Solar Bypass Diodes: Then and Now

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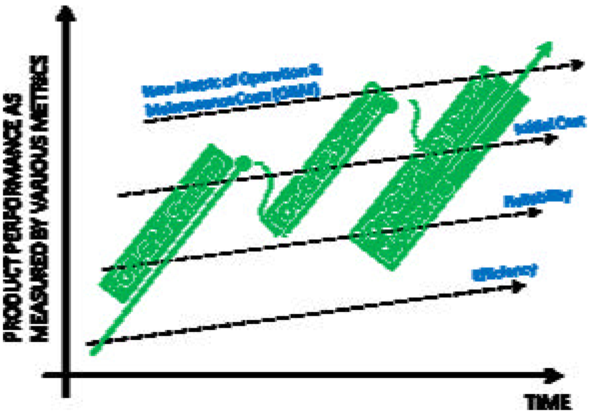
The solar industry is rapidly changing. Not only is cell efficiency making steady gains, but the users' demands are increasing as well. These changes have opened the door to innovations in technology and business models in surprising ways. With these changes, comes a new emphasis on operations and maintenance costs. A recent disruptive change is the introduction of "Individual Solar Module Performance Monitoring" solutions. This technology, which is currently deployed, will highlight previously unrecognized field failures of bypass diodes.

In the book "The Innovator's Dilemma", Clayton Christensen illustrated the nature of disruptive technology very effectively and his lessons can be extended to the solar arena. In any industry, technology evolves predictably until a point is reached where further advances require heroic efforts. Occasionally, the industry gets disrupted by radically different technology or changes in consumer patterns and the race to market continues on a more aggressive metric of acceptance. A common signature of disruptive technology is that (initially) it has worse price/performance than what exists when measured by traditional metrics of acceptance. But as the "added-value" of the new technology is recognized, the market moves onto an even more demanding metric of acceptance. Using this idea, figure 1 illustrates the progression of the solar industry.

Fig. 1.



The original usages for solar systems were for "off-grid" systems. Solar energy charged battery banks and, often, the batteries were fully charged by 11 a.m. Early adopters were interested in the metrics of "sun-to-electricity" efficiency and reliability. Next in the

evolution came the advent of "grid-connected" systems. There were hassles with local permits, but today the advantages of the "on-grid" system, by all metrics (even cost), have attracted a whole new market of residential users that enjoy watching their electrical bills drive backwards toward zero (or below) while still employing the utility grid when cloudy.

Changing Dynamics Drive Disruptive Technologies

The solar industry has now come to a crossroads. The metrics of efficiency, reliability, and installation cost are still improving, but a new trend has recently emerged. With the advent of the Power Purchase Agreement (PPA) and a greater focus on ROI, a new acceptance metric of Operation and Maintenance cost (O&M) has arrived. To support this new acceptance metric while still honoring the classical metrics of efficiency, reliability, and cost of initial capital investment, the disruptive technology of Solar Module Monitoring is poised to shake up the solar industry. The implications and consequences of this are enormous.

Lacking effective means of monitoring, owners and/or operators of solar systems (especially residential) have been virtually blind to under-performance. This has inadvertently extended a false sense of security to module manufacturers in terms of warranties because end-users are simply unaware when a partial defect in one module arises. Think about it. Trying to make repeatable real-time power measurements on one module out of the string's twenty, installed on a sloped roof, without a standardized "1-sun" calibrated energy source is almost impossible. Therefore, for the individual module, statistical methods of analysis have to be utilized. Now that these tools are entering commercial deployment, it is very likely that owners/operators will start noticing damage more frequently. Considering that it can cost $150/hour for a company to deploy field personnel to address maintenance, this may very well change the entire business model for module companies' financial warranties.

One source of solar module failure is the bypass diode. There are no hard statistics for field failure rates due to diodes. Every manufacturer closely guards failure data for competitive reasons. Second, many failures may simply go unnoticed. There is some published data to suggest that there is a problem, though. It is worth taking a moment to understand the history of bypass diodes, why they are needed and, more importantly, why they are failing.

