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Modelling of thyristor-like thin-film solar cell and simulations under different solar radiation intensities

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A thin-film floating junction solar cell that requires the deposition of alternating p and n layers has been recently introduced. A four-layer solar cell operates like a thyristor in which the triggering gate is substituted by photogenerated charge carriers. In this paper an equivalent electrical circuit model of a four-layer structure is presented. Although the J–V characteristics are still thyristor-like, this thyristor-like solar cell gives an output PV power at any sun radiation intensity.

Keywords: thyristor, solar cells, I-V characteristics.

1. Introduction

High costs of solar cell production lead researchers to investigate new cost-effective technologies. Multilayer solar cells made of low-quality materials promise to reduce the manufacturing costs of solar cells. Due to the use of poor-quality materials free carriers have short diffusion lengths. The thickness optimisation of a conventional single junction solar cell is a trade-off between the need to have a layer thickness smaller than the free carrier diffusion length and the need to have a thick cell to ensure the maximum solar spectrum absorption. Multilayer solar cells overcome the constraints of short diffusion lengths by introducing more junctions while keeping the same overall cell thickness [1].

For the optimisation of the floating junction solar cell an extended Ebers-Moll model was developed [2,3], which turns out to be a comprehensible representation for understanding the physical operation of the cell. To investigate the switching-on point of the thyristor structure, recombination currents and multiplication factor in reverse-biased junctions are added to the extended Ebers-Moll model.

This paper answers the basic question – is there any lowermost solar radiation intensity which is necessary to turn on the thyristor-like solar cell structure? Using the solar radiation intensity as a parameter, several current-voltage characteristics were calculated.

2. Modelling of solar cell structure

The four-layer solar cell structure shown in Fig. 1 requires the deposition of alternating p and n layers and electrical contacts only at the top and the bottom of the cell.

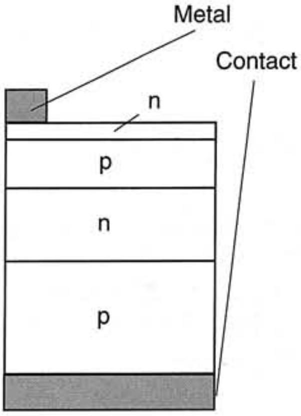

Fig. 1. Four-layer floating junction solar cell.

A four-layer floating junction solar cell operates like a thyristor in which the triggering gate current is substituted by photogenerated and collected charge carriers. The current flowing through all junctions is the same.

For the optimisation of the floating junction solar cell structure an extended Ebers-Moll model was developed [2,3]. It is a convenient tool for the analysis of an illuminated cell, but gives no information on switching from nonconducting region to photovoltaic power generation region of the thyristor-like solar cell characteristics. By adding recombination currents and multiplication in reverse-biased junctions to the Ebers-Moll model a Gummel-Poon model with neglected high-level injection effects is obtained. These effects can be omitted because only low current densities are flowing through the solar cell structure. The new equivalent electrical circuit is shown in Fig. 2.

In the equivalent circuit each junction is represented by a pair of diodes (D_1–D_3 and D_4–D_6) and current sources that describe the internal feedback paths and photogene-

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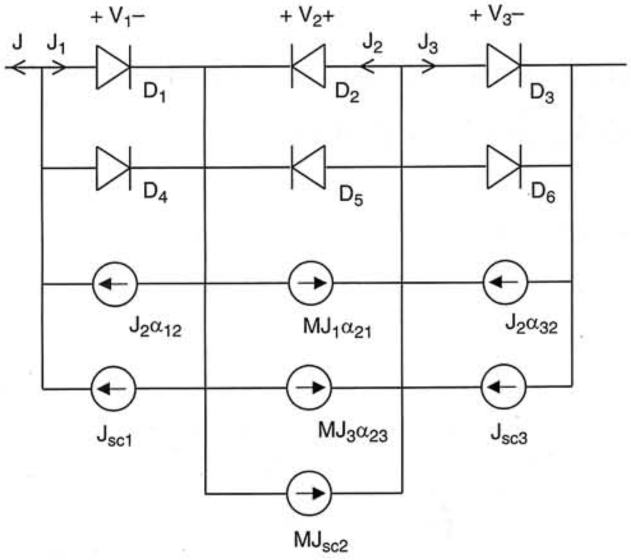

