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Optimization of the PN junction thicknesses of an InGaN-based cell coupled to a resonant cavity to improve photovoltaic conversion efficiency

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***Abstract*— Given the low conversion efficiency of Silicon-based photovoltaic solar cells compared to the available solar potential, a great deal of research has been carried out on other III-V compound semiconductor materials to improve this efficiency. This is why Gallium Indium Nitride (In.Ga.N) has been intensively studied in the photovoltaic field for the past ten years, since this alloy has a modulable energy gap that sweeps the entire visible spectrum, from the near infrared (InN gap = 0.7eV) to the ultraviolet (GaN gap = 3.4eV), good absorption and resistance to high powers. Its advantages make it an excellent candidate for the production of very high-efficiency photovoltaic cells.**

On the other hand, multi-dielectric stacks acting as resonant cavities confine light and increase the probability of absorption in the solar cell's active layers.

It is against this backdrop that, in our previous work, we have proposed a method for synthesizing resonant dielectric multilayer stacks that exalt the optical field before it reaches the cell's photoactive layers, thereby improving photon absorption on the latter. This resonant structure, coupled to a single-junction cell based on In.Ga.N after its modeling, under illumination with the $AM_{1.5G}$ spectrum in static regime has been studied and the numerical results obtained with the Matlab/Simulink software show the importance of this coupling. In order to improve the performance of the coupled cell, the influence of doping on the cell's electrical parameters has been studied in our previous work, and this work focuses on the influence of emitter and base thicknesses on the electrical characteristics of the coupled cell, such as short-circuit current density (J_{sc}), open circuit voltage (V_{oc}) and the efficiency (η). The results obtained show an improvement in the short-circuit current density of $36.5mA/cm^2$ for the control cell at $41.20mA/cm^2$ for the optimized cell ; and for the open circuit voltage of $0.94V$ for the control cell à 0.96 V for the optimized cell and, finally, with an efficiency of 30.20% for the control cell versus 34.54% for the optimized cell.

***Keywords*— Junction PN, solar cell, resonant cavity, thickness, coupling, nanostructures, Optimization, conversion efficiency**

I. INTRODUCTION

Today, the growth of the global economy and demographics, particularly in developing countries, has led to a rapid increase in energy consumption. Based on this observation, many forecasters note that primary commercial energy consumption will double by 2030 and triple by the 2050 [1]. Most of the primary energy consumed comes from fossil fuels, which are responsible for global warming because of the greenhouse gases they emit [2].

In view of the harmful effects of fossil fuels on the environment, and their depletion in the more or less long term, the search for renewable energy sources that are independent of fossil fuels and reduce global warming is becoming a palliative solution to current energy problems. These include biomass, hydraulic, wind, geothermal and solar energy. These are natural energies that are available, clean and inexhaustible on a human scale [3]. As a result, research into renewable energies, and photovoltaic energy in particular, has grown

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considerably in recent years. Solar energy is the most abundant and widely shared form of energy on earth, but its yield is still low.

In order to improve the latter, the photovoltaic industry has turned to new strategies such as the use of materials other than silicon and light trapping at the cell level [4]. The new materials most frequently used in this sector are III-V nitrides, thanks to their remarkable characteristics. Among these, Gallium Indium Nitride (In.Ga.N) has been the subject of extensive research since 2002 as a photovoltaic material, thanks to its scalable energy gap and high absorption coefficient [5], [6]. On the other hand, trapping light in resonant cavities or interference filters increases the quality factor and therefore the absorption within them [7], [8].

This is the background to this work, which focuses on optimizing the geometric parameters (in this case, layer thicknesses) of a single-junction solar cell based on Gallium Indium Nitride (In.Ga.N) coupled with dielectric nanostructures. Thus, the aim of this paper is to show the effect of the thicknesses of the N- and P-doped layers on the performance of the coupled solar cell. Therefore, starting from the standard thicknesses (195nm for the P-layer and 1020nm for the N-layer) commonly used in the industry [9], for uncoupled cells, depending on the technology, we will show that the effect of coupling requires a revision of the latter's thicknesses. The study is based on optoelectronic modelling and spectral simulations using Matlab/Simulink software to extract the electrical parameters of this new solar cell configuration.

