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Carrier propagation in sputtered *a*-Si:H

P. B. Kirby and William Paul
Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138

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Time-of-flight measurements have been made on *a*-Si:H thin films prepared by the sputtering process. The propagation of electrons can be either dispersive or nondispersive depending on the sample-preparation conditions. Samples which reveal nondispersive transport in a certain voltage and temperature regime undergo a transition to dispersive behavior when the temperature is lowered below 300 K. Activation energies for mobility of 0.18 ± 0.01 eV are obtained when the transport of electrons is nondispersive. The temperature-dependent dispersion is consistent with transport taking place by a multiple trapping process. Room-temperature electron mobilities in the range $0.1-0.5$ cm^2/V s are found for films which have a low density of states at the Fermi level. Room-temperature hole mobilities $\sim 1\times10^{-3}$ cm^2/V s are found with an activation energy of 0.4 eV. In all samples measured the transport of holes is dispersive.

INTRODUCTION

Time-of-flight experiments on the majority of insulating crystals yield unequivocal results concerning the mobility of carriers.[1] This is because carrier propagation in the applied field often follows Gaussian statistics,[2] even if the mobility is controlled by capture at a trapping level. Unfortunately, the information obtained from time-of-flight experiments on amorphous semiconductors or insulators has not been as straightforward to interpret[3] because of the spread in localized states arising from disorder and defects. Such states will have a distribution in energy and site which means that transport involving them can no longer be described by a single event time. When the distribution of event times enters into the time scale of the experiment then the measurement gives direct information on these processes.

In the time-of-flight experiment injected carriers drift under an applied field between two electrodes. Straightforward analysis of carrier propagation is possible if the capture of carriers into traps which have a thermal release time longer than the transit time does not take place. For Gaussian statistics, a constant-current transient appears with a tail that depends on the dominant dispersion mechanism.[4] In this case the mobility, defined by the transit time, is a good parameter and is a constant at all times. Such transport is referred to as nondispersive and the constant current is indicative of a pulse of carriers moving with a constant velocity between the electrodes. In amorphous materials, however, it is often found that the average velocity of carriers decreases with time during the experiment due to carriers being held at sites which have progressively longer release times.[3] In the time-of-flight experiment this reveals itself as a decrease of the current measured from time zero. Often there is no feature that can be associated with the carriers reaching the back contact. Transient photocurrents of this form have been observed in amorphous As_2Se_3 and Se at low temperatures. In many cases it has been shown that the current is well described by[3]

$$i(t)\propto\begin{cases}t^{-(1-\alpha)}, & t<t_T\\ t^{-(1+\alpha)}, & t>t_T\end{cases}\tag{1}$$

so that a fiduciary mark corresponding to a transit time appears when the current trace is displayed in units of $\log i$ vs $\log t$. Such behavior is understood by a distribution of event times with an algebraic tail,[2]

$$\Psi(t)\sim\text{const}\times t^{-(1+\alpha)},\quad 0<\alpha<1\ .\tag{2}$$

Although it is presently controversial whether hopping transport can give rise to such a distribution[5] it is now clear that transport based on a multiple-trapping model can.[6–8] In this case the distribution can arise from a spectrum of release and capture rates. Such transport is said to be dispersive.

This study is concerned with time-of-flight measurements on thin films of sputtered *a*-Si:H which have a low density of states at the Fermi level, as revealed by photoluminescence and conductance-capacitance measurements.

Recent measurements by Tiedje *et al.*[9] on glow-discharge *a*-Si:H clearly show that it is possible to obtain either highly dispersive or nondispersive electron transients, depending on the preparation conditions of the films. It was found that films displaying nondispersive behavior had higher mobilities at room temperature than in previous measurements,[10] the highest reported being 0.8 $\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$. Tiedje *et al.*[9] also made measurements on sputtered material which revealed highly dispersive transients giving mobilities that were lower than those of glow-discharge material. An interesting model for the transient response in a time-of-flight experiment has recently been put forward by Tiedje and Rose.[11] These authors suggest that the form of the transient response is explained by the continuous sinking with time of a peaked distribution of carriers down an exponential distribution of traps characterized by a steepness T_c.

EXPERIMENTAL

Measurements were performed on well-characterized Schottky diodes of Nichrome—*a*-Si—*a*-Si:H—Pt sandwiches. A 300-nm sputtered unhydrogenated *a*-Si layer creates an ohmic contact to the *a*-Si:H films. The *a*-Si:H surface was etched immediately prior to the evaporation of the Pt contact from a resistance source. In this study samples will be classified according to the density of states at the Fermi level as measured by the conductance-capacitance technique.[12]

The transient photocurrent observed in a time-of-flight experiment can be influenced by many factors besides the drift signal under direct consideration. If the mobility of carriers traveling towards the front electrode is low enough so that the carriers are not extracted during the time constant of the external circuit, then their drift will add to the observed current signal. In this paper we show that the hole mobilities in the films under study are $\sim 10^{-3}\ \text{cm}^2\,V^{-1}\,\text{s}^{-1}$ at room temperature, so that under the conditions of the experiments, where the carriers are created very close to the top electrode, their motion will not be observed. However, as the mobilities of both types of carriers decrease as the tempeature is lowered, motion towards the top electrode might be observable well below room temperature. Recombination of the overlapping carrier distributions can also influence the observed transients. However, as already mentioned, since we create the carriers close to the top electrode this influence is kept to a minimum. Artifacts can also arise from injection effects after excitation. In this study we have used only devices that display good rectifying properties at the Schottky barrier.

