Suns-photoluminescence: Contactless determination of current-voltage characteristics of silicon wafers

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In good silicon solar cells, the separation of the quasi-Fermi energies $\Delta\eta$ in the bulk is equivalent to the cell voltage. Photoluminescence is used to measure $\Delta\eta$ in both bifacial solar cells and partly processed solar cells. The bifacial cells are used to demonstrate that simultaneous measurement of the photoluminescence signal and of the variable incident light intensity yields pseudo current-voltage characteristics, equivalent to Suns-open circuit voltage (V_{OC}) measurements, but in contactless mode. The applicability of this method to unfinished solar cells, without the need for a solar cell structure, is demonstrated on silicon wafers after various processing steps. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2034109]

Simultaneous measurements of the open circuit voltage (V_{OC}) of solar cells and of the incident light intensity, commonly called Suns-V_{OC} measurements, are widely used in photovoltaics to characterize solar cells.[1,2] Suns-V_{OC} measurements on solar cell structures allow the prediction of the *I*-*V* curve that would be obtained from that cell in the case that the series resistance is zero. The main disadvantage of the Suns-V_{OC} technique is that it can only be performed on solar cell structures and that it cannot be performed in contactless mode. However, a contactless voltage measurement that could be applied to wafers at any processing stage would be of substantial benefit for solar cell development and process monitoring. It would allow the effects of individual processing steps on the device performance to be determined and consequently these processing steps to be optimized.

The possibility of determining the voltage from photoluminescence (PL) is based on the fact that the PL signal and the voltage of a solar cell are both linked to the separation of the quasi Fermi energies $\Delta\eta$. The voltage U of an ideal solar cell is given as $eU=\Delta\eta$, with e the elementary charge, while the relationship between the rate of spontaneous emission (which determines the PL signal) and $\Delta\eta$ is described by the generalized Planck's Law, which in most practical cases can be written in the simplified form[3]

$$r_{sp} = \frac{n^2}{\pi^2\hbar^3 c_0^2} \cdot \int_0^\infty (\hbar\omega)^2 \cdot \alpha_{BB}(\hbar\omega) \cdot \exp\left(\frac{-\hbar\omega}{kT}\right) \cdot \exp\left(\frac{\Delta\eta}{kT}\right) \cdot d(\hbar\omega) \quad (1)$$

with n the refractive index. The exponential relation between the luminescence intensity and $\Delta\eta$ that is predicted by Eq. (1), has been demonstrated e.g. in electroluminescence experiments on forward biased silicon solar cells.[4] The possibility of relating the luminescence intensity to $\Delta\eta$ and thus to the voltage and to the *I*-*V* curve of a solar cell, is thus by no means a new discovery.[5,6] However, applications in photovoltaics via a quantitative analysis of luminescence measurements have been limited so far.[7–10]

This letter shows experimentally that PL measurements provide a convenient way to measure a photoinduced separation of the quasi Fermi energies over a wide range of incident light intensities. It thereby demonstrates that *Suns-PL* (i.e., PL measurements in combination with measurements of the incident light intensity) yields the equivalent of Suns-V_{OC} over a wide range of the *I*-*V* curve in a contactless mode, i.e., without the need for a solar cell structure or electrical contacts. The validity of the method is demonstrated first by a comparison between Suns-V_{OC} and Suns-PL measurements on finished bifacial silicon solar cells. Its applicability to unfinished solar cells is then demonstrated by measurements on silicon wafers after various processing steps.

