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# Angle resolved characterization of nanostructured and conventionally textured silicon solar cells

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## Abstract

We report angle resolved characterization of nanostructured and conventionally textured silicon solar cells. The nanostructured solar cells are realized through a single step, mask-less, scalable reactive ion etching (RIE) texturing of the surface. Photovoltaic properties including short circuit current, open circuit voltage, fill factor (FF) and power conversion efficiency are each measured as function of the relative incident angle between the solar cell and the light source. The relative incident angle is varied from 0 to 90 degrees in steps of 10 degrees in orthogonal axes, such that each solar cell is characterized at 100 different angle combinations. The angle resolved photovoltaic properties are summarized in terms of the average, angle-dependent electrical power output normalized to the power output at normal incidence and differently textured cells on different silicon substrates are compared in terms of angle resolved performance. The results show a 3% point improvement in average electrical power output normalized with respect to normal incidence power output of RIE textured, multi crystalline Si cells compared to conventional multi crystalline Si cells and above 1% point improvement of RIE textured mono crystalline Si cells compared to conventional mono crystalline Si cells.

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*Keywords:* black silicon, reactive ion etching, incident angle, reflectance, angle-resolved characterization

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## 1. Introduction

Solar cells are generally characterized at standard test conditions i.e. at light intensity of  $1000 \text{ W/m}^2$ , AM1.5G<sup>1</sup> illumination, temperature of  $25^\circ\text{C}$  and light at normal incidence, which means that the incident simulated sunlight beam is directed at an angle of  $90^\circ$  relative to the solar cell plane. However these conditions only represent a very limited fraction of actual, realistic operating conditions for solar cells and panels. The temperature of the cell and the intensity and incidence angle of the sunlight indeed vary between different geographical locations and throughout the duration of a day and a year. Furthermore solar cells are subject to diffuse light whenever clouds, dust or any obstacles in the air scatter the sunlight before it reaches the solar cell surface. For this reason there is a need for a more detailed characterization scheme for solar cells, which takes these variations into account. In particular when considering alternative solar cell types employing features such as nanoscale texturing of the solar cell surface, the angle-resolved and low light performance becomes more important, since nanoscale texturing has been shown [1] [2] [3] to yield superior reflectance properties over a broad range of incident angles compared to conventionally textured solar cells.

We use Black Silicon (BS)[4] [5] nanostructuring to achieve low reflectance due to the resulting graded refractive index at the Si-air interface. Low broadband reflectance at different incident angles has been reported for moth-eye surfaces [6] [7] and different types of black silicon [8] fabricated by means of various methods. This work focuses on black Si fabricated by maskless reactive ion etching (RIE). Repo et al.[9] achieved a power conversion efficiency of 18.7% on  $400 \mu\text{m}$  thick float-zone Si using cryogenic deep RIE as texturing and plasma assisted

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<sup>1</sup>AM1.5G = Air Mass of 1.5 Global

atomic layer deposition (ALD) of  $Al_2O_3$  for a passivated emitter rear locally dif-  
fused (PERL) cell. Oh et al. [3] achieved a power conversion efficiency of 18.2 %  
on 300  $\mu\text{m}$  thick float-zone Si by combining a metal-assisted wet etching black  
silicon process for texturing, TMAH damage removal etch and double-sided  
30 thermal  $SiO_2$  passivation. Yoo et al. [10] used industry grade Czochralski Si  
and RIE texturing and achieved a power conversion efficiency of 16.7 %. Several  
groups have reported improved light absorption over a broad range of incident  
angles of nanostructured [11] [12] [13] [14] and differently textured Si including  
the PERL-cell [15] [16]. Considering these reported improved angle-dependent  
35 optical properties of nanostructured Si and the correlation between overcast sky  
(diffuse light) conditions and relative incident angle of the sunlight [17] [18] [19]  
[20], the relationship between nanostructured Si solar cells and angle-dependent  
photovoltaic performance is of utmost interest with respect to optimization of  
solar cell performance under realistic operating conditions such as diffuse light.  
40 Lee et al. [21] show improved average power conversion efficiency as function of  
incident angle of nanostructured thin film Si solar cells in comparison with "con-  
ventional" thin film Si cells with single and double anti-reflective (AR) coating.  
However, a detailed study of the angle-dependent photovoltaic performance of  
nanostructured, large-area Si solar cells based on industrial type Si substrates in  
45 direct comparison with conventionally textured Si solar cells, has not yet been  
reported.

This work presents an angle-resolved characterization approach of solar cells in  
general and measured angle-resolved photovoltaic properties of nanostructured  
Si solar cells in comparison with conventionally textured Si solar cells.

## 50 2. Approach

The maskless RIE process presented in this work is applied as the texturing  
step in the following solar cell fabrication process:

- Saw damage removal by etching in 30 % KOH at 75°C for 2 minutes and  
subsequent cleaning in 20 % HCl at room temperature for 5 minutes and

55 rinsing in deionized water.

- Texturing using maskless RIE at room temperature in a  $O_2$  and  $SF_6$  plasma with a gas flow ratio of  $O_2:Sf_6 \approx 1:1$ , chamber pressure of 28 mTorr, 13.56 MHz radio-frequency platen power of 30 W using a STS RIE system.
- 60 • Emitter formation using a tube furnace from Tempres Systems with liquid  $POCl_3$  as dopant source and  $N_2$  as carrier gas at a temperature of  $840^\circ C$  and atmospheric pressure for 50 min in  $O_2$  ambient, followed by removal of phosphor-silicate glass (PSG) in 5 % hydrofluoric acid (HF).
- Plasma enhanced chemical vapour deposition (PECVD) of 60 nm hydrogenated amorphous silicon nitride ( $SiN_x:H$ ) anti-reflective coating at  
65  $400^\circ C$  using a PlasmaLab System133 from Oxford Instruments.
- Screen-printing of Ag front and Al rear contacts with standard Ag and Al pastes using an Ekra X5-STs screen printer, followed by co-firing of the front and rear contacts at  $800^\circ C$  using an RTC Model LA-309 belt  
70 furnace.
- Edge isolation by laser ablation using a J-1030-515-343 FS System from Oxford Lasers Ltd.