For standard measurements a fraction of a 10-ns 3371-Å pulse from a nitrogen-pumped dye laser was focused onto the platinum contact. The incident-light intensity was varied by the insertion of neutral density filters, the light levels being kept well below space-charge conditions for all electron-drift signals. Transient currents were recorded in either single-shot on a storage oscilloscope or at 10 cycles/s with a boxcar integrator having a 2-ns gate. In the repetitive mode a frequency divider was available to eliminate the effect of buildup of trapped space charge.[13] Except at the lowest temperatures no differences were observed between the single-shot and repetitive mode of operation. The effects of any slow relaxation of the displacement current on the recorded transients were determined by varying the time between the start of the bias pulse and triggering of the laser pulse. Such currents do not influence the results presented here. Samples thicker than one micron were used so that the varying electric field in the barrier region extends for only a small fraction of the sample thickness. This will be of increasing importance the lower the density of states in the gap.

RESULTS AND DISCUSSIONS

For reasons discussed later most measurements have been made on films that have been found to display good photoluminescence properties. Figure 1 shows an electron phototransient obtained on a film that has a low density of states at the Fermi level ($N_{E_F} \sim 1.5\times10^{16}\ \text{cm}^{-3}\,\text{eV}^{-1}$). Its form is typical of that found for the majority of films we have measured in that it exhibits a rapid decrease of the photocurrent, characterizing highly dispersive transport, with no obvious feature corresponding to the injected carriers reaching the back contact. In the usual analysis of such photocurrents the transit time is identified by a change of slope on a plot of log*i* versus log*t*. The algebraic depen-

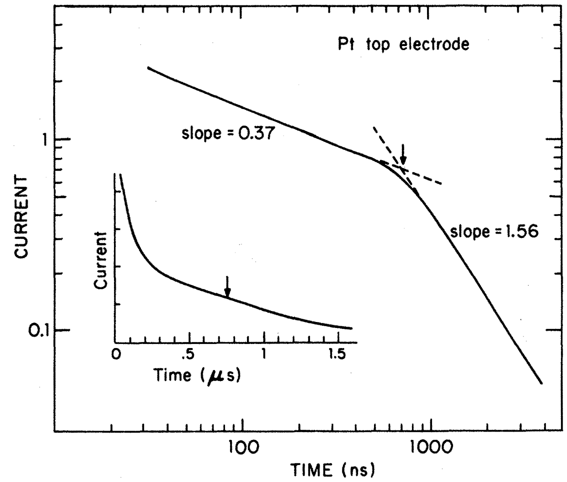

FIG. 1. Dispersive current transient in units of log$i$ vs log$t$ (main figure) and units of i vs t (inset). The arrow in the inset marks the position of the transient time obtained from the intercept of the tangents illustrated in the main figure. A field 2.8×10^4 V/cm is present and the temperature of measurement is 257 K.

dence is followed as Fig. 1 shows, and a knee is well defined. Verification of this feature as the transit time is made by the observation of a linear relationship between the applied voltage and the reciprocal transit time, as displayed in Fig. 2. Since this relationship holds the mobility is well defined in the low-voltage region. The mobility obtained from the slope of these plots is shown in the inset of Fig. 2. An activation energy of 0.23 eV is obtained, a value that is somewhat larger than previously found on glow-discharge material.[10] Figure 1 gives a value of $\alpha=0.63$ for the dispersive parameter in Eq. (1) from the pre-transit-time part of the photocurrent. The value of α is found to be dependent on the value of the electric field, as Fig. 3 displays and maximum dispersion is obtained for low fields. Similar behavior is found in crystalline anthracene and is interpreted as being consistent with a multiple-trapping model[14] Multiple trapping should also be accompained by a superlinear behavior of the reciprocal transit time on applied voltage. Scher and Montroll[2] predict a transit time that varies as $1/\alpha$. Figure 2 is clearly not in agreement with this prediction and superlinearity does not set in until the largest fields applied.

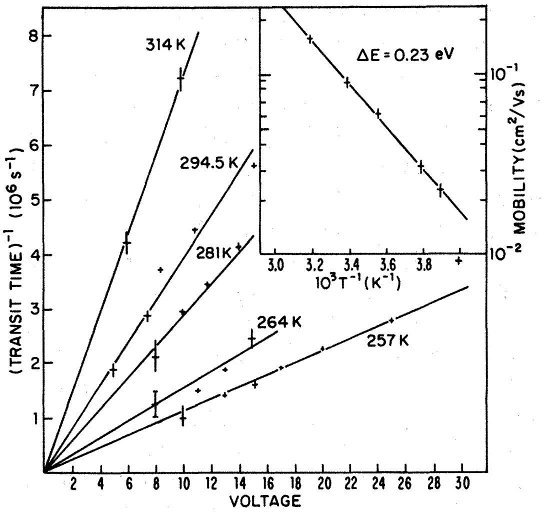

FIG. 2. Voltage dependence of the reciprocal transit time at several temperatures for the sample of Fig. 1. The inset shows the temperature dependence of the mobility calculated in the linear low-voltage region.

Although we do not understand completely the microscopic transport giving rise to the features displayed in Figs. 1—3, they do illustrate the generally dispersive behavior we have observed in films or sputtered a-Si:H prepared under different conditions. Most of the films investigated reveal low values for the activation energy of the electron mobility ($E_a < 0.25$ eV). A few samples however have $E_a \sim 0.4$ eV, more in line with the findings of Fuhs *et al.*[15] on their material produced by the glow-discharge technique. Along with the higher activation energy we find a high room-temperature mobility of 0.5 cm^{2}V^{-1}s^{-1}.

