Lithographically-definable Solar Cell Random Reflector using Genetic Algorithm Optimization

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Abstract — Randomly textured Lambertian surface provides broad band cosine emission and thus is suitable for photovoltaic application. Nonetheless, variation of efficiency and non-optimized nature of randomly textured devices are undesirable. Here it is shown that using genetic algorithm, a 4x4 binary quasi-random grating can provide 23% higher absorption than 2D periodic grating and 103.5% higher than planar cells, approaching Lambertian limit. The improvement is attributed to broad band transmission for high energy photon and broad band waveguiding effect for low energy photons. Large scale fully-optimized binary grating can potentially surpass Lambertian limit due to its optimized nature and should be employed for future thin-film photovoltaic devices to reduce film thickness and cost.

Index Terms — genetic algorithm, randomized pattern, guided mode, thin-film solar cell.

I. INTRODUCTION

Randomly textured surface provides broad band cosine emission and thus lead to so-called Lambertian limit[1]. Experimental and theoretical works have shown the superior absorption enhancement using random Lambertian surface for solar cell back or front surfaces[2-9]. Nonetheless, in order to further improve the diffraction capability of randomly textured surface and thus increase the conversion efficiency[10], optimization is essential. In addition, the geometry variation in randomly textured surfaces due to process conditions or its own randomness nature causes poor reproducibility in these devices. Previously optimization of random reflectors has been applied to 1D-profiles as in [11, 12]. In order to achieve lithographically definable random reflectors, 2D-profile optimization is necessary.

II. EVOLUTION OF RANDOM STRUCTURES

Structure consists of ZnO/Si/ZnO/Ag, and the thickness of silicon is 700nm. The Ag and ZnO layers are firstly defined, which are uniform stratum. Then an initial binary mask pattern is defined as an array of 1 and 0. 1 represents the mesa and 0 represents the etched area, and thus 1 represents ZnO while 0 represents silicon since the etched region will be conformally filled with silicon. Afterward, a uniform stratum of silicon is defined, the thickness will be the total thickness minus the groove depth of the grating. The fifth layer is again ZnO/Silicon bi-periodic stratum, and the initial binary mask can be used to define this ZnO top contact conformal coverage. The sixth layer, which is the sidewall of the top silicon grating structure, is more complicated to define. As illustrated by Fig. 1, the side wall definition can be done by dividing the empty (air) region into 9 sub-regions, and whether each sub-region should be air or ZnO is determined by whether the adjacent region is silicon or air. The last stratum is the topmost ZnO coverage, which constitutes part of the top ZnO conformal coverage. Material optical constants can be found in literature[8, 13-16].

Fig. 1. Illustration the device structures and the way to define top ZnO coverage.

Genetic algorithm (GA) is applied to conduct geometry optimization for random reflectors. GA has been shown to be successful in several different engineering fields[17-21]. It is a global optimization technique mimicking the process of
nature evolution. The structure for evolution is shown in Fig. 2.

The definition of the sixth layer is a complicated process. In general each binary mask is divided into 9 sub-regions as illustrated in Fig. 1. For region surrounding the boundary, the refractive index can actually be ZnO, silicon, or air refractive index. In the case that the adjacent region is silicon, then the refractive index of these sub-regions should be ZnO since they consist of the sidewall of the structure. In the case that the underlying layer, i.e. the silicon/ZnO bottom grating layer is ZnO, then these sub-regions should be filled with silicon and thus silicon refractive index is used. In the case that the bottom silicon/ZnO grating is silicon, then these sub-regions should be filled with silicon for conformal coverage is assumed here and the silicon layer thickness is kept the same through the entire device.

III. SPECTRAL RESPONSE AND TRANSMISSION

Fig. 2. Illustration of (a) initial ZnO pattern (b) definition of ZnO coverage layer (c) sidewall definition and (d) ZnO topmost coverage.
Calculation of poynting vector, energy loss, and integrated quantum efficiency can be referred to literatures[2, 11, 22, 23]. A 4X4 quasi-random grating provides 23% broad band improvement reference to 2D periodic grating. At short wavelength, Genetic-Algorithm(GA)-optimized structures show broad band improvement due to transmission enhancement, as will be clear in Fig. 4. At long wavelengths, Fabry-Perot type resonance is seen in 2D-periodic grating due to quasi-guided mode excitation.

