Published in Journal of Applied Physics 89, issue 9, 4971-4974, 2001
which should be used for any reference to this work


# Hole drift mobility in $\mu c$-Si:H

G. Juška,[a] M. Viliūnas, K. Arlauskas, and N. Nekrašas
*Department of Solid State Electronics, Vilnius University, Saulėtekio 9, LT-2040 Vilnius, Lithuania*

N. Wyrsch and L. Feitknecht
*Institut de Microtechnique—University of Neuchâtel, Breguet 2, CH-2000 Neuchâtel, Switzerland*

In microcrystalline hydrogenated silicon ($\mu c$-Si:H), the drift mobility dependencies of holes on electric field and temperature have been measured by using a method of equilibrium charge extraction by linearly increasing voltage. At room temperature the estimated value of the drift mobility of holes is much lower than in crystalline silicon and slightly higher than in amorphous hydrogenated silicon ($a$-Si:H). In the case of stochastic transport of charge carriers with energetically distributed localized states, the numerical model of this method gives insight into the mobility dependence on electric field. From the numerical modeling and experimental measurement results, it follows that the hole drift mobility dependence on electric field is predetermined by electric field stimulated release from localized states.

## I. INTRODUCTION

$\mu c$-Si:H is a promising photovoltaically active materials for solar cells.[1] The energy conversion efficiency of solar cells is predetermined by properties of charge carrier transport in the material. However, in the case of $\mu c$-Si:H, due to the low mobility ($\mu$) of charge carriers, the interpretation of ''classical'' investigation methods (for example, Hall effect) are problematic.[2] The heterogeneous structure and relatively high bulk conductivity ($\sigma$) of $\mu c$-Si:H also create additional problems during the measuring of charge carrier mobility by the conventional time-of-flight (TOF) method. The necessary condition for the application of TOF is that dielectric relaxation time ($\tau_\sigma = \epsilon\epsilon_0/\sigma$) has to be higher than the transit time of the photogenerated charge ($t_{tr} = d^2/\mu U$, here $d$ is the interelectrode distance and $U$ is the voltage). If this condition is not fulfilled, i.e., if $\tau_\sigma < t_{tr}$, then the amount of equilibrium charge carriers will significantly redistribute the electric field within the sample in a time interval shorter than $t_{tr}$ and, moreover, the drifting packet of charge will disappear before it achieves opposite electrode. These problems were discussed and experimentally demonstrated by TOF measurements of the drift mobility of electrons in $\mu c$-Si:H.[3] First, due to the high capacity ($C$) of thin $\mu c$-Si:H layers the time constant of the measurement circuit ($RC$, here $R$ is the load resistor used for current measurement) is comparable with the electron transit time $t_{tr}$, and due to the dependence of $C$ on voltage ($C \sim U^{-1}$), the dependence of $RC \sim U^{-1}$ is similar to that of $t_{tr} \sim U^{-1}$. This similitude may cause an erroneous estimation of the $\mu$ value. Second, measurements of charge collection coefficient dependence on delay time between applied pulse of voltage and exciting light pulse (in the time range from 50 ns to 1 ms) demonstrate the existence of a fast concentration of the electric field close to the electrodes; this can lead to an overestimation of the mobility value. Because the hole mobility is smaller than that of electrons, it is even more problematic to fulfil the $\tau_\sigma > t_{tr}$ condition. Moreover, during the measurement of the drift current of holes, the backward movement of photogenerated electrons also contributes significantly to the current because the absorption depth of strongly absorbed light ($h\nu > 1.9$ eV) is bigger in $\mu c$-Si:H than in $a$-Si:H, and can be, in a practical case, comparable to the $\mu c$-Si:H sample thickness.

The drawbacks of TOF mentioned above are absent in carrier extraction by the linearly increasing voltage method (CELIV).[4] The CELIV method is based on the analysis of the transient current, which is induced by changing a width of depletion layer (latter changing just predetermines redistribution of the electric field). This method allows us to evaluate charge carrier transport properties, including equilibrium concentration of majority carriers and their mobility. Results on electron mobility of $\mu c$-Si:H measured by CELIV and numerical modeling assuming single localized states can be found in Ref. 4.

