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Effects of temperature and series resistance on GaAs concentrator solar cell

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Abstract. Concentrators use reflection or refraction of light, or a combination of both, but concentration of light leads to a crucial heating of the cell, which involves degradation of its performance. However, solar cells especially conceived for concentration can support very intense illuminations as far as an active cooling is assured. In this work, a GaAs solar cell with $Al_xGa_{1-x}As$ window layer, operating under low injection conditions, has been studied with temperature and solar concentration. The temperature corresponding to each concentration was calculated, and then used in the calculation of photovoltaic parameters. The study was carried out under free mode conditions (without heat sink) and then under forced conditions (with a cooling system) in order to demonstrate the importance of cooling in the concentrator solar cells. The effect of series resistance on solar cell characteristics has also been studied. The simulation was carried out using SCAPS-1D simulator. The results were compared with those obtained theoretically; a good agreement was found between the two models.

PACS. 84.60.Jt Photoelectric conversion: solar cells and arrays – 42.79.Ek Solar collectors and concentrators

1 Introduction

It is well known that optical concentration offers an attractive and flexible approach to reducing high solar panels costs by substituting a part of the cells by a less expensive optical material. For instance, one cell operated under 1000 sun concentration can produce the same power output as 1300 cells under one sun [1].

The best GaAs concentrator cells have reached a very high level of development, comparable to that of the best Si cells and that is due to a set of advantages, including a high absorption coefficient, a good radiation resistance and especially high temperature operation, which is unavoidable at high concentration ratios. In general the GaAs solar cell performance exceeds greatly that of Si cells. The efficiency of concentrator cells for both materials has reached 26–28% [2]. In this work we report results obtained using both a computer simulator and a theoretical model of GaAs solar cells with $Al_xGa_{1-x}As$ window layer operating under low injection conditions. The effect of temperature, concentration ratio and series resistance were investigated.

The simulation results were carried out by the software SCAPS-1D (Solar Cell Capacitance Simulator in one dimension) [3–6]. GaAs solar cell has been simulated first by Khelifi et al. [7,8], the obtained results agreed well with the reported experimental findings.

2 Theoretical model

The effect of temperature (T) and concentration rate (C) on photovoltaic parameters of concentrator solar cells is modeled using the expressions given in reference [9]:

$$J_{sc}(T,C) = C J_{sc}(T_0, C_0) \tag{1}$$

$$V_{oc}(T,C) = V_{oc}(T_0,C_0) + \left(\frac{E_g}{e} - V_{oc}(T_o,C_0)\right) \times \left(1 - \frac{T}{T_0}\right)\left(\frac{nKT}{e}\right) + \left[\ln C - \gamma \ln\left(\frac{T}{T_0}\right)\right] \tag{2}$$

$$FF = \frac{P_m}{J_{sc}.V_{oc}.A} = \frac{J_m.V_m}{J_{sc}.V_{oc}} \tag{3}$$

$$\eta = \frac{FF.J_{sc}.V_{oc}.A}{P_{inc}} \tag{4}$$

where: $J_{sc}(T_0,C_0)$ and $V_{oc}(T_0,C_0)$ are the short-circuit current density and open-circuit voltage respectively at temperature $T_0 = 300$ K and concentration rate $C_0 = 1$ sun.

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In our case, these two parameters were calculated using the software SCAPS-1D under standards conditions $T_0 = 300$ K and $C_0 = 1$.

$J_{sc}(T, C)$ and $V_{oc}(T, C)$ are the short-circuit current density and open-circuit voltage respectively at temperature T and concentration rate C.
Eg is the energy band gap of the material,
n is the diode ideality factor, which varies between 1 to 3,
γ is a factor varying from 2 to 4,
FF is the fill factor of the cell,
A the solar cell area,
η the efficiency of the cell,
P_{inc} is the incident power, and P_m is the maximum power point on the $J - V$ curve, defined by the points J_m and V_m.

