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How cell textures impact angular cell-to-module ratios and the annual yield of crystalline solar modules

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ABSTRACT

Two emerging trends in multicrystalline silicon cell texturing are plasma texturing, and metal catalyzed chemical etching. Both processes roughen silicon surfaces in order to increase light absorption. These processes are attractive as they are applicable to diamond-wire sawn wafers. This work investigates the optical properties of these surfaces, and other conventionally textured surfaces like isotropic acidic and random pyramid textures, are investigated for cells in air and after encapsulation for a large range of angles of incidence. We find that the angular optical performance in air varies strongly with cell texture, but when embedded in a module structure these variations are significantly mitigated: the advantages of a high angular absorption of solar cells are not fully transferred to the module level. This is especially notable for plasma etched, black silicon cell structures which suffer comparatively from poorer index matching and light recycling inside a module structure. The losses caused explicitly by the module embedding (described in the cell to module ratio) are in the range of 1–5% for perpendicular incoming light, and increase to 6–15% at an angle of incidence of 70°. Based on these angular performances, we calculate the annual yield of the modules and find that it varies by less than 2% for the cell textures. Nevertheless, the annual optical yield for the black silicon cell structures are the highest, whereas the metal catalyzed chemical etching cell structures show the lowest performance. Further, we find that different annual distributions of the incoming light at the two investigated locations (Melbourne and Alice Springs) only impact the relative performance of the cell textures at high module tilt angles.

1. Introduction

Key metrics of photovoltaic (PV) cell and module performance are efficiency and power, measured under standard test conditions (STC) with normal irradiance [1]. However, in-field performance strongly impacts the final levelized cost of PV electricity where most radiation is typically non-normal [2]. Clearly, different front solar cell textures impact angular light absorption [3,4]. However, it is the angular behavior of a cell embedded in a module laminate, and how the module embedding impacts the cell angular behavior that impacts field performance. Hence, to truly reduce costs by manipulation and design of the cell front surface, the performance *after* module embedding should be considered. This work investigates cell types with various front textures including chemical and plasma etched front structures, and compare them to common isotropic acidic and random pyramid textured wafers. We focus our work on recently developed black silicon cell structures, particularly *metal catalyzed chemical etched* (MCCE) textures applied on wire sawn multicrystalline wafers, and plasma etching on previously acidic textured wafers. Both technologies are currently under investigation in industry [5], especially the MCCE process which could lead to cost reductions and can be applied directly on diamond sawn wafers [6–8].

Previous work [9–11] investigated the impact of acidic and random cell textures on module power under standard test conditions (STC) using an angle of incidence (AoI) of 0°. Other work [12,13] considered angular resolved cell and module measurements determined up to an angle of incidence of 60° and under the standardized sun spectra AM 1.5 g. In our study we show the angular resolved absorption of seven industrially relevant solar cell structures in air for angles of incidence up to 80°, which allows higher accuracy in determining the angular power output. Based on our measurements we compute the impact of embedding on the annual optical yield (AOY) of a module. Further, in [14] the performance of random, acidic, and honeycomb textured cells were investigated both in air and within a module structure, focusing

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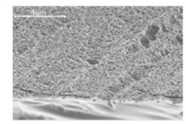
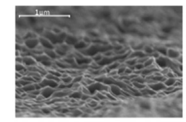
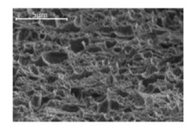
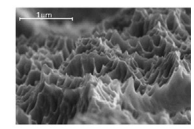
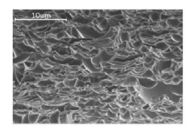
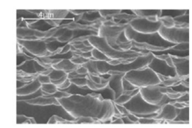
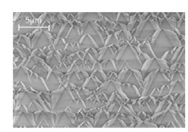
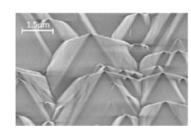
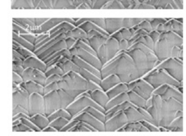
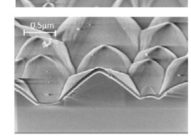
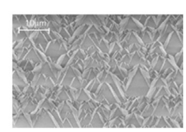
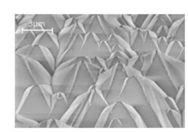
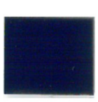
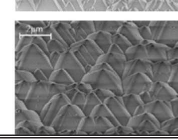
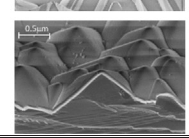
Table 1
Overview of the material and design characteristics of the investigated solar cell structures including scanning electron microscope images (SEM) with lower (left) and higher (right) magnification. The given reflectance is measured with a spectrophotometer using an integrating sphere at an angle of incidence of 8° and weighted with the AM 1.5 g spectrum and the spectral response of a solar cell.

sample	*photo*	*wafer substrate*	*front surface texture*	*backside design*	*reflectance at 8° in air (%)*	*SEM images*	
A.1		mc-Si	metal catalyzed chemical etching (MCCE) directly applied on diamond sawn wafer	screen printed aluminum	8.7		
A.2		mc-Si	same as A.1 *without front metallization*	screen printed aluminum	6.6		
B		mc-Si	*Black silicon*-plasma texture (RIE) on acidic textured diamond sawn wafer	screen printed aluminum	5.4		
C.1		mc-Si	acidic texture (isotexture)	screen printed aluminum	9.2		
C.2		mc-Si	same as C.1 *without front metallization*	screen printed aluminum	6.8		
D		Cz-Si	*Bifacial*-random pyramids (RP)	random pyramids (RP)	7.2		
E		Cz-Si	random pyramids (RP) PERC	screen printed aluminum	7.4		
F		Cz-Si	random pyramids (RP) PERC	screen printed aluminum	5.7		
G		Cz-Si	random pyramids (RP)	IBC backside structure	6.9		

on validating simulations by using external quantum efficiency (EQE) and reflectance measurements to determine the angular spectral power generation. In contrast, we use an experimental approach to investigate a wider range of industrial manufactured solar cells, focusing on black silicon structures. Particularly we examine the impact of the *module design* on angular absorption and derive from this the impact on the annual yield. We use two different common glass covers with and without an antireflective coating to demonstrate the impact on annual module performance for the seven different cell types under realistic angular distributions of light. To achieve this, we determine the optical losses caused by the module *embedding* (glass and Ethylene-vinyl acetate (EVA)) for various angles of incidence (AoI) quantified by the cell to module ratio (CTM), which is a parameter indicating optical losses explicitly caused by embedding and is described in [10,13,15].

2. Experimental approach

2.1. Samples

We investigate seven industrially processed solar cell structures from five different manufacturers (see Table 1). The cells are categorized according to their front texture, their rear structure, and the presence or absence of front side metallization. The back-end processing of the MCCE, black silicon, and isotextured samples is performed on the same pilot line using the same front and rear screen print parameters. This experimental design allows a direct comparison of these three cell types. In particular, it enables the determination of the impact of finger scattering on the module output or the CTM ratios.

We laser-cut the solar cells into samples of size $20 \times 17.5\,mm^2$. Later, we embed these into a standard module structure commonly used