Illumination Dependence of Reverse Leakage Current in Silicon Solar Cells

Carlos Enrico Clement, Jai Prakash Singh, Erik Birgersson, Yan Wang, and Yong Sheng Khoo

***Abstract*—In the modeling of PV modules under shading and low illumination, a complete description of reverse bias behavior at the cell level is critical to understanding module response. This is particularly important when dealing with high voltage configurations such as tandem and shingled modules. Current simulation studies often do not account for the effects of incident light when dealing with operating voltages approaching cell breakdown. In this article, we investigate the illumination dependence of leakage current at the onset of breakdown in crystalline silicon solar cells. A study of the most popular cell technologies in the market today reveals a light induced effect under reverse bias that is prominent for p-type and small for n-type cells. Additionally, this effect is found to be larger in mono c-Si than multi c-Si cells. Because this phenomenon is not captured in current breakdown models such as Bishop's equation, we propose a split-cell model to describe partial shading in p-type cells. The outlined approach divides the cell into two parallel regions and is advantageous for its procedural simplicity as well as its ability to generalize effects from complex shading profiles.**

***Index Terms*—Breakdown, illumination, leakage current, light induced.**

I. Introduction

THE BEHAVIOR of a solar cell at negative operating voltages or simply in reverse bias has been studied as a means to characterize cell properties and identify defects, impurities, and shunting. Techniques such as reverse bias electroluminescence and dark lock-in thermography rely on imaging of the cell at negative voltages to create spatially resolved current density maps that are useful in identifying breakdown sites and localized shunts [1], [2]. Breitenstein *et al.* [3] investigated how different dark current-voltage (*I-V*) profiles in multi c-Si cells can point to breakdown mechanisms associated with Al surface contamination, metal precipitates lying within grain boundaries or avalanche breakdown at etch pits. Such efforts to study the operation of solar cells in reverse bias are critical to our understanding of PV module behavior under shaded conditions. When a panel is subjected to uneven illumination, the resulting current mismatch between cells may force one or more cells to operate in reverse bias and thereby act as a power sink [4]. This eventually leads to module power loss and hotspot heating, with more severe cases leading to long term cell degradation and module damage. The degree to which these effects develop is largely dependent on the operating point of the shaded cell, thus a description of reverse breakdown is necessary when modeling a module's shading response and has been the subject of several research papers [5]–[7].

The model for avalanche breakdown that is most widely used is Bishop's equation [8], which is a modification of the single diode model and can be written in (1) as

$$J = J_{\mathrm{ph}} - J_0 \left[\exp\left(\frac{q\,(V + JR_s)}{nkT}\right) - 1\right] - J_{\mathrm{leakage}} \quad (1)$$

$$J_{\mathrm{leakage}} = \frac{V + JR_s}{R_{\mathrm{sh}}} \left[1 + \alpha\left(1 - \frac{V + JR_s}{V_{\mathrm{br}}}\right)^{-m}\right] \quad (2)$$

where J is the current density, V is the terminal voltage, J_{ph} is the photogenerated current, J_0 is the reverse saturation current, R_s is series resistance, n is the ideality factor, k is Boltzmann's constant, T is temperature, and q is the elementary charge of a proton. The model introduces a leakage current through the shunt resistance, R_{sh} in (2), which accounts for the cell behavior at negative voltages and is defined by three parameters: the breakdown voltage V_{br}, avalanche breakdown exponent, m, and the fraction of ohmic current involved in the leakage, α. Note that J_{leakage} is distinct from reverse saturation current through the diode term and can be several orders larger as the cell nears breakdown. Furthermore, J_{leakage} is expressed solely as a function of V where it is negligible during forward operation but significant as the voltage approaches V_{br} in reverse bias.

The conventional method of measuring a cell's reverse behavior involves performing an *I-V* sweep of the cell in the dark to extract the J_{leakage} curve. Based on an understanding of Bishop's and similar equations that describe reverse bias breakdown, the complete *J-V* curve of a cell under illumination may then

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be expressed as the superposition of the dark J_{leakage} curve with the J_{ph} and diode terms. However, this assumes that the leakage current remains independent of illumination. While this assumption has been found sufficient in many cases [9]–[11], there are nonetheless a few studies that investigate the effect of irradiance on cell parameters [12]–[15]. Since the changes in parameters are derived from forward *I-V* curves, Reich *et al*. [15] notes that apparent shifts in R_s and R_{sh} with illumination are not necessarily indicative of a physical change in resistance. Furthermore, these studies only observe the effects of illumination for a narrow window of voltages at forward and slight reverse (−0.5V) biases.

