Photonic Density of State (PDOS) Enhancement by Brillouin Zone Engineering

Sze Ming Fu [1], Yan Kai Zhong [1], Sheng Lun Yan [1], Nyan Ping Ju [1], Po Yu Chen [1], Ming-Hsuan Kao [2], Chang-Hong Shen [2], Jia-Min Shieh [2], Yi-Chun Lai [3], Peichen Yu [3], Albert Lin [1]

[1]Department of Electronic Engineering, National Chiao-Tung Univeristy, Hsinchu, Taiwan 30010

[2] National Device Laboratory(NDL), Hsinchu, Taiwan 30010

[3]Department of Photonics, National Chiao-Tung Univeristy, Hsinchu, Taiwan 30010

***Abstract* — The material absorption can be enhanced by increased photonic density of state(PDOS). Here we demonstrate that through the design in the Brillouin zone of nanophotonic light trapping structures, the PDOS can be effectively increased. The theoretical work using rigorously coupled wave calculation shows the increased spectral absorption and the optimal quasi-guided mode excitations in terms of their quality factors and the number of excited modes. The experimental work is currently ongoing and the preliminary result confirms enhanced short circuit current if the PDOS is properly adjusted. Unlike random structures, the proposed Brillouin zone engineered structures are more feasible from modeling and device process viewpoints.**

***Index Terms* —photonic density of state (PDOS), solar cell, Brillouin zone. nanophotonic light trapping.**

I. INTRODUCTION

There have been significant efforts in nanophotonic light trapping for solar cells [1-27]. Periodic structures based on grating height and grating period optimization are in general easier to model due to their finite simulation domain [7, 28-30]. It also facilitates fabrication, using common lithography techniques. Random structures [29, 31-33], on the other hand, are more difficult from simulation point of view due to its infinite dimension in calculation. Besides, the random photonic pattern fabrication is also problematic in the case of randomly textured or irregular height profiles. In some cases, the motivation of using a random structure is that it may lead to higher absorption enhancement. This is due to its larger design flexibility and its random light scattering characteristic. Nonetheless, the above-mentioned drawbacks in simulation and fabrication for random structures can be significant, and thus the fully-designed random reflectors have not been realized in practice or even in theory to date. In the case of a periodic structure, it facilitates design and fabrication. Furthermore, recent works show that periodic design may compete for random ones [29]. In this work, it is shown that the absorption in periodic design can actually be further increased by adjusting the shape of its Brillouin zone in two-dimensional photonic lattice. It is found that the adjustment in Brillouin zone can provide additional 10% enhancement, compared to solely adjusting the grating etching depth and grating period.

II. THEORETICAL ANALYSIS OF PDOS

Fig. 1 illustrates the device structures. The optimization is done in the regular device parameters including the grating height(h_g), the grating period(P), the anti-reflection coating thickness(t_{ITO}), the dielectric spacer thickness(D_{ITO}). In the case of Brillouin zone optimized design, the optimization is also done in the two-dimensional Brillouin zone shape. In order to adjust the shape, the two unit vectors a_1 and a_2 are adjusted in their length and in their angle. It is shown that the additional enhancement of ~10% can be achieved if the Brillouin zone can be optimized in its shape, compared to the baseline design where only the regular grating parameters(h_g, P, t_{ITO}, D_{ITO}) are optimized and square lattice is used. Fig. 2 shows the spectral response for the baseline square lattice grating and the Brillouin zone optimized grating. Fig. 3 demonstrates the process flow for the amorphous silicon (α-Si) solar cells. It should be emphasized that the proposed nano-photonic light trapping concept can not only be applied to α-Si technology but also can be used for any solar cell technologies without much different in principle.

