Spectral dependencies of multijunction solar cells in a wide range of temperatures

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Abstract. In this paper, triple-junction solar cells of various middle junction thickness are studied. It is shown that in samples with thin layers, an optical coupling between the top and the bottom subcell is possible as well as a direct leakage of external radiation through the middle one. True values of the spectral dependences of the external quantum efficiency are calculated in accordance with the corrective method. The proposed method reveals some difference in the negative contribution of the luminescence and the positive signal results from the light penetration.

1. Introduction
In experimental practice, the temperature of a solar cell (SC) can act as a tool for studying various phenomena that occur inside a semiconductor structure. One such example is the individual optically coupled p-n junctions, when luminescent photons are absorbed, and additional photocurrent in narrow-band junctions is generated. The optical coupling efficiency [1], i.e. how strong the link is, depends greatly on temperature. In the work, a method of temperature control over light fluxes (both external and secondary recombination) is proposed. It allows monitoring the optical coupling efficiency and stimulating radiation recycling processes [2].

The paper presents a comparative analysis of the spectral characteristics of GaInP-GaAs-Ge triple-junction SC with various thicknesses of the GaAs junction. Various combinations of generation (GaInP and GaAs), transmission (GaAs) and absorption (Ge) of radiation in the corresponding subcells are considered. Evaluation of these effects and their dependences on temperature are carried out by the spectral dependences of the external quantum efficiency of MJ SCs with the application of the current coordinate plane [3].

2. Experimental equipment
The measuring complex being used for carrying out the research combines (Fig. 1):
1. Installation for studying the spectral characteristics of the MJ SC in the range from 300 to 1900 nm and under conditions of additional light bias.
2. Cryo chamber with multi-port optical and fiber gateways for input and output of radiation. Up to six test samples can be mounted and tested in the temperature range of 80-500K inside the chamber at once.
3. Sources of powerful laser radiation for pumping subcells with non-equilibrium charge carriers and controlling the processes of photon interaction. The radiation spectrum of the sources is chosen in such a way as to provide a light bias independently for each subcell.
4. The system of mechanical manipulators for moving optical fibers in a vacuum chamber and their positioning for supplying radiation to a solar cell or reading out luminescent and reflected light signals.
5. Spectrum analyzer for recording electroluminescence spectra of the subcells and reflection spectra in the wavelength range from 300 to 1100 nm. The formed set of equipment and the developed software allow recording current-voltage characteristics and spectral dependences of the external quantum efficiency under variable illumination conditions and a wide temperature range.

Figure 1. Experimental installation for studying the temperature dependences of the photoelectric characteristics of MJ SC.

3. Experimental results
As the structure of the solar cell becomes more complex and includes large number of photoactive p-n junctions, the resulting optical interaction between subcells, in addition to its cascade nature, also turns out to be multifactorial. In particular, this means that an external light bias (oriented to the sensitivity range of only the GaInP subcell) can provoke a sequential flow of internal recombination radiation from a wide to narrow subcell, and form several optical couplings. The thinning of the middle GaAs subcell layers and the insertion of additional resonant structures (such as Bragg reflector) into the solar cell lead to the fact that along with the sequential cascade luminescent GaInP → GaAs → Ge interaction, a direct optical coupling GaInP → Ge occurs.

As is known, such luminescent couplings inevitably arise at a strong current mismatch conditions between subcells. The formation of such conditions, in turn, is a prerequisite for the successful registration of the spectral dependences of the external quantum efficiency of the MJ SC [4]. The activation of optical couplings leads to a distortion of the resulting photosensitivity of the subcell under study: within the main spectral range an uncontrolled decrease of the photoresponse is recorded, and beyond this range an artifact signal is observed [4].

In such cases, special corrective procedures are carried out to determine the true values of the external quantum efficiency of narrow band gap subcells. In recent years, a significant number of articles have been published on the measurement of the spectral characteristics of subcells under the...
conditions of optical interaction between them. The described results are limited to the consideration of only optical communication in GaInP–Ge pair. In fact, the approaches described earlier are reduced to the elimination of any artifact sensitivity of the narrow band gap Ge subcell, assuming that external radiation at these wavelengths is fully absorbed by the upper photoactive layers. However, in an MJ SC with thin middle GaAs layers, a situation is possible when external radiation penetrates directly into the Ge subcell, which is taken as an artifact signal and is erroneously eliminated by means of correction.