II. MODEL DESCRIPTION

In this study, we consider a single-junction solar cell based on Gallium Indium Nitride (In.Ga.N) coupled to a multi-dielectric resonant structure as shown on the Fig. 1. The z axis represents the depth of the solar cell. In practice, the cell dimensions along the x and y axes are very large compared to the depth of the solar cell. Current is therefore neglected in these directions.

The resonant structure consists of a superstrate (glass), alternating thin dielectric layers of high and low index, and the substrate (air). The indices of the superstrate (glass) and substrate (air) are respectively $n_o = 1.52$ and $n_s = 1$. The high-index and low-index dielectric materials used are tantalum penta-oxide and tantalum oxide, respectively (Ta_2O_5) with $n_H = 2.141$ and silicon dioxide (SiO_2) with $n_B = 1.4570$.

The $In_xGa_{1-x}N$-based thin-film mono-junction cell consists of an anti-reflective layer, a P-doped layer (emitter) and an N-doped layer (base).

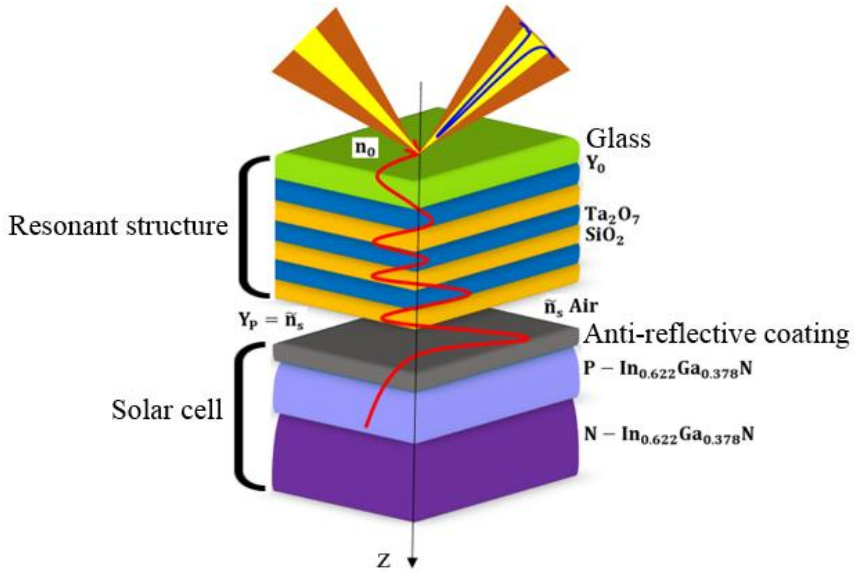

Fig. 1 Single-junction solar cell based on $In_xGa_{1-x}N$ coupled with the resonant structure

III. SOLAR CELL MODELING

To improve the performance of a solar cell, its configuration can be modified. The cell is modeled in the static regime under multi-spectral illumination. Thus, the photocurrent density for a wavelength ($J_{ph}(\lambda)$) is obtained from 3 types of current densities such as J_n , J_p et J_{ZCE} whose expressions are given below [8], [10]:

