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Modeling and analysis of grating structure for enhancing the absorbance in InGaN-based solar cell

A. Merabti[a,b,*], H. Aissani[a,b], S. Nour[a,b], R. Abdeldjebar[a], A.A. Djatout[a]
[a] *Exact Sciences. Higher Normal School of Béchar, Algeria*
[b] *Semiconductor Devices Physics Laboratory, University Tahri Mohammed Béchar, Algeria*

Good light trapping is essential to make high efficiency InGaN-based solar cells. As InGaN wafers are being made increasingly, thinner, light trapping becomes even more important. In this study, we propose a structure of one-dimensional InGaN grating for the InGaN-based solar cells is proposed. The solar energy absorption characteristics of this structure are studied by the the Finite element method (FEM) method. By alternately altering the grating depth and the filling factor, a new type of grating structure is proposed. For such a structure, different gratings are studied. Numerical computation shows that the absorptance of the InGaN grating structure is over 0.88 throughout the entire computational band. The optimum parameters of the proposed structure are period (a = 480 nm), a filling factor (ff = 50 %) and depth (d=210 nm), which indicates the proposed structured surface may have potential applications in solar cells manufacturing.

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Keywords: Absorption, FEM simulations, InGaN, Light trapping, Gratings

1. Introduction

III –V nitride semiconductors has attracted research interest as a promising platform in optoelectronics because of its unique electronic and optical properties [1]. By tuning the indium content in InGaN materials, different band gaps (wide direct band gaps ranging from 0.7 eV for indium nitride (InN) to 3.42 eV for gallium nitride (GaN)) can be obtained, making these materials inexpensive for power photovoltaic applications. This provides InGaN with a great potential for photovoltaic applications; especially, when they are used in Grating Structure solar cells, by changing their dimensions, to optimize the devices' ef-ficiency and performance. Although InGaN-based solar cells are still not fully developed, various theoretical models and numerical simulations have been conducted to investigate the performance of single and multiple-junction InGaN-based solar cells. Other properties of InGaN materials include high radiation tolerance, high mobility, and high absorption coefficient [2].

On the other hand, the device fabrication of various InGaN-based solar cells has yielded some interesting and promising results. For example, p-GaN/i-InGaN/n-GaN het-erojunction, p-InGaN/i-InGaN/n-InGaN homojunction, p-InGaN/n-InGaN homojunction and InGaN/GaN multiple quantum well solar cells have shown good photovoltaic effects [3].

Research on light trapping strategies has attracted a lot of attention in recent years. The concept of "light trapping" appeared in the early 1970s to increase the absorption of light and the efficiency of silicon cells, particularly in the near infrared [4-5]. In order to achieve high efficiencies, solar cells must exhibit high light absorption. Developing new optical structures or devices to improve light trapping within solar cells is a real challenge.

Light trapping and enhancement systems amount to lengthening the optical path of light. Alternatively, this consists in optimizing the lifetime of the photons in the medium. The goal is therefore to try to "trap" the light to increase its probability of being absorbed. Light trapping is, a key issue of reaching the ambitious cost reduction plans for the photovoltaic (PV) industry. Therefore, Light trapping increases current generation in solar cells and makes it possible to reduce material costs by utilizing thinner solar cells. In addition to the reduced material

* Corresponding author: merabti73@yahoo.com
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consumption, a thinner solar cell also relaxes the demand on material quality as the dependence of efficiency upon bulk recombination is reduced[6-7].

In this work, a new TE polarization grating structure is proposed. Our purpose is to obtain the optimal structure with high absorptance in a large wavelength range. Further-more, the structure is used in solar cells in order to improve the light-electric con-version efficiency. We investigate the possible use of InGaN nanostructures, which can be grown using the nano-selective area growth (NSAG) technique [8]. For InGaN, NSAG material has been recently shown to be free of dislocations even at high indium incorporation (up to 40%) [9].

In this paper, the numerical computation is conducted to study the spectral prop-er-ties of InGaN grating structures with different dimension by the Finite element method (FEM). From the numerical results, the effects of grating sizes and their assembly forms on the light-trapping ability of solar cells are studied.

2. Design and modeling of the grating structure

In this work, all simulations were performed at 300 K with an incident solar radia-tion of 1000 W/m2 (AM 1.5G).

The proposed device is a simple three-layered p-InGaN/p-InGaN/n-InGaN (PPN) so-lar cell with a practical thickness. The top layer and the middle layer of the p-InGaN lay-ers have different indium mole fractions (x = 0.65 and 0.75, respectively), and the bottom is an n-InGaN plane (the second p-InGaN and last layer n-InGaN have the same indium mole fraction (x= 0.65).

