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Features of charge carrier transport determined from carrier extraction current in μc-Si:H

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Abstract

Temperature and electric field dependencies of mobility and concentration transients of electrons and holes using modified charge extraction by the linearly increasing voltage (CELIV) method in slightly doped n-type, p-type and undoped microcrystalline silicon (μc-Si:H) have been investigated. The results indicates that: the mobility of majority carriers causes temperature and electric field dependencies of conductivity; the photoconductivity transient is mainly determined by transient of charge carrier concentration; at room temperature the charge carrier transport is controlled by multiple trapping to energetic distributed localised states; at lower temperature the features characteristic of hopping transport have been obtained.

1. Introduction

The energy conversion efficiency of solar cells is determined by the properties of charge carrier transport and recombination. However, in the case of μc-Si:H, due to relatively high bulk conductivity, the investigation of charge carrier transport by the time-of-flight (TOF) method is problematic or is even impossible in the case of doped layers. This inapplicability of TOF originates from the necessary condition that dielectric relaxation time (τ_σ) must be higher than charge carrier transit time (t_{tr}). If the latter condition is not fulfilled, i.e., $\tau_\sigma \leqslant t_{tr}$, the concentration of equilibrium charge carriers will significantly redistribute electric field within the sample in a time interval shorter than t_{tr} and, moreover, the drifting packet of charge will disappear before it reaches the opposite electrode. Ignoring this limit may cause an erroneous overestimation of the mobility values measured by TOF. Fulfilment of the same condition is also necessary for a correct estimation of the $\mu\tau$-product from the measurement of charge collection dependence on electric field (Hecht's curve) [1]. The charge carrier extraction by linearly increasing voltage (CELIV) method is valid for both $\tau_\sigma > t_{tr}$ and $\tau_\sigma \leqslant t_{tr}$ cases [2]. Moreover, using CELIV method the concentration and mobility of

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majority equilibrium charge carriers may be estimated independently [3].

In this paper, we present experimental results of charge carrier transport features and recombination obtained by a modified photo-CELIV method in slightly n-, p-doped and undoped μc-Si:H layers.

2. Experiment

In CELIV, a triangular voltage pulse of reverse polarity, linearly increasing at a rate A, is applied to the sandwich-type sample (d is sample thickness) with a blocking electrode and the corresponding transient current $j(t)$ is measured (see Fig. 1). The layer's bulk conductivity (σ) is then estimated according to [3]

$$\sigma = \frac{3\varepsilon\varepsilon_0}{2}\frac{\Delta j}{t_{\max} j(0)} \tag{1a}$$

or

$$\sigma = \varepsilon\varepsilon_0 \left(\frac{\mathrm{d}[j/j(0)]}{\mathrm{d}t}\right)\Big|_{t=0}. \tag{1b}$$

In the experimentally most convenient case when $\Delta j < 10 \times j(0)$ and, taking into account numerically calculated correction factor, the charge carrier drift mobility (μ) is given by [3]

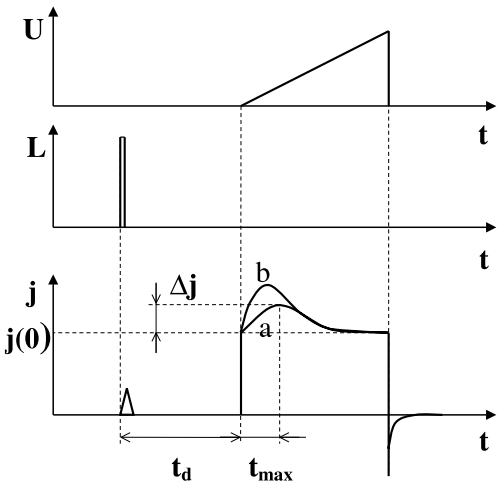

Fig. 1. Schematic illustration of CELIV method. U is the voltage applied on sample electrodes, L is the pulse of light, and j is the corresponding current transient without (a) and with illumination (b).

$$\mu = \frac{2d^2}{3At_{\max}^2(1 + 0.36\Delta j/j(0))}. \tag{2}$$

The equilibrium concentration of majority charge carriers can be estimated from the calculated σ and μ or from the difference between areas of first and of consequent pulse of current transient [2].

