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LETTER TO THE EDITOR

Enhancement of mobility at low temperatures in amorphous silicon hydride

R P Barclay

Department of Materials Engineering, University College of Swansea, Singleton Park, Swansea SA2 8PP, UK

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Abstract. In this letter, we explore the effect of carrier interaction with tail states on the mobility in amorphous silicon hydride for various model density of states profiles. Upon the assumption that multiple trapping of electrons dominates the transient response at short times, we find that a shift in the demarcation energy, E_d^*, between multiple trapping and tunnelling, to shallower energies can lead to an enhancement in the mobility for temperatures lower than 100 K.

For amorphous semiconductors in general, and in particular for a-Si:H the current interpretation of drift mobility data obtained from time of flight transients is based on the following transport mechanisms. For temperatures >100 K multiple trapping is assumed to dominate with the magnitude and temperature dependence of the mobility being influenced by the nature and energy distribution of the localized states involved (Schmidlin 1977, Tiedje *et al* 1981). For temperatures lower than 100 K, the dominant transport mechanism is assumed to be tunnelling based on the assertion that there is practically no contribution to the current trace due to multiple trapping (Spear and Cloude 1987, Spear and Cloude 1988, Heuckeroth *et al* 1991, Kemp and Silver 1991). The fact that carriers tunnel through states below E_d^*, the demarcation energy between multiple trapping and tunnelling, to dangling bond D centres, which serve as both trapping and recombination centres, situated near to the Fermi level is ignored. Since release of direct trapped carriers from D centres occurs outside the time range considered they therefore make no contribution to the transport over the first few 100 ns (Dersch *et al* 1983, Seynhaeve *et al* 1989). The enhancement of the mobility associated with multiple trapping caused by the movement of E_d^* to shallower energies as the temperature is lowered has rarely been considered as significant (Street 1984, Barclay and Boud 1991). Here, we examine the movement of E_d^* which for all model density of states, $N(E)$, investigated below leads to an enhanced capture rate into deep trapping centres and a reduction in carrier thermalization depth with temperature for the case of multiple trapping transport (Street 1984).

We examine the possibility that multiple trapping will play a significant role at low temperatures and in doing so will assume that some of the carriers captured at energy depths below the multiple-trapping regime are lost due to tunnelling to recombination centres. We will also assume that the tunnelling of carriers through the tail states to the far side electrode will yield current traces that make a small or negligible contribution to the time-of-flight current race over the time range in which multiple trapping dominates. The transit of carriers through the sample due to tunnelling in the absence of recombination taking 100–1000 times longer than for those involved in multiple trapping (see later).

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Our model density of states consists of an exponential distribution of conduction band tail states with a characteristic tail slope temperature of $T_c = 312$ K. The density of states at the conduction band edge $N(E_c)$ is taken as 4×10^{21} cm^{-3} eV^{-1}. The variation in tail state density with energy is given by $N(E) = N(E_c)\exp(-E/kT_c)$ (Tiedje *et al* 1981). We shall also investigate model distributions of $T_c = 400$ K and 500 K as well as a linear distribution of conduction band states (Spear and Cloude 1988, Marshall *et al* 1986) (see figure 1). Firstly, we examine what happens at energy depth E^* when capture into tail states competes with capture into the D centres. At this energy deep trapping will effectively reduce the number of tail states that the carriers can interact with. This occurs when the capture cross section density of states products of the D centres and tail centres at their respective energies are such that $\sigma_D N_D(E) > \sigma_t N_t(E)$ in spite of the fact that the energy position of the D centres may be deeper in the gap. Provided the energy spread of the D centres is of the order of a few kT, e.g. a recombination channel at the Fermi-level or a quasi-Fermi-level, E^* will be well defined. Thus the energy depth E^* at which deep trapping influence occurs depends critically on the capture rate into the D centres. The implications of this are discussed below. Secondly, for low temperatures we would like to estimate the change in E_d^* with temperature. In order to do this we assume that for the small range of energies involved that σ_t for the tail states is constant with energy, and for all $N(E)$ distributions we calculate the ratio of the tunnelling rate, ν_{tul}, to release rate, ν_r for tail states of depth E below the mobility edge using the following relation

