Experimental model of multi-junction solar cell: IV curve tailoring and photoresponce artifact simulation

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Abstract. This paper presents an experimental model (maquette) of a multijunction solar cell, which allows one to study the IV characteristic construction process, the influence of individual p–n junctions on the resulting IV characteristic and the causes of artifacts in measuring the spectral dependencies of external quantum efficiency.

1. Introduction
State-of-the-art high-efficient multijunction solar cells (MJ SCs) consist of some single-junction solar cells stacked upon each other, so that each layer going from the top to the bottom has a smaller band gap than the previous one, and so it absorbs and converts the photons that have energies greater than the band gap of that layer and less than the band gap of the higher layer [1]. Thus, MJ SCs based on multiple materials with different band gaps span the solar spectrum. In order to optimize conversion efficiency of a MJ SC, the photovoltaic device should absorb as much of the sunlight as possible, and so band gaps should cover a wide range. Besides, band gaps of adjacent layers should differ by the smallest possible amount, because the amount of excess energy from light converted into heat is equal to the difference between the photon energy and the band gap of the absorbing material [2]. The efficient GaInP/GaAs/Ge triple-junction solar cells being currently in production are made of GaInP (1.9 eV), GaAs (1.4 eV) and Ge (0.7 eV) (figure 1).

In recent years, several analytical methods were proposed for simulating the IV characteristics of MJ SC, whereas experimental models of MJ SCs were not elaborated and almost not mentioned in the literature [3–5]. However, the experimental simulation of the MJ SC IV characteristic is an important tool for investigating the performance of solar cells at variable irradiance, temperature and solar spectrum.

For a MJ SC with two electrical terminals, it is necessary to know the characteristics of the p-n junction of each subcell individually. Existing research methods make it possible to be performed. In particular, in recording the spectral characteristics and allocating a signal from the test subcell and excluding the influence of other subcells, one can affect selectively the individual subcells by varying the spectral composition of the incident radiation in recording the IV characteristics.
2. Experimental details
For detailed study and understanding of MJ SC IV curves formation processes and the influence of individual p-n junctions on the resulting IV characteristic and on the accuracy in obtaining the spectral dependence of photosensitivity, the specialized maquette is required to be designed and created.

In such a MJ SC maquette, each element allows simulating physically and photo-electrically the behaviour of individual subcells, tunnel diodes, variable series and shunt resistances and also diodes forming the reverse branch of IV curves.

Figure 1. Structure of a triple-junction solar cell (a) and its equivalent circuit (b).

Figure 2. Circuit of the triple-junction SC experimental model. Set of switches allows one to: 1a,b,c – change polarity of individual subcells; 2a,b,c – connect diodes for forming reverse branch of subcell IV curves; 3a,b – connect tunnel diodes; 4a,b,c – connect variable shunt resistors; 5a,b,c: pos.1 – subcells are in short circuit conditions, pos.2 – no shunt resistor in the circuit, pos.3 – shunt resistors are in the circuit; 6 – connect the maquette either to the IV characteristic recording system (OUT1) or to the IV tracer with an oscilloscope (OUT2).
The maquette consists of three identical electrical circuits, each of which is an analog of a subcell and includes a single-junction SC, a diode connected to it in parallel and a shunt variable resistance. Subcells are combined in an electrical circuit via tunnel diodes connected in series. The whole circuit is connected to an IV characteristic loading setup via a variable resistor, which plays a role of the series resistance. Depending on the task of forming the IV curves, the maquette circuit allows one to change the operation modes of subcells by the illumination level and to vary their electrical parameters (to change SC polarity, to vary the shunt resistor, to connect diodes, etc.) to the complete exclusion of any of them from the series circuit. For analyzing the shape-formation of IV curves, two output setups are provided: one is for connecting to an analog IV tracer (oscilloscope) and another one is for digital IV curve recording.

The practical maquette includes single-junction SCs of the following configurations: GaInP, GaAs with a GaInP filter, Ge with a GaAs filter with the spectral sensitivity in the wavelength ranges of 300–650, 650–900 and 900–1800 nm, respectively. Selective impact on the individual solar cells is provided by a light source based on two high-brightness 460 and 820 nm LEDs and a 1060 nm laser diode.

The elaborated maquette allows tailoring the MJ SC IV curves, investigating the effect of individual subcells on the resulting characteristic, determining the IV curve behavior dynamics in the modes of the tunnel diode peak current limitation and at increased values of the shunt series resistance. It is easy to manipulate with the reverse branch of IV curves by counter connected diodes. It is also possible to perform mismatch of the subcells’ photocurrents in a wide range of generated currents.

3. Results and discussion
For a practical solar cell, typical is the presence of a series resistance, a resistance of each p-n junction, as well as the shunt resistance that reflects possible surface and bulk current leakages. Series and shunt resistances cause losses in SCs, which lead to the fill factor and the open circuit voltage drop. As an example, figure 3 shows a simulated multi-step IV characteristics formed as composite of individual subcells curves. Changing shunt resistance of one of the subcell affects the shape of a MJ SC IV curve as a whole, and also can affect another current AC amplitude (I) measured at a certain voltage bias (Ubias).

Figure 3. IV curve of a MJ SC in conditions of current limitation by the bottom narrowband subcell photocurrent: without (a) and pronounced (b) top subcell shunt resistance: I\textsubscript{top} and I\textsubscript{bot} – photocurrents generated in top and bottom subcells at steady-state illumination, correspondingly; I – photocurrent generated in bottom subcell at chopped (AC) illumination; ΔI – difference between bottom subcell photocurrent amplitudes resulting from the impact of the shunt resistance.
In studying the photoresponse or spectral dependence of the external quantum efficiency (EQE) of individual subcells, the functional capability of the maquette allows considering individual subcells and affecting them with the aim to achieve the conditions for the mutual impact of their characteristics on the accuracy of the EQE determination and the causes of the “anomalous” photosensitivity outside the operating wavelength range typical for a tested subcell. This effect is called EQE artifact, and it appears if the subcell has a low shunt resistance or a low reverse breakdown voltage [6–8]. The main aspect of the artifact measurement is that the response of a passive subcell is simultaneously measured with the signal from the bottom subcell. The magnitude of the photoresponse artifact depends on the shunt resistance of the subcell under test and the difference between the bias currents of other subcells. The magnitude of the parasitic signal rises with lowering the shunt resistance and/or could be expressed in a small difference between the currents produced by light biasing.

4. Conclusion
The maquette presented allows investigating the influence of the shunt resistance on the tailoring of IV curves of MJ SCs and also on the procedure and measurement accuracy in terms of physics rather than mathematics, and gives an opportunity for visualizing the contribution to PV parameters being measured. The results obtained with the use of the present maquette are well agreed with theoretical and experimental data for monolithic MJ SCs. The experimental maquette is adapted to carry out scientific research in the field of photovoltaic sunlight converters and to study in door for "Optoelectronics and Nanophotonics" education topics.

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