The starting substrates were  $156 \times 156 \text{ mm}^2$  p-type, CZ mono-, multi- and quasi-mono-crystalline Si wafers with a thickness of  $200 \mu m$  and a resistivity of 1-3  
75 Ohm cm.

### 3. Characterization

Normal incidence reflectance measurements of the RIE-textured mono-, multi and quasi-mono Si surfaces were performed using a broadband lightsource (Mikropack DH-2000), an integrating sphere (Mikropack ISP-30-6-R), and a spectrometer  
80 (Ocean Optics QE65000, 280-1000 nm). The reference solar spectral irradiance

for AM 1.5 was used to calculate the weighted average reflectance in the wavelength range from 280-1000 nm. The angle-dependent optical reflectance was measured with monochromatic light from 350 nm to 1200 nm using an APEX monochromator illuminator with an Oriel Cornerstone 260 1/4m monochromator. A quartz crystal achromatic depolarizer from Thorlabs was used in the beam path to randomize the partly polarized light from the monochromator. The sample was inserted inside a 150 mm integrating sphere with a center mount configuration and rotated to any desired angle of incidence.

I-V curves and photovoltaic properties including short-circuit current,  $I_{SC}$ , open-circuit voltage,  $V_{OC}$ , fill factor, FF, and electrical output power,  $P_{el}$ , were measured on complete cells under 1 sun illumination ( $1000 \text{ W/m}^2$ , AM1.5G) using a Newport Oriel 92190 large-area Xe light source and a Keithley 2651A high-power source meter.

In order to characterize the solar cell performance at varying incident angles, I-V curves were measured on differently textured Si solar cells mounted and contacted on a stage, which prior to each I-V curve measurement was tilted to a position given by two angles,  $\theta$  and  $\phi$ , around two orthogonal axes:  $\theta$  is the tilt of the cell plane with respect to the original, horizontal x-axis and  $\phi$  is the tilt of the cell plane with respect to the tilted y-axis. The light source was fixed during all measurements. The measurement setup including the two angles  $\theta$  and  $\phi$  is sketched in Fig. 4. The incidence angle was varied using two JVL QuickStep stepping motors connected to the solar cell stage. Each angle was randomly varied in steps of  $10^\circ$  in the range  $0 - 90^\circ$  unless otherwise specified. At each angle combination,  $(\theta, \phi)$ , the I-V curve was measured under 1 sun and the result collected using LabView, such that a total of 100 I-V curves were measured for each cell. The measured I-V curves were then analyzed in order to determine  $I_{SC}$ ,  $V_{OC}$ , FF and  $P_{el}$  at each angle combination,  $(\theta, \phi)$ , using SciLab. Finally the angle-resolved photovoltaic properties were plotted and the average electrical power output normalized to the normal incidence power output was calculated in order to compare the angle-dependency of different cells. A LEO 1550 Scanning Electron Microscope (SEM) was used to characterize the

nanostructured surface topology.

#### 4. Results

An example of the nanostructured surfaces realized by maskless RIE in this  
115 work is seen in Figure 1.

The nanostructures seen in Figure 1 are conical-like hillocks randomly dis-  
tributed across the entire solar cell surface. The nanostructures are on average  
300-400 nm tall with an area density of  $\sim 100 \mu\text{m}^{-2}$ . The topology is shown with  
and without  $\sim 60\text{nm}$  PECVD  $\text{SiN}_x\text{:H}$  in Fig.1. It is seen from Figure 1(a) that  
120 the  $\text{SiN}_x\text{:H}$  AR-coating does not change the RIE-textured topology significantly,  
but makes the nanostructure edges slightly more round and smooth.

Figure 2 shows total weighted average reflectance of RIE-textured Si below  
1.1% for all three crystalline grades of Si, which is a clear improvement com-  
pared to KOH- and acidic-textured Si used in standard industrial Si solar cells.  
125 With anti-reflective coating KOH-textured Si has reflectance of 2% [22], while  
acidic-textured multi-crystalline Si has reflectance of 8% [23]. It is seen that the  
average reflectance is unaffected by the  $\sim 60\text{nm}$  PECVD  $\text{SiN}_x\text{:H}$  AR-coating.  
The results furthermore show negligible increase in reflectance after emitter dif-  
fusion. The RIE-textured Si shows  $\sim 0.1\%$  minimum reflectance independent  
130 of crystalline grade. The power conversion efficiencies at normal incidence of  
the fabricated solar cells are summarized in Table 1. Table 1 shows that the  
RIE-textured cells have lower power conversion efficiency than the convention-  
ally textured cells primarily due to lower short-circuit current, but also reduced  
open-circuit voltage. Based on IQE-measurements and LASSIE<sup>2</sup> analysis, the  
135 current and voltage losses were explained by increased emitter and surface re-  
combination [24]. For the cells fabricated in this work, the texturing and thus  
reflectance was not fully optimized. Since the RIE-texturing has been further  
optimized after these cells were fabricated, with a resulting weighted average

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<sup>2</sup>Loss Analysis of Silicon Solar cells by IQE Evaluation

reflectance below 1%, it is expected that the power conversion efficiency will  
140 be increased in future studies. In addition, optimized post RIE processing may  
reduce emitter recombination.

Figure 3 shows the total weighted (AM1.5) average reflectance as function of  
incident angle for standard, KOH-textured (squares) and RIE-textured (triangles)  
145 mono-crystalline Si substrates. The reflectance was measured using an  
integrating sphere with one axis angle variation of the incident optical fiber relative  
to the Si substrate. The results in Figure 3 show that the reflectance of RIE-textured  
Si is significantly below that of KOH-textured Si at all incident angles below  $70^\circ$ .  
Furthermore the reflectance of KOH-textured Si increases more with incident angle  
up to  $50^\circ$  than the reflectance of RIE-textured Si.  
150 For angles above  $50^\circ$  the reflectance of RIE-textured Si increases more with  
incident angle than that of KOH-textured Si. This result shows the potential  
for improved solar cell performance using RIE-texturing at non-ideal incident  
angles.

