

Extended spectral response analysis of conventional and front surface field solar cells

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ABSTRACT

Historically, spectral analysis of internal quantum efficiency has played an important role in solar cell characterization. The applicability of this technique is reassessed in view of developments over recent years as a means of determining cell optical and electrical properties. The refined technique, applicable to both conventional and front surface field devices, highlights three distinct spectral regions, allowing additional front surface investigation by blue response analysis and more simplified analysis over a weakly absorbed region where photo-generation is uniform throughout the absorber and parasitic absorption remains sufficiently constant at these wavelengths. The approach is demonstrated by application to a modern front surface field device as a complement to previous work.

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1. Introduction

As a non-destructive technique, spectral analysis of internal quantum efficiency (IQE) has long been an important part of solar cell characterization. For wavelengths that do not penetrate to the rear surface, the traditional plot of inverse-IQE versus absorption length was used to extract bulk minority-carrier diffusion lengths for thick planar devices [1]. Later, the analysis was extended to near-bandgap wavelengths allowing extraction of both electrical and optical properties of more modern cell designs featuring textured surfaces and long diffusion lengths [2].

However, non-conventional device structures, in particular rear-junction configurations that are becoming increasingly popular in silicon solar cell design, has not been addressed by this earlier work. The spectral analysis of IQE has not previously been extended to below red wavelengths, which can overlook information from the front heavily-doped region (emitter for conventional structure or front surface field (FSF) layer for rear-junction structure) that becomes gradually non-negligible as bulk thickness reduces. On the theoretical front, a non-intuitive relationship between the dark minority-carrier distribution and the photo-carrier collection probability, first identified by Donolato [3], has become more generally appreciated [4–8].

Taking note of these developments and insights, the spectral response features of silicon cells, in particular, are reassessed to

accommodate both conventional and FSF devices for wavelengths transparent to the cell anti-reflection coating (ARC). It is shown that plotting inverse-IQE versus absorption length does not give just the single linear region of classical analysis [1], or the two linear regions identified by Basore [2], but three distinct regions, where the new-found blue response region reveals information on front surface properties. Infrared analysis is also simplified by physical reasoning. It is furthermore shown that the data extraction in the new blue analysis is the same for both cell configurations as is in the improved infrared analysis, but the slope of the plot for red to infrared wavelengths in a FSF cell is opposite to that previously [2] identified for conventional devices. Therefore, the refined technique is demonstrated by application to a modern FSF device such as a recently developed 16.8% efficient FSF silicon solar cell (the most efficient among silicon cells thinner than 40 μm yet fabricated) [9], used in this work to demonstrate the new approaches.

2. Methodologies

2.1. General analysis

For a p–n junction solar cell, a reciprocity theorem for charge collection first noted by Donolato [3] relates the local collection probability of photo-generated carriers, $f_c(\mathbf{r})$, to the dark carrier distribution, so that only its dark characteristics need to be analyzed to investigate its spectral response. A very general analysis [5] of current transport in an n-type region under low-injection condition where majority-carrier current flows do not completely overwhelm minority-carrier flows gives the following steady-state form of the 3-dimensional minority-carrier current density and

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continuity equations in the dark:

$$J_p = -qDp_0 \nabla u, \quad (1)$$

$$-\nabla \times (Dp_0 \nabla u) + \frac{p_0 u}{\tau} = 0, \quad (2)$$

where q is the electronic charge, u is the normalized excess minority-carrier concentration, i.e., $u = (p - p_0)/p_0$ with p and p_0 being the minority-carrier concentration and its thermal equilibrium value respectively at the point of interest, D and τ are the minority-carrier diffusivity and lifetime at this point.

Restricting the analysis to a quasi-one dimensional situation and assuming the n-type region to be on the top. Eqs. (1) and (2) combined can be integrated to give the following general result:

$$J_p(x) = -qS_F p_0(0)u(0) - q \int_0^x \frac{p_0 u}{\tau} dx, \quad (3)$$

where the x -axis is downwards perpendicular to the cell-plane with its origin taken at the front surface, S_F is the front surface recombination velocity. Eq. (3) shows that local dark current density, $J_p(x)$, can be split into surface and bulk recombination components. Similarly:

$$u(x) = u(0) + S_F p_0(0)u(0) \int_0^x \frac{1}{Dp_0} dx + \int_0^x \frac{1}{Dp_0} \left(\int_0^x \frac{p_0 u}{\tau} dx \right) dx. \quad (4)$$

If it is assumed that $u(x)$ monotonically increases before arriving at the junction depletion edge, $x = W_J$, the following holds for the last term in Eq. (4):

$$u(0) \int_0^x \frac{1}{Dp_0} \left(\int_0^x \frac{p_0 u}{\tau} dx \right) dx < \int_0^x \frac{1}{Dp_0} \left(\int_0^x \frac{p_0 u}{\tau} dx \right) dx < u(x) \int_0^x \frac{1}{Dp_0} \left(\int_0^x \frac{p_0 u}{\tau} dx \right) dx \quad (5)$$

for $0 \leq x \leq W_J$. This relationship allows estimation of possible range of values for certain material parameters, such as τ , with sufficient knowledge of other material parameters.

The term $u(x)$ can be expanded by a Taylor series expansion:

$$u(x) = u(0) + \frac{du}{dx} \Big|_0 x + \frac{1}{2} \frac{d^2 u}{dx^2} \Big|_0 x^2 + \dots = u(0) [1 + \beta_1 x + \beta_2 x^2 + \dots]. \quad (6)$$

For small x , the largest two terms $u(0)$ and $u(0)\beta_1 x$ will dominate, where, by the boundary condition of Eq. (1) at $x = 0$, $\beta_1 = S_F/D_{n^+}$ with the subscript n^+ indicating the region to which the parameter refers.

Since $f_c(x) = u_D(x)/u_{Dj}$ where the subscript D emphasizes the dark condition and u_{Dj} is the value of u_D at the junction depletion edge [3,5,10], a set of relations for $f_c(x)$ follow immediately from the above relations for $u(x)$, with $f_c(W_J) = 1$ additionally. Note that, in the above analysis, D , τ , p_0 and S_F are assumed independent of u under the low-injection condition.

2.2. Blue response

For both conventional and FSF silicon cells, most of the incident light is absorbed within the first few microns upon entering the cell, in which case the spectral response is not complicated by rear surface reflections and the IQE at a particular wavelength, λ , is given by:

$$\text{IQE}(\lambda) = \alpha' \int_0^W e^{-\alpha' x} f_c(x) dx, \quad (7)$$

where W is the cell thickness, α' is the effective absorption coefficient for the wavelength of interest given by $\alpha'/\cos \theta$ with α being the actual value of this coefficient and θ being the angle of light propagation relative to the axis.

For wavelengths transparent to the ARC but strongly absorbed within the n^+ region, a few terms in the series expansion of $f_c(x)$ at $x = 0$ should be adequate for accurate evaluation of IQE. In this

case, Eq. (7) becomes:

$$\text{IQE}(\lambda) = f_c(0) \left[1 + \frac{\beta_1}{\alpha'} + \frac{2\beta_2}{\alpha'^2} + \dots \right]. \quad (8)$$

Keeping the two largest terms in Eq. (8) and taking the inverse give:

$$\frac{1}{\text{IQE}} \cong \frac{1}{f_c(0)} \left[1 - \frac{S_F \cos \theta}{D_{n^+}} \frac{1}{\alpha'} \right]. \quad (9)$$

Hence, plotting inverse-IQE versus absorption length for these wavelengths should allow surface properties including $f_c(0)$ and S_F to be determined for devices of both type. Note that $qS_F p_0(0)f_c(0)$ gives the front surface recombination component of the dark saturation current density by Eq. (3). Considering that the minority-carrier diffusion length is normally much larger than the thickness of the front heavily-doped region but finite compared with the base thickness, this component would be a reasonable estimate of the emitter contribution of the dark saturation current density in a conventional solar cell but a lower estimate of the base contribution in a FSF device.

An unknown referee has pointed out that several earlier works [11–13] developed relevant analytical models for the study of the front highly doped regions based on the assumption of transparency of these regions. However, Eq. (9) suggests for the first time how $f_c(0)$ and S_F can be determined from the experimental IQE data. The extraction of these surface properties does not require the assumption of transparency but $\alpha \gg S_F \cos \theta/D_{n^+}$ to ensure an accurate approximation by the largest two terms of the Taylor series expansion.

2.3. Red to infrared response

In this section, wavelengths are increased to the extent that very little light reaches the rear surface but attenuation in the front heavily-doped region is much weakened.

For conventional silicon cells, the plot of inverse-IQE versus absorption length for such wavelengths can be used to extract the effective bulk diffusion length, which can be used to estimate the base component of the dark saturation current density, as in Basore's work [2].

For rear-junction configuration, things are different because photo-carriers are to be collected near the rear. Hence, a FSF is often built near the front to repel minority-carriers from recombination at the front surface ($x = 0$), in which case the bulk carrier distribution is affected by a much smaller effective surface recombination velocity S_{eff} referred to the top of the base ($x = W_H$), defined by:

$$D_n \frac{dp_n}{dx} \Big|_{x=W_H} = [p_n(W_H) - p_{n0}(W_H)] S_{eff} \quad (10)$$

with the subscript n indicating that all minority-carrier parameters are taken at the low-side of the $n^+ - n$ junction. Therefore, plotting inverse-IQE versus absorption length for such wavelengths should give another linear region of much smaller slope, described by Eq. (9) with $f_c(0)$, S_F and D_{n^+} replaced by $f_c(W_H)$, S_{eff} and D_n respectively (as long as $S_{eff} \cos \theta/(D_n \alpha)$ remains small). This may allow similar extraction of S_{eff} and $f_c(W_H)$ that can be used to analyze the base layer.

The above plot method can give reasonable estimations only when the base is much thicker than the front heavily-doped layer as is the situation for most silicon devices, in which case a range of wavelengths can be chosen to ensure both a transparent front layer and that little light reaches the rear. Otherwise, taking little light penetration to the rear as a prior condition, this method will give overestimated effective bulk diffusion length for conventional device and inadequately large S_{eff} and $f_c(W_H)$ for FSF device due to non-negligible light attenuation in the top layer.

For FSF silicon cells, minority-carrier diffusion length appreciably larger than the width of the FSF layer ($L_{n^+} \gg W_H$ and $L_{n^+}^2 \gg D_{n^+} W_H / S_F$) as a general situation for device of reasonable performance suggests an alternative scheme to evaluate S_{eff} directly from S_F for base of practically arbitrary thickness. At the abrupt $n^+ - n$ junction,

$$N_{D^+} p_{n^+}(W_H) / n_{ie}^2 = N_D p_n(W_H) / n_i^2 = \exp[(E_{fn} - E_{fp}) / kT], \quad (11a)$$

$$qD_{n^+} \frac{dp_{n^+}}{dx} \Big|_{W_H} = qD_n \frac{dp_n}{dx} \Big|_{W_H}, \quad (11b)$$

where N_D is the doping density in the lightly-doped base and N_{D^+} is its value in the front heavily-doped region, n_i is the intrinsic carrier concentration for undoped or lightly doped silicon and n_{ie} is its effective value for heavily doped silicon, k is Boltzmann's constant, T is absolute temperature, E_{fn} and E_{fp} are the electron and hole quasi-Fermi levels which are assumed constant throughout the $n^+ - n$ junction depletion region. Combining Eqs. (2), (3), (10), (11a) and (11b), S_{eff} is found as:

$$S_{eff} = \frac{N_D n_{ie}^2 S_F + (D_{n^+} / L_{n^+}) \tanh(W_H / L_{n^+})}{N_{D^+} n_i^2 [1 + (S_F L_{n^+} / D_{n^+}) \tanh(W_H / L_{n^+})]} \approx \frac{N_D n_{ie}^2 S_F}{N_{D^+} n_i^2 [1 + S_F W_H / D_{n^+}]}, \quad (12)$$

where n_{ie} can be evaluated such as by using a recently improved apparent bandgap narrowing model [14]. Similarly, $f_c(W_H)$ can be well approximated by $(1 + S_F W_H / D_{n^+}) f_c(0)$.