In this work some features of hole mobility of $\mu c$-Si:H have been investigated by CELIV. A modeling of the results, assuming a stochastic transport caused by energetically distributed localized states, is also presented and applied for analysis of the experimental results.

## II. EXPERIMENTAL DETAILS

As CELIV can only assess the properties of the majority carriers, hole mobility has been measured on slightly doped $p$-type $\mu c$-Si:H samples. The latter have been prepared by VHF glow discharge at 130 MHz using a concentration of silane in hydrogen of 5% and a few ppm of diborane mixed to the gas phase. Samples were deposited on ZnO covered glass and fitted with a top Al electrode. For comparison a slightly doped $p$-type crystalline silicon sample with a SiN blocking interlayer was also measured.

[a]Electronic mail: gytis.juska@ff.vu.lt

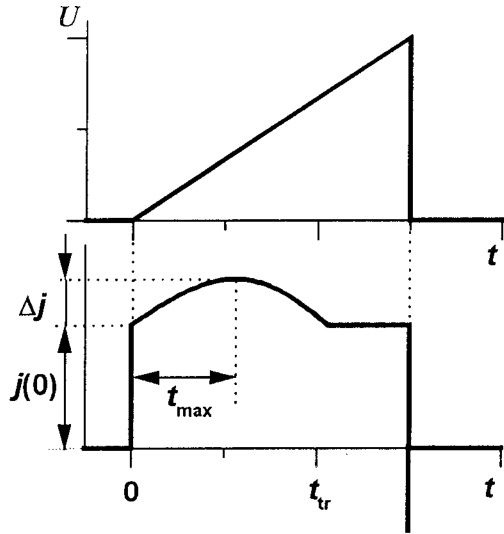


FIG. 1. Schematic illustration of CELIV. $U$ is the voltage applied to the sample and $j$ is the corresponding current transient for $\tau_\sigma = t_{tr}$.

In CELIV, a triangular voltage pulse of reverse polarity, linearly increasing at a rate $A$, is applied to the sample with a blocking electrode and the corresponding transient current is measured. In the case of only free charge carriers the current transient expression according to Ref. 4 is

$$j(t)=\frac{\epsilon\epsilon_0 A}{d}+\frac{\sigma}{\mu}\left(1-\frac{l(t)}{d}\right)\left(\frac{\mu A t}{d}-\frac{\sigma}{2\epsilon\epsilon_0 d}l^2(t)\right), \quad (1)$$

where depletion depth $l(t)$ is obtained from the Riccati equation

$$\frac{dl(t)}{dt}+\frac{\sigma}{2\epsilon\epsilon_0 d}l^2(t)=\frac{\mu A t}{d}. \quad (2)$$

An example of current transient view for $\tau_\sigma = t_{tr}$ is shown in Fig. 1. The initial step of current caused by the geometric sample capacity is given by

$$j(0)=\frac{\epsilon\epsilon_0 A}{d}. \quad (3)$$

The sample bulk conductivity may be estimated according to

$$\tau_\sigma=\frac{\epsilon\epsilon_0}{\sigma}=\frac{2}{3}t_{max}\frac{j(0)}{\Delta j} \quad (4)$$

or from the initial increase rate of the current

$$\tau_\sigma=\left(\frac{d[j/j(0)]}{dt}\right)^{-1}\Bigg|_{t=0}. \quad (5)$$

The drift mobility may be estimated from the time $t_{max}$ when the total current reaches its maximum value $j_{max}$. For low conductivity material, when $\tau_\sigma \geqslant t_{tr}$ is fulfilled, $\Delta j = j_{max} - j(0) \leqslant j(0)$, and

$$t_{max}=d\sqrt{\frac{2}{3\mu A}}, \quad (6)$$

while for high conductivity material, when $\tau_\sigma \ll t_{tr}$ is valid, $\Delta j \gg j(0)$, and

