EFFECTS OF PN-JUNCTIONS BORDERING ON SURFACES INVESTIGATED BY MEANS OF 2D-MODELING

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ABSTRACT

Several new solar cell designs, among them the Emitter Wrap Through (EWT) and the POWER solar cell, suffer from reduced fill factors. These cells have interdigitated p- and n-type regions. At the margin of these regions, the p-n junction borders on the surface causing additional recombination. We investigate by means of two-dimensional modeling the recombination mechanisms occurring in such device regions, and we give an experimental example. It is shown that a poor quality of the surface passivation near to where the pn-junction borders, is mainly responsible for the observed losses in fill factor and open-circuit voltages.

INTRODUCTION

In recent years several new solar cell designs have been investigated such as the Emitter Wrap Through (EWT) [1,2] and the POWER [3,4] solar cell. EWT cells promise a higher efficiency combined with a simplified cell interconnection in the module. POWER solar cells offer an optical semi-transparency which opens new markets e.g. in solar architecture. All these novel concepts have interdigitated p- and n-type regions. At the margin of these regions the pn-junction borders on the surface causing an increase in the second diode current density J_{02} which can significantly reduce the V_{oc} and the FF of the cell [5].

For the case of an abrupt pn-junction, Sha, Noyce and Shockley [6] developed an expression for the recombination current J_{02} within a space charge region (SCR) at an applied voltage U_a:

$$J_{02} = \frac{qWn_i}{2\tau_0} exp\left\{\frac{qU_a}{2kT}\right\} \quad (1)$$

For simplification they assumed the same minority carrier lifetimes τ_0 for electrons and holes. Furthermore they set the carrier densities n = p within the whole width W of the SCR. In reality this n = p (which leads to an ideality factor n=2) is only the case for the "sweet spot" in the junction. Refining this model including a realistic charge carrier distribution, different lifetimes for electrones and holes and an electrical field within the SCR but still assuming an abrupt pn-junction leads to complicated analytical expressions for J_{02}. For a review on SCR recombination and first, one dimensional numerical modeling see [7].

pn-junctions bordering on surfaces were already investigated in 1966 by means of analytical models [8]. In our study the influence of the surface recombination velocity and the fixed surface charge on J_{02} of a diode are investigated by means of 2-dimensional computer simulations using DESSIS [9]. The model includes the influence of a realistic diffusion profile as well as the resulting charge carrier distribution and electrical field within the SCR.

A SHORT RECAPITULATION OF SRH RECOMBINATION

The terminal current originates solely from recombination in the device. Therefore, the current-voltage (*I-V*) curve of a cell is mainly determined by the recombination processes (apart from resistive, shunt and shading losses [10]). In the SCR, Shockley-Read-Hall (SRH) recombination dominates whereas Auger recombination can be neglected due to the low charge carrier concentration in this region. The SRH theory [11,12] adequately describes the observed *I-V* curves if most of the recombination can be considered to occur via one type of recombination centre. This is usually the case in crystalline devices doped by diffusion, whereas non-crystalline devices or abrupt junctions may exhibit considerable amounts of multistep, tunneling-aided, and trap-assisted recombination processes. The well-known expressions for the SRH recombination rate is at the surface of the device (in units of $cm^{-2}s^{-1}$):

$$U_s = \frac{p_s n_s - n_i^2}{\frac{1}{S_{po}}(n_s + n_1) + \frac{1}{S_{no}}(p_s + p_1)} \quad , \quad (2a)$$

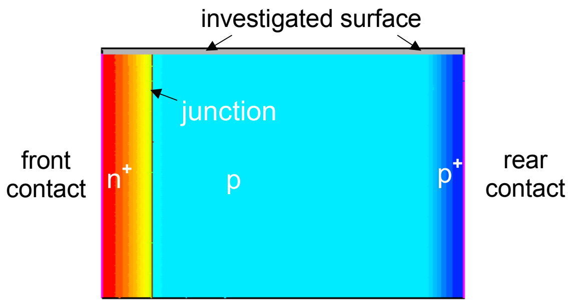
where S_{po} and S_{no} (in units of cm/s) are the surface recombination velocity parameters, and the subscript *s* denotes the surface. The constants

$$n_1 = n_i \, exp[(E_d - E_i)/kT] \quad p_1 = n_i^2 / n_1 \quad (2b)$$

are normalization parameters containing information about the energy level E_d of the recombination centre with respect to the intrinsic energy level E_i . n_i is the intrinsic density of the semiconductor. Although Eqs. 2a and 2b look simple, they describe a whole wealth of phenomena, which depend mainly on the behaviour of the electron and hole density (*n* and *p*) with respect to a given set of τ_{po}/τ_{no} and S_{no}/S_{po} ratios and E_d . In the following, we simplify the discussion by assuming that the centres have energy $E_d \approx E_i$.