The necessity of separation and identification of two spectrally close processes is obvious:

1) Penetration of external monochromatic radiation through thin GaAs layers directly into the Ge subcell and its absorption with the generation of a photocurrent (Fig. 2a).
2) Optical coupling in a pair of GaInP–Ge due to the penetration of luminescent radiation (650-670 nm) into a narrow band gap subcell with the appearance of artifact (Fig. 2b).

![Figure 2](image-url)
Adjustment of luminescent radiation wavelength can be achieved by changing the temperature of the sample. As shown earlier [5], the temperature shift of the luminescent radiation wavelength of GaAs is about 0.25 nm/K, while for Bragg reflector is only 0.07 nm/K. Thus, for SC with Bragg reflector, one can find such a temperature state, in which the reflection range of the mirror is matched with the wavelength of the luminescent radiation. Such conditions correspond to the almost complete blocking of the GaAs-Ge coupling [5]. In this case, the efficiency of the optical interaction is expected to be low. Therefore, the increase of the external quantum efficiency values in main spectral range of the Ge subcell with a simultaneous decrease of artifact photoresponse should be registered. By varying the thickness of the GaAs subcell, it is possible to control the fraction of the luminescent radiation penetrating into the Ge from the GaInP subcell (650-670 nm).

In this paper, three types of solar cells were studied. Two of them contain Bragg reflector, but have different thicknesses of GaAs subcell: 1.7 μm (SC#1) and 2.1 μm (SC#2). Sample #3 is without any built-in mirror, and the thickness of its GaAs layers is about 4 μm.

According to [5], if spectral regions of Bragg reflectance and GaAs luminescence overlap each other (SC#1 and SC#2), then blocking regime emerges in GaAs→Ge pair. Such regime exists for wide ranges of temperatures (80-273K) and wavelengths (=840-900 nm fig.2 a, b). Nevertheless, in short wavelength region (=640-820 nm) non-zero Ge photoresponse is still registered. Among possible causes of unexpected signal, the following process can be highlighted:
- Penetration of luminescent light (=680 nm) from top to bottom subcell, i.e. direct GaInP→Ge optical coupling (artifact signal);
- Penetration of external monochromatic light through the GaAs layers (valuable signal).

Clearly, that crucial role for both processes plays thickness of the middle subcell: the thinner GaAs is, the more transparent it to internal luminescent photons from GaInP as well as to monochromatic light. Penetration of luminescent light (680 nm) decrease with the temperature rise, which might be defined by increasing of “effective” absorption in GaAs layers.

In the case of thick GaAs layers (SC#3), almost all monochromatic light (680-880 nm) is absorbed in middle subcell and gives additional impact (expressed as artifact signal) into GaAs-Ge optical coupling phenomenon. Certain raise of artifact photoresponse near 820 nm (SC#1) at low temperatures may be associated with direct leakage of monochromatic light into Ge subcell.

In the case of thin GaAs subcell (SC#2), a much higher amount of external tested light (680-880 nm) can pass into bottom layers. Additional recombination flux occurs due to the escape of some luminescent photons through Bragg reflector (GaAs-Ge coupling). As the efficiency of GaAs-Ge interaction is much stronger at low temperatures [6], its impact appears to be considerable and is comparable to the corresponding influence of optical coupling in structures without Bragg mirrors (fig. 2c). At room temperatures ordinary regime of GaAs-Ge coupling is observed, and induced photoresponse is registered (SC#2 and SC#3).

Proposed in [3] method takes into account both effects of external and internal radiations on the photoresponse of narrow band gap subcells. The application of the developed approach allows determining which part of the recorded signal is artifact (and must be eliminated), and which part is direct current reaction to the monochromatic radiation. The true values of spectral characteristics of the Ge subcell at room temperature (fig. 2d) were obtained in accordance with [3]. Photocurrent density Jsc without impact of optical coupling (Fig. 2d table) were calculated for AM0 conditions. As can be seen, artifact signal was completely eliminated (500-860 nm), simultaneously with the gain of Jsc (approximately on 2 mA/cm²) in Ge subcell main sensitivity range. Nevertheless, it is hard to establish a clear boundary between the two luminescent interactions (GaInP→Ge and GaAs→Ge), expressed through the artifact sensitivity of the Ge subcell. At the same time, the obtained photosensitivity values for the Ge subcell in the range of 900–1900 nm remain slightly underestimated, causing an underestimation of its photocurrent at the level of 1-2%.

4. Conclusions
The paper demonstrates the effect of optical coupling in GaInP→GaAs and GaInP→Ge pairs on the spectral dependences of the external quantum efficiency of MJ SC. It was found that the interaction
between the top and the bottom subcells is largely determined by the thickness of the GaAs layers and of the optical tuning of the Bragg reflector.

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