centers is elastic). As a result their energy shows a dramatic increase until intervalley scattering between the central valley and the secondary minima occurs.[27,28] A theoretical curve[8] obtained by a Monte Carlo method[9,10] at 300 °K, ignoring scattering by ionized centers, is shown in Fig. 7 to reasonably fit the experimental data.

As E is further increased, an increasing number of electrons can undergo intervalley transitions; the mobility of the carriers is strongly reduced by this mechanism and a negative differential mobility is shown by the curves of Fig. 3. The threshold field decreases with decreasing temperature because the contribution of the polar optical phonons to the total scattering process decreases with the temperature and the instability situation, corresponding to the dramatic increase of their energy, is reached at lower electric fields. For electric fields equal to or larger than E_{th} the mobility is probably determined by both the intervalley and the polar optical-mode scattering. This explains the increase of both the maximum value of the drift velocity (Fig. 3) and the initial differential negative mobility (Fig. 4) with the decreasing temperature.

The theoretical calculations now in progress[8] seem to show that the percent concentration of the carriers in the secondary valleys is quite low ($\leq 10\%$) even for the highest fields experimentally reached (70 kV/cm, Fig. 3). The negative differential mobility seems therefore to be due to the "switching on" of the intervalley scattering as a randomizing mechanism rather than to the larger effective mass of the electrons in the secondary valleys.

The same calculations indicate that the population of the secondary valleys begins to assume substantial values only for fields of the order of 100 kV/cm or more. It seems therefore unlikely that the region where the curves of Fig. 3 would begin to rise again (i.e., showing a positive differential mobility) will never be reached experimentally, as the necessary fields are very near to the values corresponding to a dielectric breakdown.

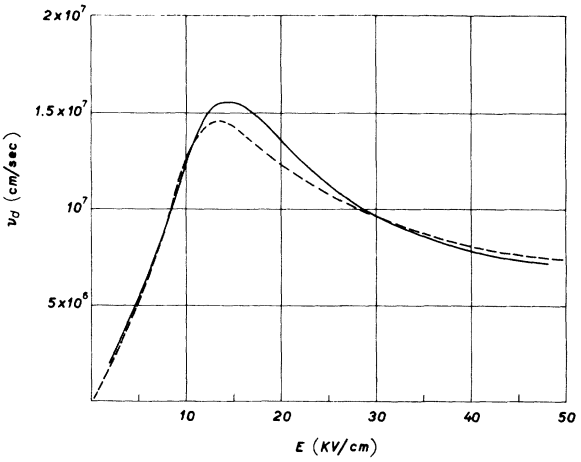

FIG. 7. Comparison between experimental (solid line) and theoretical (broken line) v_d-vs-E characteristic at 300 °K. The theoretical curve from C. Jacaboni and L. Reggiani [Phys. Letters 33A, 333 (1970)] neglects the scattering from ionized impurities.

