Journal of Advanced Research 10 (2018) 15–20

Contents lists available at ScienceDirect

Journal of Advanced Research

journal homepage: www.elsevier.com/locate/jare

Original Article

Plasmonic thin film InP/graphene-based Schottky-junction solar cell using nanorods

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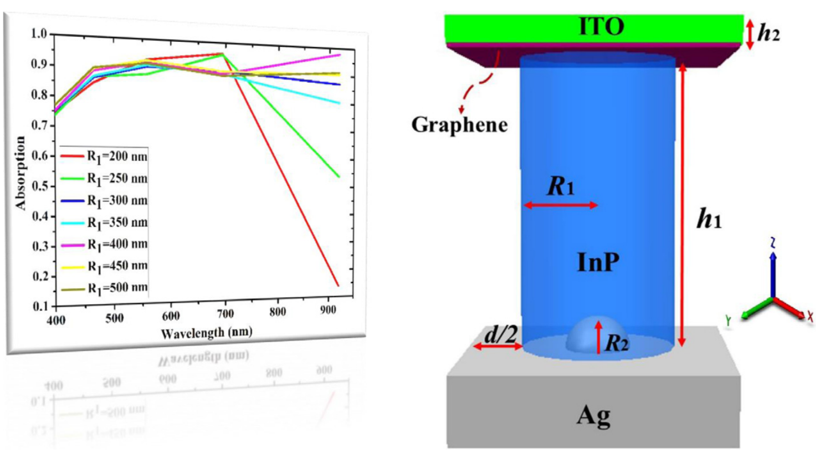
GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 September 2017
Revised 4 January 2018
Accepted 24 January 2018

Keywords:
Graphene/InP solar cells
Nanorods
Graphene
Light trapping
Short circuit current density
Finite difference method (FDM)

ABSTRACT

Herein, the design and simulation of graphene/InP thin film solar cells with a novel periodic array of nanorods and plasmonic back-reflectors of the nano-semi sphere was proposed. In this structure, a single-layer of the graphene sheet was placed on the vertical nanorods of InP to form a Schottky junction. The electromagnetic field was determined using solving three-dimensional Maxwell's equations discretized by the finite difference method (FDM). The enhancement of light trapping in the absorbing layer was illustrated, thereby increasing the short circuit current to a maximum value of 31.57 mA/cm^2 with nanorods having a radius of 400 nm, height of 1250 nm, and nano-semi sphere radius of 50 nm, under a solar irradiation of AM1.5G. The maximum ultimate efficiency was determined to be 45.8% for an angle of incidence of 60°. This structure has shown a very good light trapping ability when graphene and ITO layers were used at the top and as a back-reflector in the proposed photonic crystal structure of the InP nanorods. Thence, this structure improves the short-circuit current density and the ultimate efficiency of 12% and 2.7%, respectively, in comparison with the InP-nanowire solar cells.

Peer review under responsibility of Cairo University.
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https://doi.org/10.1016/j.jare.2018.01.008
2090-1232/

Introduction

Solar cells, which convert solar energy into electrical energy with remarkable conversion efficiencies, are attractive candidates for renewable [1], endless and clean power sources [2,3]. Meanwhile, thin solar cells are a very important class of photovoltaics and have recently become the subject of intense research, commercialization, and development efforts due to their high efficiency and low cost. Commonly, the film thickness is equivalent to two microns or less, and is used in absorptive materials devices [4]. Light trapping is one of the methods of increasing light absorption in thin film solar cells, due to multiple reflection within the absorbing layers [5–7]. Light-trapping can be achieved by the formation of a wavelength-scale texture on the substrate and by depositing thin layers of the solar cell on it [8]. Compared with the generally used Si, indium phosphide (InP) has a direct band gap of 1.34 eV [9,10], which is located in the broad range of the solar energy spectrum [11]. InP solar cells are very desirable as space solar cells [12]. Graphene is the first substance discovered with a 2D atomic crystal [13,14], having a honeycomb lattice structure. Graphene has a high carrier mobility [15], remarkable conductivity, and transparency [11]. It has great potentials for applications in the making of novel optoelectronic and electronic devices [16–20]. As a result of its special characteristics, graphene is an ideal electrode for use in thin solar film cells [11]. The graphene-semiconductor Schottky junction offers a new platform for photovoltaic devices. A Schottky junction is created if the work function difference between the metal and the semiconductor is large enough and the semiconductor carrier density is moderate or low [1]. In addition, the fabrication of Schottky junctions has the benefit of low-cost and simplicity [2].