In real conditions, current mismatch from shading can cause a cell to reach around −15 V in conventional modules. Newer configurations such as tandem cells with larger voltages and shingled modules with greater string lengths are at even higher risk of being pushed into large reverse bias [16]. Thus, it becomes critical to study the effects of illumination on cells under high reverse bias conditions. In this article, we examine the illumination dependence of leakage current for crystalline silicon solar cells. To our current knowledge, Fertig *et al*. [17] were first to note illumination effects on breakdown mechanisms in multi c-Si Al-BSF cells; in this article we perform a broader and more comprehensive investigation on the various cell technologies that are dominating the market today.

The rest of this article is organized as follows. In Section II, we discuss experimental methodology and data processing methods for quantifying and comparing illumination effects. Section III tackles variations in illumination dependence across cell technologies, and investigates the underlying physics behind this phenomenon. Furthermore, we study low illumination caused by uniform and nonuniform cases and propose a split-cell approach to modeling light-induced reverse behavior. Finally, Section IV concludes this article.

II. Methodology

A. Experimental Methods

We investigated the illumination dependence of leakage current in various cell technologies chosen for their ubiquity in today's market as well as their projected future growth. Production in the last five years has been dominated by two main cell architectures: aluminum back surface field (Al-BSF) cells and passivated emitter and rear cell (PERC), with the latter gaining market share and the former diminishing [18]. Other cell technologies such as n-type passivated emitter rear totally diffused (PERT), interdigitated back contact (IBC), and passivating contact cells such as monoPoly$^{\mathrm{TM}}$ [19] are also expected to increase in production share over the coming years. Samples from each of the five abovementioned architectures are collected and tested, spanning 18 sources (16 commercial, two research institutes) across different sizes (full, half, and shingled). For each unique cell variant, we measure three samples from the same batch, with the total sample count shown in Table I.

Each cell is fabricated into a 20 × 20 cm mini-module, using a glass-EVA-transparent backsheet configuration to minimize cell-to-module optical gains. Mini-module *I-V* curves are obtained at various illumination levels from 200 to 1000 W/cm^2 using an h.a.l.m. cetisPV flasher with an A+A+A+ sun simulator rating where temperature is maintained at $T = 25.0 \pm 0.1$ °C. Measurements at 0 sun illumination were taken by blocking the light source, however a small photocurrent (∼0.4% of I_{sc} at 1 sun) was still detected that may be due to stray reflections. Sample labeling was decoupled from the source manufacturer prior to measurement to remove any bias.

B. Data Processing

To quantify the effect of illumination on leakage current, we compare the J_{leakage} curves of a cell at 0 and 1 sun irradiance. Because $J_{\mathrm{ph}} \approx J_{\mathrm{sc}}$ and the diode current [second term in (1)] is negligible at negative voltages, we can obtain the leakage current by shifting the *J-V* curve downwards by J_{sc} [17]. We then define a critical voltage, V_{crit} as the voltage where the illuminated $J_{\mathrm{leakage,1\ sun}}$ is equal to the cell's current at maximum power, J_{mp} as shown in Fig. 1(a). We now propose a metric for quantifying illumination effects as the mean change in leakage current from dark to light, $\overline{\Delta J}_{\mathrm{leakage}}$, which is expressed mathematically in (3) as

$$\overline{\Delta J}_{\mathrm{leakage}} = -\frac{1}{V_{\mathrm{crit}}} \int_{V_{\mathrm{crit}}}^{0} J_{\mathrm{leakage}} - J_{\mathrm{leakage,\ 0\ sun}}\, \mathrm{d}V. \quad (3)$$

Using this term allows us to capture the cumulative shift in J_{leakage} up until J_{mp}, which is the upper limit of a cell's operation when undergoing shading. Numerically, we solve for this by extrapolating the two leakage curves at 200 points spaced equally along the voltage from $V = V_{\mathrm{crit}}$ to 0 V. We then take the mean difference between the 1 and 0 sun currents along these points.