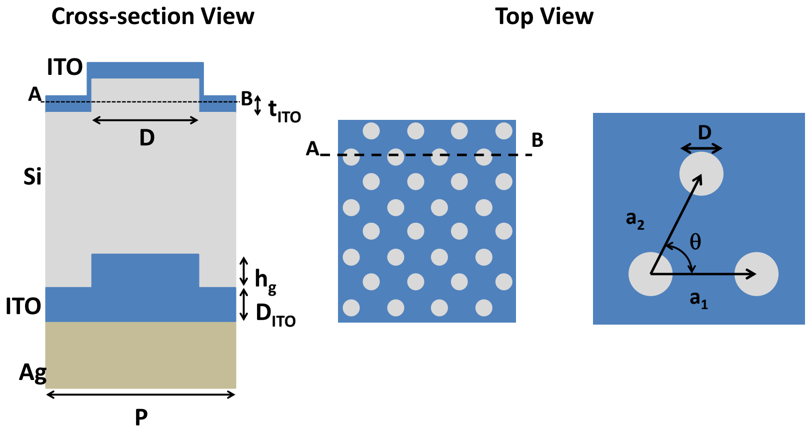

Fig. 1. Illustration of the concepts of photonic lattice optimization in its Brillouin zone. The unit vectors forming the two-dimensional (2D) photonic lattice Brillouin zone is shown. The optimization is done by varying the unit vector length, a_1 and a_2, and the angle between them, θ.

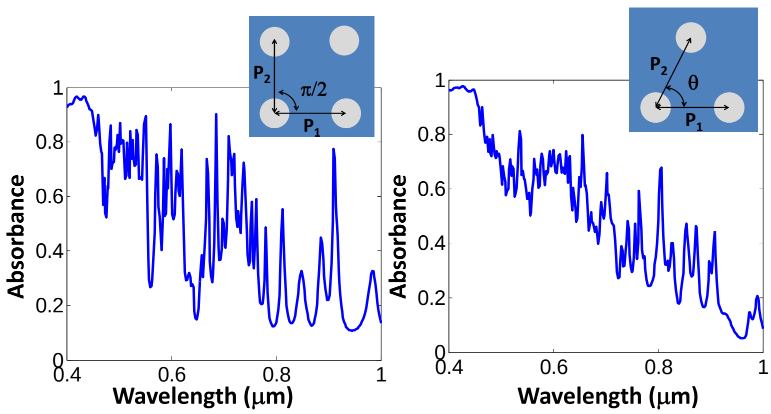

Fig. 2. The solar cell spectral response for the devices with (left) a baseline square lattice grating (right) a designed Brillouin zone lattice optimized grating.

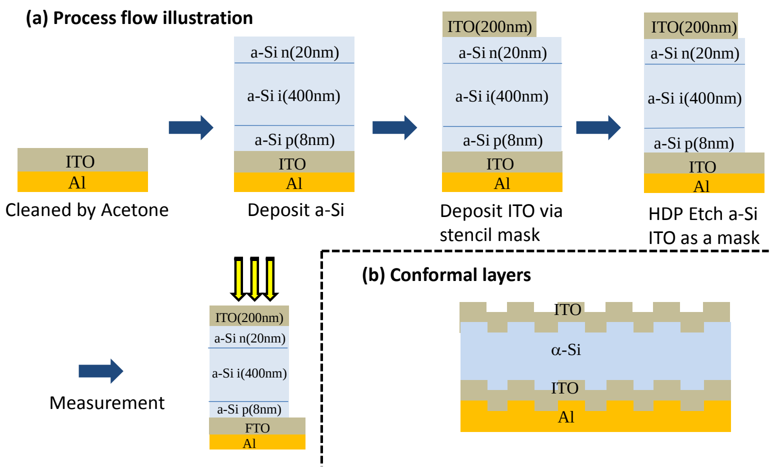

Fig. 3. Illustration of the process steps for the α-Si solar cells. It should be emphasized that although the α-Si is used here for demonstration, the proposed photonic pattern design concepts can be applied to any solar cell technologies without much difference from design point of view.

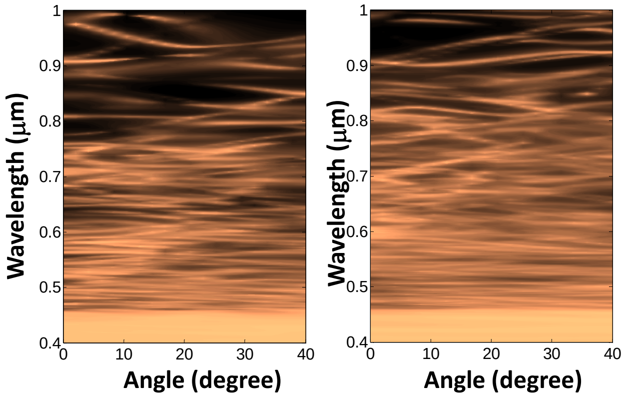

Fig. 4. The photonic bandstrucutres for (left) the square lattice grating (right) the Brillouin zone optimized grating.