APPROACH AND USED MODELS

We do not want to simulate a special solar cell and its geometry but the general effect of pn-junctions bordering on surfaces on the IV-characteristics of a solar cell. For an easy, qualitative comprehension and in order to exclude geometrical effects (e.g. current crowding), a simple, small simulation domain (5x4μm^2, see fig. 1) has been chosen. The recombination of the pn-junction bordering on a surface is dominating the device characteristics. In particular, the base region is small to reduce bulk recombination, and a heavily doped emitter and BSF reduce the impact of the contact recombination. The chosen material parameters are typical for industrial silicon solar cells.
The device simulator DESSIS numerically solves the fully coupled set of semiconductor differential equations (Poisson equation, drift-diffusion equations) iteratively, i.e. all variables are solved self-consistently.



Property	***Parameters / models***
Emitter	30Ω/sqr, 0.7μm deep, Erfc-profile
Base	$1.6*10^{16}cm^{-3}$; 1 Ωcm
BSF	$5*10^{19}cm^{-3}$, Erfc-profile
Temperature	300 K
Eff. intrin. density	Del Alamo model
Recombination	Shockley-Read-Hall, τ = 14μs
Mobility	Philips-unified-model, high-field-saturation
Defects	mid-gap defects, $E_d = E_i$

Fig.1: Scheme of the diode, parameters and models used in the simulation study

SIMULATIONS

Variation of the surface recombination velocity (SRV)

Figure 2 shows the simulated dark current J(U)-curve and the corresponding ideality factor n(U)-curve for the case of different SRV parameters $S_{n0} = S_{p0} \equiv S_0$. At low voltages the device is totally dominated by the recombination in the SCR resulting in an ideality factor of n=1.6 - 1.9. The geometry of the simulation unit has been selected to be very sensitive to surface influences. For low $S_0<10^2$cm/s, the J(U)-characteristics for U>0.3V is driven by other recombination mechanisms such as the bulk and the contact recombination with ideality n = 1.

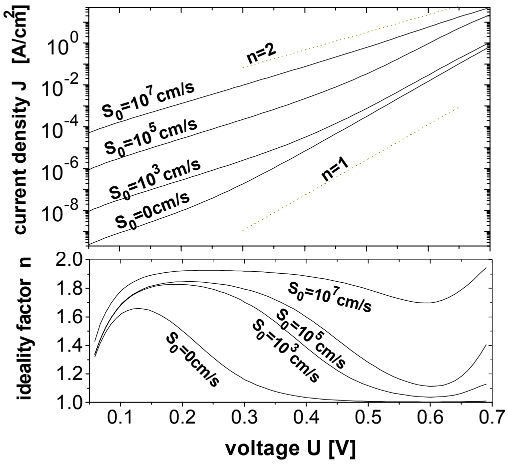


Fig.2: Simulated dark current density J(U) and ideality factor n(U) for different values of the surface recombination velocity parameter S_0. J(U) increases with S_0 and a characteristics with n>1 extends to higher voltages.

Increasing S_0 the recombination within the space charge region bordering on the surface gains of influence. The ideality factor increases and has values well above 1.0 even at voltages in the range of the maximum power point. At voltages U>0.6V the series resistance of the device limits the current density expressed in an increased ideality factor. It can be mentioned that for very high surface recombination velocities the recombination in the perimeter space charge region affects the J(U)-curve in a way that the ideality is n > 1.7 for the whole voltage range. In the case of a solar cell, this reduces the fill factor dramatically.

For solar cells with interdigitated p- and n-type regions it is important to know the quantitative contribution of the SCR-recombination at the surface to J_{02}. To investigate this impact, all other recombination sources have been switched off for the simulation. The entire current through the diode is due to recombination at the surface. The resulting dark J(U)-curves have been fitted at low voltages (U=0.1-0.3V) to obtain the saturation current density $J_{02,surf}$ depending on S_0 shown in figure 3. $J_{02,surf}$ increases linearly with S_0 until the effective SRV $S_{eff}=U_s/\Delta n_s$ reaches its maximum value when all carriers reaching the surface recombine there.. The maximum $J_{02,surf}$ = $2*10^{-8}$A/cm indicates an upper limit for the detrimental effect of a perimeter pn-junction on the cell performance and corresponds very well to experimental observations.
For crystalline silicon solar cells with life times τ>1μs (also within the overcompensated SCR), the J_{02} due to bulk recombination can be neglected as it is $J_{02}<10^{-8}$. The contribution to J_{02} by a pn-junction bordering on the cell surface on a length L_{surf} can be calculated as:

$$J_{02}(S_0) = J_{02\,surf}(S_0) \cdot \frac{L_{surf}}{A_{cell}} \qquad (3)$$

A_{cell} is the cell area.