The obtained $\overline{\Delta J}_{\mathrm{leakage}}$ values are then grouped according to cell technology so that we may compare by performing an analysis of variance. Both Shapiro-Wilk and Lilliefors tests show that normality is rejected for some of the populations. Under this criteria, a nonparametric Kruskal-Wallis ANOVA for independent samples is used to compare the medians, where it was found that the populations are significantly different ($\chi^2(6) = 94.8$, $p = 3.1 \times 10^{-18}$). All statistical analysis is performed using the software OriginPro [20].

III. Results and Discussion

A. Illumination Dependence of J_{leakage} in Popular Cell Architectures

We compare the leakage current curves of cell technologies as they are subjected to differential illumination. Fig. 1 gives a rough picture of how different architectures behave when exposed to light, where the curves shown are representative of their groups' trends. For PERT, IBC, and monoPoly$^{\mathrm{TM}}$ cells, the J_{leakage} curves are visually similar with or without illumination [Fig 1. (f)–(h)]. This is in agreement with previous models that rely on superposition of dark $J_{\mathrm{leakage,0\ sun}}$ curves. However, in PERC and Al-BSF cells, there is an obvious illumination effect on leakage current, with a visible divergence between the curves seen at as early as −5 V [Fig 1. (b)—(e)].

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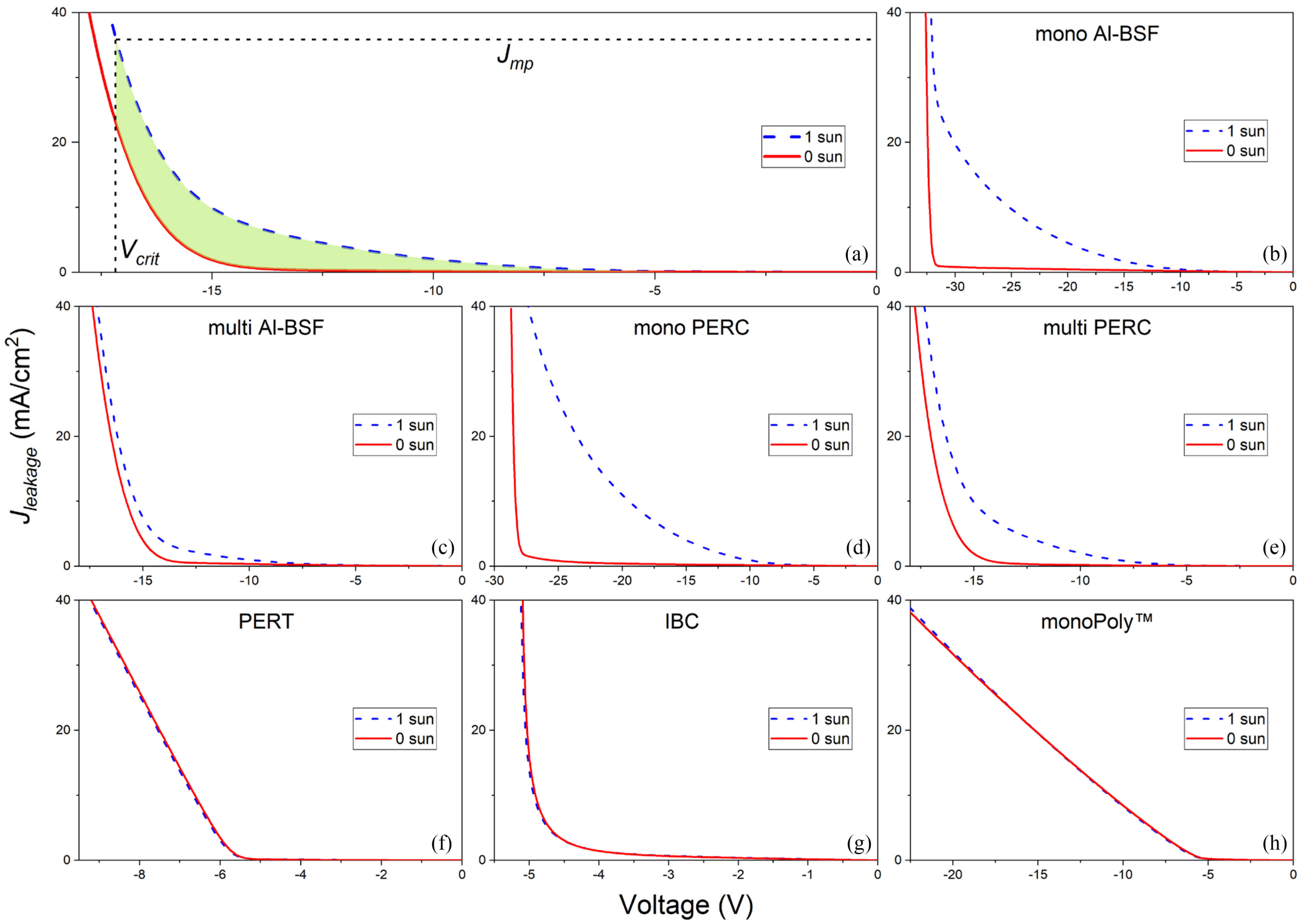