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$$J_n(\lambda) = \left(\frac{qF(1-R)\alpha L_n}{\alpha^2 {L_n}^2 - 1}\right)\left(\frac{\left(\frac{S_n\tau_n}{L_n} + \alpha L_n\right) - e^{-\alpha x_j}\left(\left(\frac{S_n\tau_n}{L_n}\right)\cosh\left(\frac{x_j}{L_n}\right) + \sinh\left(\frac{x_j}{L_n}\right)\right)}{\left(\frac{S_n\tau_n}{L_n}\right)\sinh\left(\frac{x_j}{L_n}\right) + \cosh\left(\frac{x_j}{L_n}\right)} - \alpha L_n e^{-\alpha x_j}\right) \quad (1)$$

$$J_p(\lambda) = \left(\frac{qF(1-R)\alpha L_p}{\alpha^2 {L_p}^2 - 1} e^{-\alpha(x_j + w)}\right)\left(\alpha L_p - \frac{\left(\frac{S_p\tau_p}{L_p}\right)\left(\cosh\left(\frac{H}{L_p}\right) - e^{-\alpha H}\right) + \sinh\left(\frac{H}{L_p}\right) + \alpha L_p e^{-\alpha H}}{\left(\frac{S_p\tau_p}{L_p}\right)\sinh\left(\frac{H}{L_p}\right) + \cosh\left(\frac{H}{L_p}\right)}\right) \quad (2)$$

$$J_{ZCE}(\lambda) = qF(1-R)e^{-\alpha x_j}(1 - e^{-\alpha w}) \quad (3)$$

$$J_{ph}(\lambda) = J_n(\lambda) + J_p(\lambda) + J_{ZCE}(\lambda) \quad (4)$$

Avec

- $J_n(\lambda)$: current density collected by the transmitter at a given wavelength.
- $J_p(\lambda)$: current density collected by the base at a given wavelength.
- $J_{ZCE}(\lambda)$: current density collected by the space charge zone at a given wavelength.

To demonstrate the influence of thickness on cell performance, we calculated the short-circuit current density, J_{ph} (λ) and open circuit voltage Voc under multi-spectral illumination. Consequently, the total photocurrent density, J_ph, is obtained by integrating the current density, $J_{ph}(\lambda)$ across the entire solar spectrum [11], [12].

$$J_{ph} = \int_{\lambda_{min}}^{\lambda_{max}} J_{ph}(\lambda) d\lambda = \int_{\lambda_{min}}^{\lambda_{max}} J_n(\lambda) d\lambda + \int_{\lambda_{min}}^{\lambda_{max}} J_p(\lambda) d\lambda + \int_{\lambda_{min}}^{\lambda_{max}} J_{ZCE}(\lambda) d\lambda \quad (5)$$

The expression for open circuit voltage V_{oc} dependent on inverse saturation current density J_0 is given by [13], [14]:

$$V_{oc} = \frac{K_B T}{q} \ln\left(\frac{J_{ph}}{J_0} + 1\right) \quad (6)$$

With $J_0 = qn_i^2\left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right)$ (7)

In addition, determining the final cell performance criterion requires an assessment of the cell's efficiency (η) which is given by :

$$\eta = \frac{P_m}{P_{inc}} = \frac{J_m * V_m}{P_{inc}} \quad (8)$$

IV. Results and discussions

Here, we present the results of this modelling after simulation using Matlab/Simulink software for a temperature of 300 K with optimal Na and Nd values and non-optimal thicknesses [8]. So we took the doping concentration of the layer P, $Na = 2.86\,10^{18} cm^{-3}$ with a thickness of 195 nm. The N-layer doping concentration is $Nd = 5.66\,10^{17} cm^{-3}$ with a thickness of 1020 nm.

The preliminary results obtained after modelling this cell as a reference cell show the current-voltage (J-V) and power-voltage (P-V) characteristics shown on the diagrams Fig. 2 et Fig. 3.