Recently, Schottky junction solar cells have been made with a single layer of graphene on Si substrate, so that graphene behaves as a metal [21]. Graphene-based Schottky junction solar cells have been displayed on various substrates such as CdS [22], CdSe [22], Si [22] and InP [11] with power conversion efficiencies ranging from 0.1 up to 2.86%. Miao et al. [22] demonstrated a power conversion efficiency of 8.6% for a doped graphene/n—Si Schottky junction solar cell. Shi et al. [21] have shown a TiO_2-G-Si solar cell showed excellent device parameters including an open-circuit voltage of 0.612 V, a fill factor of 72%, and an incident photon to electron conversion efficiency of up to 90% across the visible spectrum. Wang et al. [11] demonstrated a graphene/thin film InP Schottky junction. The proposed solar cell was shown power conversion efficiency of 3.3% [11].

In this article, a novel InP-based graphene-Schottky junction solar cell, composed of InP-nanorods is proposed. A thin layer of silver is deposited on one side of the nanorods with the semispherical surface serving as a back-reflector with a single layer of graphene on top of the InP nanorods, to improve the optical properties of the proposed solar cell. The indium tin oxide (ITO) and graphene layers on top of the nanorods and silver layer on the bottom of the solar cell structure form an optical waveguide which facilitates light trapping. The proposed solar cell architecture increases the light absorption, the short-circuit current density and the ultimate efficiency overall incident wavelengths in the solar spectrum from 400 to 920 nm.

Material and methods

The layer stack of the graphene-InP Schottky junction solar cell is shown in Fig. 1. This structure is periodic in the x and y directions. The specifications of layers are Indium phosphide (InP) nanorods with a height of h_1 and a radius of R_1, nano-semi sphere silver with a radius of R_2 grown on a silver-coated substrate, a single layer of the graphene sheet, an anti-reflective layer of ITO on top of a graphene layer with the thickness of h_2. The edge-to-edge distance between the nanorods of InP is equal to d.

To obtain a realistic solar cell performance, the spectrum of AM 1.5G is utilized to determine the wavelength dependent absorption ($A(\lambda)$) over the sunlight electromagnetic spectrum. The relation between the incident power, P_{in} (λ), output power, P_{out} (λ), and A (λ) are given as [23]:

$$A(\lambda) = \frac{P_{in}(\lambda) - P_{out}(\lambda)}{P_{in}(\lambda)} \quad (1)$$

This helps to calculate the weighted absorption of $\langle A_w \rangle$ within the wavelength range of λ_1 and λ_2 [24–26]:

$$\langle A_w \rangle = \frac{\int_{\lambda_1}^{\lambda_2} A(\lambda)\psi(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} \psi(\lambda)d\lambda} \quad (2)$$

Here, $\psi(\lambda)$ is the incidence solar flux per unit wavelength and λ_1=400 nm and λ_2 = 920 nm (λ_2 = 920 nm-corresponding to the band edge for InP) are assumed. Short-circuit current density (J_{sc}) can also be calculated [27] as

$$J_{SC} = \frac{e}{hc}\int_{\lambda_1}^{\lambda_2} \lambda A(\lambda)\psi(\lambda)d\lambda \quad (3)$$

Wherever h, c, and e are the Planck constant, the speed of light in vacuum space and the electron charge density, respectively. The short circuit current is proportional to the number of incident photons at the top of the bandgap; it is considered that all photons are absorbed to generate the electron-hole pairs and each photo-generated carrier can reach the electrodes [28–30]. The finite difference method (FDM) is used to determine the electromagnetic fields (optical fields) propagated through the structure. In this method, Maxwell's equations are discretized in the solar cell structure.

To evaluate the optical absorption performance of the photovoltaic, the ultimate efficiency (η) is calculated, which is described as the efficiency of the solar cell as the temperature approaches 0 K, when each photon with energy higher than the bandgap energy generates an electron-hole pair [31,32].

$$\eta = \frac{\frac{2\pi h A Q_s}{\lambda_g}}{P_{in}} \quad (4)$$

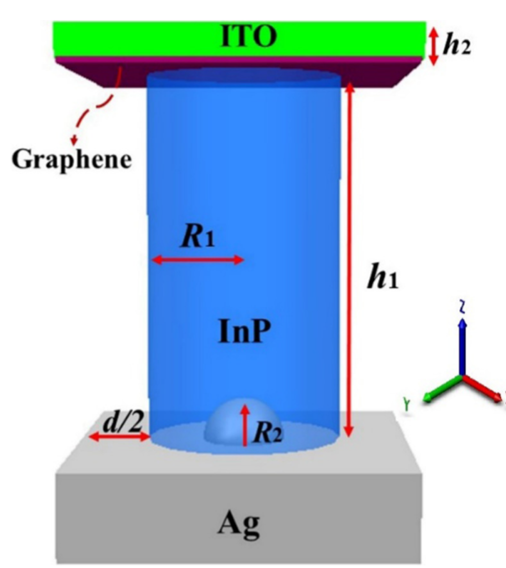

Fig. 1. Three dimensional (3D) schematics view of the InP-based graphene Schottky junction solar cell.