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Modelling and simulation of InGaP solar cells under solar concentration: Series resistance measurement and prediction

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Abstract

One of the important parameters, that commonly affect solar cell performances, is the series resistance. Such effect becomes more pronounced when working under higher illumination intensities due to higher generated photocurrents. Therefore, it is necessary to predict series resistance effects under such conditions. To know more about the series resistance effect and its interpretation, InGaP based solar cell performances were investigated, using high solar concentration levels (73.36 X, 201.19 X). To facilitate the prediction of series resistance effect, as a function of insolation level, a computerised analytical model, using neural network, is presented.

Keywords: InGaP; Series resistance; Neural network; Concentrator solar cells

1. Introduction

InGaP based solar cells are reported in both photovoltaic [1–4] and photoelectrochemical [5–8] devices. For concentrator cells designed for high solar illumination intensities, e.g., several hundred suns or more, it is essential that Ohmic losses in the cell be very small. Expressed in terms of an effective series resistance, the series resistance-area product typically should not exceed a few $m\Omega\,cm^2$. The series resistance in a solar cell may seriously affect its maximum conversion efficiency [9–11]. Earlier studies, conducted under varying illumination intensities, used a set value of series resistance R_S. The concept of an effective series resistance parameter, R_S, is only based on an approximate model. Despite that, the model provides a practical method to estimate Ohmic losses and to design concentrator solar cells. For this reason, it is important to be able to measure R_S with reasonable accuracy.

The purpose of this paper is to study the series resistance effect on InGaP based solar cell efficiencies. In order to predict the series resistance effects, an analytical model using the neural network may be employed, as described here.

2. Experimental

P–n InGaP junctions were prepared by n-doping on a p-type wafer originally grown on a 200 μm Ge substrate by epitaxy. The n-type side was 200 nm thick, with doping density 2×10^{18} Si atoms/cm^3. The p-type side was 800 nm thick, with doping density 2×10^{17} Zn atoms/cm^3.

The InGaP cells (∼2 cm × 2 cm) were coated with Ag metal. The front grid was made of 2 bus bars, 1 mm wide, with about 80 fingers of 5 μm between them. Contact thickness was 2.5 μm, while sheet resistance was 900 Ω/□. The cells were mounted on Thermalclad substrates, which are commonly used for hybrid electronic circuits. The contacts were made by pressure on one of the two bus bars, with two spring arrows, as shown in Fig. 1.

All conversion measurements were conducted under solar radiation. The concentrator system used, Fig. 2, is advantageous

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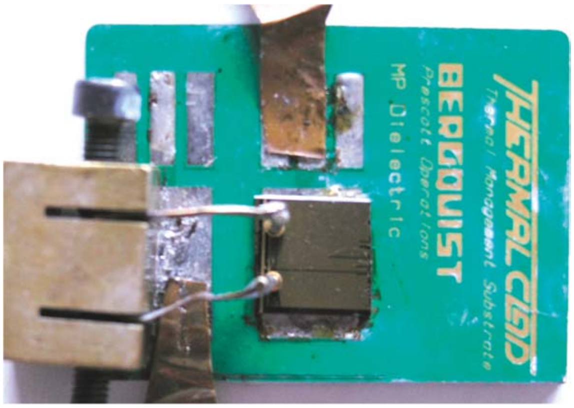

Fig. 1. InGaP solar cell display.

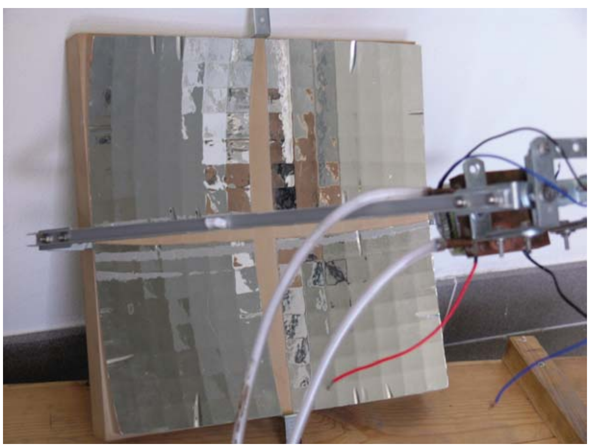

Fig. 2. The experimental Bloc.

for giving good illumination uniformity at the focus. The focus was 2 cm × 2 cm in area and was slightly larger than the dimensions of the tested cells.

A four-wire measurement was conducted. The four wires were contacted to two copper foils soldered at the substrate. A Kepco external voltage supply was used to counterbalance the voltage drop on the wires under short circuit conditions.

Cooling was performed using a Peltier heat pump. The hot side was cooled down by a high-efficiency heat exchanger with forced air. The Peltier was powered by a (3 A – 12 V) power supply.

The measured parasitic resistance introduced by this set-up was in the order of 20 mΩ. It is a minimal contribution for the tested cells. Under same experimental conditions, a good concentration solar cell shows only little degradation as a result of such parasitic effect.