There are two reasons for measuring parameters such as  $I_{SC}$ ,  $V_{OC}$ , FF and  
155 power output as function of two different incident angles and plotting the result  
in a 2-D plot such as in Figure 4: First of all, the intention of this work is to  
demonstrate a new and different method for characterization of solar cells in  
general. By measuring IV-data as function of two orthogonal incident angles in  
combination, realistic angle-resolved scenarios such as diffuse light conditions  
160 can be investigated in more detail. Secondly, this method allows for a quantification  
of any asymmetric features of the solar cell with respect to incident angle of the  
light, whether on the surface or inside the cell. Examples of this are isotropic  
compared anisotropic texturing methods and light trapping properties. We acknowledge  
that the asymmetric behaviour seen in Figure 4 is not  
165 significant considering the uncertainties of the measurement. Thus, the choice  
of a 2-D plot in this case is a demonstration of the method and its capabilities,  
rather than a thorough analysis of asymmetric angle-resolved behaviour.

Figure 4 shows that  $V_{OC}$  and FF do not change significantly for angles below  
 $80^\circ$ .  $I_{SC}$  and consequently  $P_{el}$  decrease with increasing incident angle. This

170 is expected since the optical input power,  $P$ , on the solar cell decreases with cosine to the incident angle, since the effective illuminated area decreases with cosine to the angle according to Eq. 1. In the experimental setup the optical power incident on the cell for angle variation  $\theta$  is given by

$$P = P(\theta) = \Phi_0 W^2 \cos(\theta) = P_0 \cos(\theta) \quad (1)$$

under ideal conditions. Here  $W$  is the edge length of the cell,  $\Phi_0$  is the optical 175 intensity and  $P_0$  is the optical power incident on the cell at normal incidence. The efficiency of the cell, which may be angle dependent, is

$$\eta(\theta) = \frac{P_{el}(\theta)}{P(\theta)} \quad (2)$$

where  $P_{el}$  is the electrical output power at optimal load conditions. Part of any angular dependence in the efficiency is due to angular dependence of the reflection coefficient,  $r(\theta)$ , and this dependency is made explicit, if an internal 180 efficiency  $\eta_{int}$  is defined such that

$$\eta(\theta) = \eta_{int}(\theta)[1 - r(\theta)] \quad (3)$$

The internal efficiency,  $\eta_{int}(\theta)$ , could be angle dependent due to increased photon path length within the silicon for increasing  $\theta$  and consequently increasing collection probability. Investigation of this effect is beyond the scope of this work.

185 These efficiencies are the physically relevant parameters for the cell. For convenient presentation of the raw measurement data, an artificial apparent efficiency  $\eta_{app}$  may be defined as

$$\eta_{app}(\theta) = \frac{P_{el}(\theta)}{P_0} = \eta(\theta) \cos(\theta) \quad (4)$$

and from the rightmost expression in Eq. 4, it is seen that if the cell has an efficiency without angular dependency, then the apparent efficiency has a cosine 190 angular dependency. The measured apparent efficiency for the RIE-textured mono-crystalline Si cell is plotted in Figure 5; in the plot the expected apparent efficiency given in Eq. 4 assuming a constant  $\eta$  is also shown for comparison. For

simplicity the results are only shown with angle variation in one axis. Figure 5 shows that the experimentally measured apparent efficiency is higher than expected for incident angles below  $60^\circ$ . This may in part be explained by divergence of the light source, which changes the actual optical input power according to Eq. 5.

$$P(\theta) = \Phi_0 W^2 \frac{\cos(\theta)}{1 - (\frac{W}{2L} \sin(\theta))^2} \quad (5)$$

where  $L$  is a characteristic length parameter of the divergence. Note that the term  $1 - (\frac{W}{2L} \sin(\theta))^2$  is a possible correction term related purely to the measurement setup. Eq. 5 shows that divergence of the light source accounts for measured apparent efficiency values higher than expected. However, efficiency values lower than expected, as seen for incident angles higher than  $60^\circ$  in Fig. 5, can not be explained by divergence of the light source and are most probably a result of increased reflectance at higher incident angles.  $P_{el}$  decreases according to Eq. 3 when the reflected part of the optical input power,  $r(\theta)$ , increases with incident angle as shown in Fig. 3.

In order to evaluate the actual angle dependency of the differently textured solar cells, the measured electrical power output was normalized to the electrical power output at normal incidence,  $(0,0)$ . Figure 6 shows the angle-dependent normalized power output for the RIE- and conventionally textured mono- and multi-crystalline Si cell, respectively, for comparison. Figure 6 shows that the RIE-textured mono- and multi-crystalline cells in general have slightly higher angle-resolved efficiency normalized to the efficiency at normal incidence compared to the conventionally textured cells. For certain incidence angles above  $60^\circ$  the conventionally textured mono-crystalline cell shows slightly higher normalized efficiency compared to the RIE-textured. Figure 6 also shows an asymmetric behaviour with respect to the two angles,  $\theta$  and  $\phi$ . The asymmetry occurs for both RIE- and conventionally textured cells, which indicates that the asymmetric behaviour is partly due to imperfections in the measurement setup. However, it is seen that the asymmetry is slightly larger for the conventional cells for most angles. This might be explained by the different rotational sym-

metries for the differently textured topologies: The black silicon cell - due to the random nature of the surface nanostructures should only be affected by the polar angle of the incident light, whereas the azimuthal angle should not matter. The same may not be true for KOH textured cells, where the pyramids  
 225 may be of random size, but they all share a fourfold symmetry in the azimuthal angle; it follows that some degree of variation with the azimuthal angle may be present for KOH cells.

The asymmetric behaviour may also be due to the front metallization, which  
 230 reduces the symmetry to twofold or lower.

Yet, the observed asymmetry is too small compared to the uncertainties of this measurement to conclude whether the asymmetry is actually due to topology differences or measurement inaccuracy.

