Supporting Information

Electric Power from Shadows and Indoors: Solar Cells under Diffuse Light Conditions

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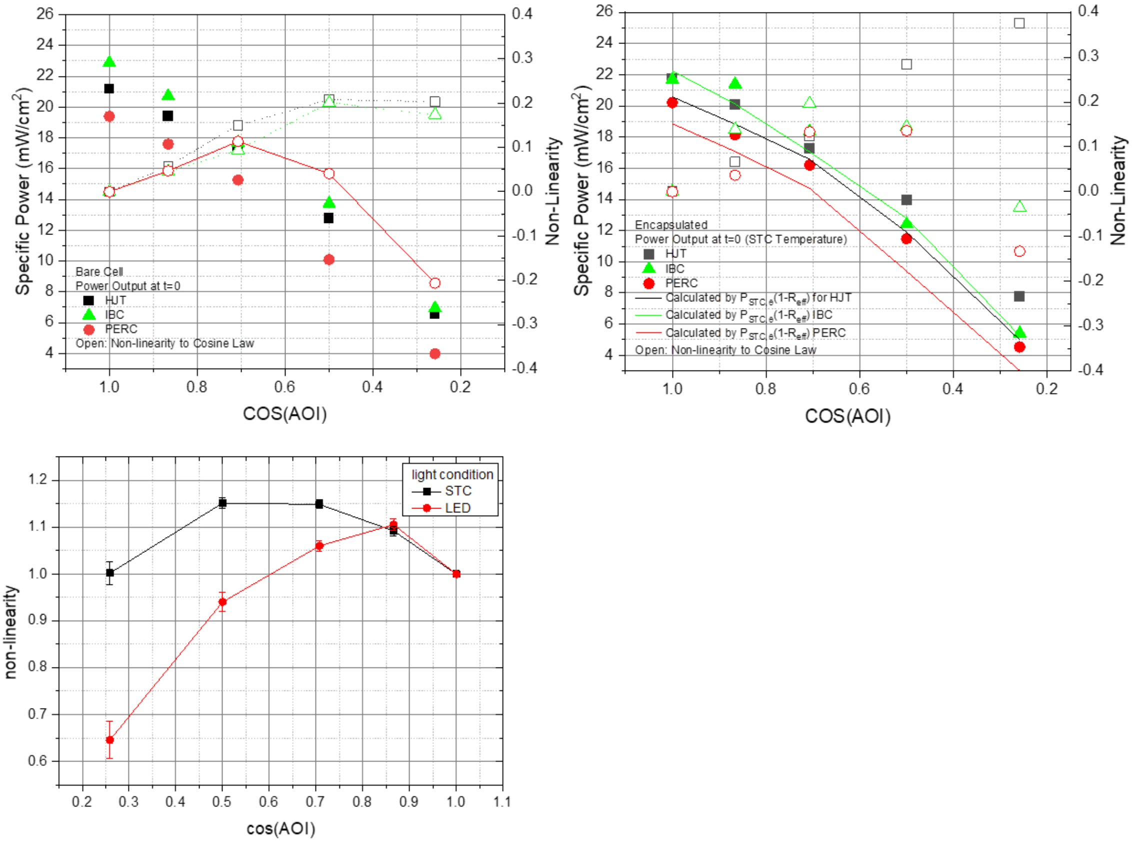


Figure S1. Specific Power and Non-linearity of solar cells under various conditions.

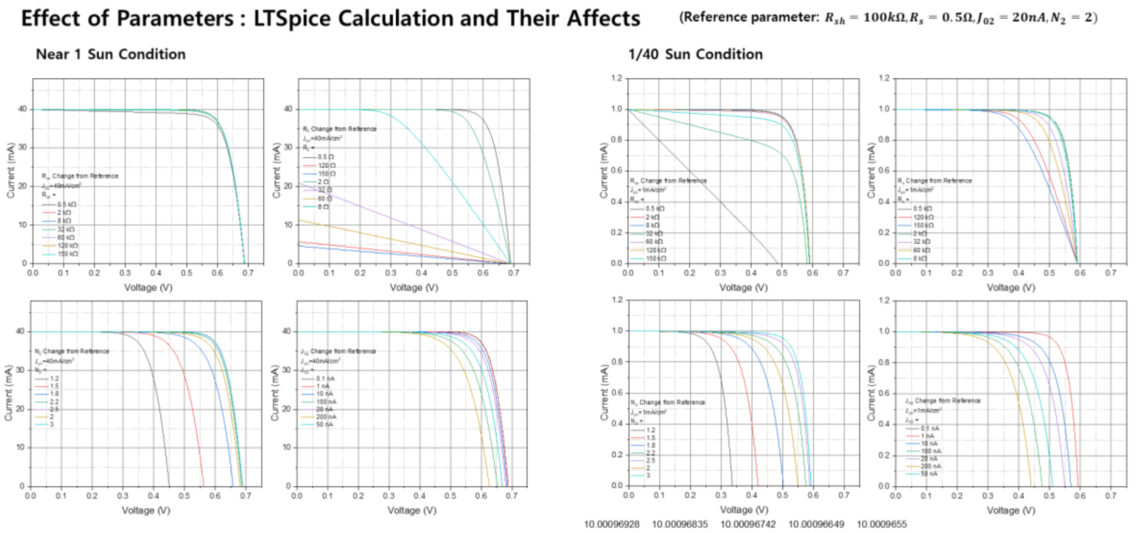
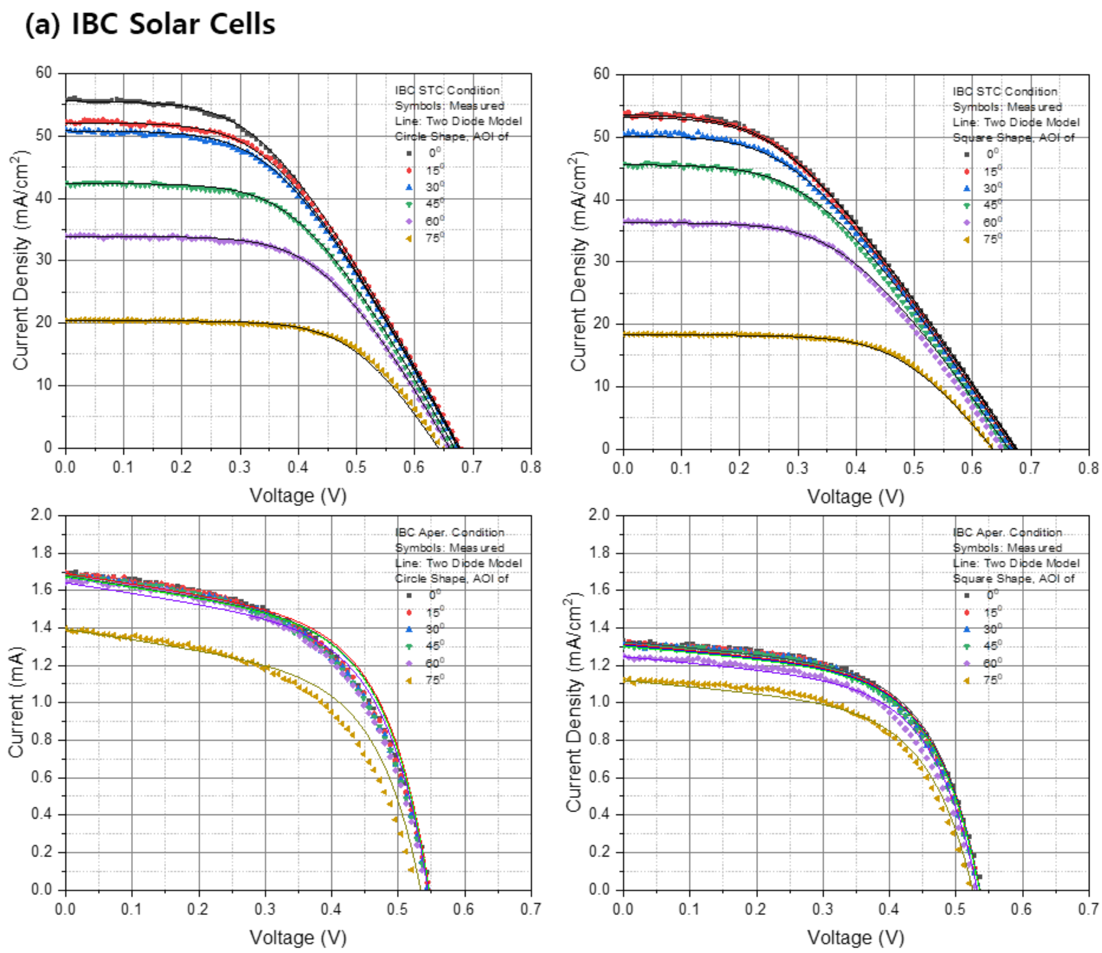


Figure S2. The effect of shunt resistance, series resistance, J_{02} and N_2 on the shape of current density – voltage curves in two-diode model. (left 4 graphs) The case of 1sun illumination and (right 4 graphs) 1/40 sun illumination.