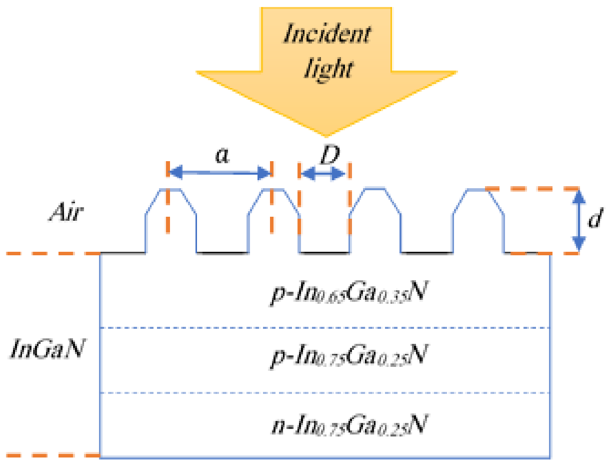

Fig. 1. Schematic of the InGaN grating structure. a is the grating period; d is the grating depth and D is the grating width.

The structure parameters for the TE polarization InGaN grating structure with operating wavelength at 420 nm are of a planar p-InGaN/p-InGaN/n-InGaN (PPN) thin-film structure is shown in Figure 1. The top p-InGaN layer was varied to maximize the absorption in the active region.

A the Finite element method (FEM) simulation software was employed to calculate the electric fields as well as absorption in the InGaN grating structure. In the FEM simulations, plane wave illumination was employed, and plane waves (with free space wave-lengths ranging from 350 to 750 nm) were incident on the front surface of the proposed device.

In order to optimize the dimensions of the proposed device (such as width, height, and period), we employed only the TE-polarized light. In our simulations, the real and imaginary parts of refractive indices of the InGaN material depend on its band gap energy (Eg), which is a function of the indium content (x) of InxGa1-x N and is given by the following relationship [10-11].

$$n(h\nu) = \left\{ a(x) \left(\frac{h\nu}{E_g}\right)^{-2} \left[2 - \left(1 + \left(\frac{h\nu}{E_g}\right)^{\frac{1}{2}} - \left(1 - \left(\frac{h\nu}{E_g}\right)^{\frac{1}{2}} \right) \right) \right] + b(x) \right\}^{\frac{1}{2}} \quad (1)$$

where E_g is the band gap of the material, n is the frequency of the laser emission, h is Planck's constant and $a(x)$ and $b(x)$ are fitting parameters. The fitting parameters $a(x)$ and $b(x)$, are obtained from spectrally resolved refractive index measurements of the binary compounds (GaN, AlN and InN), and are given by

$$a(x) = 13.55x + 9.31(1 - x) \quad (2)$$

$$b(x) = 2.05x + 3.03(1 - x) \quad (3)$$

Although the method proposed by Peng uses a greater amount of actual experimental refractive index data than that of Bergmann and Casey, the method suffers from inconsistencies similar to those found in the work of Bergmann and Casey [7].

3. Results and discussion

3.1. Effect of parameter the grating depth (d)

Figure 2. Shows the spectral absorptance of gratings depth d = 100 nm, 150 nm and 210 nm for a fixed grating width (D) of 325 nm and the grating period a = 650 nm for the normal incidence, respectively. The curves for an InGaN bulk are also shown in the same figure for comparison. Obviously, the spectral absorptance of InGaN grating structure is much larger than that of InGaN bulk. The intuitive reason for this spectral property is that the contact area between the structure surface and the sunlight is increased. Then the part of light entering the structure is increased. Photons are multi-ply-reflected inside the grooves of gratings, which leads to increase in the absorptance.

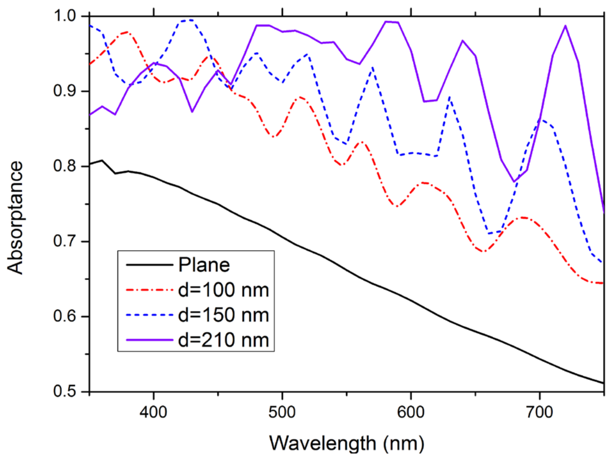

Fig. 2. The absorptance spectra of InGaN gratings with the depth h of 100 nm, 150 nm and 210 nm. The absorption properties of an InGaN bulk are plotted for comparison.

