Modelling High Built-in Electric Field Effects on Generation-Recombination Rates in Space-Charge Regions of pn a-Si:H Junctions

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ABSTRACT

A theoretical model of lateral transport of charge carriers in pn a-Si:H junctions with high built-in electric fields is proposed in which the transport of carriers is treated in a similar way to capture-emission transitions in the SRH generation-recombination approach. In this way, the tunnelling rates from transport edges to traps are expressed by an enhanced capture cross-section which strongly affects capture and emission rates of electrons and holes. The tunnelling and thermal capture and emission of carriers to and from localized states determine the occupancy function in the mobility gap of a-Si:H. Generation recombination dynamics are then expresssed by virtue of occupancy function and the continuous distribution of states in the gap of a-Si:H.

Keywords: amorphous silicon, tunnelling, GR model.

INTRODUCTION

The paper presents a mathematical model describing the high electric field effects on capture and emission mechanisms and carrier transport in the space-charge regions of pn a-Si:H junctions.

In contrast to carrier transport in homogenous resistor-like a-Si:H structures, where carrier transport at high electric fields is dominated by the hopping of carriers through nearest-neighbor tail-states, additional high-field effects become predominant in structures with high built-in electric fields. The model developed shows that the carrier transport in the space-charge regions of a-Si:H pn junctions is strongly enhanced by thermal emission of carriers over the lowered potential barrier and by the combined action of the thermal capture-release mechanism and quantum-mechanical tunnelling through a part of the built-in potential barrier.

Carrier generation from traps in the energy gap of a-Si:H is regarded as a thermally assisted tunnelling process [1] combined by the Poole-Frenkel emission over the lowered barrier [2]. In the inverse process of carrier capture, the incident carriers which take part in the tunnelling transport are majority carriers in the low field regions at the edges of the transition region. A fraction of incident carriers either surmount the barrier or tunnell through a part of the barrier. Carriers, penetrating or overpassing the barrier, are captured, thermalising to the ground level of the traps.

Adding trap-assisted carrier transitions to the pure thermal capture-emission process yields expressions for the non-equilibrium occupancy function in the presence of high electric fields. Integrating over all states in the gap results in expressions for the trapped electron and hole charge, and for generation recombination rates in the pn junction space-charge regions. The derived expressions for the generation recombination rate in a-Si:H are similar in form to equations for c-Si [3] which, however, were developed in a different way for a single trap level and did not account for Poole-Frenkel effect. Moreover, the effects of high fields on trapped carrier concentrations in a-Si:H have not been examined before.

TUNNELLING ASSISTED CAPTURE-EMISSION MODEL

Tunnelling-assisted capture and emission transitions are assumed to be two-step processes, shown schematically in Fig. 1. The tunnelling-assisted emission of carriers consists of their thermal excitation from the trap level, followed by a tunnelling transition through a part of the potential barrier. Inversely, in the capture process the carriers tunnel first to

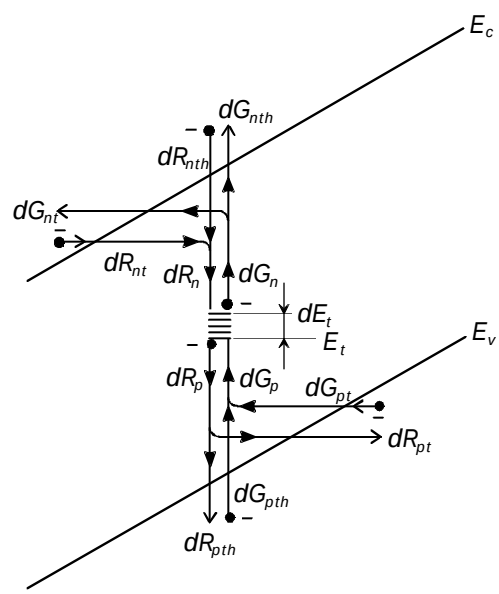

Fig. 1. Schematic presentation of pure thermal and tunnelling-assisted capture and emission of carriers, dR and dG, in energy interval dE_t at trap energy E_t.

the potential well of the trap, then thermalise to the ground level of the trap. Adding trap-assisted tunnelling transitions to the pure thermal capture-emission process will strongly increase the generation-recombination rate of carriers in the presence of high electric fields.