Typical Failure Mechanisms

Each solar string is typically comprised of 10 to 20 series-connected solar modules, each with 72 cells internally that, similarly, are all connected in series. Therefore, a typical solar string might have 1000 series-connected cells. Each of these cells produces current in direct proportion to sunlight intensity. If any of these cells become shaded, soiled or damaged, then the entire string current is limited to that of the weakest link. This, in itself, wouldn't be so bad -- it would just be a temporary loss of performance. However, the effect is much more sinister.

A typical silicon cell has a forward voltage of 0.5 volts when optimally loaded. If, for some reason (such as shading), a cell cannot produce as much current as the neighboring cells, then this same cell will now be forced into a reverse mode of operation where it now has a negative voltage of 5 to 30 volts. In truth, the solar cells are a little bit forgiving as to the mismatch But, if enough mismatch is present, then the under-performing cell will be driven into the region of reverse breakdown. With 10 to 20 solar modules connected in series, the overall DC output can easily be 400 volts. Therefore, due to Kirchhoff's Voltage Law, it is possible for the lone shaded solar cell to begin operating in reverse breakdown with 30 volts applied across it, while the remaining functional cells account for the remaining 370 volts. With cell currents approaching 10 amperes, this shaded cell could now dissipate 300 watts. This can be destructive.

The industry's solution has been to provide a bypass path. Typically, a bypass path is provided around every 12 to 24 cells (see Fig. 2). The choice of 12 to 24 cells for bypass groupings comes from a comparison of the summation of the forward voltages versus the expected breakdown voltage of the weakest cell in that grouping. For example, in a group of 24 cells, each with a forward voltage of 0.5 volts, an overall voltage of 12 volts will be produced. Each of these same cells hopefully has a reverse breakdown voltage in excess of 25 to 30 volts. If the bypass is activated, the protected local loop's voltage will be lower than the members' reverse breakdown voltages.

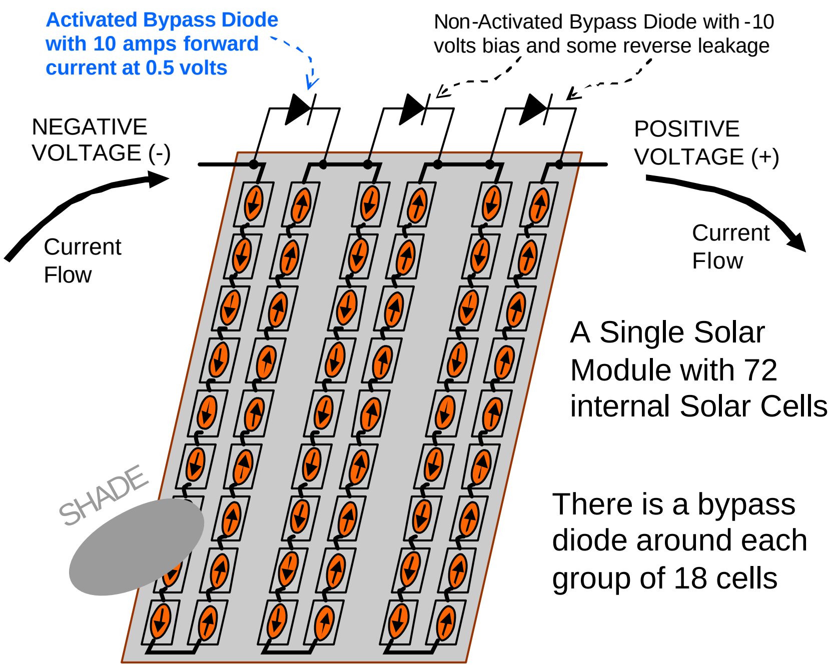


Fig. 2.

