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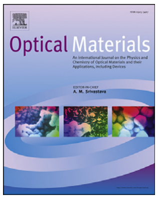

Titanium nitride as light trapping plasmonic material in silicon solar cell

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ABSTRACT

Light trapping is a crucial prominence to improve the efficiency in thin film solar cells. However, last few years, plasmonic based thin film solar cells shows potential structure to improve efficiency in photovoltaics. In order to achieve the high efficiency in plasmonic based thin film solar cells, traditionally noble metals like Silver (Ag) and Gold (Au) are extensively used due to their ability to localize the light in nanoscale structures. In this paper, we numerically demonstrated the absorption enhancement due to the incorporation of novel plasmonic TiN nanoparticles on thin film Silicon Solar cells. Absorption enhancement significantly affected by TiN plasmonic nanoparticles on thin film silicon was studied using Finite-Difference-Time-Domain Method (FDTD). The optimal absorption enhancement 1.2 was achieved for TiN nanoparticles with the diameter of 100 nm. The results show that the plasmonic effect significantly dominant to achieve maximum absorption enhancement $g(\lambda)$ at longer wavelengths (red and near infrared) and as comparable with Au nanoparticle on thin film Silicon. The absorption enhancement can be tuned to the desired position of solar spectrum by adjusting the size of TiN nanoparticles. Effect of nanoparticle diameters on the absorption enhancement was also thoroughly analyzed. The numerically simulated results show that TiN can play the similar role as gold nanoparticles on thin film silicon solar cells. Furthermore, TiN plasmonic material is cheap, abundant and more Complementary Metal Oxide Semiconductor (CMOS) compatible material than traditional plasmonic metals like Ag and Au, which can be easy integration with other optoelectronic devices.

1. Introduction

Nanoplasmonic applications and technologies have grown tremendously over the last few years [1–5]. One of the most attractive applications of plasmonics is the efficiency enhancement in photovoltaic devices [6,7]. Recently, various approaches based on light scattering at rough surfaces such as antireflection coating to minimize reflective losses, highly reflective back contacts, texturing of surfaces and interfaces, patterned black silicon surfaces and using layers with matching refractive index to preferentially scatter light into the active layer have all been used to optimize light absorption [8–11]. However, these techniques involve high processing cost leaving a need for other less expensive light trapping techniques to improve the efficiency at low cost [12].

Light trapping by plasmonic materials involves a strong interaction of light with conduction electrons in metal nanoparticles with an appropriate size and shape integrated to the surface. In this process, incident light stimulates the oscillation of conduction electrons at interfaces containing metal nanoparticles or nanostructures of subwavelength size. When the natural frequency of collective oscillating electrons matches that of incoming light, a localized surface plasmon resonance (LSPR) occurs. At plasmonic resonance, light is preferentially scattered by the nanoparticles decorating the surface of solar cell into solar cell's actively absorbing layer and improves free carrier generation. Stuart and Hall et al. instigated the pioneering work, the effect of plasmonics on silicon photo-diodes that fascinated the interest of solar cell researchers. They demonstrated an enhancement in the photocurrent of a factor 18 could be achieved for 160 nm thick silicon on insulator photo-detector at the 800 nm wavelength from approximately 100 nm sized silver particles on the surface of device [13]. Following Schaadt et al. obtained enhancement up to 80% at

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wavelength around 500 nm by depositing gold nanoparticles on highly doped wafer-based solar cells [14]. Pillai et al. deposited silver particles on 1.25 mm thick silicon-on-insulator solar cells and planar wafer based cells, and observed a significant enhancement of the absorption for both thin-film and wafer-based structures at wavelengths close to the band gap of Si. They reported a sevenfold enhancement of photocurrent for wafer-based cells at 1200 nm and up to 16-fold enhancement at 1050 nm for 1.25 mm thin silicon-on-insulator (SOI) cells [6,15]. Beck et al. showed that through the modification in local environment of silver nanoparticles, the optical absorption in the underlying silicon wafer can be enhanced five times and the external quantum efficiency by a factor of 2.3 at a wavelength of 1100 nm [16]. Later Moulin et al. reported improved light absorption from silver nanoparticles integrated on the rear side of thin film microcrystalline solar cells [17]. The effect of LSPR scattering has been reported not only for the case of silicon but also for other semiconductors; (e.g. GaAs) solar cells [18]. P. Spinelli et al. observed the absorption enhancement using silver nanoparticles on Crystalline Silicon and Amorphous silicon structures [7]. In addition, widely studied by using plasmonics nanoparticles improved the light absorption with Transparent conductive oxides (TCO) of top/bottom thin film solar cells structures has been improved [7,19–21].

Traditionally, noble metallic nanoparticles like gold (Au) and silver (Ag) are extensively used for plasmonic based thin film solar cells [20,22]. These noble metals are very prominent for their plasmonic effects in the wavelength range of the solar spectrum. However these materials were suffering major limitations such as lossy behavior, high cost, low thermal and oxidation stability, and incompatibility with industrial processes [23].