A commercial photoconductance (PC) flash tester (Sinton Consulting[11] WCT100) was modified, enabling simultaneous measurement of the incident light intensity, the PL signal, the PC signal and of the open-circuit voltage. The samples are illuminated from the front side by a 1.5 W/870 nm light emitting diode (LED) array. Data acquisition is accomplished by a multi channel 16 bit data acquisition card. Control of the LED array via a D/A output of that card allowed arbitrary waveforms to be generated and automated repetitive signal averaging. The PL emitted from the rear surface of the samples is measured by a silicon PIN diode, which is located directly behind the sample, with no dispersing elements in between. Due to reabsorption of internally generated photons the PL signal is slightly more sensitive to excess carriers that recombine near the rear surface then to carriers that recombine at the illuminated front surface in this geometry. In cases, where the relative carrier distribution changes drastically with illumination intensity this spatial dependence of the PL sensitivity could be expected to lead to a distortion of the *I*-*V* curve that is obtained from the PL signal. A quantitative analysis of this effect (detailed analysis is available on request from the authors) however shows, that even for a worst case scenario in which the carrier profile is assumed to change from a delta function on side of the wafer to a delta function on the other side of the wafer the distortion of the *I*-*V* curve is comparatively small ($\sim$9 mV for a 250 μm thick wafer) and that it can be expected to be negligible for the much smaller relative variations of the carrier profile with illumination intensity in real

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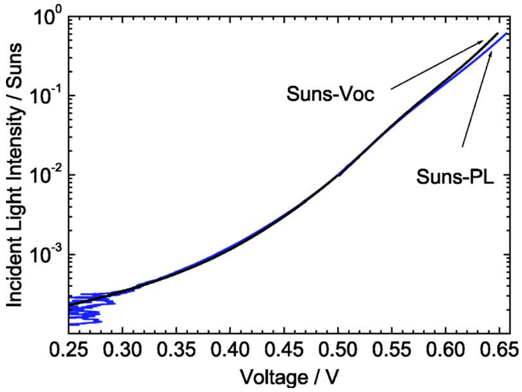

FIG. 1. (Color online) Incident light intensity as a function of the measured open circuit voltage (Suns-V_{OC}) and of the logarithm of the measured PL signal (Suns-PL).

silicon wafers. The negligible distortion of the *I-V* curve due to changes in the carrier profile is also confirmed experimentally by the good agreement between the PL data and the actual Suns-V_{OC} to be discussed below.

A 245 μm thick bifacial double-sided buried contact silicon solar cell (processing details can be found elsewhere[12]) was investigated. The incident light intensity, the open circuit voltage and the PL signal of that cell were measured simultaneously. Figure 1 shows the resulting Suns-V_{OC} curve, i.e., the incident light intensity as a function of the open circuit voltage (two separate measurements at high and low light intensity, respectively). Two characteristic features appear in the curve. First, a kink is observed at voltages between 520 mV and 630 mV, which is attributed to asymmetric Shockley-Read-Hall recombination.[12,13] The flattened region in the curve with an ideality factor $n \gg 1$ at lower voltages (<450 mV) shows that this cell is shunted. In Fig. 1 the incident light intensity was scaled into the equivalent of Suns by comparison with an open circuit voltage measurement on the same cell under one Sun illumination in a calibrated *I-V* tester ($V_{OC}=658$ mV).

Only the *relative* PL signal $I_{PL,rel}$ is measured in our setup. $I_{PL,rel}$ is converted into absolute voltages using $\Delta\eta = eU = kT^{*}\ln(I_{PL,rel}) + C$, with C a calibration factor that needs to be determined separately. The Suns-PL curve, i.e., the incident light intensity as a function of the appropriately scaled logarithm of the PL signal times kT is plotted in Fig. 1 together with the Suns-V_{OC} curves. Here the calibration factor C was varied to get the best fit between Suns-V_{OC} and Suns-PL. The Suns-PL curve very closely matches the Suns-V_{OC} curve throughout the entire voltage range from 300 mV to 630 mV. Both the kink in the curve and the shunt are clearly evident. Small deviations between Suns-V_{OC} and Suns-PL of up to 7 mV are observed at large incident light intensities ($V_{OC} > 550$ mV). These are attributed to internal series resistance losses occurring even under open-circuit conditions due to internal electron and hole currents towards the contacts within the cell. These currents result in a smaller open circuit voltage between the terminals compared to the average separation of the quasi Fermi levels inside the cell.

We also investigated nonshunted bifacial cells and found similar good agreement between Suns-V_{OC} and Suns-PL. The data from the shunted cell were chosen for Fig. 1 because the shunt leads to an additional distinct feature in the curves,

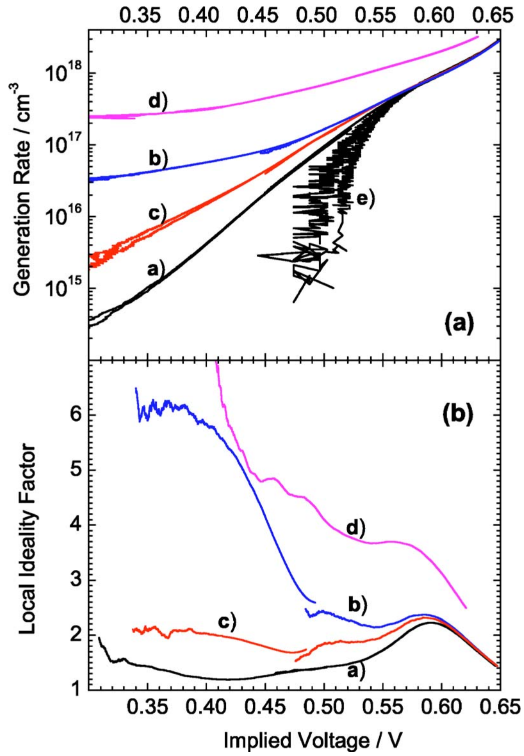

FIG. 2. (Color online) (a) Pseudo *I-V* curves (a–d from Suns-PL) obtained on a 0.5 Ω cm 365 μm thick *p*-type wafer with heavy and light phosphorous diffusion on the front and rear surfaces, respectively (see text for details). (b) Corresponding local ideality factor.

allowing a more conclusive demonstration of the equivalence between Suns-V_{OC} and Suns-PL.

To demonstrate the applicability of the Suns-PL technique to unfinished solar cells, we investigated a 365 μm thick 0.5 Ω cm *p*-type silicon wafer with a phosphorous emitter diffusion ($\sim$100 Ω/sq.) on the front surface and a lighter phosphorous floating junction diffusion ($\sim$200–400 Ω/sq.) on the back surface. An insulating thermal oxide was present on all surfaces of the wafer. This diffusion-oxidation structure is typical of the first stage in the fabrication of double-sided buried contact solar cells. In subsequent steps an edge isolation pattern was laser scribed into the rear surface followed by cleaving, the latter resulting in an 8 cm^2 wafer. Finally the front surface of the wafer was intentionally scratched with a diamond pen. Figure 2(a) shows the pseudo *I-V* curves obtained from Suns-PL data taken after each of the above steps. Figure 2(b) shows the corresponding local ideality factor curves. In the case of unfinished solar cells, the conversion of $I_{PL,rel}$ into a voltage cannot be carried out by comparison with a *measured* voltage. Instead a separate PC measurement at high light intensity, carried out under identical illumination conditions as the PL measurement was used to convert $I_{PL,rel}$ signals into absolute excess carrier concentrations Δn, as demonstrated elsewhere.[14] The *implied* voltage was then calculated from Δn according to

$$eU = \Delta\eta = kT \cdot \ln\left(\frac{n_e \cdot n_h}{n_i^2}\right) \approx kT \cdot \ln\left(\frac{\Delta n \cdot (N_D + \Delta n)}{n_i^2}\right), \quad (2)$$

with $n_i = 9.65 \times 10^9$ cm^{-3} the intrinsic carrier concentration at $T=300$ K (Ref. 15) and N_D the doping concentration. The temperature dependence of n_i was modeled according to an approximate equation discussed elsewhere.[16]