Classical SRH equation for electron capture in the energy interval dE_t at trap energy E_t [4]

$$dR_{nth} = \sigma_n \Phi_{nth} n \left(1 - f_t(E_t)\right) g(E_t)\, dE_t \tag{1}$$

where σ_n is capture cross-section, $f_t(E_t)$ is occupancy function and $g(E_t)$ is the density of states in the gap, can be rewritten for the case of tunnelling assisted electron capture in the form

$$\begin{aligned} dR_{nt} &= \sigma_n \Phi_{nt} n \left(1 - f_t(E_t)\right) g(E_t)\, dE_t = \\ &= \frac{\Phi_{nt}}{\Phi_{nth}} dR_{nth} = \Gamma_n dR_{nth} \end{aligned} \tag{2}$$

Prefactor $\Gamma_n = \Phi_{nt}/\Phi_{nth}$ represents an increase of the total electron capture in the presence of high electric field

$$dR_n = dR_{nth} + dR_{nt} = \left(1 + \Gamma_n\right) dR_{nth} \tag{3}$$

The only difference between the expressions above is in the flux of available carriers. In the case of pure thermal electron capture, this flux consists of free electron concentration n sweeping the space with thermal velocity v_{th}:

$$\Phi_{nth} = v_{th} n \tag{4}$$

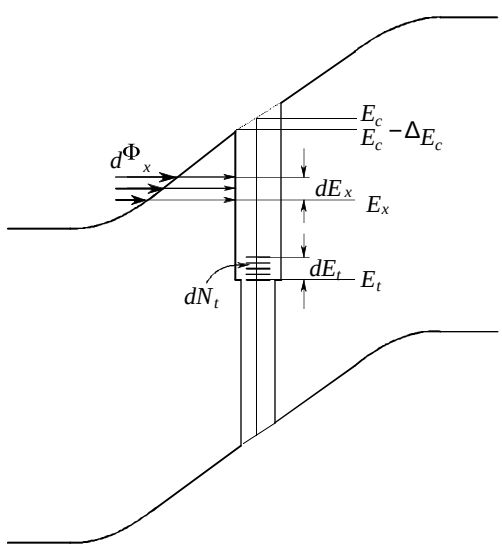

Fig. 2. Schematic presentation of energy band diagram of a-Si:H pn junction space-charge region.

In the process of tunnelling-assisted carrier capture, incident carriers which take part in transitions through and across the barrier are majority carriers outside the depletion region. Only a fraction of these carriers either surmount or penatrate the barrier. The electron flux entering the potential well of the trap can be expressed according to Fig.2

$$\Phi_{nt} = \int_{E_{\min}}^{E_c} T(E_x)\, d\Phi_x(E_x) = \int_{E_{\min}}^{E_c} T(E_x)\, v_x(E_x)\, dn_x(E_x) \tag{5}$$

where $d\Phi_x(E_x)$ is the incident flux of electrons $dn_x(E_x)$ propagating with anysotropical velocity $v_x(E_x)$, and $T(E_x)$ is tunnelling transmission probability of the potential barrier.

If the examined trap energy is below the conduction band-edge energy outside the depletion region, $E_t < E_{cn}$, the lower integration limit equals $E_{min} = E_{cn}$. If the trap energy is $E_t > E_{cn}$, the integration limit is $E_{min} = E_t$.

Assuming a triangular potential barrier below the barrier apex (the region below $E_c - \Delta E_c$), and using the one-dimensional WKB approximation for tunnelling transmission $T(E_x)$ [5]

$$T(E_x) = \exp\left[-\frac{4\sqrt{2m_n}}{3q\hbar F}\left(E_c - \Delta E_c - E_x\right)^{3/2}\right] \tag{6}$$

and, furthermore, presuming a perfect transmission above the barrier apex $T(E_x)=1$ (in the region between $E_c - \Delta E_c$ and E_c), the factor Γ_n decomposes into two parts

$$\Gamma_n = \Gamma_{nt} + \Gamma_{nPF} \tag{7}$$

with

$$\Gamma_{nt} = \int_{E_{\min}}^{E_c - \Delta E_c} T(E_x)\, v_x(E_x)\, dn_x(E_x) \tag{8}$$

and

$$\Gamma_{nPF} = \int_{E_{PF\min}}^{E_c} v_x(E_x)\, dn_x(E_x) \tag{9}$$

where the factor Γ_{nt} belongs to electron tunnelling, and Γ_{nPF} to electron emission, accounting therefore for the Poole-Frenkel effect. The lower integration limit is $E_{PFmin} = E_t$ when $E_t > (E_c - \Delta E_c)$, *and* $E_{PFmin} = E_c - \Delta E_c$ when $E_c < (E_c - \Delta E_c)$.