The Lambertian absorption limit is[24]:

$$A(\lambda) = \frac{(1-e^{-\alpha W})}{[1-(1-1/n^2)e^{-\alpha W}]}$$  \hspace{1cm} (1)

where $\alpha$ is absorption coefficient, $n$ is semiconductor refractive index, and $W$ is film thickness. Although at resonance frequency the absorption can exceed Lambertian limit for 2D periodic grating, the broad band enhancement is not as strong as GA-optimized structures. In the derivation of Lambertian limit in (1), the transmission at front surface is assumed to be unity and the front contact corrected transmission(FFCT) Lambertian limit in Fig. 3 takes into account the imperfect transmission at Air/ZnO/Silicon interface. Although at the resonance frequencies the absorbance of 2D periodic grating cell can exceed Lambertian limit, the broad band enhancement is not as strong as GA-optimized structures. This is due to the well-defined quasi-guided-modes in 2D periodic structures and thus pronounced absorption peaks are observed in spectral response. Nonetheless, at frequencies other than resonance, the absorption is much lower. Since it is difficult for guided mode to exist over entire solar spectrum for a particular incidence angle, a comprised but optimized random gratings provides higher overall efficiencies. Planar cell in general shows impedance matching characteristics at short wavelength where peaked absorbance is seen when wave impedance is matched through the solar cell stacks. It shows weak absorption at long wavelength due to insufficient light scattering, resulting from lack of large angle diffraction.

At long wavelength portion of the solar spectrum, the transmission is essentially very high due to impedance matched nature. The impedance matched condition for ZnO front contact assuming planar structure is:

$$t_{ZnO} = \frac{\lambda}{4n_{ZnO}} + \frac{m\lambda}{2n_{ZnO}}$$  \hspace{1cm} (2)

where $\lambda$ is free space wavelength, $n_{ZnO}$ is ZnO refractive index, and m is non-negative integer. For 2D-periodic grating the transmission is further improved at all wavelengths where a broad band transmission is observed instead of a perfect transmission at a single wavelength, as is the case of planar
structure. The lower transmission at short wavelength for both Fig. 4 (a)(b) is due to two factors. First is directly from (2). $n_{ZnO}$ is approximately equal to 2 and $t_{ZnO} =100$nm, the first impedance matched point is around $\lambda=800$nm, and the second is $\lambda=266.67$ nm. Since there is no impedance matched point around $\lambda=400$nm-600nm, the transmission is lower at short wavelength. The second reason is that the imaginary part of dielectric constant ($\varepsilon''$) becomes higher at short wavelength, which in turn lowers the transmission. The transmission peak around $\lambda=448.5$nm is unlikely the result of impedance matching since there is no such points in this spectral range. It is more likely due to strong waveguiding effect where the ridged-geometry guides the incident wave into silicon slab as illustrated in the inset of Fig. 4(b). The further broad band transmission improvement of random grating over 2D periodic grating is due to optimized geometry by GA.

IV. FIELD PROFILE AND WAVEGUIDING EFFECT

In Fig. 5 small penetrating depth is observed At short wavelength. At $\lambda=472.7$nm, the absorption peak is due to the Fabry-Perot type resonance, where pronounced layered field profile is the evidence of coupling into guided resonant mode. From 600nm-1000nm, broad band waveguiding effect is observed, where the incident wave is guided by the geometry of the grating structure into the silicon slab. It can be seen from Fig. 5 that the normally incident wave is obliquely penetrating into the silicon slab, which is the evidence of strong waveguiding effect. Since the quasi-guided mode is impossible to exist over entire spectral range, the randomized grating is a compromised solution over the entire spectrum and genetic algorithm is the way to find the integrated absorption peak. The s- and p- polarized spectral response shows similar absorptance due to the randomized nature. The polarization independent behavior is desired for solar cell application.

VI. CONCLUSION

Genetic Algorithm is effective in optimization of random reflector for solar cell application. The resulting geometry shows broad band field enhancement in both short and long wavelength region of solar spectrum. The enhancement in GA-optimized structure is due to broad band transmission at short wavelength and excitation of quasi-guided mode at long...
wavelength. The encoding and evolutionary scheme presented here can be applied to large scale fully optimized structure where the resulting light trapping capability can exceed randomly textured Lambertian limit due to the optimized geometry specifically w.r.t. solar spectrum, in contrast to the isotropic and randomness nature of Lambertian surface. The practicability of large scale fully optimized binary random grating is evaluated. It is pointed out that infinitely large mask is unnecessary and the practical dimension of random mask should only have to be large enough to make fringing effect negligible.

ACKNOWLEDGEMENT

We acknowledge the support of high speed computing facilities from National Center of High-Performance Computing (NCHC), Hsinchu, Taiwan. The work is funded by National Science Council (NSC), Taiwan.

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