(b) HJT Solar Cells

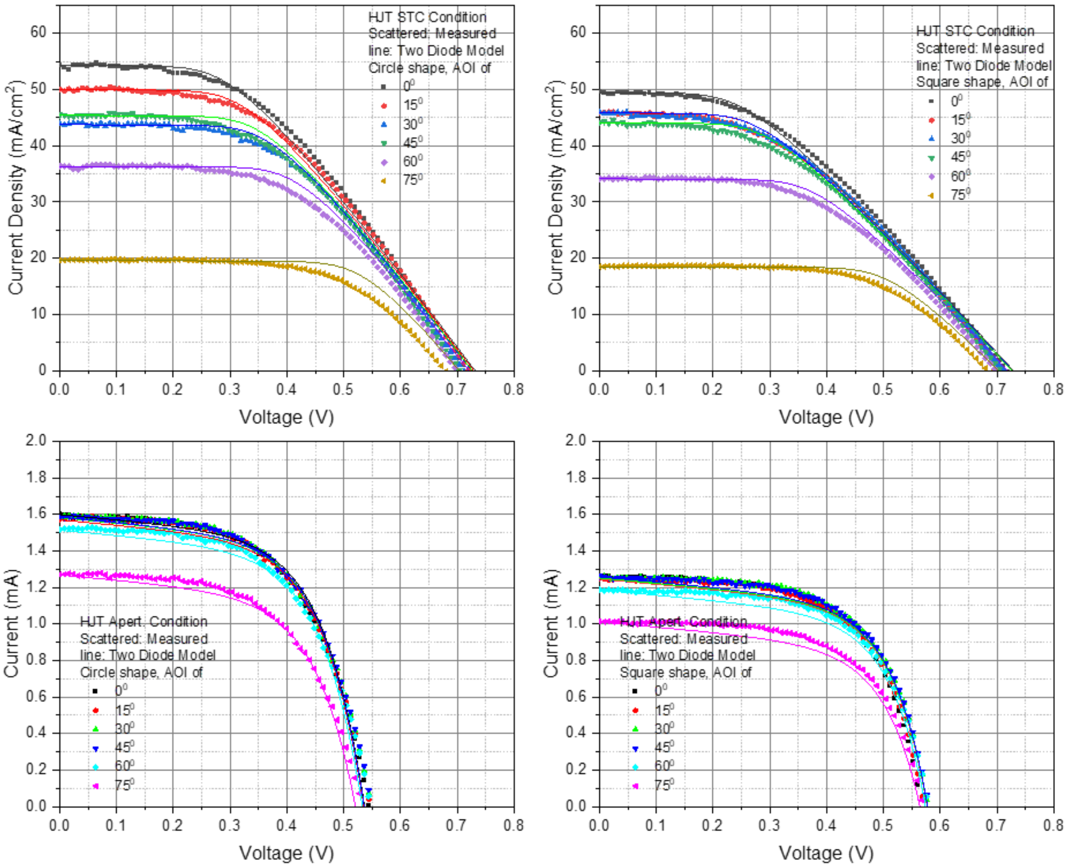


Figure S3. The fitting results of (a) IBC and (HJT) solar cells with two-diode model with measure current density and devices parameters those extracted from vertical incident light condition.

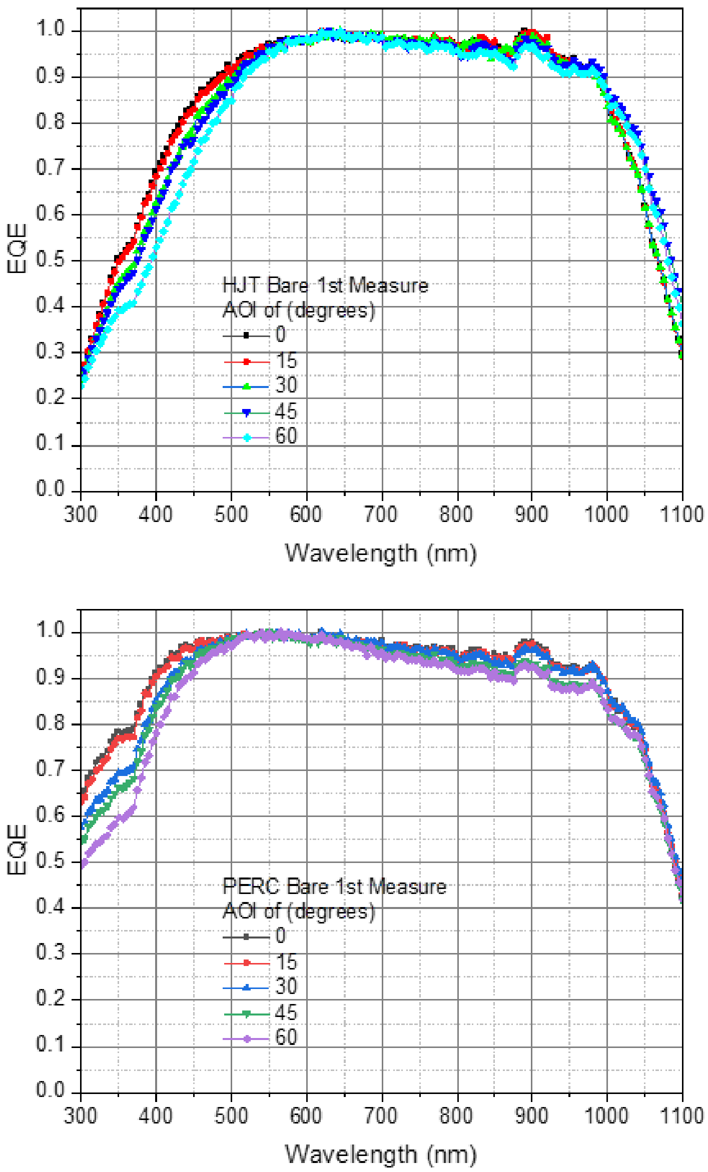


Figure S4. The EQE measured under the different AOI from PERC and HJT solar cells.

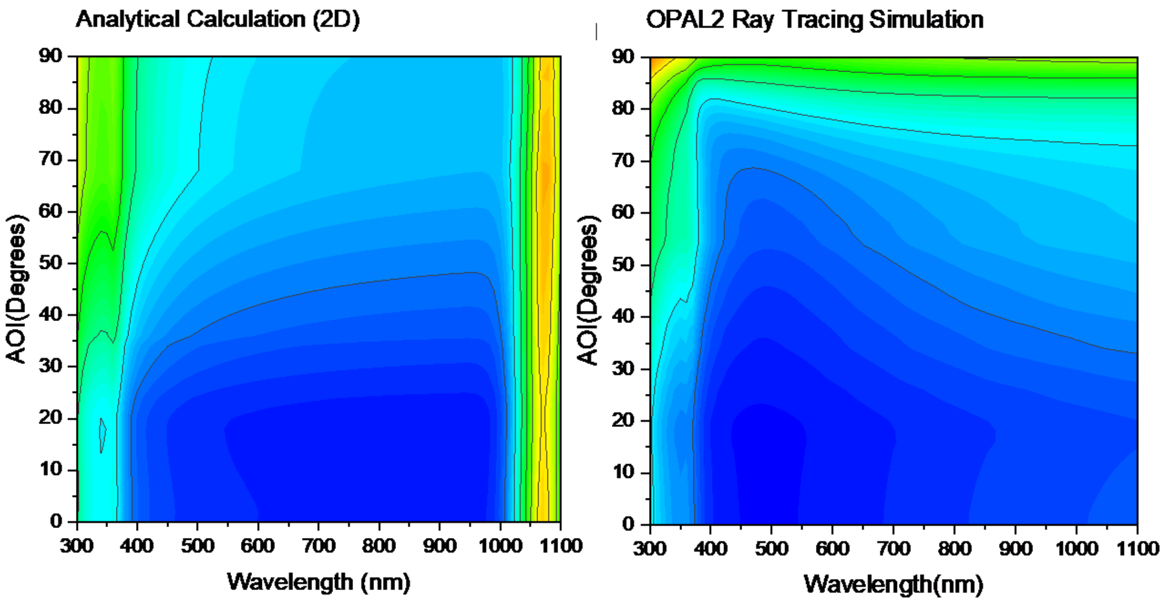


Figure S5. The calculated reflectance of solar cells using analytical and OPAL2 ray tracing method.*