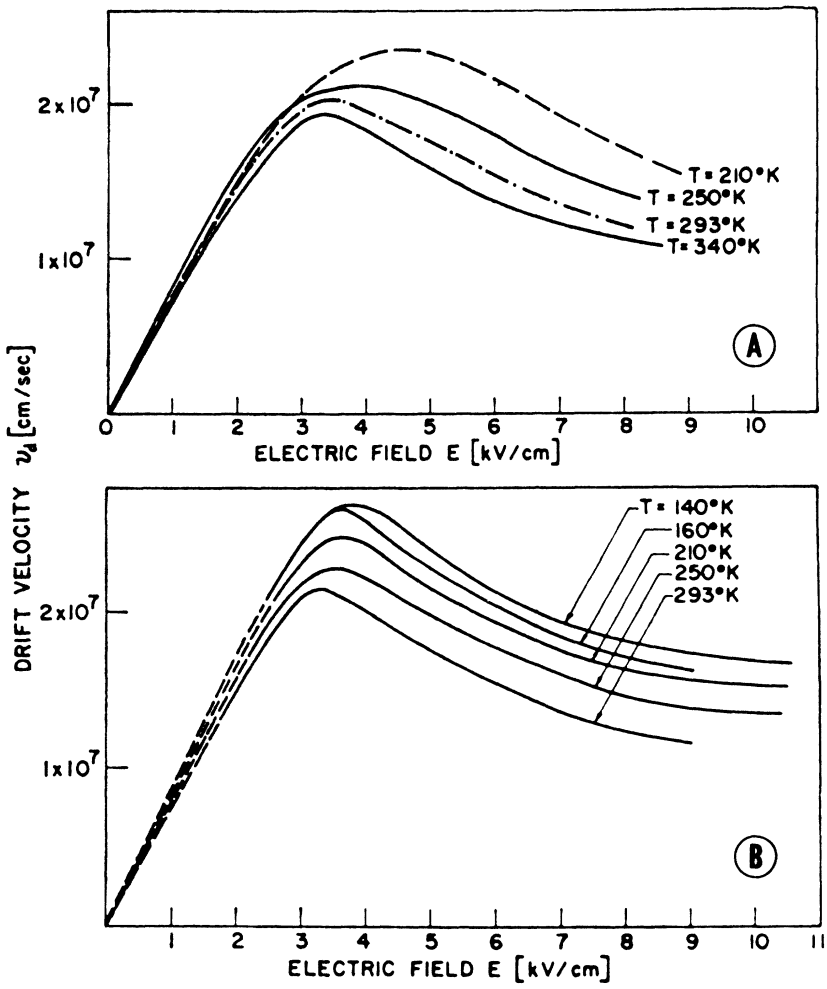

FIG. 8. Drift-velocity characteristic of electrons in two different samples of GaAs. Data from J. G. Ruch and G. S. Kino [Phys. Rev. 174, 921 (1968)].

VI. COMPARISON OF CdTe AND GaAs DRIFT-VELOCITY MEASUREMENTS

The velocity-field characteristic has also been measured for electrons in GaAs over a wide range of temperatures.[16] Pulsed-electron-beam results for two samples of semi-insulating GaAs are shown in Fig. 8. The over-all results show as in the case

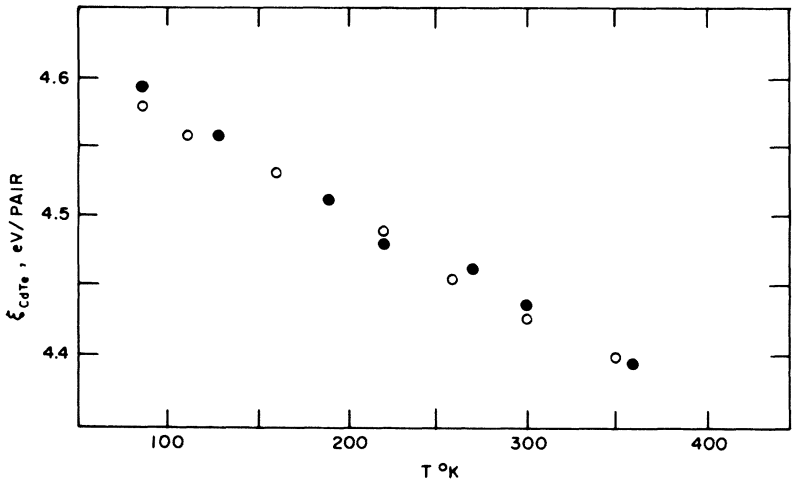

FIG. 9. Energy to form an electron-hole pair in CdTe as a function of temperature.