235 Angle-resolved properties similar to the results in Figure 4 were measured for nanostructured mono-, multi- and quasi-mono-crystalline Si cells and conventionally textured mono- and multi-crystalline Si cells for comparison. Since texturing of quasi-mono-crystalline Si cells is not yet fully established or standardized, no such cell was produced. Based on the measured angle-resolved  
 240 electrical power output, the average normalized electrical power output,  $\Psi_{av}$ , relative to the power output at normal incidence can be compared for each of the differently textured cells.  $\Psi_{av}$  is given by the expression in Eq. 6 and the resulting values of average relative power output are shown in Table 2 and Figure 7.

$$\Psi_{av} = \frac{1}{N} \sum_{\theta=0}^{90} \sum_{\phi=0}^{90} \frac{P_{el}(\theta, \phi)}{P_{el}(0, 0)} \quad (6)$$

245 In Eq. 6  $N$  denotes the total number of efficiency values which is being averaged over. In the case of averaging over incident angles in the range of 0-90° in steps of 10° in both axes,  $N = 100$ .  $P_{el}$  denotes the measured electrical power output of the cell.

The results in Figure 7 and Table 2 show that the average normalized power  
250 output is also higher for the RIE-textured cells compared to the reference cells  
in the incident angle range of  $0-40^\circ$ . Furthermore the difference between the  
RIE-textured and the reference cells is even more significant in this smaller  
range of angles closer to normal incidence. This angular range is arguably more  
interesting than  $0-90^\circ$  due to e.g. higher sunlight intensity close to normal  
255 incidence and the effective restriction of incident angles of light reaching the  
solar cells due to refraction and reflection of light from the protective glass  
covering solar cells in practice. In order to account for these differences, it is  
needed to do a complete weighing of the different incident angles and angle  
ranges. Such analysis is out of the scope of this work, but the results indicate  
260 the need for a more detailed analysis.

## 5. Discussion

The results in Table 1 show that the RIE-textured cells have lower power  
conversion efficiency at normal incidence due to increased surface recombination  
of the RIE-textured cells [24].  
265 However, the average electrical power output normalized to the power output at  
normal incidence shown in Figure 7 is higher for the RIE-textured cells compared  
to the conventionally textured cells; both for mono- and multi-crystalline Si.  
This indicates a less angle-dependent power output of such nanostructured Si  
solar cells compared with conventionally textured Si solar cells in general. Less  
270 angle-dependent power output implies potentially higher power output over a  
broad range of incident angles representing e.g. angle variation during daily  
and yearly operation of solar cells and panels. Furthermore, and perhaps more  
importantly, such less angle-dependent behaviour as seen on Figure 7 represents  
improved performance under diffuse light conditions for nanostructured solar  
275 cells compared with conventionally textured solar cells. Since diffuse light is a  
realistic and important operating condition, which affects the performance of  
commercial solar cells and panels significantly, this result shows the potential

of nanoscale texturing, such as maskless RIE-texturing, as a way of improving the overall performance of Si solar cells by enhancing the diffuse and low light performance and thus create a more stable and angle-independent solar cell performance.

## 6. Conclusion

A method for angle-resolved characterization of solar cells in general and measured angle-dependent photovoltaic properties of nanostructured and conventionally textured mono, multi and quasi-mono crystalline Si solar cells, respectively, have been presented. Compared with conventionally textured cells the nanostructured solar cells have lower power production over a broad range of incident angles due to lower power conversion efficiency in general. However, the RIE-textured multi-crystalline Si cells show a 3% point improvement in average normalized angle resolved power output compared to conventionally textured and the RIE-textured mono-crystalline Si cells show above 1% point improvement compared to conventionally textured.

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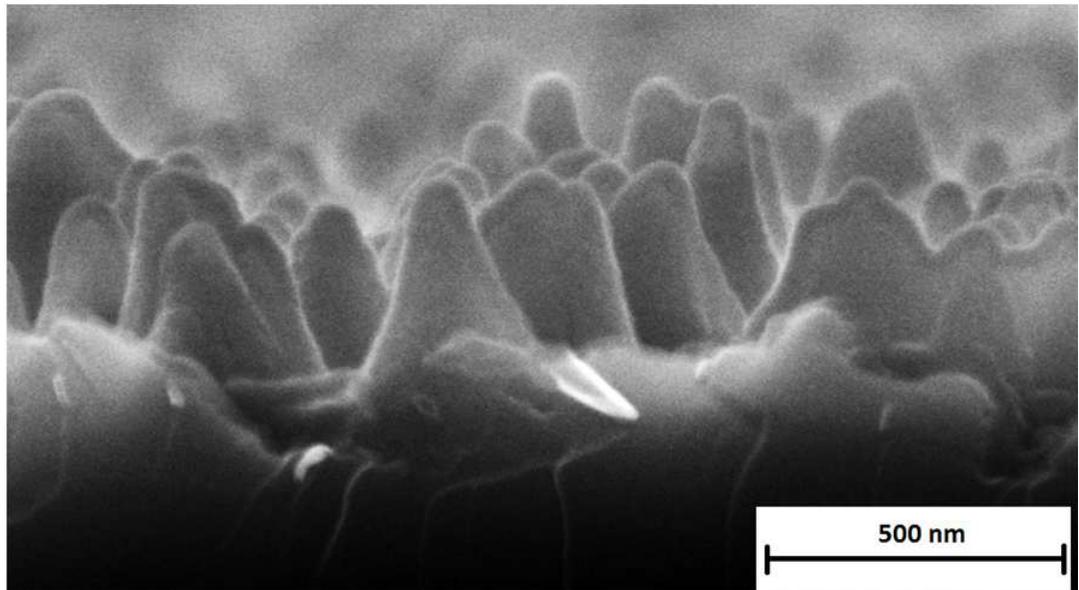
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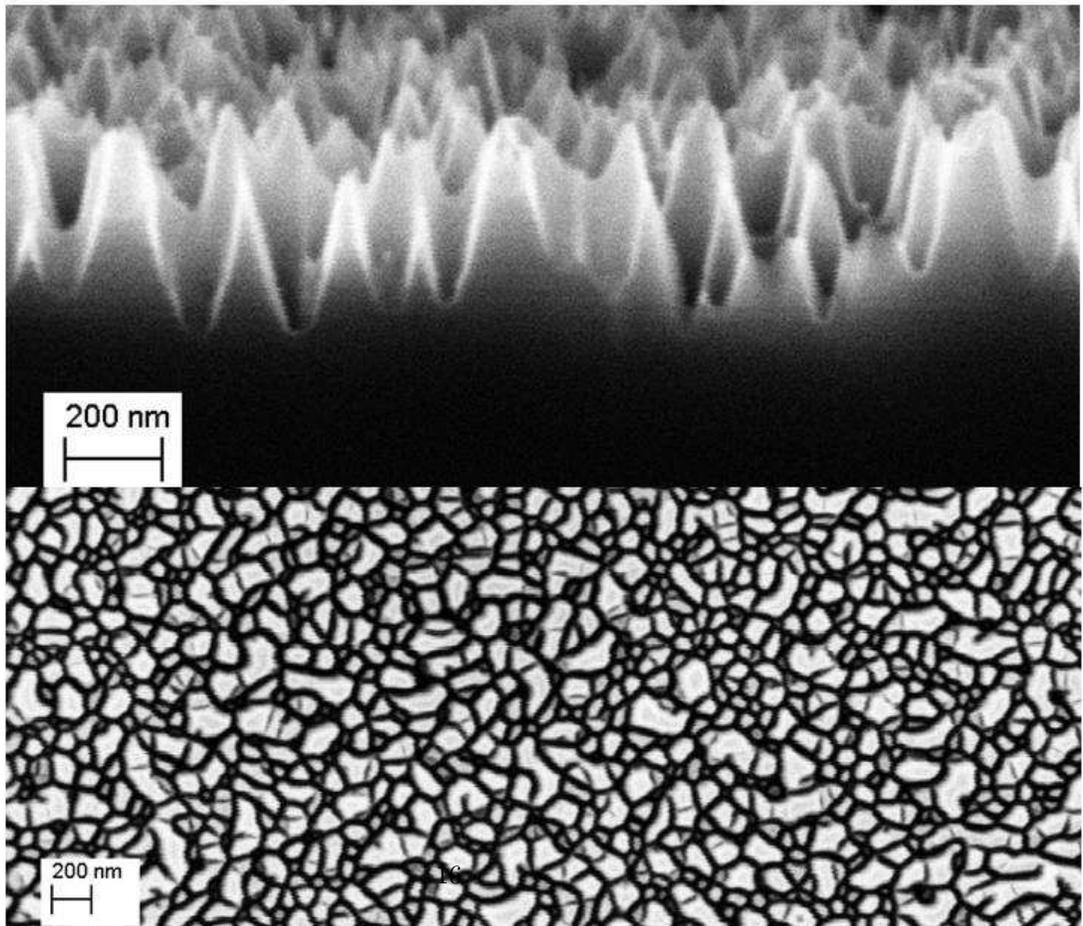
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(a)