$$\nu_{tul}/\nu_r = \nu_t \exp(-2R/R_0)/\nu_t \exp(-E/kT) \tag{1}$$

where ν_t, the attempt to escape frequency for tail states has been calculated from recent estimates of capture cross section using the principle of detailed balance, to be in the range 10^{10}–10^{11} Hz (Marshall *et al* 1986). Following Street (1984) we consider only carriers that tunnel down in energy taking R_0 to be 12 Å (estimated from photoluminescence measurements) and assume R_0 to be constant with energy. An examination of the effect of tunnelling up in energy on ν_{tul} shows that ν_{tul} varies by as little as 2% for a hopping energy of 2 meV (at 40 K). We also calculate the intersite spacing R from $R \sim N(E)^{-1/3}$ (Marshall *et al* 1986). As well as this we assume that σ_D is temperature dependent but realize that σ_D will be enhanced by tunnelling. For the purpose of this work diffusive capture will not be considered but we understand that qualitatively the change in capture cross section will be similar to that described elsewhere (Street 1984).

Upon examination of equation (1), we find that the rate of hopping through the tail states increases when compared to the rate of release to the band with increasing energy depth as the temperature is lowered. The change in rates leads to a reduction in E_d^* and as a consequence extends the temperature range over which multiple trapping is significant provided that energy depth $E_d^* < E^*$. For the model distributions described above and for the calculated ν_r and ν_{tul} shown in figure 2, we can estimate E_d^* from the energy at which $\nu_r > \nu_{tul}$. Provided the carriers have had sufficient time to thermalize down to E_d^* the transit time t_T may be obtained from $t_T = t_0 + M_d\tau_{r,d}$, where $\tau_{r,d}$ is the release time from the deepest states encountered (at E_d^*), M_d the number of trapping events per transit into those states and t_0 the free carrier transit time (Schmidlin 1977). A decrease in E_d^*/kT with decreasing temperature leads to a reduction in the effective carrier transit time and hence an increased mobility when $M_d\tau_{r,d} > t_0$. An indication of the enhancement for different $N(E)$ is illustrated in figure 3 with the onset of the increase shifting to lower temperatures for narrower tail state widths.

It is worth noting that the rate of change of E_d^*/kT with temperature can be increased or decreased by simply modifying the $N(E)$ close to the band edge. For example for the linear

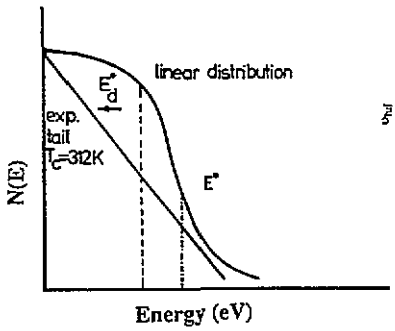

Figure 1. The exponential (T_c = 312 K) and the linear $N(E)$ distributions are sketched (Spear and Cloude 1988). E^* represents the energy at which thermalization is limited by direct capture into deep trapping/recombination centres. The value of E^* depends critically on the capture rate into D centres involved. E_d^* on the other hand is the demarcation energy between multiple trapping and tunnelling which shifts towards the band edge as the temperature is lowered.

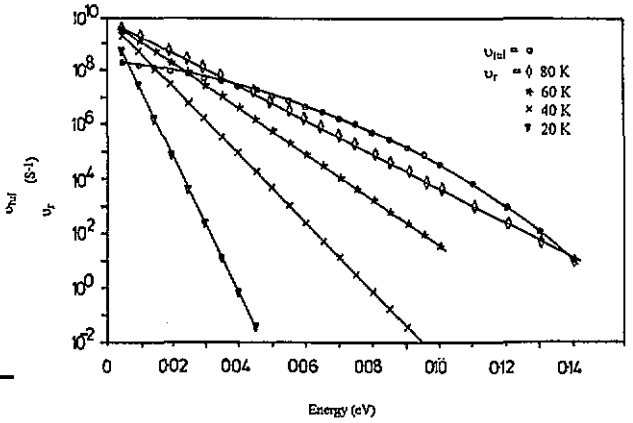

Figure 2. The release rate ν_r is compared to the tunnelling rate ν_{tul} as a function of energy depth for the T_c = 312 K distribution. When $\nu_r > \nu_{tul}$ a value E_d^* can be estimated.