The $J - V$ characteristic of the cell is described by the standard double-exponential model:

$$J = J_{sc} - J_{01}\left[\exp\frac{(V + JR_s)}{KT} - 1\right] + J_{02}\left[\exp\frac{(V + JR_s)}{2KT} - 1\right] \quad (5)$$

where: J_{01} and J_{02} are the saturation current densities of the diodes. R_s is the series resistance. High values of R_s can reduce the short-circuit-current and the open-circuit voltage. Therefore the effect of series resistance in solar cells can lead to a remarkable degradation of fill factor and efficiency. The shunt resistance is neglected.

To calculate the temperatures corresponding to each values of the concentration rate we solved numerically the heat transfer equation of the solar panel in equilibrium with the ambient atmosphere for different solar heat flux. The calculation details can be obtained in reference [10].

3 Solar cell structure details

Figure 1 shows the structure of the cell used in the simulation. The cell input parameters are those of a solar cell grown by metalorganic chemical vapor deposition technique (MOCVD). The device included a 300 Å $(Al_{0.9}Ga_{0.1})As$ front window layer which is nearly transparent to photons with energies below 3 eV. It prevents minority carriers in the emitter from diffusing to the front surface of the cell, where they could recombine at high rate. The highly doped buffer layer is used as a minority carrier mirror at the rear of the cell. Additional details of the structure can be found in reference [11].

Numerical simulations of the structure were carried out using SCAPS-1D. The materials parameters used are the same as those cited in reference [11]. For the absorption coefficient data, we used those given in reference [12]. The concentration illumination light are calculated for each rate of concentration varying from 1 to 10 suns, and inserted as input data in SCAPS-1D.

Other parameters that are temperature dependent, such as the effective density of states in conduction and valence bands, thermal velocity and mobility of charge carriers were calculated separately and then introduced in SCAPS.

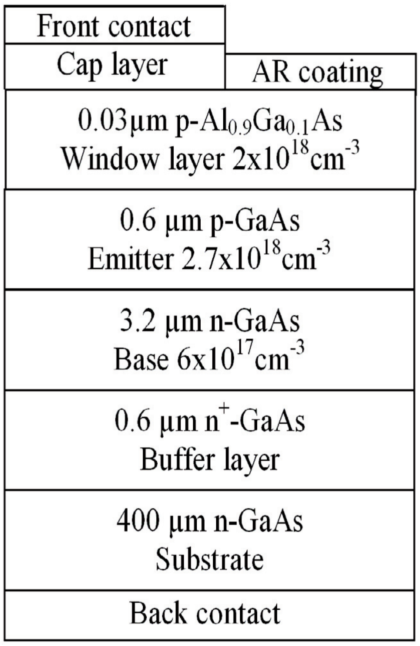

Fig. 1. AlGaAs/GaAs solar cell structure.

4 Results and discussion

4.1 Optical concentration and temperature effects

GaAs cells operating at high concentration absorb a large amount of heat, from infrared radiation, thermalization of recombined carriers and flow of high currents in resistive emitters and gridlines. However, junction temperature can easily exceed 50 °C under realistic operating conditions [1].

In order to evaluate the effect of concentration and temperature on the solar cell performances, short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF) and conversion efficiency (η) are calculated as a function of concentration rates, with and without cooling system.

The solar cell outputs (J_{sc}), (V_{oc}), (FF) and (η) are shown in Figures 2–5 respectively. The different temperatures calculated for the corresponding variations of concentration rates are shown on the curves by (T_{free}), which represent the temperatures of the free mode (without cooling). Elsewhere the temperature of the sink is taken as 300 K.

We found a good agreement between parameters calculated using equations (1–4) and those simulated with SCAPS-1D.