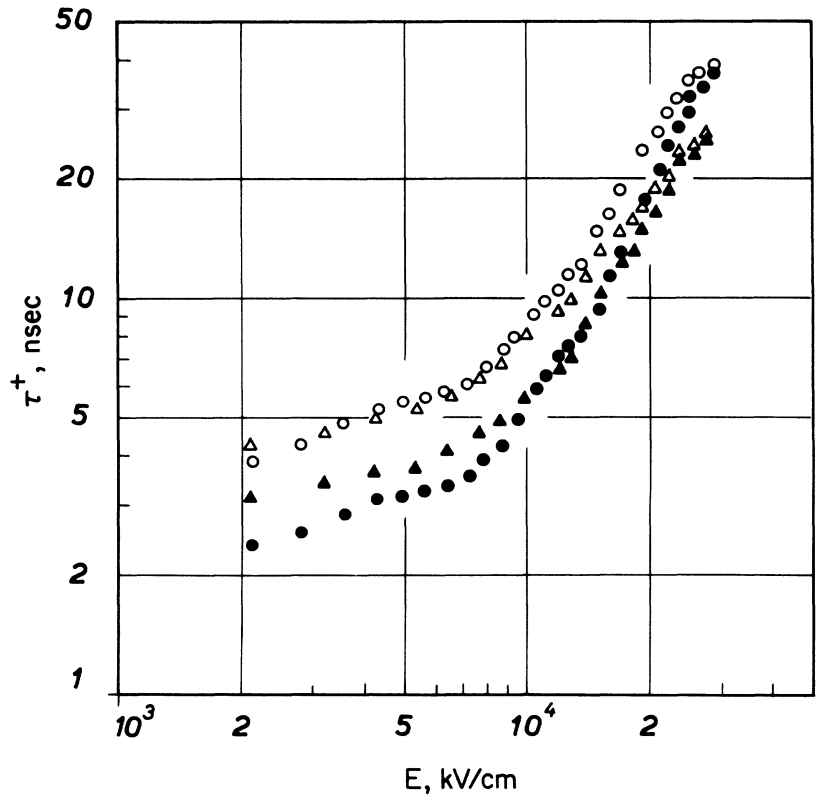

FIG. 10. Electric field dependence of the electron mean free drift time τ^+ at 300 °K in semi-insulating CdTe. Circles refer to a 675-μm-thick sample; triangles refer to a 445-μm-thick sample. Data account for (▲, •) or ignore the plasma time effect (△, ○).

of CdTe a general increase in the drift velocity with a decrease in temperature and no strong evidence of a minimum velocity being reached. The threshold field occurs approximately a factor of 5 less than in CdTe and moves with temperature in a direction opposite to that of CdTe. The threshold field is expected to be smaller in GaAs than in CdTe because of the weaker electron-phonon coupling. Calculations of the drift-velocity characteristic in GaAs[9,10] and in CdTe[8] without considering scattering by ionized centers indicate an increase in the threshold field with increasing temperature.

Because of the lower threshold field in GaAs scattering by ionized centers has a more significant effect on its position. The fact that the lattice temperature has a weak influence on the low-field mobility as in CdTe is evidence that the transport properties of the material are not entirely controlled by phonon scattering, but are influenced by scattering by ionized centers. Note in Fig. 8(a) that there is a decrease in the drift velocity with decreasing temperatures below the threshold field at 210 °K. Such behavior is also found in CdTe at 77 °K. However in contrast to CdTe the drift-velocity characteristic at and beyond the threshold field varies between the two samples. For example, at 210 °K the shape of the peak in Fig. 8(a) is quite broad when compared to the shape of the peak in Fig. 8(b). There is also a corresponding shift in the threshold field from 4.7 kV/cm [Fig. 8(a)] to 3.5 kV/cm [Fig. 8(b)]. It is likely that better control of native defects and foreign atoms would result in more uniform drift-velocity characteristics from sample to sample and more predictable performance of microwave devices.

VII. DEPENDENCE OF THE ELECTRON TRAPPING TIME ON ELECTRIC FIELD

In the course of the drift-velocity measurements at room temperature we were able to observe a variation of τ^+ with the electric field.[11] Although direct measurement of τ^+ could be obtained from the current pulse, improved accuracy especially at higher fields was possible by first measuring the amplitude of the fast component of a voltage transient and then calculating τ^+ using Eq. (5) and appropriate values of T_R obtained from the drift-velocity characteristic (Fig. 3). As a more precise value of Q was needed, alpha particles from ^{241}Am (5.477 meV) were used as the source of ionizing radiation and the energy to form an electron-hole pair in CdTe was redetermined. The energy to form an electron-hole pair from 80 to 350 °K is shown in Fig. 9.[19] Semi-insulating material with a τ^+ of approximately 100 nsec was used in this analysis. The value of ϵ that we measured at room temperature ($\epsilon = 4.43 \pm 0.05$ eV) is very close to the value reported recently with low-resistivity ma-