For the case of d = 210 nm, the absorption curve respectively has a peak and a valley in the vicinity of wavelength 480 nm and 650 nm. Furthermore, such peak and valley are shifted toward to the short wave with increase of d. Meanwhile, it is observed that the more than one peak and valley may appear with increase of d. This feature is due to the fact that the microcavity effect is dependents upon the parameters of the microcavity structure. The excitation wavelength of microcavity effect varies with d.

The absorptance of the three grating surfaces is higher in some wave bands but lower in other bands. For example, the grating structure with d = 210 nm has a higher absorption spectrum in the region of 480–650 nm. The absorption spectrum exhibits larger value for the case of d = 150 nm and 210 nm. Under the standard incidence of AM1.5G, Here it is assumed that each absorbed photon produces one electron hole.

3.2. Effect of parameter the filling factor (ff)

The influence of the width (D) on the absorption is studied with different filling factor $(ff = D/a)$. Figure 3. Shows the effect of the filling factor of the grating structure on the surface absorptance. These curves are computed for the grating structures with three filling factors of 0.3, 0.5 and 0.7 at the fixed grating depth d= 210 nm and the grating period a = 650 nm, The absorption of unpatterned layer InGaN is also shown for comparison. The figure shows that the absorptance of the structure with filling factor 0.5 is the highest within the most wave-bands except that the wavelength of about k = 380 nm and 670 nm. It is also observed that the absorption curve broadens in the region of k = 430 nm and 600 nm.

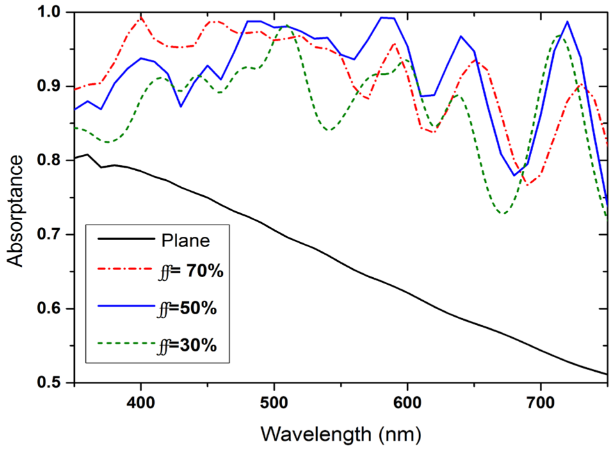

Fig. 3. The effect of filling factor on the absorption properties of the assembly grating structure.

3.3. The optical spectra

Figure 4 shows the optical spectra of the InGaN plane and the InGaN grating structure. The Fig. 4 (a) and the Fig. 4 (b) are corresponding to the InGaN plane and the InGaN grating structure, respectively.

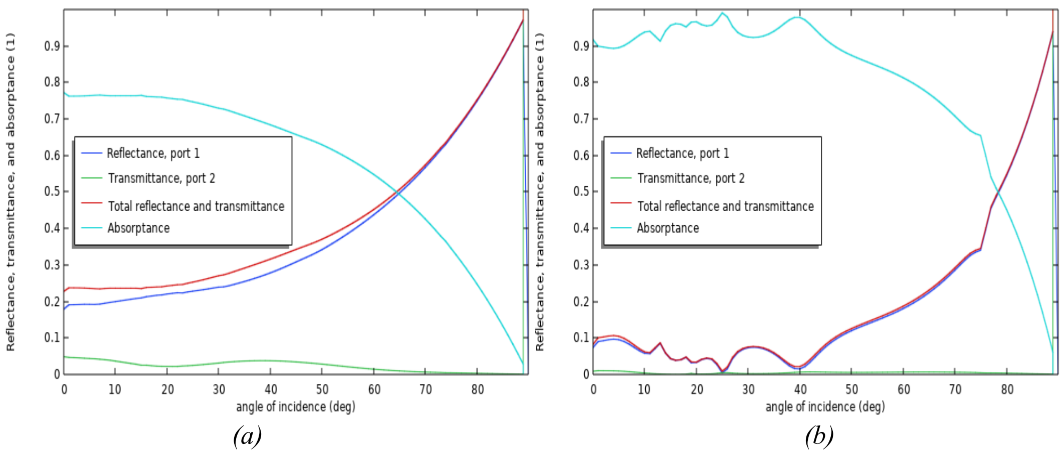

Fig. 4. The optical spectra of the (a) InGaN plane and (b) the InGaN grating structure.