Short-circuit current increases with increasing concentration rate and temperature, as it is predicted by equation (1). But we can see that (J_{sc}) is not temperature-dependent, this can be attributed to increased sun light absorption, since semiconductor band gap decrease with

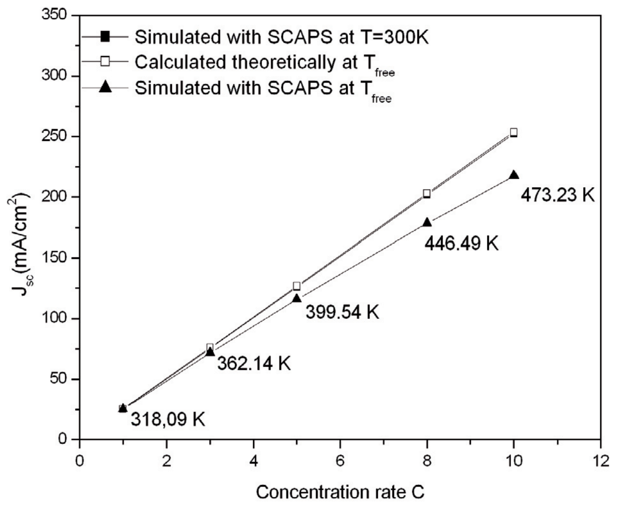

Fig. 2. Simulated and calculated short-circuit current versus concentration rate with and without cooling.

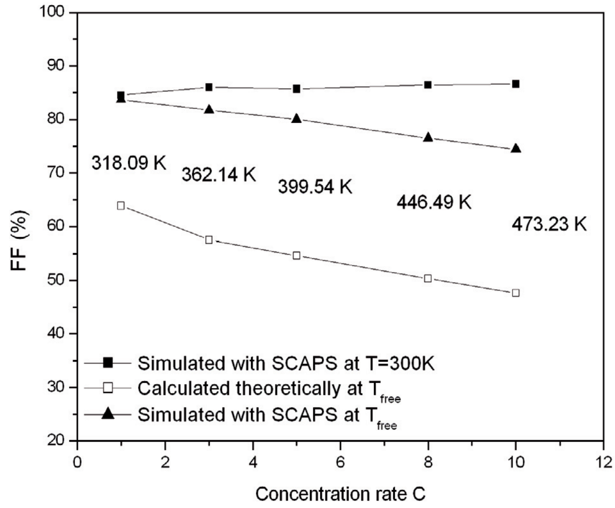

Fig. 4. Simulated and calculated fill factor versus concentration rate with and without cooling.

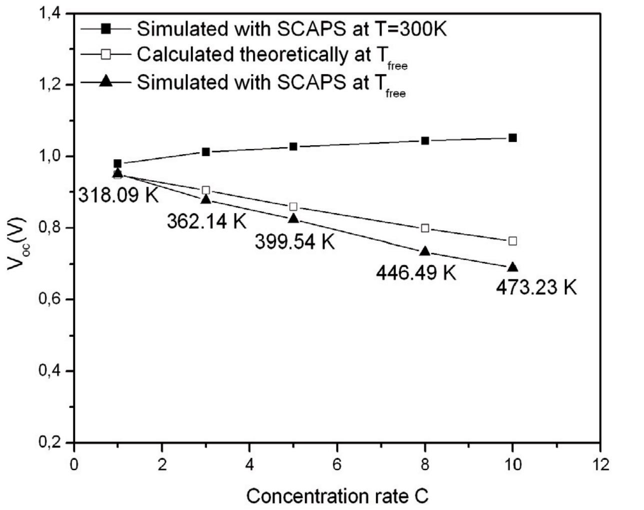

Fig. 3. Simulated and calculated open-circuit voltage versus concentration rate with and without cooling.

