

## MANIPULATING REVERSE CURRENT IN 21% N-MWT CELLS

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**ABSTRACT:** Metal wrap through (MWT) cells and modules offer technology that combines a front junction cell with an all back contact module interconnection offering potential for higher efficiency, improved cost to power ratio, lower electrical cell to module losses, and improved module aesthetics. For the best conversion efficiency, isolation of the vias for the emitter contacts is key to reduce shunting pathways. However, in reverse bias conditions, the vias are also a controlled current pathway for homogenous dissipation of heat, offering new design opportunities for diode free, shade tolerant modules. We have developed a process for via isolation in high efficiency n-MWT cells where the behavior under reverse bias can be tuned with little impact on illuminated I-V curve and efficiency. We find that after the first exposure to reverse bias, the efficiency of these cells stabilizes and further reverse bias soaking or testing has little impact on performance. Further, these cells were processed into single cell laminates for simulated hot spot testing. The laminates with the highest reverse current performed best under all shading conditions (20%-100%) and were in fact the only laminates that survived all shading conditions without breakage, hot spot development, or significant conversion efficiency reduction.

**Keywords:** MWT, reverse breakdown, hot spot testing, shade tolerant modules, diode free modules

## 1 INTRODUCTION

In traditional front junction solar cells, with contacts on both surfaces, high current flow under reverse bias conditions, commonly referred to as  $I_{rev}$ , is indicative of depletion region or bulk material defects and shunts. These defects often lead to localized heating and hot spot formation when the module is partially shaded. Typically, module manufacturers require that the dark current under -12 V bias is much less than 1 A to ensure module reliability. Interdigitated back contact (IBC) cells and modules, however, have demonstrated good reliability in spite of high dark currents under reverse bias due to the spatially distributed  $n^+p^+$  regions [1].

Metal wrap through (MWT) technology and architecture combines easy front side junction formation with all back contact module technology. It also offers improved module aesthetics and cell to module gain with simple cell processing. MWT also offers a unique paradigm of behavior in reverse bias.

Inherently, the MWT architecture offers a second current pathway through the BSF-bulk-via contact region on the rear side of the device. In illuminated conditions, high resistivity and low current or  $I_{rev}$  of this pathway is desired and has been the goal of previous work [2]. The vias and plug metallization that carry the front emitter contact to the rear side of the device would ideally only contact the  $p^+$  portion of the device and be highly resistive to the n-type material under forward bias and illuminated conditions. However, we will show that under reverse bias, a Schottky-type contact with a low breakdown voltage, offers a well distributed and safe pathway for power dissipation.

Throughout the development of the MWT architecture, the reverse bias characteristic of MWT has been engineered to have a high breakdown voltage and low  $I_{rev}$  at -10 V bias; similar to that required for standard front junction device [2]. Even in with this condition, MWT cells have shown lower module temperature in hot spot testing with MWT laminates as compared to standard front junction laminates [3]. The lower temperature has been explained as due to the fact that the vias are distributed across the device. Additionally, the rear metal

foil used in the MWT modules, as compared to standard tabbed interconnections used in the front junction devices, may also increase heat distribution [4].

In this contribution, we show that in n-type MWT cells with the potential conversion efficiency greater than 21%, the reverse bias characteristic can be manipulated and tuned during cell processing by varying the emitter contact via isolation. With this capability, the breakdown voltage, resistance of the vias, and  $I_{rev}$  through the vias can be engineered for better cell and module performance. We show that an nMWT laminate with high  $I_{rev}$  has improved performance under a variety of partial shading conditions as compared to low  $I_{rev}$  nMWT. The ability to tune the reverse bias behavior of a cell allows optimization on the cell level for improved module performance and reliability and engineering of a cell ideal for a shade-tolerant, diode-free module concept.

## 2 EXPERIMENT

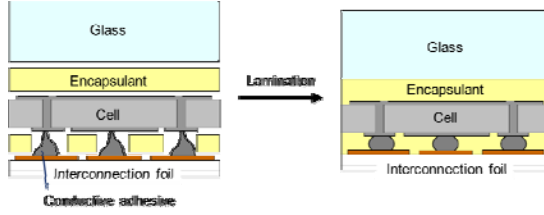
### 2.1 Laminate Preparation and Characterization

Three groups of nMWT cells were prepared with a 6x6 via configuration using our standard process as outlined elsewhere [5], with three different methods of via isolation. All cells were made from n-type CZ wafers with low resistivity (< 10 Ohm cm). Illuminated I-V curves are measured on a Wacom solar simulator with a specially designed MWT chuck, by sweeping the voltage from -0.2 V to 0.7 V. Dark I-V curves are subsequently measured by sweeping the voltage from -10V to 1V.

Dark current pathways are evaluated using dark lock-in-thermography with voltage modulation (VoMoLIT) under 0.7 V forward bias and -5 V reverse bias. Images are averaged for 30 seconds.

Three single cell laminates were prepared from each group of cells using back contact foil technology [6]. In this process the cell is placed on an interconnection foil [7] as seen in Figure 1 below. Contact is made to the foil through the 36 emitter via contacts and directly to the rear BSF contacts using a conductive adhesive. The whole stack is placed with encapsulant and non-tempered glass on the front in the laminator. The conversion

efficiency of the laminate is also measured on the Wacom sun simulator for both light and dark I-V measurements.



**Figure 1:** Cross-sectional schematic of laminated cell

## 2.2 Adapted hot spot testing

Based upon the IEC 61215 [8], we developed a modified version of the hot spot testing for a single cell laminate. The laminates are placed in front of an Eternal Sun module tester [9] where the illumination intensity can be varied to simulate partial shading of the single cell. A calibrated FLIR infrared camera is located behind the laminates such that it can image the temperature of the laminates through the back sheet. Due to changes in emissivity, a thermocouple was used to calibrate the temperature of the camera at room temperature. The laminates were illuminated with the sun simulator for 30 minutes to come to an equilibrium temperature before external power is applied.

In order to simulate the behavior of these cells in a 60-cell module with bypass diodes for hot spot testing and shade tolerance testing, we use single quadrant power supplies connected in reverse bias to mimic the behavior of the other cells in the module. We assume that all other cells are similar in I-V characteristic and fully illuminated. We also assume in this case that bypass diodes are used for 20 cell strings. Using these criteria, and assuming only one cell in the module is shaded, we apply an external power in reverse bias of either -12V or the current at maximum power point ( $I_{mpp}$ ), whichever occurs at the lowest reverse voltage for that laminate. The resulting powers and the mode (either voltage or current limited) for each setup are shown in Table I. It should be noted that when the applied power is current limited, it suggests such a cell is self-limiting in these conditions; therefore the bypass diode is not limiting the total power dissipation and full  $I_{mpp}$  is conducted by the shaded cell.

After power is applied, one infrared camera image is taken every 30 seconds for one hour. Since all laminates are measured at the same time and in the same camera frame, we assume that any changes in emissivity and calibrated temperature of the laminates can be accounted for in the relative differences between laminates.

The laminates were tested under 50% shade conditions first, followed by 20% shade conditions and finally 100% shade conditions.

**Table I:** Power in W dissipated in reverse in laminate in different shade conditions. Also indicated is whether the power was current (I) or voltage (V) limited.

| Power (W)    | Iso. A | Iso. B  | Iso. C |
|--------------|--------|---------|--------|
| 20% shading  | 81 - I | 41 - I  | 41 - I |
| 50% shading  | 71 - V | 83 - I  | 58 - I |
| 100% shading | 14 - V | 103 - V | 68 - I |

## 3.1 Cell Characterization

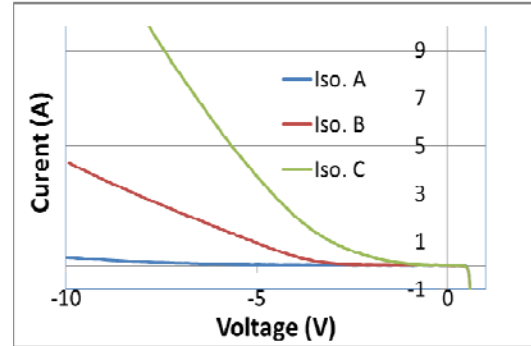
All the cells perform similarly under one sun illumination. The isolation method seems to have little impact on the nMWT emitter contact for collection of minority carriers under illumination. The average cell efficiencies for each group are reported in Table I along with average voltage at maximum power point ( $V_{mpp}$ ) and current at the maximum power point ( $I_{mpp}$ ). These values were used to estimate the necessary bias for hot spot testing. Cell efficiencies in this specific experiment are close to 20%.

In a later process run, isolation methods A and C were repeated with better material and an improvement in an unrelated process step. For both groups, average cell efficiency was greater than 20.8% with peak efficiency of 21.0%. Isolation method B was not repeated.

**Table II:** Average cell performance with uncertainty for each method of via isolation used in this experiment. Each group consists of 12-15 cells.

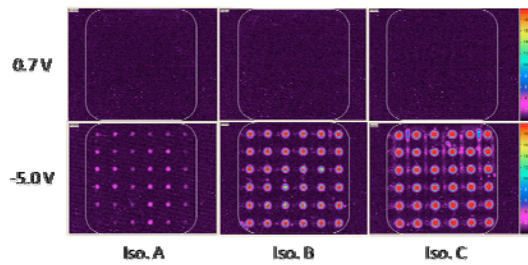
|                               | Iso. A   | Iso. B   | Iso. C   |
|-------------------------------|----------|----------|----------|
| $\langle \eta \rangle$        | 19.7(5)% | 19.8(3)% | 20.0(3)% |
| $\langle V_{mpp} \rangle$ (V) | 0.540(2) | 0.531(9) | 0.541(5) |
| $\langle I_{mpp} \rangle$ (I) | 8.6(1)   | 8.7(5)   | 8.8(1)   |

The dark I-V behavior of these cells under reverse bias voltage varies with the method of via isolation, as can be seen in Figure 2. Isolation A results in low  $I_{rev}$  at -10V: the target of standard front junction silicon cells. Isolation B results in higher  $I_{rev}$  at -10V. Isolation C has even higher  $I_{rev}$  such that it reaches  $I_{mpp}$  at  $< 8$  V. It can be seen from Table II, that Isolation B results in slightly lower efficiency than the other groups; nor is the reverse bias behavior ideal, as we shall see below.



**Figure 2:** Dark I-V of cells used in the partial shading experiment.

Dark lock-in-thermography images of each of these cells can be seen in Figure 3. From here we see that there are no specific hot spots or shunts for any of the cells under forward bias. However, in reverse bias, most of the current and heat dissipation occurs in the emitter contact vias. At -5V, the vias with Isolation C show the greatest change in temperature; under these conditions, more power is dissipated in these vias than in the other two cells. It should be noted that these cells are not the same cells used in laminate testing, but similar and representative.



**Figure 3:** Dark lock-in thermography of cells with different via isolation methods in forward (top row) and reverse (bottom row) bias conditions. Images are accumulated for 30 seconds. Cell outline is approximate and added to indicate the area of relevance.

### 3.2 Laminate Characterization

Laminates were made with cells from each group according to the process outlined above. These laminates were also tested on the Wacom sun simulator. After lamination, the dark I-V curves were measured as seen in Figure 4 and labeled as 'Initial'. Cell to laminate power ratios were approximately 100%.

After the initial I-V measurements, the laminates were 'dark soaked' for 30 minutes with an externally applied reverse bias, also limited at -12V or  $I_{mp}$ , as explained above. No evidence of structural laminate damage to either the glass or cell was seen. The I-V curves were re-measured. As seen in Figure 4,  $I_{rev}$  of Isolation A and Isolation B increase. Isolation C also increases but a by a smaller amount. Illuminated I-V (not shown) does not reveal a statistically significant change in efficiency.

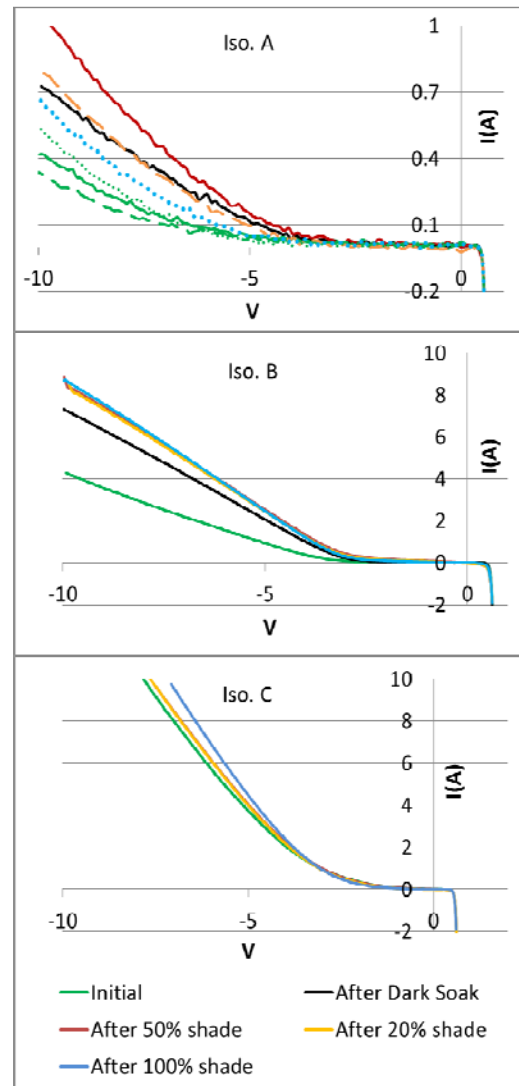
Figure 5 shows the infrared images of the laminates during hot spot testing with various shadow fractions. The peak and average temperatures across the cell area of the laminate (as measured by the IR camera) are shown in Table III. Dark I-V curves taken between each test are seen in Figure 4.

#### 3.2.1 Isolation A

Isolation A, with the lowest  $I_{rev}$ , is typical of the reverse bias behavior required by module manufacturers and is most similar to front junction cell performance. However, such a cell must be used in combination with bypass diodes in order to ensure that the voltage does not exceed -12 V, especially under partial shading conditions.

Modelling predicts that the Isolation A would have the poorest performance under low partial shading conditions. This is because this cell, assuming it is in a 20 cell string with a diode, will operate voltage limited at approximately -12 V, but the current is determined by the light generated under illumination. Thus, less shadow results in higher current and power dissipation.

During the initial test, under 50% shadow fraction, the module developed a hot spot as can be seen in second row of Figure 5. This spot resulted in power being dissipated over only the lower half of the cell instead of over the whole cell. Therefore, while the average laminate temperature is only 110°C, the peak temperature reaches 152 °C and is actually higher than what is seen for the other two laminates. After this test, this laminate was replaced with another Isolation A laminate.



**Figure 4:** Dark I-V curves of the laminates after each stage of the experiment. For Isolation A, all three laminates used are shown: the first used for the dark soak and 50% shade (solid), the second for the 20% shade (dashed), and the third for 100% shade test (dotted).

Fewer than 20% shade, Isolation A should result in the highest temperatures. The IR results show that both the peak and average temperatures of the Isolation A laminate are hotter than the other two laminates. In this case, the heat is not concentrated at a single hot spot and the cell did not fail during the test. From the IR image, we see that the heat seems to be spread across the entire area of the cell and not concentrated at the vias.

Under 100% shading, Isolation A shows the best behavior with peak temperature less than 60 °C. However, during the setup of the experiment and the application of bias voltage, the laminate used in the previous test developed an extreme hot spot that resulted in irreversible damage to the laminate. Temperature was not measured during this process. A third new laminate was substituted and resulted in the temperatures measured for 100% shade experiment.

Figure 4 shows the Isolation A dark I-V curves before and after the first two parts of the experiment; initial,

after the dark soak, and after 50% shading. For Isolation A, the  $I_{rev}$  at -10V increased after the initial dark reverse bias soak. After the hot spot developed during the 50% shade experiment, the  $I_{rev}$  increased again. Similarly, measurements of the other Isolation A laminates, also shown in Figure 4, indicate similar increases in  $I_{rev}$  after the first long exposure to reverse bias.

**Table III:** Laminate temperature during shading tests. Bold indicates best performing laminate in each testing condition.

| Temp. (°C)   | Iso. A    |           | Iso. B |      | Iso. C    |            |
|--------------|-----------|-----------|--------|------|-----------|------------|
|              | Avg.      | Max.      | Avg.   | Max. | Avg.      | Max.       |
| 20% shading  | 114       | 129       | 90     | 98   | <b>76</b> | <b>86</b>  |
| 50% shading  | 110       | 152       | 118    | 137  | <b>93</b> | <b>106</b> |
| 100% shading | <b>49</b> | <b>58</b> | 109    | 145  | 106       | 135        |

### 3.2.2 Isolation B

Isolation B was expected to be the least favorable type of isolation in shaded conditions. For 50% and 100% shading this laminate had the highest average temperature. Most of the heat is dissipated through the vias. Under 20% shadow fraction, the temperature of the cell was above 90°C but was lower than the Isolation A module. In this case, similar to Isolation A, the heat is dissipated uniformly across the cell area and not localized to the vias. During the first test at 50% shading, the laminate glass (non-tempered) cracked. However, we found that the cell itself did not crack and the same laminate was used for all shade experiments and I-V testing.

Figure 4 shows the dark I-V curves after each stage in of the test.  $I_{rev}$  increases after the initial reverse bias soak and the 50% shade test, but thereafter it stabilizes.

### 3.2.3 Isolation C

Isolation C has the lowest resistance vias and the lowest breakdown voltage. In the case of a standard front junction device, this would be a non-ideal behavior because it would suggest that there would be a shunting pathway or defect through the junction region and therefore likely hot spot development in shading conditions. Instead, with an nMWT cell specifically engineered to have low resistivity around the vias under high reverse voltage, the extra current pathway may help prevent hot spot formation.

The impact of the low resistivity vias is seen for the low shade conditions: 20% and 50%. In these tests, the laminate remained below 110°C. In the case of 20% shadow the temperature is limited to less than 86°C.

Under 100% shading conditions, the laminate temperature of Isolation C significantly increases. However, all of the heat in this case is well distributed across the 36 vias and therefore the temperature gradient is such that it does not lead to cracking. Further the temperatures here are comparable to the Isolation A laminate under 20% shade conditions but Isolation C does not develop a hot spot.

The dark I-V curves in Figure 4 show that the  $I_{rev}$  behavior of Isolation C is more stable throughout testing as compared to the other two isolation methods. There is no significant change after the initial dark soak and only after the 100% shade experiment is there a slight increase  $I_{rev}$ . In this case, the increase in  $I_{rev}$  indicates lower

resistivity in the vias and therefore would potentially further decrease the temperature of the laminate in reverse bias conditions.

## 4 DISCUSSION

There are three power can be dissipated in an MWT cell driven into reverse bias by the rest of the module. The first is power dissipated across the whole cell junction area. Second, the power is dissipated over a defect in the cell that offers a shunt in reverse bias or that develops when the reverse voltage increases. Third, unique to an nMWT cell, the power is dissipated through the  $n^+$ -metal contact at the via where the plug paste contacts the bulk material. Uniform dissipation of power across the cell results in lower localized temperature and smaller temperature gradients; while local heating (i.e. hot spots) often leads to cell failure or module failure due to shunt formation and glass breakage.

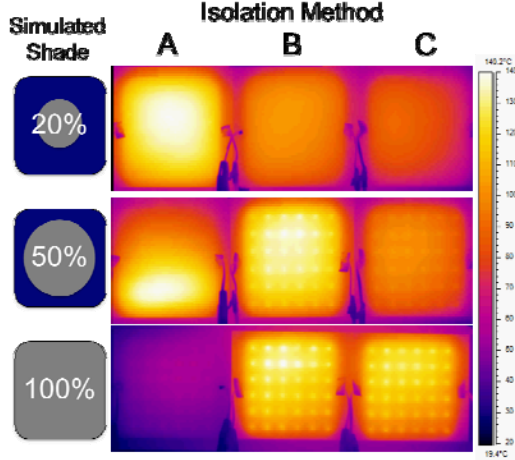
The introduction of vias with controlled isolation from the bulk/BSF offers a mix of local and distributed power dissipation. The vias are a well distributed pathway but also a localized pathway specifically designed to carry currents on the order of  $I_{mpp}$ . They also offer potential mitigation of hot spots at defects that might irreversibly damage the overall performance of the cell. The existence of 36 low resistance current paths will decrease the amount of current dissipated in a defect, thereby resulting in lower local temperatures and less potential damage. However, the resistance of the via isolation must also be low enough to prevent the formation of an extreme hot spot at the via resulting in module failure.

In this experiment, we see both of these failure methods in Isolation A and B. The failure of two laminates with Isolation A indicates the potential failure due to hot spots, much like a typical front junction device. The cracking of laminate B is the result of too much localized heating of the vias. Isolation C however, shows good performance and stability with high  $I_{rev}$  and low resistivity of the vias.

For Isolation A, safe module behavior in all conditions requires the use of a bypass diode. The bypass diode limits the bias voltage and thereby the power dissipated in the shaded cell. However, this also limits the amount of current conducted by the Isolation A cell in reverse bias, limiting the current of the rest of the string. For Isolation A, under 100% shade, the temperature is lower but the current is also limited to 1.2 A, leading to a significant overall decrease of potential output power of the string. Scaling to a 60-cell module of similar cells, this would result up to a 30% decrease in module output power. Thus Isolation C type cells could also potentially improve module shade tolerance and yearly energy yield.

Of course, it is also required that the conversion efficiency and performance under forward bias and illuminated conditions is stable. Table IV shows the initial laminate efficiency and changes in efficiency during the experiment. From Figure 4, we see that  $I_{rev}$  increases until it stabilizes for all three isolation methods. However, the efficiency actually improves for all via isolation methods unless there is damage to the cell during the testing. This change seems to be related to the temperature and possibly due to better contact with the module. While the differences are small and are within the error of the testing apparatus, it suggests that laminates with reverse behavior more like Isolation C or

with even lower breakdown voltage could increase yield, have better shade tolerance, and less need of diode protection.



**Figure 5:** IR camera images of the rear of the laminates when they are hottest during the partial shade tests.

At this point, we have only tested a few laminates of each type. These may not correctly represent all cells with these characteristics. Other sources of error include variation in emissivity that may introduce systematic error in absolute temperature readings. An improved calibration of temperature on the IR camera or a more direct method of monitoring temperature would be necessary to estimate this error. The shade tests were performed in the same setup and arrangement of laminates and temperatures measured in the same camera frame in order to gain better relative comparison of results. Regardless of absolute temperature, Isolation C survived all testing without damage or failure, suggests that it may have unique characteristics for a module.

**Table IV:** Relative change in efficiency of laminates after each stage of the experiment.

|                  | Iso. A              | Iso. B  | Iso. C |
|------------------|---------------------|---------|--------|
| After 50% shade  | - 1.0% <sup>†</sup> | - 2.6%* | + 0.2% |
| After 20% shade  | + 0.4%              | + 0.3%  | + 1.1% |
| After 100% shade | - 0.2%              | + 0.2%  | + 0.4% |

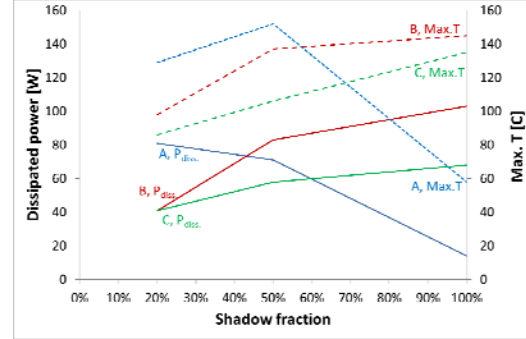
<sup>†</sup> Laminate developed hot spot

\* Laminate glass cracked during test

Partial shading was simulated as a lower intensity of incident light across the whole area of the single cell. In reality, shading on this level would likely be more of a localized issue. From the perspective of power dissipation under reverse bias conditions, such a test should represent similar behavior for a shaded cell in a module that is driven into reverse bias and must dissipate a certain amount of power. However, because of the relationship between local via dissipation and overall cell dissipation, more the balance of localized and distributed heating merits further investigation.

For standard front junction devices, Wohlgemuth previously demonstrated that maximum power dissipation could occur under partial cell shading conditions other than 100% cell shade, which was previously prescribed by the hotspot test IEC 61215 from 1993 [10]. Because of this, he advocated a revised

hotspot test. Bende confirmed Wohlgemuth's finding with simulations that the shade fraction for which maximum dissipation occurs depends on the reverse behavior [12]. Our results clearly illustrate this modelling. Geisemeyer demonstrated both experimentally and through simulations that the most critical hotspot temperatures do not always coincide with the maximum power dissipation for front junction cells [13]. This work confirms this finding for nMWT cells as well as illustrated in Figure 6.



**Figure 6.** Dissipated power (solid) and maximum temperature (dashed) versus shadow fraction for all three via isolation methods.

## 5 CONCLUSION

The vias in the nMWT architecture offer a unique way to control behavior in reverse bias. With a simple processing step, the exact behavior can be tuned from the high breakdown voltage and low  $I_{rev}$  as seen in Isolation A type cells or tuned to lower breakdown voltage as in Isolation C. However, the in-between state, similar to Isolation B should be avoided.

With simulated module level hot spot testing, we have demonstrated that Isolation C, with low resistivity vias, may offer significant advantages over Isolation A. Laminates with the via isolation method C, survived all partial shade and hot spot testing. Unlike a defect shunt, the vias are designed to carry current and high reverse power and are potentially less likely to cause irreversible damage in the cell. We have also shown good stability of the illuminated I-V characteristic in cells with Isolation C type characteristics made with this process. The Isolation C cell would also act to self-limit the power dissipated over the cell while still conducting the full  $I_{mpp}$  of the rest of the module, resulting in better shade linearity and improved yearly energy yield.

High  $I_{rev}$ , low resistivity vias in nMWT cells and modules could result in lower module temperature under partial shade conditions, better shade linearity and result in higher yearly energy yield as compared to typical high breakdown voltage cells with low  $I_{rev}$ . When combined with new module concepts, such as the TESSERA [10], they could be introduced as a method for making shade tolerant, diode-free modules.

MWT is more than just a transitional technology between front junction cells and IBC cells. The scalability, improved aesthetics, and better cell to module power ratio offer significant and advantages over front junction devices but with easier cell manufacturing processes than existing commercial IBC cells. The emitter contact vias also offer a way to tune reverse bias

behavior independently of the conversion efficiency and thereby, offering freedom of module design for improved performance in variable architectures or environments.

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