Fig. 2. Extended Ebers-Moll model of a four-layer solar cell.

rated currents. The first diode (D_1–D_3) carries the dark current density

$$J_i = J_{si}\{\exp(V/V_T) - 1\}, \tag{1}$$

where J_{si} denotes the dark saturation current density of the ith junction and $V_T = kT/q$. The recombination currents in the space-charge region are added to the Ebers-Moll model by diodes (D_4–D_6). Each diode carries the dark recombination current density is equal

$$J_j = J_{sj}\{\exp(V/n_j V_T) - 1\}, \tag{2}$$

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 current was calculated using the Boltzmann quasi-equilibrium carrier concentrations in the space-charge regions and standard Shockley-Read-Hall theory for the recombination-generation rate [5].

$$R = \frac{np - n_i^2}{\tau(n + p + 2n_i)}, \tag{3}$$

where n_i, n and p represent the intrinsic, electron and hole concentrations respectively, and τ denotes the lifetime of the carriers. For the calculation of recombination currents the average value of free carriers lifetime τ was used.

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

$$J_{i+1}\,\alpha_{i,i+1} \text{ and } J_{i-1}\,\alpha_{i,i+1}, \tag{4}$$

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 of i^{th} junction.

The collection of photogenerated charge carriers at the i^{th} junction is modelled by the current source J_{sci}.

At the AM1.5 illumination all p-n junctions are forced into forward voltage regime, while at no illumination the central junction (D_2) is reverse-biased. Switching the thyristor to its on-state occurs at the so-called breakover point. To calculate the switching-on characteristics of the thyristor-like solar cell, we presume that the multiplication factor M for collected carriers at the reverse biased junction can be expressed as

$$M = \frac{1}{1 - (V_2/V_{BR})^m}, \tag{5}$$

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

3. Simulation

All calculations were made for a previously optimised cell at the AM1.5 solar radiation intensity. The lifetimes of free carriers in our optimised cell were derived using a model from the numerical program MEDICI [7], while the mobilities were calculated using a concentration dependent model [8]. For an asymmetrical junction with a concentration ratio $10^{18}/10^{16}$, the saturation recombination current density $J_{si} = 5.58\times10^{-17}$ A/cm² was calculated. The corresponding diode factor was set n = 2. The corresponding J–V characteristics of the four-layer solar cell and a conventional p-n single junction solar cell are shown in Fig. 3.

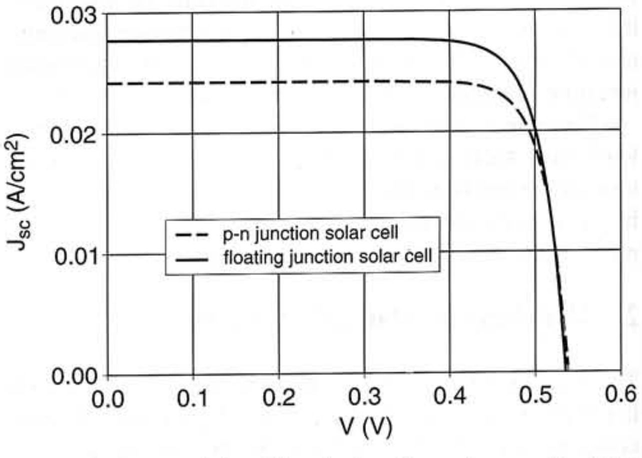

Fig. 3. J–V characteristics of floating junction and conventional p-n junction solar cells.

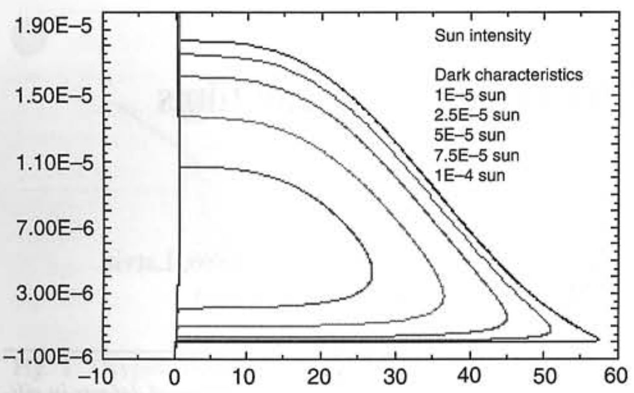

Fig. 4. J–V characteristics of floating junction solar cell at different sun intensities.