(*S. C. Baker-Finch, K. R. Mcintosh, *Prog. Photovolt.: Res.* Appl. 2011: **19**: 406)

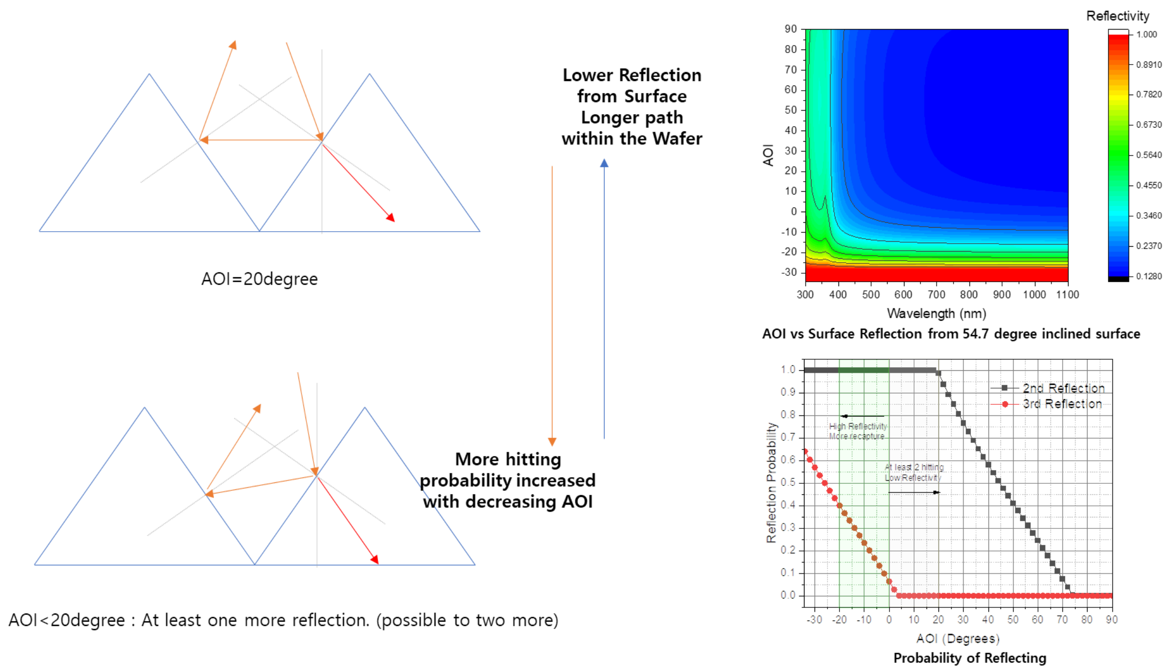


Figure S6. The probability of 3rd hit and ray indication near the 'Reflectivity Valley' AOI angles.

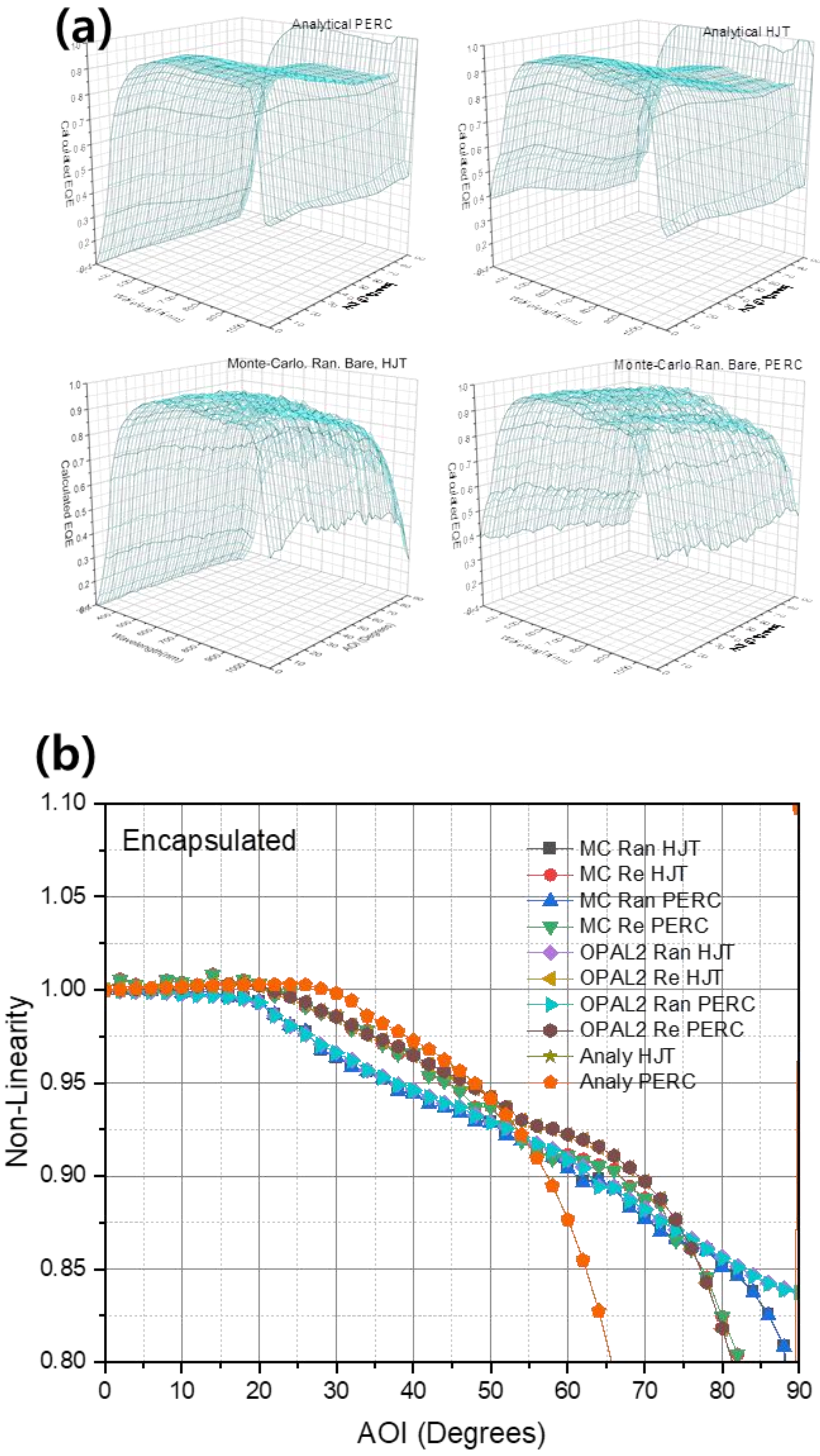


Figure S7. (a) The other calculation method for reflectivity of solar cell surface due to AOI and texture. (b) calculated short circuit current density under 1sun spectrum according to AOI.

