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Nano-photonic and nano-plasmonic enhancements in thin film silicon solar cells

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ABSTRACT

We design, simulate and fabricate enhanced thin film silicon solar cells using periodically textured photonic crystal substrates. We utilize a thin film absorber layer consisting of a superlattice of alternating hydrogenated amorphous silicon (a-Si:H) and nano-crystalline silicon (nc-Si). Rigorous vectorial simulations optimized the periodically patterned solar cells by solving Maxwell's equations in Fourier space. Simulations found optimized architectures for a triangular lattice of metallic nano-cones as a back-reflector, and a conformal solar cell geometry. The periodically patterned photonic crystal based substrates achieve (1) high diffraction, enhancing the path length of light in thin absorber layers and (2) plasmonic concentration of light intensity. Simulations predict an absorption enhancement of 43% for a 12-period superlattice of 800 nm thickness. The optimized pitch of the photonic lattice is near 700 nm. Experimentally the periodically patterned substrates were fabricated with nano-imprint lithography, and utilized as a substrate for the superlattice cells. We measured a large photo-current enhancement between the textured photonic crystal based superlattice cell and the flat cell of 21%, together with long-wavelength quantum efficiency enhancements beyond 600 nm. This is an approach to achieving thin film solar cells with high currents through advanced light-trapping techniques on novel materials.

1. Introduction

A very attractive low-cost thin film solar cell is the micro-morph architecture [1] consisting of a tandem cell with high band gap hydrogenated amorphous silicon (a-Si:H) as the upper cell, on a lower band-gap nano-crystalline silicon (nc-Si) bottom cell [1,2]. The top a-Si:H cell absorbs the shorter wavelengths of the solar spectrum, whereas the red and near-infrared wavelengths (upto the band edge of 1100 nm) are absorbed in the bottom nano-crystalline cell. Mature thin film deposition technology can manufacture such cells over very large areas on both rigid and flexible substrates. A record stabilized cell efficiency of 11.7% has been reported for these micro-morph cells [3,4]. Large area solar cells on flexible plastic substrates, such as kapton and polyethylene naphthalate (PEN), are particularly attractive for conformal solar panels on non-planar surfaces.

Thin film silicon-based solar cells composed of nano-crystalline silicon (nc-Si) or hydrogenated amorphous silicon (a-Si:H) suffer from poor absorption of red and near-infrared photons (at wavelengths $\lambda > 650$ nm) in thin absorber layers. The absorption length of near-infrared photons exceeds 1–2 μm beyond $\lambda = 700$ nm, and exceeds the thickness of absorber layers, which are typically 1–1.5 μm for the nc-Si layer, and just 300 nm for the amorphous layer in micro-morph tandem cells. Thicker c-Si solar cells also exhibit similar light harvesting problems [1] for near-infrared wavelengths below the silicon band edge (1100 nm).

The traditional approach to light trapping in thin film solar cells utilizes randomly textured back reflectors composed of either annealed Ag or etched Ag and ZnO, to randomize light in substrate nip cells and increase the path length of light in thin absorber layers (Fig. 1). Random textures scatter light stochastically at the back reflector, through all angles, thereby increasing the path length of photons within the absorber layer. For an ideal loss-less Lambertian scattering surface, which reflects incoming light uniformly into all angles, the enhancement factor of the path length inside the absorber layer has a limiting value of $4n^2$ [5] where n is the wavelength-dependent refractive index. This factor can be derived by summing the trapped rays [6], or more elegantly by comparing the area of the escape cone with the complete phase space i.e. the surface area of the sphere for modes within the

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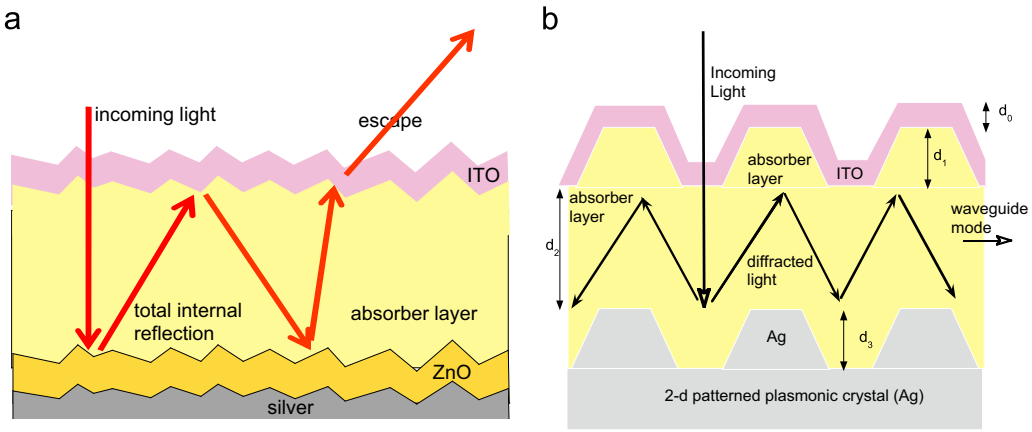