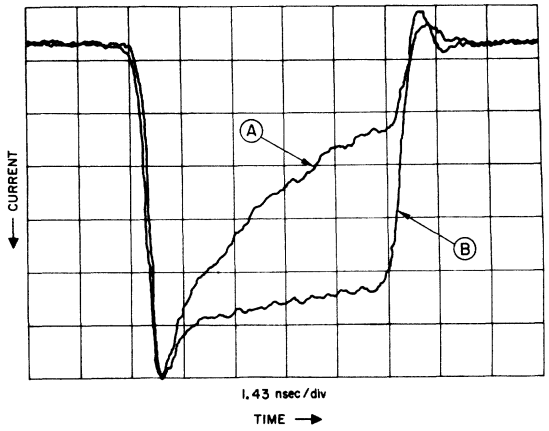

FIG. 11. Current waveforms obtained with the pulsed electron accelerator showing the electric field dependence of the mean-free drift time τ^+. Waveform (A) was taken at a field of 7.8 kV/cm, waveform B at a field of 32 kV/cm. The transit times T_R are identical but waveform (B) shows that the trapping time strongly increases. The horizontal sensitivity is 1.43 nsec/division.

terial.[29] Figure 10 shows that τ^+ increases from ≈ 3 nsec at an electric field of 2 kV/cm to ≈ 30 nsec at an electric field of 30 kV/cm. Closed data points correspond to values of τ^+ calculated from the Hecht relationship without correcting for the plasma time.[20] Open data points indicate the values of τ^+ corrected by taking into account measurements of plasma time in CdTe.[30] Corrected and uncorrected data correspond, respectively, to transit times of T_R and T'_R, which are related by the following expression:

$$T'_R = (T_R^2 + t_p^2)^{1/2} . \quad (6)$$

Here t_p is the plasma time. The corrected data are in good agreement with those obtained by the electron gun. The dependence of τ^+ on electric field is so strong that the amplitude of the fast component kept increasing with electric field even beyond E_{th}, where the drift velocity decreases (see Fig. 3). Low-τ^+ material ($\tau^+ \approx 4$ nsec) was intentionally used in this experiment to improve the accuracy of our measurements. With higher τ^+ material the charge collection efficiency was complete (within experimental error) at low electric fields and it was impossible to measure any variation of τ^+ as a function of E. The accuracy in determining τ^+ decreases with increasing values of τ^+. Since the charge collection efficiency asymptotically approaches unity at large values of τ^+ a small error in determining the pulse amplitude would result in large fluctuation in τ^+. The largest error in τ^+ is about $\pm 15\%$ and occured when the charge collection efficiency was 92%. The results of Fig. 10 were checked by comparing the fast current wave shapes obtained with the electron accelerator. Figure 11 shows current wave shapes at the same drift velocity but with two different values of the field. The results do not leave any doubt of the fact that the higher electric field corresponds to a higher value of τ^+. Determination of τ^+ directly from the current waveform is in principle superior to that carried out on the integrated wave shape. However, the overshoot and ringing of the electronics make a direct evaluation of τ^+ impossible at very short transit times.

The fast increase of τ^+ for fields higher than 8 kV/cm can be explained only as a decrease of the capture cross section (see Sec. II). If the trapping centers are positively charged (Coulomb attractive capture) the observed decreasing of the cross sections can be explained either as a geometrical one[31] or as due to the heating of the electrons by the field.[32,33] If the trapping centers are neutral only the second of the two previously mentioned mechanisms can be invoked. According to a recent theoretical calculation,[8] the temperature of electrons in CdTe at 300 °K shows a dramatic increase from 700 to 10 000 °K when the field passes from 6 to 20 kV/cm. This behavior of the electron temperature strongly supports the theory that the increase of τ^+ is essentially an hot-electron effect. Repulsive (negative) trapping centers are obviously ruled out since their capture cross section should increase rather than decrease when the energy of the electrons is increased by the field.[21]

VIII. CONCLUSION

These results indicate that the transient technique is a useful tool to characterize the semi-insulating materials. Accurate measurements were possible with CdTe since the electron trapping times ($4 < \tau^+ < 100$ nsec) were much greater than the subnanosecond period necessary to generate an electron-hole pair with the electron beam accelerator. Measurement of the electron drift velocity as a function of temperature and electric field has provided direct information concerning the transport properties. The threshold field and the initial negative differential mobility behave in a manner consistent with intrinsic material. No evidence of a minimum in the drift velocity beyond the threshold field was found. At low electric fields and at low-temperatures, variations in the drift velocity from sample to sample were found and are presumed to be associated with scattering by ionized centers. An increase in the electron trapping times with increasing electric field was also found and is associated with the heating of the electron distribution.