Finally, inserting into Eqs. (8) and (9) the expression for incremental electron concentration $dn_x(E_x)$ [6]

$$dn_x(E_x) = n_n \left(\frac{m_n}{2\pi kT}\right)^{1/2} \exp\left(-\frac{mv_x^2}{2kT}\right) dv_x \qquad (10)$$

and assuming the constancy of the electron quasi-Fermi level in the space-charge region, factors Γ_{nt} and Γ_{nPF} are obtained in the form

$$\Gamma_{nt} = \frac{1}{\sqrt{6\pi}\,kT} \int_{E_{\min}}^{E_c - \Delta E_c} \exp\left(\frac{E_t - E_x}{kT}\right) - \frac{4\sqrt{2m_n}}{3q\hbar F}\left(E_c - \Delta E_c - E_x\right)^{3/2} dE_x \qquad (11)$$

$$\Gamma_{nPF} = \frac{1}{\sqrt{6\pi}} \exp\left(\frac{E_c - E_{PF\min}}{kT}\right) \qquad (12)$$

The effects of Γ_{nt} and Γ_{nPF} can be visualized as an increase in the apparent capture cross-section $\sigma_n(1+\Gamma_n)$. High electric fields enhance the lateral transport of carriers, being captured, with the consequence of an enlarged capture cross-section. Calculated plots of Γ_n of a p+n+ a-Si:H junction with forward bias of 10mV, presented in Fig.3 for different locations in the space-charge region, show that factor Γ_n extends to very high values. Therefore, the apparent cross-section grows for several decades, with the consequence of increasing strongly the recombination currents in the space-charge region.

The capture of holes at the traps in the gap is a very similar process. Hole capture is enhanced for the factor $(1+\Gamma_p)$ with respect to classical SRH theory.

The emission of electrons and holes from traps, which is obtained on the principle of detailed balance in thermal equilibrium, grows accordingly with rising factor Γ.

Accounting for all possible steady-state arrivals and departures of electrons and holes to and from traps, the non-equilibrium occupation probability f_t at trap energy E_t is obtained

$$f_t = \frac{\sigma_n(1+\Gamma_n)n + \sigma_p(1+\Gamma_p)p_1}{\sigma_n(1+\Gamma_n)(n + n_1) + \sigma_p(1+\Gamma_p)(p + p_1)} \qquad (13)$$

which again has the same form as SRH occupancy function [4], with the exception of terms $(1+\Gamma_n)$ and $(1+\Gamma_p)$, which in the case of high built-in electric fields result in greatly

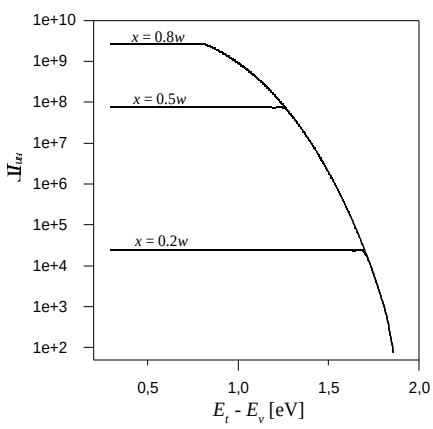

Fig. 3. Calculated factor Γ_n in a forward biased (V_F=10mV) p^+n^+ a-Si:H junction as a function of trap energy in the gap with position x in the space-charge region as the parameter.

