INP SOLAR CELL IMPROVEMENT BY INVERSE DELTA-DOPING

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ABSTRACT

Recombination loss mechanisms in InP homojunction solar cells are analyzed using numerical modeling. To reduce the junction leakage current, it is proposed to introduce a thin undoped layer with low recombination center density near the *pn*-junction. This inverse delta-doping is found to be most beneficial in low efficiency p^+n-InP cells, improving the open circuit voltage by 50 mV, the fill factor by 0.09, and the efficiency by 2 percentage points.

INTRODUCTION

InP solar cells are attractive for power source applications in space since their radiation-induced degradation is lower than that of the commonly used GaAs and Si solar cells [1]. With a direct band gap of E_g=1.35 eV at room temperature, InP cells are expected to show energy conversion efficiencies η near the theoretical limit of about 26% for AM0 illumination [2]. The highest measured efficiency of InP homojunction cells is 19.1% AM0 ([3]: MOCVD, n^+p-cell). This discrepancy is mostly due to high recombination losses at the front surface, limiting the short circuit current density j_{sc} and to some extend also the open circuit voltage V_{oc}. When the front surface recombination is reduced by using, e.g., strained $In_{0.4}Al_{0.6}As$ window layers [4], the bulk minority carrier lifetime becomes the limiting factor for the efficiency. At 10^{18} (10^{17}) cm^{-3} doping density, measured bulk lifetimes are about 100 (300) ns for holes in *n*-InP and about 0.5 (2.0) ns for electrons in *p*-InP; the latter are much smaller than for GaAs (see review in [5]). These lifetimes are controlled by radiative band-to-band transitions and by Shockley-Read-Hall (SRH) recombination, respectively. In InP cells, grown on foreign substrates, misfit dislocations reduce the lifetimes and cause poor performance with efficiencies even below 10% [6]. Small minority carrier lifetimes lead to high internal recombination losses, especially near the *pn*-junction, where the SRH recombination rate is largest and dominates the junction leakage current, that is known to be detrimental to the open circuit voltage.

This paper analyses the recombination losses in detail and investigates the influence of a thin undoped layer which is introduced close to the *pn*-junction. In lowly doped InP, minority carrier lifetimes of 3 μs for holes [7] and 0.3 μs for electrons [8] have been measured. Thus, the thin undoped layer is expected to have a lower recombination center density than the bulk material (inverse delta-doping [9]). The analysis employs the solar cell simulation software PC-1D [10] using the standard set of InP material parameters. Already optimized device parameters are taken from [11] for a high efficiency p^+n-InP homojunction cell with slight derivations in the lifetimes according to [5] (see Tab. 1).

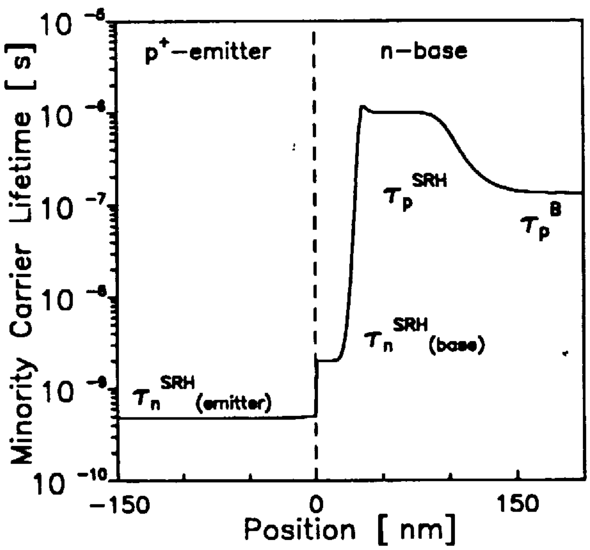

Figure 1: Profile of the minority carrier lifetime near the metallurgically abrupt p^+n-junction of the InP solar cell given in Tab. 1.

