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On the meaning(fullness) of the intensity unit 'suns' in light induced degradation experiments

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Abstract

In many studies on light induced degradation (LID) phenomena, light intensity is specified in the unit 'suns'. However, the actual meaning of this expression is rather undefined at least if a light source with its spectrum deviating from sun's spectrum is used, e.g., a halogen incandescent lamp featuring a distinctly red shifted black body spectrum. Within this contribution it is shown that the different spectrum can imply different photon fluxes depending on the interpretation of the unit 'sun'. Furthermore, it is shown that also the quantitative determination of intensity can yield different photon fluxes if the sensitivity of the detector is not taken into account. Finally, it is shown that also the optical properties of sample and setup yield different absorbable photon fluxes or generation. All three effects should be taken into account when describing and comparing LID studies.

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Keywords: light induced degradation; LID; silicon;

1. Introduction

In recent years studies on light-induced degradation (LID) phenomena have gained attention for the development of highly efficient solar cells which are not only more sensitive to bulk and surface defects being present right after fabrication, but also to defects developing afterwards. LID in the bulk occurs virtually on any material, be it LeTID in mc-Si [1], FeB-LID (mainly mc-Si) [2], Cu-LID [3], BO-LID (mainly Cz-Si) [4] or even FZ-Si [5] often used as reference material. Surface passivation like SiN_x:H [6] is also known to react to illumination.

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In many investigations, the light intensity is given in the unit 'suns' or 'suns equivalent' which seems to be a rather undefined description. In this paper, the meaning of the expression 'suns' is discussed with respect to spectral properties, quantitative determination and optical properties of sample and experimental setup.

2. Spectral properties

The expression 'suns' or '1 sun' most probably originates from standard test conditions (STC) defined in IEC 60904 [7] and especially the ASTM G173 spectrum known as the reference spectrum AM 1.5g. $P_{G173}(\lambda)$ describes the sun's spectrally resolved power density spectrum after passage of earth's atmosphere. Sun appears roughly as a black body radiator of ~5700 K and the total power density p_{G173} is standardized to 100 mW/cm^2 by

$$p_x = \int_0^{\infty} \Phi_x(\lambda) \cdot \frac{hc}{\lambda} \, d\lambda \tag{1}$$

For a PV device, the photon flux $\Phi_{G173}(\lambda) = P_{G173} / (hc/\lambda)$ (with hc/λ being the photon energy) is a more suitable entity yielding a usable (absorbable) photon flux ϕ in the electron-hole generation range of 280-1200 nm of $\phi_{G173} \approx 2.9\times10^{17}$ /cm^{2}s according to the definition

$$\phi_x = \int_{280\,nm}^{1200\,nm} \Phi_x(\lambda) \, d\lambda \tag{2}$$

However, virtually no lab-style LID investigation utilizes the sun directly or a sun simulator (with a costly high pressure metal vapor plasma discharge lamp). Very often halogen incandescent lamps are used, fewer investigations use alternative light sources such as LEDs or lasers.

Halogen incandescent lamps are fairly good black body radiators with temperature of ~2950 K. The according spectrum (approx. a black body spectrum) $\Phi_{BB3k}(\lambda)$ is distinctly red shifted as compared to $\Phi_{G173}(\lambda)$ (see Fig. 1 left) with maximum photon flux around 1250 nm. The usable photon flux ϕ_{BB3k} is now a question of definition. Some authors refer to a comparable total power density of p_{BB3k} = 100 mW/cm^2 ($\phi_{BB3k} \approx 1.7\times10^{17}$ /cm^{2}s;–40%), some to a comparable photon flux $\phi_{BB3k} \approx 2.9\times10^{17}$ /cm^{2}s ($p_{BB3k} \approx 166$ mW/cm^2; +66%), some to a 'current equivalent' (discussed later on). Assuming every author describes properly his experimental setup, a noticeable deviation of –40% in usable photon flux ϕ or +66% in power density p at '1 sun' occurs.

The (virtually) monochromatic spectra of LEDs and lasers are by far not comparable with a broad blackbody spectrum. Nevertheless, the same issue arises regarding definition. The values of power density p and photon flux ϕ for selected wavelength are shown in tables 2 to 4 in the appendix. The general advantage of LEDs and lasers is that virtually every photon contributes to generation of excess charge carriers. The ratio of photon flux ϕ to power density p scales linear with wavelength: $\phi/p \sim \lambda$. Hence the longer the emitted wavelength, the more efficient the conversion of power density to photon flux as can be seen from Table 2.