The room-temperature value of the mobility for the 4.6-μm-thick sample of Fig. 1 is 0.1 cm^2 V^{-1}s^{-1}, a factor of 2 larger than reported by Tiedje *et al.*[9] on their sputtered a-Si:H. We have observed similar values of mobilities on identically prepared 1-μm films. This is not in agreement

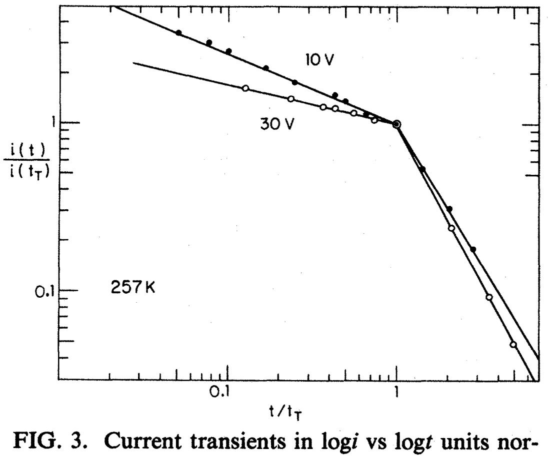

FIG. 3. Current transients in log$i$ vs log$t$ units normalized to their respective transit times for two applied voltages at a constant temperature.

with a suggestion by Datta and Silver[16] that the mobility measured should scale as the square of the thickness of the sample based on the hypothesis that what is being measured is a space-charge relaxation current.

In a subset of sputtered films we have observed constant-current pulses more typical of nondispersive behavior. A single-shot transient displaying this behavior is shown in Fig. 4. The rectangular shape is similar to those reported by Tiedje *et al.*[17] on a subset of their film which they have shown are described by nondispersive Gausssian statistics. We have observed all of the effects reported by these workers. Thus the transport, in those of our films displaying these features, also seems to be governed by Gaussian statistics so that the mobility, on this time scale at least, does not depend on time. The transient in Fig. 4 is very different from that of Fig. 1. Marked in Fig. 4 is the transit time which corresponds in the Gaussian case to the peak of the transiting carrier distribution reaching the back contact of the Schottky diode. Although it is not possible to describe the falloff in terms of diffusion alone, we will show that the time for the current to reach half of its initial value is a good measure of the transit time.[4] That this fiduciary mark varies in the correct manner is shown in Fig. 5 where the reciprocal transit time is plotted as a function of applied voltage. It is linear as expected for Gaussian transport.

In Fig. 6(a) the phototransients obtained from an 8.2-μm film are shown for differing applied voltages. The absence of an initial peak in the transients means that carriers are trapped into localized states very quickly, within the time constant of the measuring circuit. Indeed it seems that a propagating Gaussian pulse is established within the risetime of the signal. The trends with voltage are similar to those observed in glow-discharge material[17] and so we take the propagation of carriers to be the same in both types of films. The initial peak observed in the low-field transients, and shown for 6-V bias in Fig. 6(a), has been explained as being due to electron transit through the high-field Schottky-barrier region.[17] We disagree with this identification for our sputtered film, as a simple calculation shows that the time to transit a barrier region is not consistent with the times involved in Fig. 6(a). In order to test this more fully we have performed measurements on identical samples with Nichrome instead of platinum as the top electrode. Current-voltage measurements reveal little barrier, and hence there is only a small field near the metal contact. Figure 6(b) shows that the low-voltage transients are independent of the presence of a field near the top electrode. It is noticeable from Fig. 6(b) that the transients display increasing dispersion at lower voltages which suggests that nondispersive behavior is both temperature and voltage dependent. Thus at 300 K for the sample of Fig. 6(b), the transient shows slightly dispersive behavior when 8.2 V is applied across the sample, however at higher temperatures this dispersion decreases and a rectangular-shaped pulse is observed. Thus, there seems to be a temperature for any voltage at which the transport of carriers becomes nondispersive.

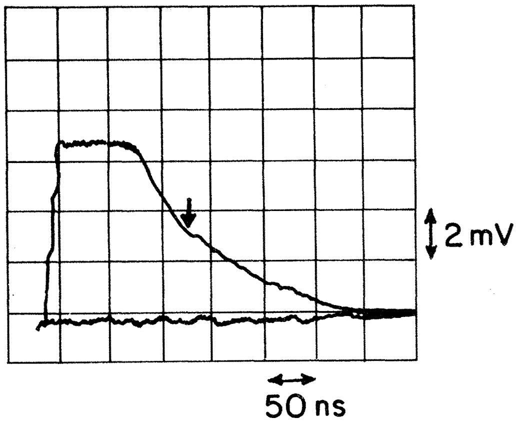

FIG. 4. Single-shot phototransients for a sample displaying nondispersive behaivor. The sample thickness is 1.35 μm and 1.5 V is applied across the sample.

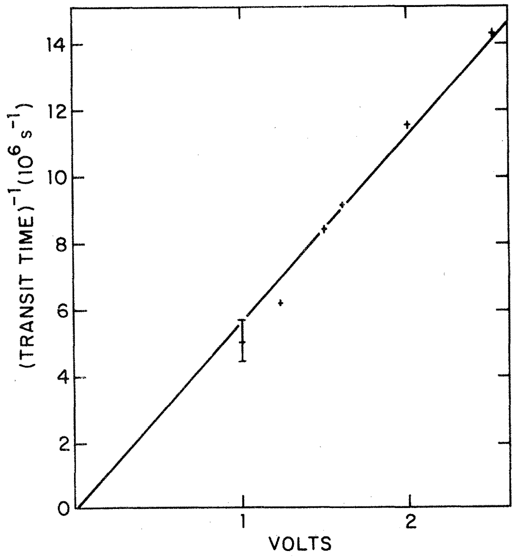

FIG. 5. Voltage dependence of the reciprocal transit time for a sample displaying nondispersive behavior.