3. Results and discussion

3.1. *Temperature and series resistance effects*

Enhancement, of solar cell conversion efficiencies, demands maximization of the three main cell photovoltaic parameters, namely: short-circuit photo-current density (J_{SC}), open-circuit voltage (V_{OC}) and cell fill factor (CFF). As the insolation level is increased (by a factor of C), in J_{SC}, V_{OC} increases logarithmically according to Eq. (1):

$$(V_{OC})_C = (V_{OC})_{1SUN} + U_T \ln C \tag{1}$$

where U_T is the thermal voltage, typically 26 mV at 28 °C.

Generally CFF increases as V_{OC} increases, mostly because of reduced diode current. However, CFF is most dependent on parasitic factors, such as shunt resistance and, most importantly at high illumination levels, series resistance.

The efficiency-concentration relation is described [12] by Eq. (2):

$$\eta(C)_{R_s} = \eta(C)_{R_s=0} - \frac{P_{R_s}(C)}{C P_i} = \eta(C)_{R_s=0} - \frac{R_s C^2 I_{SC}^2}{C P_i} \tag{2}$$

which after rearrangement becomes:

$$\eta(C)_{R_s} = \eta(1)\left[1 + \frac{n_f kT}{q V_{OC}(1)} \mathrm{Log}(C) - \frac{R_s C^2 I_{SC}^2}{C P_i}\right] \tag{3}$$

where

- $\eta(1)$, $V_{OC}(1)$ are respectively the efficiency and the open-circuit voltage under one sun.
- C is the concentration ratio
- q is the electron charge,
- P_i is the incident power,
- n_f the diode ideality factor,
- I_{SC} is the short-circuit current,
- $\frac{kT}{q} = U_T$ is the thermal voltage.

Practically, the efficiency increases with solar concentration, according to Eq. (3), reaches a maximum and decreases (Fig. 3). The efficiency lowering is due to two parameters: the temperature and the series resistance. The temperature dependence of the cell efficiency is of critical concern in a concentrator cell. This is because high insolation levels may elevate the cell temperatures well above ambient ones. It is well known that temperature affects performances of single junction [13] and

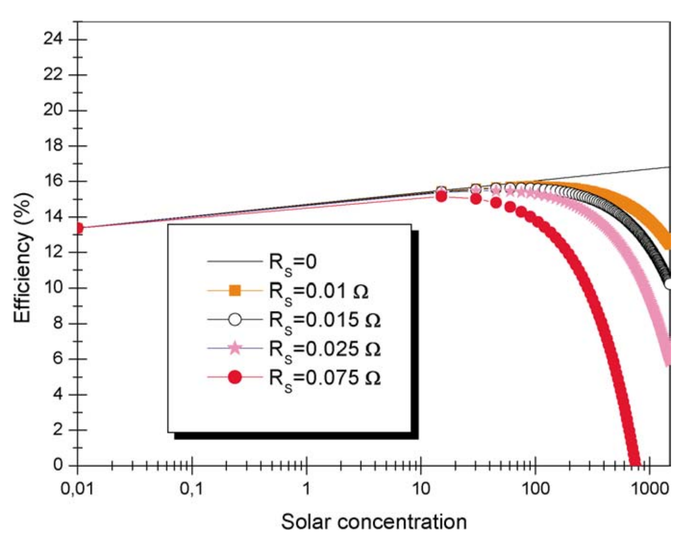

Fig. 3. Variation of the efficiency with solar concentration for different series resistances.

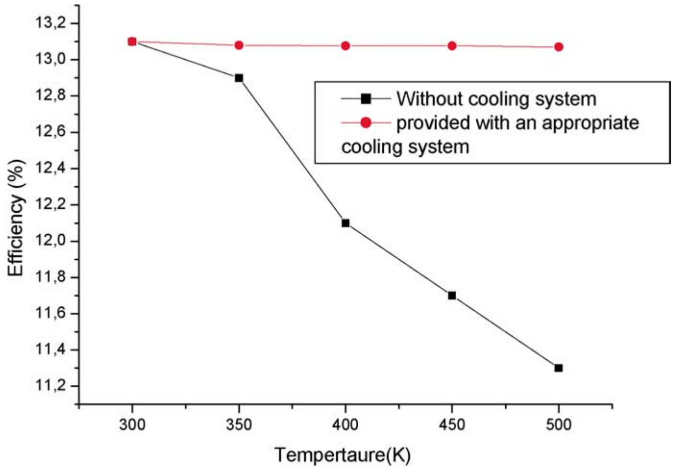

Fig. 4. Temperature effect on the device performance.

tandem [14] solar cells. The effect of temperature on lowering GaInP/GaAs solar cell efficiencies is reported in literature [2]. Such lowering is exhibited in lowering V_{OC} value as temperature increases. Passive and active cooling techniques are competing for heat removal from high-illumination photovoltaic cells, used with sunlight concentrators, to increase their output powers. Fig. 4 shows that effectively cooling retains solar cell efficiency. The primary dependence of efficiency is due to temperature dependence of V_{OC}. The temperature dependence of V_{OC} is shown in Eq. (4):

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{J_{SC}}{J_0}\right) \tag{4}$$

where J_0 is the diode saturation current density ($\mathrm{A\,m^{-2}}$).

