A QUASI-STEADY-STATE OPEN-CIRCUIT VOLTAGE METHOD FOR SOLAR CELL CHARACTERIZATION

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ABSTRACT: We present a method to determine solar cell properties during processing after junction formation. The method involves simultaneous measurement of the open-circuit voltage of solar cells and the corresponding incident light intensity. A monotonically-varying illumination from a flashlamp is used to produce a voltage vs. illumination curve in a fraction of a second. The rate of change of the illumination is chosen to be low enough to permit a simple steady-state analysis of the data. The "quasi-steady state" open-circuit voltage method (qssV_{oc}) has important advantages over the classic I_{sc}-V_{oc} technique for simplifying the data acquisition. This simplification allows a greatly expanded use of open-circuit-voltage data for characterizing the solar cell during fabrication. The methods of analyzing the data are reviewed. It is shown that contact formation, shunts, materials quality, surface passivations, and minority carrier lifetime can be tracked or optimized at most fabrication steps. For fundamental studies, the qssV_{oc} technique can have important advantages over both photoconductance studies and open-circuit voltage decay methods for studying minority-carrier lifetime.
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1. INTRODUCTION

I_{sc}-V_{oc} measurements are a well-known procedure to characterize solar cells. Very early in the history of solar cell analysis, it was seen that this curve contained information about the fundamental diode characteristic free from series resistance effects [1].

An example of the method is shown in Fig. 1. The J_{sc}-V_{oc} curve is taken by measuring J_{sc} and V_{oc} at a number of incident light intensities and plotting the two against each other. This J_{sc}-V_{oc} curve is compared in Figure 1 with the measured illuminated-IV curve of the solar cell. The IV curve is plotted as (J_{sc}-J) vs. V, the "shifted" IV curve. The J_{sc}-V_{oc} curve, taken alone, is the best measure of surface, junction, and bulk recombination limits to the device performance. It also provides unambiguous determination of the shunt resistance. At the maximum power voltage, the difference between these two curves is a very relevant measure of series resistance. The voltage drops that appear when current is drawn from the cell are primarily due to series resistance. These voltage drops also include subtle effects from the 3-dimensionality of the device operation as well as injection-level-dependent minority-carrier profiles and lifetimes. A more recent discussion of these issues is given in [2].

This data acquisition and analysis is seen as the least ambiguous method to identify and separate the recombination, shunting, and series resistance effects that determine the solar cell electrical characteristics. Despite a general acceptance of this method as being the most accurate and relevant to both the science and engineering of solar cells, routine use of this technique is not common. As generally practiced, it requires a finished solar cell with low series resistance, a sophisticated 4-point probe station, measurement equipment capable of taking data over several orders of magnitude of light intensity, and a temperature-controlled stage to maintain cell temperature under high illuminations of light.

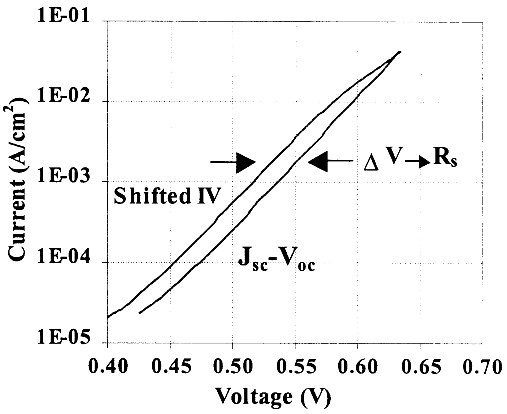

Figure 1. Comparison of J_{sc}-V_{oc} curve with the "shifted" illuminated IV curve.

This paper advocates a much broader application of a J_{sc}-V_{oc} technique as a stand-alone method to investigate materials quality, device design, and process control throughout the solar cell fabrication process. This goal can be realized through a simplification of the data acquisition method.

2. EXPERIMENTAL METHOD

A convenient way of constructing the J_{sc}-V_{oc} curve has recently been described [3]. In this technique, the short-circuit current of the cell is not actually measured at every light intensity. Instead, the incident light intensity is measured with a calibrated reference solar cell. This incident light intensity can be converted to a measure of current by using the short-circuit current or the modelled photogeneration of the test sample. Nearly 40 years ago, this method of using a separate sensor to measure light intensity was suggested for characterizing solar cells with high series resistance[1]. The method was especially useful for early cells predating those with grids.