Fig. 1. (a) Visualization of the parameters used to quantify illumination effects. $\overline{\Delta J}_{\mathrm{leakage}}$ is equal to the area highlighted in green divided by $-V_{\mathrm{crit}}$. (b)–(h) J_{leakage} profiles of different cell technologies under dark and 1 sun illumination. The selected curves are representative of the general trends observed during measurements.

A boxplot comparison of the cell technologies using the $\overline{\Delta J}_{\mathrm{leakage}}$ metric is shown in Fig. 2 from which a few observations can be made. The first is that illumination seems to increase J_{leakage} in p-type cells such as PERC and Al-BSF, while the effect is pronouncedly smaller for n-type cells by at least an order of magnitude. Further analysis shows that the illumination effect on the n-type is on average negative (one sample t-test, $p_{\mathrm{PERT}} = 0.004$, $p_{\mathrm{IBC}} = 0.001$, and $p_{\mathrm{monoPoly}} = 0.002$) leading to a slight decrease in J_{leakage} with irradiance.

One possible accounting for this effect is that in avalanche breakdown, impact ionization may be further multiplied through the introduction of photogenerated minority carriers that themselves gain sufficient kinetic energy as they cross the space-charge region [21]. We investigate further by extracting dark *J-V* curves of random samples from each cell technology at $T = 25$ and 50 °C as seen in Fig. 3 where all show a shift to the left with increase in temperature. This observance of a positive temperature coefficient further supports the possible presence of avalanche effects in our sample of cells. However, it must be noted that the dependence of the light induced effect on wafer type and its asymmetry in magnitude is not yet fully understood. Nevertheless, its discovery allows us to define the scope upon which the previous superposition assumption is considered to be valid.

The second observation is that for both p-type cells, mono c-Si variants display a higher $\overline{\Delta J}_{\mathrm{leakage}}$ than their multi c-Si counterparts. This may be explained by the generally larger breakdown voltages found in mono cells ($V_{\mathrm{br}} = -20$ to -35 V) than in multi cells ($V_{\mathrm{br}} = -14$ to -18 V). At greater reverse voltages, the internal electric field across the depletion region is stronger. This leads to higher impact ionization rates and subsequently higher J_{leakage} as crossing charge carriers gain more energy.

B. Partial Shading and Low Irradiance

In describing scenarios of low illumination, it may be important from a modeling perspective to distinguish between uniform low irradiance, which is observed at different times of the day or during overcast weather, and nonuniform low illumination that results from shadows and shading elements. Since both cases achieve the same effect of lowering I_{ph} albeit through dissimilar means, it is worth investigating whether a meaningful difference exists in terms of their leakage current effects. We measure the