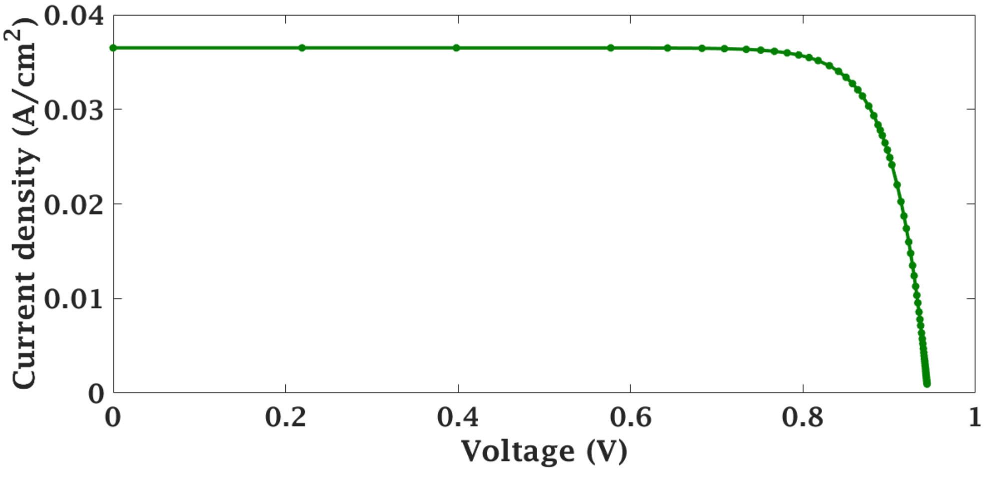

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Fig. 2 Current-voltage characteristic of reference cell

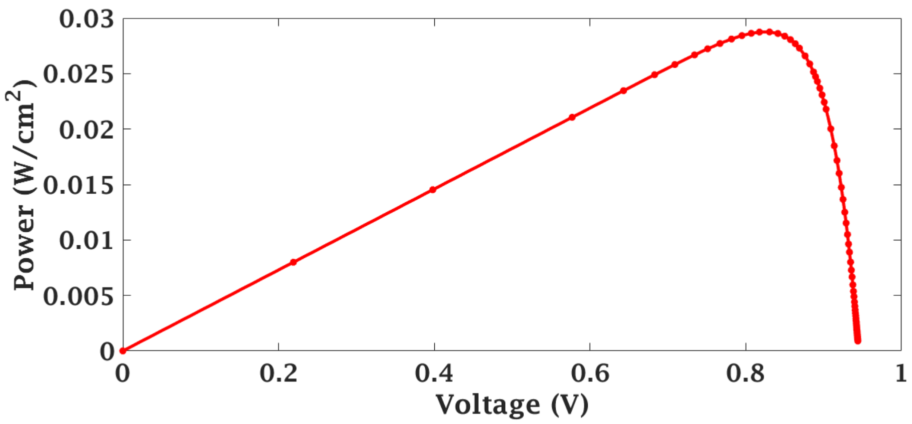

Fig. 3 Power voltage characteristic of reference cell

According to these two curves, we had an open circuit voltage of $V_{oc} = 0.94$ V and short-circuit current density $J_{sc} = 36.5\ mA.cm^{-2}$ for a maximum power of $28.75\ mW.cm^{-2}$. The resulting yield is 30.20%.

To further improve the conversion efficiency of this reference cell, we optimized it by studying the effect of coupling on the thicknesses of the P and N layers. Thus, through a parametric study of thicknesses and by fixing the doping of the layer N to $Nd = 5.66\ 10^{17} cm^{-3}$ and the layer P to $Na = 2.86\ 10^{18} cm^{-3}$, we find :

- Layer thickness P : $z_j = 130$ nm
- Layer thickness N : $H' = 820$ nm

Based on these results, we were able to determine the current-voltage (J-V) and power-voltage (P-V) characteristics of the optimized solar cell under illumination $AM_{1.5}$ $(0.1W/cm^2)$ and temperature $(T = 300\ K)$. Thus, the (I-V) and (P-V) characteristics resulting from this simulation are represented respectively on the Fig. 4 et Fig. 5.