As the concentration ratio increases, the attendant increase in short-circuit current causes the detrimental effects of the cell series resistance to become progressively more important. The series resistance will reduce the efficiency in two ways [12]. Firstly, some of the electrical power which is generated by the intrinsic device is dissipated as Joule heat in the resistive regions. Secondly, the presence of the later resistive voltage drop in the emitter causes the junction potential to be a function of position. Similar behaviours have been reported for single junction and tandem solar cells [2,15].

In order to minimize the series resistance effect, the grid dimensions could be optimized for maximum cell output power. The cell design must cope, however, with some problems related to the high energy flux under concentration. In particular, the high current density, in the cells, leads to collection losses that are mostly prominent in concentrated solar light cells [16]. The various power losses caused by the grid are [17–19]:

- losses due to the grid shadow,
- losses in grain boundaries due to the metal/semiconductor contact,
- power dissipated in the resistance of layer between bars, and
- losses in the grid metallization.

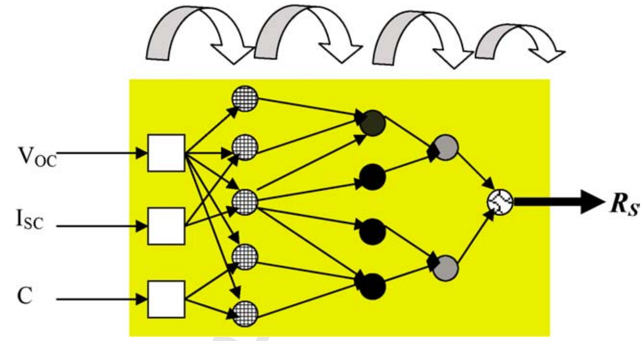

Fig. 5. Schematic neural network bloc.

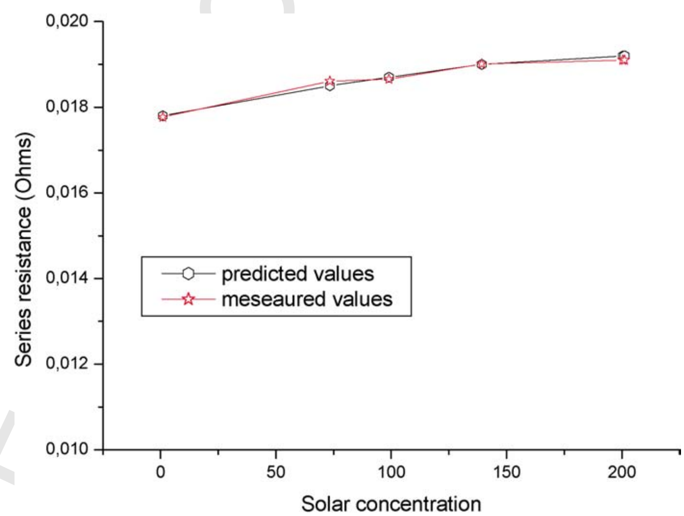

Fig. 6. Predicted and measured series resistance values at different solar concentrations.

3.2. Series resistance prediction and neural network bloc

In order to predict the series resistance effect, on device performance, as a function of insolation level, we employ a computer program using neural network, as shown in Fig. 5.

Typically, a neural network is initially "trained" or fed with large amounts of data and rules about data relationships. In addition, neural networks provide very close approximations of the correct answer with high speed.

Our multilayer perceptron neural network, using a supervised learning algorithm, includes three layers, where the inputs are: V_{OC}, I_{SC} and C: the solar concentration level. The target (output) is the series resistance. Thus, the proposed neural network predicts the series resistance value. The network itself evaluates the influence and dynamically readapts it depending on the obtained results in the learning and training process. The simulation was conducted with a good error of 2.3%, which is improvable if an appropriate choice of neural network model is chosen. The simulation results are illustrated in Fig. 6.

4. Conclusions

InGaP based solar cells, used in concentration systems, exhibit rapid efficiency lowering with higher temperatures, while working at low insolation levels. Moreover, the series resistance

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is concentration level dependent. Therefore, prediction of this detrimental parameter is necessary to estimate Ohmic losses and to design concentrator solar cells. Furthermore, careful processing control must be realized, as it may facilitate characterizing concentrator solar cells. An analytical model, using the neural network, was developed to predict the series resistance effect. The model was successfully applied to conventional InGaP based concentrator solar cells, as the predicted series resistance values showed good agreement with measured values. Such a model may also well be extended to other devices.

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