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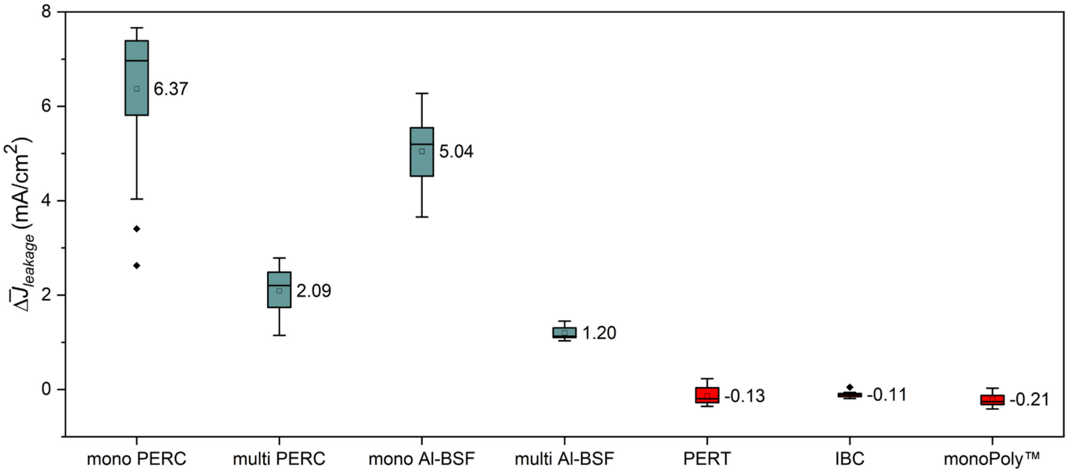

Fig. 2. Average change in J_{leakage} as illumination is increased from 0 to 1 sun. Green boxplots indicate a positive change in leakage current while red boxplots indicate a negative shift.

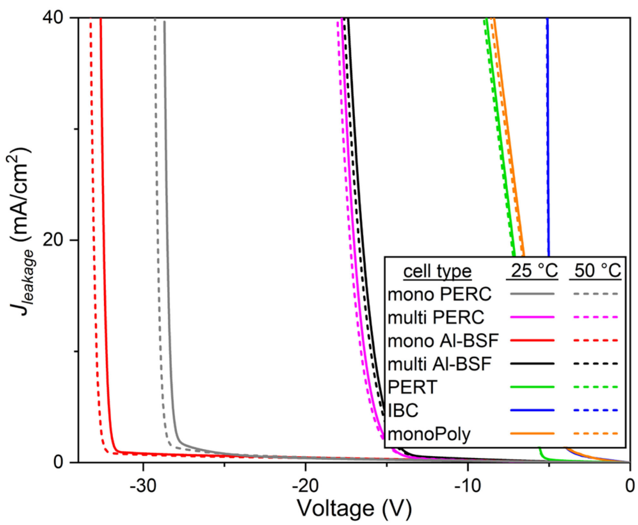

Fig. 3. Effect of temperature on dark *J-V* curves of randomly selected cell samples. For all cases when temperature is increased from 25 to 50 °C, we observe a leftward shift in the breakdown voltage. This points to avalanche effects as the dominant breakdown mechanism.

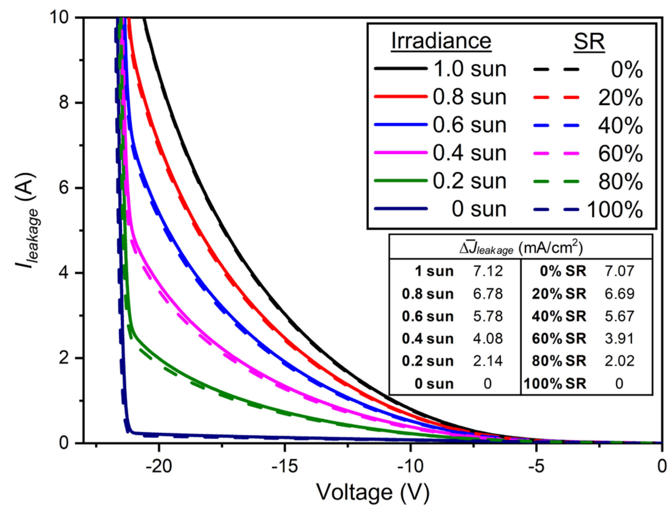

Fig. 4. I_{leakage} curves of a mono p_{PERC} cell at variable irradiance (uniform illumination) and shading ratios (nonuniform illumination). $\overline{\Delta J}_{\text{leakage}}$ is also tabulated, where corresponding cases show similar values.

reverse *I-V* curves of a mono PERC cell at various irradiance levels from 0 to 1 sun at 0.2 sun increments. Afterwards, the same cell is subjected to partial shading through the application of an opaque aluminum tape, while being flashed at 1000 W/m^2. We vary the shading ratio, SR from 0 to 100% in 20% increments such that there is an equivalence between the two cases. During our experiment, we ensured that for corresponding pairs in this study (e.g., 0.8 suns and 20% SR), the measured I_{sc} values are within 0.2% of each other. The obtained leakage current curves are shown in Fig. 4, where equivalent cases seem to behave similarly. In both scenarios, we see the same evolution of leakage current as photogeneration is increased by an equivalent amount. That is, the illumination effect may be adequately described as a function of the cell's total I_{ph}, regardless of the spatial distribution of incident light.

