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Current invariant as a method of searching for the optimum band gap of subcells of multijunction solar cells

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Received October 23, 2023
Revised November 28, 2023
Accepted November 28, 2023

The possibility of application of a semiempirical expression, which specifies the principal saturation currents of a $p-n$ junction, in calculation of the efficiency of multijunction solar cells is examined. This expression relies on the following current invariants obtained earlier: J_{Z1} for saturation current J_{01} (ideality factor $A = 1$) and J_{Z2} for saturation current J_{02} ($A = 2$). It is demonstrated that the use of J_{Z1} and J_{Z2} provides an opportunity to enhance the accuracy of calculations considerably relative to the standard techniques based on the Shockley–Queisser solar cell model. The introduction of saturation current J_{02} into calculations is a novel feature. It is demonstrated that the addition of J_{02} is a prerequisite to realistic estimation of the efficiency of multijunction solar cells with more than two subcells.

Keywords: solar cell, saturation current, current invariant, efficiency.

DOI: 10.61011/PJTF.2024.05.57182.19776

The study of multijunction (MJ) solar cells (SCs) is a rapidly developing trend in modern photovoltaics. Four-, five-, and (in more recent times) six-junction SCs are being developed alongside the classical three-junction SC technology [1]. A number of technological approaches to production of MJ SC structures [2] are known. Each of them limits the choice of semiconductor materials for the fabrication of subcells. Therefore, an optimum set of subcell materials needs to be determined for each approach. This requires estimating the parameters of MJ SCs as functions of combinations of band gaps of subcells.

Several studies focused on the calculation of optimum band gaps have already been published [3–9]. They rely on the so-called calculation principle of detailed balance proposed by Shockley and Queisser [10]. Owing to the use of certain idealizations in the detailed balance model, all calculation techniques based on this method yield significantly overstated values of SC efficiency. In the case of the AM1.5 solar spectrum and conversion of direct solar radiation, the magnitude of overstatement for single-junction SCs may be on the order of 4−7 absolute percent (the calculations in [3,9] yielded a value around 32.5%). This is significant compared to the efficiency of single-junction SCs (15−28% [1]). As the number of subcells increases, the difference between calculated and experimental efficiency values becomes more profound, reaching 17 absolute percent. Specifically, the approximate efficiency calculated in [3,6] for two- and six-junction SCs is 40 and 56%, respectively; in experiments, values on the order of 33 and 39% have been reported for the same MJ SCs [1].

The search for a calculation method providing realistic SJ efficiency estimates is a relevant objective that, if achieved, will contribute to the optimization of existing MJ SC designs and precise engineering of new ones. In the present study, a novel approach to MJ SC efficiency calculations is proposed and tested. This approach implements the concept suggested in [9]: the use of a semiempirical expression for determination of the saturation current. An essential novelty consists in the introduction of two saturation currents, which characterize two principal mechanism of current flow through a $p-n$ junction, into calculations. The first saturation current (J_{01}) specifies the current with ideality factor $A = 1$ that is supported either by recombination in quasi-neutral regions [11] or by interband recombination in the space charge region. The second saturation current (J_{02}, $A = 2$) specifies the current supported by recombination via deep levels in the space charge region [12]. Methods based on the Shockley–Queisser model have so far provided only calculated J_{01} values, although J_{02} often exerts a considerable influence on the current–voltage curve of an SC. An approach relying on two known current invariants (J_{Z1} and J_{Z2}) was chosen as a semiempirical method for calculation of saturation currents. These invariants establish the dependences of both saturation currents on band gap E_g and temperature T [13–15]:

$$J_{0,A} = J_{ZA} \exp\left(\frac{-E_g}{AkT}\right), \qquad (1)$$

where k is the Boltzmann constant and J_{Z1} and J_{Z2} are current invariants (constants: $J_{Z1} \approx 2.5 \cdot 10^5$ A/cm^2, $J_{Z2} \approx 1.4 \cdot 10^2$ A/cm^2).

Just as in other studies, photogenerated (PG) currents of subcells (J_g) were determined using the standard method for calculation of photocurrents from an energy spectrum of incident radiation [16]. All the modeled subcells were assumed to have a hundred-percent external quantum efficiency for all photons with energies above the band gap of a subcell. Thus, sets of J_{01}, J_{02}, and J_g values were determined with the use of (1) and via calculation of the PG current for a given set of band gaps of all subcells. The obtained vales and the two-diode model expression

$$J = J_g - \left[J_{01}\exp\left(\frac{qV}{kT}\right) + J_{02}\exp\left(\frac{qV}{2kT}\right)\right] \qquad (2)$$

were used to calculate current–voltage curves of all subcells, which were then processed to determine the MJ SC efficiency. In (2), q is the electron charge. If a wider-gap subcell in a pair of two nearby (neighboring) subcells had a higher PG current, the possibility of J_g current matching was taken into account (currents were averaged).