2.4. Infrared response

As the wavelengths increases, significant light will reach the rear surface of the cell with a large fraction reflected towards the front surface. Basore [2] was the first to point out the special properties of the IQE in this weak absorption region, developing quite complex expressions for spectral response analysis in this region. (At least three angles of light propagation are involved, i.e., the two path angles on the first double-pass across the cell which are well-defined by internal topographies of front and rear surfaces, respectively, and the effective path angle when the light direction could be considered fully randomized after a small number of double passes [2].) However, the key features can be readily understood on the physical ground that photo-carrier generation is essentially uniform throughout the cell volume for weakly absorbed light with sufficiently large number of light paths.

The collection probability, η_{c0} , for uniform generation is just the average value of $f_c(x)$ over the cell volume. The IQE would equal η_{c0} were it not for parasitic absorption of light that does not result in electron-hole pair generation. Generally, for such a process,

$$IQE = \frac{\eta_{c0} \alpha}{(\alpha + \alpha_p)}, \quad (13)$$

where α is the band-to-band absorption coefficient and α_p is the effective parasite component such as from free carrier absorption. (In previous subsections, parasitic absorption was neglected for its magnitude being negligible compared with α for short wavelengths.)

Free carrier absorption does not occur uniformly over the cell volume but is stronger in the front heavily-doped region. Hence, contributions to α_p by this mechanism should be weighted by the volume over which they occur. Other parasitic component such as absorption in the rear metal reflector can be included as an effective α_p contribution by assigning an effective absorption coefficient that gives the same loss per double-pass across the cell. Since the effective path length of weakly absorbed randomized light per double pass is approximately four times the cell thickness, the rear reflector gives an effective α_p contribution of $(1 - R_b) / (4W)$ where R_b is the rear metal reflectance and is assumed constant for all passes. In general, optical loss due to light escaping from the active

cell volume in a direction not detected either due to detector placement or absorption will give another contribution to α_p .

From Eq. (13), plotting inverse-IQE versus absorption length should give a linear relationship over a weakly absorbed spectral range with the vertical intercept equal to $1/\eta_{c0}$ and the horizontal intercept equal to $-1/\alpha_p$ provided that both η_{c0} and α_p remain sufficiently constant at these weakly absorbed wavelengths. The previously noted uniform generation warrants the constancy of η_{c0} and defines the lower bound of the wavelength, which varies with the absorber thickness in practice and is typically between 1000 nm and 1100 nm for silicon solar cells. An upper bound of the wavelength can be defined by considering the required constancy of α_p and stability of α at long wavelength. Among the three mentioned components in α_p , free carrier absorption is a much stronger increasing function of wavelength [15] compared with the other two components. Hence, this component should be kept small to ensure an overall constancy of α_p with wavelength. Further, temperature-induced variation in the bandgap also makes the band-to-band absorption coefficient α too uncertainty at very long wavelengths [2]. Therefore, an upper bound of 1120 nm is recommended for the infrared response analysis. Finally, it should be noted that the data extraction in infrared analysis is independent of cell configuration as is in blue analysis.

3. Experimental data

As in Fig. 1, the experimental silicon cell [9] that will be used to demonstrate the new features of the analysis has a FSF rear-junction configuration and consists of, from top to bottom, a 75 nm SiON ARC, a thin heavily-doped n -type (n^+) region with shallow surface texture, an 18 μm n -type base, a 1 μm rear heavily-doped p -type (p^+) emitter, a rear mirror with point contact and a bonded steel substrate. Further, the properties, in particular the doping density, are considered uniform in each domain. The top n^+ region, with $N_{D^+} = 5 \times 10^{17} \text{ cm}^{-3}$, incorporates uniform pyramids of $< 2 \mu\text{m}$ height and an underlying homogeneous layer of $< 1 \mu\text{m}$ thickness (the effective value of W_H is estimated to be 1.5 μm). The doping densities of the n -type base and p -type emitter are $N_D = 5 \times 10^{15} \text{ cm}^{-3}$ and $N_A = 5 \times 10^{17} \text{ cm}^{-3}$, respectively. At 25 $^\circ\text{C}$, $n_i = 8.6 \times 10^9 \text{ cm}^{-3}$ for lightly-doped silicon.

Fig. 2 shows the measured IQE data of the FSF ultra-thin device. Fig. 3 shows the inverse-IQE data for absorption length up to $W/3$ ($< 5\%$ light penetrates to the rear for any optical path) with evidence for two predicted regions of vastly different slope. The linear region on the left corresponds to the wavelength range 420 nm to 600 nm approximately. For wavelengths below 400 nm, absorption in the ARC suppresses the measured IQE. Depending on the pyramid angle of the textured surface, $\cos \theta$ would be 0.75–0.79 [16,17]. Assuming

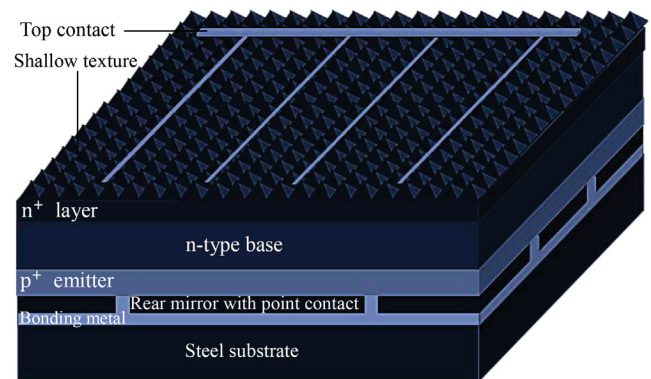


Fig. 1. Device structure for ultra-thin front surface field silicon solar cell on steel substrate.

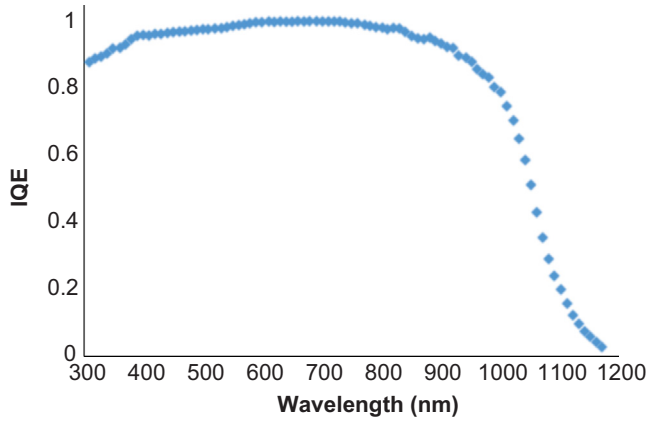


Fig. 2. Measured IQE data of the front surface field ultra-thin device.

cos $\theta = 0.77$, the steep linear fit corresponds to $S_F/D_{n^+} \approx 193/\text{cm}$ or $S_F \approx 1075 \text{ cm/s}$ for $D_{n^+} = 5.56 \text{ cm}^2/\text{s}$ (estimated online [18] using $N_{D^+} = 5 \times 10^{17} \text{ cm}^{-3}$ and room temperature). The vertical intercept gives a value of $f_c(0)$ of 0.957.

For this ultra-thin device, the FSF layer is semi-transparent for $1/W_H < 1/\alpha < W/3$, therefore S_{eff} and $f_c(W_H)$ cannot be estimated reasonably by the plot method (giving inadequately large limit of 90 cm/s and 0.996 approximately) and direct evaluation scheme introduced at the end of Section 2.3 needs to be used. Noting that the two fits cross at an absorption length of about $2 \mu\text{m}$, approximately equal to $W_H/\cos \theta$, it can be deduced that surface recombination dominates recombination within the n^+ layer, i.e., $S_F \gg W_H/\tau_{n^+} = W_H D_{n^+}/L_{n^+}^2$ and $L_{n^+} \gg W_H$. Hence, $S_{\text{eff}} \approx 23 \text{ cm/s}$ by Eq. (12) for $n_{ie} \approx 1.5n_i$ using the improved bandgap narrowing model [14] and $f_c(W_H) \approx 0.984$.