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[1]K. R. Zanio, J. Neeland, and H. Montano, IEEE Trans. Nucl. Sci. NS17, 287 (1970).

[2]R. O. Bell, N. Hemmat, and F. Wald, IEEE Trans. Nucl. Sci. NS17, 241 (1970).

[3]M. R. Oliver and A. G. Foyt, IEEE Trans. Electron. Devices ED14, 617 (1967).

[4]G. W. Ludwig, IEEE Trans. Electron. Devices ED14, 547 (1967).

[5]J. Kieffer and A. Yariv, Appl. Phys. Letters 15, 26 (1969).

[6]C. Canali, M. Martini, G. Ottaviani, and K. R. Zanio, Phys. Letters 33A, 241, (1970).

[7]P. N. Butcher and W. Fawcett, Proc. Phys. Soc. (London) 86, 1205 (1965).

[8]C. Jacoboni and L. Reggiani, Phys. Letters 33A, 333 (1970).

[9]W. Fawcett, A. D. Boardman, and S. Swain, J. Phys. Chem. Solids 31, 1963 (1970).

[10]J. G. Ruch and W. Fawcett, J. Appl. Phys. 41, 3843 (1970).

[11]C. Canali, G. Ottaviani, M. Martini, and K. Zanio, Solid State Commun. 9, 163 (1971).

[12]J. W. Mayer, in *Semiconductor Radiation Detectors*, edited by G. Bertolini and A. Coche (North-Holland, Amsterdam, 1968), Chap. 5.

[13]K. R. Zanio, W. M. Akutagawa, and R. Kikuchi, J. Appl. Phys. 39, 2818 (1968).

[14]W. E. Tefft, J. Appl. Phys. 38, 5265 (1968).

[15]C. Cavalleri, G. Fabri, E. Gatti, and V. Svelto, Nucl. Instr. Methods 21, 177 (1963).

[16]J. G. Ruch and G. S. Kino, Phys. Rev. 174, 921 (1968).

[17]J. W. Mayer, J. Appl. Phys. 38, 296 (1967).

[18]W. D. Davis, Phys. Rev. 114, 1006 (1959).

[19]A. Alberigi Quaranta, C. Canali, G. Ottaviani, and K. R. Zanio, Nuovo Cimento Letters 4, 908 (1970).

[20]A. Alberigi Quaranta, M. Martini, and G. Ottaviani, IEEE Trans. Nucl. Sci. NS16, (1969).

[21]W. E. Spear, J. Phys. Chem. Solids 21, 110 (1961).

[22]A. Alberigi Quaranta, F. Cipolla, and M. Martini, Phys. Letters 17, 102 (1965).

[23]A. Alberigi Quaranta, C. Canali, and G. Ottaviani, Appl. Phys. Letters 16, 432 (1970).

[24]A. Alberigi Quaranta, C. Canali, and G. Ottaviani, Rev. Sci. Instr. 41, 1205 (1970).

[25]W. E. Spear, J. Non-Cryst. Solids 1, 197 (1970).

[26]B. Segall, M. R. Lorenz, and R. E. Halsted, Phys. Rev. 129, 2471 (1963).

[27]E. M. Conwell, *High Field Transport in Semiconductors*, in Solid State Physics, edited by F. Seitz and D. Turnbull (Academic, New York, 1967), Suppl. 9.

[28]H. Frölich, Proc. Roy. Soc. (London) 188, 532 (1947).

[29]A. Cornet, P. Siffert, A. Coche, and R. Triboulet, Appl. Phys. Letters 17, 432 (1970).

[30]C. Canali, M. Martini, G. Ottaviani, K. Zanio, and A. Alberigi Quaranta (unpublished).

[31]A. Alberigi Quaranta, A. Taroni, and G. Zanarini, IEEE Trans. Nucl. Sci. NS15, 373 (1968).

[32]G. A. Dussel and R. H. Bube, J. Appl. Phys. 37, 2797 (1966).

[33]V. L. Bonch-Bruevich and E. G. Landsberg, Phys. Status Solidi 29, 9 (1968).