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Analysis of Solar Cell Quality Using Voltage Metrics

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Abstract — The highest efficiency solar cells provide both excellent voltage and current. Of these, the open-circuit voltage (V_{oc}) is more frequently viewed as an indicator of the material quality. However, since the V_{oc} also depends on the band gap of the material, the difference between the band gap and the V_{oc} is a better metric for comparing material quality of unlike materials. To take this one step further, since V_{oc} also depends on the shape of the absorption edge, we propose to use the ultimate metric: the difference between the measured V_{oc} and the V_{oc} calculated from the external quantum efficiency using a detailed balance approach. This metric is less sensitive to changes in cell design and definition of band gap. The paper defines how to implement this metric and demonstrates how it can be useful in tracking improvements in V_{oc} , especially as V_{oc} approaches its theoretical maximum.

Index terms — detailed balance, performance, photovoltaic cells, recombination, voltage metric

I. INTRODUCTION

The detailed balance approach of calculating solar-cell efficiency quantifies the optimal band gap for a chosen solar spectrum [1]. Achievement of the highest efficiencies requires not only an optimal band gap, but also high material quality. If material quality is poor, photocarriers quickly recombine nonradiatively through electronic states associated with defects in the crystals or at their surfaces. The photovoltage can be an excellent indicator of the quality of the active layers of the solar cell because it directly reflects nonradiative recombination (including unavoidable Auger recombination [2]) in the cell and is frequently used when comparing cells with similar band gaps.

Since the photovoltage depends on the band gap, many researchers have used the difference between the band gap and the V_{oc} as a more consistent indicator of material quality, allowing all types of solar cells to be compared by a simple metric. King [3] has referred to this metric as W_{oc} , and most reports are that a good solar cell can achieve a W_{oc} of about 0.4 V under one-sun illumination, although King calculates the limit for W_{oc} as ~ 0.24 - 0.29 V, depending on band gap. Recently, Alta Devices has reported very high V_{oc} 's for GaAs cells, achieving a W_{oc} that is close to 0.3 V [4].

In this paper, we suggest that the difference between the measured V_{oc} and the detailed-balance theoretical limit for V_{oc} (we call this W_{db}) is a better metric than W_{oc} in a number of ways. First we review the detailed-balance calculation and how it can be done accurately using the actual absorptivity approximated by the external quantum efficiency. Then, we show that when absorptivity varies (e.g. due to changing

thickness of the active layers), the theoretical limit for the V_{oc} also varies, even when the band gap is fixed and there is no evidence of nonradiative recombination. We show how the detailed-balance metric is less dependent on measurement and analysis details than W_{oc} , thus providing a more robust metric for material quality. Finally, we demonstrate the value of using the metric for interpreting experimental data.

II. DETAILED-BALANCE AND OTHER MODELS

The detailed-balance approach to calculating theoretical efficiency limits was first introduced by Shockley and Queisser [1], providing an elegant way to account for photon recycling. It makes use of Planck's law of radiation and Kirchhoff's law of thermal radiation to calculate the radiative emission from the surface based on the absorptivity. In contrast, the radiative emission in the *bulk* is often quantified by the *bulk* radiative lifetime and is commonly used when modeling solar cells using the continuity equations. Although the continuity equations use relationships that are considered foundations of solid-state physics (Poisson's equation, etc.), it is cumbersome to include reabsorption of the emitted photons. The elegance of the detailed balance approach is its ability to include reabsorption and reemission (sometimes called photon recycling) of photons implicitly.

III. METHOD

The detailed-balance method predicts cell J-V characteristics by balancing the radiation absorbed and emitted at the surface, usually assuming that radiative recombination is the only source of loss in the cell [1,2]. Using Kirchoff's law of thermal radiation, one can derive the expressions,

$$J(V) = J_0 e^{\frac{qV}{kT}} - J_{sc} \quad (1)$$

$$J_{sc} = \int_0^\infty q b_s(E) a(E) dE \quad (2)$$

$$J_0 = \int_0^\infty q b_e(E) a(E) dE \quad (3)$$

where q is the electron charge, a is the cell absorptivity, b_s is the solar flux (here, we use AM1.5G to include both direct and diffuse radiation), and b_e is the black body emitted flux from the cell under zero bias (assuming a perfect back reflector):

$$b_e(E) = \frac{2\pi}{h^3 c^2} \frac{E^2}{e^{E/kT}} \quad (4)$$

Typically, these equations are simplified by assuming $a(E)$ is a unit step from the band gap, but with numerical integration, it is possible to include realistic expressions for material absorptivity. Because b_e is largest for small E , J_0 depends very strongly on the shape of the absorptivity $a(E)$ at the band edge. Here, we use three approaches approximating $a(E)$:

(1) unit step absorption;

(2) an idealized model for GaAs absorptivity using the Beer-Lambert law with direct band gap transitions, with L thickness of the cell in microns, roughly scaled to GaAs experimental absorption data [5]:

$$a(E) = 1 - e^{-4L(E-E_g)^{1/2}} \quad (5)$$

An series of absorptivity curves are shown in Figure 1, calculated using this method.;

(3) using the external quantum efficiency (EQE) curves for actual cells, as discussed in more detail in ref. [6].