Now applying Eq. (4) to the base region (i.e., $x = 18 \mu\text{m}$, S_F and $f_c(0)$ are replaced by S_{eff} and $f_c(W_H)$, and $D_n = 11.64 \text{ cm}^2/\text{s}$). From relation (5), the bulk lifetime, τ_n , is around $22 \mu\text{s}$. This corresponds to a bulk minority-carrier diffusion length $\sim 160 \mu\text{m}$ and base component of the dark saturation current density, $J_{ob} = 2.5 \times 10^{-13} \text{ A/cm}^2$. As $qS_{\text{eff}}p_{0n}f_c(W_H) \approx 5.4 \times 10^{-14} \text{ A/cm}^2 < J_{ob}$ for $p_{0n} = 1.5 \times 10^4 \text{ cm}^{-3}$, bulk recombination dominates recombination within the n -type base. The total dark saturation current density, J_o , is around $4 \times 10^{-13} \text{ A/cm}^2$ suggesting that the base is still the major contributor to determining the experimental open-circuit voltage albeit not an overwhelmingly high contribution for the present ultra-thin structure. Assuming no carrier recombination and $f_c(x) \approx 1$ within the rear emitter, the emitter component $J_{oe} \approx 1.5 \times 10^{-13} \text{ A/cm}^2$ and approximately equals $qn_{0p^+}S_R$ where n_{0p^+} is the minority-carrier concentration in emitter in thermal equilibrium and S_R is the rear surface recombination velocity. Hence, an upper bound of S_R is estimated as 6300 cm/s for $n_{0p^+} = 1.5 \times 10^2 \text{ cm}^{-3}$. However, a large uncertainty in J_{oe} means that S_R can be much smaller than this estimated upper bound.

Now moving to weakly absorbed spectrum where photo-generation is uniform throughout the absorber. For the device in Fig. 1, at 1120 nm where the absorption length is 5 mm (~ 60 double passes across the cell), the contribution by volume of free carrier absorption in the lightly doped base region to α_p is estimated (using Eq. (4.8) of Ref. [15]) as $0.016/\text{cm}$, while those from the top n^+ region and the rear p^+ emitter are estimated as $0.13/\text{cm}$ and $0.083/\text{cm}$, respectively. The angularly averaged rear metal reflection is estimated as 92%, giving a much larger α_p contribution of $9.8/\text{cm}$ for $W \approx 20.5 \mu\text{m}$.

Fig. 4 shows the plot of inverse-IQE versus absorption length for weakly absorbed light for the ultra-thin device. Fitting over the 0.21 mm to 5 mm range (2.5 to 60 double passes) gives $\eta_{c0} = 0.985$ and $\alpha_p = 11/\text{cm}$. The η_{c0} value is consistent with the values of $f_c(0)$

and $f_c(W_H)$ determined from the earlier discussion for short wavelengths while the α_p value is consistent with the estimated values of various parasite components. That α_p is slightly larger than the sum of estimated free carrier and rear parasite components is most likely due to the previously mentioned optical loss due to light escape and the overestimation of $4W$ path length per double pass across the cell volume. Assuming the dominance by the error in the linear fit, the uncertainties in these fitted values are likely to be around 1% by noting the close-to-unity coefficient of determination ($R^2 \approx 0.9995$).

4. Further discussion

Blue response gives information on front surface properties. Although the approach for extracting S_F and $f_c(0)$ in blue analysis is the same for both conventional and FSF cells, the data application for further analysis is slightly different. For conventional device, $qS_Fp_{0n}f_c(0)$ can be used to estimate the emitter component of the dark saturation current density assuming negligible carrier recombination within the thin emitter; while for FSF device, except evaluating the surface recombination current, S_F and $f_c(0)$ can also be used to find S_{eff} and $f_c(W_H)$ for further analysis of the base as demonstrated in Section 3.

Red to infrared response reveals bulk properties. The data extraction scheme in red to infrared response for FSF device is different from a previous [2] method for conventional device but it still

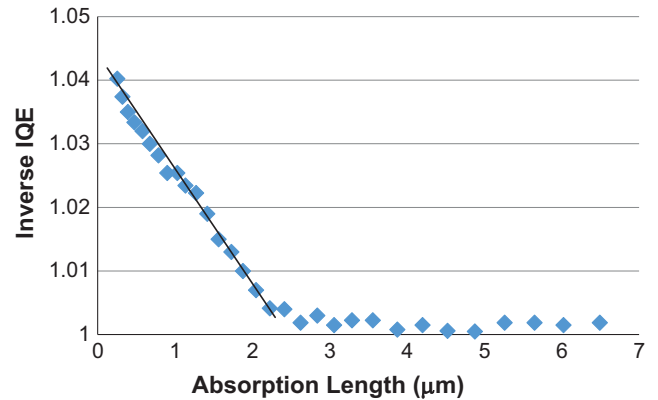


Fig. 3. Inverse-IQE data for absorption lengths up to one third of the cell thickness. The steep linear region on the left corresponds to the wavelength range 420 nm to 600 nm and the horizontal region corresponds to the wavelength range 600 nm to 730 nm approximately.

