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Improved modeling of photoluminescent and electroluminescent coupling in multijunction solar cells

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ABSTRACT

The performance of tandem stacks of Group III–V multijunction solar cells continues to improve rapidly, both through improved performance of the individual cells in the stack and through increase in the number of stacked cells. As the radiative efficiency of these individual cells increases, radiative coupling between the stacked cells becomes an increasingly important factor not only in cell design, but also in accurate efficiency measurement and in determining performance of cells and systems under varying spectral conditions in the field. Past modeling has concentrated on electroluminescent coupling between the cells, although photoluminescent coupling is shown to be important for cells operating near their maximum power point voltage or below or when junction defect recombination is significant. Extension of earlier models is proposed to allow this non-negligible component of luminescent coupling to be included. The refined model is validated by measurement of the closely related external emission from both single and double junction cells.

1. Introduction

Limiting solar cell performance is obtained when cells operate at the radiative limit, with all recombination in the cell occuring radiatively. This situation was first analyzed by Shockley and Queisser [1] for individual cells, with the analysis subsequently extended to multiple junction cell stacks by several authors [2–5]. Marti et al. [5] in particular studied the consequences of radiative coupling between the cells in this limit. Brown and Green [6] showed how radiative coupling could improve the balance between cell currents in blue rich spectra. The performance of experimental cells has since improved sufficiently that radiative coupling now needs to be taken into account in cell design [7], measurement [8] and in predicting cell and system performance under varying spectral conditions [6].

Published analyses to date include electroluminescent (EL) coupling between the cells but neglect the photoluminescent (PL) coupling due to carrier generation from light absorption within each cell. While both refer to reabsorption of higher bandgap cells' rear emission by lower bandgap cells, the former is a component due to EL emission and the latter is a component due to PL emission at short circuit. The neglect of this PL coupling component is appropriate for limiting efficiency calculation due to the often-implicit assumption of infinite carrier mobilities [2–6]. However, for practical cells, PL coupling can be an important coupling component near the maximum power point voltage where cells would ideally operate or when junction depletion region recombination is the dominant component of total device recombination.

Low injection is assumed throughout the bulk regions of individual cells. The current–voltage characteristics of each junction i in a series-connected multijunction solar cell can be formulated generally as the difference between a recombination component J_i^{rec} and a light generated component J_i^L

$$J(V) = J_i^{rec}(V) - J_i^L \tag{1}$$

where J is negative in the power producing quadrant. The light generated component J_i^L is limited by the ideal current $J_i^{L\,max}$ that would correspond to all carriers photogenerated in the cell of interest being collected and therefore contributing to current output. The actual current collected will be a fraction of this ideal current with this fraction approaching unity for good quality cells. Following the approach described elsewhere [9], J_i^{rec} can be expressed generally as the sum of two components:

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$$J_i^{rec}(V_i) = J_i^{01}\left(e^{qV_i/kT} - 1\right) + J_i^{0m}\left(e^{qV_i/mkT} - 1\right) \tag{2}$$

where J_i^{01} and J_i^{0m} are the reverse saturation components of the two current components and V_i is the voltage across the cell corrected for series resistance effects. The first term describes recombination in the bulk regions of the device under low injection conditions [10,11], including band-to-band radiative processes, non-radiative recombination through defect levels and Auger recombination [12]. The second term with $m > 1$ describes recombination via defects in junction depletion regions [13] and other regions where electron and hole concentrations are comparable [the second term can also include recombination through defect levels in bulk regions under high level injection; under these conditions, a third term of the same form as the second but with $m = 2/3$ could be added to describe Auger recombination [12,14] although accommodated by the first term where $m = 1$ under low level injection conditions; radiative recombination remains described by $m = 1$ term under both low and high level injection conditions [12,14]].

These equations apply for each cell in the stack but with different values of the parameters for each cell. The EL current in cell j due to the EL flux emitted by a higher bandgap overlying cell i can be expressed as follows [9]:

$$J_{ij}^{EL} = \eta_{ij} J_i^{01}\left(e^{qV_i/kT} - 1\right) \tag{3}$$

where η_{ij} is a coupling efficiency, restricted to a value less than unity since not all recombination in cell i is radiative, some light is emitted in directions where it will not reach the underlying cell, some will be reabsorbed in the emitting cell. As elsewhere [9], this leads to the following expression relating J_i^{rec} and J_{ij}^{EL} if the minus 1 term is neglected

$$J_i^{rec} = \frac{J_{ij}^{EL}}{\eta_{ij}} + J_i^{0m}\left(\frac{J_{ij}^{EL}}{\eta_{ij} J_i^{01}}\right)^{1/m} \tag{4}$$

This allows the EL component to be determined. For the particular but common case where $m = 2$, the following simple analytical solution can be found:

$$J_{ij}^{EL} = \eta_{ij}\left[\sqrt{\varphi_i^2 + J_i^{rec}} - \varphi_i\right]^2 \tag{5}$$

where $\varphi_i = \frac{J_i^{02}}{2\sqrt{J_i^{01}}}$ is a previously [9] defined parameter associated with the light-emitting upper cell i.

