Transfer Of Power By Photons In HCPV Triple-Junction Cells

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Abstract: We report the results on measurements of electroluminescence and photocurrent, arising due to photoexitation of the top sub-cell of an InGaP/GaAs/Ge solar cells by focused light from the green laser (λ=532 nm). The excitation intensity was chosen in such a way, that it would produce the photocurrent equal to that flowing through the top p-n junction under conditions of 500x-concentrated sunlight illumination and connection to the optimum external load (5÷10% of short-circuit current value). There existed two luminescent signal: first one due to photoluminescence (PL) at recombination of photogenerated charge carriers not collected by the p-n junction; second one due to electroluminescence (EL) at recombination of carriers, collected by the p-n junction, and injected backward under open-circuit conditions. They could be measured separately owing to difference in the spatial distribution along the cell surface. Photocurrent, induced in the middle GaAs sub-cell by the top sub-cell EL was measured by comparison of their IR signal with a similar signal arising at passing the forward current through a triple-junction cell. The photocurrent, induced by transfer of EL from the GaAs sub-cell to the bottom Ge sub-cell was measured as the short-circuit current of a triple-junction cell. It was found that, in operational conditions of the HCPV InGaP/GaAs/Ge solar cells, transfer of the excitation power from top to middle and from middle to bottom sub-cells takes place at a level of about 5%. This process results in corresponding increase in excitation intensity of two latter sub-cells in comparison with the conditions expected from sun spectrum intervals, suitable for the materials of these sub-cells.

Keywords: Triple-junction solar cells; Photoexitation; Photoluminescence; Electroluminescence.
PACS: 88.40.jp; 78.20.-e ; 78.60.Fi ; 78.55.Cr

INTRODUCTION

In solar cells based on semiconductor materials with “direct” band structure, luminescent light of secondary nature may play a noticeable and even significant role. For instance, in one of the first works of the Ioffe’s team on high concentration AlGaAs/GaAs solar cells [1], sunlight was absorbed in a layer of a luminescent $Al_{0.1}Ga_{0.9}As$ solid alloy, and, in turn, luminescence from this layer generated the photocurrent in a GaAs-based p-n junction. For the first time, in that publication, a spatial electroluminescent picture of a cell under forward-biased conditions was employed for characterization of the ohmic losses in a cell contact grid. Somewhat later, the “luminescent” approach to cell characterization had been elaborated, assuming a generic similarity of the photo-voltaic and electro-luminescent processes in such a type of cells [2,3]. In particular, it was possible to estimate, or even to evaluate, the main PV parameters of a direct bandgap PV cell with a p-n junction by the contactless methods (collection efficiency, open circuit voltage, sheet resistance and others), by analyzing only PL- and EL- signals from a cell wafer under photoexitation.

Triple-junction InGaP/GaAs/Ge cells are characterized by intensive EL arising in both top and middle sub-cells under forward-bias conditions. The same conditions are realized in these cells under solar illumination, in particular, in the regime of the maximum output power. Therefore, it is expected that EL arising due to solar excitation should affect the output parameters of the cells. This work is devoted to evaluation of the process of the power transfer from wider- to lower-gap sub-cells, which is caused by luminescence of the sub-cells’ materials under shorter-in-wavelength photoexitation.

THE SAMPLES AND EXPERIMENTAL METHODOLOGY

In Fig. 1, the cross-section of a triple-junction cell is shown, and the conditions of the photoexitation and measurements are presented.

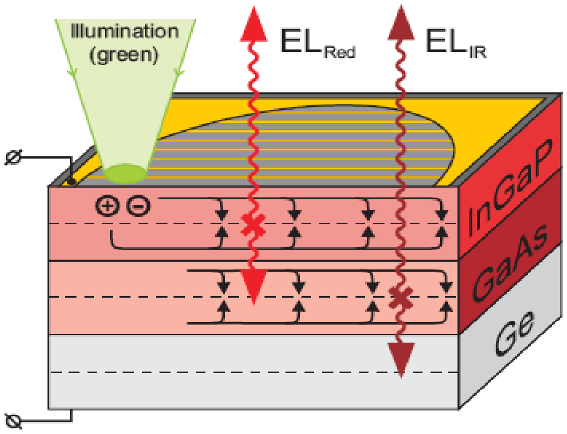

FIGURE 1. Cross-section of a triple-junction cell and the conditions of the photoexitation and electroluminescent signals' measurements.