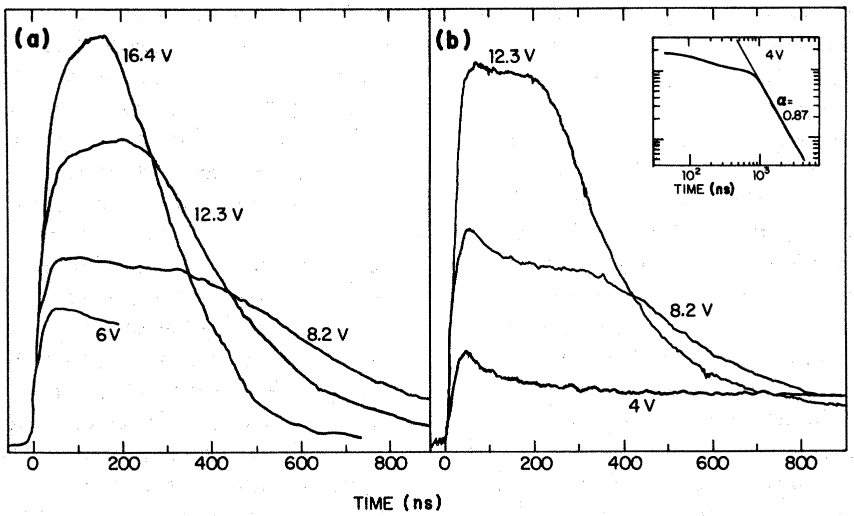

FIG. 6. Voltage dependence of the shape of the electron photocurrent transients at 300 K. (a) corresponds to a sample with a platinum top contact and (b) with Nichrome. The samples, prepared in the same sputtering run, are of somewhat different thicknesses.

A considerable number of different factors can lead to dispersive characteristics of excess carrier-transit pulses. For example, macroscopic inhomogeneity of the electric field or trap density, space-charge accumulation, and specimen-thickness variations can produce such characteristics. It is possible to exclude the latter two for the conditions of these experiments but the influence of microstructure is more difficult. However, whatever the cause, there are important consequences for steady-state measurements which are performed at low voltages and depend on dispersion for their explanation. A dispersion that depends on the applied voltage suggests that the number of trapping events is important in controlling the observed dispersion of carriers.

We now turn to a discussion of the effect of temperature on the constant-current pulses. In Fig. 7 we show the evolution with temperature of the phototransients obtained on a a-Si:H film[18] which is nondispersive at room temperature and for voltages greater than 10^4 V/cm. A dramatic change occurs in the pulse shape when the temperature is lowered below 290 K. Down to 225 K a feature corresponding to carriers reaching the back contact is still observable on a linear axis, while at still lower temperatures a featureless decay is obtained.

In the nondispersive region it is possible to obtain mobility values (that are independent of applied voltage) by two methods. The transit time can be taken as the point at which the slope changes on a linear plot, corresponding to the first carriers reaching the back contact. Alternatively the time for the signal to reach half its initial value can be used as the fiduciary mark. The mobility values obtained using these two methods are different but an activation energy of 0.19 eV (Fig. 7)

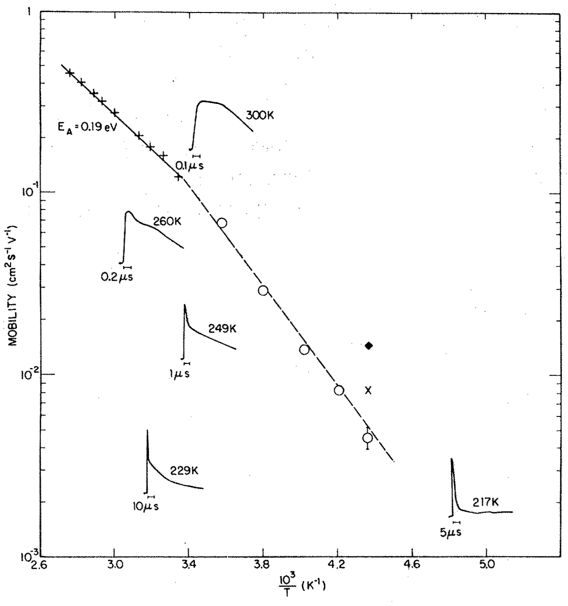

FIG. 7. Temperature dependence of the electron drift mobility for an applied electric field of 1×10^4 V/cm (+ and ○). Representative current transients observed at various temperatures are displayed in linear units. The field dependence of the mobility is shown at $T=230$ K (× and ◆ refer to electric fields of 3×10^4 and 4×10^4 V/cm, respectively). The sample thickness is 8.2 μm.

is obtained in both cases. Our experience with all films having nondispersive regimes is to find a value of 0.18 ± 0.01 eV for the activation energy in the nondispersive region.

In the dispersive region the transit time is determined from a plot of log*i* vs log*t*. The results for one voltage are given in Fig. 7 as a function of temperature. Although there appears to be a slight change of slope through the transition region this is due to the dispersive-current signal resulting from a stochastic process. In Fig. 7 we show the different values of mobility obtained for different applied fields at 230 K. It is possible to choose a voltage so that no change in the activation energy is observed in the two regimes, which suggests that the same basic mechanism of carrier propagation prevails in the temperature range covered by these experiments. The nonlinear field dependence of the transit time, apparent from Fig. 7, contrasts with the linear dependence in the nondispersive region. At low tempertures "universality" of the current transients is increasingly observed as shown in Fig. 8.

Figure 9 shows the development of the logarithmic current as the temperature changes in terms of the pre-transit and post-transit slopes of a log*i* vs log*t* representation. According to the stochastic model of Scher and Montroll,[2] non-Gaussian transport, which is governed by a distribution function of the form $\Psi(t) \propto t^{-(1+\alpha)}$, should be described by $0<\alpha_i=\alpha_f<1$. Figure 9 clearly shows the development from Gaussian to non-Gaussian transport in these terms although $\alpha_i \neq \alpha_f$. The temperature dependences of α_i and α_f are very similar to those found for *a*-Se by Pfister.[18] It has been suggested[7] that a more complicated distribution function than that of Eq. (2) can account for α_i not being equal to α_f, and also for the dependence of α_f on temperature.