Here the formulation differs from that given earlier [9]. Since this EL component is zero when the voltage across cell i is zero, it follows that this model predicts no luminescent coupling from cell i to cell j when cell i is short-circuited. In actual cells, photoluminescence does occur at short circuit [15], being zero only in the ideal case of infinite carrier mobility as noted elsewhere [16]. In cells under illumination, carriers build up across the base region on short circuit, with these giving rise to what is referred to in this work as a PL contribution. Given the linearity of the equations governing the carrier build-up, this contribution would be expected to be proportional to the short-circuit current J_i^L but would be bounded by the amount of recombination occurring on short-circuit, which can be expressed as $(J_i^{Lmax} - J_i^L)$. Here, $J_i^{L\,max}$ is the maximum possible value for J_i^L when all photogenerated carriers in cell i contribute to its light generated current. Hence, the total luminescent coupling current in cell j becomes:

$$J_{ij}^{LC} = J_{ij}^{EL} + J_{ij}^{PL} = \eta_{ij}\left[\sqrt{\varphi_i^2 + J_i^{rec}} - \varphi_i\right]^2 + \kappa_{ij} J_i^L \tag{6}$$

where $\kappa_{ij} \approx \eta_{ij}(J_i^{L\,max}/J_i^L - 1) \ll \eta_{ij} < 1$. Note that this approximation would slightly underestimate κ_{ij} for a usual cell i but moderately overestimate κ_{ij} for a rear-junction cell i. The additional term will be large compared to the first when $J_i^{rec} \ll \kappa_{ij} J_i^L/\eta_{ij}$, as is the case for voltage in cell i below the maximum power point voltage, or when $J_i^{rec} \ll \varphi_i^2$, as is the case when junction defect recombination dominates in this cell, as likely at low illumination levels. The light-generated current term, J_i^L, on the far right of Eq. (6) is given by:

$$J_i^L = J_i^{LExt} + \sum_{h=1}^{i-1} J_{hi}^{LC} \cong J_i^{LExt} + J_{(i-1)i}^{LC} \tag{7}$$

where J_i^{LExt} is the current generated by the externally incident light source. The approximation follows if each cell is opaque to its overlying cell's band edge luminescence.

With this modification to the definition of the luminescent coupling current, the analysis can proceed by expressing the total recombination current in cell i in terms of light generated currents as in earlier [9] work. One further refinement that could be worth considering if sufficient information is available is that, as apparent from the approximate expression above, κ_{ij} can depend upon the spectral composition of J_i^L. Noting that J_i^L can be expressed as the sum of an external J_i^{LExt} and internal luminescent coupling component $\sum_{h=1}^{i-1} J_{hi}^{LC}$ with the latter generated by photons of energy at the upper end of the energy range incident on cell i and hence absorbed closer to its junction, $\kappa_{ij} J_i^L$ in Eq. (6) could be replaced by the more complex expression:

$$\kappa_{ij} J_i^L = \kappa_{ij}^{Ext} J_i^{LExt} + \kappa_{ij}^{LC} \sum_{h=1}^{i-1} J_{hi}^{LC} \tag{8}$$

where κ_{ij}^{Ext} would be larger than κ_{ij}^{LC}, for the normal cell structures. The term in κ_{ij}^{LC} disappears if i is the uppermost cell.

For a tandem stack of arbitrary number of cells in the order of descending bandgaps, only cells above the limiting junction have an impact on the overall current output. This simple principle suggests a sequential algorithm for extracting κ_{ij} and other fitting parameters of each cell i. In brief, second-junction limited cases should be analyzed first to extract the luminescent coupling parameters of the top cell; then, third-junction limited cases can be investigated with the parameters of the top cell inserted to facilitate the extraction of the corresponding parameters of the second cell on top, and so on. The consequences of neglecting the PL coupling can be severe in some cases, particularly the extreme cases that are conducive to extracting the coupling parameters.

From Eq. (6), the PL coupling current J_{ij}^{PL} becomes significant when either $\kappa_{ij} J_i^L/\eta_{ij}$ or φ_i^2 is comparable with or greater than J_i^{rec}, where $\kappa_{ij} J_i^L/\eta_{ij} \approx (J_i^{L\,max} - J_i^L)$. Taking the positive correlation between J_i^{rec} and J_i^L into account, the former condition can be regarded as a restriction on the position of the operating point (lower than maximum power point voltage), with no restriction on the absolute magnitude of the voltage, it can refer to a wide range of illumination intensities. The later condition, however, requires $J_i^{rec} \ll \varphi_i^2$ with φ_i being a constant, which more often refers to low illumination levels where J_i^{rec} is always small.

Measuring a closely related emission component, the light emitted from the top surface of the cell stack, validates the presence of the additional PL term and its dependencies. In general, we can express the top surface emission current for each cell J_i^{em} in terms of the luminescence coupling components by introducing empirical coupling constants β that connects the external emission arising from cell i to the luminescent currents induced in the immediately underlying cell j[17]: