MWT CELLS FOR SHADE-LINEAR, DIODE-FREE MODULES

B.K. Newman, E. Bende, J. Loffler, J. Wang, J. Zhai, D. Liu, Z. Wang, Y. Chen, J. Shi

***Abstract*— Metal wrap through (MWT) technology is an all back contact cell technology where the front emitter contact is extended through a laser-drilled via to the rear cell surface. The vias act as a pathway for current under both forward and reverse bias voltage conditions. Through engineering the vias, we tune the resistivity under reverse bias voltage of nMWT cells such that the vias act as in-cell bypass diodes without impacting the 21% light conversion efficiency. In this contribution, back contact foil laminates made from these cells are tested under partial shade conditions as part of a simulated string with bypass diodes. The laminates with low resistance in reverse bias survive simulated hot spot testing without performance degradation or mechanical failure. The temperature distribution suggests power dissipation well distributed through the vias. The dissipated power under reverse biasing as a function of shade fraction agrees well with an analytical model. Further, the reverse voltage does not exceed the bypass diode threshold voltage under any single cell shade conditions. From these tests and simulations we show that modules made from nMWT cells with high current in reverse bias can be implemented in a shade-linear, diode-free module concept.**

***Index Terms*—Irev, cSi modules, back contact, hot spot testing**

I. INTRODUCTION

Conventional c-Si modules are protected against damage in partial shade conditions by wiring a bypass diode in parallel and reversed polarity to a string of 20-24 cells. In a multiple cell string, each cell acts like a current source such that when one cell is shaded, the current from the remaining unshaded cells must still pass through the shaded cell; this drives the shaded cell into reverse bias. If there is a localized low resistance pathway, such as a crystalline defect, an impurity, a micro-crack or an edge shunt, the reverse bias voltage can result in localized power dissipation and non-uniform heating, the formation of a so-called ‘hot spot’. Hot-spots can result in permanent shunts, cell cracks, module glass cracks, and in extreme cases, even fire. To protect against this, a bypass diode offers an alternative pathway for the current and limits the possible reverse bias voltage to around -10 V to -12 V. This can result in more than 90 W of power dissipation across a shaded cell and global maximum power point tracking, gMPPT, found in many modern inverters and power optimizers, is expected to exacerbate this problem [1].

However, bypass diodes add to the bill of materials and thus also result in higher levelized cost of electricity. Three or more diodes are typically used per module resulting in higher costs and an increased risk of electrical component failure during the lifetime of a module. Bypass diodes also contribute to shade intolerance and shade non-linearity and can lower the overall energy yield of a system. When one cell is partially shaded (as little as 20% lower total illumination), the photocurrent of the entire string will be shunted across the bypass diode and the module output decreases by as much as 33%.

In modules with bypass diodes, a shaded cell can still experience a reverse bias voltage as high as -12 V. In order to insure against hot spot formation, conventional front junction solar cells are typically tested in the dark with reverse bias voltage. Cells with more than 2 A at –12 V bias voltage are assumed to have a low resistivity defect that will lead to hot spot formation and not selected for use in modules [2]. However, as demonstrated by Sunpower , interdigitated back contact (IBC) cells and modules have demonstrated good reliability in spite of high dark currents under reverse bias due to the spatially distributed n^+p^+ regions [3].

In MWT cells, the front emitter contacts are extended to the rear of the cell through laser drilled vias. These vias are evenly distributed across the cell. With simple processing variations of the contact around the vias, we can control the reverse bias voltage characteristic of the solar cell. This introduces a set of parallel dark current pathways evenly across the cell and if engineered correctly, can be conducting under reverse bias voltage only. In this paper, we show that this distributes the power dissipation more uniformly across the entire cell. As shown in Figure 1, these pathways do not cross the junction area of the cell and may also make the cell more tolerant of possible defects in the junction area that could lead to module failure. Additionally, this results in cells that could be implemented safely in a diode free module with improved

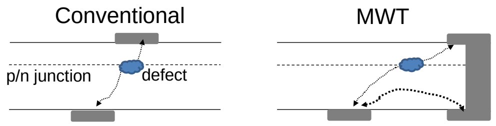

Figure 1. Schematic drawing of current pathways under reverse bias in a conventional cell and an MWT cell.

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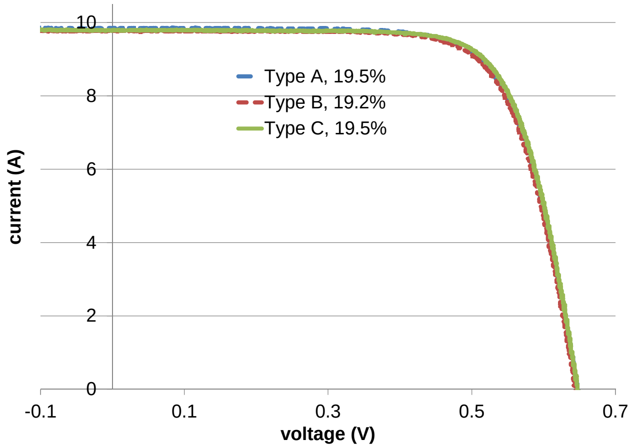

Figure 2. IV curves of each type of encapsulated cell before hot spot testing. Encapsulated cell efficiency is also reported.

shade performance.

In previous work, we have shown n-type MWT cells with conversion efficiencies as high as 21% where we can tune the resistance under reverse bias of the front emitter contact vias [4]. This results in the ability to tune MWT cells and modules along a continuum from the conventional high resistivity, low current characteristic (we will refer to as Type A) or a low resistivity, high current (referred to as Type C) characteristic when under reverse bias with good shunt resistance under forward bias and no negative impact on conversion efficiency.

In this contribution, we construct single nMWT cell laminates with encapsulated cell efficiency greater than 19% of cells with three different reverse bias characteristics. We apply a simulated hot spot test and measure total power dissipation as well as the spatial maximum and spatial average temperature and analyze the temperature distribution as a function of shade fraction. We compare the results to modelling of the behavior of full strings under all possible shading conditions. We find that a module made from Type C cells would be more shade linear, especially under low partial shade conditions and could be implemented without bypass diodes for further cost savings and potentially higher electrical yield under realistic partial shading conditions.

II. METHOD

We prepared a number of single cell laminates using nMWT cells with a 6x6 via pattern. Cell preparation is detailed elsewhere [5,6]. Cells are tested and then sorted based upon the illuminated conversion efficiency under standard test conditions and dark reverse IV characteristics with a Wacom solar simulator. Multiple single cell laminates were made from cells with each of Type A, B, and C reverse characteristic using back contact foil technology [7]. In this process the cell is placed on interconnection foil [8]. Conductive adhesive is printed at each of the 36 vias for the emitter contact and 45 BSF contact points. A stack of backsheet foil, cell, encapsulant, and non-tempered glass is laminated. Contact is made to the cell during the lamination process.

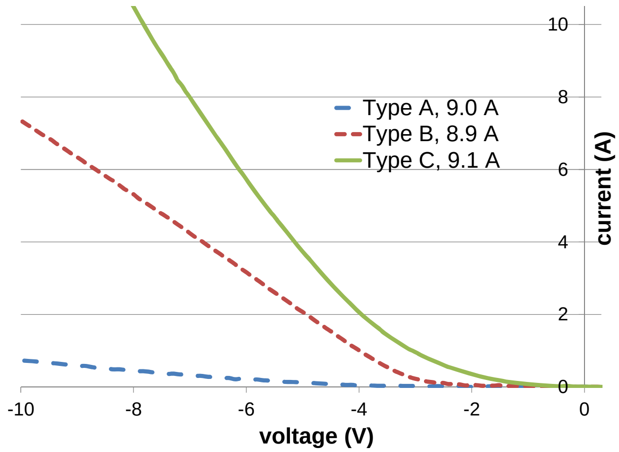

Figure 3. Dark IV of each laminate before hot spot testing. I_{mpp} of the illuminated IV curve is also reported for reference.

After lamination, the cells are measured on a Pasan flash tester to establish initial encapsulated cell efficiency. Single cell laminates of each type with similar encapsulated cell efficiency, Figure 2, were selected for further hot spot testing. All laminates used in testing have conversion efficiencies > 19% before hot-spot testing.

The laminates are hot spot tested mimicking IEC 61215 [9] under variable shade conditions using an external power supply to mimic a connected string of 20 cells with a bypass diode in parallel. The external power supply is either current (9 A) or voltage (-12 V) limited depending on the shaded cell characteristics. Partial shade is simulated homogenously on the single "shaded" laminate by uniformly reducing the intensity of the incident spectrum from an Eternal Sun solar simulator. Temperature is measured with a calibrated FLIR IR camera imaging the rear of each laminate through the backsheet. The three laminates are places side-by-side and measured simultaneously for direct comparison. The laminates are left for one hour and imaged every 30 seconds. Between measurements, each laminate is allowed to cool and then inspected for cracks, damage, and IV tested in both light and dark conditions.

Due to laminate failure during hot spot testing, we had to replace the Type A laminate with a different laminate for each of the different shade conditions. The same Type B and Type C laminates were used for all shade conditions. However, the Type B laminate also developed a crack in the non-tempered glass after 50% shade testing. The cell did not show evidence of cracking and the efficiency of this laminate was not drastically impacted so it was also used in the subsequent shade tests.

We use an analytical simulation model implemented in MS Excel where the IV curve of the cells is described by the explicit function form of the one-diode equation [10] for its forward behavior, utilizing the fundamental Lambert-W function. The reverse behaviors (A-C) were described by either exponential functions or second order functions obtained by fitting the experimental dark, reverse IV curves shown in

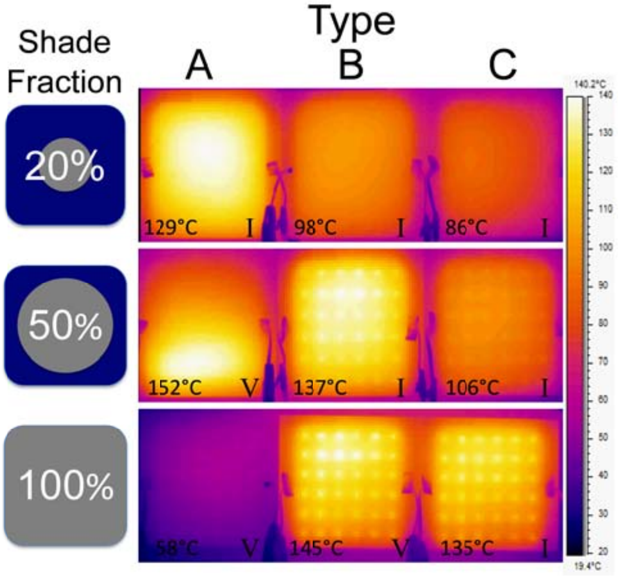

Figure 4. Infrared images of three types of laminates after one hour of hot spot testing in different shade conditions. All images are through the back sheet. Maximum temperature is reported in lower left corner. The limit of external applied power source, either current (I) or voltage (V), is indicated in the lower right corner.

Figure 3.

We assume a bypass diode wired on the turn of a 20 cell string and a gMPPT inverter in this system. In the study, we varied the shadow fraction, f, by shifting the dark IV curve of a single shaded cell in the string by the factor (1-f) I_{ph}, where I_{ph} is the photon current. We calculate the imposed current on a shaded cell by summing the current through the unshaded cells and the current through the bypass diode. We derive the voltages across all components and thus compute the generated power of the unshaded cells, the dissipated power of the diode, and for the shaded cell either the dissipated (reverse) or generated (forward) power. For the simulation, we assume defect free cells without localized hot spots.

III. RESULTS

Infrared images of the nMWT laminates after one hour of hot spot testing are seen in Figure 4. From these images we extract information about the maximum and average temperatures as well as the distribution of the heat. The maximum measured temperature in each test setup is also shown and whether the external power supply mimicking the rest of the string was voltage (V) or current (I) limited is indicated in the lower right corner. The maximum temperature is over 100°C, except in the case of Type A cells in full shade and Type B and Type C cells in 20% shade.

The Type A laminates most closely resemble the current standard in the PV industry. However, it can be seen from the images that under low partial shade fraction, these cells also form very hot areas. In the case of 20% shade, the whole cell is very warm, likely due to homogenous current dissipation mostly through the junction and dark current pathways across the junction but not through the vias. This is suggested by the in ability to make out the vias in the infrared image. The extreme heating caused a 1.0% relative efficiency decrease after testing. In 50% shade, we also observe very high localized temperatures. Upon inspection, these are shown to be a hot spot defect where a bubble was formed in the backsheet. Due to these results, we conclude that the Type A laminate only passes a hot spot test in the 100% shade condition and is more prone to defect failure.

The Type B laminate is hotter under all shade conditions as compared to the Type A and Type C laminates. While the maximum temperatures are high for all shade conditions, the vias are clearly visible. This suggests that the vias act to distribute the power dissipation more evenly over the cell. However, we observe a decrease in efficiency after 100% shade testing and an increase in the reverse current at a given voltage after all shade tests. In addition, the non-tempered glass was observed to crack after the 50% shade test. Results suggest that this laminate type is not suitable for safe and stable module applications.

The Type C laminate also exhibits high maximum temperatures in higher shade conditions. However, the vias are clearly visible and suggest that the power is distributed across the cell by the vias. Unlike the other two laminates, no mechanical defects were observed and the efficiency measured after each shade test remained stable and actually increased slightly after the series of hot spot testing resulting in a relative efficiency improvement of 0.4% to 19.6%. This difference is mostly due to a slightly decreased series resistance and improved fill factor likely from the cell module connection. The current under reverse bias also increased slightly after the first partial shade test but then stabilized. This however, seemed to lead to overall less total power dissipation throughout the following experiments.

IV. DISCUSSION

The experimental results suggest that a Type C cell can be used in module without failing due to hot spot formation or performance degradation. In order to understand the behavior of a full string, we simulate the current-voltage characteristics of a partially shaded cell in a 20-cells string. In this simulation we considered the module with the shaded cell as being part of a big system. Moreover, we considered an inverter with a global MPPT as part of the system. When in such a system a solar cell is sufficiently shaded two power maxima on system level arise. One maximum occurs at low current and high voltage where the shaded cell is still in forward condition. The second maximum occurs at higher current and low voltage, where the shaded cell is in reverse. For a notional system with an infinite number of modules the global maximum power will occur when the system is operated at the nominal maximum power point current ($I_{mpp,nom}$), i.e. the I_{mpp} under shadeless conditions. However, under real circumstance, e.g. a system consisting of 25 modules, the global MPP will also occur close to nominal I_{mpp} in case of partial cell shading.

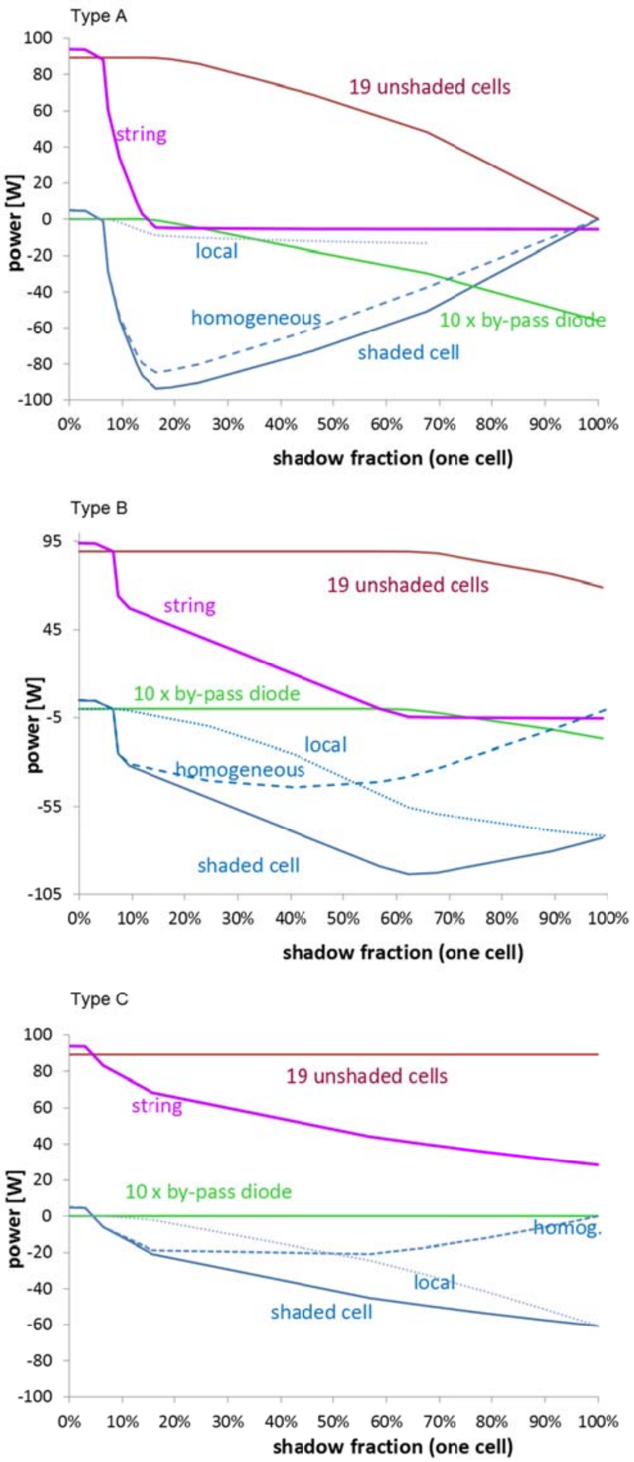

Figure 5. Simulated power generated (positive) or dissipated (negative) by different components in a string for each cell Types A-C. Simulation is based on a 20 cell string with one shaded cell and a bypass diode wired in parallel. The actual power dissipated over the bypass diode is multiplied by a factor of 10 for scaling purposes.

For the sake of simplicity we imposed $I_{mpp,nom}$ to the system, thereby mimicking the infinite system. Since all modules and thus all strings are connected in series, we only need to analyze the very string that contains the shaded cell. Here we define the string as the series connection of twenty cells with a bypass diode connected in parallel on the turn as in a standard module. The sum of the current through the diode (I_D) and the current through the shaded cell which equals 19 illuminated counterparts (I_{cells}) add up to $I_{mp,nom}$.

Figure 5 shows the results of this simulation for strings made with the various reverse characteristics of cells. The power dissipated over the bypass diode is shown here multiplied by a factor of 10 to see it on the same scale. In the case of Type A, the power generated by the string quickly decreases to zero with even 20% shade on a single cell. At low shade fraction, the shadowed cell can dissipates more than >95W. The diode in this case starts conducting around 15% shade fraction. The same is true for the Type B string in Figure 5 but here the critical shade fraction is closer to 50%. This corresponds to the experimental data for both laminate types as they switch from current limited to voltage limited (by the bypass diode) for higher shade fraction. As the shade fraction increases, the power dissipated by the shaded cell decreases and power on the bypass diode increases, but the string does not produce power. Therefore, the system will lose output from 20 cells with even a very small shade fraction on a single cell.

On the other hand, in a string with Type C cells, as shown in Figure 5, the power dissipated over the shaded cell increases with increased shade fraction. Therefore the whole string will be more shade tolerant, especially for low levels of partial shade. The maximum dissipated power over the shaded cell will occur at 100% shade of a single cell but the maximum dissipated power is only slightly more than 60W. Since the cell still passes the current, the decrease in power from the string, and even the entire module if there are no diodes is limited in the case of a single or few fully shaded cells. Finally, we note that the bypass diode is never conducting in the Type C case as the reverse bias voltage is never above the diode threshold. This corresponds to the cell limited current limitation observed in the experiment.

Figure 6 shows the measured power dissipation and average temperature for all laminates during the experiment. The total power dissipation as a function of shading is fundamentally different for the various reverse characteristics and is in good agreement with the simulation. The only deviation is for laminate B where we do not observe the decreased power dissipation in the 100% shade condition. From this and subsequent dark IV curve measurements we find that the Type B laminate becomes more like a Type C laminate after the 50% shade hot spot test. However, due to the higher breakdown voltage, it still dissipates significantly more power than the Type C laminate.

For the power dissipated by the shaded cell we made a distinction between two types:

1. The *local* power originating from dark current paths over the pn-junction; and
2. The *homogeneous* power caused by pushing the photon current through a potential barrier height of the junction.

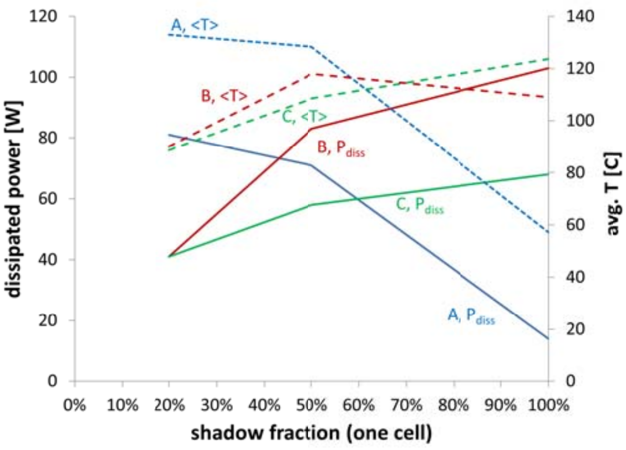

Figure 6. Measured total power dissipation across the shaded cell and average laminate temperature during hot spot testing.

These components are simulated and shown in Figure 5. We use the average temperature, shown in Figure 6, as a proxy for the homogenous dissipation. The simulated homogenous power dissipation and experimentally measured average temperatures agree suggesting that the average temperature could be used as a proxy for understanding the power dissipated over the junction. However, the localized heating due to dark current paths can lead to maximum temperatures that do not clearly correspond to the total power dissipation. This is in good agreement with previous work by Bende [1] and Geisemeyer [11] suggesting that hot spot behavior of modules depends not only on the total power dissipation but also on its spatial distribution and heat transfer. The visibility of the vias in the infrared images of the MWT cells in Figure 4 for type B and C cells suggests that the vias can play a key role in distributing power and thereby heat more uniformly across the cells. Previous work [5] also suggests that the foil interconnection might also play a role in more evenly distributed heat in back contact cell structures.

V. CONCLUSIONS

In typical cells, high current, $I_{rev,}$ under reverse bias conditions requires that the current pass through the junction. Therefore, defects in the junction area are susceptible to form localized hot spots and possible degradation or ultimate failure of the cells and possibly the entire module. Therefore, bypass diodes are placed in parallel to carry the current under reverse bias conditions, such as shade. This also results in loss of power generation from an entire string of cells, typically 20, in parallel with this diode at very low levels of partial shade as soon as sufficient reverse voltage is applied.

nMWT cells have been made with 21% efficiency and variable reverse bias resistance as shown in Figure 2 and Figure 3 [4]. The Type C cells offer another unique characteristic in that the vias, distributed evenly across the cell can also carry current under reverse bias. As these experiments show, the cells perform better under all partial shade conditions except full shade of a single cell. However, even in this mode, they still have a lower maximum temperature than a typical Type A cell under 20% shade conditions.

With global MPP tracking, as shown by the authors in Ref. [1], a system could be driven into reverse at very low shade levels. Our results support the need for hot spot testing to explore a variety of partial shade conditions and system configurations and not only rely on temperature measurements [12]. For typical Type A cells, the current passes through the lowest resistivity pathway and could pose a safety concern. Under low shade levels, Type C cells will dissipate less power than Type A cells. Further, the bypass diode would not activate under any shade conditions as the system would be current limited and never reach the voltage threshold. This leads to significantly improved shade tolerance and linearity for improved energy yield of such a module. Finally, our results show that the distributed nature of the vias results in lower maximum cell temperatures in Type C cell laminates over the whole shade range.

We postulate that such Type C cells could be used in diode-free, shade tolerant modules safely. To improve performance it would be beneficial to design cells with even lower resistance under reverse bias. Work is ongoing to tune the process further to make cells with lower break down voltage. These cells would dissipate even less power in any shade conditions leading to better overall module shade linearity. Additionally, new standards for testing and sorting Type C cells would need to be developed in order to ensure that the low resistivity under reverse bias is due to the vias and not a defect. Specific design and optimization of cells with an eye toward the improved performance of the modules will lead to cheaper, safer, and higher yield modules for various applications and system configurations.

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