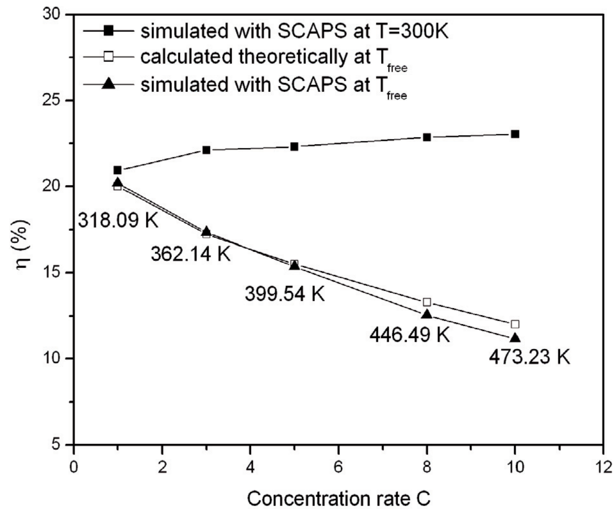

Fig. 5. Simulated and calculated solar cell efficiency versus concentration rate with and without cooling.

temperature, therefore more photons with lower energies are absorbed. However, the band gap narrowing with temperature leads to a reduction in (V_{oc}) and thereafter in (FF). The increase in (J_{sc}) is not enough to make up for the loss in (V_{oc}), so the efficiency also decreases with temperature.

In this case we conclude that the operation of concentration solar cells in free mode (without cooling) does not represent great interest in energy production. So, in order to extract the maximum advantage from the use of optical concentrators we must keep the temperature of the cell cooled close to ambient temperature.

In concentration solar cell technology this can be achieved by cooling. However, there are two types of cooling: passive cooling and active cooling [9,13], and the optimum cooling solution differs for the various types of concentration geometry: single solar cells geometry, linear geometry or densely packed modules geometry.

- In single solar cells geometry, sunlight is usually focused onto each cell individually. So each cell has an area equal to that of the concentration available for heat sinking. These cells typically only need passive cooling even for very high concentrations, such as cooling by air radiation. The cooling device is made up of linear fins on all available heat sink surfaces. It was recognized that passive cooling is more efficient for cells if their size is reduced (∼5 mm diameter) [14,15]. Heat sinks for such small cells would be similar to those used for power semiconductor devices.
- In linear geometry, where parabolic troughs or linear Fresnel lenses are used to focus the light onto a row of cells, both passive and active cooling can be used. For passive solution, cells are cooled using heat sinking or by a heat pipe approach. Also some new solutions were suggested for passive cooling by forced convection, such as microchannel heat sinks, which are very promising because they have the option

of being incorporated in the cell manufacturing process [13]. For active cooling, the row of cells is cooled by fluid (liquid or gas) flow through channels or an internally finned aluminum pipe. The fluid should be capable of absorbing and releasing heat by transporting it through its movement [13].

– In the case of densely packed modules geometry, each of the cells has only its rear side available for heat sinking, which implies that passive cooling cannot be used in this configuration. The active cooling concept is based on water cooling circuit, in which water flow through small parallel channels in thermal contact with the cells.

In other technologies, the cells are submerged in a circulating coolant liquid, by this way heat is transferred from two cell surfaces instead of one. Also the coolant acts as a filter by absorbing the incoming low-energy radiation before it reaches the cells. The coolant liquid must be dielectric to provide electrical insulation of the cells [13].

This was a short summary of cooling solutions for concentration solar cells. Nonetheless, experimental works are needed to know the best method of cooling for each system and to determine the costs of these performance cooling options which are not yet confirmed in the literature.

4.2 Series resistance effect

There are several physical mechanisms responsible for the series resistance, the major contributors are the bulk resistance of the semiconductor, the sheet resistance of the metallic contacts and interconnections, and the contact resistance between the metallic contacts and the semiconductor.

In concentrator solar cell it is important to minimize series resistance, as mentioned above (Sect. 4.1) an important part of heat is due to the flow of high currents in resistive emitters and gridlines (Joule effect).