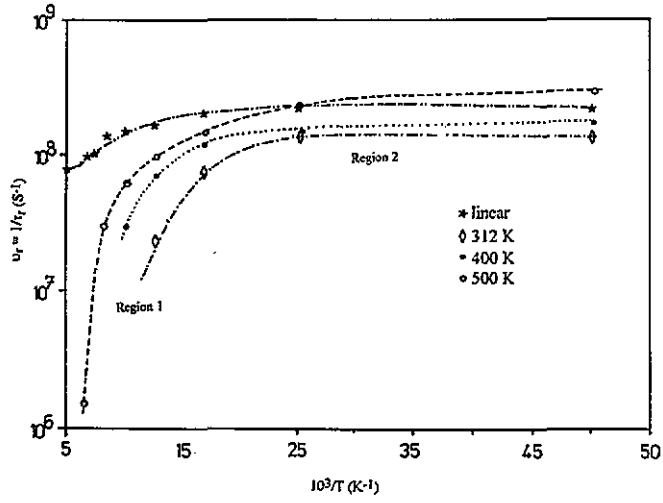

Figure 3. The release rate estimated from E_d^* is plotted as a function of inverse temperature for all the $N(E)$ investigated. This rate can be related to the transit time t_T of carriers as discussed in the text.

distribution of states the onset of the sudden increase in ν_r shifts to higher temperatures. We must stress that at these comparatively high temperatures we are dealing with the short time response due to carrier interaction with shallow states situated at the initial demarcation energy and that a second demarcation energy may exist, separating tunnelling from multiple trapping, for the linear $N(E)$ at deeper energies where again $\nu_r > \nu_{tul}$. The current trace associated with multiple trapping will then consist of a fast response associated with carriers interacting with states down to E_d^* with the second slower response associated with multiple trapping in tail states in the vicinity of the second demarcation level (Monroe

1985) occurring outside the time window of a typical transient photoconductivity. Further tunnelling components may contribute to the current trace at times longer than t_t. The total charge collected during a charge collection experiment will then consist of contributions due to multiple trapping and tunnelling less the charge that is lost due to recombination. Obviously the amount collected will depend on the value of M_d at E_d^*. The tunnelling contribution and the loss due to recombination increases as M_d increases.

Further to this, we would like to suggest that energy E^* may be reduced even further during a transient photoconductivity experiment by either (i) pulsing with radiation of sufficient intensity to cause a shift in the Fermi-level position to a higher concentration of recombination centres of similar or larger capture cross section or (ii) by doping the specimen with boron creating more D^+ dangling bond centres. For instance the increase in capture rate due to ballistic capture into neutral recombination centres of density 5×10^{15} cm^{-3} and of $\sigma_D \sim 270$–$1000\sigma_t$ would place E^* at energies low enough to affect the mobility at low fields even for $T > 100$ K (see below). The ratio is calculated from the latest estimates of the attempt to escape frequency for the respective states involved, the lower limit corresponds to $\sigma_D = 2.7 \times 10^{-15}$ cm^{-2} from Street's data whereas the upper limit is estimated from $\sigma_D = 1 \times 10^{-14}$ cm^{-2} (for $\nu = 1 \times 10^{13}$ Hz) (Street 1984). These are compared to the $\sigma_t \sim 1 \times 10^{-17}$ cm^{-2} estimated for tail states from drift mobility measurements (Marshall *et al* 1986). A further factor of up to $\times 30$ for electron capture into D^+ centres would place E^* even closer to the band edge (Spear *et al* 1985). This could result in the following; firstly the magnitude of the drift mobility in the high temperature region may be affected resulting in a decrease in the activation energy as a function of capture rate into the D centres (Barclay *et al* 1987) and secondly, for $T < 100$ K the component of the current trace due to multiple trapping will move to shorter times resulting in a higher associated mobility provided the deepest states encountered (prior to transit) are at or above E^*.

To conclude, we note, having taken into account recent estimates for σ_D and σ_t, that for the model $N(E)$ profiles chosen for a Si:H, experimentally accessible effective transit times are obtainable for electron transport due to multiple trapping as opposed to tunnelling and that the magnitude of mobility that can be estimated is of the same order as the experimental values published by Spear and Cloude (1987, 1988).

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