The applicability of the method was examined by comparing calculated efficiencies of various SCs with experimental ones. Both single- and multijunction SCs were included into this comparison. Their efficiency was measured for the AM1.5G spectrum under direct (unconcentrated) sunlight. The majority of experimental data were taken from the current table of record SC efficiencies [1]. Since this table contains no data on a four-junction SC, the values for it were taken from [17]. All calculations were performed twice: with the mechanism of current flow with $A = 2$ taken into account and with this mechanism neglected. The latter variant corresponds to the case of very small J_{02}, which may be achieved in high-quality $p-n$ junctions. In addition, J_{01} was calculated in accordance with the Shockley–Queisser detailed balance technique. The expression for J_{01} given in [18] was used in this calculation; current J_{02} was assumed to be zero.

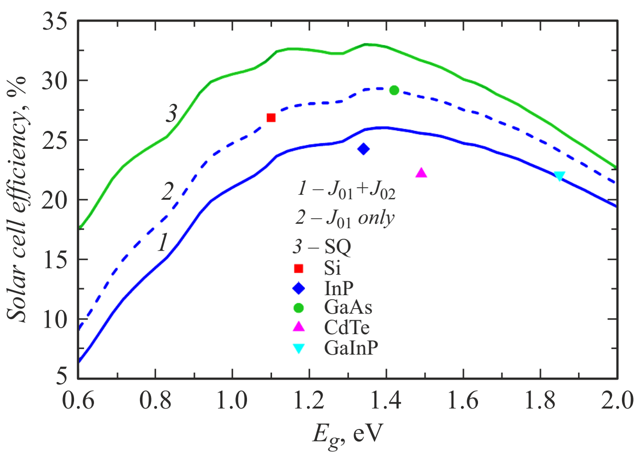

Figure 1. Calculated efficiency of a single-junction SC as a function of the band gap of its $p-n$ junction. Curves *1*, *2*, and *3* represent the results obtained using the two-diode model, the one-diode model (without saturation current J_{02}), and with the saturation current calculated based on the Shockley–Queisser model, respectively. Points denote the experimental data for various SCs.

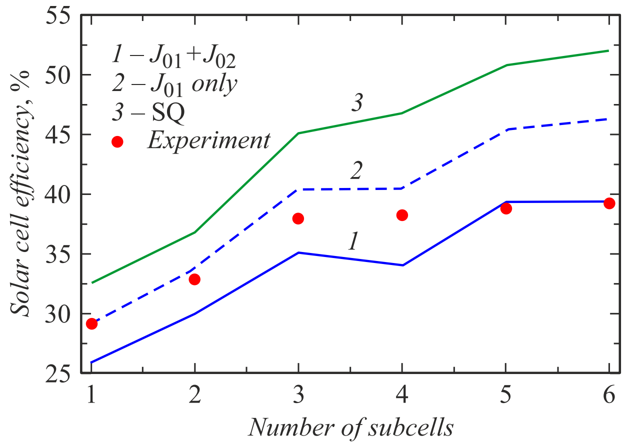

Figure 2. Experimental data on the record efficiency of SCs with a different number of subcells (from 1 to 6) and the results of calculation of efficiency performed using the proposed method. Curves *1*, *2*, and *3* represent the results obtained using the two-diode model, the one-diode model (without saturation current J_{02}), and with the saturation current calculated based on the Shockley–Queisser model, respectively.

Figure 1 presents the data for single-junction SCs. It is evident that the efficiency of the best-studied and best-optimized Si and GaAs SCs is characterized well by the proposed model with only J_{01} included. Other samples are closer to the model with two saturation currents. The efficiency of a CdTe-based SC is significantly lower than the calculated value. This may be attributed either to a low external quantum efficiency (an efficiency of 100% was assumed in calculations) or to the presence of additional leakage channels (tunnel current) that are not incorporated into the used two-diode model (*2*).

Figure 2 presents the data on record-high efficiencies of SCs with different numbers of subcells. All experimental points fall within the interval between two variants of calculation performed using the proposed method; notably, as the number of subcells increases, it becomes more and more necessary to include the recombination current flow mechanism ($A = 2$). This may probably be attributed to the fact that the number of defects producing deep levels is likely to increase as MJ SC structures grow more complex. Consequently, the rate of recombination via these levels should increase, and the influence of recombination current should become more profound. Therefore, both saturation currents need to be taken into account in the process of MJ SC engineering. The proposed method satisfies this requirement.

Thus, the use of current invariants J_{Z1} and J_{Z2} in the determination of saturation currents provides an opportunity to obtain an MJ SC efficiency estimate that is much more accurate than the one provided by the detailed balance model. This becomes evident if one compares the data in Figs. 1 and 2. The proposed method is highly accurate, which makes it a promising tool for the optimization of existing MJ SC designs and engineering of new ones.

Funding

This study was supported by a grant from the Russian Science Foundation, project № 22-19-00158 (https://rscf.ru/project/22-19-00158/).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin