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Addressing limitations of photoluminescence based external quantum efficiency measurements

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The spectral response of photoluminescence is a contactless method that provides a measurement of the relative external quantum efficiency of silicon solar cells and wafers. This method is accurate only if the measured luminescence originates from the radiative recombination of voltage dependent carriers. This paper investigates the impact of luminescence from voltage independent carriers in heavily diffused regions and other spurious sources of luminescence, such as luminescence from dielectric layers. A method, based on partial shading, is then demonstrated to record luminescence from only the voltage dependent carriers. This method is shown to provide accurate relative external quantum efficiency on cells and partially processed wafers. The relevance of the dependence of the measured data on the angular distribution of the incident light is demonstrated in this context, which explains errors in previously published data. *Published by AIP Publishing.*
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I. INTRODUCTION

The external quantum efficiency (EQE) is commonly used to characterise the performance of solar cells including optical reflection, surface recombination, and parasitic absorption. The EQE of a device is a measure of its particle conversion efficiency from incident photons to electrons extracted as a function of the illumination wavelength. Traditionally, EQE is measured using monochromatic illumination and measuring the illumination intensity and the device's short circuit current (EQE_{Jsc})

$$EQE_{Jsc}(\lambda) = \frac{J_{sc}(\lambda)}{N_{ph}(\lambda)}, \tag{1}$$

where J_{sc} is the short circuit current density per unit area, N_{ph} is the incident photon flux, and λ is the wavelength.

EQE_{Jsc} involves the measurement of the current extracted from a device, requiring that the device has good electrical contacts: EQE_{Jsc} can only be measured on fully processed devices. Several alternative spectral response techniques have been proposed to overcome this limitation, including the spectral response of the open circuit voltage (EQE_{Voc})[1] and the spectral response of photoconductance ($EQE_{\Delta\sigma}$).[2,3] This paper focuses on a third technique that can be applied to devices at any stage of cell production, namely, the spectral response of photoluminescence (EQE_{PL}).[4,5] It was shown previously that experimental artefacts occur in EQE_{PL} data in the long wavelength range; when measured on typical front junction solar cells, these artefacts result from voltage independent carriers located in the bulk and at the rear surface.[4]

This paper extends previous work by highlighting and quantifying additional potential pitfalls associated with EQE_{PL} measurements and by demonstrating an elegant experimental approach to avoid these artefacts. The potential pitfalls all relate to luminescence contributions from sources that are unrelated to the terminal voltage, specifically luminescence generated in front surface passivation layers and luminescence from heavily diffused regions. Solar cells with different SiN_x layers and diffusions are used to show that these mechanisms can have a significant effect on the measured EQE_{PL}. So, in Secs. II A and II B, we show the impact of such spurious luminescence sources on an EQE_{PL} measurement.

The following relation for EQE_{PL} can be considered an extension of Rau's reciprocity relation,[6] which makes no assumption on the excess carrier density profile or the location of absorption

$$EQE_{PL}(\lambda) - \frac{I_{PL-SC(\lambda)}}{N_{ph}(\lambda)} \propto EQE_{Jsc}(\lambda), \tag{2}$$

where λ is the illumination wavelength, $I_{PL\text{-}sc}$ is the PL intensity from the voltage independent carriers, and N_{ph} is the number of incident photons. EQE_{PL} provides a relative measure of the EQE only when $EQE_{PL}(\lambda) \gg \frac{I_{PL-sc}}{N_{ph}}(\lambda)$. Previously, $I_{PL\text{-}sc}$ was associated exclusively with carriers in the bulk which do not contribute to the terminal voltage or current,[6] a definition we now extend to luminescence from any source that does not contribute to the terminal voltage or current

$$I_{PL-sc} = I_{PL-Bulk} + I_{PL-Diffusion} + I_{PL-Other}, \tag{3}$$

where $I_{PL-Bulk}$ and $I_{PL-Diffusion}$ are the voltage independent carriers in the bulk and diffused regions, respectively, and $I_{PL-Other}$ represents luminescence from other layers, such as SiN_x. Note that voltage independent carriers in a diffused layer can represent both carriers in a dead layer and carriers that cannot be collected by the junction because of a small diffusion length. The artefacts resulting from the last two terms in Eq. (3) are discussed in more detail below.

In Secs. III A and III B of this paper, we demonstrate *contactless electroluminescence* (EL) as an elegant experimental approach to avoid the above artefacts. In the context of shunt detection, Sinton described the concept of measuring luminescence from a shaded section of a solar cell, while the surrounding non-shaded region is illuminated.[7] In practice, this was implemented by placing a photodetector face down onto the cell. While the external excitation is optical, the detected luminescence signal stems from carriers that are injected electrically into the shaded region and hence the terminology *contactless electroluminescence*. Note, the contactless EL technique is limited to samples after junction formation, whereas EQE_{PL} can be performed before junction formation.

In the context of EQE measurements, Davis *et al.* recently demonstrated the contactless EL measurement principle with spectrally variable and localised illumination.[7] They pointed out a substantial benefit over the conventional EQE_{PL} approach, i.e., that such measurements should be unaffected by voltage independent carriers. Their experimental proof of concept data showed relatively coarse qualitative agreement with EQE_{Jsc} data, with strong deviations observed, in particular for textured monocrystalline cells.[8,9]

Here, we apply contactless electroluminescence with full area (except for the detection region) spectrally variable illumination on multi and monocrystalline cells and extend the approach to partially processed wafers prior to metallisation. The overestimation of EQE_{PL} due to the spurious luminescence discussed earlier can be avoided by this method, and an excellent agreement with EQE_{Jsc} is observed for both multi- and monocrystalline samples. Experimental data and optical simulations are used to show that the angular distribution of the incident monochromatic light is the likely cause of the deviations between EQE_{Jsc} and the contactless EL approach reported in Ref. 9.

II. MOTIVATION-IMPACT OF VOLTAGE INDEPENDENT CARRIERS ON EQE$_{PL}$

To demonstrate the impact of voltage independent carriers on EQE_{PL}, screen printed solar cells with different diffusions and SiN_x layers were studied. The sample set consists of samples with significant luminescence from both the front diffusion and dielectric surface layers. Measurements of EQE_{PL} were performed with an experimental set-up that was built in house, as shown in Fig. 1. The illumination is provided by light-emitting diode LED arrays containing 8 different types of LEDs, with peak wavelengths in the range from 365 nm to 660 nm (FutureLED GmbH). The spectral width of the LEDs

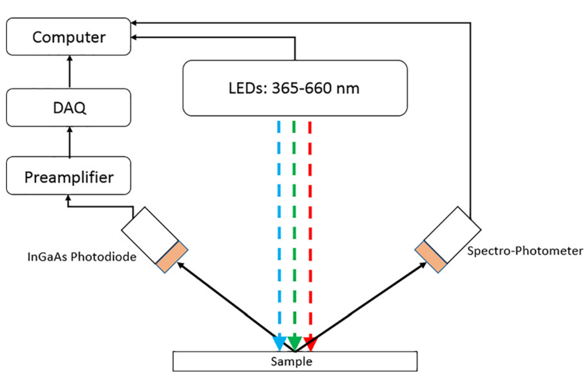

FIG. 1. Schematic of the EQE$_{PL}$ measurement set-up.

was confirmed to have a negligible effect on our measurements.[10] An InGaAs photodiode was used to measure the luminescence intensity, while the spectrum was measured in separate experiments with a CCD based spectrometer (BwTek Sol 1.7). To prevent the detector from measuring the LED emission, a 900 nm long pass filter was placed in front of the detectors.

Given its robustness against injection dependent lifetime, all experimental data shown in this paper were obtained with the constant output method rather than the constant photon flux method.[1,4] The constant signal method is also advantageous for the contactless EL technique, described in more detail below, as it reduces the impact of lateral series resistance.

A. Effect of heavy diffusion

The impact on EQE_{PL} measurements of luminescence from diffused regions is now demonstrated. The sample investigated is a p-type screen printed solar cell with a heavy phosphorous diffusion, resulting in a sheet resistance of 43 Ω/sq. The IQE of the device at a short illumination wavelength is reduced at short wavelengths due to carriers being generated in the diffused region recombining prior to reaching the junction. The EQE_{PL} of the cell was measured first using the conventional constant signal method. The results are shown in Fig. 2 as blue crosses. In a second iteration of the experiments, a measurement under short circuit conditions was performed for each illumination wavelength at each illumination intensity, and at each wavelength, the corrected PL signal ($I_{PL} - I_{PL,sc}$) was held constant across all wavelengths. This procedure ensures that the bulk Si remains at the same injection level across all wavelengths.

The measured EQE_{PL} and EQE_{Jsc} are shown in Fig. 2(a), where EQE_{PL} was normalised to EQE_{Jsc} at long wavelengths. The EQE_{PL} data that are based on the uncorrected PL signal (blue crosses) overestimate EQE_{Jsc} at short wavelengths. In contrast, the short circuit current corrected EQE_{PL} data, shown as black stars in Fig. 2(a), are found to be in excellent agreement with EQE_{Jsc}. The open-circuit minus short-circuit measurements shown in Fig. 2(a) are provided to confirm that the overestimation is not an issue with the calibration of the measurement system but a real artefact of this measurement method. The cause of this overestimation of the EQE by the uncorrected EQE_{PL} can be observed in the spectral PL measurements, shown in Fig. 2(b). The spectral PL measurements were taken at the illumination intensities that provide a constant short circuit corrected PL intensity. The PL spectrum at 365 nm shows a broadened luminescence emission compared with the spectrum measured using 660 nm excitation. This broadening is observed to become increasingly prominent as the illumination wavelength is swept from 505 nm to 395 nm. The additional luminescence is attributed to luminescence from the heavily doped phosphorous region on the front of the device. Such room temperature luminescence from doped regions has been previously reported, where the change in the emission spectrum was attributed to bandgap narrowing.[11–13] The short wavelength light is absorbed mainly in the front diffusion, from where a fraction of the carriers do not reach the junction. The emission can thus be attributed to voltage

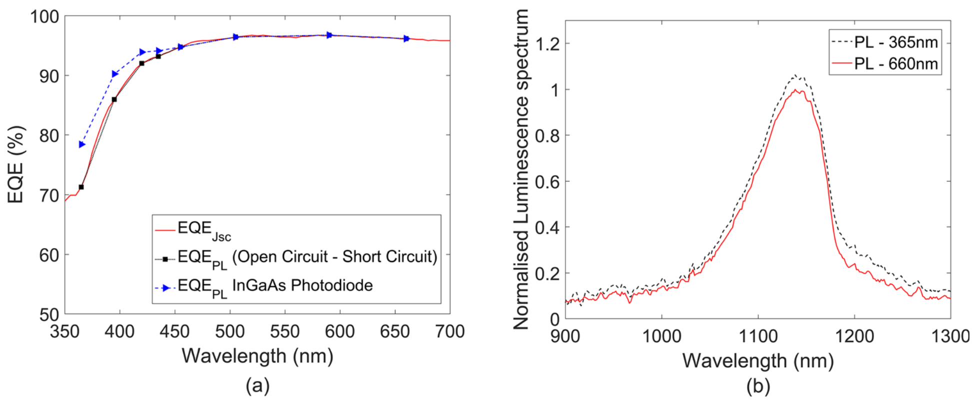

FIG. 2. The impact of a heavy diffusion on EQE_{PL} (a): Comparison of EQE_{Jsc} with EQE_{PL} and (b) PL spectrum from the sample measured with 365 and 660 nm excitation wavelengths. The difference between the normalised PL spectrum at 365 nm and PL at 660 nm represents the luminescence from voltage independent carriers.

independent carriers in the phosphorus diffusion, in analogy to the voltage independent carriers in the bulk which were described recently.[14] In the case of longer wavelength excitation, most of the light is absorbed in the bulk and the impact of the phosphorus diffusion on the overall PL spectrum is negligible.

We note that the sample studied in this section has a heavy diffusion, providing significantly lower sheet resistance than the one found in modern industrial cells. For modern industrial cells, the luminescence from phosphorus diffusion has a much smaller impact. The substrate can be either mono- or multi-crystalline silicon. Comparing the PL emission spectrum at the shortest and longest excitation wavelengths or measuring luminescence at short circuit for a solar cell at different excitation wavelengths is an effective method to determine whether EQE_{PL} is affected by voltage independent carriers.

B. Impact of the luminescence from dielectric layers

In the above measurement, the luminescence from the dielectric coating, here SiN_x, did not impact the measured EQE_{PL}. Unfortunately, this is generally not true. The PL emission from SiN_x, and other dielectric coatings, is heavily dependent on the type of deposition system, the deposition conditions, and the resulting film composition.[15]

A screen-printed cell with both a heavy diffusion and a SiN_x coating that is known to have a high PL intensity and a spectrum that is strongly red shifted into silicon's luminescence band was investigated. The luminescence emission from SiN_x, with 405 nm excitation, is shown for the sample from Sec. II A in red and for the new sample in blue in Fig. 3. Both spectra are shown on the same scale. The Si luminescence spectrum can be seen from 950 nm. The enhanced emission of the spectrum results in a significant impact of the luminescence from SiN_x on the measured EQE_{PL}.

The EQE_{PL} of the cell was measured with an InGaAs photodiode and is shown in Fig. 4. For comparison, the conventional EQE_{Jsc} was measured with a monochromator based EQE measurement system (PV Measurements QEX7). The EQE_{PL} measured using the constant signal method overestimates the actual EQE_{Jsc} at short wavelengths. In contrast, the short circuit corrected EQE_{PL} agrees well with EQE_{Jsc}, reconfirming Eq. (2). These results are analogous to the observations in Sec. II A, except that here the overestimation of the EQE_{PL} stems from both the heavily doped emitter and the SiN_x luminescence, evident from the spectral PL measurements shown in Fig. 4(b). Comparison of the spectrum for the excitation wavelengths of 365 and 660 nm shows a vertical shift and an additional peak in the 365 nm data as compared with the 660 nm data. This extra luminescence is the cause of the deviation between EQE_{PL} and EQE_{Jsc}. The vertical shift, seen most clearly in the spectral range of 950 nm to 1000 nm in Fig. 4(b), is the result of the tail from SiN_x, shown in Fig. 3. The extra peak, with a maximum at 1160 nm, is unrelated to the SiN_x emission and due to luminescence from the heavily diffused region. Similar to Sec. II A, we note that the relative impact of such spurious luminescence on the EQE_{PL} will depend on the device being measured. Measuring the PL spectrum at different excitation wavelengths allows quantifying this effect and its impact on the EQE_{PL}. We further note that the artefacts from SiN_x can be suppressed by shifting the detection

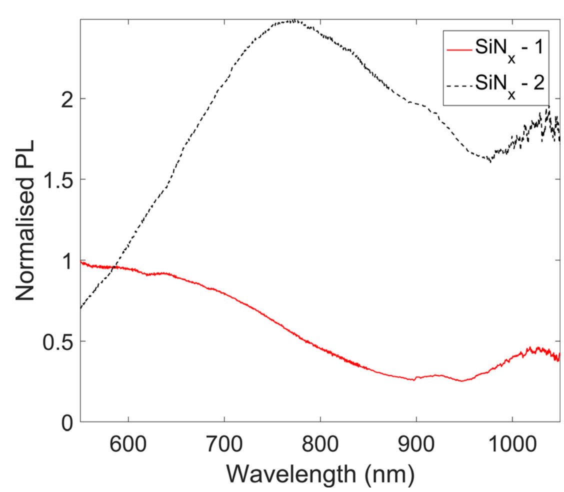

FIG. 3. Comparison of luminescence from two different SiN_x layers used in Sec. II A and here. The spectra were measured using an excitation wavelength of 405 nm and are plotted on the same scale. The spectrum is calibrated for detector's spectral response up to 1000 nm.

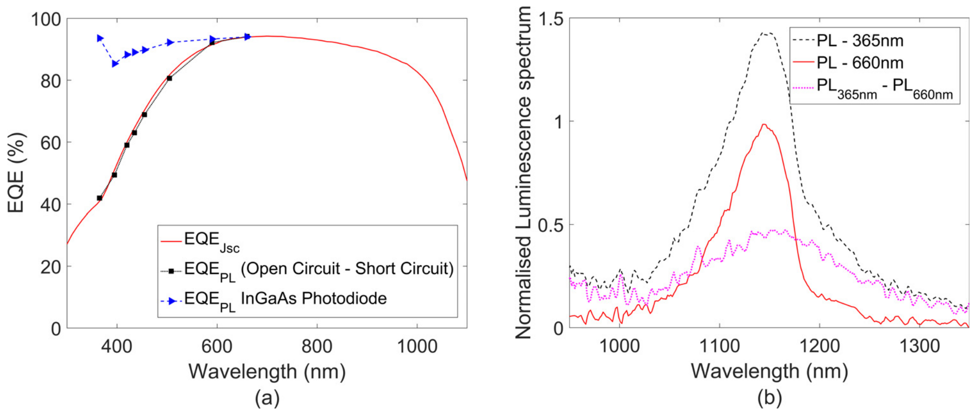

FIG. 4. The impact of a strongly luminescing dielectric on (a) EQE_{PL} measured with (black squares) and without (blue triangles) short circuit signal correction and (b) the spectral PL emission from the sample at 365 and 660 nm excitation wavelengths, all shown on the same scale. The difference between the PL at 365 nm and PL at 660 nm represents the luminescence emission not related to the voltage of the device.

spectrum to longer wavelengths, which will reduce the decreasing SiN_x luminescence strongly, while still allowing the band-to-band emission peak to be detected.

III. CONTACTLESS ELECTROLUMINESCENCE

Section II discussed the limitations of using the spectral response of PL to provide a relative measure of the conventional EQE. In this section, we show that by measuring contactless electroluminescence (EL) instead of PL, the above problems arising from luminescence unrelated to the terminal voltage can be avoided. In contactless EL, a fraction of a solar cell or a diffused wafer is illuminated and the luminescence from a non-illuminated or shaded region is monitored. The contactless EL was proposed earlier to detect shunted silicon solar cells,[7] for non-contact imaging of the series resistance[16] and EL imaging of PV modules.[17] It was also applied to partially processed wafers to measure the emitter sheet resistance in a contactless fashion.[18] Recently, the contactless EL approach was proposed for quantum efficiency measurements on cells.[9] The excess carriers that are generated in the illuminated regions can only move significant distances laterally via drift and hence the limitation of the method to samples with lateral transport channels such as the emitter or metal contacts. The luminescence signal measured from non-illuminated regions is thus caused by electrically injected carriers. It is dependent only on the voltage dependent carriers and thus avoids the previously mentioned effects, as pointed out earlier by Davis *et al.*[9] Here, we show measurements on solar cells using an improved experimental approach, which avoids substantial experimental deviations between EQE data obtained from contactless EL and conventional short circuit current density based EQE measurements, as reported by Davis *et al.*[9] In this context, the angular distribution of the incident excitation light is shown to be a crucial parameter, particularly for textured monocrystalline solar cells.

We also extend the technique to wafers after junction formation. In solar cells under low illumination, carriers move from the illuminated regions to the dark region through the metal grid. In wafers with a diffusion layer, we can still measure luminescence from the "dark" regions which, similar to the previous case, will be a measure of the voltage dependent carriers.[18] Thus, we can measure the relative spectral response of the voltage dependent carriers in partially processed diffused wafers.

To experimentally verify this, we modified our previous set-up to shade the area from which the luminescence signal is collected, as shown in Fig. 5. Illumination in this set-up is from an LED array with 8 different LEDs with a centre wavelength ranging from 365 nm to 660 nm. The contactless EL is measured by placing an InGaAs photodetector facing down onto the sample. To confirm that no light entered this region, the luminescence signal with the device held at short circuit was measured. This was found to be several orders of magnitude below the luminescence intensity of the device

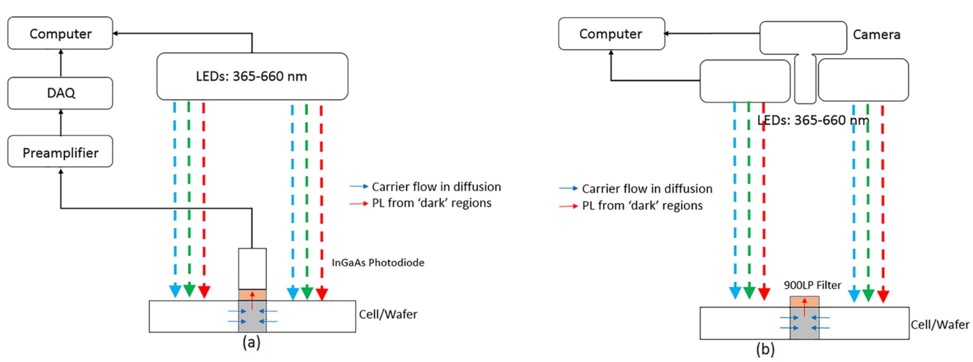

FIG. 5. Schematic of the modified set-up to measure contactless EL. (a) The detector is placed directly onto the sample, so that it shades the sample. (b) In separate experiments, PL images were measured using an InGaAs camera, with an LP filter, causing a non-illuminated shaded region from which luminescence emission could still be detected, as described earlier.[18]

when at open circuit, confirming an appropriate level of optical isolation. A camera was also installed to acquire the spatial variation in luminescence between illuminated and non-illuminated regions, as shown in Fig. 5(b). Here, a long pass filter was placed onto the cell that prevented the illumination entering the cell but allowed the PL signal from underneath the filter to pass through, similar to the approach presented in Ref. 4. The luminescence from the sample was measured using an InGaAs camera.

A. Measurements on screen printed cells

The spectral response (EQE_{PL}) was measured with the modified set-up on the cell presented in Sec. II which exhibited significant deviations between EQE_{PL} and EQE_{Jsc}. The results from the *contactless EL* (EQE_{EL}) are shown in Fig. 6(a). The EQE_{EL} data from the modified set-up are in excellent agreement with the conventional EQE_{Jsc}. The PL spectra from the shaded and non-shaded regions of the cell were measured at different excitation wavelengths. In the nonilluminated section, the PL spectrum, shown in Fig. 6(b), did not change with the illumination wavelength, confirming that the measured signal originated only from voltage dependent carriers, whereas in the non-shaded region, the above-mentioned increase in the spectrum for short wavelength excitation is observed. This demonstrates that the overestimation of EQE in the conventional EQE_{PL} from spurious luminescence is avoided in EQE_{EL}.

Photoluminescence images of the same sample taken under 365 and 660 nm are shown in Fig. 6(c). The luminescence image for the 660 nm illumination shows an almost uniform emission across the entire sample, including the filtered region. The small reduction of the intensity in that region is caused by the non-unity filter transmission. The otherwise uniform emission intensity is the result of (a) the illumination intensity being sufficiently low to cause negligible lateral series resistance losses, and (b) at 660 nm illumination, there is almost no voltage independent carriers. In contrast, the luminescence image acquired with 365 nm illumination shows a significant difference between the shaded and the non-shaded area. Note that the luminescence intensity in both areas remains relatively flat, as the series resistance does not significantly affect the lateral movement of carriers. The difference between the shaded and non-shaded area is thus a result of the voltage independent carriers described in Sec. II B, which are only generated in the sample area located outside the filter.

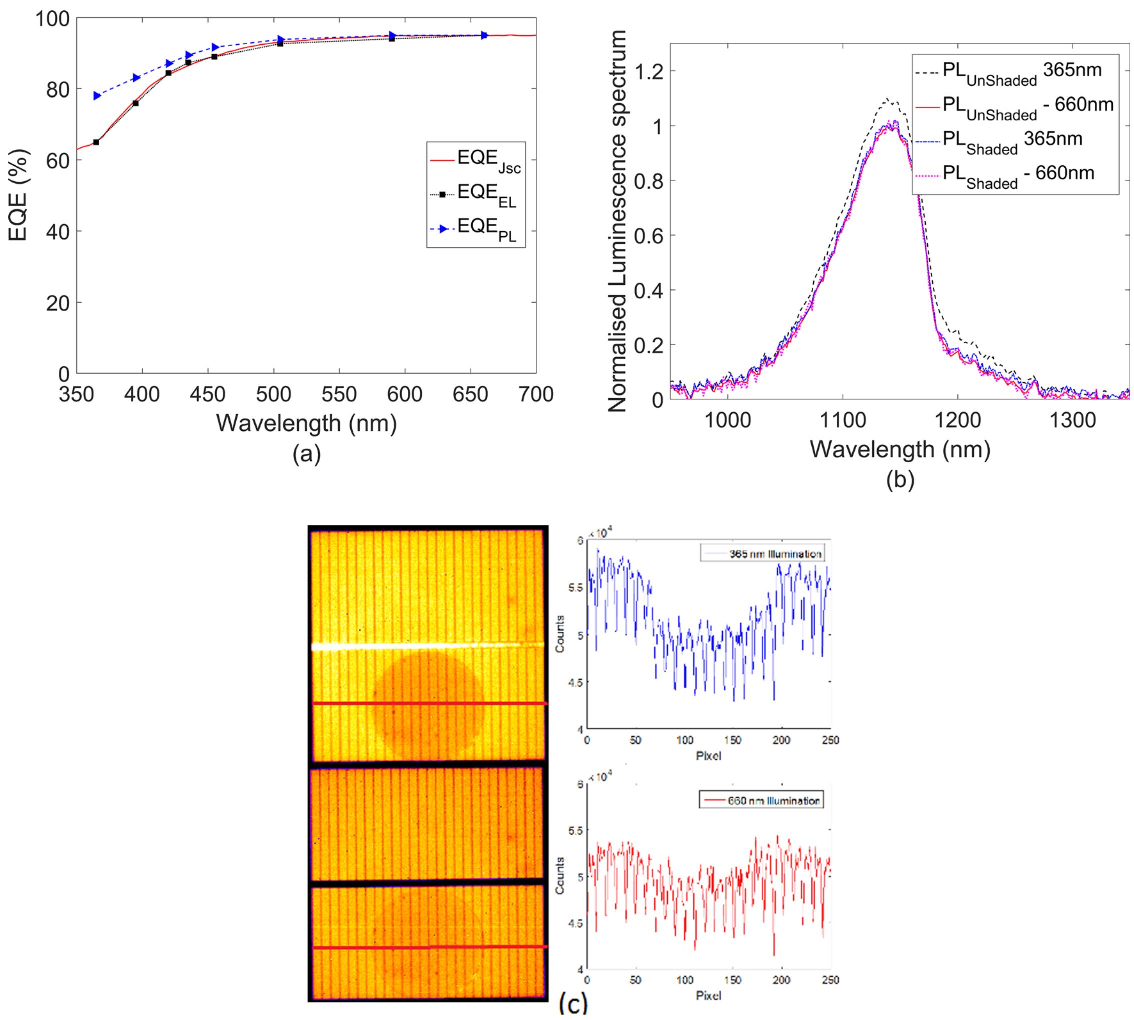

FIG. 6. (a) Comparison between EQE_{Jsc} measured with a monochromator based tool, EQE_{PL} measured without shading the cell, and EQE_{EL} measured by shading the cell. (b) The PL spectrum from the shaded and unshaded regions of the cell at 365 and 660 nm illumination, respectively. The PL_{Shaded} for each wavelength is normalised to 1. (c) PL images of the cell at 365 and 660 nm illumination with a 900 long pass filter placed on top.

B. Measurements on partially processed wafers

In Sec. III A, we demonstrated a modified approach of measuring contactless EL and that it provides an accurate relative measurement of the finished cell's EQE. We now extend this approach to partially processed wafers. In the previous case of cells, the voltage dependent carriers generated in the illuminated regions of the cell can move laterally through the grid. For partially processed wafers with a junction but without the metal grid, bulk excess minority carriers can only move laterally and reach the shaded region of the wafer through the phosphorus diffusion. Although the emitter sheet resistance[18] is a significantly larger lateral resistance than the metallised grid, the PL intensity from the shaded region still represents only voltage dependent carriers, particularly when performed with the constant output method as described in Sec. II. Thus, the EQE_{EL} measured on wafers can provide a relative measure of the EQE at every stage of processing after junction formation. This method cannot be applied on wafers without a junction, as the carriers are not able to travel laterally by drift but rather are limited by their effective diffusion length.[19] For non-diffused wafers, the conventional EQE_{PL} is thus the only option, and strategies to avoid artefacts, as described above must be applied.

The sample investigated here was an n-type Si wafer with a resistivity in the range of 4–5 Ω-cm. The wafer was symmetrically Boron diffused, with a resultant sheet resistance of 35.6 Ω-sq, and symmetrically coated with SiN_x. The processing resulted in a sample with an effective lifetime of 70 μs at an excess carrier density of 10^{15} cm^{-3}, as determined with quasi steady state photoconductance (Sinton Instruments WCT-120).[20] The EQE_{PL}, EQE_{EL}, and the PL spectrum are shown in Fig. 7. As in the previous experiments, the conventional EQE_{PL} is significantly higher than EQE_{EL}, suggesting the impact of voltage independent carriers. Good agreement is observed for all spectra in Fig. 7(b), except for the spectrum measured with short wavelength excitation in the non-shaded region. The enhanced spectral intensity is caused by voltage dependent carriers, as discussed above.

IV. IMPACT OF ANGULAR EMISSION OF LEDs

In this section, a potential pitfall associated with the use of LEDs with wide angular emission on EQE measurements, or in fact any other spectral data, such as e.g., light IV curves or conventional EQE_{Jsc} data, is discussed. Since LEDs can provide high illumination intensity with a relatively narrow emission spectrum, they are being used in several characterisation tools in photovoltaics[21,22] including EQE measuring systems.[23–25] However, LEDs typically have very wide emission angles. When not accounted for, this can result in incorrect measurement results for the spectral response, as will be shown below. We believe that the experimental deviations between EQE data from contactless EL and conventional EQE_{Jsc} data, reported by Davis *et al.*,[9] are largely due to this effect.

In the standard configuration in our experimental system, the maximum angle for illumination at any wavelength on any part of the sample is less than 10°. To illustrate the impact of the angular distribution, our experimental set-up was modified to provide up to 25° illumination angles. EQE_{Jsc} was measured on a textured mono-crystalline standard screen-printed cell with both the narrow angle and wide-angle set-ups and is shown in Fig. 8. For comparison, EQE_{Jsc} measurements were also performed using a commercial diffusive monochromator based EQE measurement system (PV Measurements QEX7), labelled in Fig. 8 as EQE_{Ref}. Good agreement is observed between the narrow angle measurement in our system and the monochromator based system, a demonstration of the excellent match in calibration between the two systems. In contrast, the EQE_{Jsc} measured using the wide-angle LED set-up leads to a strong underestimation of the EQE. The wide-angle measurement represents the average of a range of illumination angles from 0° to 25°. For a more detailed analysis of the angular effects, the EQE_{Jsc} was measured using the monochromator based system but with different angles of incidences (0° to 40°). For each measured angle, the angular distribution is only ±4°. A similar underestimation of the EQE was reported in Davis' EQE_{EL} studies, which were performed with an LED illumination source.[9] The international standard used for solar simulators (IEC 60904-9: Solar simulator performance requirements) does not provide a maximum limit on the incidence angle. Thus, if collimation of light is not ensured, it could lead to an incorrect measurement of EQE, even with an AAA rated light source. Given the strong effect on EQE demonstrated here, IV measurements themselves can be expected to be affected significantly if light sources with a large angular distribution are

