Modelling Multilayer Semiconductor Structures

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ABSTRACT

The interest in multilayer thin-film semiconductor structures is becoming bigger day by day. For multilayer structures both, low-quality and good-quality materials are used.

An extended Ebers-Moll model for simulating multilayer structures was developed. The standard Ebers-Moll model for a transistor structure was extended to be used for more junctions. In addition photogenerated current, recombination current in space-charge region and carrier multiplication are added to the model. This model is actually used for a four-layer structure but can be easily extended to be used for any multilayer semiconductor device.

Keywords: modelling, multilayer devices, extended Ebers-Moll model.

1 INTRODUCTION

A lot of numerical simulators that offer complex simulations are available these days. They can simulate several semiconductor structures quite well, but give no information about the physical operations of those structures. Despite all these helpful numerical simulators we need to know how the semiconductor device operates.

In our work an extended Ebers-Moll model for simulating multilayer semiconductor devices was developed [1, 2]. The model is based on standard transistor Ebers-Moll model [3]. This model was modified and extended to be used for a multilayer device. First of all we add recombination current in the space-charge regions and free carrier multiplication in reversed biased junctions. To use it also for photo triggered devices we add photogenerated current to the model.

This model is a comprehensible tool for analysis of several multilayer semiconductor structures. The model can be used for photo-sensors, hetero-junction structures and also for novel multilayer solar cells.

In the paper the extended Ebers-Moll model is described and its use for simulating a multilayer floating junction solar cell is presented.

2 EXTENDED EBERS-MOLL MODELL

The semiconductor multilayer structure is shown schematically in Fig. 1a. The current flowing over all *pn* junctions is the same. A good insight into the physical operation of the semiconductor device can be obtained by means of an extended Ebers-Moll model (Fig. 1b). Each junction in this model is represented with two diodes (D_1-D_n and D_{n+1}-D_{2n}) and current sources that represent the internal feedback paths and photogenerated current.

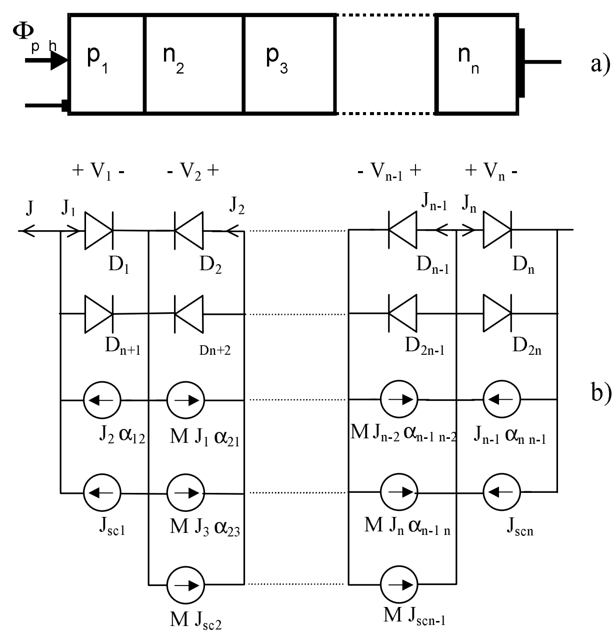

Fig. 1: A multilayer semiconductor structure (a) and its equivalent circuit model (b).

The first diode carries the dark current density

$$J_i = J_{si}\left(e^{\frac{V_i}{V_T}} - 1\right), \qquad (1)$$

where J_{si} denotes the dark saturation current density of the i-th junction and $V_T = kT/q$. The dark current density is a function of the material physical properties and is calculated using the typical semiconductor equations (continuity equation, Boltzmann equations...).

The second diode represents the recombination current density in the space-charge region. The recombination current density can be expressed as

$$J_j = J_{sj}\left(e^{\frac{V_j}{n_j V_T}} - 1\right), \qquad (2)$$

where J_{sj} denotes the dark recombination current density of the j-th junction and n_j the corresponding diode factor. The diode factor is usually a number between 1 and 2 [4].