Commercially available InGaP/GaAs/Ge cells with designated illumination area of 1.7 mm in diameter and dense contact grid were employed for luminescent experiments. The top InGaP-based sub-cell was subjected to local photoexitation by the green laser (λ=532 nm). Laser photons are completely absorbed in the top sub-cell material generating electron-hole pairs. A part of these pairs is not collected by p-n junction due to recombination losses, but may produce photoluminescence (PL) after radiative recombination. A source of PL photons is located just within the laser spot. The main part of the photogenerated carriers are collected by the p-n junction. In open circuit conditions, electrons and holes flow along the n- and p-regions of the InGaP sub-cell and recombine producing red electroluminescence (EL), in the same way, as it is in a conventional LED under forward-bias conditions.

the isotropic nature of the spontaneous radiation and a high value of the refraction index in cell materials result in a situation, when a huge part of the internally generated luminescent light can not go out from the device. It means that many of the EL photons generated in the top sub-cell are absorbed in the GaAs-based sub-cell, or in the areas covered by the contact grid and the bus bar. Infrared EL radiation arises due to current generation and its flow through the GaAs-based p-n junction under open circuit conditions in the middle sub-cell. A significant part of this radiation can produce photocurrent in the Ge-based sub-cell.

It is obvious that the short circuit current in a triple-junction cell will exist under described above green illumination. It should be strongly limited by the current arising in the Ge-based sub-cell after two acts of "EL conversion": from "green" to "red", and from "red" to "IR". the efficiency of this conversion corresponds to efficiency of power transfer by photons from wider- to narrower-bandgap sub-cells. On the other hand, the current leakages in the GaAs- and Ge-based p-n junctions may affect the flow of the initial current directly generated in the top cell. That is why the methods of independent measurements of the photocurrents in individual sub-cells have been elaborated.

Photocurrent generated in the top sub-cell was measured by three methods. The first method was simply to measure the short circuit current in a single-junction AlGaAs/GaAs cell of the identical geometry, characterized by similar external collection efficiency of carriers at λ=532 nm, under the same conditions of illumination. The second method was a "standard" one consisted in illumination by modulated green light together with excess DC light bias of the middle and bottom sub-cells. A result of measurement was the modulated current in the external circuit. The third method consisted in comparison of the "red" EL signals from the tested cell under green illumination and that at flowing of the forward current from the external source through the cell. The current through the cell, at which these "red" signals were equal, was taken as a photocurrent, generated in the top sub-cell under green photoexitation. A special spectral and spatial filtering of the rays from the cell was employed for separation of the "red" signal in this "luminescent" method of photocurrent measurement.

Photocurrent generated in the middle sub-cell was measured by the method with modulated green light and excess DC light bias of the Ge sub-cell. Another method was "luminescent" one similar to described above.

The photocurrent arising in Ge-based sub-cell was measured simply as a short circuit current of the cell.

CHOICE OF THE EXITATION LEVEL

Intensity of the green excitation was chosen in the interval corresponding to the densities the photocurrent from 0.05 to 0.5 A/cm^2 generated in the top sub-cell. This choice was associated with real operational conditions of the triple-junction solar cells under high concentration. Indeed, at the photocurrent density of 5÷10 A/cm^2, 5÷10% of the current in the maximum power point of the I-V curve (depending on the quality of a p-n junction and internal ohmic losses) are injected through the p-n junction producing luminescence. Just this amount of luminescent photons can affect the PV parameters of a cell.

All the measurements were carried out in pulse (modulated) regime of the laser to prevent local overheating of the cells. The input variable parameter in the measurements was the averaged density of the photocurrent generated by green light in the top sub-cell, values of which were calibrated with the help of a reference AlGaAs/GaAs cell. Due to the difficulties at measurements of the EL signals at lower excitation levels and possible presence of current leakages in the sub-cells, five cells were selected and involved in the identical experiments for better trustworthiness of the results.

RESULTS AND DISCUSSION

In Fig. 2, plots of the short circuit current density in a set of the triple-junction cells under varied in intensity green photoexitation are presented. For the horizontal axis, the photoexitation level is transformed into the density the photocurrent generated in the top sub-cell. The same transformation has been applied for all plots below. The values on the vertical axis of Fig. 2 should correspond to the photocurrent arising in the Ge-based sub-cell after two-step conversion of light in the cell heterostructure.