(b)

Figure 1: SEM-image at  $45^\circ$  (a,b,top) and  $0^\circ$  (b,bottom) tilt of the RIE-textured Si surface with (a) and without (b)  $\sim 60\text{nm}$  PECVD  $\text{Si}_x\text{:H}$  AR-coating, respectively.

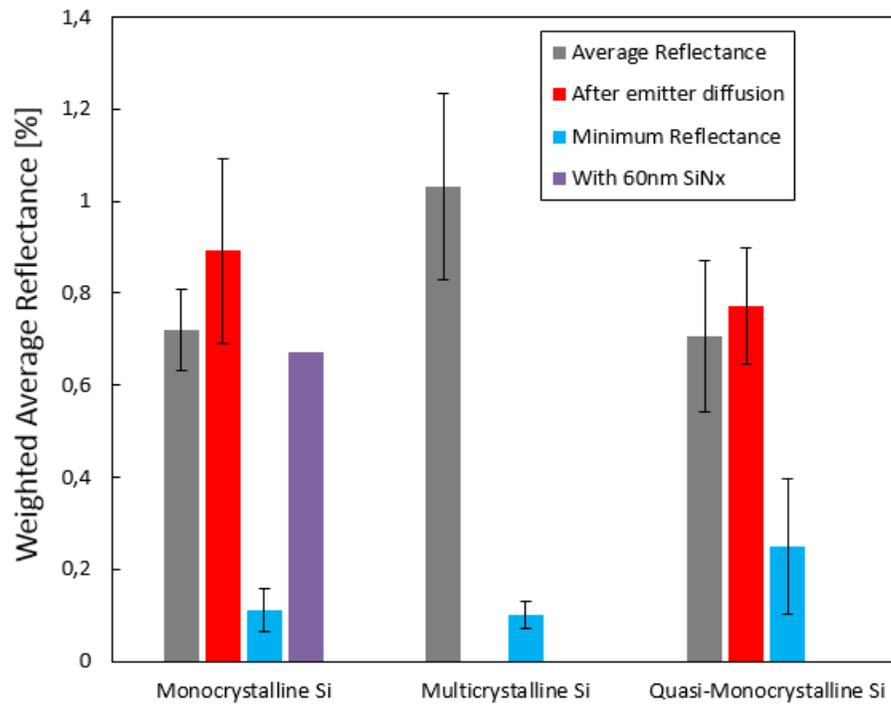


Figure 2: Total weighted (AM1.5) average reflectance before and after emitter diffusion as well as the minimum reflectance of mono-, multi- and quasi-mono Si surfaces, respectively. The average reflectance of RIE-textured mono-crystalline Si with  $\sim 60\text{nm}$  PECVD  $\text{SiN}_x\text{:H}$  AR-coating is also shown.

<i>Normal Incidence</i>				
Cell	Efficiency [%]	$J_{SC}$ [mA/cm <sup>2</sup> ]	$V_{OC}$ [mV]	FF
Conventional Mono	17.8	36.8	619	0.78
Conventional Multi	16.5	34.4	619	0.77
RIE Mono	16.5	35.2	609	0.78
RIE Multi	14.5	31.7	592	0.77
RIE Quasi-Mono	13.0	30.0	575	0.75

Table 1: Power conversion efficiency, short-circuit current, open-circuit voltage and fill factor at normal incidence of conventionally and RIE-textured mono-, multi- and quasi-mono-crystalline Si cells, respectively.