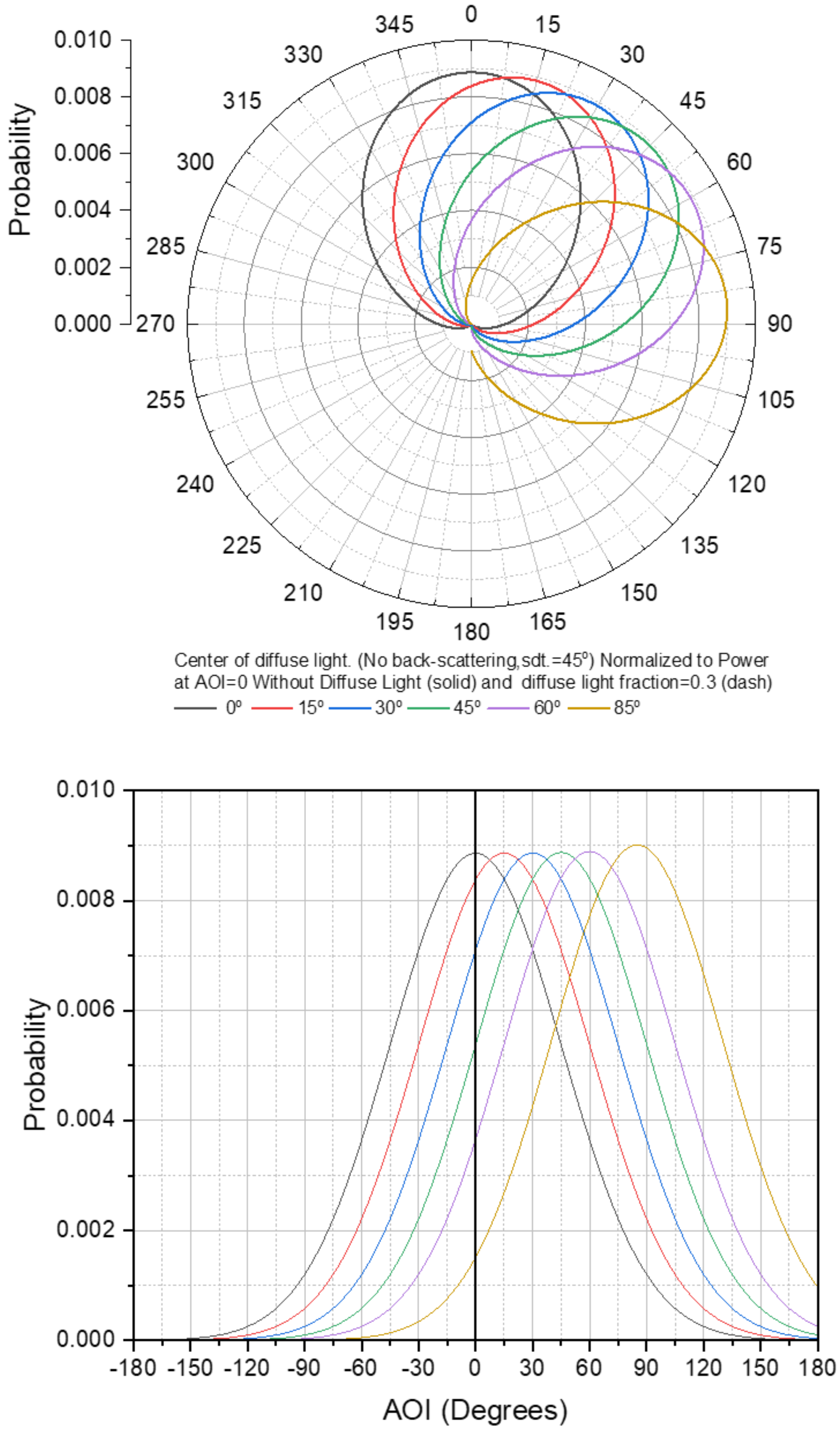


Figure S8. Polar (up) and cartesian (orthogonal coordination) (down) expression of light distribution

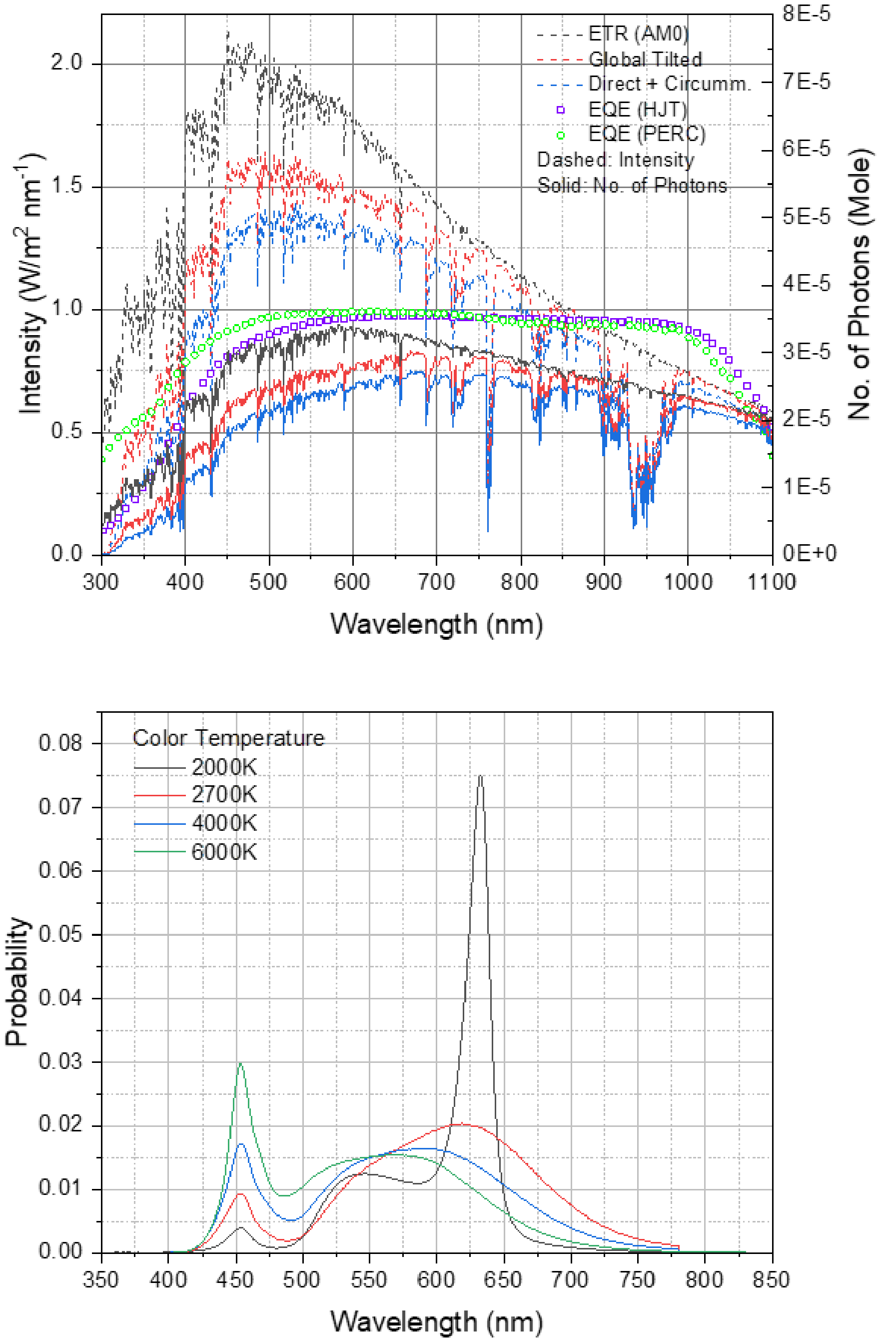


Figure S9. Spectra of solar irradiation (up) and LED with different color temperature

