Numerical simulation of the carbon nanotubes transport layer influence on performance of GaAs solar cell

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Abstract. In this paper we present the results on simulation of the photovoltaic properties of the conventional one junction GaAs solar cell modified with a transparent transport layer. The use of the transport layer allows reduction of the top layer lateral resistance leading to rise of the cell efficiency. In the modeling, we considered three different materials of the transport layer namely, ITO, AZO and carbon nanotubes. The optimum values of the transport layer thickness and distance between the metallic grid bars corresponding to the highest theoretical efficiency are obtained. With light concentration, 17.3%, 10.5 % and 15.1% efficiency was reached for SC with CNT, ITO and AZO transport layers respectively.

1. Introduction

High cost of the solar cells (SCs) based on expensive substrates such as Ge and GaAs synthesized via MOCVD or MBE dictates necessity of the light concentration system use in order to reduce area of the photoactive element. In addition, 10-100 times increase of the luminous flux allows rise of the solar cell efficiency due to increase of the cell nominal voltage [1]. The light concentration requires optimization of the carriers collection in the top grid contact and improved heat dissipation.

Lateral spreading of the carries in the SC takes place mainly in the upper emitter layer and wide band gap window layer. Correspondingly, resistances of the latter layers play the main role in the total resistance of the cell, limitation of fill factor and SC current. Conventional method for improvement of the ohmic losses in SC upper layers is fabrication of the dense metal contact grid on the SC surface allowing carriers collection from these layers. However, the metal grid is not optically transparent limiting the radiation absorption. An alternative approach is fabrication of additional transparent layer over the wide band gap window providing high electrical conductivity such as graphene [2]. Use of this layer allows to increase distance between the grid bars and consequently to improve transparency of the contact layer.

In this report, we study theoretically the effects of different material transport layers used in conventional GaAs cell on the SC photovoltaic properties.
2. Calculation

In our simulations we considered AlGaAs/GaAs heterostructure SC, synthesized on 300 µm thick GaAs substrate. The calculations were carried out in Silvaco TCAD software package. Material parameters (carriers life time and mobility) were approximated according the concentration dependent. Shockley-Read-Hall model [3] [4] and Lombardi constant voltage and temperature (CVT) model [5] respectively. We also considered radiative and Auger recombination [6].

We performed the calculation with a different top transparent conductive layers. Considered materials for the top conductive layer were carbon nanotubes (CNT), indium tin oxide (ITO) and aluminum zinc oxide (AZO). ITO and AZO was approximated as a semiconductor with known parabolic carriers dispersion law. Linear dispersion law typical for graphene was taken for CNT. Carbon nanotubes were considered a three-dimensional semiconductor with dummy parameters. The parameter values of the materials are shown in Table 1. In order to calculate the light dissipation in the considered layer we took into account refractive index and light absorption coefficient of the materials. The data was taken from [7], [8] and [9].

| Material | Electron affinity (eV) | Bandgap (meV) | Electron density of states (10^15 cm⁻³) | Hole density of states (10^18 cm⁻³) | Base doping level (10^17 cm⁻³) | Doping type | Permittivity |
|----------|------------------------|---------------|----------------------------------------|-----------------------------------|-------------------------------|------------|-------------|
| CNT      | 4.2                    | 10            | 8.75 × 10^{15}                         | 8.75 × 10^{15}                    | 6.4 × 10^{17}                 | p-type     | 15.0        |
| ITO      | 4.7                    | 4.0           | 2.5 × 10^{19}                          | 8.87 × 10^{18}                    | 4.5 × 10^{19}                 | n-type     | 11.1        |
| AZO      | 4.3                    | 3.37          | 2.5 × 10^{19}                          | 8.87 × 10^{18}                    | 2.0 × 10^{19}                 | n-type     | 11.1        |

Increase of the transport layer thickness leads to decrease of the SC resistance but, on the other hand, leads to rise of the unwanted light absorption in the transport layer. Due to the latter facts, an optimal thickness of the transport layer exists. The relation between transparency and the sheet resistance for the considered materials is presented in Figure 1.

![Figure 1: Relation between transparency and materials sheet resistance](image-url)

We considered the SCs without antireflection coating since the studied effects relates to
conduction properties of the transport layers. Consideration of the anti-reflection coating is a simple numerical problem that was out of the investigation scope.