For determination of charge carrier recombination kinetics we have developed a photo-CELIV method: the layer is illuminated by pulse of bulk absorption light and, after some delay time t_d, the triangular pulse of voltage is applied to the sample electrodes. From the area difference between current transients with and without pre-illumination, the dependence of residual amount of charge carrier (n of n-type sample) on t_d has been obtained. In order to exclude charge carrier extraction by intrinsic electric field, the latter has been compensated by externally applied constant voltage. Compared to transient measurements of $\sigma(t)$ such as switch-off illumination or transient photocurrent (TPC) experiments [4], the main advantage of photo-CELIV is that $n(t)$ and $\mu(t)$ can be estimated independently. Additionally, due to the fact that in switch-off illumination and TPC experiments co-planar electrodes are used, the charge carriers move along layer's surface, while in photo-CELIV they are extracted across the sample.

The measurements by CELIV method have been performed using a maximum voltage of $U = 25$ V and the duration of voltage pulses was varied in a 100 ns to 100 ms time interval. A laser diode with a wavelength of $\lambda = 650$ nm has been used for bulk illumination. The layers – undoped, slightly (few ppm) doped by diborane for p-type or by phosphine for n-type – were deposited from SiH_4 ($\sim 5\%$) diluted in H_2 by conventional RF or VHF PE-CVD techniques. The samples were deposited on ZnO covered glass substrates and semitransparent Al electrodes were deposited as top layers.

3. Results

Although the electric field changes during charge carrier drift (in CELIV method), the main extraction of charge carriers occurs at $U = A \times t_{\max}$. Fig. 2 shows the dependencies of hole mo-

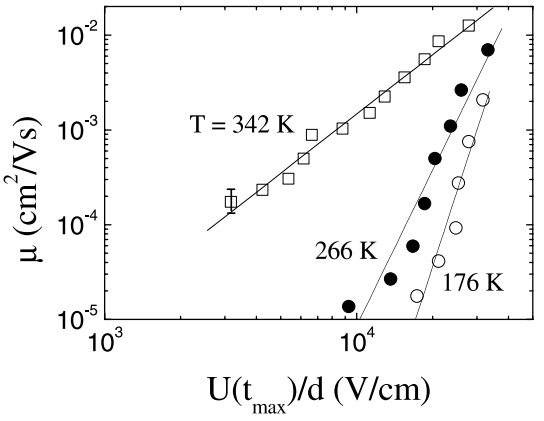

Fig. 2. Hole drift mobility dependence on voltage at t_{max} for p-type μc-Si:H ($d = 2.15$ μm) at different temperatures.

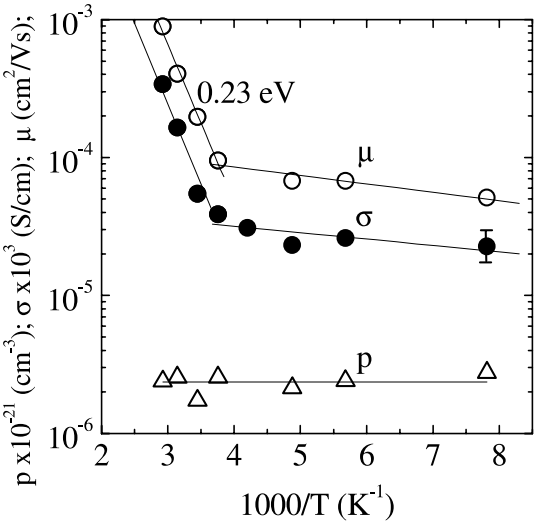

Fig. 3. Temperature dependencies of bulk conductivity σ, hole drift mobility μ, and hole concentration p for p-type μc-Si:H ($d = 2.15$ μm) at a voltage increase rate of $A = 5 \times 10^4$ V/s.

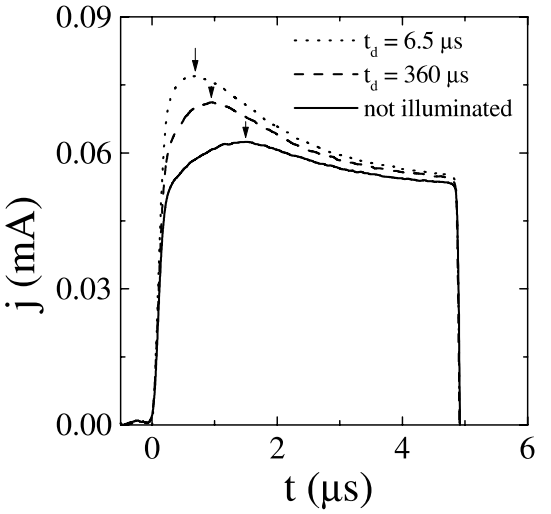

Fig. 4. Typical photo-CELIV current transients at $A = 6 \times 10^5$ V/s for different delay time t_d at room temperature.