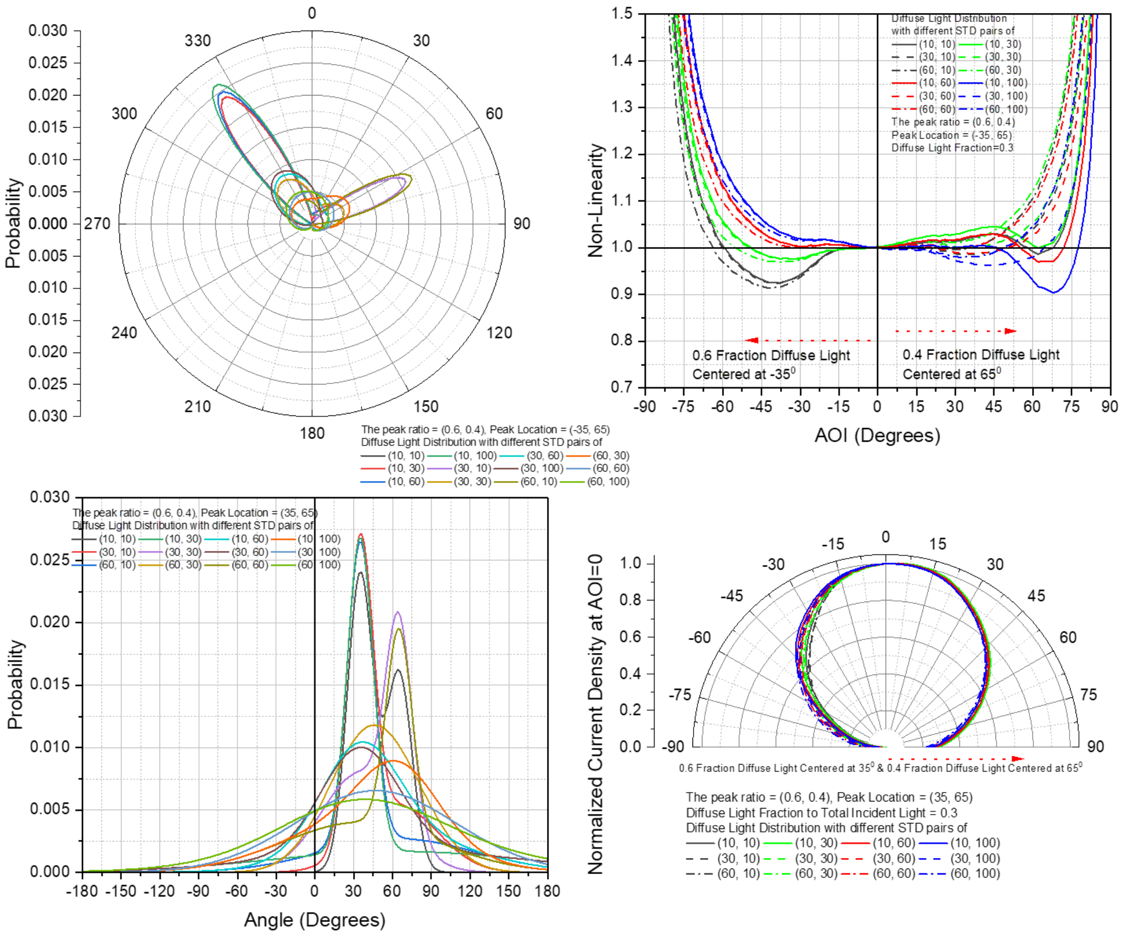


Figure S10. The light distribution with double diffuse light source with various STD and their effects on current density and current density non-linearity

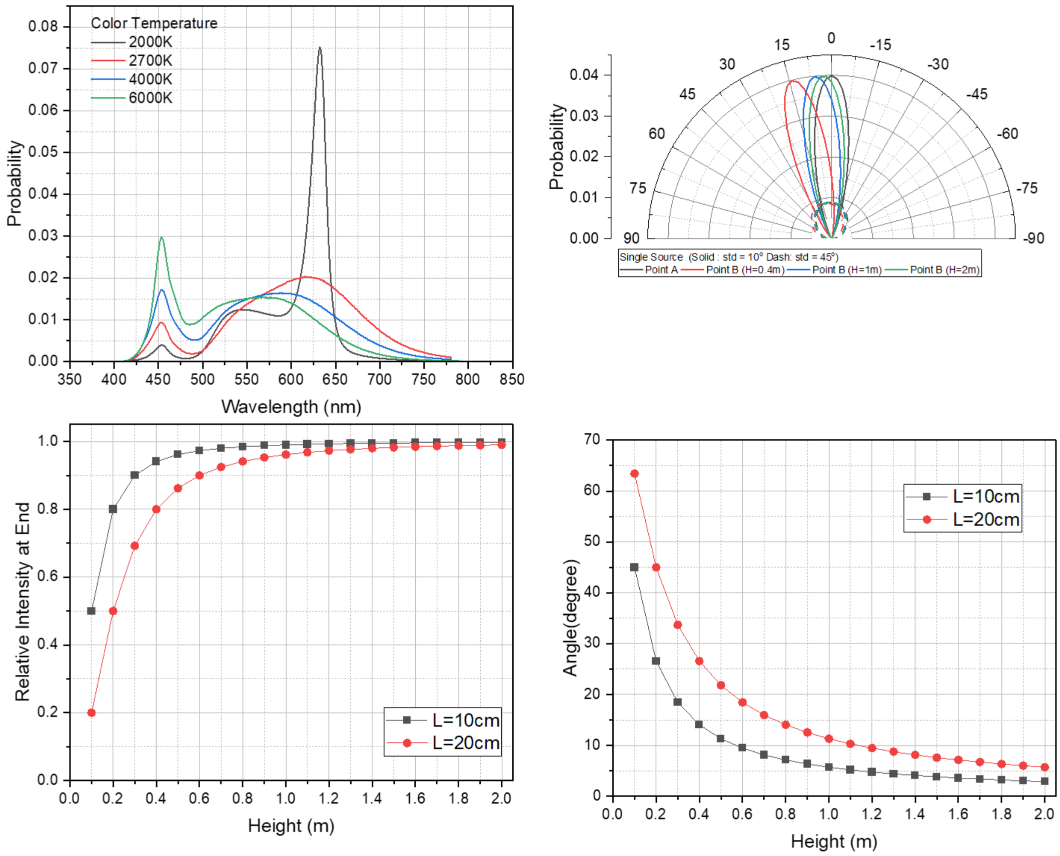
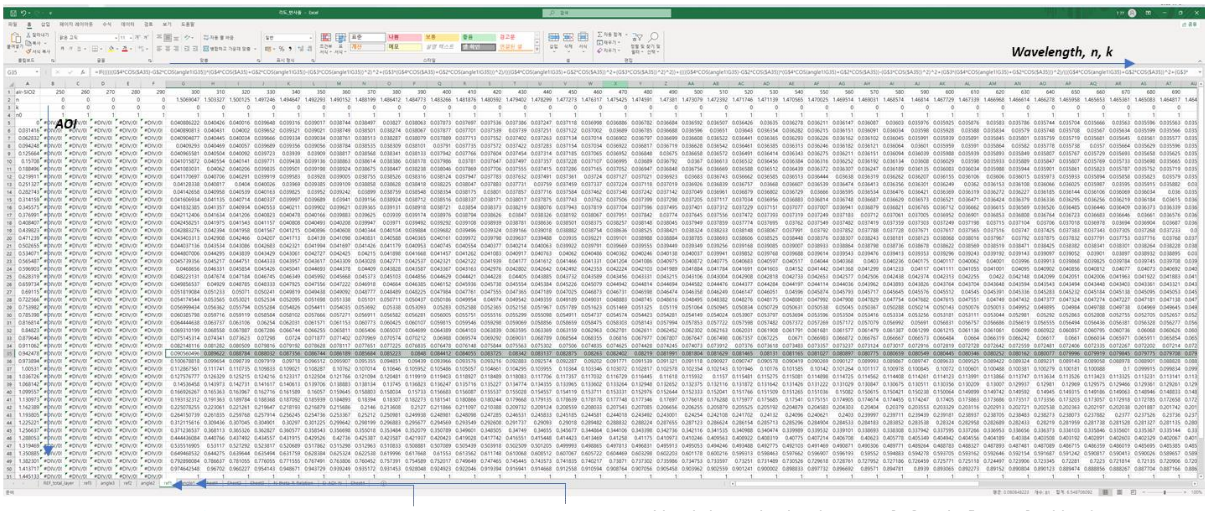


Figure S11. Light distribution of single lightening source with STD of 10 and 45° that located on the vertically on the solar cell with heights, H. The relative intensity at both ends compared to center.

