Spectrum tuning in multi-junction solar cells measurements

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Abstract. This paper presents the technique of spectrum tuning in the multi-lamp solar simulator's workspace and accuracy (uncertainty) evaluation for measurement results of spectral irradiance in order to determine its suitability for GaInP/Ga(In)As/Ge multi-junction solar cells testing has been performed.

1. Introduction
At the research and development stage of multi-layer nanoheterostructures for multi-junction (MJ) GaInP/Ga(In)As/Ge solar cells (SCs), it is necessary to ensure matching the photocurrents for GaInP and Ga (In)As subcells of the entire MJ SC. For getting the optimum value of the MJ SC efficiency such matching should be at a maximum photocurrent, which could be achieved in the selected structure of GaInP/Ga(In)As/Ge MJ SC. It is known that the achievement of complete matching is extremely challenging, both in architecture (the choice of semiconductor materials of the multilayer structure) and technological (terms and conditions of the growth of the semiconductor layers in the formation of multi-junction structure) reasons. In measuring I-V characteristics of MJ SC on solar simulators (SSs), the photocurrent mismatch may arise by two reasons:
- non-optimal spectral response of the subcells, which results in the difference between values of photocurrents at a preset spectral irradiance formed by SS;
- dissimilarity of the spectral irradiance generated by SS from the standard one [1] leads to the subcells’ photocurrent mismatch even for a MJ SC with initially photocurrent matched subcells.

In the paper, a procedure for tuning the spectral irradiance in a multi-lamp SS has been proposed, and accuracy estimation for photovoltaic parameters in measuring GaInP/Ga(In)As/Ge MJ SC has been performed at the condition of “blue-red ratio” variation in a spectral irradiance of the pulsed SS.

2. Technical and metrological characteristics of the pulsed solar simulator
The SS under consideration ensures both forming of irradiance with characteristics according to class A in correspondence with [1] and dynamic correction of the spectral irradiance. The picture of the pulsed SS is in figure 1. The irradiance source of SS is constructed on the base of two closely located xenon lamps, which allows tuning the “blue-red ratio” in the spectral irradiance due to the principle of optical absorption of irradiance of one lamp in the gas discharge plasma of another one. Each lamp generates a light pulse with a flat part duration of 1 ms. During this time, both the measurement of the spectral irradiance in the place of a SC location (by means of a high-speed spectroradiometer) and the record of SC I-V characteristic (by an analog-digital converter in supplying sweep voltage to a SC) can be performed. The time-dependences of the flash illumination intensity, voltage applied to a solar cell and current flowing through the SC are presented in figure 2.
In varying supply voltage on the lamps the gradual variation of the irradiance intensity in three spectral ranges is ensured, that allow adjusting precisely the spectral irradiance with simultaneously maintaining the value of the spectral mismatch within acceptable limits in regard to class A \cite{1}.

The basic technical and metrological characteristics of the pulsed SS are presented in table 1.

**Table 1. Basic technical and metrological characteristics of the pulsed SS**

| Characteristic                                      | Value    |
|-----------------------------------------------------|----------|
| Flat part duration of irradiance pulse (at deviations not greater than \( \pm 2\% \)), ms    | 1.0 – 1.2 |
| Voltage applied to the SC from an active load, V   | +/- 12   |
| Current being registered, A                        | 0 – 10   |
| Accuracy in measuring voltage and current, %       | \( \pm 0.2 \) |
| Duration of recording the dark and light I-V characteristcs, ms | 1        |
| Duration of measuring one pair of “current-voltage” values, \( \mu s \) | 8 – 10   |
| Irradiance (spectrum AM1.5D), W/m\(^2\)            | 1000     |