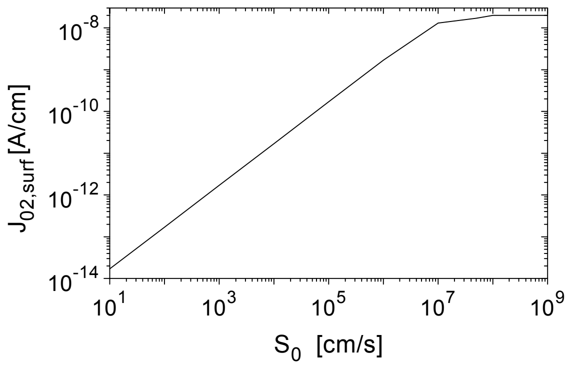


Fig. 3: Dark saturation current density $J_{02,surf}$ due to a pn-junction bordering on a surface depending on the surface recombination velocity parameter S_0. $J_{02,surf}=2*10^{-8}$A/cm indicates an upper limit for the detrimental effect of a surface pn-junction.

For conventional flat solar cells (junction borders on the surface only at cell edges) J_{02} only reaches significant values $>10^{-8}$A/cm^2 for the case of very small cells ($A_{cell} \leq$ 4cm²). For cells with interdigitated p- and n-type regions, L_{surf} becomes longer. For example for POWER values as high as L_{surf} = 4000cm cells (A_{cell} = 10x10cm²) can lead to $J_{02} > 10^{7}$A/cm^2 which can reduce the fill factor significantly.

This effect has been observed experimentally [5].

Variation of the surface charge Q_f

In order to reduce the SRV, solar cell surfaces are covered with dielectrics such as silicon dioxide or silicon nitride. Due to dangling bonds these dielectrics are normally positively charged with surface charge densities in the range of 10^{10}-10^{12}cm^{-2}. Depending on the charge density and the background doping, a depleted or even inverted region is created underneath the surface of a p-type region. For the case of rear side passivation of high efficiency solar cells, the effect of surface charges has been investigated extensively [13]. In contrast to the rear surface which affects the cell characteristics especially in the case of good quality silicon with high minority carrier diffusion lengths, the p-type region in the neighborhood of a pn-junction bordering on a surface is very sensitive to surface passivation even for diffusion lengths shorter than the cell thickness.

The characteristics of the simulated device have been investigated for the case of different surface charge densities. The charges have been assumed to be fixed, no changing of the charge densities with varying injection level occurs. With increasing Q_f density, the layer underneath the p-type surface becomes more and more depleted. If the Q_f exceeds a certain limit which depends mainly on the background doping of the p-type wafer (in this study $N_A=1.6*10^{16}$cm^{-3} → $Q_{f,limit} \approx 2*10^{11}$cm^{-2}), an inversion layer is formed (see inset in Fig.4). The inversion channel borders on the metallurgical pn-junction and lengthens the effective pn-junction. The inversion breaks down in the region of the BSF. Consequently the lengthening of the junction within a real solar cell depends on its geometry, i.e. the distance between junction and BSF.

Furthermore it is very important that the rear contact is electrically isolated from the inversion channel. If there are shunts through the BSF, the rear side is connected via the inversion channel to the front side and the cell becomes shunted. This effect has been observed for POWER- as well as EWT-solar cells for the case that a highly charged silicon nitride has been deposited over interdigitated p- and n-type regions simultaneously.

Figure 5 shows the dark J(U)-curve for different surface charge densities. For disappearing surface recombination (S_0=0) (hollow symbols in Fig.5) a slight increase in the current density at low voltages can be remarked for the case of highly charged surfaces. This is due to the effective lengthening of the pn-junction described above. The shorter the bulk minority carrier diffusion length the stronger this effect will be.