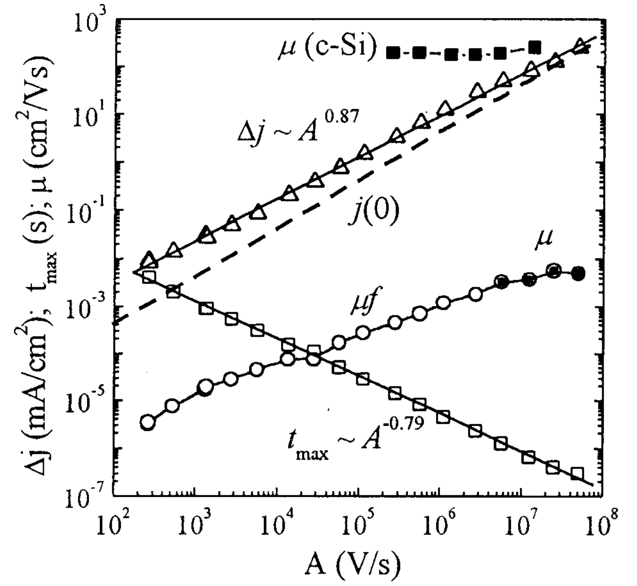


FIG. 2. $\Delta j$, $j(0)$, $t_{max}$, and $\mu$ or $\mu f$ dependencies on voltage increase rate $A$ at room temperature for a 2 $\mu$m thick $p$-type $\mu c$-Si:H sample. The drift mobility of holes measured by CELIV in slightly doped crystalline Si is shown for comparison.

$$t_{max}=\left(\frac{\tau_\sigma d^2}{\mu A}\right)^{1/3}. \quad (7)$$

In the case of a single deep trapping level when the capture time $\tau_C > t_{tr}$, the mobility $\mu$ can then be estimated from Eq. (6) or (7). For lower voltage, when $\tau_C < t_{tr}$, the $\mu f$ product is estimated [here $f = \tau_C/(\tau_C + \tau_R)$ is the trapping factor of charge carriers and $\tau_R$ is re-trapping time]. Further details on the numerical modeling can be found in Ref. 4.

Experimentally, CELIV measurements of $p$-type $\mu c$-Si:H were performed using a maximal voltage of $U = 25$ V. The duration of triangle voltage pulses were varied in a 100 ns to 100 ms time interval. Experimentally it is most convenient to make measurements at a rate $A$ when $\Delta j \cong j(0)$. Then the value of drift mobility was estimated from Eq. (6), taking into account a correction factor $K = 1 + 0.36\Delta j/j(0)$

$$\mu=\frac{2d^2}{3At_{max}^2 K}, \quad (8)$$

which is estimated from the numerical calculation of Eqs. (1) and (2) and is valid for $\Delta j \leqslant 10 j(0)$.

## III. EXPERIMENTAL RESULTS

The values of $\Delta j$, $j(0)$, $t_{max}$, and $\mu$ or $\mu f$ obtained experimentally by CELIV as a function of the voltage increase rate $A$ are shown in Fig. 2. For the determination of $A$, which separates $\mu$ and $\mu f$, i.e., at which $\tau_C = t_{tr}$, the voltage when the collected charge $Q/Q_0$ of Hecht's dependencies saturates was measured (Fig. 3) and $(\mu\tau_C)_p \cong 2 \times 10^{-8}$ cm$^2$/V was estimated. From this dependence follows $(\mu\tau_C)_p \gg (\mu\tau_C)_n$ because the collected charge is much higher when the positive electrode was illuminated. Moreover, the lower saturation magnitude of charge collection in

