Tunneling-assisted currents in n^+p^+ amorphous silicon junctions

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ABSTRACT

A theoretical model for the tunneling transport of charge carriers in forward-biased heavily doped amorphous silicon pn junctions was recently presented. In this paper, in addition to current-voltage characteristics in the forward direction, reverse-voltage characteristics are calculated and compared to the measured characteristics. The trap-assisted tunneling transport of carriers is described in terms of tunneling factor Γ, which can be treated as an effective increase in the apparent capture cross-section of carriers. Crucial factors affecting highly enhanced recombination-generation currents due to tunneling-assisted capture-emission and to potential barrier-lowering (Poole-Frenkel effect) at forward and reverse bias are discussed.

Keywords: amorphous silicon, pn junction, tunneling currents.

1 INTRODUCTION

The model for the tunneling-assisted generation-recombination rate in the space-charge region of a heavily doped n^+p^+ amorphous silicon (a-Si) junction was presented at the MSM99 conference in San Juan last year [1]. A theoretical model for capture-emission transitions in the presence of a high built-in electric field in the space-charge region was later described [2], and the calculated forward current-voltage characteristics were compared to the measured characteristics of experimental n^+p^+ a-Si:H samples.

It has been shown [2] that in certain regions, such as the space-charge regions of pn junctions, the quantum tunneling of charge carriers from energy bands to traps, and the reverse process, may comprise an essential part of the whole capture and emission dynamics, resulting in very high generation-recombination currents. The resulting high conduction mechanism has advantages when making low-resistivity electrical contacts in stacked a-Si solar cell structures [3].

2 GENERATION-RECOMBINATION CURRENTS IN n^+p^+ a-Si JUNCTION

All currents occurring in a pn junction can be visualised as generation-recombination currents. The basic transport processes under forward bias, shown in Fig. 1, include the transport of electrons from the n layer to the p layer, and of holes in the opposite direction. In the first transport path the electrons behave like an electron gas and follow drift-diffusion equations. The excess electron concentration vanishes by recombinations, partly within the space-charge region and partly inside the p layer. The rest of the injected electrons disappear upon ohmic contact with the p layer. In the second transport path, the electrons, with oriented velocities in towards the potential barrier, penetrate the barrier in front of the potential wells of traps by quantum mechanical tunneling. Following this carrier transfer, electrons thermalize to the ground levels of traps, and disappear in recombination with holes.

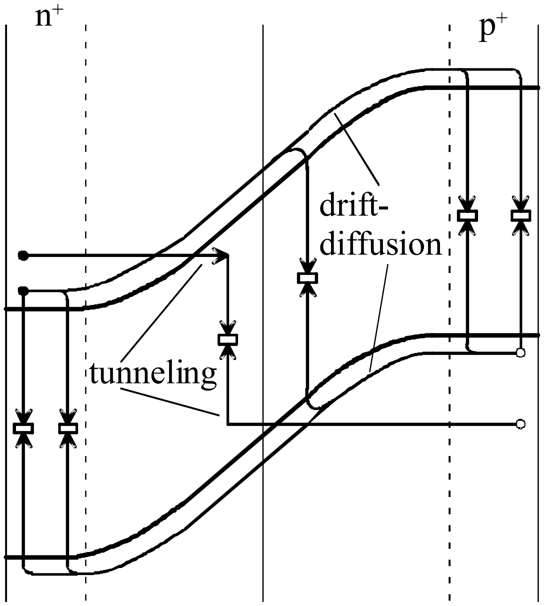

Figure 1. Basic transport paths in pn junction under forward bias.

2.1 Tunneling-assisted capture-emission process

To maintain tunneling-assisted recombination currents, the necessary condition is a high electric field accompanied by a steep potential barrier. A typical example of a structure with a high built-in electric field is a pn a-Si junction with a high doping concentration on either side of the junction. In the case of impurity concentrations, N_A and N_D, in the range of 10^{18} cm^{-3}, it can be calculated that the built-in electric field in the vicinity of the metallurgical junction is higher than 10^5 V/cm, and that the thickness of the pn junction transition region is in the range of 50 nm. In these circumstances, the barriers between energy bands and the potential wells of the traps then enable the large tunneling transport of carriers. Tunneling transitions to and from traps in thermal equilibrium are fully balanced, with the consequence that there is no net transport of carriers. Out of thermal equilibrium, however, the capture of carriers to the traps and their re-emission to energy bands are not mutually balanced, resulting in large electric currents. Under forward voltage conditions, carrier capture predominates over carrier emission, with the consequence of high recombination currents. Under reverse voltage, the emission of carriers from the traps prevails over carrier capture so that the carrier generation current flows in the opposite direction.