The method (3) assumption is valid unless there are states, especially near the band edge, that contribute to absorption and emission, but do not result in collected carriers. These near-band-edge states would be visible in electroluminescence data, since $b_e(E)$ is largest at low energies. We have verified that this assumption is correct in three of our GaAs cells studied here, whose EL data are shown in Fig. 2. Short-wavelength losses will also cause the EQE to deviate from absorptivity, but these losses have a very small impact on V_{oc} (< 5 mV difference), as discussed in ref. [6].

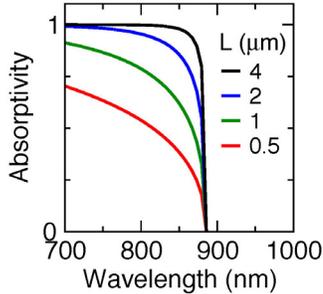


Fig. 1. Absorptivity calculated using the Beer-Lambert relationship. A simple direct gap model for the absorption coefficient is employed, scaled to experimental GaAs values.

Using approaches (1) and (2), we can predict the dependence of V_{oc} figures of merit on band gap and absorber thickness, and using approach (3), we can apply these figures of merit to actual cells to determine their validity. The figure of merit W_{db} is calculated by taking the difference between the ideal V_{oc} and experimental V_{oc} , with the ideal V_{oc} calculated using the cell EQE and the detailed balance approach.

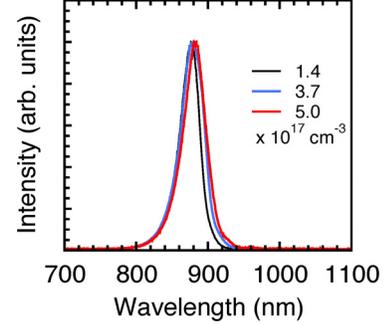


Fig. 2. EL data for three GaAs cells studied here, with different carrier concentrations, as noted. These data show the strong band edge emission and absence of optically active near-band-edge states.

IV. RESULTS: COMPARISON OF METRICS

To compare the three voltage metrics (V_{oc} , W_{oc} , W_{db}), we vary the absorptivity by varying the band gap and the thickness.

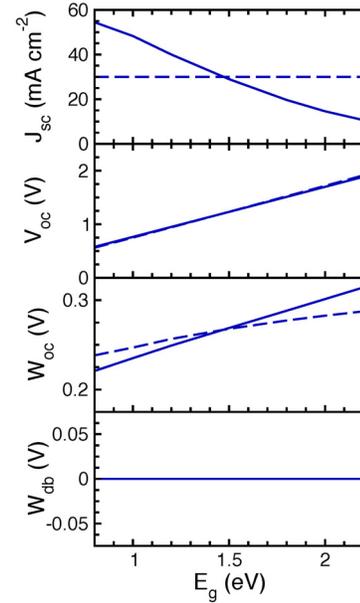


Fig. 3. J_{sc} , V_{oc} , W_{oc} and W_{db} as a function of band gap using detailed-balance calculations of an ideal material with step edge absorptivity. Solid lines: raw data, dashed lines: adjusted by changing the light intensity to keep J_{sc} constant with respect to changes in band gap.

A. Vary Band Gap

Using a step-edge absorption model (1), the photocurrent, photovoltage, W_{oc} , and W_{db} are shown in Fig. 3 as a function of band gap. The systematic increase of photovoltage, and decrease of photocurrent with increasing band gap are similar to what has been reported elsewhere. The metric, W_{oc} , is plotted two ways: one assumes the photocurrent that is shown in Fig. 3, solid line, resulting in a penalty on the V_{oc} as the

band gap increases and the photocurrent decreases. When comparing V_{oc} or W_{oc} values for multiple samples, most researchers will consider applying a correction to scale all measurements to a common photocurrent value. The “ W_{oc} corrected” value in Fig. 3 uses 30 mA/cm^2 for all band gaps. W_{db} in Fig. 3 has a null value as the calculation is considering idealized materials.