The α_i obtained from the initial slope of the log*i* vs log*t* plot decreases as the temperature decreases, which is consistent with a multiple-trapping process since the carriers are interacting with traps that are distributed in energy. A linear decrease has recently have been found to describe the data in measurments of transient photoconductivity on *a*-As_2Se_3 (Ref. 19) and Si:H doped with phosphorous[20] and taken as evidence for an exponential distribution of trapping states. The phototransients obtained in time-of-flight experiments on glow-discharge-produced *a*-Si:H have recently been explained by Tiedje and Rose[9] in terms of the progressive thermalization of carriers down an exponential distribution of trapping states. Their model predicts that the mobility should have a power-law dependence on temperature in the nondispersive regime. However, our measurements show the mobility to be an exponential function of temperature when the transport is nondispersive. The difference might be due to the exponential trap distribution not extending continuously to the conduction-band extended states.

Values of α as a function of temperature on sputtered *a*-Si:H have also recently been obtained by Ray *et al.*[21] from measurements of induced optical absorption. Contrary to the results found here they deduce a relatively temperature-

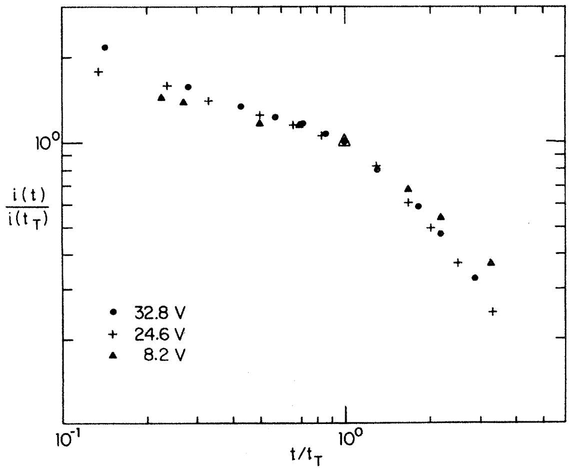

FIG. 8. Transient currents in units of log*i* vs log*t* at constant temperature for different applied voltages. The traces are normalized with respect to the transit time on the log*t* axis.

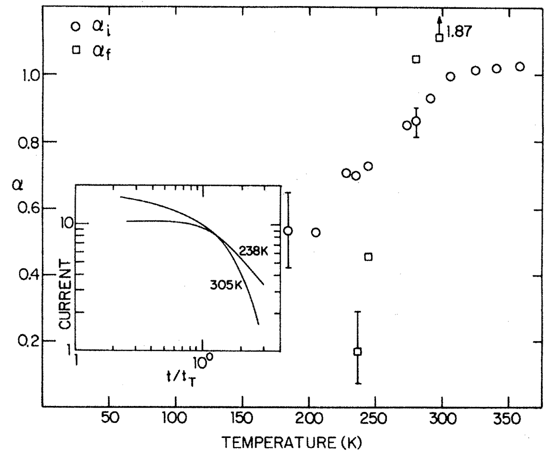

FIG. 9. Temperature dependence of the dispersion parameter α obtained from the initial and final slopes of a log*i* vs log*t* representation of the photocurrent transients. The inset shows current traces in logarithmic units at two temperatures.

TABLE I. Measured parameters for two films, one of which has a nondispersive regime. PL denotes photoluminescence.

Material property	E^{04} (eV; 300 K)	E^{03} (eV; 300 K)	PL Intensity	PL Peak energy (eV)	PL Width (eV)	C_h (at. %)	$N(E_F)$ ($\mathrm{cm^{-3}\,eV^{-1}}$)
Nondispersive film	2.07	1.82	0.77	1.46	0.34	15	1.5×10^{16}
Dispersive film	2.05	1.85	1.0	1.44	0.31	20	1×10^{16}

insensitive α and suggest hopping as the dominant method of carrier propagation in their sputtered *a*-Si:H. In our samples, however, which have a low density of states at the Fermi level, and activated (band) transport, the transport of carriers gives rise to a temperature-dependent α usually associated with a multiple-trapping process. Further comparisons of time-of-flight and induced-optical-absorption measurements on similar samples are planned to explore these differences.

The occurrence of nondispersive behavior observed in some films is not easily associated with any particular measured parameter. Table I compares measurements that have been performed on the films of Figs. 1 and 6; the former always displays dispersive behavior, while the latter has a nondispersive regime. More statistics will be needed before the importance of the hydrogen content can be evaluated. It is expected that a transition from dispersive to nondispersive behavior should be evident in other measured parameters that are influenced by the amount of dispersion involved in carrier transport. However we have found that the observation of nondispersive or dispersive behavior is dependent on both the temperature and voltage. Thus, at room temperature, whether carrier propagation follows Gaussian or non-Gaussian statistics depends on the value of the electric field present during the measurement. In particular, for photoconductivity experiments where the electric field across the specimen is typically $\sim 1\times10^{3}$ V/cm, the drift of carriers at room temperature will be dispersive. It seems probable, however, that well above room temperature the transition to nondispersive transport should be evident in photoconductivity measurements. We are presently pursuing this line of research. Voltages greater than 1×10^{4} V/cm are present in measurements that involve Schottky barriers and so it seems possible that at room temperature the motion of electrons in the depletion region can be controlled by Gaussian statistics and a mobility that is independent of time.