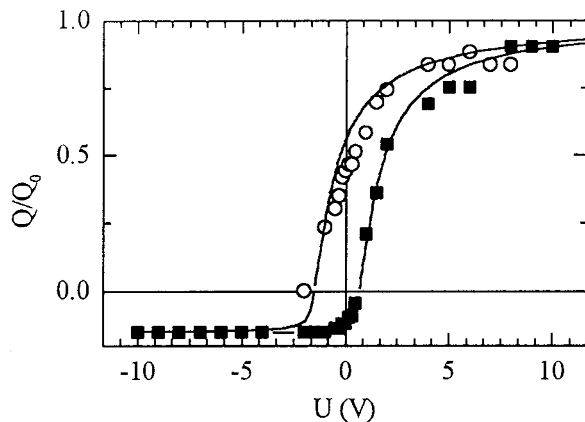


FIG. 3. Hecht's curves of a $p$-type $\mu c$-Si:H layer illuminated through the ITO (■) or Al (○) electrode; $h\nu=2.6$ eV. Positive voltage applied on illuminated electrode.

the case when the negative electrode is illuminated indicates that this is caused not by electron drift but by a drift of holes from the absorption depth back to the illuminated electrode. A voltage value where $Q=0$ points to an electric field at the illuminated electrode.

The estimated values of $\mu c$-Si:H hole mobility at $t_{\max}<\tau_C$ are slightly higher than ones of $a$-Si:H. From the experimentally measured dependencies of $t_{\max}$ on $A$ at different temperatures (180–300 K) and at the electric field value ($F=3\times10^4$ V/cm) where $t_{\text{tr}}<\tau_C$, the hole mobility activation energy 0.2 eV was estimated. The imperfection of CELIV is that the electric field is nonconstant during charge carrier extraction. However, the main extraction occurs at the moment $t=t_{\max}$ when the strongest electric field is achieved.

For comparison, the mobility $\mu$ of slightly doped $p$-type $c$-Si measured by CELIV is also shown (Fig. 2). In this sample a Hall mobility of holes of 290 $\text{cm}^2/\text{V s}$ was measured at room temperature.

## IV. MODELING AND DISCUSSION

The measured electron extraction by CELIV and modeling in the case of single localized states demonstrate the existence of two maximums in the current transient, in a region of voltages at which $\tau_C\cong t_{\text{tr}}$.[4] However, for $p$-type samples, the CELIV experiment demonstrates continuous power law $t_{\max}\sim A^{\gamma}$ dependence.

We think that the barrier model, which is generally used for the interpretation of electronic properties in polycrystalline materials, is unsuitable for $\mu c$-Si:H because density of free and trapped charge carriers in localized states is comparable with the density of crystallites ($10^{15}$–$10^{16}\,\text{cm}^{-3}$); and the Debye screening length is longer than the dimensions of crystallites. The experimental results showing big mobility activation energy, similar to that of $a$-Si:H mobility, led us to presume a decisive influence of localized states. Thus numerical modeling was carried out assuming a stochastic transport of holes in the case of an exponential distribution of localized states $N(E)\sim\exp(-(E/E_0))$. Modeling indicated that the dependencies of $\Delta j$ and $t_{\max}$ are close to a power law dependence, $\Delta j\sim A^{\beta}$ and $t_{\max}\sim A^{\gamma}$, and are qualitatively

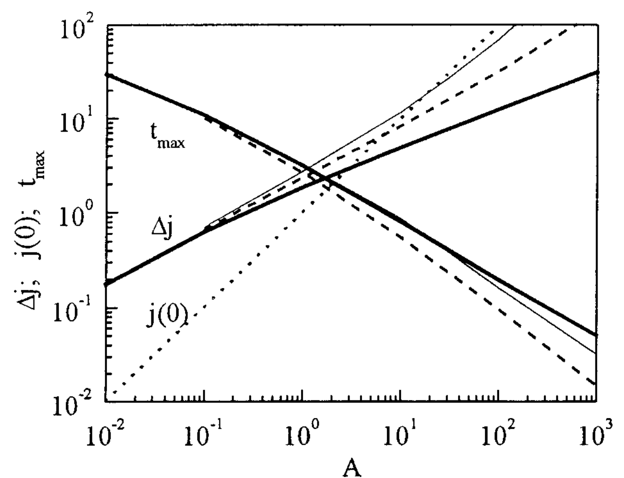


FIG. 4. Numerical modeling of $\Delta j$, $j(0)$, and $t_{\max}$ transients in the case of an exponential distribution of localized states when $E_0/kT=1.5$ and $A=100$. Fine solid lines show the case when $\tau_R\sim\exp(-0.1F)$, dashed lines correspond to the case when $\mu\sim\exp(0.1F)$, and thick lines demonstrate the case when both $\tau_R$ and $\mu$ are independent of electric field.

