Textured solar cell modeling in TCAD

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Abstract. We investigate one of the promising methods for increasing the output characteristics of solar cells - surface texturing. The structures and characteristics of microcrystalline silicon solar cells are simulated. Solar Cells with different surface geometries are compared. The first type is the classic flat structure. The last and the most effective is Solar Cell with the surface in the form of microscopic pyramids separated by flat regions.

1. Introduction

There are two types of energy sources, non-renewable and renewable, which are widespread in a present-day world. Renewables include hydropower, wind, geothermal, biomass and solar energy [1]. Let’s consider the features of solar energy as a renewable energy source.

The most widespread material from which solar cells have been made for many years is silicon. The first structures were made on monocrystalline silicon. Now it is polycrystalline/microcrystalline and amorphous silicon. In addition to silicon, solar cell structures are made on GaAs and its solid solutions; on CIS (CuInSe₂), CIGS (Cu (In, Ga)Se₂) structures; on transparent metal oxides (i.e. ITO, ZTO); on several types of organics, etc. [2].

A typical solar cell is inflexible and flat. But there are firm and flexible structures, which are suitable for use on embossed surfaces, become more popular nowadays [3].

The surface of the cell is smooth in the classic version of the solar cell structure. It is covered with protective translucent/transparent films. Depending on the structure of the SC, the film can be dielectric or conductive. Classical dielectric films are SiO₂, SiO₂+TiO₂, etc. The typical conducting film is ITO [4].

To increase the output power, and, consequently, the efficiency of solar cells, various methods of changing its structure are used. One of these methods is to give the surface a texturing of various types [5].

Modern technologies make it possible to create solar cell surface relief with the best and the most powerful effective shapes. In some multi-crystalline solar cells, it was found that one of the best ways to achieve good material quality is the material deposition on a rough surface. Therefore, solar cells with a textured rear surface instead of a textured front surface have been investigated experimentally. In order to model the resulting effects, the influence of single surface texture was investigated.

For the first time, we investigate the classical flat solar cell structure, with typical electrophysical parameters. Next step we modify the solar cell top surface and analyze its behavior in this section.

2. TCAD Modeling

In our investigation, we simulate a Solar Cell based on a silicon substrate and doped with boron ($10^{14}$ cm$^{-3}$). A heavily doped region is formed on the backside for the anode contact ($10^{18}$ cm$^{-3}$). The bottom
contact is made from a transparent conductive metal oxide ITO (thickness 0.5 μm) by ion-beam sputtering.

A p-type region (10²⁰ cm⁻³ on the top) with a thickness of about 0.5 μm is created in the upper part of the structure by ion implantation of phosphorus. A thin transparent conductive layer of ITO cathode (its thickness is 0.1 μm) is applied to it.

The dimensions of the simulated classical flat structure (in 2D) are 2 μm in width and 6 μm in height (figure. 1). The depth of the simulated structure is taken equal to 2 μm (the square of the surface is considered).

To form a relief on the surface of the structure, regions of a regular geometric shape — pyramids and parallelepipeds of various depths and heights of walls (table 1) — are etched before the p-type ion implantation process.

We analyzed several types of structures and discover that a structure with pyramidal peaks (call it “small peaks”) of 0.5 μm peak height, 3 μm peak width and a valley between peaks width of 1 μm was recognized as a promising type of modification (figure 2).

For each structure specific material parameters were configured in TCAD. For silicon, the charge carrier mobility was specified as typical for the polycrystalline material of solar cells (µn = 20, µp = 1.5). The bandgap (eg₃₀₀ = 1.9) and the concentration of intrinsic charge carriers (n₀₃₀₀ = 2.5e20, nᵣ₃₀₀ = 2.5e20) also were specified for each structure. To calculate the spectral characteristics of ITO, a table from the Sopra database was attached to the model. The resulting solar cell structure was maintained for further analysis.

In the next step the current-voltage characteristics (IV) were simulated for all constructed structures. For the modeling, standard Shockley-Reed-Hall models and Auger recombinations were used.

Under such conditions (without lighting), for each type of solar cell surface, a dark IV characteristic was calculated in the range from 0 to 2 V with a step of 0.1 V. It was taken as the basis for further calculation of the characteristics of solar cells under illumination.