The results presented in the figure show the InGaN grating structure in existence is propitious to trap the sunlight and reduce the reflectance of the solar cells.

3.4. Field distribution in various structure

To gain a better understanding of the absorption mechanism, the electric field intensity distribution wavelength is shown in Figure 5, which is normalized by the electric field intensity of the incident plane wave. As can be seen from the figure, there are large electric field intensity enhancement and concentration into the inside the InGaN grating structure, which shows a typical feature of guided mode. The enhancement of absorption can be attributed to the guided mode resonance.

As a result, more light confinement can be seen inside the active region. The radiation is absorbed near the surface and fails to penetrate enough into the inside the InGaN grating structure, at high wavelengths. The Electric field density plots confirm that InGaN grating structure are much efficient compared with the InGaN plane structure.

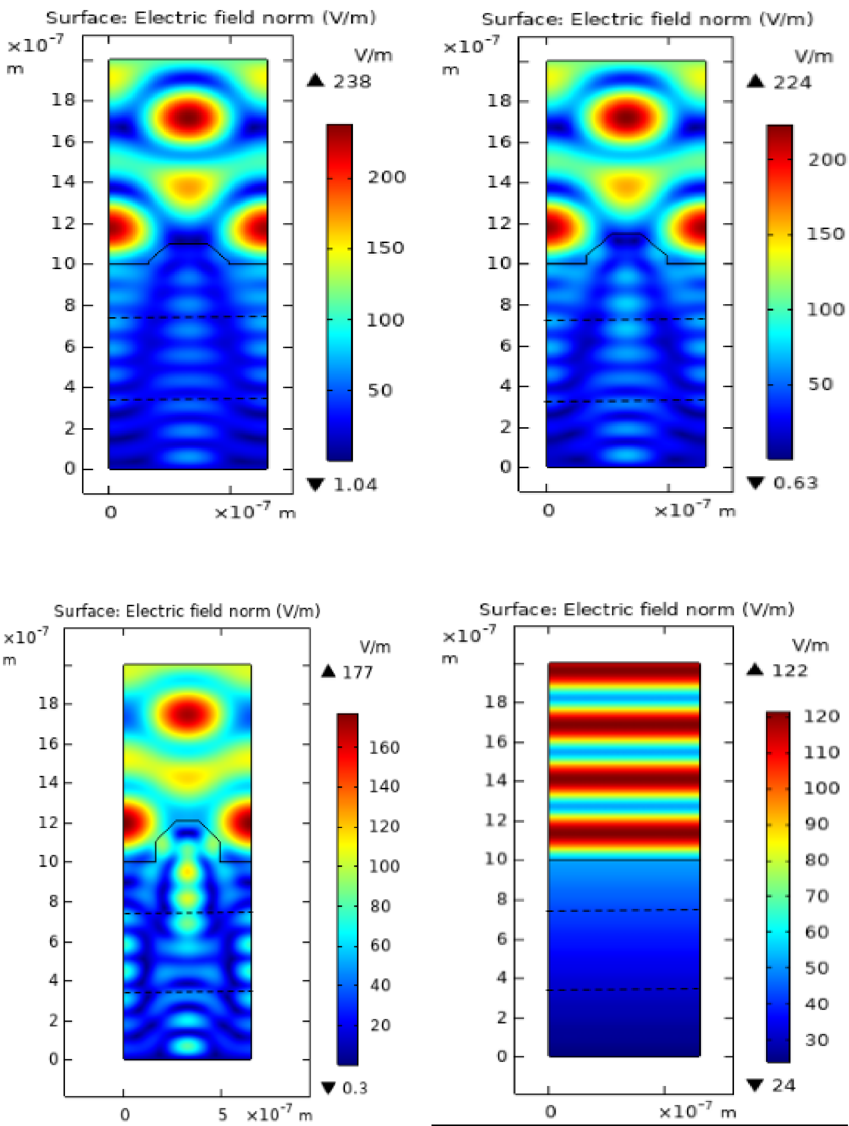

Fig. 5. Electric field intensity distribution obtained a=480 nm, D=222 nm and k=550 nm,for InGaN gratings for with the depth : a) 100 nm, b)150 nm , c) 210 nm , and d)plane InGaN structure.

4. Conclusion

We have shown the potential of an InGaN-based grating structure for light-trapping purposes. This is an improvement of considerably better compared to a reference structure with the same thickness, but they are also particularly sensitive to absorption in the wavelengths ranging from 350 to 750 nm. The increase in absorption is due to enhanced path length inside the structure. In this work, we also show the influence of grating thickness on the light harvesting. Finally, the simulation results and the proposed structure could be used as guidelines to designing and fabricating high-performance InGaN-based solar cells.

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