In the structure shown in Figure 1, the emitter and the base were relatively highly doped to minimize bulk resistance [11]. Values of contacts resistance (between the gridlines and the cap layer) less than $10^{-5}\ \Omega\,\mathrm{cm}^2$ are usually acceptable and can be realized using a thin alloyed layer of Au/Zn/Au (for a p-type emitter) or Au/Ge/Ni/Au (for n-type emitter) [2]. Series resistance reported in reference [11] is quite low ($\sim$5 mΩ).

In SCAPS software, one can introduce different series resistance values, to study its effect on the solar cell output. In this work we calculated the fill factor and the efficiency of the concentrator solar cell versus concentration rate, for different series resistance.

From Figures 6 and 7 we can easily remark that the (R_s) has a significant effect on the (FF) and (η). A series resistance of only 1 Ω can lead to a crucial degradation in the fill factor and the efficiency particularly for high C values, when (FF) decreases at a rate of about 0.5% per decade, while (η) decreases at rate of 2% per decade.

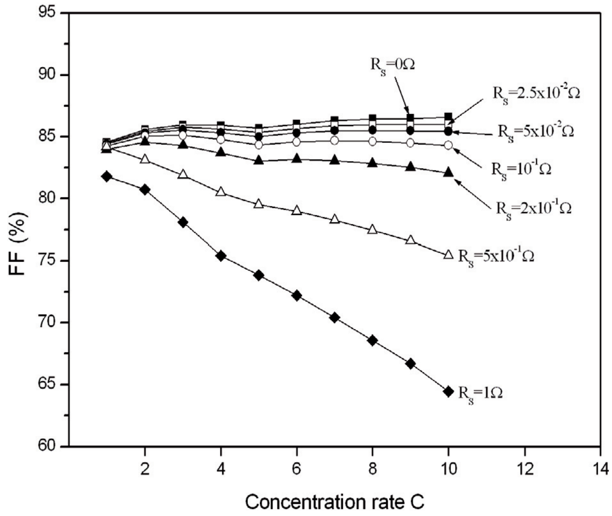

Fig. 6. Effect of series resistance on solar cell fill factor at $T = 300$ K.

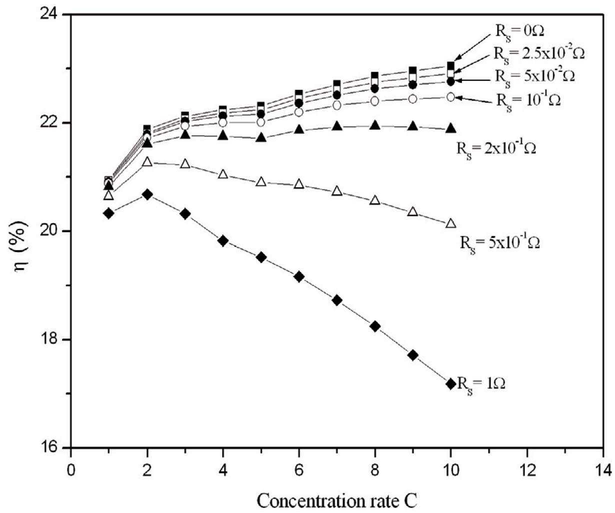

Fig. 7. Effect of series resistance on solar cell efficiency at $T = 300$ K.

5 Conclusion

The effects of temperature and series resistance on AlGaAs/GaAs concentrator solar cell operating under low injection have been investigated.

The solar cell outputs were calculated theoretically and by simulation using the software SCAPS. We found a good agreement between the two results.

The operation of the cell was studied in the two following cases: in free mode (without cooling) and a forced mode (with cooling). We noticed a remarkable degradation in the solar cell outputs in the free mode operation.

Solar cells operating under sunlight concentration suffer from heating effect, which can be crucial at high sunlight concentrations. For that reason the use of a cooling system is very necessary for a better operation of these cells.

High series resistances also lead to a degradation in concentrator solar cells performance especially when the concentration increases. So it is important to minimize series resistance in these cells.

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