The Analytical Method Procedure for Reflectivity of Solar Cells

Step 1. Optical Reflectivity of Smooth Solar Cell Surface

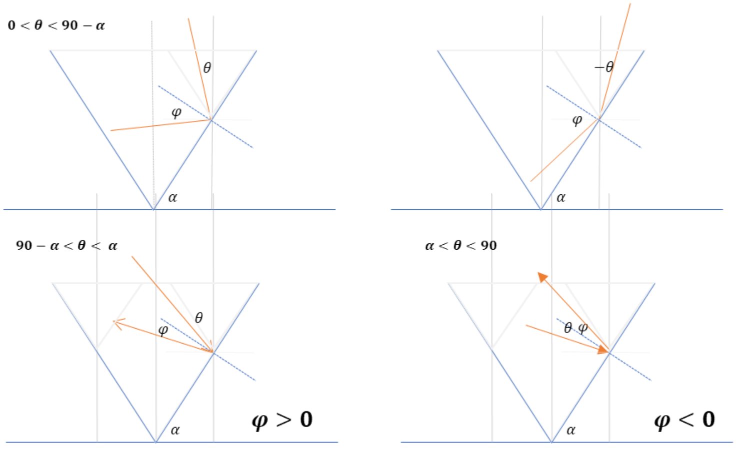
- The current density depends on the light intensity and generation rate. Therefore, AOI induced optical changes including reflectivity and light travel path can induced non-linearity from cosine of AOI. Simple example is Fresnel Effect by AOI in flat surface, that makes reflectivity changes. Start from the consideration of Fresnel Effect by AOI in flat surface of solar cells.
- High refractive index of Si results in high reflectivity. Therefore, the surface of Si is coated by SiO2/SiNx anti-reflective thin films inducing gradual increasing of refractive index in solar cell.
- However, the effect of AOI is somewhat complex due to, AOI is only incident angle to first surface (i.e. SiO2) and the different layers makes different incident angles to next layer according to Snell's law. (it is a sort of Fresnel Relation) Therefore, Actual calculation needs reflecting at each layer and incident angle at each layer.



Reflectivity at 2nd layer ◀ θ_t a 2nd layer ◀ Reflectivity at 1st layer ◀ θ_t a 1st layer *(the calculation is done by utilizing matrix for θ_t and Reflectivity of each layer)*

Step 2. The Effect Surface Texture - Geometrical Consideration (Analytical Model)

- The alkali etching of (001) Si induces etching with 54.7 degrees angle . (reference page)
- For symmetric 2D array of c-Si surface (with SiO2/SiNx coating) can be used for modeling of surface textures.
- More detail Results are in Progress in Photovoltaics: Research and Applications, 19 (2011) 406. However, it contains only vertical incident light. In addition, the their results for regular or random shaped reverse or pyramid texture pattern shows little effect. However, their approaches and ideas were used for the calculation. : $R_{total} = \sum_i R_i f_{i\ i}$ where R_i denotes the reflectance of *i* path and f_i is probability of that path.
- If Si surface is textured with periodic 2D structures, the AOI and 1st reflection angle has following dependence.



Reflection Angle by AOI in Texture

1) $\boldsymbol{\alpha - 90° < \theta < 9°0 - \alpha}$ **:** $\varphi = \alpha - \theta$

2) $\boldsymbol{\theta \geq 90° - \alpha}$**:** $\varphi = \alpha - \theta$

3) φ Sign: if light incidents to the surface from upper direction of vertical line of surface and if light comes from lower direction of vertical line of surface, it is positive (+) and if opposite direction, it is negative(-).

Step 3. Probability of Recapture on Textured Surface Multiple Reflection

Multiple Reflection

- $\varphi_{i+1} = \varphi_i + 2\alpha - 180^\circ$ where φ_{i+1} is next reflection to φ_i if possible.

Probability of Rebound

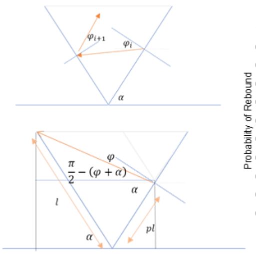
- If reflected light with φ at point pl from the bottom reaches end of opposite side, the p becomes the probability of rebound from opposite side when reflected angle is φ because, the light reflected from closer to bottom than pl can reach opposite side.

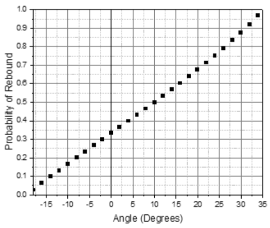
- Simple geometry gives the relation: $p = \dfrac{\sin\alpha - \cos\alpha\,\tan\left(\frac{\pi}{2} - (\alpha+\varphi)\right)}{\sin\alpha + \cos\alpha\,\tan\left(\frac{\pi}{2} - (\alpha+\varphi)\right)}$ and it looks like linear.
- Probability of $i+1^{th}$ rebounding according to φ_i

  $\varphi_i \geq 90 - \alpha : 1$

  $\varphi_i \leq -2\alpha + 90 : 0$

  $-2\alpha + 90 < \varphi_i < 90 - \alpha$: the probability is p.





- The table of φ_i and probability to next reflection according to AOI. Max. 3 reflection is possible.

AOI	Reflection 1		Reflection 2		Reflection 3	
(degrees)	φ1	probability to next reflect	φ2	probability to next reflect	φ3	probability to next reflect
-34	88.7	1	18.1	0.640453818	-52.5	0
-32	86.7	1	16.1	0.604408363	-54.5	0
-30	84.7	1	14.1	0.569082288	-56.5	0
-28	82.7	1	12.1	0.534370549	-58.5	0
-26	80.7	1	10.1	0.500174677	-60.5	0
-24	78.7	1	8.1	0.466401595	-62.5	0
-22	76.7	1	6.1	0.432962555	-64.5	0
-20	74.7	1	4.1	0.399772173	-66.5	0
-18	72.7	1	2.1	0.366747537	-68.5	0
-16	70.7	1	0.1	0.333807368	-70.5	0
-14	68.7	1	-1.9	0.300871214	-72.5	0
-12	66.7	1	-3.9	0.267858662	-74.5	0
-10	64.7	1	-5.9	0.234688552	-76.5	0
-8	62.7	1	-7.9	0.201278172	-78.5	0
-6	60.7	1	-9.9	0.167542425	-80.5	0
-4	58.7	1	-11.9	0.133392942	-82.5	0
-2	56.7	1	-13.9	0.098737123	-84.5	0
0	54.7	1	-15.9	0.06347709	-86.5	0
2	52.7	1	-17.9	0.027508514	-88.5	0
4	50.7	1	-19.9	0	-90	0
6	48.7	1	-21.9	0	-90	0
8	46.7	1	-23.9	0	-90	0
10	44.7	1	-25.9	0	-90	0
12	42.7	1	-27.9	0	-90	0
14	40.7	1	-29.9	0	-90	0
16	38.7	1	-31.9	0	-90	0
18	36.7	1	-33.9	0	-90	0
20	34.7	0.985279464	-35.9	0	-90	0
22	32.7	0.937699316	-37.9	0	-90	0
24	30.7	0.892205763	-39.9	0	-90	0
26	28.7	0.848560453	-41.9	0	-90	0
28	26.7	0.806552707	-43.9	0	-90	0
30	24.7	0.765995083	-45.9	0	-90	0
32	22.7	0.726719717	-47.9	0	-90	0
34	20.7	0.688575274	-49.9	0	-90	0
36	18.7	0.651424388	-51.9	0	-90	0
38	16.7	0.615141491	-53.9	0	-90	0
40	14.7	0.579610964	-55.9	0	-90	0
42	12.7	0.544725538	-57.9	0	-90	0
44	10.7	0.510384903	-59.9	0	-90	0
46	8.7	0.476494481	-61.9	0	-90	0
48	6.7	0.442964328	-63.9	0	-90	0
50	4.7	0.40970815	-65.9	0	-90	0
52	2.7	0.376642383	-67.9	0	-90	0
54	0.7	0.343685344	-69.9	0	-90	0
56	-1.3	0.310756415	-71.9	0	-90	0
58	-3.3	0.277775256	-73.9	0	-90	0
60	-5.3	0.244661011	-75.9	0	-90	0
62	-7.3	0.211331523	-77.9	0	-90	0
64	-9.3	0.177702498	-79.9	0	-90	0
66	-11.3	0.143686647	-81.9	0	-90	0
68	-13.3	0.109192744	-83.9	0	-90	0
70	-15.3	0.074124612	-85.9	0	-90	0
72	-17.3	0.038379989	-87.9	0	-90	0
74	-19.3	0.001849255	-89.9	0	-90	0
76	-21.3	0	-90	0	-90	0
78	-23.3	0	-90	0	-90	0
80	-25.3	0	-90	0	-90	0
82	-27.3	0	-90	0	-90	0
84	-29.3	0	-90	0	-90	0
86	-31.3	0	-90	0	-90	0
88	-33.3	0	-90	0	-90	0
90	-35.3	0	-90	0	-90	0