C. Modeling of Illumination Effects

It is clear that for p-type cells, there exists an additional light-induced reverse current that is not sufficiently accounted for by current breakdown models. The deviation between the often-used Bishop's model and experimental measurements is even greater as the cell is pushed further into negative voltages. With increasingly popular design architectures such as shingling and tandem modules that produce higher voltages, shaded cells are more at risk of operating within this domain. Therefore, a model that adequately captures this effect is important to our understanding of these new module types .

We propose a split-cell model to describe partial shading in cells that exhibit illumination dependent behavior in their leakage current. The approach works by first obtaining the unshaded *I-V* parameters of a cell at both 0 and 1 sun irradiance using Bishop's equation. Then to simulate partial shading, we

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TABLE I
SAMPLE SIZE PER CELL TECHNOLOGY CHARACTERIZED IN THIS STUDY

Technology	base doping	samples
mono PERC	p-type	24
multi PERC	p-type	12
mono Al-BSF	p-type	18
multi Al-BSF	p-type	15
PERT	n-type	18
IBC	n-type	9
monoPoly™	n-type	9

TABLE II
PARAMETERS USED IN SPLIT-CELL MODEL

Parameter	0 sun	1 sun
I_{ph} (A)	0	9.39
J_0 ($1{\times}10^{-12}$ A·cm^{-2})	2.44	2.44
R_s (Ω·cm^2)	0.747	0.747
R_{sh} (kΩ·cm^2)	208	19.3
V_{br}	-21.8	-70598
α	0.01	1
m	2.06	12410

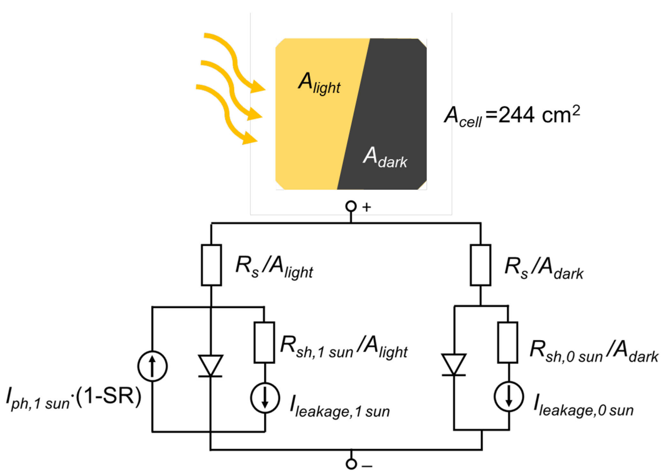

Fig. 5 Shaded cell and its equivalent circuit diagram using a modification of Bishop's model.

divide the cell into parallel-connected light and dark areas with each region modeled separately as shown in Fig. 5. The photogeneration term is omitted for A_{dark} while I_{ph}, J_0, R_s, and R_{sh} are corrected based on their corresponding areas. To demonstrate the viability of this model, we simulate partial shading on a mono p_{PERC} cell ($A_{\mathrm{cell}} = 244$ cm^2) using LTspice circuit modeling software where the extracted parameters are shown in Table II. *I-V* curves are generated for shading at 20% increments using both Bishop's and our proposed split-cell model, which are then compared to experimental data as shown in Fig. 6. Because Bishop's model does not sufficiently account for illumination effects, the leakage current is understated leading to a divergence between experimental and simulated curves at higher reverse voltages. By contrast, our split-cell model manages to capture the impact of illumination, where the evolution of the reverse *I-V* curve from flat at 100% to rounded at 0% shading is mirrored in our simulation data. The advantage of this approach is in its simplicity (only two *I-V* measurements are needed) as well as its applicability to other forms of low illumination. As discussed in the previous section, both uniform and nonuniform illumination produce similar effects on leakage current provided that the aggregate I_{ph} is the same. Therefore, the light induced effects from the two scenarios are reducible to their overall photogeneration, thus simplifying modeling on more complex shading patterns that may involve some combination of the two. Rather than adjusting cell parameters based on areas, we may similarly correct based on the ratio of the shaded cell's I_{ph} to $I_{\mathrm{ph,1\ sun}}$.