Under the AM1.5 illumination the characteristics of a four-layer solar cell are diode-like. In the dark the characteristics are thyristor-like. In the blocking region the central junction is reverse-biased. Under illumination the photogenerated current causes the central junction to be less and less reverse-biased until the characteristics become diode-like. The blocking region under increased illumination becomes smaller and moves to higher currents, as it is evident from Fig. 4.

The magnified parts of the J-V characteristics, showing the PV power generation region as a function of solar radiation intensity, are shown in Fig. 5.

All junctions in the photovoltaic power generation region are generally forward-biased, only the third junction can be slightly reverse-biased at small terminal voltages and under low illumination. Even in these circumstances the cell generates an output power.

A comparison between the four-layer solar cell and the single junction solar cell structure under an illumination of 0.1 AM1.5 is shown in Fig. 6. From this figure it is evident that the multilayer solar cell has worse performance under low illuminations which is the consequence of recombinations in space-charge regions. Using several junctions provides better photogenerated carrier collection but increases the recombination losses.

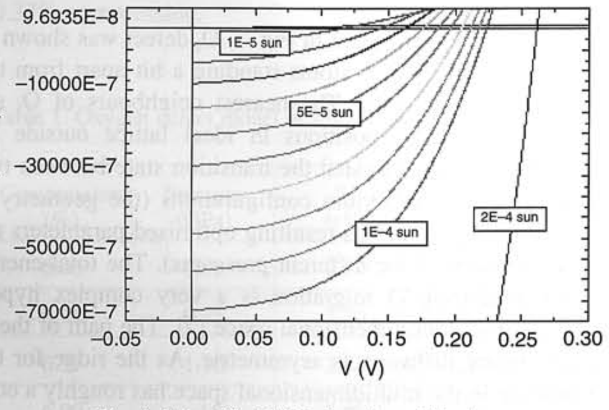

Fig. 5. Magnified J–V plots from Fig. 4.

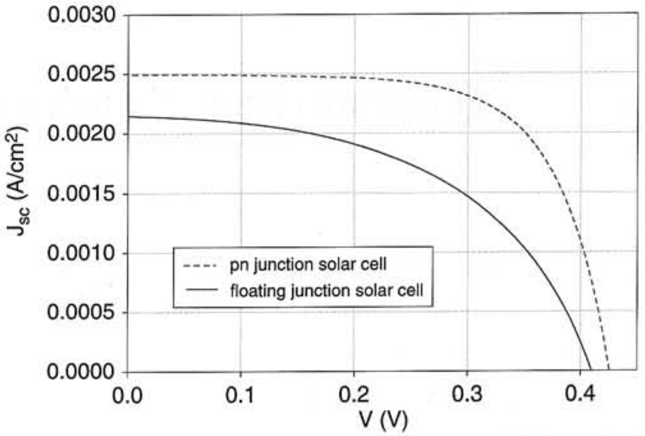

Fig. 6. J–V characteristics of floating junction and conventional p-n junction solar cells under illumination of 0.1 AM1.5.

4. Conclusions

An extended Ebers-Moll model, which includes recombination currents and carrier multiplication in reverse-biased junctions, was used for the examination of switching-on characteristics of a four-layer thyristor-like solar cell. The recombination current was calculated using Boltzmann quasi-equilibrium carrier concentrations and the SRH theory.

Several J–V characteristics were calculated to study the turning-on point of a multilayer solar cell. The simulations showed that the cell generates an output power at any solar radiation intensity although the characteristics are still in forward blocking region.

The comparison between the floating junction solar cell and a conventional p-n junction solar cell made of low-quality material shows that the multilayer solar cell has worse performance than the single junction solar cell under low illuminations.

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