Direct GaInP-to-Ge optical interaction in the triple-junction solar cells with thinned intermediate GaAs subcell

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Abstract. In the present work processes of direct light coupling in the triple-junction solar cells between top GaInP (wide band gap) and bottom Ge (narrow band gap) subcells are considered, when parameters of intermediate optical medium (comprised of middle GaAs p-n junction layers) are changed. Conditions of luminescent coupling gain and blocking are studied in multijunction structures with selectively tuned built-in photonic structures such as Bragg reflectors. An ability to manage the efficiency of optical interaction between subcells is investigated.

1. Introduction

Effect of luminescent (optical, light) coupling appears inside multijunction GaInP-GaAs-Ge solar cells when narrow band gap subcell absorbs a part of recombination irradiance that comes from adjacent p-n junction with wider band gap. Such a coupling can influence on solar cell photovoltaic characteristics (such as spectral dependencies of external quantum efficiency), and, in some extent, on accuracy of their determination [1–3]. Efficiency of optical coupling, or in other words, the measure of impact of luminescent light of one subcell on the photocurrent of generated by another one, is usually characterized by the dimensionless quantity \( \gamma \) via equation [4]:

\[
\gamma = \frac{J_N}{J_W} - 1,
\]

where \( J_W, J_N \) – photocurrents in wide and narrow band gap subcells, respectively.

In practice the description of optical coupling phenomenon in triple-junction GaInP-GaAs-Ge solar cells are constrained only to adjacent pairs of subcells (GaInP→GaAs and GaAs→Ge) and interaction between top→bottom p-n junctions is neglected: assumed that recombination photons are completely absorbed in optically thick GaAs subcell layers [4, 5]. The present research shows that such a simplification inapplicable for multijunction structures with built-in Bragg reflectors. In that type of solar cells GaAs layers are considerable thinner rather than in the same structures without photonic structures, and could be transparent for luminescent photons forthcoming from top GaInP subcell.

2. Experimental results

In the paper, the optical coupling effect between top GaInP (wide band gap) and bottom Ge (narrow band gap) subcells is investigated as a function of characteristics of the optical medium, is the middle
GaAs subcell layers and Bragg reflector (BR). As objects of research the following triple-junction solar cells were chosen:

1) SC#1 with BR, \( d = 1.7 \, \mu m \);
2) SC#2 with BR, \( d = 2.2 \, \mu m \);
3) SC#3 without BR, \( d = 4 \, \mu m \).

Parameter \( d \) corresponds to the thickness of the middle GaAs p-n junction. All samples have a high radiative recombination yield. BR of the SC#1 and SC#2 have the same composition and number of photonic layers, which were built-in between the middle and bottom subcells. BR has photonic band gap, that coincides with the wavelength of the GaAs luminescent radiation. Thus, BR can reflect recombination photons and block optical coupling between middle and bottom junctions in the wide range of temperatures 80-300K [7]. In the solar cell without BR SC#3 the leakage of luminescent light from GaAs to Ge subcell is sufficient, whereas optical coupling in GaInP-Ge pair is extremely weak due to thick GaAs middle layers.

![Figure 1](image_url)

**Figure 1.** Temperature dependencies of induced luminescent photocurrents of the Ge subcell: SC#1 (a), SC#2 (b), SC#3 (c), under external light illumination of blue laser (450nm) with the intensity \( E \). Vertical dashed lines (red (a), blue (b), green (c)) correspond to the equal conditions of illumination, for which the comparison of photocurrents was made on (d). Grey region illustrates the photonic band gap of Bragg reflectors with optical coupling blocking conditions for the samples SC#1 and SC#2. Red and blue arrows after 300K show further direction of the dependencies.
A special feature of these studies is the use of external illumination from a single source of narrow-band radiation (blue laser 450 nm), which is in the range of the spectral sensitivity of the top wide-band gap subcell. Therefore, inside the semiconductor structure the cascade of luminescent coupling mechanism was able to initiate [8]. As a result, tree coupled pairs of subcells (GaInP→GaAs, GaAs→Ge, and GaInP→Ge) were formed.

Experimental studies at different temperature and illumination regimes for tested samples have demonstrated that in blocking mode for optical interaction between GaAs→Ge (SC#1 Fig.1a and SC#2 Fig.1b), the Ge subcell photocurrent is characterized by linear dependency from external light bias. The thinner the thickness \( d \) is, the stronger \( J_{Ge}^E(E) \) inclines from linearity. For the sample SC#3 (Fig.1c) Ge subcell photocurrent is described by sub-linear law and is mostly determined by luminescent light coming from adjacent GaAs due to the much higher efficiency of optical coupling \( \gamma \) between middle-bottom junctions, rather than in top-bottom pair.

In this case, the magnitude of the induced current \( J_{Ge}^E \), under equal conditions of the external illumination, is minimal for the sample SC#3 with coupled GaAs-Ge subcells (green line Fig. 1d). This behavior can be explained by the energy that transferred to the bottom junction by luminescent photons from GaAs (1.4 eV) and GaInP (1.8 eV). Obviously, the contribution to the photocurrent from the latter will be much higher, even with a small number of them. With an increase in the thickness of the middle subcell, the intensity of such radiation is decreased exponentially, and already at a depth of 4 \( \mu \)m it turns out to be so low that it cannot have a significant effect on the contribution to the photocurrent of the bottom subcell (Fig. 2a).

![Graph](image)

**Figure 2.** (a) – GaInP luminescent intensity decay depending on penetration depth in semi-logarithmical scale. Vertical lines correspond to the thicknesses of GaAs subcell layers: green SC#1, magenta SC#2, orange SC#3. Blue and red dependencies are determined for temperatures 80K and 300K. (b) - Temperature dependency of light coupling efficiency for multijunction solar cells with (red curve for SC#1 and blue one for SC#2) and without (green line for SC#3) built-in Bragg reflector. Grey region corresponds to photonic band gap of Bragg reflector for SC#1 and SC#2.

An increase in temperature leads to the GaInP luminescence wavelength shift to a longer wavelength region of the spectrum (from 640 to 660 nm at the heating by 220K), and to the change of the absorption coefficient of the GaAs p–n junction [9]. The absorption coefficient during heating increases by approximately an order of magnitude, which reflects in the increase of the photocurrent of the Ge subcell. However, instead of the expected growth, the drop of the \( J_{Ge}^E \) is observed for all studied samples (Fig. 1d). The heating of the structure provokes a replacement of the dominant recombination mechanism from radiative to nonradiative, which is assumed causes a decrease in the photocurrent of the narrow-gap Ge subcell.
During the investigation it was found that for solar cells with BR for each new temperature mode exists some superposition of optical interaction between three junctions (determined by material band gap, optical thickness of semiconductor layers, radiative and absorption properties) and photonic structure characteristics. Adjusting sample temperature, it is possible to set different conditions of luminescent interaction including the ones when optical coupling in GaAs-Ge pair is fully blocked. On the temperature dependency of the light coupling efficiency the blocking state is characterized by the minimum of the function (Fig. 2b).

3. Conclusion

In the present work a processes of direct light coupling between top GaInP (wide band gap) and bottom Ge (narrow band gap) subcells are considered when parameters of intermediate optical medium (comprised of middle GaAs p-n junction layers) are changed. The values of light coupling efficiency for pairs of subcells incorporated in multijunction structures of different composition and architecture are analyzed and compared. To tune the reflectivity of BR, wavelength of luminescent light and coupling efficiency level the temperature of the devise has been varied gradually.

References

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