Fig. 1. Schematics of light trapping in (a) a randomly textured cell and (b) a periodically textured solar cell, where diffraction causes waveguide modes.

semiconductor layer [7]. Many approaches have optimized the light scattering and cell performance and a root mean square (rms) texture of ~40 nm for annealed Ag has been found to be near-optimum for nip cells [8]. It has been of great interest to reduce losses within the back reflector that are due to local plasmonic excitations within the metallic texture. Alternatively, highly textured transparent conducting oxides (TCOs) such as ZnO can scatter and randomize light within superstrate pin solar cells and yield high efficiency nc-Si cells with LPCVD ZnO [9,10]. A long-standing goal is to approach or even exceed the Lambertian limit for light-scattering. The $4n^2$ factor reaches a value of 45–50 for silicon based materials, in the limit of weak absorption i.e. near the band edge of the material.

A more recent approach to light-trapping involves periodically structured photonic or plasmonic back reflectors (BRs), following the large body of work in developing artificial photonic structures to control and manipulate light [11]. Plasmonic and photonic crystal back-reflectors are an attractive solution to light-trapping of long wavelength photons [7,12–23]. A periodically structured back-reflector diffracts long-wavelength photons into guided modes that traverse in the plane of the absorber layer (Fig. 1), thereby substantially enhancing the absorption at near-infrared-wavelengths [13,17,19]. A periodic metallic back-reflector can support surface plasmon (SPs) propagating parallel to the interface, where the light intensity is strongly enhanced leading to enhanced light absorption. It is also of great interest to compare the performance of periodic back-reflectors with random scattering structures and with the Lambertian limit.

Since the photonic and plasmonic enhancements have been previously reported by several groups in thin film a-Si:H and nc-Si solar cells [9,10,15–19], we focus our attention on a novel absorber layer consisting of a novel *multi-layer superlattice* of nc-Si and a-Si:H as the absorber layer [24] which has not been previously investigated for photonic enhancements. This superlattice combines the high absorption of a-Si:H with lower band gap nc-Si. These super-lattices permit independent control of crystallinity [24–27], columnar microstructure, and grain size, features not possible with traditional nc-Si solar cells. Previously superlattices with a-Si:H/a-SiN:H multilayers were grown and studied with optical measurements that were interpreted to show quantum confinement effects [27]. These superlattices have not received the same attention as the amorphous or nano-crystalline materials, and a most relevant question is the motivation to investigate semiconductor superlattices.

Semiconductor superlattices, with alternating layers of lattice-matched crystalline semiconductors (e.g. GaAs/AlGaAs or Si/Si_xGe_{1-x}) have a rich history of physics where many new phenomena have been observed [28]. New physical phenomena include the one-dimensionally quantized states of electrons and holes in superlattices and resonant tunneling between quantum well sub-bands that can be tuned by electric fields. The super-lattices have either type I or type II band alignment—which critically affects the transport properties. Technologically, modulation doping where the higher band gap layers are doped in either III–V or group IV superlattices, have resulted in record carrier mobility that exceed those of the parent crystalline material [29,30]. Superlattices with narrow band gap materials have led to quantum cascade lasers operating at infrared wavelengths. All of these rich physical phenomena have been observed in crystalline systems, where superlattices require lattice-matched components, otherwise the density of interfacial defects is very large. The underlying constraint of lattice-matching is no longer present in the growth of amorphous layers. Furthermore hydrogen can effectively passivate coordination defects. It is of fundamental interest then to investigate whether such superlattices can be grown in amorphous semiconductor systems, and whether analogs of any of these novel physical effects for crystalline systems can be observed. It is the motivation of this paper to fundamentally investigate whether amorphous superlattices can be grown, and explore their potential application to solar cells. More fundamental studies of amorphous superlattices should be undertaken to explore possible quantization effects which have been suggested previously [27]. Although we have not undertaken such studies in this paper, they would be ideal for exploration in more general fundamental materials studies.

Superlattices utilizing amorphous layers have also been proposed as materials for the channel region of thin film transistors [31], that utilize the planar transport properties of the low band gap layers.

2. Design principles for periodic back reflectors

Three primary design principles underlie the physics of periodic back reflectors. The first is the strong *photonic* diffraction of waves by the periodic back reflector. To elucidate this we first consider the random back reflector. Random back reflectors function by scattering light through random angles at each reflection from the back surface. If the angle of incidence at the top surface of the absorber layer is smaller than the critical angle the light ray will be lost in the escape cone at the top surface (Fig. 1). If the incidence angle is greater than the critical angle the light ray is trapped inside. As evident in Fig. 1, after multiple reflections a ray can escape from the top surface.

The behavior of the periodic back reflector (Fig. 1) is markedly different since the entire wave-front is coherent and hence all points within the wave-front behave in the same way. The modes within a thin layer are reflected from the top and bottom of the absorber layer and are trapped in the layer when the round trip phase difference $\Delta\phi$