Impact of Surface Texture on Bifacial Silicon Heterojunction Solar Cell Carrier Loss

Erin M. Tonita, Christopher E. Valdivia, and Karin Hinzer
SUNLAB, Centre for Research in Photonics, University of Ottawa, Ottawa, ON, Canada

***Abstract*— We investigate the impact of surface texturing on current loss as a function of depth and wavelength in high efficiency bifacial silicon heterojunction solar cells operating at their maximum power output. We couple 3D ray tracing with TMM thin-film boundary conditions for optical simulations and solve Poisson's drift-diffusion equations to calculate carrier recombination under both front and rear illumination. For front (rear) AM1.5G illumination at normal incidence, regular inverted pyramids out-perform planar surfaces and upright pyramid texture efficiencies by 17.1% rel. (17.9% rel.) and 1.4% rel. (1.0% rel.), respectively. Reduced carrier loss for inverted pyramid textures is calculated to be primarily due to a reflectivity decrease of 63% (76%) compared to planar surfaces which results in enhanced carrier-generation at depths further into the c-Si substrate. The benefit of inverted pyramidal light-trapping will be further enhanced when higher angles of incidence are considered, with angular performance particularly relevant for the rear-side.**

Keywords*— bifacial photovoltaics, silicon heterojunction, surface texture, recombination, optoelectronic modelling.

I. Introduction

Light management techniques such as anti-reflection coatings and nano- or micro-scale surface texturing are commonly used in indirect semiconductor-based solar cell design to enhance current density and increase overall cell efficiency. Developments in lithography and large-area patterning techniques allow for fabrication of regular upright and inverted pyramid texturing, in addition to the conventional acid-bath etched random pyramids. For simulating the design and optimization of such structures, coupling of multiple optical models is required to handle both internal features below the wavelength of light and structures on the order of 200 µm. Bifacial models are additionally complex as they must account for light-collection on both front and rear faces. Despite their growing popularity, with bifacial solar cells predicted to reach 60% of the solar market-share by 2029[1], characterization of their performance has yet to be standardized due to difficulty in both modelling and measuring bifacial illumination[2][3].

In this work, we simulate the sources of current loss in high-efficiency bifacial silicon heterojunction (SHJ) cells under front and rear illumination for three cases (Fig. 1a-c): planar surfaces, regular upright pyramidal textures, and regular inverted pyramidal textures, with pyramids at silicon's characteristic base angle of 54.7° to a height of ~ 7 µm. We simplify our discussion below by limiting to normally-incidence light, but will present results for 0-80° angles of incidence.

II. Model

Optoelectronic simulations are completed in Synopsys TCAD Sentaurus. Our modelled cell structures are provided in Fig. 1, with layers of indium tin oxide (ITO) and hydrogenated amorphous silicon (a-Si:H) as labelled. For optical simulations, we combine a Monte Carlo ray tracing algorithm with Transfer Matrix Method (TMM) boundary conditions on the c-Si substrate to accurately treat the absorption, transmission, and reflection of thin film conformal layers. All generated carriers in thin film layers are assumed to have zero collection efficiency, in agreement with experimental measurements[4]. We perform optical simulations in 3D on a single pyramid unit cell and extract a 1D-equivalent carrier generation profile, following Ref. [5], which is then applied across the unshaded regions of the 2D electrical domain. We model electrical performance by solving Poisson's equation coupled with electron and hole continuity equations. Further details and experimental validation of our model are provided in Ref. [6].

III. Results and Discussion

We calculate generation and recombination rates throughout the c-Si substrate for our three considered structures with the standard incident solar spectrum of AM1.5G. Figure 2a shows

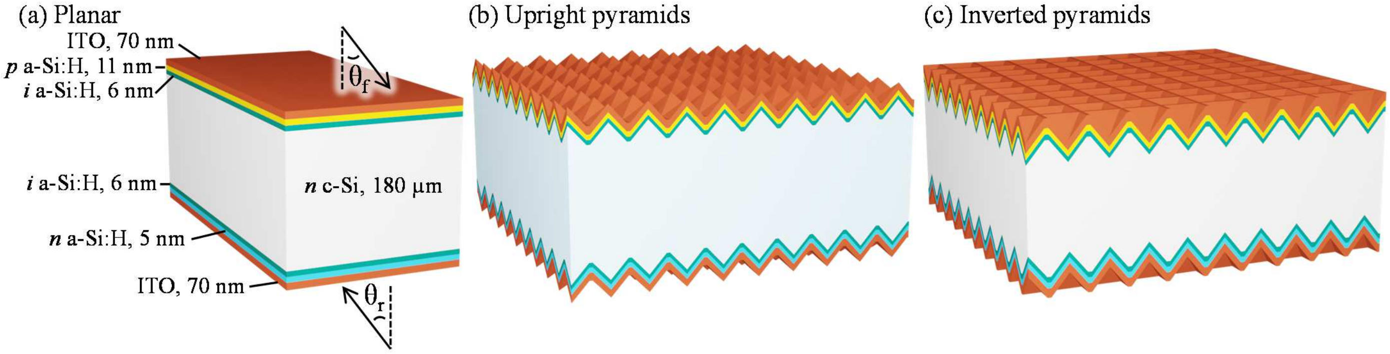

Fig. 1. Modelled bifacial SHJ cell structure with varied texturing (not to scale). Layer thicknesses are labelled. The AOI of incoming rays is pictured for front and rear illumination, given by θ_f and θ_r, respectively.