It was assumed that the luminous flux corresponds to the spectrum of AM1.5. The radiation source is located above the middle of the structure. Wavelengths from 0.3 to 1.2 microns are analyzed. The data on the change in intensity was used for further analysis of the characteristics of solar cells.

After the light radiation modeling, the IV characteristic of the solar cell was calculated under its illumination (from 0 to 2 V in 0.1 V increments). The simulation results for every flat SC and SC, which showed the best characteristics, are given below (figure 3).
Table 1. Solar cell surface structure.

| Solar Cell type           | small peaks (best results) | large peaks | trapezoid shapes | jagged structure of various depths | flat | rectangular |
|---------------------------|----------------------------|-------------|------------------|-----------------------------------|------|-------------|
|                           | 1                          | 2           | 3                | 4                                 | 5    | 6           |
| apex angle from normal    | 75°                        | 55°         | < 75°            | < 45°                             | -    | 0°          |
| width of bottom, um       | 3                          | 3           | < 3              | < 2                               | -    | 2           |
| width of top flat surface, um | -              | -           | < 2 um           | -                                 | -    | 2           |
| Solar Cell Structure      |                            |             |                  |                                   |      |             |

Figure 2. Solar Cell with small Peaks on top (materials and carrier concentration).

During the simulation, the basic parameters were calculated so we can analyze the textured solar cells’ characteristics. Short circuit current and open circuit voltage were determined. The short circuit current was determined on the IV curve when illuminated at a point of zero on the X axis. The open circuit voltage was determined at zero on the Y axis.

The power of solar cells was calculated on the results of the IV characteristics under illumination and was a determining parameter for further analysis of the efficiency of solar cells.
3. Results and Discussion
When we changed the surface structure of the solar cells, texturizing them (figure 2), we increased its effective area but left the original cell’s dimensions. With the shape of the surface relief changing, the percentage of absorbed and reflected radiation changes too. Five types of surface topography were investigated (table 2). The results were compared with each other and with the original flat SC structure.

The experiment results were that during the formation of rectangular valleys, the maximum effective power emitted by SCs worsened compared to a flat structure (1.51 W·10⁻⁹ for rectangular SC and 2.01 W·10⁻⁹ for flat SC, respectively).

When a jagged structure of various depths was formed on the surface, the maximum effective power increased by 0.15 W·10⁻⁹ compared to the flat SC. Other surface configurations showed similar power growth (structures 1-3 in Tab. 1-2). The best result of all modeled structures was shown by a solar cell with small peaks on the surface of the structure (structure 1 in table 1 and 2). The selection of the angle at the top of the pyramid ensured the greatest absorption of the incident light (figure 4).

The analyzed parameters to determine the most effective SC were its power (figure 5), short circuit current, open circuit voltage (table 2), and IV characteristics (figure 3). It can be seen that for all structures the open circuit voltage remained almost unchanged, while the short circuit current changed to a large extent. Consequently, the configuration of the IV and the power curves changed. Figures 3 and 5 compare the initial flat SC and the most optimized SC with small peaks. The discrepancy between the values corresponds to the calculated values of the short circuit current.

| Solar Cell type | small peaks (best results) | large peaks | trapezoid shapes | jagged structure of various depths | flat | rectangular |
|----------------|---------------------------|-------------|------------------|----------------------------------|-----|------------|
| Iₛₛ⁻¹⁰⁻⁹, A    | 3.028                     | 2.97        | 2.98             | 2.84                             | 2.82| 2.33       |
| Vₒ𝑐, V         | 1.1                       | 1.1         | 1.1              | 1.0                              | 1.1 | 1.1        |
| Pₘₚₘ⁻¹⁰⁻⁹, W    | 2.16                      | 2.15        | 2.12             | 2.02                             | 2.01| 1.51       |

**Table 2. Results of Modeling.**

*Figure 3. Comparison IV of solar cell (marked) with small peaks and flat solar cell (solid); anode current and cathode current Y-axis, respectively.*
4. Conclusion

The best performance results were obtained from solar cells with small and large peaks, while gaining a power gain of 7.5% and 7%, respectively, compared with a flat structure. Other surface options also give an increase in power due to an increase in the effective surface area per unit length of solar cells and optimal configuration of reflection and absorption, but last is not so strong.

References
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