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Double Injection Current Transients in a-Si:H

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In this work we present results of both computer modelling and experimental studies of double injection current transients in amorphous hydrogenated silicon thin layers.

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1. Introduction

Many organic materials have been synthesized recently, especially for electronic applications (light emitting diodes, solar cells, etc.), therefore new diagnostic methods and improvement of existing ones are needed for testing these materials. One of methods for charge carrier transport studies is double injection (DoI) current transient technique. It allows to investigate charge carrier mobilities, recombination [1, 2] and trapping features [3] in the disordered materials. This experimental technique is very simple as compared to other methods. If the trapping is not significant (or absent), the sum of charge carrier mobilities ($\mu_{\text{fast}} + \mu_{\text{slow}}$), the mobility of the slowest carriers and bimolecular recombination coefficient could be determined [4]. In this work we demonstrate new possibilities of DoI technique in the case when trapping cannot be neglected. DoI method was applied to investigate the charge carrier transport in a-Si:H. Because a-Si:H is the well investigated material, we can directly compare the obtained results with the known ones and make conclusion about its applicability. DoI technique was also used in the investigation of the trapping features of new organic materials for bulk heterojunction solar cells [5].

2. Results and discussion

a-Si:H p–i–n structure with thickness d of 6 μm was investigated. The sample was prepared in a plasma enhanced chemical vapor deposition reactor on

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ITO covered glass substrate: the bottom layer was 600 nm thick p-type, the middle layer was intrinsic a-Si:H and the top layer was 62 nm thick n-type a-Si:H. A semitransparent Al electrode was evaporated, with subsequent etching of the n-type layer around this electrode in the SF_6 plasma.

Investigation of a-Si:H structure with DoI method showed that the shape of the current kinetics depends on the pulse repetition rate (Fig. 1). At low repetition rate or in a single shot mode the current rise until the value determined by the bimolecular recombination is delayed (by time $t_{\rm del}$) in comparison with the rise at high repetition rate. The illumination of the structure gives the same shape of current as at high repetition rate. From this the assumption was made that this can be caused by deep trapped charge carriers (release from the traps lasts up to tenths of seconds). The computer modelling was used for clarification of this point.

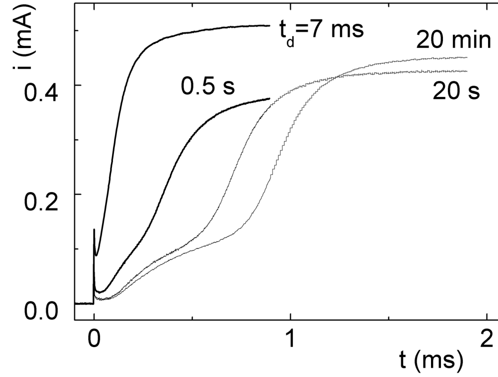

Fig. 1. Experimental DoI current kinetics in a-Si:H. Amplitude of voltage pulse $U=$ 30 V, initial current peak corresponds to electrons transit time $t_{\rm tr\ fast}=110$ ns. $t_{\rm d}$ is duration time between voltage pulses.

The movement of both (fast and slow) charge carriers across the sample was modelled for the different density of trapping levels, $n_{\rm loc}$ and $p_{\rm loc}$, and different trapping times $\tau_{\rm cn}$ and $\tau_{\rm cp}$, respectively. The calculated current kinetics is shown in Fig. 2. The results of the calculation were normalized to time when the charge carriers meet, $t_{\rm tr}=d^2/[(\mu_{\rm fast}+\mu_{\rm slow})U]$, and the sum of stationary space charge limited currents densities ($j_{\rm sclc}$). The normalized density of trapping levels $n'_{\rm loc}$ (or $p'_{\rm loc}$) is

$$n'_{\rm loc}=\frac{en_{\rm loc}Sd}{CU}, \tag{1}$$

where $C=\varepsilon\varepsilon_0 S/d$ is the capacitance of the sample and S is the area of the contact.

When fast charge carriers are trapped, a significant decrease in the current is observed after the transit of fast charge carriers, or even during transit. This feature has not been observed when slow charge carriers are trapped. This allows

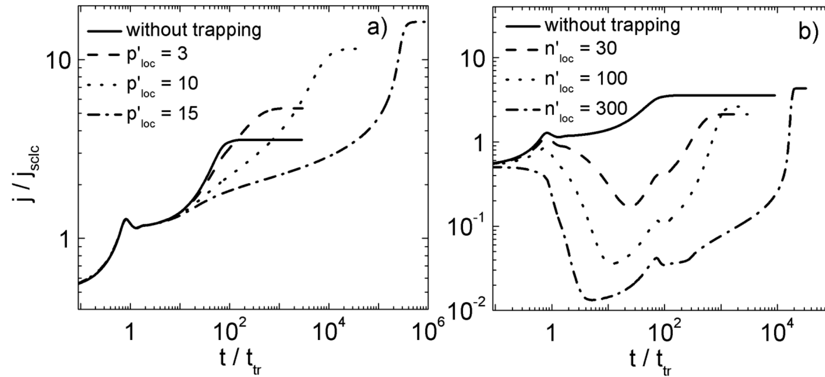

Fig. 2. Numerically modelled DoI current kinetics: (a) slow charge carriers are trapped, (b) fast charge carriers are trapped.

us to state that if the current decrease is observed experimentally indeed, the trapping of fast charge carriers into deep traps is taking place. If trapping is significant, DoI current decreases exponentially $\sim \exp(-t/\tau_{\rm cn})$, and the calculation of trapping time with sufficient accuracy could be performed.