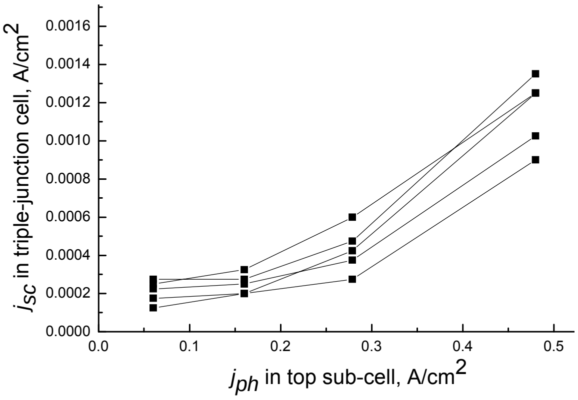

FIGURE 2. Short circuit current density of the triple-junction cell at green photoexitation transformed into the density of the photocurrent generated in the top sub-cell.

Confirmation of this fact is found by the "luminescent" measurements. In Fig. 3, EL signals in arbitrary units are presented measured in the cells at the same as in Fig.2 photoexitation intensities. Fig. 4 shows photocurrent density values in the top sub-cell measured by a "standard" method with the DC light bias of the middle and bottom sub-cells (dashed lines), and that obtained by comparison of the EL signals (see the previous Section). One can see a reasonable agreement between three methods of current measurements. In the case of the "luminescent" approach, a tendency to disagreement is revealed at higher photocurrent densities, which may be explained by a more sensitive voltage drop at distribution of the photocurrent along the p-layer of the top sub-cell. Fig. 5 presents the same results regarding to the middle sub-cell in the triple-junction structure. Again, there exists a good agreement between "direct" and EL measurements, and without tendency to saturation owing to lower currents.

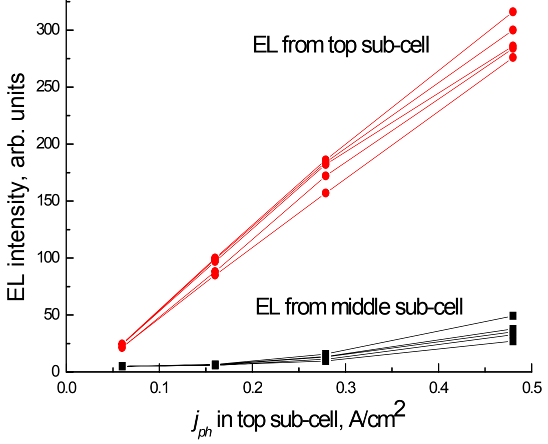

FIGURE 3. EL signals in arbitrary units measured in the cells at the same as in Fig.2 photoexitation intensities.

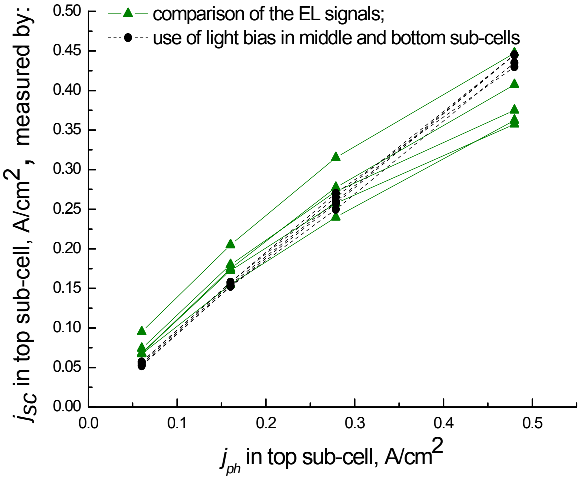

FIGURE 4. Photocurrent density in the top sub-cell measured by a method with the DC light bias (dashed lines) in comparison with that from EL measurements.

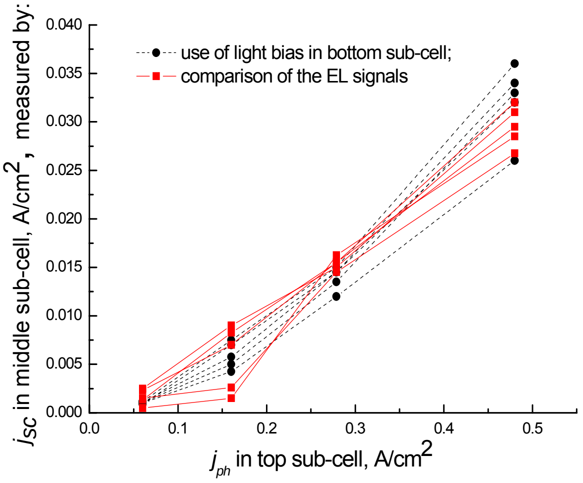

FIGURE 5. Photocurrent density in the middle sub-cell measured by a method with the DC light bias (dashed lines) and that from "luminescent" measurements.