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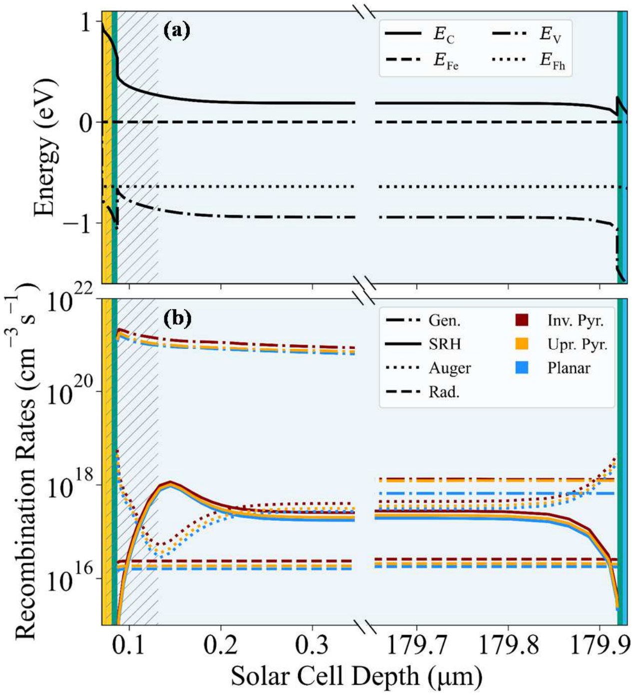

Fig. 2. (a) Electronic band structure and (b) generation and recombination rates for the bifacial SHJ under front illumination at P_{max} for varied textures.

the band alignment of our inverted pyramid device under front illumination at maximum power operation (P_{max}). Electrons travelling in the conduction band face a 0.15 eV barrier at the front a-Si:H/c-Si interface followed by a 0.3 eV rise, while holes in the valence band face a 0.45 eV band-offset at the rear interface. These barriers reduce minority carrier surface recombination. Shockley-Read-Hall (SRH), Auger, and radiative recombination rates are plotted in Fig. 2b for the three devices, alongside their respective generation rates. As expected, SRH and Auger recombination rates peak and dip, respectively, around the depletion region. As in other high-quality c-Si devices, Auger recombination is dominant. Although not depicted, under rear illumination recombination rates are increased by an order of magnitude. For both illumination scenarios, a substantial drop in carrier generation can be seen for the planar structure compared to pyramid textures, particularly at depths further from illuminated surfaces.

The impact of surface texturing on device performance at P_{max} is depicted in Fig. 3, with the proportion of current lost to parasitic absorption in front and rear thin films ($J_{A,films}$), transmission (J_T), reflection (J_R), and recombination (J_{rec}), provided for 300-1200 nm. Additional cell performance metrics of short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and efficiency (η), are labelled for AM1.5G illumination. Inverted pyramids demonstrate the greatest cell efficiency of 21.9%, which is 1.4% rel. and 17.1% rel. larger than that of upright pyramids and planar textures, respectively. This is a result of both decreased reflection and transmission of 6.3% and 23% compared to upright pyramids and 63% and 59% compared to planar textures. This same analysis has been repeated for rear-side illumination, finding an increase in efficiency of 1.0% rel. and 17.9% rel. by using inverted pyramids compared to upright pyramids and planar surfaces. However, rear-side efficiency is decreased compared to front-side by 3.7% rel., 3.2% rel., and 4.3% rel. for inverted, upright pyramids, and planar textures, respectively. This is due to the increased carrier diffusion lengths required to reach the front p-n junction resulting in increased recombination.

IV. Summary

Inverted pyramidal texturing provides the highest efficiency performance for studied bifacial SHJ cells under both front and rear illumination. A further break-down of carrier losses under dual illumination and with varying angles of incidence, which is particularly important for rear-side energy yield, will be presented at the conference.

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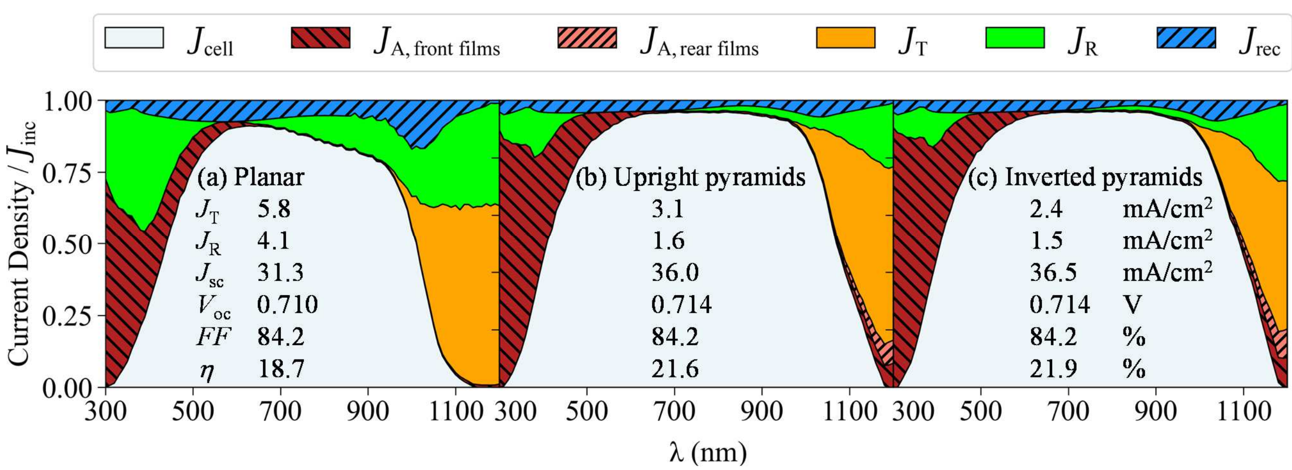

Fig. 3. Sources of current loss at P_{max} for normal-incidence front illumination with front and rear surface textures as labelled.