An ideal voltage metric would not change as cell band gap is changed, so that different materials may be compared on the same scale. W_{oc} , especially when corrected for photocurrent, varies much less than V_{oc} (note the different scales), and is thus a much better metric than V_{oc} alone in describing cell quality [3]. W_{db} , however, does not vary at all with band gap, providing a better metric for comparing cells with different band gaps or absorption edge shapes.

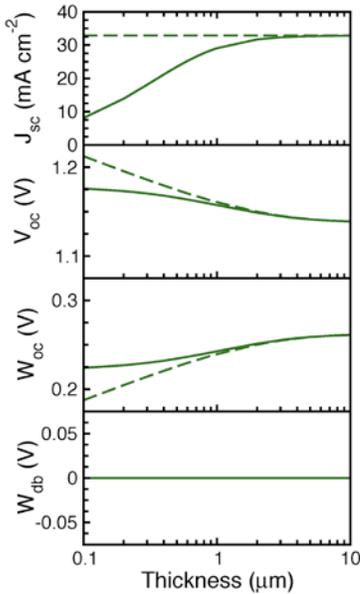


Fig. 4. J_{sc} , V_{oc} , W_{oc} , and W_{db} as a function of GaAs thickness as calculated for ideal samples using detailed balance with method (2) for absorptivity. Solid lines: raw data, dashed lines: corrected by changing the light intensity to keep J_{sc} constant with respect to changes in band gap.

B. Varying Thickness

As solar-cell structures are optimized, layer thicknesses are often varied. When coupled with light trapping, thinning of silicon cells is well known to increase efficiency. Here, using the crude absorption model (2) described above with a band gap of 1.4 eV , the absorptivity was calculated for a range of layer thicknesses and the resulting photocurrent and photovoltage were calculated assuming ideal solar cell behavior under the detailed-balance model. These are plotted in Fig. 4 along with W_{oc} and W_{oc} corrected to the current found for an infinitely thick sample.

Because the calculation in Fig. 4 assumes that *all* samples are ideal, we would expect that a good metric would show no

change as the thickness is varied. Instead, we see that the photovoltage increases as the sample is thinned. This is because the thinner cell effectively appears to have a higher band gap (less absorption at the band edge, as shown in Figure 1), increasing V_{oc} . The values for W_{oc} plotted in Fig. 4 were calculated with the band gap = 1.4 eV , as assumed in the absorption model. Both V_{oc} and W_{oc} change by about 10 mV per factor of two change in the thickness when the photocurrent is not saturated at the high-current end. One notes that the change in W_{oc} for thin cells will partly be a result of the changing photocurrent. When this is adjusted, we can see that the W_{oc} metric is even more sensitive to thickness variations. In Fig. 4, the W_{db} metric does not change at all with thickness because of the assumptions made in the calculations, and thus is a better voltage metric for cells of varying thickness.

V. APPLICATION TO EXPERIMENTAL DATA

A. Thickness Dependence Example

Two GaAs cells were grown with base thicknesses of $1 \mu\text{m}$ and $3 \mu\text{m}$ using conventional epitaxial growth and processing techniques, but without antireflection coating. The performance of the two cells is summarized in Fig. 5 and Table 1. The material quality is believed to be equivalent between the two cells.

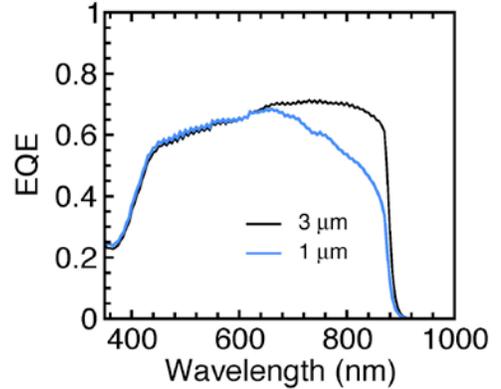


Fig. 5. EQE results on 1- and 3- μm thick GaAs cells.

Since the GaAs cells studied here are essentially identical besides their thickness, their different voltages are expected to be entirely an effect of changing thickness. Thus, an appropriate voltage metric would be unchanged for these two cells. Indeed, W_{db} is exactly the same (99 mV) for the two cells, as shown in Table 1. W_{oc} , on the other hand, varies by up to 13 mV between the two, as shown in Table 2, and varies by different amounts depending on how the band gap is calculated: by fitting the EQE edge to Eq. (2); by choosing the energy where the EQE drops to 50% of its maximum value; or by performing a linear fit to the EQE edge and defining the band gap as the intercept of that line. These data show that neither V_{oc} alone nor W_{oc} is a good metric for assessing cell

quality when thickness is varying, though, in this case, using the 50% of the maximum EQE as the band gap works reasonably well.