Before leaving electron transport it is worth pointing out that some of the films investigated do not fall into the categories discussed so far. In particular, in some films ($<1\ \mu$m) whose transients display the features of dispersive transport, it has not been possible to define a transit time on a log$i$ vs log$t$ scale. This might be partly due to the rapidly varying electric field extending over a range comparable to the film's thickness. However, this cannot explain the results on thicker films having a high density of states at the Fermi level ($N_{E_F}\sim 5\times10^{17}\ \mathrm{cm^{-3}\,eV^{-1}}$). A typical transient for such a sample is shown in Fig. 10, drawn in units of log$i$ vs log$t$. The general shape is independent of the voltage. The falloff from time zero is very fast. Larger-state densities result in a faster falloff. Since this effect is only observed in films which have a large density of states at the Fermi level a possible explanation is that the rapid falloff is due to the electrons sinking quickly into traps which lie deep within the gap. The state densities at which these deep-trapping effects become very important are also those for the observed luminescence quantum efficiency drops. If the observed decrease was due to carriers falling into a peaked

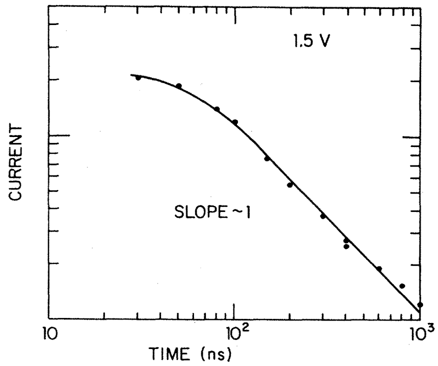

FIG. 10. Electron phototransients observed in samples which have greater than $1\times10^{17}\ \mathrm{cm^{-3}\,eV^{-1}}$ states at the Fermi level.

distribution of deep states, one might expect a well-defined transit time due to carrier transport of the resulting peaked distribution of trapped carriers. So one must appeal to either a slowly varying density of deep states or a peaked distribution of injected carriers descending rapidly towards the Fermi level. Recent models of dispersive transport (Tiedje and Rose,[11] Orenstein and Kastner[19]) rely on the assumption of an energy-independent captures cross section for carriers falling into trapping states from the conducting level. If this were always true it would be expected that the deep-trapping effects observed in undoped films would also be observed in *a*-Si:H doped with phosphorous when the density of states at the Fermi level is greater than 5×10^{17} $\mathrm{cm^{-3}\,eV^{-1}}$. However, we do not observe deep-trapping effects in such films in either time-of-flight or photoconductivity-decay measurements (Kirby[22] and Hvam and Brodsky[20]) which implies that the energy dependence of the capture cross section can be of crucial importance. It might prove possible to take account of this cross-section energy dependence in the models of Orenstein and Kastner[19] and Tiedje and Rose[11]; it seems likely that such weighting will slow the carriers at a particular *energy* location. We must expect this effect to arise from the particular charge state of defects in the gap.

We now turn to a brief discussion of the transients observed when the Schottky diode is forward biased. In a time-of-flight experiment this usually corresponds to the motion of holes across the sample. Figure 11 shows typical effects that are observed as a function of low forward bias. We feel that these current reversals as a function of voltage are consistent with electron and hole drift in the negative field due to the Schottky barrier. The details of the current reversals are complicated, the width of the depletion region, which itself is controlled by the density of states in the gap, being an important factor.

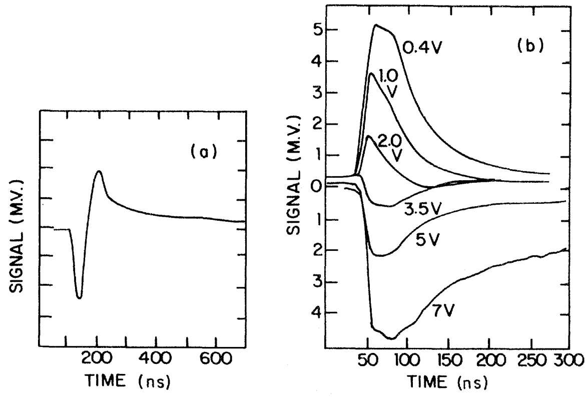

FIG. 11. Low forward-bias phototransients.

At high voltages it has been possible to measure hole mobilities as a function of temperature. All phototransients observed to date under forward bias have been dispersive though a feature is often seen at high temperatures. This is shown in Fig. 12 and might indicate a transition to nondispersive behavior at higher temperatures. The hole mobilities measured on samples having a range of density of states at the Fermi level show a smaller range of values than found for electrons. The activation energies of the mobilities are also fairly independent of sample variation. The measured values of mobility are higher than previously reported for glow-discharge material,[23] although the activation energies obtained are similar. The fact that the mobility values obtained are similar, and independent of the density of states at the Fermi level, might mean that the state densities near the valence-band edge are independent of the number of defects whose energy levels lie at the Fermi level. Alternatively, this behavior might be expected if the holes form polarons.

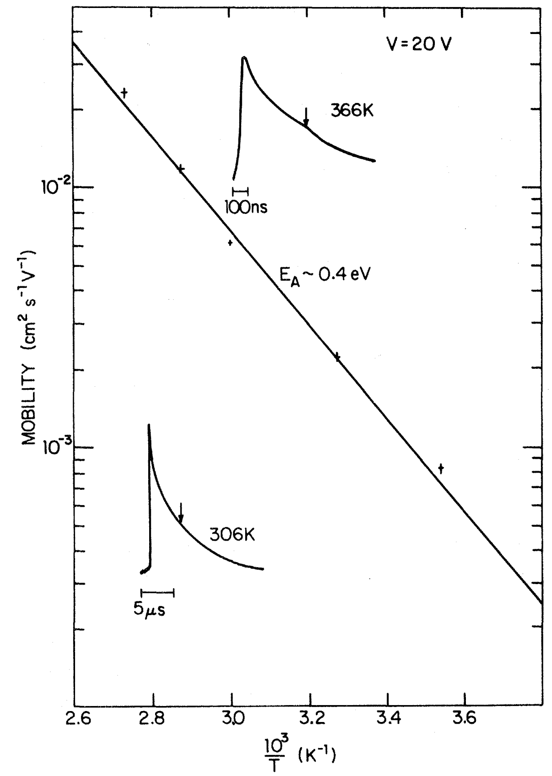

FIG. 12. Temperature dependence of the hole drift mobility. The sample thickness is 4.6 μm. Representative photocurrent decays are shown in linear units.