$\Psi_{av}$ [%], [ $\theta$ ; $\phi$ ]	[0-90°;0-90°]	[0-40°;0-40°]
RIE Mono	30.44	75.15
RIE Multi	31.13	75.69
RIE Quasi-Mono	32.16	76.81
Conventional Mono	29.22	70.39
Conventional Multi	28.18	72.62

Table 2: Average normalized electrical power output relative to the power output at normal incidence, averaged over a range of incident angles from 0 to 90° and 0 to 40°, respectively, in two orthogonal axis for conventional and RIE-textured mono-, multi- and quasi-mono-crystalline Si solar cells, respectively.

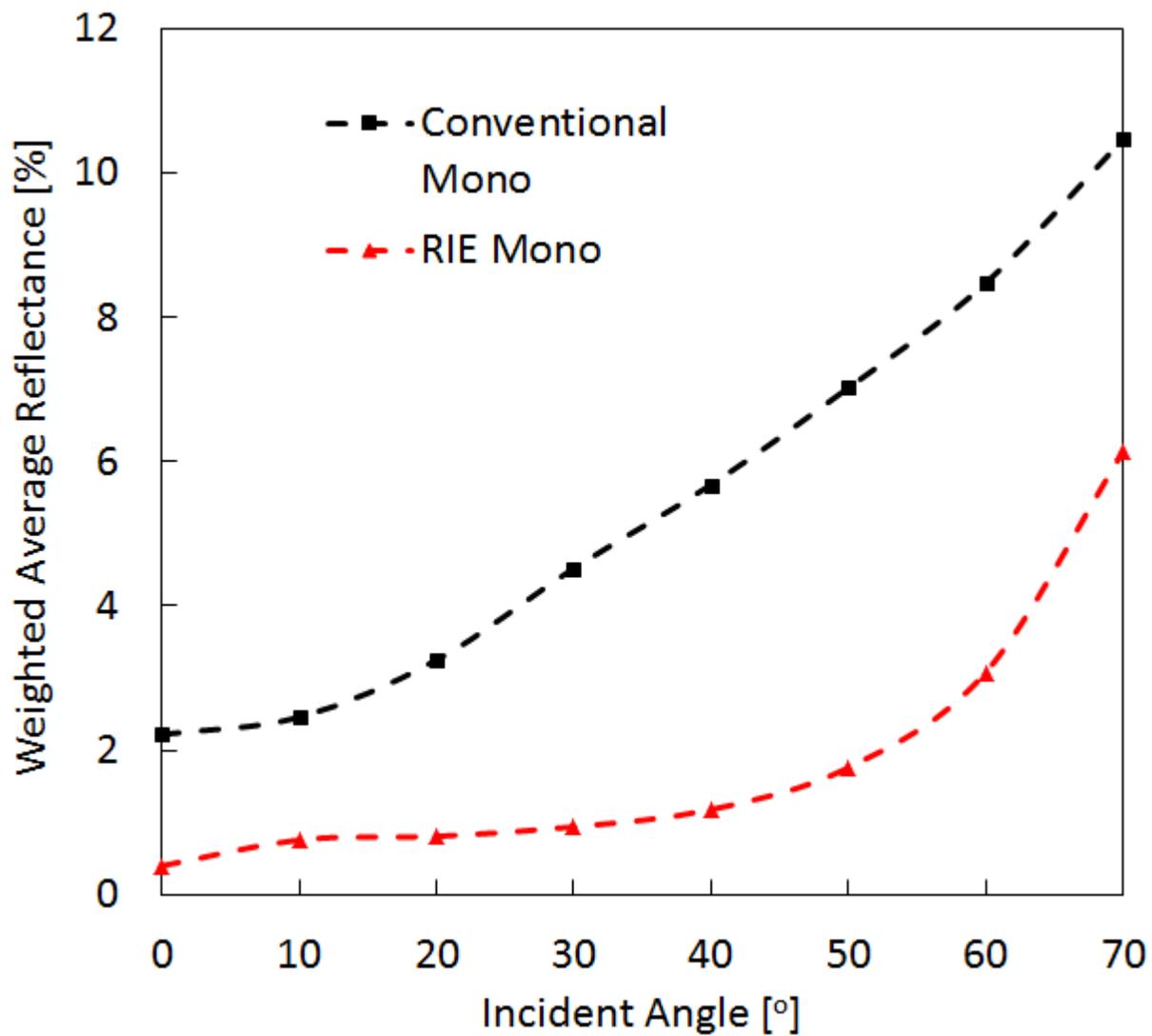


Figure 3: Incident angle dependent total weighted average reflectance of KOH-textured (squares) and RIE-textured (triangles) mono-crystalline Si substrates