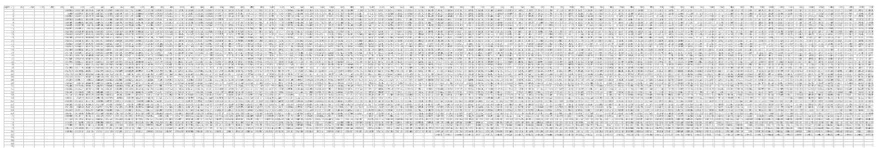
Step 4. Calculation of Reflectivity from φ_i , p and Reflectivity Table step by step from first incident, 1st reflection, and so on.

Calculation

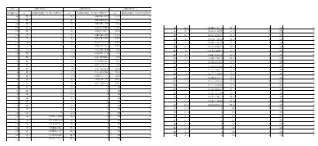
- Reflectivity Table: it is calculated table shows reflectivity of SiO2/SiNx/Si flat surface according to wavelength and incident angle (φ_i)
- For each reflection, due to the calculated φ_i for each step, the reflectivity can be obtained from the table.
- There are 3 reflections possible. Therefore total reflectivity for a AOI and wavelength can be obtained:

$$R_{AOI,\lambda} = R_{1,AOI,\lambda}\left(1 - p_{2,AOI,\lambda}\right) + p_{2,AOI,\lambda}\left\{R_{1,AOI,\lambda}R_{2,AOI,\lambda}\left(1 - p_{3,AOI,\lambda}\right) + R_{1,AOI,\lambda}R_{2,AOI,\lambda}R_{3,AOI,\lambda}p_{3,AOI,\lambda}\right\}$$

Reflectivity Table for SiO2/SiNx/Si



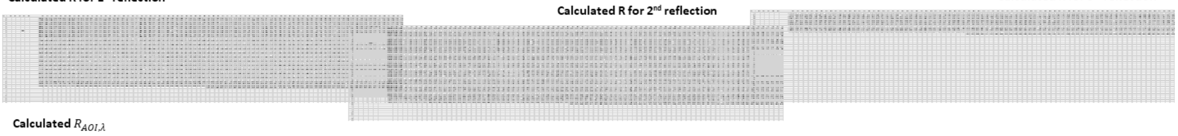
Calculated Table for φ_i , p



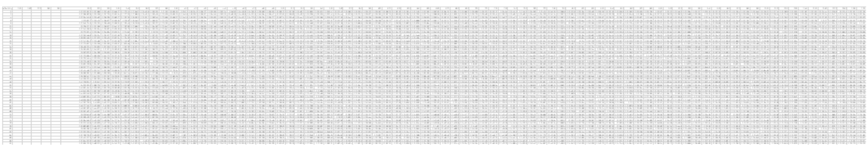
Calculated R for 1st reflection

Calculated R for 2nd reflection

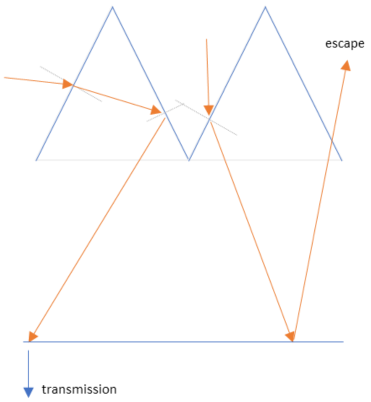
Calculated R for 3rd reflection



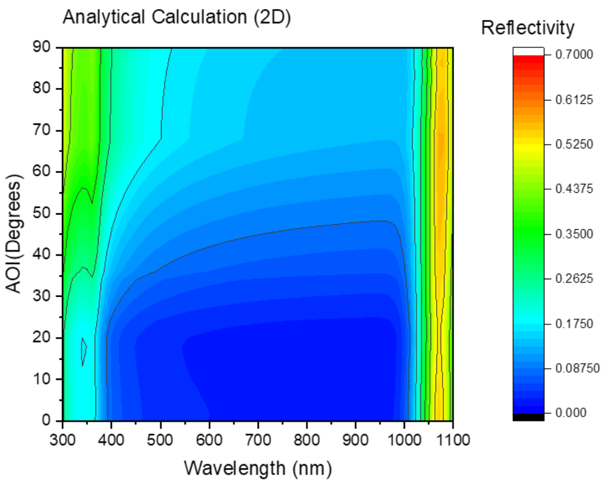
Calculated $R_{AOI,\lambda}$



Step 5. What Happens to Transmitted Photon into Si: Absorbed or reflected again.

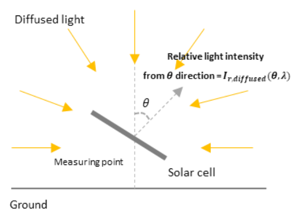


- The entered light to texture can be escaped by reflection from the bottom
- The absorption by travel path $t_e = \frac{2t_w}{\sin\left(\frac{\pi}{2}-\alpha+\varphi\right)}$ and Beer-Lambert Law $\frac{I}{I_r} = P_{2,i} = exp(-\gamma t_e)$ where γ is absorption coefficient of Si wafer according to the wavelength.
- The additional reflection is $(1-R_1P_1)R_{b1}P_{e,1} + R_1P_1(1-R_2P_2)P_{e,2}R_{b2} + R_1P_1R_2P_2(1-R_3P_3)P_{e,3}R_{b3}$
- The Recapture of Escaped photon is not considered and it makes relatively overestimate the reflectivity

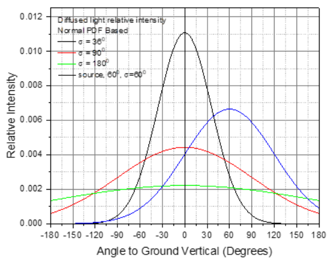


The Calculation Details for Source Rotation Case and Cell Rotation Case.

Case 1. The Diffused Light. How to Treat?



Gaussian Distribution



How to obtain angular distribution of 'Diffused Light'?

- The light distribution in diffused light by single source is assumed as Gaussian distribution type, expressed as $I_{r,diffused}(\lambda) = \frac{F(\lambda)}{\sqrt{2}\sigma(\lambda)}\exp(-\frac{(\theta-\mu(\lambda))^2}{2\sigma(\lambda)^2})$, where μ is the angular direction of diffused light source and σ is the parameter to represent dispersity.
- To satisfy the definition of angular distribution, $\iiint_{-\pi}^{\pi} I_{r,diffused}\, d\theta d\psi d\phi = 1$. For the simplified analysis considering 2D case (only one angular dimension), $\int_{-\pi}^{\pi} I_{r,diffused}(\theta,\lambda)d\theta = 1$ .Therefore, the distribution function is given $I_{r,diffused}(\theta,\lambda) = \frac{1}{F'(\lambda)\sqrt{2}\sigma(\lambda)}\exp(-\frac{(\theta-\mu(\lambda))^2}{2\sigma(\lambda)^2})$, where $F'(\lambda) = \int_{-\pi}^{\pi}\frac{1}{\sqrt{2}\sigma(\lambda)}\exp\left(-\frac{(\theta-\mu(\lambda))^2}{2\sigma(\lambda)^2}\right)d\theta$, If there are multiple light diffusing sources, $I_{r,diffused}(\theta,\lambda) = \sum_i \eta_i(\lambda) I_{rdiffused}(\theta,\lambda)$ and η_i is the fraction of each source so that $\sum_i \eta_i = 1$.
- Then, total current can be expressed as $j_{total} = (1-f(\theta))I_0\int_0^{\infty}\cos\theta_i\, EQE(\theta_i,\lambda)I_{rs}(\lambda)d\lambda + f(\theta)I_0\int_0^{\infty}\int_{-\pi}^{\pi}\sum_i\frac{\eta_{i(\theta)}F_{i(\theta)}}{\sqrt{2}\sigma_{i(\theta)}}\exp\left(-\frac{(\theta-\mu_i(\theta))^2}{2\sigma(\theta)_i^2}\right)EQE(\theta_i,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$.
- The problem is the diffused light distribution and its fraction are dependent on the AOI and surroundings. We need proper assumption for that.
- The Current density at the AOI of 90° (experimentally measured) can gives some issues.
- The I-V curve under AOI can be derived from $J = J_{ph} - J_{01}\left\{\exp\left[\frac{q(V+JR_s)}{kT}\right]-1\right\} - J_{02}\left\{\exp\left[\frac{q(V+JR_s)}{N_2kT}\right]-1\right\} - \frac{V+JR_s}{R_{shunt}}$ by substitution of j_{total} for J_{ph} . (two diode model)
- This analysis can be applied indoor PV directly if we set the diffused light fraction as unity. Then the Gaussian distribution to angled light source can be treated. However, in this case some more detail treatment should be followed for more precise model. From this simple format.