bility on $U(t_{max})/d$ for different temperatures in a p-type sample ($d = 2.15$ μm). Here it is clearly seen that there is the strong mobility and mobility activation energy dependency on electric field. In Fig. 3 we plotted the temperature dependencies of σ, μ and of hole concentration (p), which demonstrate that conductivity dependence on temperature is caused by $\mu(T)$. Analogous results have been obtained in n-type μc-Si:H where the electron concentration has been estimated to be weakly dependent on temperature (see Table 1).

The typical transients of extraction current obtained by photo-CELIV are shown in Fig. 4. In Fig. 5 the charge carrier concentration and mobility dependencies on time t after photogeneration are plotted. This time was estimated as $t = t_d + t_{max}$ when the majority of residual charge carrier has been extracted. From Fig. 6 a slow

Table 1
Mobility μ, equilibrium charge carrier concentration, activation energies of bulk conductivity ΔE_σ, concentration ΔE_n, mobility ΔE_μ and lifetime $\tau_{1/2}$ of μc-Si:H samples at room temperature

Sample	d (μm)	μ (cm²/V s) $T = 300$ (K) $A = 10^8$ (V/s)	Concentration (cm^{-3})	ΔE_σ (eV)	ΔE_n (eV)	ΔE_μ (eV)	$\tau_{1/2}$ (μs)
p-type	2.15	0.032	$p = 2 \times 10^{15}$	0.23	0	0.23	6800
Undoped	8.0	3	$n = 7 \times 10^{13}$	0.18	0.06	0.12	100
n-type	2.3	0.28	$n = 1.8 \times 10^{14}$	0.33	0.09	0.24	–

The average error for μ, n, p, $\tau_{1/2}$ do not exceed 30%, and for ΔE are 0.025 eV.

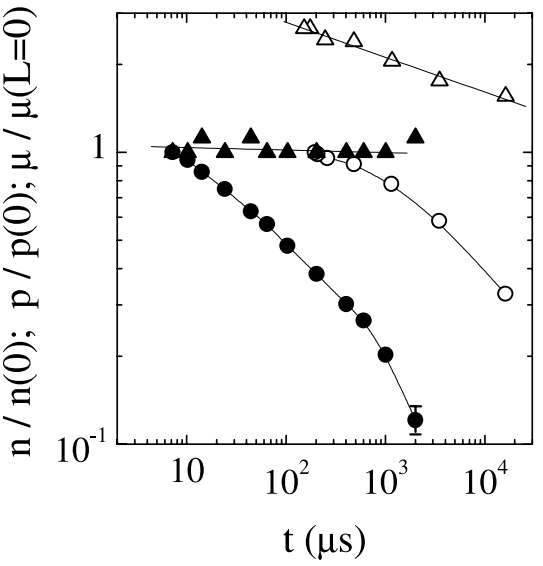

Fig. 5. Concentration (circle) and mobility (triangle) dependencies on time t of photogenerated electrons (solid symbols) in undoped μc-Si:H ($d = 8$ μm) and holes (open symbols) in p-type μc-Si:H ($d = 2.15$ μm) at $T = 300$ K.

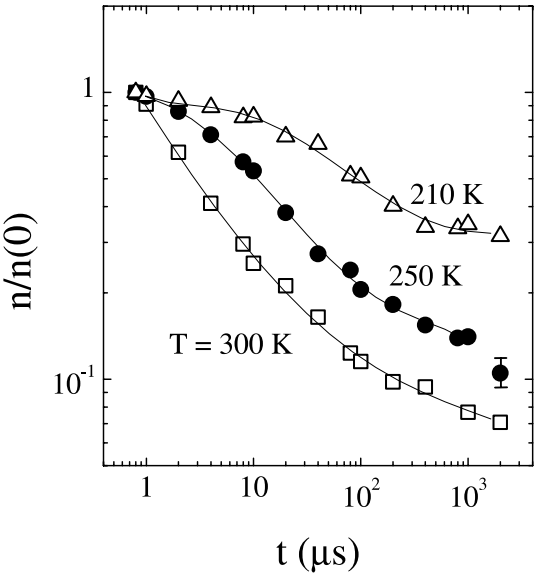

Fig. 6. Concentration transients of photogenerated electrons at different temperatures for n-type μc-Si:H ($d = 1.6$ μm).

