Tuneable and spectrally selective broadband reflector – Modulated photonic crystals and its application in solar cells

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ABSTRACT

One dimensional photonic crystal has been developed as a broadband dielectric reflector, the stopband of which could be selectively tuned based on absorption spectrum of the absorber material. The design parameters and factors which contribute to the tunability of the photonic crystals are analyzed through simulations and experiments. The photonic crystal structures are fabricated using silicon rich silicon nitride and silicon oxynitride thin films deposited by PECVD at 200 °C. Modulated photonic crystal with a broad bandwidth, having an integrated reflectance of 97.6% in the wavelength range 580–1200 nm has been fabricated and applied in an amorphous silicon thin film solar cell as the back reflector. The optical performance of solar cells with these back reflectors has been studied in the longer wavelength as against the conventional metallic back reflector. The characterization of the thin film silicon solar cell with these photonic structures presented a short circuit current density of 14.77 mA/cm^2. The angle dependent behaviour of the photonic crystal has been studied using angle dependent current-voltage measurement and a future prospectus of these structures as passivation layer for ultra thin crystalline silicon solar cells is also highlighted.

1. Introduction

With the prospect of reducing the cost of electricity from solar energy, it is imperative to decrease the overall cost of solar cell by reduced material usage. Therefore the decrease in thickness of the solar cell has to be accompanied by light trapping methodologies for improved efficiency of the solar cell. One of the conventional ways to achieve enhanced light trapping is by having a nearly 100% Lambertian back reflector which will diffusely reflect light back into the active thin film solar material. The back reflector coupled with scattering at the textured surface will increase the optical path travelled by light through multiple reflections in the cell and hence increase in light absorption. Therefore if we have a dielectric slab having a perfect 100% Lambertian scattering at the back coupled with front texture then the hypothetical classical absorption limit (Yablonovitch, 1982; Tiedje et al., 1984) is given by 4n^2 where n is the real part of the complex refractive index of the dielectric slab. In case of a solar cell where the dielectric slab is silicon wafer having a refractive index n = 3.5 then light trapping can theoretically improve the absorption factor by 50 (Yablonovitch and Cody, 1982). The light trapping plays a crucial role in achieving higher efficiencies for the different thin film and ultra-thin c-Si solar cells. In the case of thin film silicon solar cells, the conventional metallic back reflector like silver (Ag) have high reflectance however the textured

surface of the metal suffer from surface plasmon absorption losses (Springer et al., 2004). An alternate back reflector can be a Bragg reflector also called as one dimensional photonic crystal (Yablonovitch, 1987) (1DPC), which could ideally reflect near to 100% light over a specific wavelength band. 1DPC are structures in which there is periodic arrangement of varying dielectric media along a single axis (along one dimension) in such a way that the periodicity results in a periodic dielectric function for the propagating light wave. The periodic stack has alternate high and low refractive index material; and light gets scattered from each interface. If the optical path length between two light waves from the interface is half of the wavelength of light then they interfere constructively such that there is no net transfer of energy in the forward direction. The range of frequencies for which the photon is forbidden in the forward direction is called a Photonic stopband and the structure so fabricated is called a quarter wave stack photonic crystal. Though extensive work has been done on integrating photonic crystals with plasmonic grating for enhanced light harvesting (Biswas and Xu, 2012; Zeng et al., 2008; Zhou and Biswas, 2008) by creating resonant modes of surface plasmon-polaritons which will confine light waves to the interface, these methodologies require additional lithography and etching steps which further increase the complexity of cell processing. 1DPC are relatively simpler to fabricate and uses the same deposition technique which is currently used in commercial solar cells

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and hence can be easily integrated to cell fabrication pilot line. In this paper we have developed a Photonic crystal for which the photonic stopband can be selected and tuned as per the spectral requirement of the solar cell in addition to the "modulated" features (Krc et al., 2009), hence referred as Tuneable and Spectrally Selective Broadband Reflector Modulated Photonic Crystal (TSSBR-MPC).

TSSBR-PC is fabricated using alternate layers of high and low refractive index materials in such a way that the Photonic Band Gap (PBG – range of frequencies over which light gets reflected completely from the PC) (Yablonovitch, 1987; O'Brien et al., 2008) can be selected as per the absorption spectrum of the solar cell by changing the thickness, number of layers and by using varying refractive index materials (Krc et al., 2009). This selectivity in reflection can be extremely beneficial for different types of Solar cells as the reflector can be custom made for the specific cell. There are also reports on the application possibility of PC back reflectors for monocrystalline (Zeng et al., 2006) and multicrystalline (Ivanov et al., 2009) solar cells to improve the light trapping. Different types of Bragg reflectors have been proposed as the back reflector for thin film solar cells and a few groups have reported their integration in amorphous and microcrystalline thin film silicon solar cells (Krc et al., 2009; Mutitu et al., 2010; Kuo et al., 2012; Isabella et al., 2012), dye sensitized solar cells (Colodrero et al., 2012; Heiniger et al., 2013), organic and polymer solar cells (Lunt and Bulovic, 2011; Yu et al., 2013; Betancur et al., 2013), III-V solar cells (Johnson et al., 2005; Tsai et al., 2013; Tobin et al., 1991) and thermophotovoltaics (Florescu et al., 2007). One of the interesting applications of TSSBR-PC would be in "micromorph" tandem cells (Fischer et al., 1996) and triple junction solar cells (Yan et al., 2006; Kim et al., 2013) where a modified TSSBR-PC can act as selective intermediate reflector for a-Si:H, a-SiGe:H and μc-Si:H having bandgap 1.75, 1.45 and 1.1 eV respectively. In this application as selectively reflecting intermediate reflector, for each absorber layer it would reflect only the desired spectral range of light which can be absorbed by that absorber layer, whereas it will act as an intermediate window for the remaining wavelength of light. In this paper we are presenting the design principles underlying the fabrication of TSSBR-MPC through simulation and experiment and the characterization of the TSSBR-MPC that we fabricated. As a proof of concept we have integrated TSSBR-PC in thin film amorphous silicon solar cells and the performance for the cells with different reflectors at the bottom are compared. The application potential of dielectric reflectors as the back surface passivation layer and reflectors for ultrathin crystalline silicon solar cells is also presented.