Calculation protocol

① **Obtain $\boldsymbol{EQE(\theta,\lambda), I(\lambda)}$** (matrix form, $\boldsymbol{I(\lambda)}$ as photon concentration. Raw value or normalized

② For actual calculation, $\boldsymbol{EQE(\theta,\lambda)}$ is obtained from the calculated condition of Ran.& MC ray condition. The IQE is obtained at the AOI=0 by $\frac{\boldsymbol{EQE(0,\lambda)}}{\boldsymbol{T(0,\lambda)}}$. The $\boldsymbol{EQE(\theta,\lambda)}$, then, can be obtained by $\boldsymbol{IQE(\theta,\lambda), = IQE(0,\lambda)(1-R(\theta,\lambda)) = \frac{EQE(0,\lambda)}{1-R(0,\lambda)}(1-R(\theta,\lambda))}$

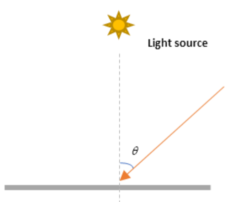
③ **If $\boldsymbol{\theta_c}$ is not zero, i.e. the cell is oblique aligned, the proper range for integration.**

④ **Variables & visualization**

Case 2. Rotating Cell Angle, Fixed Light Source(EQE: MCray based Calculated, Spectrum: 1sun)

The Measurement Condition.

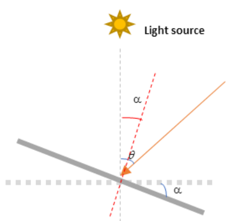
- Then, total current can be expressed as $j_{total} = (1-f)I_0\int_0^{\infty}\cos\theta_i\, EQE(\theta_i,\lambda)I_{rs}(\lambda)d\lambda + fI_0\int_0^{\infty}\int_{-\pi}^{\pi}\sum_i\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)EQE(\theta_i,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$ if illumination condition is under cosine law and $j_{total} = (1-f)I_0\int_0^{\infty}EQE(\theta_i,\lambda)I_{rs}(\lambda)d\lambda + fI_0\int_0^{\infty}\int_{-\pi}^{\pi}\sum_i\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)EQE(\theta_i,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$ for each AOI.
- In this case the AOI is function of cell rotation angle $\theta_i = \theta - \alpha$. Therefore the relative incident angle to cell is changed by rotation angle and it gives two effects on diffused light effect.
- First Effect: the integration range changes $-90° < \theta_i < 90°$. Therefore, according to $\theta_i = \theta - \alpha$, the rotation angle gives different integral range by roatation angle.
- Second Effect: The incident angle to the cell changes. It gives modification of proper EQE value corresponding to incident angle to cell.
- Therefore, the scattered light effect is given as $fI_0\int_0^{\infty}\int_{-\frac{\pi}{2}+\alpha}^{\frac{\pi}{2}+\alpha}\sum_i\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)EQE(\theta-\alpha,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$ that is function of rotation angle.
- This condition is actually measurement condition. Consider the difference to other cases/.
- ***How to Treat Power current density at $AOI = 90°$: at the same time how to determine the scattered light fraction in AOI test?***



Rotation angle=0

AOI to Cell = Angle for Distribution= θ

AOI for Parallel Light = 0

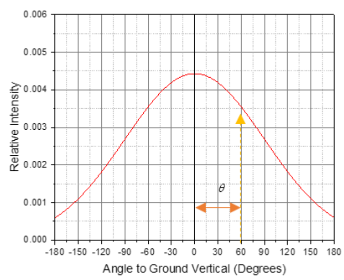


Rotation angle=α

Angle for Distribution= θ

AOI to Cell (by diffused light) = θ- α

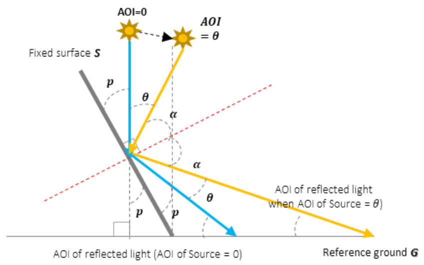
AOI for Parallel Light = α



Case 3. Fixed Cell Angle, Rotating Light Source(EQE: MCray based Calculated, Spectrum: 1sun)

Actual Application

- Then, total current can be expressed as $j_{total} = (1-f)I_0\int_0^\infty \cos\theta_i \, EQE(\theta_i,\lambda)I_{rs}(\lambda)d\lambda + fI_0\int_0^\infty \int_{-\pi}^{\pi}\sum_i \frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)EQE(\theta_i,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$ if illumination condition is under cosine law and $j_{total} = (1-f)I_0\int_0^\infty EQE(\theta_i,\lambda)I_{rs}(\lambda)\,d\lambda + fI_0\int_0^\infty \int_{-\pi}^{\pi}\sum_i \frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)EQE(\theta_i,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$ for each AOI.
- There could be numerous situations. However, we try to categorize into three cases.
- **Case 1) Constant Fraction:** The diffused light independent on AOI. (angle of source) That exists as background or noise. However, exists.
- **Case 2) Reflection by Fixed Object:** The AOI of light source makes different reflection from fixed surface. The situation depicted, the AOI of reflected light by fixed surface ***S*** when AOI = 0 is given by $\frac{\pi}{2}-2p$ and it is only function of fixed surface angle.
- If light source is moving to AOI=θ, the same surface induced AOI to the ground G to $\frac{\pi}{2}-2p-\theta$.
- Therefore, the total distribution is shifted by AOI (i.e. θ) so that the $\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i)^2}{2\sigma_i^2}\right)$ term is moved changed to $\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{\left(\theta-(\mu_i-\theta_{AOI}\right)^2}{2\sigma_i^2}\right)$ where θ_{AOI} is the AOI of Light Source.
- At the same time, when the reference ground has inclined angle of η, the angle for EQE changed so that the diffused light form should be changed into $fI_0\int_0^\infty \int_{-\pi}^{\pi}\sum_i \frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\mu_i-\theta_{AOI})^2}{2\sigma_i^2}\right)EQE(\theta_i+\eta,\lambda)I_{r,sp}(\lambda)\,d\theta\,d\lambda$.



- **Case 3) Reflection by Scattering:** The particles and molecules in the atmosphere induce Mie scattering and Rayleigh Scattering. Actually these scattering effects induced light distribution into space dependent on the AOI.
- The Rayleigh scattering induced forward and backward light distribution with lateral portion. However, we must consider that the scattered light may scattered again (or several times) by near particle and molecules. Therefore, some portion is dispersed in the atmosphere as constant form (considered as Case 1).
- Even in this case, the AOI has some effects on the diffused light distribution by more light from light source direction. This can be expressed as a additional diffused light distribution centered at the AOI, i.e. $\frac{\eta_i F_i}{\sqrt{2}\sigma_i}\exp\left(-\frac{(\theta-\theta_{AOI})^2}{2\sigma_i^2}\right)$.