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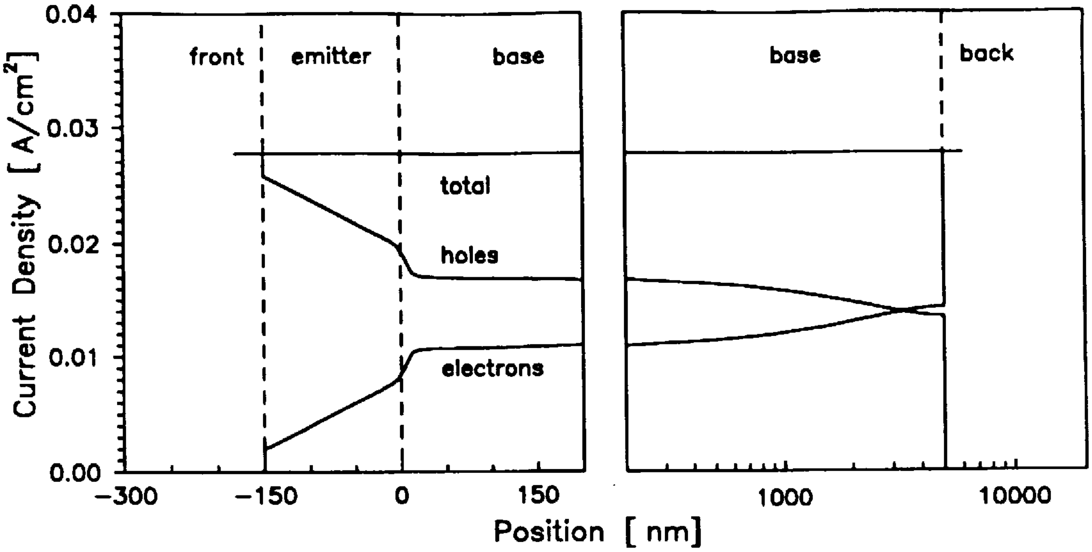

Figure 2: Profile of electron, hole and total dark current density within the p^+n-cell at open circuit voltage.

RECOMBINATION LOSS ANALYSIS

For n-doped bulk material, the carrier recombination rate R is determined by the lifetime τ_p and the density p of minority carriers. Besides SRH recombination via defect levels (lifetime τ_p^{SRH}), electrons and holes also recombine by radiative band to band transitions ($\tau_p^B = 1/B_p n$) and by nonradiative Auger transitions ($\tau_p^C = 1/C_p n^2$)

$$R = \frac{p}{\tau_p} = p\ \left(\frac{1}{\tau_p^{SRH}} + \frac{1}{\tau_p^B} + \frac{1}{\tau_p^C}\right) \qquad (1)$$

(p and n exchanged for p-doping). The majority carrier lifetime is normally assumed equal to the minority carrier lifetime since it is mostly unknown and irrelevant for bulk recombination. In our analysis, the majority electron lifetime is adopted from reported lifetime measurements on p-doped InP, where electrons are minority carriers (analog for holes, see Tab. 1). With the Auger coefficients $C_p = 8.7 \times 10^{-30}\mathrm{cm}^6/\mathrm{s}$ and $C_n = 3.7 \times 10^{-31}\mathrm{cm}^6/\mathrm{s}$ and the coefficient $B_p = B_n = 6.6 \times 10^{-11}\mathrm{cm}^3/\mathrm{s}$ for radiative recombination [12] [1], the Auger process dominates only for $n \geq 10^{19}\mathrm{cm}^{-3}$ in InP. At $10^{17}\mathrm{cm}^{-3}$ doping density, direct radiative band-to-band transitions exhibit a lifetime $\tau_n^B = \tau_p^B = 150\mathrm{ns}$ (radiative limit). Due to reabsorption of emitted photons, this lifetime has to be multiplied with the photon recycling factor to compare with measured numbers [7]. From measurements of the minority lifetime reported above it can be deduced, that bulk n-InP is almost free of effective recombination centers (i.e., the SRH lifetime τ_p^{SRH} is much higher than the radiative limit τ_p^B) whereas SRH recombination limits the minority lifetime essentially in bulk p-InP. The SRH carrier lifetime depends on the capture cross section and the density of available recombination centers, which are mostly unknown in real InP devices.

In the space charge region near the pn-junction, the recombination behavior becomes more complicated since the carrier densities $n(x)$ and $p(x)$ now change drastically as a function of the distance x from the metallurgical junction. The minority carrier lifetime $\tau(x)$ is plotted in Fig. 1 as function of the local position. Approaching the junction from the n-doped base, the radiative lifetime τ_p^B rises by orders of magnitude since the electron density decreases. Thus, the SRH lifetime becomes dominant for holes. The recombination rate $R(x)$ goes through a maximum close to the cross-over of $n(x)$ and $p(x)$, occurring at $x = 35\mathrm{nm}$ in Fig. 1 (zero bias). Passing through the cross-over, majority carriers become minority carriers, i.e., the minority lifetime is now limited by the electron value τ_n^{SRH} in the base even when the local position is still inside the n-doped base region. Crossing the metallurgical pn-junction, the minority electron lifetime jumps to the lower emitter value due to the higher doping.