Along with the multitudinous applications mentioned above, it is also important to emphasize on the plausible applications of TSSBR-PC in silicon wafer photovoltaic technology. P-type c-Si solar cells with Al-BSF suffer from high recombination losses at the rear side and parasitic absorption losses (Ingenito et al., 2014a). The longer minority carrier life times, less sensitivity to impurities of n-type wafers, absence of boron-oxygen complexes as observed in p-type wafers, no light induced degradation, potential to give high open circuit voltage and high conversion efficiency has generated considerable interest for n-type silicon solar cells recently (Ingenito et al., 2016). Bifacial solar cells with high conversion efficiencies have been demonstrated (Böscke et al., 2013) and industries have shown interest in these bifacial modules since there is no additional cost in cell and module manufacturing processes, could be easily implemented in the current production lines and are scalable for commercial production. The bifacial cell with light coming from both sides is not practical at all geographical locations, since the albedo light may be insufficient. In such cases, a white reflector film is preferred to be used at the rear side, but is limited with their reflectivity around 85% (Alcántara et al., 2014). Metal free reflectors based on distributed bragg reflectors which could have nearly 100% reflectivity has been proposed as a replacement for white reflecting films to enhance the light trapping by Ingenito et al. (2016). Another interesting possibility of these dielectric mirrors is their dual nature which we have demonstrated earlier (Soman and Antony, 2017); where they will act as
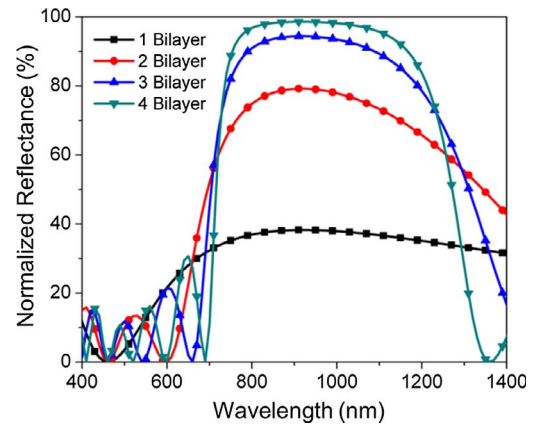

Fig. 1. The simulated reflectivity curves of photonic crystals with different number of bilayers.

nearly 100% reflectors and by suitably selecting the first dielectric material in the stack, they would also act as a passivating stack for achieving higher life time. By carefully choosing Silicon Oxynitride (SiON) or non-stoichiometric Silicon Nitride (SiN) as the first layer of the dielectric stack we could passivate p or n-type surfaces effectively.

Another area of application of our work is in ultra-thin crystalline silicon solar cells since light trapping is a vital aspect in thin silicon substrates due to the low absorption coefficient in the near infrared region of the solar spectrum and can help to achieve low cost flexible solar cells without sacrificing efficiency (del Cañizo et al., 2009; Goodrich et al., 2013). Ultrathin silicon solar cells are an area of interest since they further reduce production cost, use lesser raw material, reduce bulk recombination and light induced degradation (Ingenito et al., 2014b). Ingenito et al. (2014b) has already demonstrated light trapping structures showing absorption very close to $4n^2$ classical limit in ultrathin c-Si solar cells using distributed back reflector at the rear side along with random pyramidal structure. With wafers less than 35 μm achieving 99.8% implied photocurrent density it is possible to fabricate ultrathin c-Si solar cells with these advance light trapping schemes.

2. Experimental details

The fabrication of the Photonic Crystal (PC) has been done using a parallel plate radio frequency plasma-enhanced chemical vapor deposition (rf-PECVD) system. We have used alternating layers of hydrogenated amorphous Silicon Nitride (a-Si$_x$N$_y$:H) and Silicon Oxynitride (a-SiO$_x$N$_y$:H) thin films having different compositions (Soman and Antony, 2017) for making tunable and selective reflector. The a-Si$_x$N$_y$:H films mentioned in this paper are deviated from their stoichiometry and are made silicon rich, hence it will be mentioned as Silicon Rich Silicon Nitride (SRSN) in the remaining part of the text unless and otherwise specified. SRSN layers were deposited by varying ammonia (NH$_3$) to silane (SiH$_4$) gas flow ratio from 1 to 0.0625, and we have obtained SRSN layers of varying refractive index from 2.35 to 3.29 (at 632.8 nm, measured using F40 Filmetrics Reflectometer). Similarly Silicon Oxynitride layers (represented as SiON) with refractive index varying from standard Silicon nitride of 1.95–1.53 were obtained by varying the silane (SiH$_4$), hydrogen (H$_2$) and nitrous oxide (N$_2$O) gas flow ratios. The gas flow ratio for the deposition of SRSN (Q$_H$) and SiON (Q$_L$) are given by,

$$Q_H = \frac{\varnothing_{NH_3}}{\varnothing_{SiH_4}} \tag{1}$$

$$Q_L = \frac{\varnothing_{N_2O}}{\varnothing_{N_2O} + \varnothing_{SiH_4}} \tag{2}$$