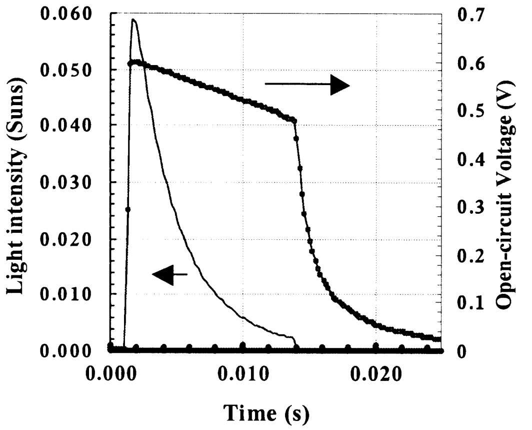

Fig. 2 The illumination vs. time from a flash lamp (left axis) and the open-circuit voltage of a solar cell (right).

Figure 2 shows an example of data from a V_{oc} vs. incident light intensity measurement (Suns-V_{oc}) taken with a flashlamp and a digital oscilloscope. Note that the light is slowly varying, with a time constant of 4 ms, such that the solar cell voltage is in quasi-steady-state with the light intensity. This can be verified by the rapid drop-off in voltage at the end of the light pulse that indicates that the cell responds to changes in light intensity without significant delay. The short light pulse does not heat the sample significantly, even at relatively-high light intensity.

2. STANDARD LOG-LINEAR DIODE ANALYSIS AND THE DETECTION OF CONTACT PROBLEMS

A plot of the Suns-V_{oc} data taken as in Figure 1 is shown in the form of a standard diode analysis in Fig. 3. An interpretation of these characteristics leads to the determination of saturation current densities and ideality factors. The data in Fig 1, as shown on a log-linear plot in Figure 2, can be fit with $J_{o1}=1.18\text{x}10^{-13}$ A/cm^{-2} (n=1 component), $J_{o2}=5.5\text{x}10^{-9}$ A/cm^{-2} (n=2 component), and a shunt resistance, $R_{shunt}=2.7\text{x}10^{4}$ Ω. In this case, the measured short-circuit current was used to convert the illumination scale from suns to current density.

One interesting aspect of open-circuited measurements taken as a function of the light intensity instead of the short-circuit current is that only a crude contact is required to the doped regions of the solar cell. In many cases, simply probing the doped region with a sharp probe is a sufficient contact. The primary requirement is that the contact resistance of the probe to the silicon should be less than the input impedance of the measurement instrument (typically, a 10^6-Ohm oscilloscope). Although the data in Fig. 3 was taken on a finished solar cell, data of this quality can often be acquired directly after junction formation without metalized contacts. This expedient is especially useful for research or on exploratory devices where valuable device and materials information can be obtained even before a contact technology is developed or implemented. Some care must be taken to insure that the probed contacts are ohmic. The convenience of probing devices without metalization motivates this potential compromise.

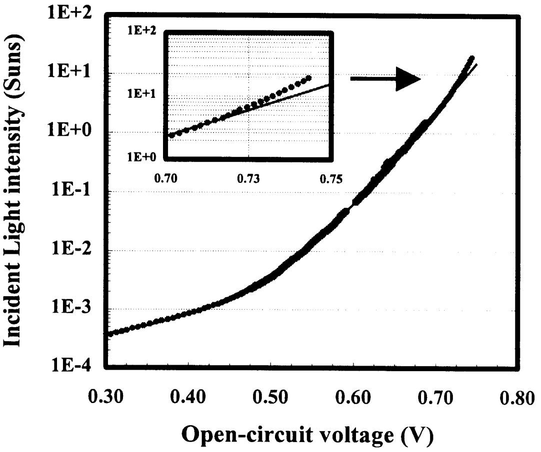

Fig. 3. The illumination-V_{oc} ("Suns-V_{oc}") curve from QSSV_{oc} data taken as shown in Fig. 2 (with curve fit).

