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Hot Electrons in Amorphous Silicon

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At extremely high electric fields ($F \leq 0.55$ MV/cm) and high temperatures ($300 < T < 450$ K), full deactivation of the electron drift mobility in amorphous hydrogenated silicon (*a*-Si:H) is obtained and therefore the shallow trapping is substantially reduced. New data clearly demonstrate that the free electron (band) mobility in *a*-Si:H decreases when the electric field increases, contrary to other disordered materials (e.g., amorphous selenium). In this sense the free carrier transport in *a*-Si:H is similar to the hot carriers in crystals when phonon scattering prevails.

In many disordered solids the existence of the disorder-induced localized band tail states leads to the fact that the observed (drift) mobility (μ) is smaller than the free carrier (band) mobility (μ_0) and often to a dispersive charge transport. The quantity μ_0 is of fundamental importance, the direct measurement of which is, however, extremely difficult.

On the basis of scaling theory [1], it is generally predicted (and proved for amorphous Se [2]) that in disordered structures the free carrier mobility continuously increases with the energy (E) above the mobility edge (E_g).

Although amorphous hydrogenated silicon (*a*-Si:H) is the most studied amorphous semiconductor, there are still a lot of open questions such as the following.

What is the precise value and the temperature (T) dependence of the electron free carrier mobility in extended states [3]? Does μ_0 really increase with increasing kinetic energy E as predicted by scaling theory? Why is trapping of the carriers into the (tail) states, which controls the drift mobility, not observed in the optically detected picosecond time-of-flight (TOF) transients [4]? Why is high electric field (F) induced impact ionization not observed in *a*-Si:H, in contrast to *a*-Se [5,6], although from the results of the quantum efficiency investigation it is known that in *a*-Si:H the free carrier thermalization distance is longer [7], the mobility is higher, and the energy gap is smaller than in *a*-Se [2]?

Significant achievements in the study of the free carrier behavior in a *a*-Si:H have been obtained by femtosecond pump and probe laser techniques: very fast charge carrier thermalization (≥ 1 eV/ps) [8], very short scattering time (~ 0.5 fs) [8,9], and, correspondingly, very small mean free path λ [approximately equal to the interatomic distance (a_i)] have been obtained. These results indicate very small free carrier mobility ($\mu_0 \approx 10$ cm^2/V s). A similar μ_0 value has been estimated from the high temperature saturation tendency of the $\mu(T)$ dependence [3] and from the high F subnanosecond $\mu(F)$ dependence [4,10].

The aim of this paper is to use the TOF technique to investigate the transport properties of the free electrons in *a*-Si:H, while eliminating the influence of the localized tail states by measuring at the highest possible electric fields and at high temperatures.

For our TOF studies high quality reverse biased *p-i-n* structures, specially designed to allow the application of the highest possible electric fields, were used. These sandwich samples (with thickness d) were placed into a coaxial waveguide matched with a real-time 6 GHz oscilloscope which allowed us to measure the drift current transients down to subananosecond times [10]. The charge carriers were generated by a laser pulse ($h\nu$ = 2.3 eV and half-width $t_p \approx 17$ ps) suitably delayed after the application of the voltage pulse. The delay time was varied in order to check the absence of intrinsic electric field redistribution especially at high temperatures and at high electric fields. From the experimentally measured transit time t_{tr} the value of the drift mobility $\mu = d/t_{tr}F$ was obtained. To exclude effective thickness problems [11] we used the "small signal" mode.

There are three temperature regions of *a*-Si:H with characteristic transport properties. In the low temperature region ($t < 100$ K) the electron transport is dispersive: the drift mobility is a function of the electric field, time, and interelectrode distance. The dispersion parameter is independent of temperature, but clearly depends on the electric field. These results have been interpreted as field enhanced band-tail hopping [12].