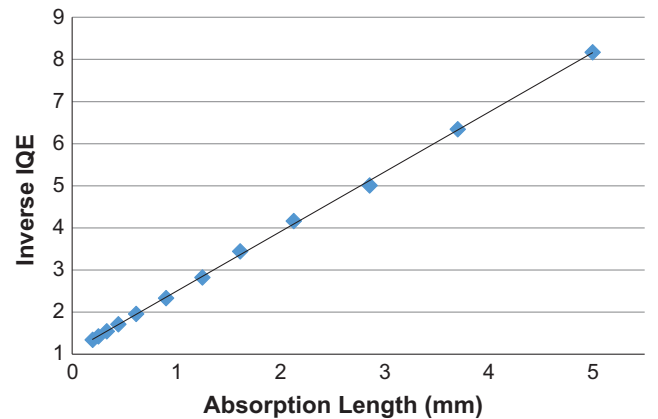


Fig. 4. Inverse-IQE data over the weakly absorbed spectral range (1010 nm to 1120 nm for the present thin silicon device) where photo-generation is essentially uniform throughout the cell volume.

derives data necessary to evaluate the base contribution of dark saturation current density as shown in earlier sections. By Eq. (9), the slope of the plot of inverse-IQE versus absorption length for red to infrared wavelengths in a FSF cell is opposite to that in a conventional cell. This is because varying absorption length in this region will redistribute photo-carriers towards one side, which makes the overall carrier collection easier for one structure but more difficult for the other due to the opposite positioning of the p–n junction. Further, for rear-junction cell without FSF, red to infrared response aligns with blue response, and plotting inverse-IQE versus absorption length for light transparent to ARC will give only two linear regions.

Infrared response evaluates overall carrier collection and parasitic absorption of a device in weakly absorbed spectrum where photo-generation is essentially uniform throughout the cell volume. Hence, infrared analysis is independent of device configuration by its physical feature.

It should be noted that a sufficiently thick base ($\sim 100\ \mu\text{m}$) means more qualified experimental data for red to infrared analysis, which will increase the reliability for data extraction by the plot method in red to infrared analysis especially for FSF device. However, increased device thickness means less qualified data for weakly absorbed analysis where photo-generation needs to be uniform. For FSF device, reasonable performance with $f_c(x)$ close to unity uniformly throughout the cell volume means a narrow floating range for bulk lifetime evaluated by relation (5) in red to infrared analysis as in the present case. However, more accurate IQE data is necessary for analyzing such high performance devices.

5. Conclusions

In summary, the extended spectral analysis of internal quantum efficiency (IQE) accommodates both conventional and front surface field solar cells as a non-destructive characterization technique. It is shown that, in general, three linear regions are likely when plotting inverse-IQE versus inverse absorption coefficient for wavelengths where the anti-reflection coating is transparent. In more detail, the newly discovered blue response analysis gives front surface properties (i.e., S_F and $f_c(0)$) that can be used to estimate the emitter contribution of dark saturation current density for a conventional cell or derive effective front surface properties referred to the top of the base (i.e., S_{eff} and $f_c(W_H)$) for bulk analysis of a front surface field cell; the red to infrared analyses of conventional and front surface field cells are different in data extraction but both are dedicated to evaluate the bulk contribution of dark saturation current density; the infrared analysis is additionally simplified compared to previous work and gives overall photo-carrier collection and parasitic absorption in a weakly absorbed spectrum where photo-generation is uniform throughout the absorber volume and parasitic absorption remains sufficiently constant at these wavelengths. The refined technique is demonstrated by application to a modern front surface field

device as a complement to previous work, producing a set of consistent values of essential cell parameters.

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