Although not intuitive, data taken under open-circuited conditions can be valuable for monitoring the contact properties of the solar cell. Metal contacts are frequently modeled as a Schottky barrier formed by the metal on silicon in parallel with some form of leakage. The leakage might be from the metal doping the silicon or from thermally-assisted tunneling through the potential barrier. Under one-sun conditions for a well-formed contact, the Schottky barrier is effectively shorted by the leakage. However, at some high-level light intensity on a poorly-formed contact, the Schottky diode will build up a voltage opposing the solar cell junction voltage by generating a current that the leakage is unable to fully shunt.

An indication of this contact effect is seen in Fig. 3. At the highest light intensities, the slope of the curve has an ideality factor less than unity. This frequently indicates a contact problem and in this case is due to Schottky barrier effects at the contact between the p-type silicon and the rear aluminum contact.

A more obvious example of this contact effect is shown for an industrial solar cell in Figure 4. Above incident light intensities of 10 suns, the voltage actually drops with increasing light intensity. By monitoring the open-circuit voltage at light intensities significantly higher than the operating conditions, this effect can be used to anticipate problems in the contact formation. Departures from ideal behavior can often be seen before they result in a yield loss due to low efficiency. This method may prove to be a good diagnostic or process-control technique.

3. PHOTOVOLTAIC IV CURVES

An alternative presentation of Suns-V_{oc} data is shown in Figure 5. By again using the superposition principle, an implied photovoltaic I-V curve can be constructed from the Suns-V_{oc} data taken as in Figure 2. At each open-circuit voltage, the implied terminal current is given by:

$$J_{terminal} = J_{sc}(1\text{-suns}) \qquad (1)$$

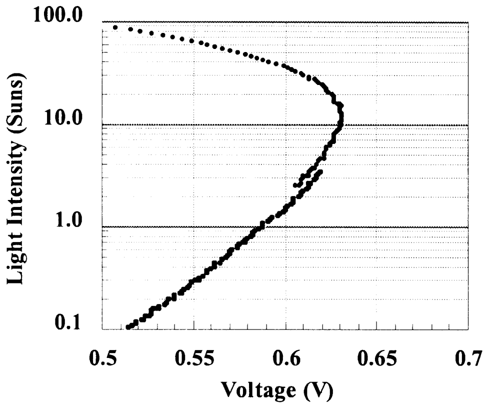

Figure 4. The illumination-V_{oc} curve. A poor contact produces an opposing voltage at high light intensities.

This yields the characteristic photovoltaic I-V curve format with the customary interpretation of fill factor, efficiency (without series resistance), and shunt. In Figure 5, the results that really matter to the solar cell efficiency are visually obvious due to our familiarity in interpreting these curves. It is immediately seen if the shunt is having a major effect on the maximum power point. The upper bound on efficiency, given by the curve constructed from Suns-V_{oc} data, is clearly displayed.

It is our experience that a presentation of Suns-V_{oc} data in the form of a photovoltaic IV curve, with a "pseudo-efficiency", FF, and V_{oc} is much more quickly adopted and used for both research and process control than the same data presented as in Figure 1 or 3.

As discussed in the last section, this "Pseudo"-IV curve can be measured very early in the process, by probing the silicon after junction formation. This allows the presentation of very fundamental properties of the material, junction, and surface passivation before the "back end" processing has complicated the interpretation. This permits the qualification of rather basic materials and device experiments using the "pseudo-efficiency" constructed from Suns-V_{oc} data as a primary measurement criteria. The "back end" metalization processes can then be monitored for voltage loss and shunts during metalization application and sintering steps.

In addition, by eventually comparing the Suns-V_{oc} curve in Fig. 5 with the actual measured I-V curve of the finished solar cell, the series resistance determination is precise. It is simply the difference between the two curves at the knee. Since the implied I-V curve from the open-circuit voltage has the shunt and ideality factors fully characterized, the differences between the two curves is quite clearly isolated to be due to series resistance. This analysis is actually identical to the method shown in Figure 1.