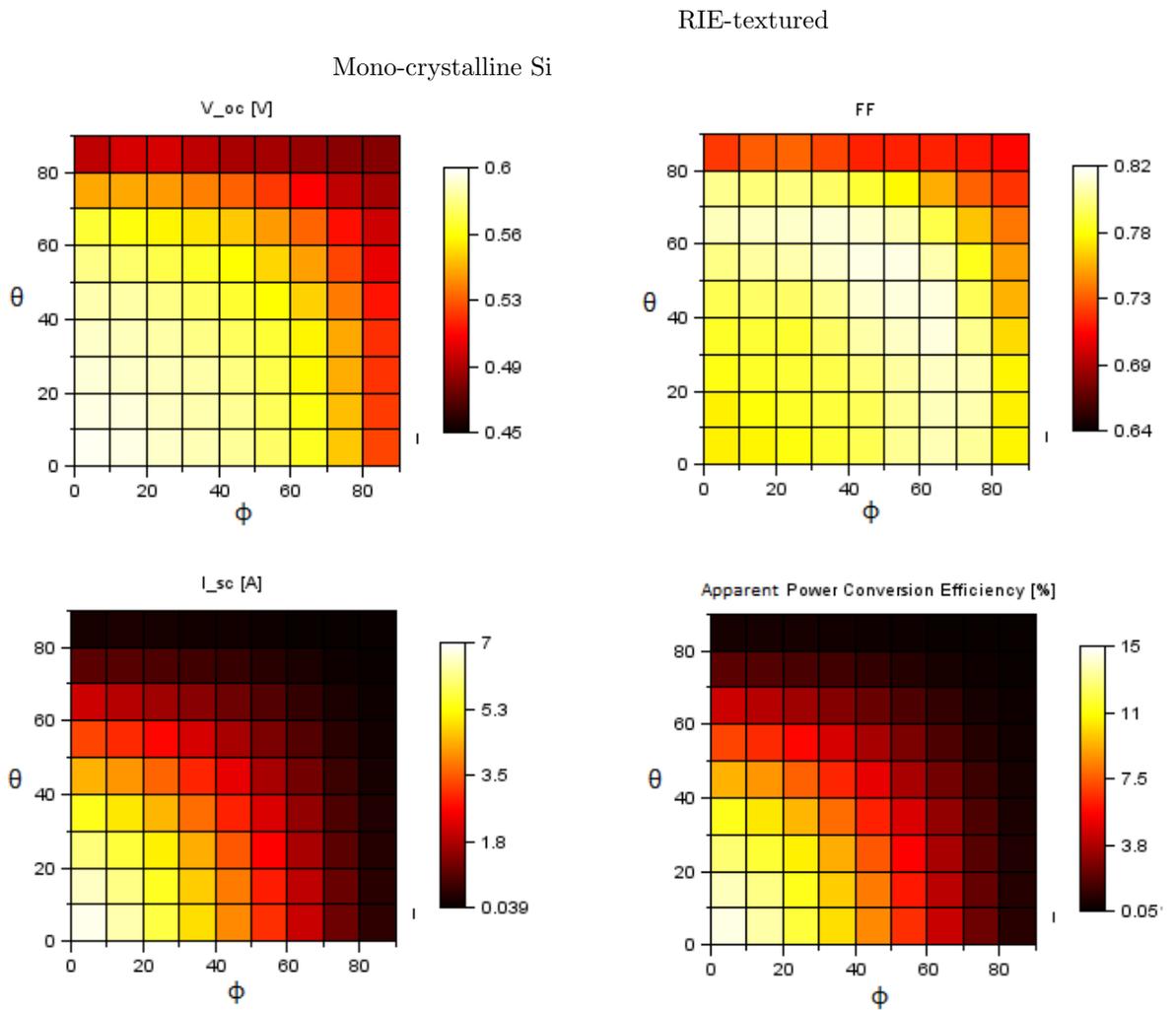
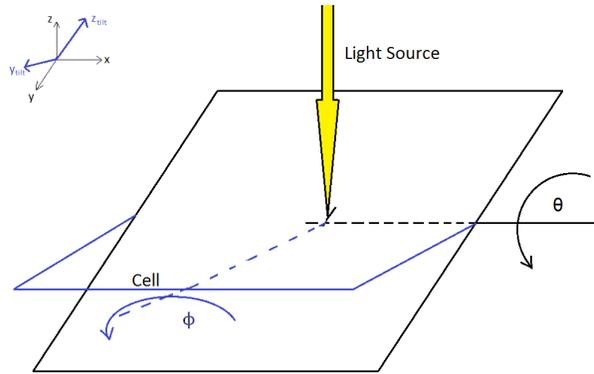


Figure 4: Angle-resolved measurement including short-circuit current, open-circuit voltage, fill factor and power conversion efficiency. The result is for a RIE-textured mono-crystalline Si solar cell. A sketch of the measurement and coordinate system is seen in the top of the figure. The angles,  $\theta$  and  $\phi$  are indicated.

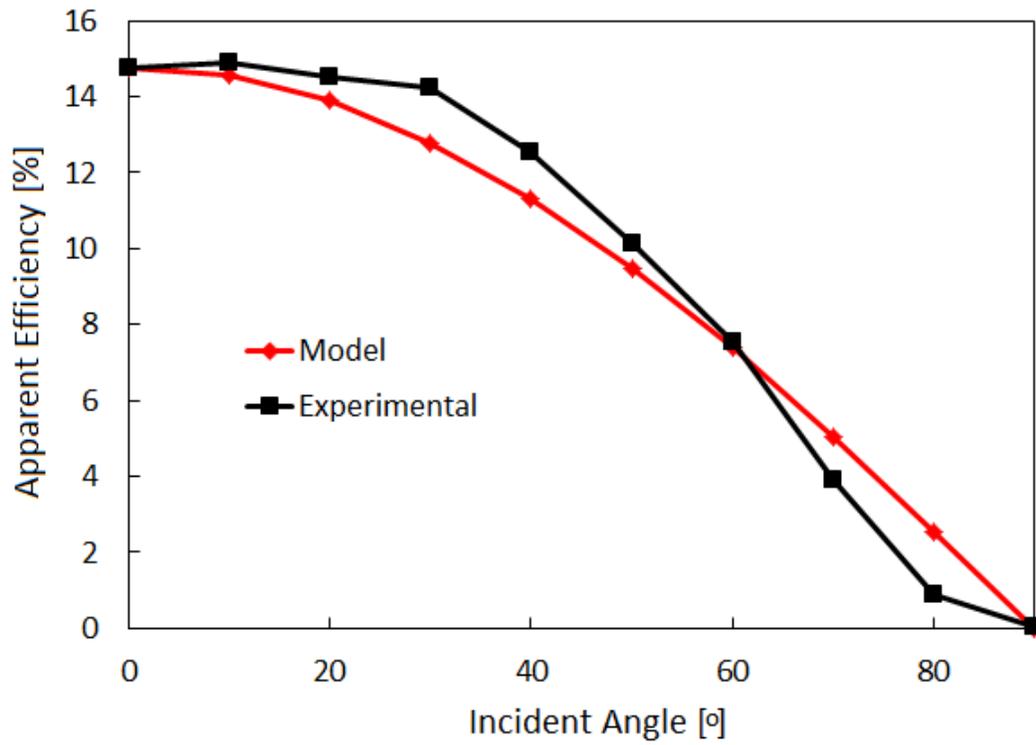


Figure 5: Angle-resolved apparent efficiency measurement as function of the incident angle in one axis in comparison with the expected apparent efficiency decreasing with cosine to the angle. Experimental data for the RIE-textured mono-crystalline Si solar cell are shown.