Due to n-type conductivity of ITO and AZO and p-type conductivity of the CNTs we modeled SCs with n-type window for ITO or AZO and p-type window with CNTs layer.

In the first part of the modeling we optimized thickness, doping level and composition of the one-junction SC layers without the transport layer. Our simulations showed that SCs with n-doped emitter and without it have similar efficiencies. We assume that this effect relates to the absence of lateral current. The design of the optimized structure is presented in tables 2-3.

Table 2: Structure parameters for CS with CNT.

| Layer     | Material      | Thickness | Doping type | Doping level |
|-----------|---------------|-----------|-------------|--------------|
| 4th       | Transport layer | CNT       |             |              |
| 3rd       | Window        | Al$_{0.5}$Ga$_{0.5}$As | 20 nm | p-type | $5 \times 10^{18}$ |
| 2nd       | Base          | GaAs      | 2.6 µ | n-type | $2 \times 10^{16}$ |
| 1st       | BSF           | Al$_{0.3}$Ga$_{0.7}$As | 20 nm | n-type | $5 \times 10^{18}$ |
| Substrate | GaAs          | 300 µ     | n-type     | $1 \times 10^{18}$ |

Table 3: Structure parameters for CS with ITO and AZO.

| Layer     | Material      | Thickness | Doping type | Doping level |
|-----------|---------------|-----------|-------------|--------------|
| 4th       | Transport layer | ITO or AZO |             |              |
| 3rd       | Window        | Al$_{0.5}$Ga$_{0.5}$As | 20 nm | n-type | $5 \times 10^{18}$ |
| 2nd       | Base          | GaAs      | 2.0 µ | p-type | $6 \times 10^{16}$ |
| 1st       | BSF           | Al$_{0.3}$Ga$_{0.7}$As | 20 nm | p-type | $5 \times 10^{18}$ |
| Substrate | GaAs          | 300 µ     | p-type     | $1 \times 10^{18}$ |

Figure 2: Efficiency depending on distance between metal contacts in case of different transport layers
After the design optimization, we performed simulations of the SC with the different transport layers and without it varying the distance between the contact bars. The results of the calculations are shown in Figure 2. For the SC without the transport layer, an optimum distance of about 500nm for both n- and p-type window SCs corresponding to the maximum efficiency exists. The latter phenomenon relates to influence of two opposite effects: increase of ohmic losses with the distance and corresponding drop of the light reflection from the contacts.

In the SCs with the transport layer, ohmic losses in the upper layers are insufficient so efficiency does not drop with the distance between the bars. In the further simulations of the SCs with the transport layer, the distance between the contacts was set to 1300 µm corresponding to the SC efficiency saturation.

![Figure 2: Efficiency depending on luminous flux and transport layer thickness](image)

In the final part of our investigation, we simulated the efficiency of the SCs with different transport layers under the concentrated light. The numerical modeling results of the SC efficiency dependence on the light concentration and sheet resistance of the transport layer are shown in Figure 3. Due to monotonic relation between the sheet resistance and the layer...
thickness an optimized value of the latter can be obtained. Solar cells with n-type window (ITO and AZO) demonstrate worse efficiency due to lower hole mobility in the p-type substrate. Worth noting, that in case of ITO transport layer, the major factor limiting the efficiency was high electron affinity of the ITO and consequently existence of the potential barrier between the transport layer and window.

3. Summary
In this work, we carried out the numerical simulations of the conventional GaAs SC enhanced with the additional transport layer placed at the top surface of the SC. The optimal thickness of different materials conductive layer, as well as distance between the metal grid bars have been calculated. Without the light concentration, efficiency grows from 12.8 % to 14.5% when AZO is added and from 15.3% to 15.5% when CNTs layer is added. The maximum efficiency for the SC with ITO transport layer was 10.3%. With light concentration, 17.3%, 10.5 % and 15.1% efficiency was reached for SC with CNT, ITO and AZO transport layers respectively. Use of the transport layers allows increase of the distance between the contact bars and their width. Consequently, this approach is assumed very promising for the factory application due to possibility of the screen printing use instead of the lithography methods.

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