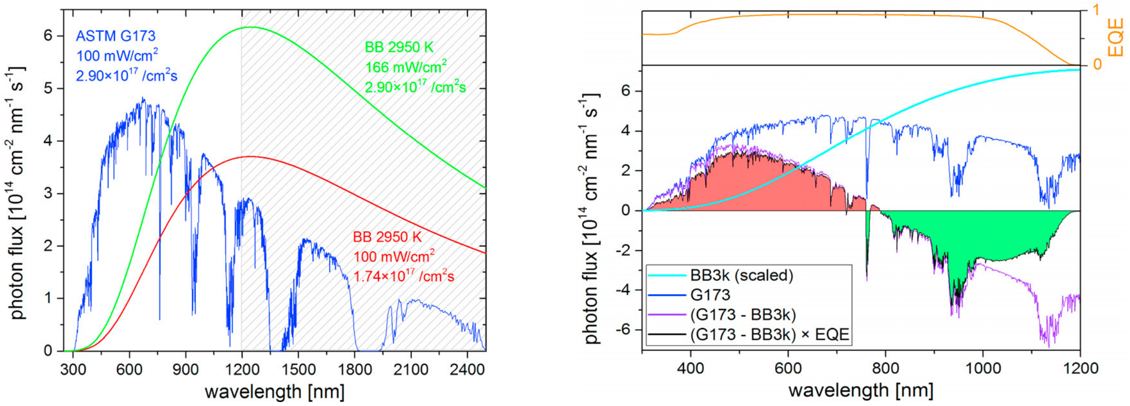

Fig. 1. (left) G173 photon flux spectrum and two 2950 K blackbody spectra (BB3k) scaled to 100 and 166 mW/cm^2, respectively. Also denoted is the usable photon flux. (right) G173 photon flux spectrum (blue) and a 2950 K blackbody spectrum (BB3k, cyan) scaled to yield the same j_{sc} with the shown EQE (orange, top). In consequence, the red and green area of the EQE weighed difference spectrum match each other.

3. Quantitative determination

Measuring total power density p or usable photon flux ϕ is not that straightforward as it might appear. Determining the total power density is challenging as it requires coverage of the whole spectral range, but it is possible, e.g., using calibrated bolometric sensors. However, it seems straightforward to determine the usable photon flux using an optical sensor like a 'calibration solar cell'.

Short circuit current density j_{sc} of a solar cell (a measure of received photons) is the convolution of photon flux spectrum $\Phi_x(\lambda)$, reflection $R(\lambda)$ and internal quantum efficiency $IQE(\lambda)$.

$$j_{sc}^{(x)} = q \cdot \int_{280nm}^{1200nm} \Phi_x(\lambda) \cdot \underbrace{(1 - R(\lambda)) \cdot IQE(\lambda)}_{EQE(\lambda)} \, d\lambda \tag{3}$$

It seems reasonable to match the short circuit current j_{sc} under the different spectra which is most probably what is meant with the expression 'current equivalent to 1 sun'. Using, e.g., the 166 mW/cm^2 $\Phi_{BB3k}(\lambda)$ ($\phi_{G173} = \phi_{BB3k} \approx 2.9\times10^{17}$ /cm^{2}s) spectrum as a reference point and a scaling factor as matching parameter, the following equation has to be fulfilled.

$$\Delta j_{sc} = j_{sc}^{G173} - j_{sc}^{BB3k} = q \cdot \int_{280nm}^{1200nm} \left(\Phi_{G173} - scaling \cdot \Phi_{BB3k}\right) \cdot \underbrace{(1 - R) \cdot IQE}_{EQE} \, d\lambda = 0 \tag{4}$$

The actual scaling factor now depends on the chosen cell's external quantum efficiency $EQE(\lambda)$. The situation is visualized in Fig. 1 (right) for a PERC-type cell (Cz-Si, random pyramid texture, front emitter, not degraded). The scaling factor controls the balance between red and green area in the integral of the EQE weighed difference spectrum. In the chosen example, matching j_{sc} yields a scaling factor of 1.23 (+23%) meaning the usable photon flux has to be adapted to $\phi_{BB3k} \approx 3.6\times10^{17}$ /cm^{2}s ($p_{BB3k} \approx 205$ mW/cm^2). The increased usable photon flux ϕ_{BB3k} is a direct consequence of the relatively low sensitivity in the near infrared region which is an inherent issue of silicon based detectors. The situation can get even worse if a cell with full area Al alloyed rear side is used instead of a PERC-type cell thus featuring worse passivation which reduces EQE in the near infrared further.