In Fig. 2 one can observe that delay time $t_{\rm del}$ strongly depends on the density of the trapping levels $n_{\rm loc}$ and $p_{\rm loc}$ (close to exponential dependence; see Fig. 3). Obviously, the described above dependence will be observed only when trapping time of the fast charge carriers is smaller than the transit time of the slow charge carriers ($\tau_{\rm cn} < t_{\rm tr\ slow}$). Analytical expression of this dependence is difficult to obtain, so the analysis was limited to numerical results. Qualitatively, this could be explained by blocking of injection by the injected and trapped charge near electrode. This process continues till all trapping levels are occupied and only then DoI current sharply rises. These results allow us to estimate the density of the trapping levels in the materials using DoI current kinetics. The value of $n_{\rm loc} = 1.5 \times 10^{17}$ cm^{-3} was obtained from experimental DoI current transient in a-Si:H (Fig. 1 and Fig. 3). It appears to be slightly larger than reported previously in [6].

Stationary current of DoI could also be slightly influenced by density of trapping levels (see Fig. 2). If slow charge carriers are trapped, the value of saturated DoI current increases when the density of trapping levels increases. When fast charge carriers are trapped and density of trapping levels is increasing, then the value of saturated DoI current decreases in the beginning, later it increases and exceeds the value of saturated DoI current without trapping. This dependence of saturated DoI current was observed experimentally (Fig. 1) and it is yet another proof that in the investigated a-Si:H sample the electrons are captured by deep trapping levels. When trapping is absent or insignificant, the bimolecular recombination coefficient B could be calculated from the saturated value of DoI current $i_{\rm s}$ [4]:

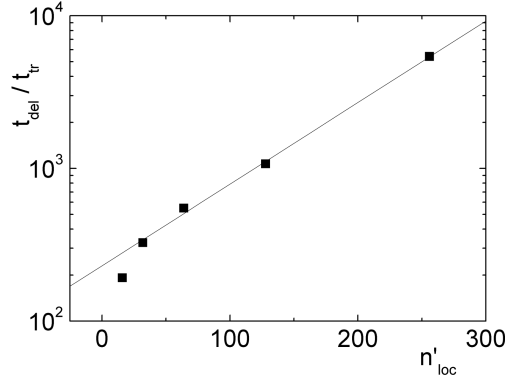

Fig. 3. Dependence of delay time $t_{\rm del}$ on the density of trapping levels $n'_{\rm loc}$ (fast charge carriers are trapped).

$$B = \frac{9\pi}{4}\left(\frac{C}{i_{\rm s}}\right)\mu_{\rm fast}\mu_{\rm slow}B_{\rm L}\left(\frac{U}{d}\right)^4. \quad (2)$$

However, when the trapping appears stronger, this formula becomes less accurate and B is just another parameter used in the fitting procedure. In our calculations the value of $B = 0.006B_{\rm L}$ was used, where $B_{\rm L}$ is the Langevin-type recombination coefficient $B_{\rm L} = e(\mu_{\rm fast} + \mu_{\rm slow})/\varepsilon\varepsilon_0$. Similar situation is also observed with the mobility of slow charge carriers $\mu_{\rm slow}$, calculated from the derivative of DoI current maximum time $t_{\rm slow}$ [2]:

$$\mu_{\rm slow} \approx 0.75\frac{d^2}{Ut_{\rm slow}}. \quad (3)$$

From the experimental DoI currents the value of the mobility of 0.1 $\mathrm{cm}^2/(\mathrm{V\ s})$ for fast carriers was evaluated. It is lower than the one obtained from time of flight (TOF) and carrier extraction by linear increasing voltage (CELIV) measurements because of RC integration. The mobility of slow carriers could not be obtained because of strong trapping.

The results obtained from DoI are in good agreement with previously reported ones. However, estimation of certain parameters in the new materials could be complicated, for example, due to highly dispersive transport.

In conclusion, the results obtained from numerical modelling and experiment show that DoI current transients technique could be used for investigation of trapping processes in disordered materials. It is possible to determine whether fast or slow charge carriers are trapped, also to evaluate density of deep traps and charge carriers lifetime. In order to successfully use DoI technique for new materials transport studies it is desirable to supply method with additional results obtained with different techniques (TOF, CELIV, etc.), because there is a large number of free parameters in the numerical modelling and the results may be unreliable.

Acknowledgments

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