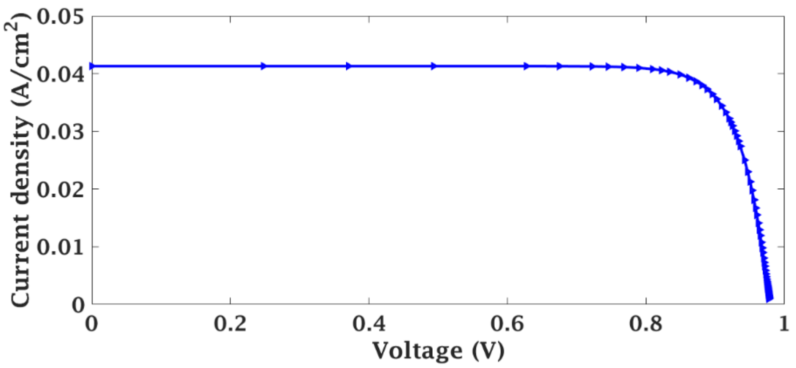

Fig. 4 Current-voltage characteristic (J-V) of optimized cell

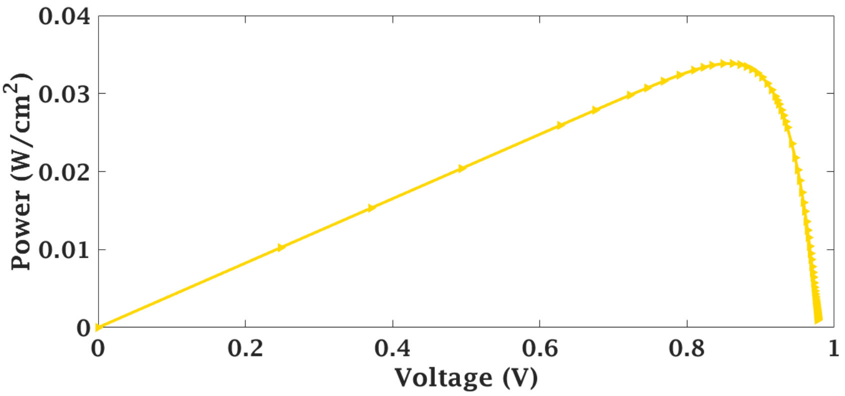

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Fig. 5 Power-voltage (P-V) characteristic of optimized cell

Based on these two characteristics, we have calculated the parameters of the optimized solar cell, which are grouped in table I.

TABLE I OUTPUT PARAMETERS OF THE OPTIMIZED COUPLED CELL

Parameters	Values
$V_{co}(V)$	0.96
$J_{sc}(mA.cm^{-2})$	41.20
$P_{max}(mW.cm^{-2})$	32.89
η (%)	34.54

In this section, we will carry out a comparative study between the reference cell and the optimized cell in order to see the influence of the cell layer thicknesses. The current-voltage J(V) and power-voltage P(V) characteristics of these two cells are shown respectively on the Fig. 6 et Fig. 7.