As an example, the same data in Figure 2 for a high-efficiency cell is shown in Figure 5. The Suns-V_{oc} data is shown in comparison to a conventional IV curve on the finished solar cell. The curves closely follow each other. The measurement of the IV curve gives an efficiency of 20.8% with a fill factor of 0.816. The curve constructed from the Suns-V_{oc} data indicates a pseudo-efficiency of 21.3%, with a fill factor of 0.835. A comparison clearly indicates that total elimination of series resistance and transport effects would only improve this cell from 20.8 to 21.3%. At 21.3%, the limitation to voltage and fill factor is now known to be due to the recombination within the solar cell.

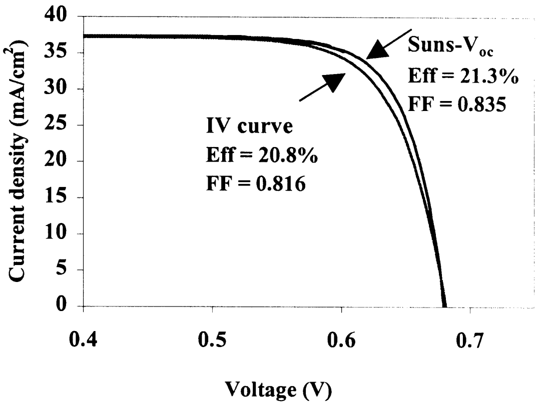

Figure 5. The same Suns-V_{oc} data as in Figure 3, plotted as a photovoltaic IV curve and compared to the IV curve taken on the finished cell.

4. LIFETIME DETERMINATION FROM V_{OC} DATA

It can also be important to relate the electrical characteristics of the device to the physical properties of the semiconductor material. The voltage in a solar cell can be used to calculate the minority carrier density.

$$\Delta n(0)[N_A + \Delta n(0)] = n_i^2 \exp\left(\frac{V_{oc}}{kT/q}\right) \quad (2)$$

By equating the generation rates in the solar cell with the excess carrier density as determined in (2), it can be shown that the effective lifetime can be directly written as a function of the measured voltage:

$$\tau_{eff} = \frac{n_i^2 \exp\left(\frac{V_{oc}}{kT/q}\right)}{J_{ph}[N_A + \Delta n]/qW} \quad (3)$$

Equation 3 assumes a uniform carrier density across the wafer. Other special cases can be derived as desired. As an example, in ref [5], a study of the Auger recombination in concentrator solar cells was done using Suns-V_{oc} data and eqs. 2 and 3 with a small correction to account for 3-D effects.

Lifetime determination using the qssV_{oc} method parallels and complements a quasi-steady-state photoconductance technique, (qssPC), that has recently achieved widespread use [6]. The two methods differ in the way in which the excess carrier density within the semiconductor is sensed. In qssV_{oc} minority carriers are determined by the voltage at a pn-junction while in qssPC the cumulative photoconductance is used. The V_{oc} technique requires a pn-junction and at least crude 2-point probed electrical contact. Photoconductance measurements can be performed on wafers in a contactless way. The qssV_{oc} method permits exploration of very low excess-carrier-density levels. It allows detailed monitoring of the last steps of a solar cell fabrication process, the formation of the metal contacts, where metalization can limit photoconductance detection.

Note that careful control of the temperature, knowledge of the intrinsic carrier density n_i and the dopant density is necessary to obtain the lifetime from a measurement of the voltage. In contrast, the photoconductance method needs carrier mobilities and is relatively insensitive to temperature.

Figure 6 shows lifetime results determined from Suns-V_{oc} data from a 1.5 Ohm-cm mc-Si silicon wafer with a front phosphorus diffusion and rear local boron diffusions on an oxidized surface. This data is compared to data taken on the same sample using the QSSPC technique [6]. There is good agreement in the minority-carrier density injection range from 2E13 to 3E16. At low carrier densities, photoconductance data shows an artificially high lifetime, due to trapping [7]. Although this behavior can be modeled in order to extend the useful QSSPC data down to lower carrier densities, the results will have uncertainties when there is trapping present. In contrast, the trapping has negligible effect on the measured device voltage. In practice, Suns-V_{oc} data can be used to measure lifetimes at minority carrier densities less than 1E9 cm^{-3}. The minority-carrier density at the operating point for solar cells is generally in the range of $1x10^{14}$ to $1x10^{16}$ cm^{-3}. Either method would work well for this sample for this range. For some multicrystalline samples, the trapping can obscure photoconductance data in the important carrier-density range, and voltage data would give less uncertainty in the lifetime measurement.