To discuss the limitations of the open circuit voltage, a forward bias of $V = V_{oc}$ is applied, where the photocurrent is just compensated by the recombination current. The recombination losses can be analyzed quantitatively, plotting the *dark* current density distri-

[1] The usage of GaAs values for B in [5] is misleading

Parameter	Unit	Emitter	Base
thickness	μm	0.15	5.0
doping	cm^{-3}	10^{18} (p)	10^{17} (n)
bulk electron mobility	$cm^2/(Vs)$	2250	3545
bulk hole mobility	$cm^2/(Vs)$	69	144
SRH electron lifetime	ns	0.5	2
SRH hole lifetime	ns	1000	1000
bulk minority lifetime	ns	0.5	130
surface recombination	cm/s	10^4	10^7

Table 1: Parameters of the high-efficiency InP p^+n-homojunction solar cell assumed in the analysis.

butions $j_n(x)$ and $j_p(x)$, whose slope is a measure of the recombination rate (Fig. 2). The total dark current density is $j_{dark}(V_{oc}) = j_n(x)+j_p(x) \simeq 28$ mA/cm² with $j_n = 0$ at the front surface and $j_p = 0$ at the back surface of the p^+n-InP cell. Front surface recombination lowers j_p by 2 mA/cm². In the p^+-emitter region, j_p is reduced by 6 mA/cm² due to the rather short electron lifetime. Within only 30 nm of the space charge region, j_p then drops by 3 mA/cm² because of high SRH recombination. Another 4 mA/cm² is lost in the n-base bulk region and the remaining 13 mA/cm² are vanishing at the back surface that has a large recombination velocity. The steepest slope of j_n and j_p, i.e., the highest recombination rate inside the device occurs within a thin base region next to the metallurgical pn-junction where $n \simeq p$. These losses are determined by SRH recombination via defect levels in the band gap.

INVERSE DELTA-DOPING

In our example p^+n-cell (see Tab. 1), the SRH lifetime of holes is assumed to be $\tau_p^{SRH} = 1\mu s$, since the measured minority lifetimes τ_p are dominated by the radiative limit τ_p^B and thus, a more precise value of τ_p^{SRH} is unknown. SRH electron lifetimes $\tau_n^{SRH} \approx \tau_n$ are taken from the measurements reported. The bulk minority lifetimes correspond to diffusion lengths of $L_n = 2\mu m$ in the emitter and $L_p = 7\mu m$ in the base. Two-layer antireflective coating (50 nm ZnS, 100 nm MgF_2), 5% grid shadowing and 0.3 Ωcm^2 series resistance are also considered. Under 137.2 mW/cm² AM0 illumination at 25°C, the calculated performance data of this high-efficiency p^+n-cell are $j_{sc} = 38.0$ mA/cm², $V_{oc} = 980$ mV, $FF = 86.0\%$, and $\eta = 23.3\%$.

In the following, we analyze the introduction of a thin intrinsic layer with higher SRH lifetime into the space charge region (inverse delta-doping). From Fig. 1 it is obvious, that the inverse delta-doped layer should be introduced at the base side next to the metallurgical pn-boundary. A layer thickness of 50 nm is sufficient to cover the region with heavy recombination. With

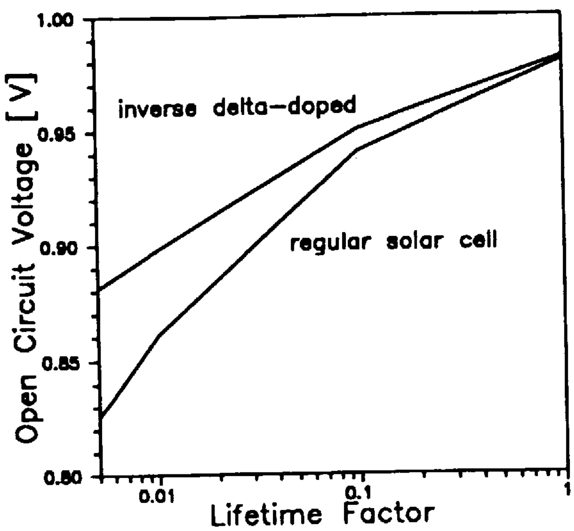

Figure 3: Improvement of the open circuit voltage by inverse delta-doping as function of a reduction of the SRH carrier lifetimes given in Tab. 1.