The recombination saturation current and the diode factor can be calculated using the standard SRH theory [5] and Boltzmann quasi-equilibrium carrier concentrations in the space-charge regions.

The internal feedback paths, which exist within the multilayer structure, are represented by equivalent current sources

$$J_{i+1}\ \alpha_{i,i+1} \text{ and } J_{i-1}\ \alpha_{i,i-1}, \qquad (3)$$

where α denotes the corresponding short-circuit transfer ratio (current gain). This is the ratio between collected charge carriers at (i-1)-th or (i+1)-th junction and injected carriers over the i-th junction. The short-circuit transfer ratios are indexed as in the original paper of Ebers and Moll [3]. These internal feedback paths have a great impact on the semiconductor structure performance.

An illuminated semiconductor multilayer device can be simulated with added current sources J_{sci}, that represent the photogenerated and collected free carriers at each junction.

The multiplication factor M for collected carriers at the reverse biased junctions can be expressed as

$$M = \frac{1}{1-\left(\frac{V_k}{V_{BR}}\right)^m}, \qquad (4)$$

where V_{BR} denotes the breakdown voltage, V_k denotes the reverse biased junction voltage and the exponent m for silicon is a number between 2 and 7 [6].

3 MODELLING MULTILAYER SOLAR CELLS

We developed this model to analyse multilayer solar cells, although it can be used for several other multilayer structures.

The semiconductor structure that we analysed was a four-layer floating-junction solar cell. The structure is schematically shown in Fig. 2. The structure is a stack of alternating p and n layers with a top and a bottom electrical contact.

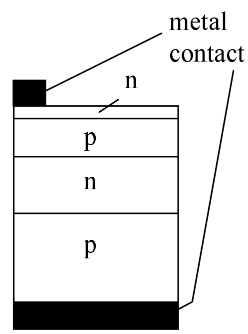

Fig 2: Four-layer floating-junction solar cell.

First we try to optimise the short-circuit current density and the open-circuit voltage. Both characteristic parameters of the solar cell are analysed with a simplified model. We do not take in regard the recombination in the space-charge region and the multiplication factor of free carriers. The simplification was made because of easier analytical analysis. The recombination in space-charge region was added afterwards. The simulations showed that the optimum criteria derived without recombination currents in the space-charge regions are valid even if recombination currents are considered.

3.1 Short-circuit Current

Under illuminations all pn junctions are forced into the forward voltage regime. The equivalent circuit for a four-layer structure yields the expression

$$V_1 - V_2 + V_3 = 0, \qquad (5)$$

which shows that the central voltage drop V_2 is higher then the other two (V_1 and V_3). Dark current densities J_1 and J_3 are therefore much lower than the dark current density J_2. Neglecting for this purpose the diodes D_1 and D_3 a simplified model for short-circuit conditions, shown in Fig. 3, can be used.

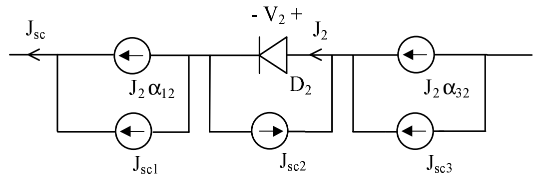

Fig. 3: Simplified equivalent circuit of 4-layer cell for short-circuit conditions.

From the equivalent circuit in Fig. 3 it can be easily demonstrated that the maximum value of short-circuit current density J_{sc} approaches the sum of individual photogenerated currents at each junction

$$J_{sc} = J_{sc1} + J_{sc2} + J_{sc3} \tag{6}$$

on condition that the sum of current gains approaches unity

$$\alpha_{12} + \alpha_{32} \to 1 \tag{7}$$

In reality both dark current densities cannot be neglected but it has no impact on the condition (7). The condition is fulfilled when the transport factors for injected minority carriers in the second and third layer approach unity.