The fact that the activation energies of electron and hole mobilities can be quite different (0.18 vs 0.4 eV) and the difference in mobility values is only 2 orders of magnitude at room temperatures means that it is possible for hole motion to contribute significantly to the total photoconductivity at experimentally accessible temperatures. This might be observable in photoconductivity temperature dependencies.

The dispersion parameter for holes α characterizing the time-dependent mobility, is found to vary from sample to sample. It has been found that films in which the electron transients are lifetime limited, as described earlier, can or cannot be lifetime limited for holes. Films which have very strong electron-lifetime limitations for electrons also display hole-lifetime-limited transport. However, in films with $N_{E_F} \sim 1 \times 10^{17}$ cm^{-3} V^{-1} where the electron transients decay rapidly, hole transport is not lifetime limited. This implies that deep-electron trapping is favored over deep-hole trapping. This can be explained by the intervention of states (or events) that stop the hole carriers from descending to the Fermi level. The formation of polarons, or trapping at states which have large capture cross sections would provide such a mechanism.

LIFETIMES OF CARRIERS

In the time-of-flight experiment the mobility of carriers can only be extracted if the time for a deep-trapping event to occur is longer than the transit time of carriers across the sample. A deep trap in this case is one whose release time of a carrier to the conducting level is long compared to the time scale of the experiment. Thus, if a transit time for carriers reaching the back contact is discernible on the recorded phototransient, this time puts a lower limit on the carrier lifetime.

We have already mentioned that for films having a large density of states at the Fermi level, the lifetime of electrons and holes can be very short (less than 100 ns). Also, for a given density of states at the Fermi level, loss of carriers to deep traps is more likely for electrons than for holes. The fact that a signal is observed at all in films having a high density of states at the Fermi level means that carriers, once excited, are not immediately trapped into deep states. Capture initially must take place into shallow states, and then after numerous release and trapping events a carrier finally ends up in a deep trap.

Films which have a low density of states at the Fermi level reveal a dramatic lengthening of the time for deep trapping to occur. Figure 7 shows that a feature corresponding to electrons reaching the back contact is observable after 10 μs below room temperature. We can take this value as a lower limit for the lifetime of the electrons with respect to deep trapping at low temperatures. Similar values for carrier lifetimes have recently been found by Snell,[24] from studies of injected carriers in *a*-Si:H *p*-*n* junctions, the *a*-Si:H being prepared by the glow-discharge technique. It seems, then, that the deep-trapping lifetime in *a*-Si:H prepared by the glow-discharge technique and sputtering can be similar. We also find equally long lifetimes for holes.

The lifetimes of carriers quoted here might well change if the carrier of opposite sign were present, as is the case in photoconductivity experiments. The presence of the opposite-charge carrier will change the capture cross section of the trap. However, since the minimum deep-trapping lifetimes obtained for both carriers from time-of-flight measurements are equally long, the assigned lower limit should be valid for capture into deep traps in photoconductivity measurements.

SPACE-CHARGE EFFECTS

Under high-incident-light intensities we have observed classical space-charge-limited (SCL) electron-current transients of the type commonly observed in materials characterized by nondispersive transport. The upper trace in Fig. 13 shows the phototransients observed in the nondispersive regime when the number of carriers injected is greater than the charge, (C V), induced on the electrodes by the applied field. After an initial current spike, a cusp occurs which is followed by a long tail. Similar effects are observed in crystalline iodine, anthracene, amporphous selenium, and *a*-Si:H, prepared by the glow-discharge technique.[1,17] The lower trace in Fig. 13 is obtained under identical conditions except that the temperature is lower and is in a regime where the transport of carriers is dispersive. It seems that if the dispersion in the carrier packet is too large, classical SCL transients will not be observed.[8] The correct treatment of space-charge-perturbed currents when a blocking-front contact is present has been given by Papadakas.[25] His analysis predicts exactly the shape observed in Fig. 13 (upper trace). It would be useful to have such an analysis for the case where the mobility is a decreasing function of time.

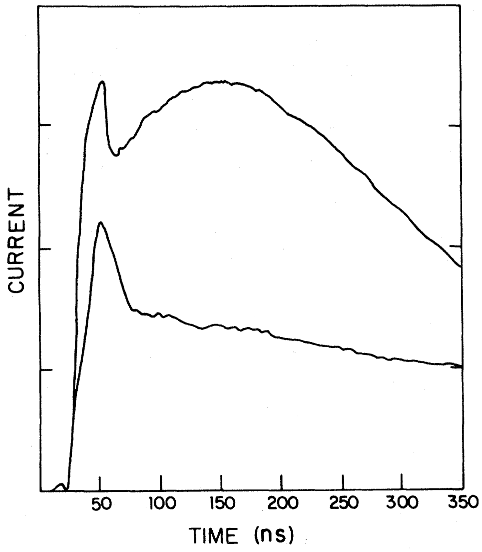

FIG. 13. Transient currents observed under high injection conditions in a nondispersive regime (upper trace) and dispersive regime (lower trace). The applied voltage and light intensities are the same for both traces.