The photonic bandstructure is shown in Fig. 4. The quasi-guided mode excitations can be easility observed. The photonic density of state (PDOS) directly affect the number of quasi-guide mode excitations. Nonetheless, it should be emphasized that the solar cell absorption enhancment is not only related to the number of mode exciations, it is also demtermiend by the mode quality, i.e. Q-factor. The moderate Q-factor is mroe appropriate for absorption enhnacent. High Q resonant peaks are of narrowband nature while low Q resonant modes are leaky. The adjustment in the 2D photonic lattice Brillouin zone can be very useful for achieving the most optimzed mode exciations in terms of the number of excited modes and the mode quality.

III. Preliminary Experimental Works

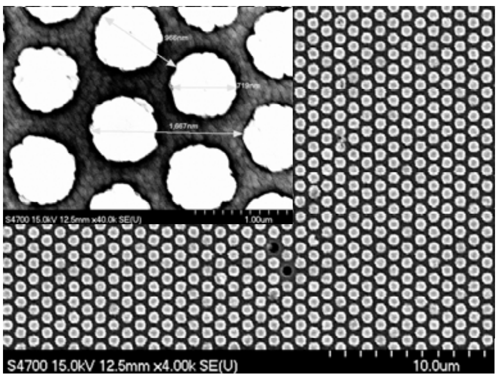

Fig. 5. The scanning electron microscopy (SEM) micrograph for the solar cell photonic patterns.

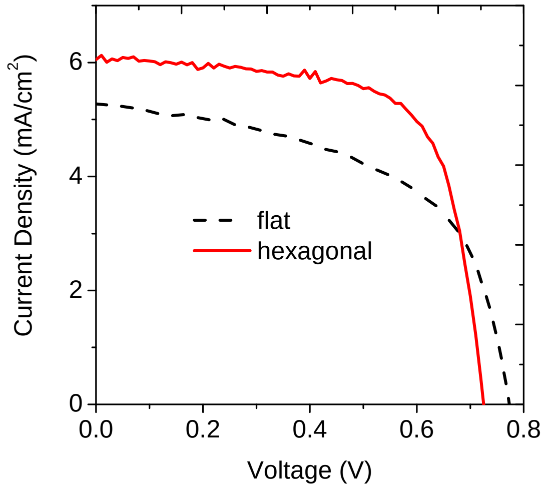

Fig. 6. The preliminary experimental result for Brillouin zone optimized solar cells. The deposition conditions are being adjusted for higher efficiency devices.

Previously >9% efficiency amorphous silicon solar cells using high density plasma chemical vapor deposition (HDPCVD) [34] have been fabricated in National Device Laboratory, Taiwan (NDL). Currently, newly-installed plasma enhanced chemical vapor deposition (PECVD) is being adjusted using process parameter splits for high efficiency solar cells. Patterned aluminum is used as substrates. The bottom indium tin oxide(ITO) is then deposited using sputtering. Afterward, the p-i-n amorphous silicon film is deposited on ITO and the thickness of p, i, and n layers are 8nm, 400nm and 20nm, respectively. The p-i-n silicon film is deposited by very high frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) at 250^{o}C. The top indium tin oxide(ITO) thickness is 200nm and is also deposited by sputtering. A shadow mask is placed on top of α-Si:H during ITO deposition to form the patterned ITO electrodes. In order to realize bottom contact, reactive ion etching (RIE) using CF_4/Argon(Ar) at 20 mtorr is employed to etch the portion of silicon film which is not covered with ITO, and the contact to the bottom ITO layer is achieved. Aluminum ohmic contact can be formed on the top and bottom ITO layer, but based on our measurement, probe directly in contact with ITO leads to similar measurement result.

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