3. **Procedure for spectrum tuning in measuring I-V characteristics of MJ SCs**

The theoretical basis of the proposed procedure is a well-known fact about the high sensitivity of the fill factor (FF) for I-V characteristic to photocurrent matching of the subcells: it reaches the minimum in the state of matched photocurrents \cite{2-4}. The procedure for tuning the spectral irradiance in measuring I-V characteristics of MJ SC on SS contains the following steps:

1) Measurements of the spectral irradiance should be performed in varying voltage on simulator lamps (in varying the “blue-red ratio” in the spectrum) with using a high-speed spectroradiometer.
2) Plots of dependencies of real values and confidence interval for photocurrent density of MJ SC’s subcells on the lamps voltages should be formed. The following expression should be used in calculating the current density:

\[ J_{ph} = \int_{\lambda_1}^{\lambda_2} E(\lambda) \cdot SR(\lambda) \cdot d\lambda, \]  

(1)

where \( E(\lambda) \) – spectral irradiance of the SS; \( SR(\lambda) \) – dependence of the spectral response on wavelength \( \lambda \) for subcells of MJ SC.

3) Range of voltages on the lamps confined by the projections of cross-section points of the confidence interval’s lines for photocurrent density of MJ SC’s subcells should be determined. This range determines the permissible variation of the “blue-red ratio” in the simulator’s spectrum, at which the required subcells’ photocurrent matching or mismatching is ensured.

4) Plot of the dependence of the MJ SC efficiency on voltage on the lamps should be formed, and the expanded uncertainty caused by the ambiguity in choosing voltages on the lamps (“blue-red ratio” in the simulator’s spectrum) should be estimated.

At the initial step of the procedure realization, measurements of the spectral irradiance in varying voltage on the simulator’s lamps (varying the “blue-red ratio” in the simulator’s spectrum) were carried out (figure 3) with using high-speed spectroradiometer “Flash Measurement System UV-VIS-IR”, for which the traceability of spectral irradiance measurement results to SI units was ensured. The main element of the spectroradiometer’s construction is a multi-element photodetector (CCD matrix), cells of which detect spectral lines of the incident irradiance converting them into a current signal.

![Figure 3. Spectral irradiance in the simulator’s workspace at changing voltage on the lamps (a variation of "blue-red ratio" in the simulator’s spectrum) and standard spectrum AM 1.5](image)

The spectral irradiance data produced by spectroradiometer could be determined as follows [5]:

\[ Y_{SS,i} = \frac{Y_{SS,i}}{R_i k_{L}(\lambda_i) k_{T}(\lambda_i)}, \]  

(2)

where \( Y_{SS,i} \) – signal of the \( i \)-th pixel of the CCD matrix in measuring the spectral irradiance; \( R_i \) – spectral photoresponce of the \( i \)-th pixel of the CCD matrix being determined in calibrating the spectroradiometer sensitivity to the spectral irradiance; \( k_{L}(\lambda_i) \) – correction factor allowing for the spectroradiometer signal nonlinearity; \( k_{T}(\lambda_i) \) – correction factor allowing for the effect of temperature on the spectral irradiance measurement result.
The uncertainty budget of the spectral irradiance measurement result is presented in table 2.

At the next step, spectral dependences of the external quantum yield (spectral response) of the MJ SC’s subcells were recorded on an installation elaborated in the Laboratory for Photovoltaic Converters of the Ioffe Institute [4]. The principle of these measurements bases on comparing photocurrent values of the tested and reference SCs [7].

**Table 2.** Uncertainty budget of the spectral irradiance measurement result (type A and type B evaluation methods [6])

| Value $X_i$ | Standard uncertainty $u(x_i)$ | Probability distribution | Sensitivity coefficient, $c_i$ | Contribution to the standard uncertainty $u_i(y)$, % |
|-------------|-------------------------------|-------------------------|-----------------------------|-----------------------------------------------|
| $Y_{SS,i}$  | 0.600 %                       | Gaussian                | 1.0                         | 0.11                                           |
| $R_i$       | 0.520 %                       | Gaussian                | 1.0                         | 0.27                                           |
| $k_i(\lambda_i)$ | 0.580 %                 | Rectangular             | 1.0                         | 0.012                                          |
| $k_y(\lambda_i)$ | 0.576 °C              | Rectangular             | 0.05 %/°C                   | 0.029                                          |
| $Y_{SS}(\lambda_i)$ |                       |                         |                             | 0.28                                           |