Because of the interchangeability of photoconductance and Suns-V_{oc} data offered by equations 2 and 3, the methods for diagnosing recombination mechanisms that have been developed for the QSSPC technique [8] are directly applicable to Suns-V_{oc} data. These include the comparison of results from front and back illumination, as well as blue vs. infra-red light to identify the limiting recombination mechanism in the device.

The qssV_{oc} method has important advantages over the traditional open-circuit voltage decay (OCVD) method for lifetime measurements. OCVD is based on measuring the decay of the open-circuit voltage of pn junction diodes after a delta-function current or illumination pulse. In particular, the qssV_{oc} method is not affected by the junction capacitance of the device. This capacitance can completely mask the lifetime measurement at low carrier density levels in the OCVD method [4]. Attaining this major advantage does not compromise the simplicity of the measurement. With qssV_{oc}, a ramp rate for the flash-intensity variation can be chosen to be much slower than the RC time constant of the scope impedance and junction capacitance. Data acquisition can still be accomplished in a fraction of a second, without significant sample heating.

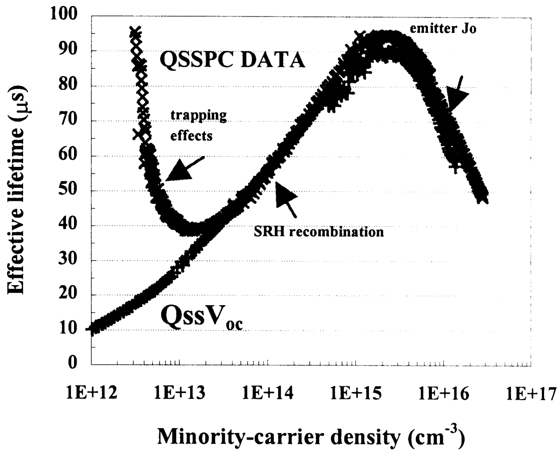

Fig. 6. A lifetime analysis comparison from QSSPC and QSSV_{oc} data (1.5 Ohm-cm multicrystalline wafer).

5. CONCLUSION

A classic technique, the use of J_{sc}-V_{oc} curves to analyze solar cell parameters, can be applied much more generally than is commonly practiced. By measuring illumination vs. V_{oc} rather than J_{sc} vs. V_{oc}, the technique can be extended to most samples as soon as junctions exist. No metalization is required. This allows studies of basic materials and device properties at early stages in the device process sequence. The materials and device properties can be followed through each step with the differences immediately apparent. Presentation of this data in the form of a characteristic photovoltaic IV curve gives a universally recognized metric that can be applied to data from both unfinished and finished devices. The use of Suns-V_{oc} data to determine lifetime can present important advantages over both photoconductance and OCVD measurements.

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REFERENCES:

[1] M. Wolf and H. Rauschenbach, Advanced Energy Conversion, V 3. pp 455-479 Apr.1963

[2] A.G. Aberle, S. R. Wenham, and M. A. Green, Proc. IEEE Photovoltaics Specialist Conference, pp. 133-139, May 1993.

[3] R. A. Sinton, 9th Workshop on Crystalline Silicon Solar Cells and Materials, NREL/BK-520-26941, August 1999.

[4] M. A. Green, Solid State Electronics, Vol 26, no. 11 pp 117, 1983.

[5] R. A. Sinton and R. M. Swanson, Trans. Elec. Dev. V. 31 No. 6, pp1380-1389, 1987.

[6] R. Sinton and A. Cuevas, Appl. Phys. Lett., V. 69, no. 17, pp. 2510-2512, 1996.

[7] D. MacDonald and A. Cuevas, Progress in Photovoltaics, June 2000.

[8] A. Cuevas and R. A. Sinton, Progress in Photovoltaics, Vol. 5, pp. 79-90, 1997.