The tunneling capture of an electron, shown schematically in Fig.2, consists of two steps:

- electron quantum tunneling from the conduction band in the n$^+$ layer to the potential well of the trap
- electron thermalisation to the ground level of the trap.

In addition to tunneling, a part of incoming electrons can surpass the lowered edge of the potential barrier, representing the Poole-Frenkel process. This transmission of electrons can be treated as the tunneling transition, with the tunneling transmission probability being equal to 1.

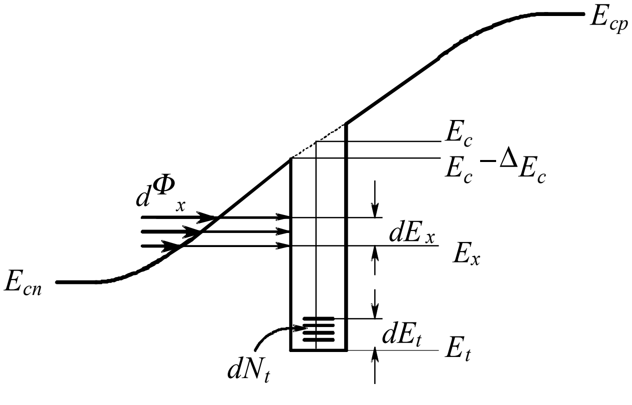

Figure 2. Schematic presentation of tunneling-assisted electron capture.

A convenient way of expressing the tunneling-assisted capture analytically is to modify the classical SRH equation for thermal electron capture to form [2]

(1)

where σ_n is the capture cross-section, f_t is the occupancy function and g is the density of states in the gap. The flux Φ_{nth} of electrons n in the conduction band sweeps the volume with thermal velocity v_{th}

(2)

The additional flux Φ_{nt} in Eq. (1) equals the sum of all electrons penetrating or surmounting the potential barrier

(3)

where $d\Phi_x(E_x)$ is the incident flux of electrons $dn_x(E_x)$ in the incremental energy interval dE_x, striking the potential barrier with velocity $v_x(E_x)$ in the x-direction. Part of the incident electron flux penetrates or overpasses the potential barrier, which is characterised by its transmission probability $T(E_x)$. If the examined trap energy E_t is below the conduction band-edge E_{cn} outside the depletion region, the integration limit $E_{min} = E_{cn}$. If the trap energy is higher than E_{cn}, the integration limit $E_{min} = E_t$.

Keeping the constancy of momentum associated with the parallel movement of electrons and the conservation of total electron energy, and assuming a constant electron quasi-Fermi level in the space-charge region, the tunneling factor for electrons Γ_n can be written in the form [2]

(4)

Assuming a perfect transmission above the barrier apex $T(E_x) = 1$ and using the one-dimensional WKB approximation for triangular barrier transparency, the expression for Γ_n decomposes into two terms

(5)

where the first term describes the electron emission over the barrier, thereby accounting for the Poole-Frenkel effect, and the second term belongs to the electron-tunneling contribution. The energy E_{PFmin} comes from the lower integration limit in calculating the Poole-Frenkel contribution. That is, $E_{PFmin} = E_t$, when $E_t > (E_c - \Delta E_c)$, and $E_{PFmin} = E_c - \Delta E_c$ when $E_t < (E_c - \Delta E_c)$.

Tunneling factor Γ_n affects electron capture by the additional lateral transport of electrons which penetrate or surpass the potential barrier to the potential wells of the traps. This effect can be treated as an effective increase in the apparent capture cross-section $\sigma_n(1+\Gamma_n)$. The plots in Fig. 3 show the calculated factor Γ_n of a n^+p^+ a-Si structure with $N_D = 2{,}5{\cdot}10^{18}$ cm^{-3} and $N_A = 2{\cdot}10^{18}$ cm^{-3} for different values of bias voltage in the middle of the depletion region. As a consequence of the growing integrated contribution of electrons tunneling from the conduction band to the traps, tunneling factor Γ_n increases if the trap energy moves deeper into the gap away from the conduction band. When the trap energy drops below E_{cn}, which equals the lower limit of integration E_{min}, factor Γ_n saturates. The effect of forward voltage is to lower the potential barrier, but at the same time to decrease the slope of the barrier, which has the dominant effect on reducing the tunneling transparency and factor Γ_n. With a growing reverse-bias voltage, the height of the barrier increases and the electrical field increases as well, resulting in a more transparent potential barrier and a higher value of factor Γ_n. The derived expression for Γ_n agrees with that given by Hurkx et al. [4] for the single energy of traps in the case of crystalline Si. In addition, the developed model accounts for the two separate processes: tunneling and Coulomb-well lowering.