As a result of statistical analysis of measurement data, standard uncertainties (type A [6]) were obtained, which characterize similarity of results in measuring the spectral response at a definite photocurrent signal: $u_{SR} = 0.18 \%$.

On the base of experimental dependencies $SR(\lambda)$ and $E(\lambda)$, estimates of the photocurrent densities for the subcells of MJ SC were accounted in correspondence with the expression (1), and the dependencies of the subcells’ photocurrent densities on voltage of the lamps were constructed (figure 4). The spectral dependences of the external quantum yield (spectral response) of the GaInP/Ga(In)As/Ge MJ SC’s subcells are depicted in figure 5.

**Figure 4.** Dependence photocurrent density values ($J_{ph}$) on voltage on the lamps (dashed lines indicate the boundaries of the confidence intervals for photocurrent density values: $J_{GaInP}^{AM1.5}$, $J_{GaAs}^{AM1.5}$, $J_{Ge}^{AM1.5}$ are the subcells’ photocurrent density values at standard spectrum AM 1.5D)

**Figure 5.** Spectral dependence of External Quantum Efficiency for GaInP/Ga(In)As/Ge MJ SC’s subcells
Then positions of confidence interval’s boundaries for subcells’ photocurrent density were determined by the results of calculation of the combined expanded uncertainty in correspondence with the expression:

\[ U_{\text{ph}} = \pm 2 \sqrt{u_{E(\lambda)}^2 + u_{\text{SR}}^2}, \]  

(3)

where \( u_{\text{SR}} \) – standard uncertainty of the subcell’s spectral response; \( u_{E(\lambda)} \) – standard uncertainty of the spectral irradiance for the multi-lamp SS.

The estimated combined expanded uncertainty is \( U_{\text{ph}} = \pm 0.66 \% \). The calculated boundaries of the confidence intervals are shown in figure 4. Projections of the cross-section points of the confidence interval’s lines have allowed determining the range of lamps voltages (variation of the “blue-red ratio” in the spectral irradiance of SS), at which a designed or required subcells’ photocurrent mismatch was ensured with conforming accuracy.

At the final step of the procedure realization, measurements of the GaInP/Ga(In)As/Ge MJ SC output photovoltaic parameters have been carried out in varying “blue-red ratio” in the simulator’s spectrum, and dependence of the FF versus lamp’s voltage were constructed (figure 6). At every change of the “blue-red ratio” in the spectral irradiance, a control of the irradiance in the simulator’s workspace by the GaAs monitor cell was performed.

![Figure 6. Dependence of the fill factor on voltage on the simulator’s lamps](image)

4. Conclusion

Calculation results have shown that for considered type of MJ SC the equalization of photocurrents in GaInP- GaAs subcells pair is expected to be at spectral irradiance formed by dual-lamp pulsed SS at approximately 810 V on the lamps (figure 4). On the basis of experimental I-V recording the minimum value of the fill factor, indicating the photocurrent matching condition, is reached at lamp voltage of 800 V (figure 6). Since both obtained values are within the tolerance of the lamp voltage variations at accurate tuning the spectral irradiance (0 – 40) V. So proposed technique of spectral irradiance tuning allows reaching the required photocurrents mismatch for MJ SC with high precision.

The presented example shown that for MJ SC under study the photocurrent mismatch corresponding to AM1.5D standard test condition is proposed to be at (870 ± 20) V on the solar simulator’s lamps and, thus, the accurate cell efficiency could be determined through I-V recording at this simulator’s spectrum.
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