analogous to experimental results (compare Fig. 4 and Fig. 2). For a more quantitative comparison with the experimental results, the voltage increase rate $A$ was selected in order to get $\Delta j\cong j(0)$. By changing $E_0$, and, thus by changing the dispersion coefficient of stochastic transport $\alpha=kT/E_0$, it was obtained that $(\beta+\gamma)<0$ and $(\beta-\gamma)\cong1$. Note that the shape of $j(t)$ transient in this case should be sublinear when $t<t_{\max}$ (Fig. 5). However, experimentally, the shape of $j(t)$ was superlinear and $(\beta-\gamma)>1$. Such a discrepancy may be caused either by a mobility $\mu\sim\exp(aF)$ or by retrapping from trapping states with a characteristic time $\tau_R\sim\exp(-bF)$ dependent on electric field. In both cases, the current transient is then superlinear (Fig. 5) and $(\beta-\gamma)$ increases together with $a$ or $b$ (see Fig. 6). However, when the mobility depends on electric field, $(\beta+\gamma)$ is independent of $a$ (Fig. 6), while for $\tau_R(F)$,

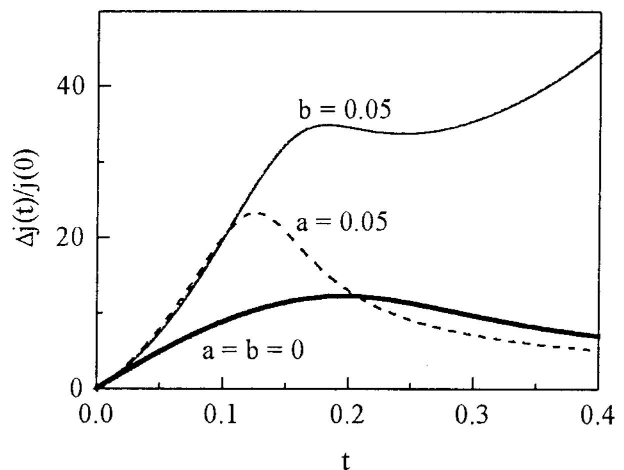


FIG. 5. Extraction current transients for $A=100$ ($A=1$ corresponds to the case $t_{\text{tr}}=\tau_{\sigma}$). Current density is normalized to $j(0)$ at $A=1$ and time is normalized to $\tau_{\sigma}$. The fine solid line corresponds to the case when $\tau_R\sim\exp(-0.05F)$, the dashed line corresponds to the case when $\mu\sim\exp(0.05F)$, and the thick line demonstrates the case when both $\tau_R$ and $\mu$ are independent of electric field $F$.

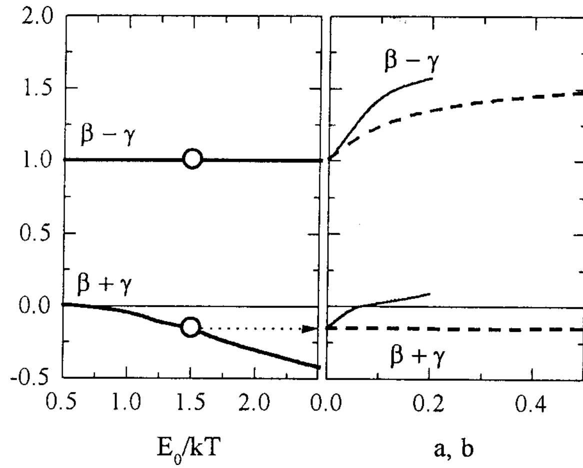


FIG. 6. Numerical modeling of $(\beta+\gamma)$ and $(\beta-\gamma)$ as the functions of $E_0/kT$, $a$, and $b$ for $E_0/kT=1.5$. Here the density of localized states is $N(E)\sim\exp(-E/E_0)$, and $\mu\sim\exp(aF)$ and $\tau_R\sim\exp(-bF)$.