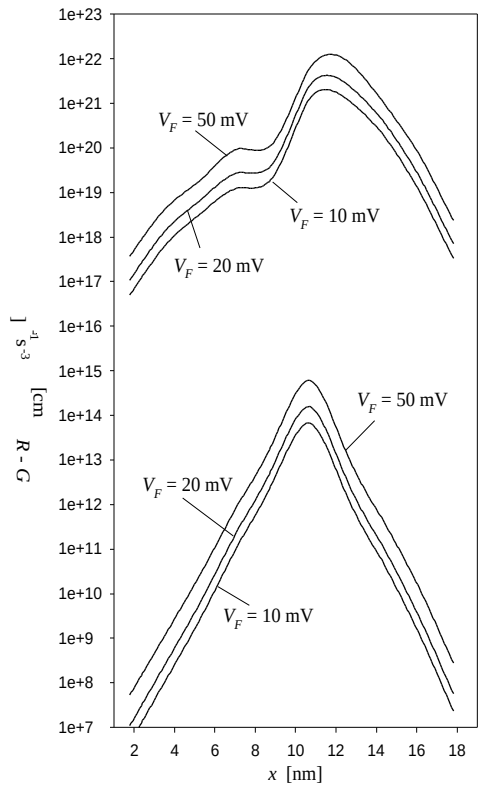

Fig. 4. Recombination rate profile in forward biased p+n+ a-Si:H junction with forward bias voltage V_F as the parameter.

enlarged apparent capture cross-sections σ_n and σ_p.

Assuming two types of traps, acceptor-like and donor-like, $g_A(E_t)$ and $g_D(E_t)$, the net trapped electron density n_t (and trapped hole density p_t) is obtained by integrating over all occupied acceptor-like (empty donor-like) states in the gap.

Finally, the net generation-recombination rate is obtained by integrating overall capture and emission contributions of traps in the gap

$$G - R = \frac{n_i^2 - pn}{\int_{E_v}^{E_c} \left[\frac{g_A dE_t}{\frac{n+n_1}{\sigma_{pA} v_{th}(1+\Gamma_{pA})} + \frac{p+p_1}{\sigma_{nA} v_{th}(1+\Gamma_{nA})}} + \frac{g_D dE_t}{\frac{n+n_1}{\sigma_{pD} v_{th}(1+\Gamma_{pD})} + \frac{p+p_1}{\sigma_{nD} v_{th}(1+\Gamma_{nD})}} \right]} \qquad (14)$$

As expected, the derived expression has the same form as the classical SRH equation [4], with a single difference, which comes from Γ_n and Γ_p values, accounting for trap-assisted tunnelling transport and Poole-Frenkel effect.

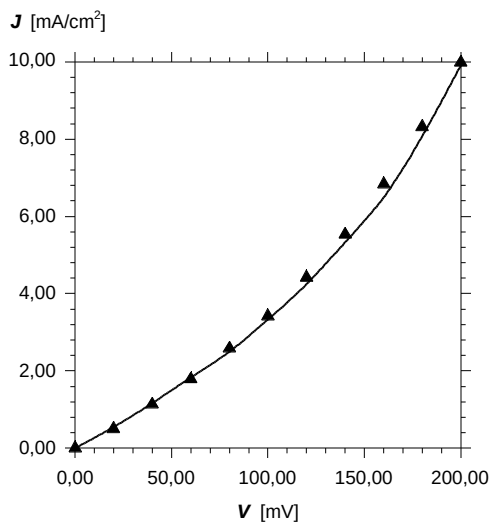

Fig. 5. Calculated and measured current-voltage characteristics of p+n+ a-Si:H junction.

The calculated profile of recombination rate in a p+n+ a-Si:H junction is shown for different values of forward voltage in Fig. 4. It can be observed that the consideration and non-consideration of trap-asisted transport results in greatly differing recombination rates. Highly enhanced recombinations due to tunnelling transport and the Poole-Frenkel effect are also reflected in current-voltage characteristics, shown in Fig.5, where the calculated characteristics using the developed model are compared to the measured characteristics of p+n+ a-Si:H samples.

CONCLUSIONS

A theoretical capture-emission model was developed describing the additional transport paths of charge carriers in pn a-Si:H junctions in the regions of high built-in electric field. This model was derived on the basis of carrier tunnelling and enhanced thermal emission of carriers to the capturing funnels with their subsequent thermalisation to the ground levels of the traps. Effects of these additional carrier transitions were expressed in terms of enlarged capture cross-sections with the consequence of greatly increased generation-recombination rates within the space-charge regions of pn a-Si:H junctions. A good agreement between calculated current-voltage characteristics and measured characteristics of p^+n^+ a-Si:H experimental samples was obtained.

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