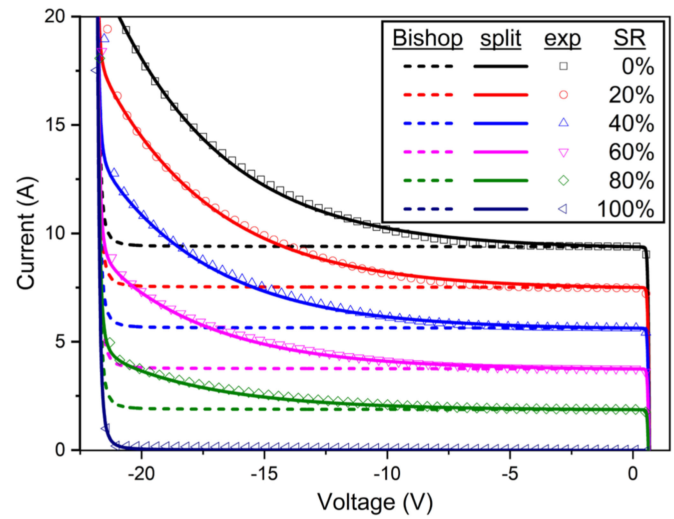

Fig. 6. Simulated and experimental *I-V* curves of a mono PERC cell under variable shading. While the curves produced by Bishop's model simply translate upwards or downwards depending on the level of shading, the split-cell model better captures the leakage current evolution as it responds to incident light.

We must, however, note that in the absence of a widely accepted physical explanation and corresponding mathematical description of this phenomenon, we resort to using Bishop's equation to describe leakage current for cells under illumination despite its intended scope being limited to light independent avalanche breakdown. Curve fitting on $I_{\mathrm{leakage,1\ sun}}$ manages to achieve good fit (adj $R^2 = 0.99987$); however, it does yield physically meaningless values for V_{br} and m as seen in Table II. A more complete physical description of this phenomenon would have to account for light induced effects based on underlying cell physics in order to yield realistic parameters. Nevertheless, from a modeling perspective, this approach does provide a good approximation in predicting the operating point of a light sensitive cell under various forms of shading. Additionally, we note that the outlined approach assumes a uniform leakage current response to light, i.e., there are no localized shunts or sites where current flows preferentially. Therefore, it is more likely to yield accurate results for mono than multi c-Si cells.

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IV. Conclusion

In this article, we investigated the effect of illumination on the reverse leakage current across some of the most commonly available crystalline silicon cell technologies in the market today. Through this comprehensive study spanning over 100 cell samples, we identified a significant increase in leakage current with illumination for p-type cells. Furthermore, this light-induced $\overline{J}_{\mathrm{leakage}}$ is greater in mono c-Si than multi c-Si, with mono-PERC cells showing an average increase in leakage current of $\overline{\Delta J}_{\mathrm{leakage}} = 6.37$ mA/cm^2 at 1 sun irradiance. This phenomenon may have arisen from increased instances of impact ionization due to the injection of photogenerated carriers. Such behavior is currently not accounted for in reverse breakdown descriptions such as Bishop's equation for avalanche breakdown, and may limit the validity of these models especially when dealing with modules that are at risk of developing large reverse bias voltages.

In order to model this light dependent behavior for partially shaded cells, we propose a split-cell approach that adequately captures the evolution of the J_{leakage} curve at intermediate shading values. This model may be further generalized to include more complex shading scenarios, whereby a simple analysis using the aggregate I_{ph} is sufficient to predict the behavior of the shaded cell. The work done here provides a useful starting point for more accurate simulations of new technologies such as shingled and tandem cells. Additionally, further study into the phenomenon described in this article may bring about new insights to cell physics and other light induced effects, or aid in the improved characterization of p-type c-Si cells.

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