In the case of a realistically SRV = 1000cm/s, the Q_f gains much of an influence. With $Q_f > 0$, bumps in the J(U)-curve appear which move with increasing Q_f from higher to lower voltages. For very high Q_f, the bump disappears and the J(U)-curves lie well beyond that for the non-charged case. This effect is a result of the depletion or inversion condition at the p-type surface. At small $Q_f < Q_{f,limit}$, a shallow channel underneath the surface is depleted. As a consequence, the minority carrier injection for U > 0V in this region is higher than for the case of Q_f = 0 leading to an increased surface recombination rate. It is important to mention that there are two junctions, the np-junction and the pp$^+$-junction at the BSF. For the case of a depleted region, the potential step at the pn-junction is reduced whereas that one at the pp$^+$-junction is increased. The applied external voltage U is distributed among both junctions. With increasing voltage electrons are injected in the depleted p-type region. At a certain voltage that depends on the degree of depletion (i.e. the Q_f), the carrier concentrations of holes and electrons within the depleted channel become

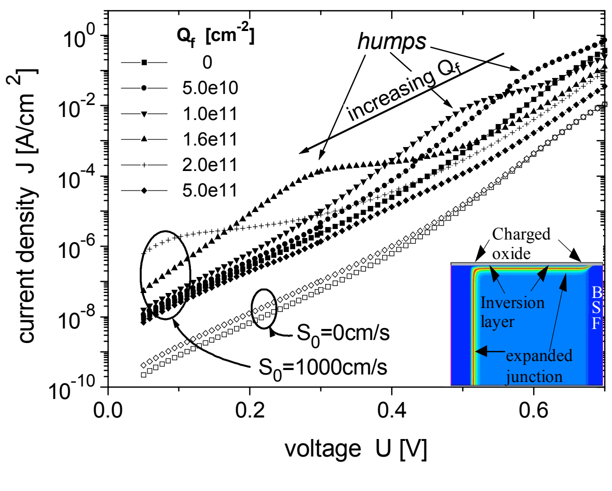


Figure 4: Modeled dark-IV-characteristics for different surface charge densities Q_f. Humps occur due to the transition from p- to n-typ behaviour within the depleted region underneath the charged surface (see text).

equal, $n_S = p_S$, leading to a very high recombination rate (cp. eq.2). At this stage the voltage drop distributes equally among both junctions. For further increasing voltage, n becomes larger than p, leading to a slower increase of the surface recombination rate with the voltage. The external voltage mainly drops at the pp^+-junction. The hump in the J(U)-curve is a result of the transition from a (p > n)-behavior at low voltages to a (n > p)-behavior at high voltages.

In the case of very high $Q_f > Q_{f,limit}$, the surface channel is already inverted at U = 0V and n > p applies. This leads to a reduced effective SRV.

Figure 5 shows illuminated J(U)-curves for different Q_f. It can be seen that the characteristics are heavily affected in the case of $5*10^{10}cm^{-2} < Q_f < 1*10^{11}cm^{-2}$, i.e. deep depletion within the surface channel. With these Q_f the fill factor as well as V_{OC} of a solar cell would be reduced significantly.

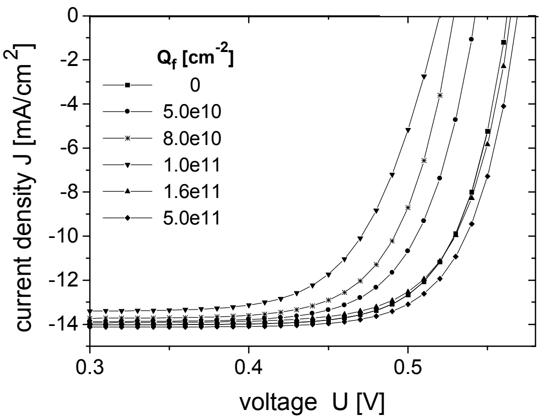


Figure 5: simulated, illuminated J(U)-characteristic for different surface charge densities Q_f. $Q_f < 10^{11}cm^{-2}$ reduces fill factor and V_{OC}.

CONCLUSIONS

In novel solar cell concepts with interdigitated p- and n-type-regions, the effect of the pn-junctions bordering on the surface must be taken into account. This effect becomes stronger the longer the open pn-line is and the higher the effective surface recombination velocity is. The presented simulations give an upper limit of $2*10^{-8}$A/cm for its contribution to the second diode saturation current for the case of a maximum SRV. This value corresponds well to experimental observations.

In the case of a charged surface passivation layer, additional recombination at the p-type surface occurs if the charge is not as high as to create an inversion layer underneath the surface. Humps in the IV-curve appear due to the transition from depletion to inversion in the surface layer reducing V_{OC} and FF. This effect is known from the rear surface of high efficiency solar cells. For industrial solar cells with short carrier life times the rear surface has less of an impact but high minority carrier injection occurs to the regions in the neighborhood of the pn-junction. Therefor cells with a long line of pn-junctions bordering on the surface should be passivated using a highly charged dielectric layer, $Q_f > Q_{limit}$.

To prevent shunts care must be taken during processing not to create an electrical contact from the BSF to the depletion or inversion layer underneath the p-surface next to the BSF.

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