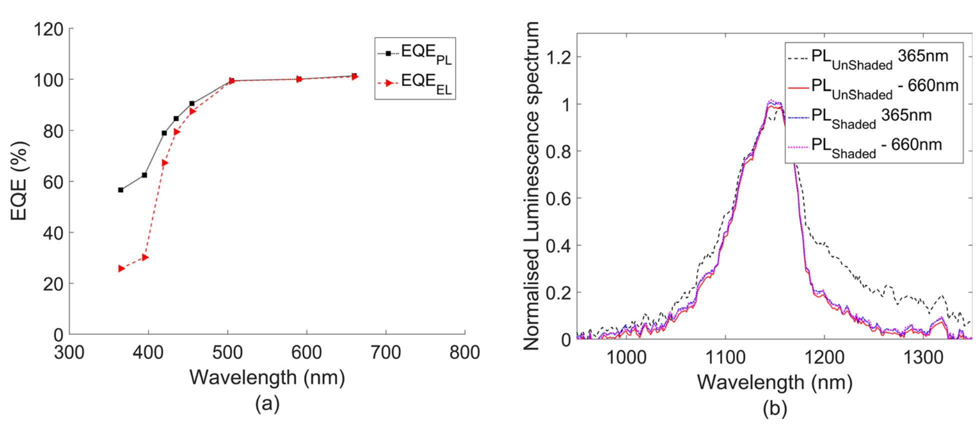

FIG. 7. (a) Comparison between EQE_{PL} measured without shading the wafer and EQE_{EL} measured by shading the wafer. (b) The PL spectrum from the shaded and unshaded regions of the wafer at 365 and 660 nm illumination. The spectra are normalised to 1.

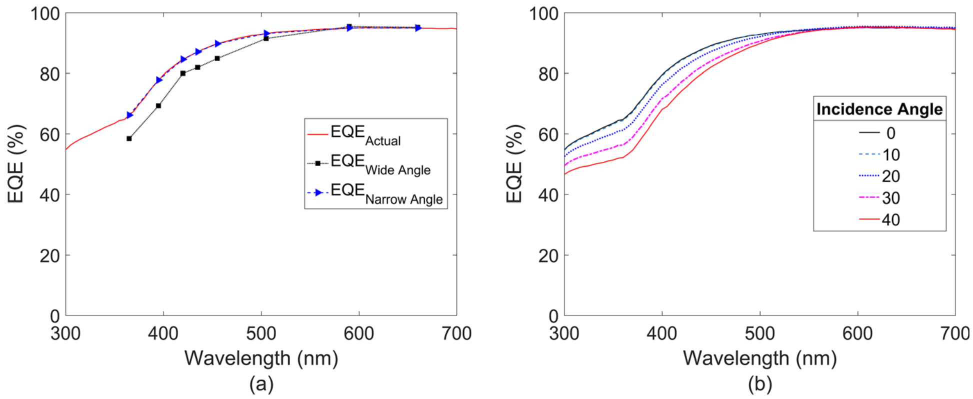

FIG. 8. (a) Comparison of EQE_{Jsc} measured on a standard EQE_{Jsc} system (EQE_{Ref}) and on our LED based system with wide and narrow angular distributions of the illumination. (b) EQE_{Jsc} measured on a standard monochromator based EQE system at different angles of incidence.

employed. This may be a significant issue for LED based cell testers or module testers. From the data shown in Fig. 8(b), we can conclude that a maximum illumination angle of 10° should be used to keep relative experimental errors in the measured EQE data within 1%.

V. CONCLUSION

EQE_{PL} is a very useful technique that can provide a relative measure of EQE_{Jsc}. However, while using this method, it must be ensured that the luminescence from voltage independent carriers and other spurious luminescence, whether they are in the passivation layer, diffused regions, or in the bulk, are negligible compared to the total luminescence from the voltage dependent carriers. If the likely source of spurious luminescence is known, an appropriate choice of detector can make the measurement more robust against this effect. The shape of the PL spectra from the device under the shortest and the longest wavelength illumination can be used as a simple but accurate measure to check for such effects. Generally, these artefacts have less impact on high quality samples with high effective minority carrier lifetime, in which the band-to-band luminescence associated with voltage dependent carriers is larger.

A method to completely avoid these problems on structures after junction formation is contactless EL. Here, the sample is partially shaded in the region from which the luminescence is measured, while the area surrounding the shaded region is illuminated with variable wavelengths. This method provides an accurate measurement of the relative EQE for both fully processed cells and for diffused wafers. It was also demonstrated that if the light source that has an angular distribution of emission is great than 10°, the measured EQE will be incorrect. This effect was demonstrated to be large for textured monocrystalline samples. This effect is of general relevance for and photovoltaic equipment with an LED based light source, e.g., EQE tools and light IV tools.

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