In recent years, transition metal nitrides set the new trend in novel plasmonic materials having great attention and specifically, Titanium Nitride and Zirconium Nitride are known for their unique properties similar in the behavior of metals [24]. G. Naik and V. Shalaev et al. group have been proposed and experimentally demonstrated transition metal nitrides like TiN as an alternative class of materials for practical plasmonic applications in the visible and infrared range [25–28]. This material exhibits optical properties analogous to that of gold for plasmonic applications [29,30]. Therefore, Titanium Nitride (TiN) has sparked as a potential candidate for broadband absorption covering the entire visible-infrared regions of the electromagnetic spectrum with a surplus benefits such as low loss and cost, high thermal and oxidative stability, unlike Au and Ag. TiN is fully compatible with the existing CMOS fabrication techniques in addition TiN exhibits biocompatibility [19,31–33].

Recently, Khalifa et al. theoretically demonstrated and improved the optical absorption enhancement by incorporating the TiN nanoparticles in Amorphous Silicon Heterojunction solar(Silica/Ag/(TiN)/ZnO/a-Si/ITO) and Organic solar cells(TiN/P3HT:PCBM/PEDOT:PSS/ITO/Glass). In this paper, we numerically studied how the plasmonic material TiN nanoparticles influence the light trapping and absorption enhancement in thin film crystalline silicon solar cells structure(Au/TiN/μ- Crystalline Silicon) which is contrast from others [5,19,26] and also showed dramatic enhancement in the region 600 nm–1100 nm. The absorption enhancement of silicon layer in solar cell with spherical TiN and Au nanoparticles of different sizes has been discussed in detail and compared by using Lumerical FDTD Solutions. Our results show that the optimal absorption enhancement up to 20% for TiN Nanoparticle at diameter 100 nm in the visible region (600–1100 nm) opens up the possibility of its use in thin film silicon solar cells. Our results confirm that even though the simulation structures are different but it confirms TiN is suitable alternative plasmonic material, comparable and in near future it is expected to replace the traditional plasmonic materials (Au and Ag). We believe that these results will help to understand the effect of plasmonic TiN nanoparticles can trap the light inside the simulated structure by various methods and improved the absorption in Crystalline Silicon Solar cells. Our further experimental investigation is in this direction to verify and improve the absorption enhancement with a combination of different Ag/Au/TiN nanoparticle parameters like diameter, period, height and surface coverage on thin film silicon solar cell. Simulation results show that TiN has comparable performance with Au and in addition this material provides its own indispensable advantages over Au and Ag. The insights in this paper suggest that TiN can be a potential plasmonic material for thin film photovoltaics, Visible and infrared applications and optoelectronics.

2. Structure and simulation method

For FDTD Simulation, we studied Titanium Nitride (TiN) and Gold (Au) nanoparticles on thin film silicon solar cell of thickness 2 μ m placed at center of the solar cell as shown in Fig. 1. The nanoparticle diameters were varied from 0 to 200 nm and the periodic boundary conditions (PBC) in the lateral direction and also perfectly matched layer (PML) were used. A plane wave was used to incident normally on thin film solar cell with the wavelength range from 300 nm to 1100 nm. Absorbed power in the silicon for individual nanoparticle diameters (P_{abs}) was determined according to the FDTD conditions and finding the optimum value of the nanoparticle size by using sweep parameter. The absorption enhancement with optimum nanoparticle diameter on silicon solar cell with and without nanoparticles was calculated. The dielectric constants of Gold, TiN and Si were taken from Palik [34]. The efficiency of solar cell was estimated through our numerical computations results in terms of standard solar cell optical performance parameters like Quantum Efficiency (QE) [25,35,36].

$$QE(\lambda) = \frac{P_{abs}(\lambda)}{P_{inc}(\lambda)} \tag{1}$$

where $P_{abs}(\lambda)$ and $P_{inc}(\lambda)$ are the power of the absorbed light and incident light within the Si Solar cell respectively. Using the QE, IQE defined as the ratio of amount of charges collected by the solar cell to the number of photons per second absorbed and as written as follows [35];

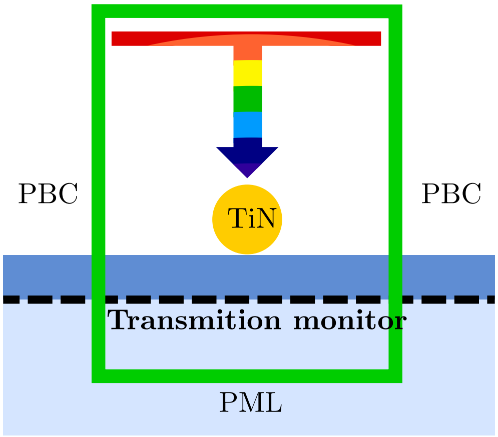

Fig. 1. Schematic picture of typical Single Metal nanoparticle placed on thin film Silicon solar cell.