CONCLUSIONS

We have found that lifetime limitations of propagating carriers restrict the measurement of electron carrier mobilities, using the time-of-flight technique, to films of sputtered *a*-Si:H that have fewer than 5×10^{17} $\mathrm{eV}^{-1}\,\mathrm{cm}^{-3}$ states at the Fermi level. In our films deep trapping of electrons, for a given density of states at the Fermi level is more likely than the loss of holes to deep traps.

Measurements on films which have a low density of states at the Fermi level ($N_{E_F} < 5\times10^{17}$ $\mathrm{eV}^{-1}\,\mathrm{cm}^{-3}$) have revealed a range of dispersion in the drift of electron carriers. The dispersion is consistent with a multiple-trapping process with a dispersion parameter that depends on temperature. Samples which display dispersive transport over the complete accessible temperature and voltage range have a spread in the activation energies of the electron mobilities. The highest electron room-temperature mobility found in our films is 0.5 $\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ which occurs in specimens which have the largest activation energy of mobility.

In a subset of samples we have observed that electron propagation can be controlled by nondispersive Gaussian statistics. Thus, the mobility in sputtered *a*-Si:H can be a constant in time. The occurrence of nondispersive behavior is dependent on both the temperature and voltage of measurement. At room temperature (300 K) nondispersive current transients are observed in these films for an applied voltage greater than 1×10^4 V/cm. The nondispersive region has an activation energy of 0.18 ± 0.01 eV for all films studied to date. Below room temperature a transition to dispersive carrier transport is observed and universality of the phototransients is observed at the lowest temperature (220 K). At low temperatures the value of mobility obtained depends on the applied voltage, a characteristic of a stochastic transport process. Changes in the activation energies of the electron mobility through the transition from nondispersive to dispersive behavior are also understood in terms of this stochastic process.

We have observed nondispersive behavior only in a certain voltage and temperature range accessible to the time-of-flight technique. Below 350 K dispersive behavior is always observed at sufficiently low voltages. These findings have important consequences for other measurments, such as induced optical absorption and photoconductivity whose results are controlled by the dispersion in the transport of carriers. We are presently devising experiments to test these ideas.

We have made measurements of hole mobilities. Dispersive hole phototransients have been observed in all cases, though occasionally a feature, corresponding to carriers reaching the back contact, is observed at high temperatures. Activation energies of 0.4 eV are found for hole motion. This value and the absolute values of mobilities at a given temperature are found to be fairly independent of the density of states at the Fermi level.

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[1] L. B. Schein, R. W. Anderson, R. C. Enck, and A. R. McGhie, J. Chem. Phys. 71, 3189 (1979).

[2] H. Scher and E. W. Montroll, Phys. Rev. B 12, 2455 (1975).

[3] G. Pfister and H. Scher, Adv. Phys. 27, 747 (1978).

[4] G. Juska, A. Matulionis, and J. Viscakas, Phys. Status Solidi 33, 533 (1969).

[5] M. Pollak, Philos. Mag. 36, 1157 (1977).

[6] J. M. Marshall, Philos. Mag. 36, 959 (1977).

[7] J. Noolandi, Phys. Rev. B 16, 4466 (1977).

[8] F. W. Schmidlin, Phys. Rev. B 16, 2362 (1977).

[9] T. Tiedje, B. Abeles, D. L. Morel, T. D. Moustakas, and C. R. Wronski, Appl. Phys. Lett. 36, 695 (1980).

[10] W. E. Spear and P. G. LeComber, J. Non-Cryst. Solids 8-10, 727 (1972).

[11] T. Tiedje and A. Rose, Solid State Commun. 37, 49 (1980).

[12] The values used in this paper for the state densities at the Fermi level are calculated using the analysis of P. Viktorovitch and G. Moddel, J. Appl. Phys. 51, 4847 (1980). Recently imporved computational analysis by R. Weisfield at Harvard suggest that these state densities might be over estimated by up to a factor of 3.

[13] W. E. Spear, J. Non-Cryst. Solids. 1, 197 (1968).

[14] J. B. Webb, D. F. Williams, and J. Noolandi, Solid State Commun. 31, 905 (1979).

[15] W. Fuhs, M. Milleville, and J. Stuke, Phys. Status Solidi B 89, 495 (1978).

[16] T. Datta and M. Silver, in *Tetrahedrally Bonded Amorphous Semiconductors, Carefree, Arizona, 1981,* edited by R. A. Street, D. K. Biegelsen, and J. C. Knights (American Institute of Physics, New York, 1981), p. 202.

[17] T. Tiedje, C. R. Wronski, B. Abeles, and J. M. Cebulka, Solar Cells 2, 301 (1980).

[18] We draw the reader's attention to the similarities in the present data with those found in amorphous selenium. G. Pfister, Phys. Rev. Lett. 36, 271 (1976).

[19] J. Orenstein and M. Kastner, Solid State Commun. 40, 85 (1981).

[20] J. M. Hvam and M. H. Brodsky, Phys. Rev. Lett. 46, 371 (1981).

[21] S. Ray, Z. Vardeny, and J. Tauc, in *Tetrahedrally Bonded Amorphous Semiconductors, Carefree, Arizona, 1981,* edited by R. A. Street, D. K. Biegelsen, and J. C. Knights (American Institute of Physics, New York, 1981), p. 253.

[22] P. B. Kirby, unpublished work in this laboratory.

[23] D. Allan, Philos. Mag. B 38, 381 (1978).

[24] A. J. Snell, W. E. Spear, and P. G. LeComber, Philos. Mag. B 43, 407 (1981).

[25] A. C. Papadakis, J. Phys. Chem. Solids 28, 641 (1967).