In the medium temperature range (100–270 K) the electron transport is also dispersive, but the dispersion parameter increases with temperature and is only a weak function of the electric field. In this temperature region multiple trapping into almost exponentially distributed band-tail states is assumed. At high electric fields ($F > 10^5$ V/cm) an additional term [$\mu \sim \exp(eaF/kT)$ with $a \cong 1$ nm] [10,13] of a nondispersive nature has been observed, the origin of which is still not fully clear.

For $T > 270$ K the electron drift mobility is thermally activated and nondispersive, and transport is controlled by equilibrated multiple trapping [3]. The value of μ_0 ($7 < \mu_0 < 13$ cm^2/V s) has been estimated from the $\mu(T)$ saturation tendency at high temperatures [3] and from the $\mu(F)$ dependence in a high electric field [4,10].

Figure 1 shows the temperature dependence of the electron drift mobility measured by TOF on a 10 μm thick a-Si:H p-i-n diode at low field (0.05 MV/cm) and at high field (0.5 MV/cm). The high F results indicate almost zero activation energy of the drift mobility (E_μ). As illustrated in Fig. 2 full deactivation ($E_\mu = 0$) is achieved at $F = 0.55$ MV/cm. The surprising finding is that the value of the high F deactivated mobility ($\mu \approx 2.5$ cm^2/V s), which should approach μ_0, is smaller than the estimated low field μ_0 (about 7 cm^2/Vs; see below).

This indicates that μ_0 decreases with high electric fields. This seems to be supported by the small decrease of the drift mobility observed at the highest fields for $T = 450$ K in Fig. 3. Although this decrease is rather small, it was clearly confirmed also on other samples. At high T and medium field a field independent μ has been observed also in Ref. [4]; see × in Fig. 3.

There is a tight relation between the drift mobility and the density of the tail states [$N(E)$], and so before detailed analysis of the data shown in Figs. 1–3 we have to summarize what we know about $N(E)$.

An exponential conduction band tail state distribution $N(E) = N_0 \exp(-E/kT_0)$ with T_0 in the range 250–300 K is commonly used for a a-Si:H. In Ref. [14] $N(E)$ was evaluated from the drift mobility activation energy field dependence $E_\mu(F)$, and it was concluded that the exponential $N(E)$ changes to a linear one near the mobility edge. However, if we calculate $N(E)$ according to the same method and take into account the experimentally observed [10,13] factor $\exp(eFa/kT)$ in the electric field dependent drift mobility, we have found that the exponential $N(E)$ distribution with $T_0 = 270$ K extends up to the electron mobility edge [15]. For such single exponential distribution and the case of equilibrium multiple trapping ($T > T_0$) the electron drift mobility in the low electric field limit is, according to [16],

$$\mu = \mu_0(T)(1 - T_0/T). \qquad (1)$$

This equation can be used for the determination of the $\mu_0(T)$ dependence at low electric fields (see also [4]).

The experimental data in Fig. 1 can be fitted by two sets of parameters: a temperature independent $\mu_0 = 6.5$ cm^2/V s and $T_0 = 267$ K (dashed line) or by a physically more realistic expression $\mu_0(T) = 7.5\sqrt{300/T}$ cm^2/V s and $T_0 = 270$ K (full line). Both of these μ_0 values coincide with other results [3,8,10] and confirm the diffusion model of transport of free electrons. Therefore at high temperature and high electric field the measured temperature and field independent value $\mu = 2.5$ cm^2/V s is smaller than $\mu_0 \approx 7$ cm^2/V s (Fig. 3). This may be explained only if the free carrier mobility μ_0 decreases when the electric field increases. This is evident also from the fact that $\mu(1/T)$ dependences for different F cross at $1/T \neq 0$ (see Fig. 1).