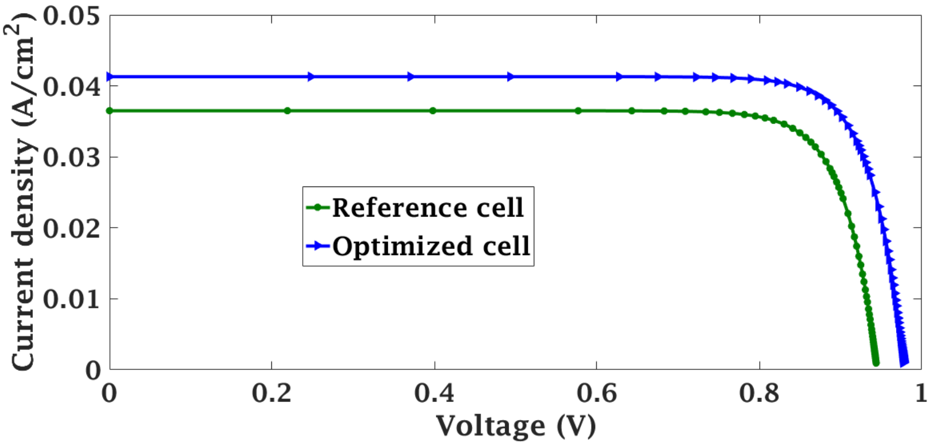

Fig. 6 Current-voltage characteristic of both cells

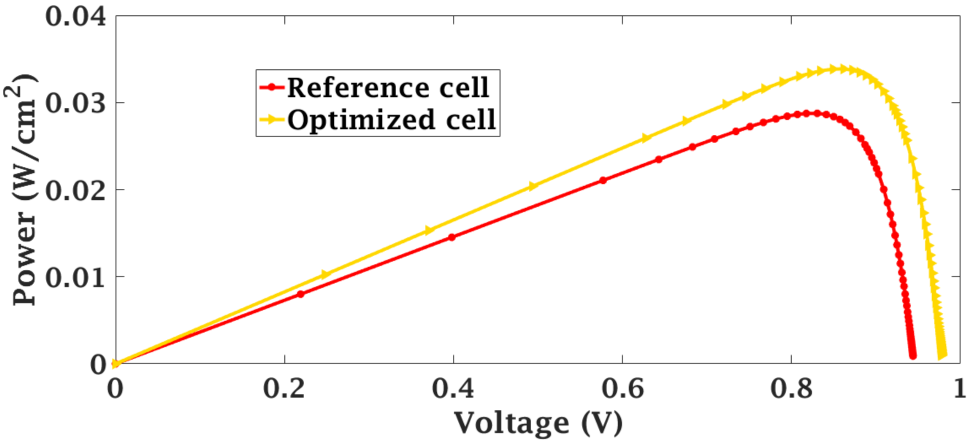

Fig. 7 Power-voltage characteristic of the two cells

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From these two curves we can see that the current-voltage I(V) and power-voltage P(V) characteristics of the optimized cell are significantly better than those of the reference cell. The photovoltaic parameters extracted are shown in table II below.

TABLE II OUTPUT PARAMETERS OF BOTH CELLS

	Jsc (mA/cm^2)	**Voc (V)**	**Pmax (mW/cm^2)**	**Ƞ (%)**
Reference cell	36.50	0.94	28.75	30.20
Optimized cell	41.20	0.96	32.89	34.54

According to this table, the performance of the optimized cell is better than that of the reference cell, with an efficiency of 34.54% for the optimized cell compared with 30.20% for the reference cell. The difference in performance between these two structures can be explained by the fact that resonant structures make it possible to increase local light intensity in the cell ; which requires fine-tuning of thicknesses to match resonant wavelength. The thicknesses of the emitter (P-layer) and base (N-layer), 130nm and 820nm respectively for the optimized cell, represent the optimum thicknesses for obtaining greater collection efficiency in the Space Charge Zone (SCZ), thereby increasing the short-circuit current density.

V. CONCLUSION

In this paper, we have modeled a single-junction solar cell based on Indium Gallium Nitride (In.Ga.N) coupled to a multi-dielectric resonant structure under multispectral illumination in the static regime. We simulated this cell using Matlab/Simulink software, with optimal emitter and base doping, to obtain preliminary results with a conversion efficiency of 30.20%. To improve its performance, we modified the cell's geometrical parameters by modifying the thicknesses of the emitter and base. As a result, the best performances are obtained with 130nm thickness for the emitter and 820nm thickness for the base, giving an optimum conversion efficiency of 34.54%. However, we note that the influence of emitter thickness on cell performance is much greater than that of base thickness. However, for a more complete parametric study of the cell geometry, it would be necessary to take into account the influence of the thicknesses of the anti-reflective layer and the air gap between the resonant structure and the solar cell.

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