down of the electron recombination with decreasing temperature is observed. In Table 1, due to a non-exponential decay of charge carrier concentration $\tau_{1/2}$ corresponds to the time duration for the concentration decrease by a half. From the results mentioned above it follows that the photoconductivity decay, especially in n-type μc-Si:H, is caused not by the mobility but by the charge carrier concentration decay. In p-type μc-Si:H, a decay of hole mobility, with a reduction of exciting light intensity at constant t_d was also obtained. The latter observation indicates that $\mu(t)$ dependence is not caused by a direct mobility decrease with time due to stochastic transport but indicates to the mobility dependence on position of quasi-Fermi level.

4. Discussions

In μc-Si:H the drift mobility values experimentally obtained by different authors vary over a wide range and exceed in some cases 10 cm^2/V s. Such large disparity may be caused by both the heterogeneity of layers and by the experimental conditions of the measurement techniques. For example, in TOF a decisive role is played by relatively high conductivity, which reduces τ_σ, and, as a consequence, leads to overestimated values of μ. Another possible reason may be that after prolonged exposition to air the surface conductivity of layers increases up to $10^{-4}\ \Omega^{-1}\ cm^{-1}$ [5]. In CELIV measurements the latter results in an increase of the sample capacitance, as estimated from the $j(0)$, i.e., in a decrease of the effective thickness of layer, which leads to an overestimation of μ also. According to our measurements, at room temperature, the mobility and the mobility activation energy values are close to those of a-Si:H and, in some of the samples, are even lower. This correlates with the results of [6] where by changing the amount of hydrogen in the layer, in the vicinity of the transition from amorphous to microcrystalline material, the mobility decreased and the lifetime of charge carriers increased. The experimental results showing a big mobility activation energy led us to presume a decisive influence of the localised states. It is interesting to compare the $n(t)$ transients with analogous results of a-Si:H where photocurrent decay slows down, while photo-induced absorption decay accelerates with temperature [7]. Our μc-Si:H

measurement results shows that the decay of $n(t)$ accelerates with temperature (see Fig. 6). The hyperbolic shape of the recombination transients together with the accelerated decay with temperature suggests that this is caused by multiple trapping to energetically distributed localised states. In [3], according to the numerical modelling results, assuming stochastic transport of charge carriers with energetically distributed localised states, the method for evaluation of possible reasons of μ dependence on electric field has been proposed. For μc-Si:H the measurements indicate that the release of trapped carriers stimulated by the electric field is a more likely reason for the $\mu(F)$ dependence.

The barrier model usually used for the interpretation of charge carrier transport in polycrystalline materials cannot be applied for μc-Si:H because the size of the small crystallites (~ 30 nm) is much smaller than the Debye length and is even comparable to the wavelength of electron. Experimentally it has been obtained that the electron and the hole concentrations are independent of both electric field and temperature. This suggests that doping level determines charge carrier concentration. Taking into account the size of crystallites, their concentration was evaluated in the order of 10^{16} cm^{-3}. Thus, it is lower than equilibrium charge carrier concentration, i.e., there is less than one free electron in a single crystallite.

At lower temperature ($T < 250$ K), the decreases of both conductivity and mobility activation energies are related to charge carrier hopping through the localised states in the vicinity of the Fermi energy. We believe that the non-activated but relatively high, for hopping, mobility value is only determined by the charge carrier jumps between crystallites. Thereby the distance covered by hopping reduces the total drift distance.

5. Conclusions

We have shown that in slightly doped p-type and n-type μc-Si:H the mobility of majority charge carriers is lower as one of undoped μc-Si:H. The concentration of majority charge carriers is independent of temperature and electric field. Thus, the thermal activated character of bulk conductivity is given by charge carrier mobility. Using photo-CELIV method we have shown that the photoconductivity transient is mainly conditioned by the delay by multiple trapping charge carrier recombination but not by the mobility.

Finally, from the experimental results, we may conclude that at room temperature the charge carrier transport is controlled by trapping into energetically distributed localised states and that the mobility dependence on electric field is predetermined by electric field stimulated release from localised states. At lower temperature the charge carrier transport demonstrates characteristic features of hopping through localised states in the vicinity of the Fermi energy.

Acknowledgements

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