Thickness (μm)	Meas. J_{sc} (mA/cm^2)	Meas. V_{oc} (V)	Cal. V_{oc} (V)	W_{db} (mV)
1	18.0	1.055	1.154	99
3	20.0	1.042	1.141	99

Table 1. Experimental and calculated data for GaAs cells using detailed balance and EQE.

E_g Method	E_g (V)		W_{oc} (mV)		ΔW_{oc} (mV)
	1 μm	3 μm	1 μm	3 μm	
Fit to Eq. (2):	1.408	1.408	353	366	-13
50% of max EQE value:	1.428	1.412	373	370	3
Linear fit to EQE edge	1.396	1.394	341	352	-11

Table 2. W_{oc} metric for GaAs cells using three different methods of defining band gap. Since the two cells are identical besides thickness, ΔW_{oc} should be zero.

B. Antireflective Coating Example

Application of an antireflective coating should not change the intrinsic material quality, and thus an appropriate voltage metric should likewise be unaffected. Three GaAs cells were grown with different doping levels, characterized, and then AR-coated. A pair of representative uncoated and coated EQE and EL curves are shown in Figure 6a,b. The band edge for the uncoated material exhibits interference fringes due to the lack of AR coating: the back surface of the cell is highly reflective, and the fringes arise from interference between the incident light and light reflected from the back. Such behavior would make conventional routes to assess the band gap challenging. The correlated peak positions between the EQE and EL indicate that the primary emission is at the band edge.

Figure 6c shows W_{db} calculated for the three cells before and after the AR coating. The W_{db} changes by less than 7 mV upon AR coating. The utility of the W_{db} metric in determining device quality is supported by the near-irrelevance of the AR coating to the magnitude of W_{db} . The absolute magnitude of W_{db} for these cells (~ 150 mV) is entirely due to losses within the cell.

VI. CONCLUSION

As solar cells approach their theoretical limits, it is increasingly important to have good metrics to compare cells of different types and understand subtle differences in voltage.

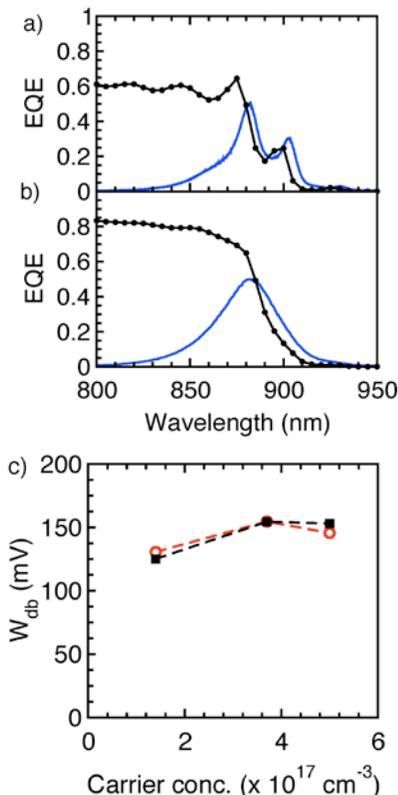


Fig. 6. a) EQE and EL of GaAs cell (a) before and (b) after AR coating. (c) W_{db} for cells before (red) and after (black) AR coating reveals minimal change in W_{db} .

The voltage metric W_{oc} has been a good rule of thumb for many years, but becomes less certain when used for cells of widely varying band gap or even small changes in cell thickness, and depends on how band gap is defined. We have proposed a new metric, W_{db} , which directly compares V_{oc} to the V_{oc} calculated using the cell EQE in the detailed-balance method. This metric does not change with thickness or band gap, is simple to calculate, does not require a definition of the band gap, and provides an absolute, metric for material quality.

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REFERENCES

- [1] W. Shockley, H.J. Queisser, *J. Appl. Phys.* 32, 510 (1961).
- [2] T. Tiedje, E. Yablonovitch, G.D. Cody, B.G. Brooks, *IEEE Trans. Electron Dev.* ED-31, 711 (1984).
- [3] R.R. King et al., *Prog. Photovolt: Res. Appl.* 19, 797 (2011).
- [4] B.M. Kayes et al., *Proc. 37th IEEE PVSC* p. 000004, (2011).
- [5] M.D. Sturge, *Phys. Rev.* 127, 3 (1962) 768.
- [6] E.S. Toberer, A.C. Tamboli, S.R. Kurtz, in prep.