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The collection probability and spectral response in isotype heterolayers of tandem solar cells

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Abstract

An analytical model for the position-dependent collection probability in uniformly doped one-dimensional layers with abrupt compositional and bandgap changes is presented. The collection probability is derived from coupled system of diffusion equations for low-level injection of photo-generated minority carriers in a stack of isotype heterolayers. Collection probability maintained continuity across isotype heterojunctions despite discontinuities of excess minority carrier concentration. An estimate for window and BSF passivation showed that the effective surface recombination velocity exponentially depended on the energygap difference, and linearly depended on increased doping, reduced mobility and increased thickness of sub-diffusion length passivation layers. Analytical expressions for the photo-generated current, and the internal quantum efficiency from each heterolayer were developed, and applied to the analysis of reported spectral response of a dual junction GaInP/GaAs tandem solar cell. Calculated internal quantum efficiencies closely matched reported experimental results, with the exception of sub-band absorption due to sub-bandgap deficiencies in the optical models and photon recycling. Calculated spectral response showed that upper $AlInP_2$ window, quasi-neutral emitter, and SCR layers dominated collection of photo-generated carriers in the top $GaInP_2$ cell, whereas, the base dominated collection of photo-generated carriers in the bottom GaAs cell. Results show that augmenting Hovel's three layers (emitter, SCR, and base) analysis with the response from the top window layer should be sufficient to capture the spectral response of solar cells with thin passivation layers.

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1. Introduction

The concept of collection probability (f_c) is of great importance in the understanding and analysis of solar cells [1,2]. Green defines the collection probability f_c as "the position-dependent probability a minority generated carrier has of contributing to the photo-generation current of a solar cell" [1]. Both spectral response and photo-generation current are determined by integrating the product of the last collection probability times the position dependent photo-generation rate for a given wavelength and a radiation spectrum respectively. High efficiencies greater than 30% have been obtained for III–V tandem solar cells [3] based on GaInP/GaAs system [4], with current record efficiency of 39% at 236 suns from triple junction GaInP/GaAs/Ge solar cells reported by the Spectrolab/NREL group [5]. The last efficiency records make tandem III–V cells the solar cell of choice in current space applications, and concentrator terrestrial solar cell technologies [6]. These tandem solar cells are made of many MOCVD grown "uniformly" doped heterolayers, such as the window, emitter, base, and back-surface field regions (BSF) in each subcell. More heterolayers are utilized for tunnel

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Nomenclature

f_c, $f_{c,i}$	the position-dependent collection probability
J, J_i	current density of minority carriers
D, D_i	diffusion constant of minority carriers
τ, τ_i	recombination time constant of minority carriers
L_D, $L_{D,i}$	diffusion length of minority carriers
$\Delta(x, L_D, D, W, S)$	collection probability function (6b)
δn, δp	excess minority electrons, and holes
$g(x)$	generation rate profile
W, W_i	width of the isotype heterolayer
$u(r)$	del Alamo and Swanson's normalized excess minority carriers variable [18]
S_i^{eff}	effective back surface recombination velocity for layer i (7a)
$S_{i\|(i\pm1)}^{\mathrm{elect}}$	electric surface recombination velocity for layer-i induced by the next layer-$(i \pm 1)$
$S_{i\|(i\pm1)}^{j}$	collective interface and SCR recombination velocity at the $i-(i \pm 1)$ heterojunction
$n_{i,j}$	intrinsic carrier concentration in the jth layer
$N_{A,i}$, $N_{D,i}$	density of ionized acceptors, and donors in the ith layer
$m_{e,i}$, $m_{h,i}$	density of states effective mass for both electrons and holes in the ith layer
$\Delta E_{g,2-1}$	energy gap difference between materials 2 and 1
α, n	absorption, and optical constants
ε_2	imaginary part of the dielectric constant
ϕ_i^+, ϕ_i^-	absorption intensity coefficient for incident and reflected waves in the ith layer
$F_{\mathrm{AM1.5G}}$, $F_{\mathrm{AM1.5D}}$	AM1.5G global, and AM1.5D-low-AOD solar radiation spectrum
$\langle g_i \rangle_{\mathrm{AM1.5G}}$, $\langle g_i \rangle_{\mathrm{AM1.5D}}$	position-dependent AM1.5G and AM1.5D-lowAOD generation profile
J_j^{ph}	photo-current in the jth tandem cell
IQE_j, IQE_i	internal quantum efficiency of the jth cell, and the ith layer
i	is the index of the p_i-layer or n_i-layer if indicated

junctions acting as "ohmic contacts" between tandem cells [3]. Typical designs for these solar cells involve at least two isotype heterolayers with the BSF and window regions passivating the base and emitter of each subcell. In the present paper, an analytical model for the position-dependent collection probability is derived for many isotype heterolayers, and subsequently applied to calculate both the photo-current and spectral response (internal quantum efficiency) of tandem solar cells. Relevance of analytical models stems from three important purposes: (1) analysis of device performance with a reduced set of material parameters, (2) characterization of the last material parameters, and (3) expression of an equivalent circuit.

Carrier generation/recombination and injection in multilayer solar cells affects both the photo-generated current J_{ph}, and the dark current J_{dark}, both of which are fundamental in solar cell efficiency. Most theoretical analysis focused on calculating the latter, J_{dark}, in many isotype homolayer [7–9], and heterolayer [10] regions. Theoretical analysis of J_{dark} through minority carrier injection across isotype high–low neutral regions have long been performed and utilized in the design and optimization of solar cells [7–9]. DeMoulin et al. [10] extended minority carrier injection analysis to dual isotype heterolayers in BSF layer passivation of solar cells. The latter paper showed that wide gap heterojunctions produced smaller effective recombination velocity S_{eff}; thus, better passivation performance, than isotype high–low homojunctions, as experimentally verified by [11]. Typically, the last S_{eff} is combined with Hovel's analysis [12] for the calculation of photo-generated current J_{ph} in the SCR and its adjacent layers of the emitter or base. At higher photon energies or larger thicknesses, collection from secondary passivating heterolayers is significant, especially in frontal window layers. Although some attention had been given to isotype homolayers [13]; none has been implemented to the calculation of the photo-current from many isotype heterolayers, which is addressed in this paper.

Generalized reciprocity theorem for charge collection in semiconductors showed that the collection probability is proportional to excess dark minority carriers at low injection [14–17]. Utilizing del Alamo and Swanson's normalized excess minority carriers $u(r)$ variable [18]; Green generalized the reciprocity theorem to three-dimensional geometries with variable bandgap including abrupt compositional changes [17]. The reciprocity theorem has not been applied in calculating collection probabilities of isotype heterolayers; but has been applied to isotype homolayers as a numerical solution for injection into a non-uniformly doped semiconductor [13]. Extension of the last analysis to heterojunctions is complicated by discontinuity of excess minority carriers across the SCR of isotype heterojunctions [10], which results from: (1) continuity of the quasi-Fermi levels, (2) difference in doping and intrinsic carrier concentration n_i, and (3) interface and space charge recombination.

In the present paper, a general analytical model is developed for the position-dependent collection probability in uniformly doped one-dimensional layers, with abrupt compositional and bandgap changes, through to the effective back surface recombination velocity at each interface. This model is applied to cascades of many isotype heterolayers in both bases and emitters of a GaInP/GaAs tandem solar cell developed by NREL [19]. The generation profile, collection probability, and spectral response for the photo-generated current are calculated for both top GaInP and bottom GaAs tandem cells, and compared with reported experimental values.