Another issue is degradation of bulk lifetime. One might come up with the principally good idea that a stable reference cell for intensity calibration is favorable for long term reproducibility. However, stabilizing cell performance by degrading the cell means near infrared sensitivity suffers even more from low bulk lifetimes and the scaling factor increases even further.

It is also worth noting that the capability of the front (and rear) surface morphology to trap light makes a difference. A textured cell captures by far more efficiently long wavelength light than a flat cell. This is reflected in the respective EQE in the IR range.

The scaling procedure described by Eq. 4 also remains valid for LEDs and laser. The values of power density p, photon flux ϕ and short circuit current density j_{sc} for selected wavelength regarding different calibration procedures are shown in tables 2 to 4 in the appendix.

4. Optical properties of sample and setup

How many charge carriers are generated in the sample depends strongly on the optical properties of the sample and these may differ massively. Solar cells with surface texture trap light by far more effectively than a planar lifetime sample does. Lifetime sample means in this context a more or less (chemically) polished flat silicon wafer with both sided ARC/passivation layer, however, it should be kept in mind that the exact surface morphology might differ from institution to institution and experiment to experiment.

The usable generation density g can be defined as all photons not lost by reflection $R(\lambda)$, transmission $T(\lambda)$ or parasitic absorption $A(\lambda)$ (either in dielectric layers or when reflected at commonly used metallic sample mount) according to the equation

$$g = \int_{280nm}^{1200nm} \Phi(\lambda) \cdot \underbrace{\left(1 - R(\lambda) - T(\lambda) - A(\lambda)\right)}_{G(\lambda)} d\lambda \tag{5}$$

The example of a lifetime sample shall be discussed in the following. The lifetime sample shall consist of a perfectly flat silicon wafer of 200 µm covered by a 75 nm thick SiN_x:H ($n \approx 2$ @ 600 nm) layer on both sides. The lifetime sample lies on a perfectly polished sample mount made of aluminum which is highly reflective within the spectral range of interest. The reflection of the sample mount was calculated according to published n & k values [8] so that parasitic absorption in the aluminum may explicitly occur. Reflection $R(\lambda)$, parasitic absorption $A(\lambda)$ as well as generation $G(\lambda)$ are shown spectrally resolved in Fig. 2 (left). Long wavelength light >1000 nm penetrates the silicon sample and is reflected at the sample mount. Total reflection is a superposition of (first bounce) front reflection and rear side reflection after the first and second pass (even more were accounted for in the calculation, but only the first two passes are shown). This helps to understand that generation at high wavelength results from multiple passes, and using a reflective sample mount or no sample mount at all will make a difference. Furthermore, it can be seen that parasitic absorption does not only occur in the blue range in the SiN_x:H layer but also in the sample mount in the IR range even though aluminum is highly reflective.

The generation $G(\lambda)$ drops significantly in the IR range where a halogen incandescent lamp (BB3k) exhibits its highest photon flux $\Phi_{BB3k}(\lambda)$. This is also depicted in Fig. 2 (right) where losses in generation $G(\lambda)$ are illustrated as colored areas. While moderate losses in the $\Phi_{G173}(\lambda)$ spectrum (bluish area) occur in the blue as well as in the IR range, the halogen incandescent lamp loses massively in the IR range where photon flux $\Phi_{BB3k}(\lambda)$ is especially strong (reddish area). In other words, roughly 36% of the incident photon flux $\Phi_{BB3k}(\lambda)$ are not usable for the lifetime sample while only 20% are lost in $\Phi_{G173}(\lambda)$.

The specific photon flux generating excess charge carriers in the sample now depends strongly on the definition of '1 sun'. If power density p is matched ($p_{G173} = p_{BB3k} = 100\,mW/cm^2$), incident photon flux ϕ_{BB3k} is not only reduced by 40% compared to ϕ_{G173} (see Table 2), generation g_{BB3k} is furthermore stronger reduced by optical losses (RTA) than g_{G173}. In the end, generation g_{BB3k} equals $g_{G173} \cdot (1–40\%) \cdot (1–36\%) / (1–20\%) \approx g_{G173} \cdot (1–63\%)$. In other words, illumination with a halogen incandescent lamp (BB3k) with power density p_{BB3k} matched to that of sun's spectrum p_{G173} will deliver 63% less generated excess charge carriers (see Table 1).