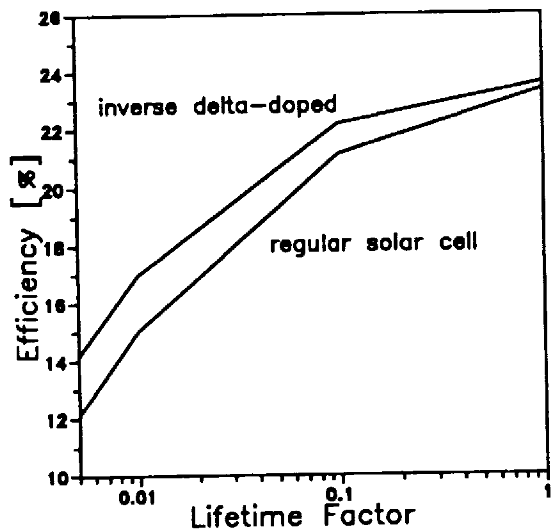

Figure 4: Improvement of the solar cell efficiency by inverse delta-doping as function of a reduction of the SRH carrier lifetimes given in Tab. 1.

Parameter	j_{sc}	V_{oc}	FF	η
Unit	mA/cm^2	mV	%	%
standard cell	38.0	982	86.7	23.6
(a) no reflection	41.3	984	86.6	25.7
(b) $S_B=10^4$cm/s	38.9	987	86.8	24.3
(a) and (b)	42.3	990	86.7	26.4

Table 2: Calculated performance of the inverse delta-doped solar cell including parameter improvements.

10^{15}cm^{-3} doping density, SRH lifetimes of 80 ns for electrons and 20 μs for holes are deduced from [5].

The resulting changes of V_{oc} and η are given in Figs. 3 and 4 as function of the SRH lifetime - actual p^+n-InP cells have lower lifetimes than assumed in Tab. 1 and exhibit efficiencies below 16% [13]. Inverse delta-doping is shown to be most beneficial in InP cells with such poor performance, improving the efficiency by up to 2 percentage points and the open circuit voltage by up to 50 mV. In the same example, the fill factor FF is increased from 75% to 84% with low lifetimes.

Tab. 2 shows the results with inverse delta-doping of the high-efficiency cell (Tab. 1) and also with further device improvements added. The highest calculated efficiency of 26.4% lies above the limit that assumes regular pn-junction recombination.

Both n^+p- and p^+n-cells have the potential to show similar high efficiencies with differently optimized parameters [14]. For comparison, we use the same cell parameter as in Tab. 1 with exchanged type of doping to simulate an n^+p-InP cell. Compared to Tab. 1, only the bulk minority lifetime is now 50 ns in the n-emitter (radiation limit) and 2 ns in the p-base. Under 137.2 mW/cm^2 AM0 illumination at 25°C, the calculated performance data of this n^+p-cell are j_{sc} = 36.7 mA/cm^2, V_{oc} = 903 mV, FF = 85.4%, and η = 20.6%. This is not an optimized cell and the efficiency is close to the maximum value measured (19.1% [3]). With 50 nm inverse delta-doping the efficiency improves by only 0.04%, with an 100 nm thick layer by 0.14% and with 150 nm by 0.22% since the lowest minority carrier lifetime now occurs in the bulk of the p-doped base. In n^+p-cells, the recombination at the pn-junction is smaller than in p^+n-cells since the inversion of minority and majority carriers now leads to a very high lifetime τ_p^{SRH} in the base region next to the metallurgical pn-junction (compare Fig. 1). Thus, inverse delta-doping is less beneficial in n^+p-cells than in p^+n-cells.

SUMMARY

In p^+n-InP homojunction solar cells, the lowest carrier lifetime and the highest internal recombination losses occur in a small base region next to the metallurgical pn-junction. Inverse delta-doping at this position clearly improves the solar cell performance. This improvement is largest in InP cells with small lifetime in the bulk material. In n^+p-InP cells, inverse delta-doping is less beneficial since the high hole SRH lifetime is now dominant at the pn-junction.

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