$(\beta+\gamma)$ increases and even becomes positive. These cases demonstrate that different shapes of current transient can be obtained for $t>t_{\max}$ (see Fig. 5). With an increase of $b$ the maximum of current transient even disappears, especially at a high voltage increase rate. This is due to the fact that, during extraction of charge carriers from localized states, the electric field concentrates close to the contact and, at the same time, stimulates charge carrier generation in this region, which induces a further increase in electric field. Experimentally, the coefficients $a$ and $b$ may be changed by changing temperature. Both increase when temperature decreases. Thus the latter effect might be used for comparison of modeling to experiment and also to examine the nature of charge carrier transport dependence on electric field. Here, one has to note that $(\beta-\gamma)$ is insensitive to a mobility dependence on electric field: when $a$ changes from 0 to $\infty$, $(\beta-\gamma)$ changes from 1 to 2.

So far, investigations of holes of $\mu c$-Si:H have demonstrated that $(\beta-\gamma)>1$ and $(\beta+\gamma)>0$; and both increase when temperature decreases. This points to that $\tau_R(F)$ plays a decisive role in the hole transport dependence on electric field.

For electrons of $\mu c$-Si:H the shallow and deep traps are relatively well-separated energetically and a model with one localized state is approximately valid.[3,4] As follows from experimental results of Ref. 3 (see Fig. 4) for high $A$ when $t_{\mathrm{tr}}<\tau_C(\beta-\gamma)\cong 1$ and $(\beta+\gamma)\cong 0$. Therefore in room temperature the influence of electric field to transport parameters is insignificant. However, for low $A$ when $t_{\mathrm{tr}}>\tau_C$ then $(\beta-\gamma)>1$. The latter points to a decisive role of $f$ dependence on electric field.

## V. CONCLUSIONS

The numerical modeling of charge carrier transport by CELIV, assuming an energetically distribution of localized states, allowed us to propose possible reasons for the drift mobility dependence on electric field. If it is caused by stochastic transport then $(\beta-\gamma)=1$ (here $\Delta j\sim A^{\beta}$ and $t_{\max}\sim A^{\gamma}$), while if it is predetermined by a mobility dependence on electric field then $(\beta+\gamma)$ is independent of temperature, and if it is caused by an electric field stimulated release of charge carriers from localized states then $(\beta+\gamma)$ increases when temperature decreases. So far, measurements in $\mu c$-Si:H indicate that the electrical field stimulated release of carriers seems the more likely reason for the observed dependence of the mobility on electrical field. Experimentally measured temperature and electric field dependencies of hole mobility in $\mu c$-Si:H are close to the ones observed in $a$-Si:H. These observations suggest that hole transport can be controlled by intercrystallite material.

## ACKNOWLEDGMENT

Financial support from Lithuanian VMSF Grant No. T432 is acknowledged.

[1] A. Shah, E. Vallat-Sauvain, P. Torress, J. Meier, U. Kroll, C. Hof, M. Goerlitzer, N. Wyrsch, and M. Vaneček, Mater. Sci. Eng., B **69–70**, 219 (2000).

[2] N. F. Mott and E. A. Davis, *Electron Processes in Non-Crystalline Materials* (Clarendon, Oxford, 1979), Vol. 2, p. 664.

[3] G. Juška, K. Genevičius, M. Viliūnas, K. Arlauskas, A. Fejfar, and J. Kočka, J. Non-Cryst. Solids **266–269**, 331 (2000).

[4] G. Juška, K. Arlauskas, M. Viliūnas, and J. Kočka, Phys. Rev. Lett. **84**, 4946 (2000).