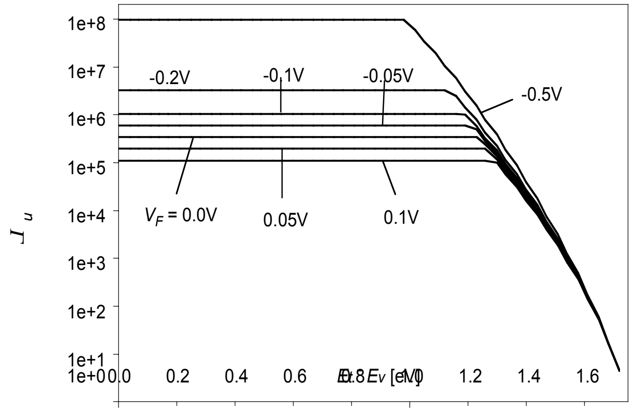

Figure 3. Calculated factor Γ_n as a function of trap energy and bias voltage.

The tunneling-assisted thermal emission of electrons from traps in the gap back to the conduction band is the opposite process to electron capture. Equations for electron emission from traps are obtained on the principle of detailed balance in thermal equilibrium. It turns out that electron emission in the presence of tunneling transport increases by the same factor $(1+\Gamma_n)$ as electron capture.

The same procedure which has been used for electrons can be applied to the analysis of holes which tunnel to the potential wells of traps from the valence band in the p^+ a-Si:H layer. As a result, a set of expressions for the capture of holes is obtained, analogous to equations for electrons [2].

The rest of the p^+n^+ a-Si junction modeling is the same as the case of low electric field conditions [5]. Arrivals and departures of electrons and holes at donor-like and acceptor-like traps determine the occupancy of traps and the incremental generation-recombination rate. Integrating all states in the gap, the expression for total generation recombination rate is obtained.

2.2 Calculated n^+p^+ a-Si junction characteristics

The developed modification of the SRH generation-recombination model has been applied to the calculations of pn a-Si junction characteristics, shown in Fig. 4. The selected doping concentrations were $N_D = 2.5.10^{18}$cm^{-3} and $N_A = 2.10^{18}$cm^{-3}. The donor-like and acceptor-like density of state distributions was chosen in accordance with the data of Zeman et al. [6].

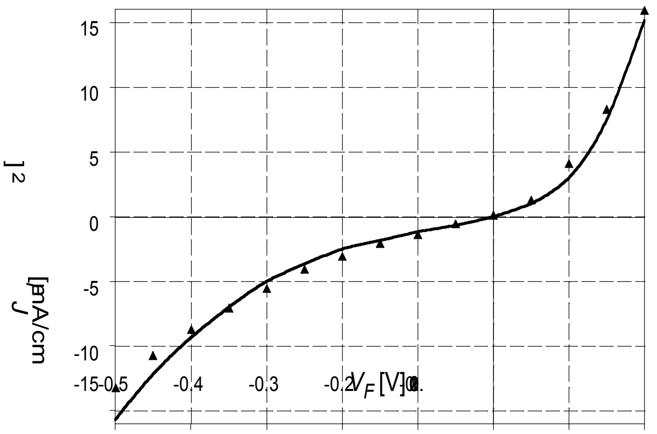

Figure 4. Calculated (solid line) and measured (triangles) characteristics of pn a-Si junction.

The calculated plots drawn in Fig. 4 by solid lines agree well with the measured characteristics given by triangles. The main contribution to large currents at low values of forward and reverse voltage comes from tunneling-assisted transitions to and from traps in the gap of a-Si. The recombination current at forward bias grows in accordance with the high values of tunneling factors for electrons and holes, Γ_n and Γ_p. The generation current under reverse bias also increases due to the rising values of tunneling factors with a rising electric field under reverse-bias conditions.

3 CONCLUSION

The thermally-assisted tunneling of carriers through the barrier and emission over the barrier to the traps in the gap of a-Si greatly increase carrier capture and emission rates in the space-charge region of heavily doped p^+n^+ a-Si junction, resulting in strongly increased generations and recombinations, and in very large electric currents at low values of forward and reverse bias voltage.

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