Analysis of a multi-junction solar cell with shunted subcells using SPICE

E D Filimonov, S A Kozhukhovskaia, M A Mintairov and M Z Shvarts
Ioffe Institute, 26 Politekhnicheskaya str., St Petersburg, 194021, Russia
E-mail: dexterfree1@gmail.com

Abstract. In the paper a generalized equivalent circuit based on the SPICE model of a multi-junction solar cell allowing forming and studying current-voltage characteristics is presented. The negative effect of the low shunting resistance on determining true values of a subcell current at different mismatches of p-n junction photocurrents in measuring a spectral dependence of photosensitivity was investigated.

1. Introduction
In recent years a variety of analytical and numerical methods have been used for simulating multi-junction solar cells (MJ SCs) with applying certain commercial software. Among standard software packages, the most widely used by developers and researchers of MJ SCs is the SPICE type program (Simulation Program with Integrated Circuit Emphasis). Such programs allow forming equivalent circuits of different complexity, investigating interaction of circuit elements, analyzing the processes taking place with regard to different operation conditions and accounting for peculiarities of semiconductor structures being studied [1-3]. In the present work, formation of a MJ SC equivalent circuit was carried out on the base of the QUCS (Quite Universal Circuit Simulator) software instrument with using the SPICE model optimized for describing a triple-junction SC. The GaInP (1.9 eV)/GaAs (1.42 eV)/Ge (0.66 eV) structure has been chosen as an object for simulation.

2. The model
To describe SC I-V characteristics, a generalized model of a MJ SC allowing one to present a semiconductor PV converter as an electric circuit was used (figure 1(a)). Such a circuit consists of three distributed elements, each of which reproduces a characteristic of a definite p-n junction (subcell) and includes the following components:
- current source setting the value of the subcell photocurrent \( J_{ph} \);
- diode for forming the forward branch of I-V characteristic;
- diode for forming the reverse branch of I-V characteristic;
- resistance \( R_{ov} \) connected in series to the “reverse branch” diode for controlling its curve slope;
- shunt resistance \( R_{sh} \) simulating different current leakages and internal ohmic losses.

A series resistance \( R_s \) responsible for ohmic losses on contacts is also included into the circuit. Electric parameters of the circuit components have been chosen in correspondence with standard characteristics of state-of-art semiconductor SCs [4]. In the work, considered were specimens of 1cm² in area.
Figure 1. (a) – equivalent circuit based on the SPICE model of a MJ SC (parameters of the circuit components: $J_D$ – p-n junction saturation current; $J_{rev}$ – reverse saturation current; $V$ – circuit voltage).(b), (c), (d) – simulated load I-V characteristics of the top, middle, bottom subcells, respectively. (e) – MJ SC general curve with accounting preset current mismatches between subcells.

In developing the model, peculiarities of the MJ SC design and methods for its photovoltaic characteristics investigating have been taken into account [5], which has allowed constructing a detailed SPICE model of a MJ SC ensuring a feasibility to form dark and load I-V characteristics of both the whole SC (figure 1(e)) and each junction separately (figures 1(b), 1(c), 1(d)). Depending on the set task, the proposed model allows one to:
- estimate the effect of the shunt and series resistances on the values of a MJ SC short circuit current or of separate subcells photocurrents being registered at a preset bias voltage;
- study the effect of diode characteristics of individual subcells (reverse saturation current, dark current) on the total I-V characteristic of a MJ SC depending on the photocurrent mismatch level;
- control the level of the mentioned photocurrent mismatch creating conditions typical for operation of a MJ SC and its subcells in both real conditions of daylight and in carrying out special investigations (first of all spectral dependencies of the external quantum yield of a photoresponse of separate subcells in a MJ SC).

It should be noted that just a feasibility to form operation states of a MJ SC determined by a strong photocurrent mismatch between $p$-$n$ junctions is a key point at simulating the conditions for correct recording and analyzing spectral dependencies of the external quantum yield of a photoresponse of separate subcells in a MJ SC.

3. Results and discussion

Let us consider a MJ SC I-V characteristic in conditions typical for obtaining spectral dependence of a photosensitivity. For this, we created a light shift, at which the photocurrent $J_{bot}^{ph1}$ of the Ge subcell is substantially smaller than photocurrents of other wideband subcells, and limitation by GaAs subcell current takes place within the GaInP-GaAs pair (see figure 1(e)). Registration of the $J_{bot}^{ph1}$ value is performed at the certain bias voltage, which value depends on the SC’s level of illumination: $U_{BIAS}>U'_{BIAS}$ (figure 2, for simplicity the I-V characteristic of the top GaInP subcell is not shown).

![Figure 2](image-url)

**Figure 2.** I-V characteristic of a MJ SC in conditions of a photocurrent limitation by a bottom narrow bandgap subcell: without (1, 3) and with (2, 4) current leakages in the top wide bandgap subcell at various current difference between the GaAs and Ge subcells $J_{bot}^{ph1}$, $J_{bot}^{ph3}$, $J_{bot}^{ph2}$.

If there is a small shunt resistance of a $p$-$n$ junction or a pronounced current leakage in the wideband subcell, a slope on its I-V curve appears in the vicinity of the point of short circuit current. At a certain value of shunt resistance in the GaAs subcell the influence arises from this “shunt” on to the recorded Ge subcell photocurrent, which is expressed in its decrease $J_{bot}^{ph2}$, $J_{bot}^{ph3}<J_{bot}^{ph1}$ (see figure 2). In case of a weak current difference $J_{bot}^{ph1}$ between the GaAs and Ge subcells such an influence starts to play a considerable role already at an insignificant GaAs subcell I-V characteristic slope, i.e. at a rather high shunt resistance (figure 3).

The obtained uncontrollable decrease of the Ge subcell photocurrent can also emerge in measuring the spectral photoresponse, when illumination of the Ge subcell is performed by frequency modulated monochromatic radiation [6] resulting in inflated values of the external quantum yield. It is obvious that, to decrease the effect of the “shunted” $p$-$n$ junction on the tested subcell photocurrent, it is necessary to ensure a significant exceeding by that junction photocurrent. However, at small values of the shunt resistance, the negative effect mentioned above can’t be avoided.
Thus, it has been shown that, in investigating the spectral dependencies of the external quantum yield of the photoresponse of subcells with pronounced current leakages in the photoactive $p$-$n$ junctions, the greatest possible difference between their photocurrents should be sought.

4. Conclusion

In the work, a distributed equivalent circuit based on the SPICE model of a MJ SC is proposed. Its feasibilities in forming I-V characteristics of semiconductor structures with different physical properties have been demonstrated. The main aim of the research was in considering the negative effect of current leakages in $p$-$n$ junctions on the value of the tested subcell photoresponse being registered. Understanding of the processes of mutual effect of the subcells will allow determining correct conditions for recording spectral dependencies of the photoresponse. The results obtained with the help of the SPICE model agree well with the theoretical and experimental data on practical monolithic MJ SCs [7].

Acknowledgments

Support for this work comes from the Russian Foundation on Basic Research (Grant 14-08-01222-a)

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