If short circuit current density j_{sc} is matched ($j_{sc,G173} = j_{sc,BB3k} = 37.9\,mA/cm^2$), the incandescent lamps photon flux ϕ_{BB3k} even exceeds that of the sun's spectrum ϕ_{G173} by 23% (see Table 4). As generation g_{BB3k} suffers from ~16% higher RTA losses than g_{G173}, gain and loss virtually compensate each other and g_{BB3k} equals g_{G173} (see. Table 1).

Thus matching short circuit current density j_{sc} is in this case the better method than matching power density p in order to match the generation g. However, it should be kept in mind that the EQE of the solar cell plays an important role in the calibration procedure and the virtually perfect result is rather accident than intention. It should be noted that the cell in this example featured a random pyramid texture while the lifetime sample was assumed perfectly flat.

Using a flat solar cell for a flat lifetime sample does not mandatorily yield the best result for a comparable generation g.

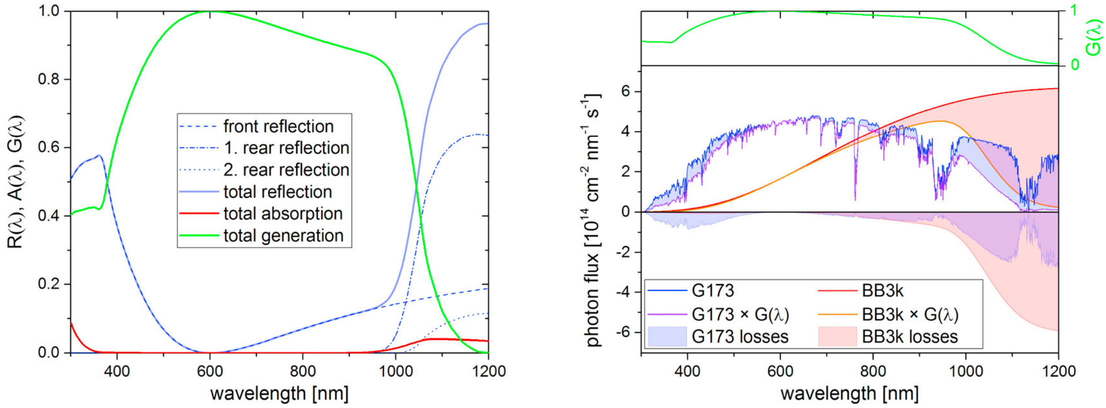

Fig. 2. (left) Reflection R(λ), parasitic absorption A(λ) and generation G(λ) for a 200 µm thick perfectly flat lifetime sample with both sided 75 nm thick SiN_x:H ARC layer on a highly reflective aluminium sample mount. Depicted as dashed lines is the composition of the total reflection of direct front reflection as well as first and second pass reflection. (right) Losses in photon flux of a lifetime sample on the highly reflective sample mount for sun's spectrum Φ_{G173} and the incandescent lamps blackbody spectrum Φ_{BB3k}.

Table 1. Calculated photon flux ϕ and generation g (absolute values and deviation to the value of the reference spectrum G173) for different spectra normalized either to the same power density p or alternatively to short circuit current density j_{sc}.

source	p [mW/cm²]	j_{sc} [mA/cm²]	ϕ [10^{17} /cm²s]		RTA loss	g [10^{17} /cm²s]	
G173	100		2.9		–20%	2.3	
BB3k	100		1.7	–40%	–36%	1.1	–63%
850 nm (LED)	100		4.3	+47%	– 9%	3.9	+68%
G173		37.9	2.9		–20%	2.3	
BB3k		37.9	4.3	+23%	–36%	2.3	– 0%
850 nm (LED)		37.9	2.6	–11%	– 9%	2.4	+ 2%

The same calculations account for the other light sources as well. Listed in Table 1 is the example for 850 nm LEDs. Especially IR LEDs convert power density p efficiently to photon flux ϕ. If power density p_{850} is matched to p_{G173}, the photon flux ϕ_{850} surpasses ϕ_{G173} by almost 50%. Thanks to limited optical losses of only around 9%, generation g_{850} surpasses g_{G173} by 68% (see Table 1). If instead the short circuit current density j_{sc} is matched, generation g_{850} virtually matches g_{G173}.

As in the case of the halogen incandescent lamp, it makes a huge difference whether power density p or short circuit current density j_{sc} is matched. The better choice would be to match short circuit density j_{sc} in order to achieve comparable generation g.

5. Conclusion

For most light induced degradation investigations, the generation g is the relevant entity. The exact value depends on the spectral properties of the light source, the optical properties of the sample and especially on what entity is quantified and matched. As photon flux and generation g are often hardly determinable, power density p or short circuit current density j_{sc} of a 'calibration solar cell' are often used to describe light intensity. The unit 'suns' or rather '1 sun' is defined from the sun's reference spectrum ASTM G173, linking power density $p_{G173} = 100\,mW/cm^2$ to a photon flux $\phi_{G173} \approx 2.9\times10^{17}\,/cm^2s$. However, it should be noted that for deviating spectra power density p and photon flux ϕ scale differently.

As demonstrated, matching the power density p_x of an arbitrary spectrum $\Phi_x(\lambda)$ to p_{G173} can lead to strongly deviating generation g_x. It therefore does not seem to be reasonable to match the power density p_x to p_{G173}. It is found that matching short circuit current density $j_{sc,x}$ to $j_{sc,G173}$ yields a more comparable generation g_x. For typical halogen incandescent lamps (as most commonly applied light sources) the difference in generation can be in the order of 60% depending on which entity is matched.

However, it should be kept in mind that the short circuit density j_{sc} depends on the external quantum efficiency EQE which again depends on the capability to trap light in the IR range (low reflection) as well as on the capability to convert generated excess charge carrier density to short circuit density (high IQE, long effective diffusion length).

Furthermore, it is unclear in some publications how the calibration of intensity was performed or what entity was actually quantified, and whether the given information on, e.g., applied power density, refers to sun's spectrum or to the actually applied spectrum. In consequence, experimental results on reaction rates (which may depend on injection level and thus generation g) can be irreproducible if not even misleading. It is therefore suggested that authors at least clearly state their calibration procedure in detail. It seems reasonable to match short circuit current density of a 'calibration solar cell', however, as the result depends on applied spectrum and cell's EQE, both should be stated as well.

Last it should be noted that the calculations in this contribution are based exemplarily on the reference spectrum ASTM G173. In reality, the spectrum of solar simulators or flashers may deviate from the used reference spectrum according to their classification [9]. Severe spectral deviation in the reference measurement may lead to deviating results in, e.g., the short circuit density $j_{sc,ref}$.

Appendix A. Quantitative comparison of different calibration procedure

A.1. Matching power density

Table 2. Calculated photon flux ϕ and short circuit current density j_{sc} (absolute values and deviation to the value of the reference spectrum G173) for different spectra normalized to the same power density p.

Source	p [mW/cm^2]	ϕ [$10^{17}\,/cm^2s$]		j_{sc} [mA/cm^2]	
G173	100	2.9		37.9	
BB3k	100	1.7	–40%	18.5	–51%
635 nm (LED)	100	3.2	+10%	48.1	+27%
850 nm (LED)	100	4.3	+47%	62.6	+65%
950 nm (LED)	100	4.8	+65%	70.5	+86%
808 nm (laser)	100	4.1	+40%	57.0	+51%
1064 nm (laser)	100	5.4	+85%	39.9	+ 5%

A.2. Matching photon flux

Table 3. Calculated power density p and short circuit current density j_{sc} (absolute values and deviation to the value of the reference spectrum G173) for different spectra normalized to the same photon flux ϕ.

Source	p [mW/cm²]		ϕ [10^{17} /cm²s]	j_{sc} [mA/cm²]	
G173	100		2.9	37.9	
BB3k	167	+67%	2.9	30.8	–19%
635 nm (LED)	91	– 9%	2.9	43.6	+15%
850 nm (LED)	68	–32%	2.9	42.5	+12%
950 nm (LED)	61	–39%	2.9	42.8	+15%
808 nm (laser)	71	–29%	2.9	40.7	+ 7%
1064 nm (laser)	54	–46%	2.9	21.6	–43%

A.3. Matching short circuit current density

Table 4. Calculated power density p and photon flux ϕ (absolute values and deviation to the value of the reference spectrum G173) for different spectra normalized to the same short circuit current density j_{sc}.

Source	p [mW/cm²]		ϕ [10^{17} /cm²s]		j_{sc} [mA/cm²]
G173	100		2.9		37.9
BB3k	205	+105%	3.6	+23%	37.9
635 nm (LED)	79	–21%	2.5	–13%	37.9
850 nm (LED)	61	–40%	2.6	–11%	37.9
950 nm (LED)	54	–46%	2.6	–12%	37.9
808 nm (laser)	66	–34%	2.7	– 7%	37.9
1064 nm (laser)	95	– 5%	5.1	+75%	37.9

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