In Figures 6 and 7, the top-to-middle and middle-to-bottom current transfer ratios due to EL in top and middle sub-cells are presented. If the photocurrent density in the top sub-cell is 0.5 A/cm2 and corresponding ratios are 0.065 (Fig. 6) and 0.03 (Fig. 7), it ensures current transfer from the top to bottom sub-cells on the level of 0.001 A/cm2, which is in a good agreement with result of Fig. 2.

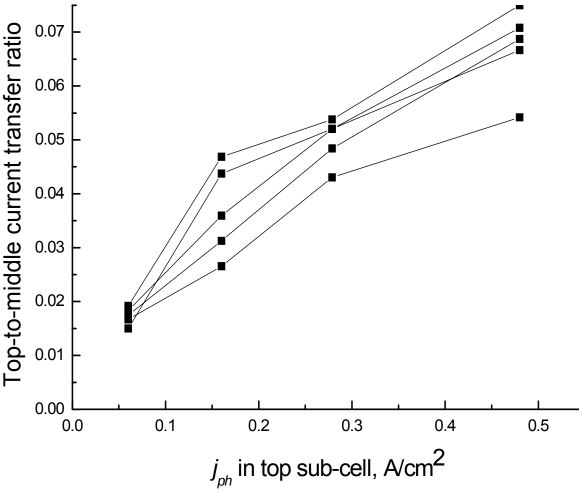

FIGURE 6. Top-to-middle current transfer ratio due to electroluminescence in the top sub-cell.

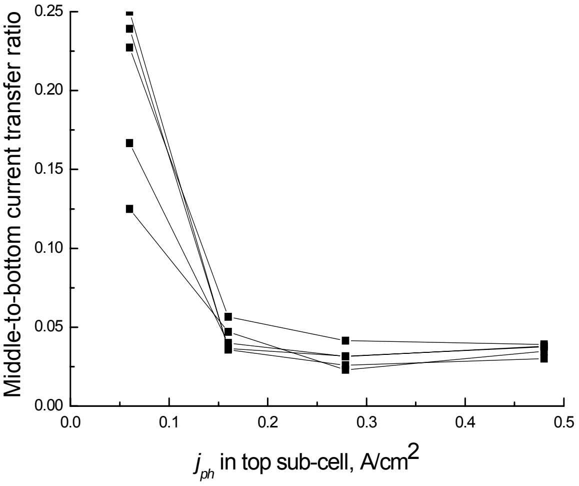

FIGURE 7. Middle-to-bottom current transfer ratio due to electroluminescence in the middle sub-cell. Apparently, the values in the left parts of the curves are not reliable due to low accuracy of luminescence measurements at low light intensities.

Therefore, the power transfer (photocurrent transfer) by photons in triple-junction cells is low enough –on the level of 3-6% in the conditions corresponding to the maximum power point of the I-V curve. Of course, above percentage is related only to the current flowing through the p-n junction, but not to the whole current produced by solar photoexitation. One may be disappointed by this result. Indeed, in similar InGaP material lattice-matched with GaAs and grown by liquid phase epitaxy, the internal quantum efficiency of radiative recombination was measured as about 60% at even lower illumination levels [4] and with increase at more strong illumination. In GaAs itself, the values of more than 90% were measured [5]. On the other hand, presence of the p-n junction reduced significantly luminescent intensity at low current densities due to non-radiative recombination of carriers in the space charge region [5]. Obviously, Fig.3 demonstrates an increase in power transfer at higher photocurrent densities owing to preferential contribution of the diffusion mechanism of the current flow.

In spite of an insignificant role of luminescence in solar energy conversion process, luminescent methods of contactless characterization of the multijunction cells at photoexitation could be successfully applied. High intensity of EL from an individual sub-cell is a cumulative factor indicating both high value of the external quantum efficiency at the photocurrent generation and high value of the voltage applied to the p-n junction in open circuit conditions. Our further work will be aimed in corresponding study.

ACKNOWLEDGMENTS

This work has been supported by the Russian Foundation for the Basic Research (Grants 09-08-00412-a and 09-08-12202).

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