So the $\exp(eFa/kT)$ factor (observed in Refs. [10,13] and evident also from the 295 K data in Fig. 3), increasing with increasing F, cannot be related to μ_0 which decreases with increasing field and that is the reason why we attribute the origin of this factor to the field dependence of the band-tail trapping-retrapping process. As the simplest phenomenological description we have assumed field assisted thermal release from traps within the multiple trapping model. For the concentration of trapped carriers (n_t) at energy E below the mobility edge ($E = 0$)

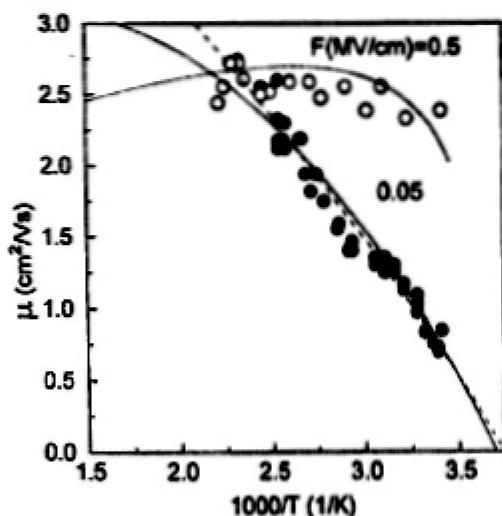

FIG. 1. Temperature dependence of the electron drift mobility at different electric fields for 10 μm thick a-Si:H p-i-n structure. Points—experiment, full curves—calculated according to Eqs. (3) and (5). Meaning of the full and dashed line for $F = 0.05$ MV/cm—see text. Note linear vertical scale.

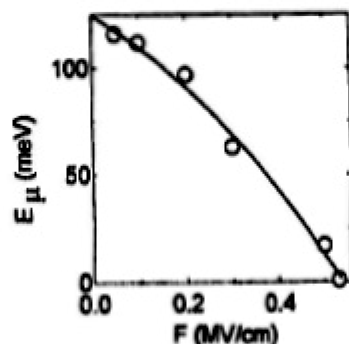

FIG. 2. The electron drift mobility activation energy (E_μ) measured below 300 K, as a function of the electric field (F) for 10 μm thick a-Si:H p-i-n structure. Solid line is simply a guide for the eye.

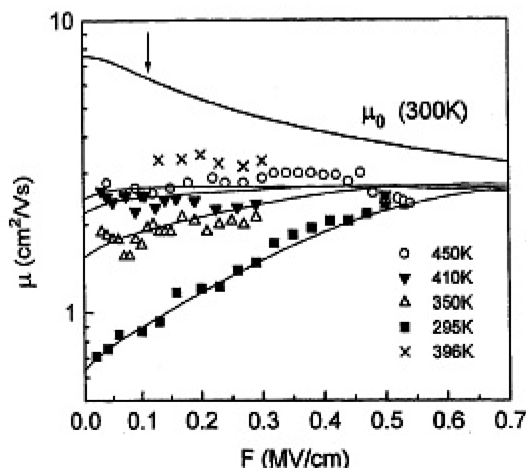

FIG. 3. Electron drift mobility (μ) as a function of the electric field (F) at different temperatures for 10 μm thick a-Si:H p-i-n structure. Points—experiment, full curves—calculated according to Eqs. (3) and (5). Bold line—free electron mobility μ_0 calculated for $T = 300$ K according to Eq. (5). Arrow indicates the field at which the drift velocity is equal to the velocity of sound. ×—recalculated from the optical measurements of the drift velocity according to Ref. [4] ($d = 2$ μm).

we can write a kinetic equation

$$\frac{dn_t(E)}{dt} = \gamma n N_0 \exp\left[-\frac{E}{kT_0}\right] - \gamma n_t(E) N_0 kT \exp\left(-\frac{E - eFa}{kT}\right), \quad (2)$$

where γ is the trapping (and emission) coefficient and $N_0 kT$ the effective conduction band edge density. Then in thermal equilibrium ($T > T_0$) $dn_t(E)/dt = 0$ and the drift mobility is

$$\mu = \mu_0\left[\frac{n}{n + \int_0^\infty n_t(E)\,dE}\right] = \mu_0(F,T)\left[1 + \frac{\exp(-eFa/kT)}{T/T_0 - 1}\right]^{-1}. \quad (3)$$

It is evident from Eq. (3) that for high T, and/or high F, μ has to approach μ_0. For low F we obtain Eq. (1). For medium temperatures ($T < T_0$) the drift mobility is controlled just by the energies E in the interval $0 < E < E^*(t) = eFa + kT\,\ln(\nu t)$, from which carriers can be emitted (by field or temperature) during the time t. This leads to dispersive transport, and in Eq. (3) to the substitution of infinity in the integral upper limit by $E^*(t)$ and in analogy with [16] to

$$\mu \sim \left(\frac{F}{d}\right)^{T_0/T-1} \exp\left(\frac{eFa}{kT}\right), \quad (4)$$

as has been experimentally observed [10,13].

Since in our experiment at high electric field the drift velocity exceeds sound velocity ($v_s \approx 8.5 \times 10^5$ cm/s [17]), we attribute the decrease of the free carrier mobility to the emission of acoustic phonons when $\mu_0 F > v_s$, according to the classical Shockley formula for crystalline semiconductors [18]:

$$\frac{\langle E\rangle}{kT} = \frac{\mu_0^2(0)}{\mu_0^2(F)} = \frac{1}{2}\left(1 + \sqrt{1 + [C\mu_0(0)F/v_s]^2}\right), \quad (5)$$

where $\langle E\rangle$ is the mean kinetic energy of hot carriers. Note that this expression has been successfully used also for organic molecular crystals ($C = \sqrt{3\pi/8}$ [19]) and gases ($C = 1.32$ [20]) with a similarly small value of mobility and with the mean free path also comparable to the interatomic distance ($\lambda \approx a_i$).

The fit of Eqs. (3) and (5) to the experimental results is shown in Fig. 3 for $T_0 = 270$ K, $\mu_0 = 7.5\sqrt{300/T}$ cm^2/V s, $a = 1.4$ nm, $C = 1.58$, and $v_s = 8.5 \times 10^5$ cm/s. The $\mu_0(F)$ dependence calculated according to Eq. (5) for 300 K is shown (see bold line in Fig. 3) for comparison. In this simplified description we have used typical parameters, and they fit the experimental results very well. Moreover, on the basis of the above model some puzzling experimental facts are easily explained. First of all, it becomes clear that for $F = 0.2-0.3$ MV/cm, used in optical transient experiments [4], μ_0 is already decreased by the electric field, the difference between μ and μ_0 is much smaller than usually assumed, and so it is difficult to observe mobility time dependence [4]. Second, the fact that μ_0 decreases with increasing field allows us to understand why band-to-band impact ionization does not occur even for extremely high F and thick samples. The impact ionization efficiency β, which is very sensitive to sample thickness (d), is expressed as [5]

$$\beta = \exp\left[\frac{edF}{\langle E\rangle}\exp\left(-\frac{\Delta E}{\langle E\rangle}\right)\right], \quad (6)$$

where ΔE is the impact ionization energy equal to the energy gap (1.8 eV) in materials with a low mean free path (in which the momentum need not be conserved). The experimental quantum efficiency results in an extremely thick a-Si:H p-i-n structure (50 μm) demonstrate no charge multiplication (see Fig. 4). From the experimentally estimated value $\beta < 1.05$ for $F = 0.5$ MV/cm and

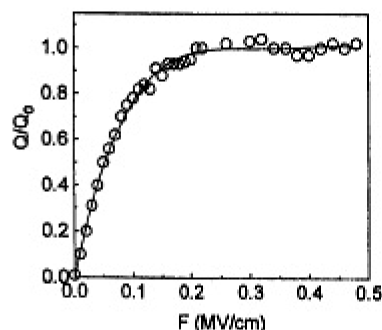

FIG. 4. Charge collection coefficient (Q/Q_0) as a function of the electric field measured at room temperature on 50 μm thick a-Si:H p-i-n structure.