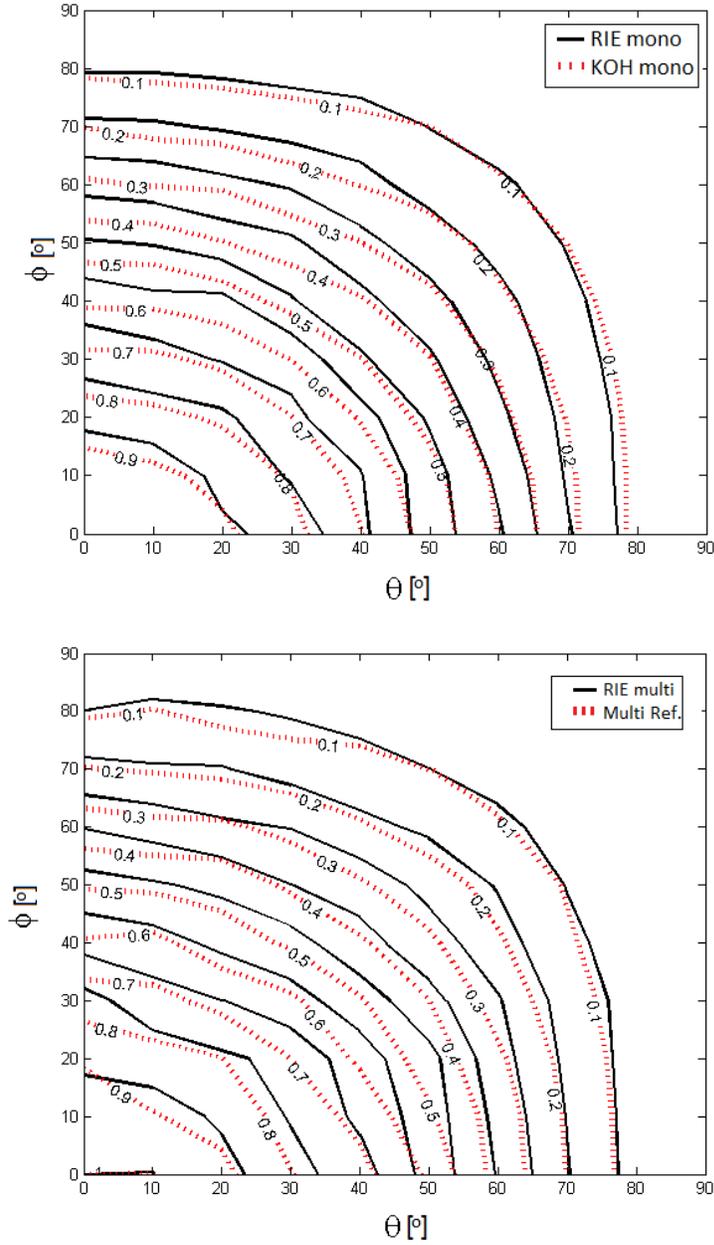


Figure 6: Angle-resolved electrical power output normalized to the power output at (0,0) for the RIE-textured and conventionally textured mono- (top) and multi-crystalline (bottom) Si cell, respectively.

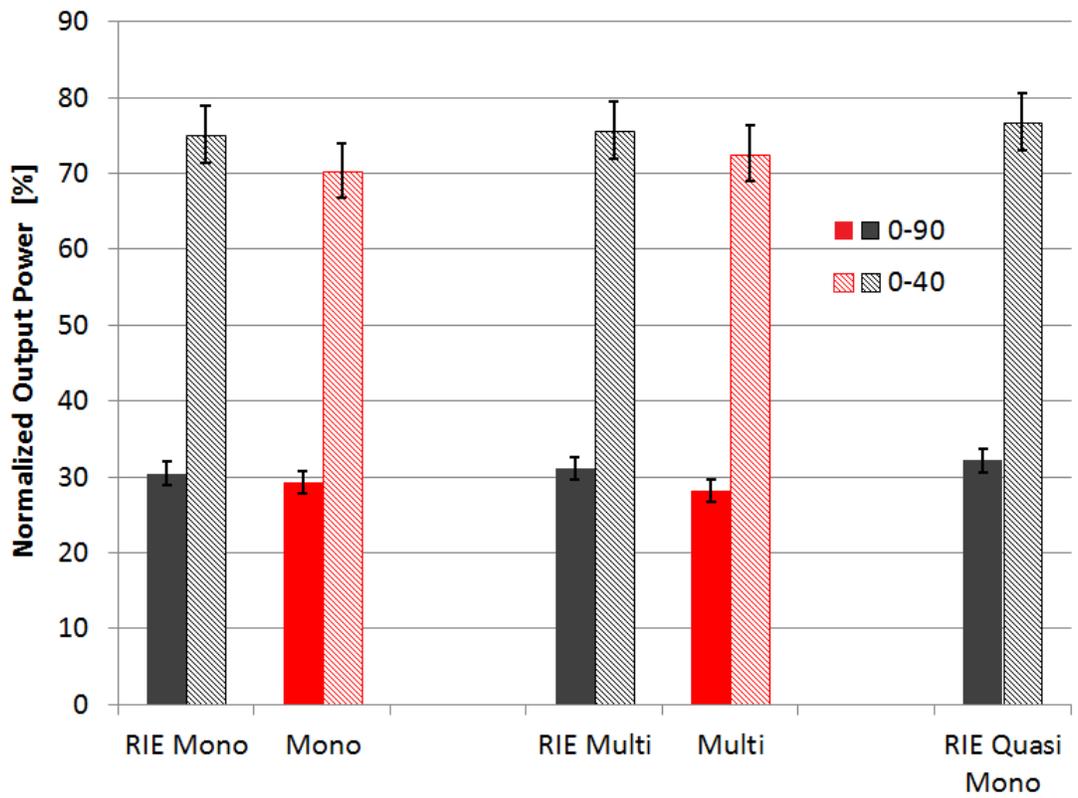


Figure 7: Average normalized electrical power output in the range  $0-90^\circ$  and  $0-40^\circ$ , respectively, relative to the power output at normal incidence for conventionally and RIE-textured mono, multi and quasi-mono-crystalline Si cells, respectively.