The as-processed wafer [curve a in Fig. 2(a)] has an ideality factor >1 throughout the entire *I-V* characteristics. At voltages around 590 mV a hump is observed, that is typical for a strongly asymmetrical Shockley Read Hall lifetime and that has been shown to severely limit a cell's fill factor.[12] Several mechanisms can cause this asymmetric SRH recombination including diffusion-induced misfit dislocations,[12] laser-induced defects,[17] and metallic point defects.[18]

The laser-written edge isolation pattern on the rear surface leads to a shunt that is clearly evident in the corresponding Suns-PL curve ($n>6$, curve b). Because the emitter is wrapped around the edges of the wafer the influence of the shunt is very pronounced. After cleaving, the Suns-PL data (curve c) show a reduced influence of the shunt, which is due to the fact that the electronic path between the more heavily diffused front side emitter and the shunted region at the back via the edge is now interrupted. Instead of the shunted region an extended $n=2$ region is now observed at voltages <400 mV. This $n=2$ region has previously been observed in the *I-V* curve of finished double sided buried contact solar cells and has been assigned to enhanced edge recombination,[13] an interpretation which is conclusively confirmed by our measurements. Both the laser scribing and the cleaving strongly affect the *I-V* curve at low voltages (<500 mV) but have no significant influence at $V>580$ mV. The voltage of the cleaved wafer is only one millivolt smaller than the voltage of the initial wafer. The top curve in Fig. 2(a) (curve d) shows that scratching the front surface leads to a severe shunt like behavior and also to a quite substantial loss of voltage.

For comparison we also measured PC signals on the initial wafer.[19] The Suns-implied-V_{OC} curve [implied V_{OC} according to Eq. (2)] from PC is plotted in Fig. 2 (curve e). While good agreement is observed at large voltages (>600 mV), the curve starts deviating dramatically from the expected *I-V* curve at voltages <570 mV. These deviations result from a large overestimation of the excess carrier concentration at low light intensities due to the presence of excess carriers accumulated in the space charge regions on both sides of the wafer.[20,21] These deviations show that whenever a space charge region is present within a wafer due, e.g., to an emitter diffusion or fixed charge within dielectric passivation layers, PC measurements are unsuitable to determine the *I-V* curve of unfinished solar cells at low voltages.

All curves in Fig. 2 consist of two separate measurements. The practical detection limit of the PL setup, which corresponds to a voltage of ~ 300 mV is reached with a sinusoidal light intensity profile with a total duration of only six seconds, while the voltage range 450 mV$<V<$650 mV can accurately be accessed with a single scan in fractions of a second. The speed of the data taking is thus not a limiting factor, even for industrial applications, with the loading of the sample into the set up currently the most time consuming process.

This letter demonstrates that calibrated photoluminescence measurements provide an accurate contact-less method to measure the open-circuit voltage. Simultaneous PL and V_{OC} measurements on bifacial solar cells can be used for the calibration of relative PL signals into voltages. Alternatively a combination of PL and PC measurements can be used to convert relative PL signals into absolute excess carrier concentrations and subsequently into implied voltages. The calibration of the PL signal into Δn using PC data is ideally carried out at large light intensities at which the above mentioned experimental artifacts in PC measurements[20,21] are expected to be small.

Very good agreement has been observed between Suns-PL and Suns-V_{OC} measurements on finished bifacial solar cells. The ability to monitor the influence of individual processing steps on the *I-V* characteristics with Suns-PL has been demonstrated by measurements on silicon wafers after several processing steps. Suns-PL thus combines the advantages of PC and Suns-V_{OC} measurements, as it has been demonstrated to enable rapid contactless characterization of silicon wafers and is insensitive to experimental artifacts resulting from excess-carriers accumulated in space charge regions.[20,21] The Suns-PL technique will allow greater insight into the influence of *individual* processing steps on device performance thereby allowing a more effective optimization of these processes. This is not possible with conventional methods because the latter are either affected by experimental artifacts or cannot be applied until after at least a basic solar cell structure has been processed.

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