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Performance enhancement of thin film solar cell based on extraordinary transmission

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ABSTRACT

A novel approach based on the extraordinary transmission is proposed to improve the photovoltaic properties of thin film solar cells. In this approach, a perforated gold film with a periodic array of square holes is embedded inside the absorber layer of the solar cell at an optimum depth. The gold film also serves the purpose of an electrode to take dc output. The transmission of light through the film takes place due to the extraordinary transmission which leads to significant absorption increase in the absorber layer. To achieve the optimal response the periodicity of holes is varied and the corresponding solar cell parameters including short-circuit current and efficiencies are calculated. Here, we report that the increased absorption of solar energy gives almost twofold enhancement in short-circuit current density and optical conversion efficiency of the solar cell. The investigation is performed using finite difference time domain (FDTD) computational method.

1. Introduction

Opto-electric conversion of the most available renewable solar energy has potential to solve the energy crisis problem of modern scenario. To minimize the cost of the solar cell, which used to rely on semiconductor wafer the overall thickness of the solar cell has been reduced; henceforth the focus has been shifted towards the thin film solar cells (TFSC) [1–3]. The thickness of the thin film solar cells lies in few microns in which the thickness of the absorber active layer ranges around hundreds of nanometers. The photovoltaic technology has always been suffering from inefficient light trapping mechanism in the absorber active layer, which results in low optical conversion efficiency in solar cells. Plasmonic metal nanostructures effectuated their advantageous importance in improving the performance of the thin film solar cell so far [3]. Many approaches involving nano-particles have reported improved short-circuit current density and conversion efficiency [4–9]. Several nanostructures including tungsten grating [10], checkerboard perforated metal film [11], fan-shaped gold nano-antennas [12], metallic cuboids [13], and nanoantennas with hybrid plasmonic wave [14] have been reported in this field. Extraordinary transmission of light is a phenomenon related to diffraction of light through a subwavelength aperture in a metallic film, the transmission through the aperture is proportional to $(d/\lambda)^4$, where d is the diameter of aperture and λ is the wavelength. More advantages can be drawn by forming an array of apertures since it gives transmission far greater than its anticipated limit [15,16]. The extraordinary transmission has been reported for many applications such as near-field

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microscopy and optical modulation [17]. Although the phenomena of extraordinary transmission have already been used to enhance the performance of the solar cell (Table 1).

In the proposed work, a perforated thin gold film with a periodic array of square holes is embedded inside the absorber layer. The motive of this is to boost the transmission in the active layer by maintaining the same refractive indices on both the sides of the film; another advantage of placing the film inside the active layer is to utilize the whole top surface for solar illumination. Unlike the conventional solar cell instead of placing a separate anode on the top which reduces the illumination area, the film itself can be used as an anode. A similar type of anode was used by Stephan Y. Chou, and Wei Ding in Ref. [18], where they kept the perforated metal film on the top of the active layer.

2. Thin film solar cell based on extraordinary transmission

2.1. Design

The layout of the proposed solar cell (unit cell) is depicted in Fig. 1. The proposed structure of the solar cell is a five-layer structure having an anti-reflection coating (ARC) of Indium Tin Oxide (80 nm) on top. The perforated film of gold (15 nm) with periodic array of square holes ($100 \times 100\ nm^2$) is embedded inside the GaAs wafer at a depth of 20 nm. The GaAs region below the gold film is considered as the absorber layer (365 nm). The performance of the solar cell is calculated with ARC first and then without ARC. For illumination, a plane wave of 1 V/m is incident normally on the solar cell; later the source is normalized with respect to AM1.5 solar spectrum to calculate the electrical parameters of the solar cell [19].

Lumerical FDTD simulator has been used to observe the response of the complete solar cell, the unit cell is surrounded by periodic boundaries on side walls and perfectly matched layers (PML) on top and bottom. In the structure the square slot is discretized as $5 \times 5 \times 2\ nm^3$ and the rest of the computational domain is discretized as $10 \times 10 \times 10\ nm^3$. A planar monitor of exactly the same dimension of the slot is placed in the middle of the absorber layer to calculate the transmission. The hole periodicity is varied from 200 nm to 500 nm in the steps of 100 nm to achieve the optimal response. Further, the structure is exported to Lumerical Device simulator to calculate the electrical parameters such as short-circuit current density, open circuit voltage, fill factor and conversion efficiency. The proposed structure is compared with the simple solar cell and when the top 20 nm GaAs layer is removed (i.e. when the perforated gold film is placed on the top of absorber layer). To validate our simulation procedure the solar cells reported in Refs. [4] and [14] are re-implemented, the obtained results are in fair agreement with the reported ones.

2.2. Extraordinary transmission enhanced absorption

At optical frequencies, the electron cloud oscillations present at the metal-dielectric interface are called surface plasmon polaritons (SPP) or surface plasmons. When light passes through a subwavelength aperture of a metallic film, the transmission of light reaches its peak when the energies of surface plasmons modes on both sides are matched. In our case, the same phenomenon is taking place. When the incident solar radiation passes through the square hole, the hole behaves like a subwavelength cavity for the evanescent modes and the energy is coupled to the other side of surface plasmons, the wavelength corresponding to the different orders of maximum transmission is governed by the following relation [16]:

$$\lambda_{max} = \frac{a}{\sqrt{i^2 + j^2}} \sqrt{\frac{\varepsilon_{GaAs}\varepsilon_{Au}}{\varepsilon_{GaAs} + \varepsilon_{Au}}} \tag{1}$$

Here, a is the lattice constant, ε_{Au} and ε_{GaAs} are the dielectric constants of the Gold and GaAs, respectively. And 'i' and 'j' are integer mode indices. The above expression is in fair agreement for $a = 200$ and 300 nm at the wavelength of 778.89 nm where the dielectric constant of gold and GaAs are -23.87 and 13.35 respectively.

In order to achieve maximum transmission the permittivity, both sides of the gold film should be kept the same [16]. The depth at which the metal film is embedded is optimized so that it can capture the maximum impinging radiation. Moreover, a larger depth will not serve the purpose since the radiation will get reduced before even reaching the metal film, subsequently,

Table 1
Previously reported work on thin film solar cells based on extra-ordinary transmission.

Ref.	Design	Mechanism
[10]	Semiconductor layer with Tungsten grating on top and substrate of Tungsten	Extraordinary optical absorption in the active layer due to cavity like resonance and weakly bound surface waves
[11]	Ultrathin semiconductor layer (15 nm) with a solid nanoscopically perforated metal film and substrate of same metal film	Nanoscopically perforated metallic film & and ultrathin absorber layer form a meta material effective medium for negative refraction
[12]	Metalic cuboids placed on SiO2 passivation layer with Si absorber at bottom	Excitation of surface plasmons
[18]	Multilayer structure incorporating metallic film with circular hole perforation on top of active layer	Plasmonic cavity with subwavelength hole array increases absorption

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