The criteria for current gains α_{21} and α_{23} can be obtained from the initial equivalent circuit (Fig. 1) for a four-layer device. It turned out that the condition $J_1 \to 0$ demands $\alpha_{21} \to 1$ and $J_3 \to 0$ demands $\alpha_{23} \to 1$. It means that high emission efficiency for injected carriers is mandatory. Both conditions cannot be satisfied at the same time, because, as it was mentioned above, both dark diode current densities (D_1 and D_3) cannot be neglected. Usually the dark diode current density J_1 is much lower than the other two and can be neglected.

3.2 Open-circuit Voltage

The second important parameter for solar cells is the open-circuit voltage. The simplified equivalent circuit for open-circuit conditions consists of three separated simple circuits, shown in Fig. 4.

Adopting previously derived conditions and taking into account Ebers-Moll relations

$$J_{s1}\alpha_{21} = J_{s2}\alpha_{12} \quad \text{and} \quad J_{s3}\alpha_{23} = J_{s2}\alpha_{32}\ , \tag{8}$$

the maximum V_{oc} is expressed in the form

$$\begin{aligned} V_{oc} &= \frac{kT}{q}\ln\frac{J_1 J_3}{J_2}\frac{J_{s2}}{J_{s1}J_{s3}} = \\ &= \frac{kT}{q}\ln\frac{J_{sc1}+J_{sc2}+J_{sc3}}{J_{s2}(1-\alpha_{12}\alpha_{21}-\alpha_{23}\alpha_{32})} \end{aligned} \tag{9}$$

and the three junction voltages are the same, $V_1 = V_2 = V_3 = V_{oc}$.

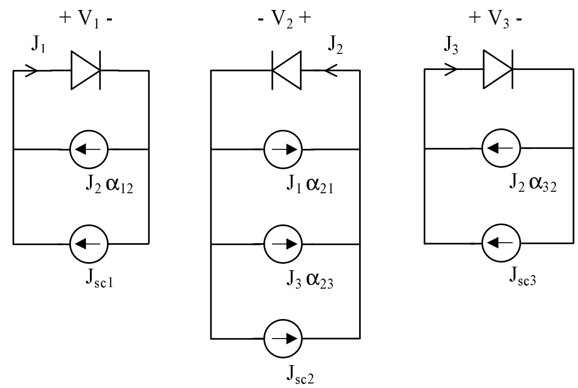

Fig. 4: Simplified equivalent circuit of 4-layer cell for open-circuit conditions.

3.3 Recombination

The recombination in space-charge regions has a great impact on the solar cell performance when the material quality is low. They must be considered in analysis, but the simulations showed that all previously mentioned conditions for short-circuit current and open-circuit voltage are valid and can be used.

For a four-layer solar cell the recombination currents also give the possibility to simulate the turning-on point of the thyristor-like structure.

4 COMPARISON WITH A NUMERICAL SIMULATOR

All simulations we made were compared with the results derived with numerical simulator MEDICI [7]. A comparison between efficiencies of the same cells was made.

First we optimised the four-layer solar cell with the extended Ebers-Moll model and then we simulated this unchanged solar cell structure with the numerical simulator MEDICI. The basic parameters like surface recombination and SRH recombination lifetimes were set to the same values.

The solar cell efficiency at a SRH recombination lifetime of 10^{-6}s was 12.9% while the extended Ebers-Moll model was used and 11.9% while the numerical simulator MEDICI was used. In the analytical simulations the recombination diode factor was n=2. The differences between results are more evident at higher SRH lifetimes, where the efficiencies derived with MEDICI are lower than those derived with the extended Ebers-Moll model. The differences are a result of more accurate numerical simulations.

5 CONCLUSION

An extended Ebers-Moll model for simulating multilayer semiconductor devices was developed. The model is a convenient tool for examination of physical operation of different structures.

We used the model for simulating and optimising a floating junction solar cell, although it could be used for several other multilayer semiconductor structures.

The simulation results for a multilayer solar cell derived with the extended Ebers-Moll model were compared with numerical simulations. The comparison showed that the results are quite similar. The differences are more evident if materials are better (higher free carrier lifetimes) because of more accurate results made with numerical simulator.

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