Initially, the industry used PN diodes to provide the bypass path. These bypass diodes had a forward voltage of 0.7 to 1.0 volts and reverse breakdown rating of 600 volts. With low amperage, the diode's heat was acceptable. But as the cell efficiency improved and the wafer size increased, the string currents increased to 5, 6, 8 and even 10 amperes. This drove the industry to adopt Schottky diodes. With Schottky forward voltages of 0.4 to 0.5 volts, power dissipated during bypass mode was cut in half. From a heat-management perspective, this helped. But unlike classical PN diodes, Schottky diodes typically have reverse breakdown voltages of 40 to 60 volts. This introduced new problems. Schottky diodes are leaky at high temperatures and they are easily permanently damaged by transient energy. If they fail "open," this can leave the corresponding cells in the grouping vulnerable to a destructive "hot spot" event during the next occurrence of shading or soiling. If they fail "shorted," this will (at a minimum) steal produced energy.

There is one more subtle benefit to the bypass diode. With solar arrays, DC voltages are present and arcing can be disastrous. Unlike an AC system where the arc might be able to self-clear at the "zero-crossing" of the 50/60Hz waveform, a DC-generated arc will not self-extinguish. Bypass diodes provide some (by no means complete) protection against "series" arcs within the module itself, because they limit the local arcing voltage to 10 to 20 volts. This is very important.

The bypass function may be ready for a new technology. There are a few companies that have recently developed a new category of diode. This new technology is promoted as a lossless diode because it might have a 40-50 mV forward voltage rather than the Schottky's 0.4 volt forward voltage (the definition of "lossless" varies widely and should be examined closely with respect to operating conditions and lifetime expectations). Under reverse bias, these "lossless" diodes have high temperature leakages measured in micro-amperes rather than the milli-amperes of Schottky diodes.

The evolution of bypass diode technology can perhaps be better understood with the help of the following figure (see Fig. 3).

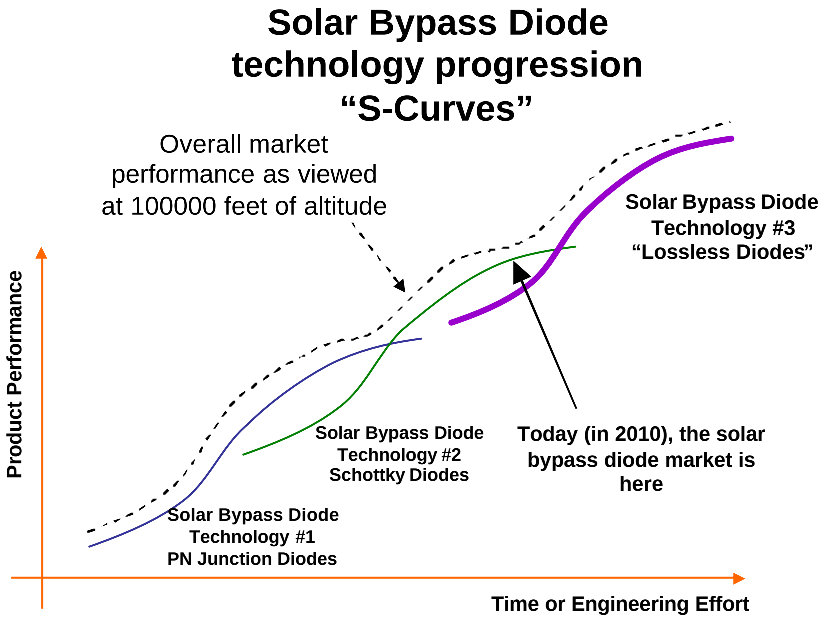


Fig. 3.

This brings the interesting question of whether diodes are failing in the field and, if so, what are the causes of failure.

All modules must pass IEC 61215 and part of this test relates to bypass diodes. This test is not a measure of reliability. It is merely a qualification test that looks at the survivability/performance of the module (and diode) against its rating under controlled conditions. This test produces virtually no information as to the expected time-to-failure rates of the diodes in the field.

Even though IEC 61215 is just a "spot" test, an interesting result was recently presented by TamizhMani, et al. ("Failure Analysis of Design Qualification Testing: 2007 vs. 2005") showing that, between 2005 and 2007, 31 percent of the silicon modules submitted for IEC 61215 testing failed the bypass diode test. Comparatively, from 1995 to 2005, only 4 percent of the submitted modules were failing due to the bypass diode test. During the diode shading test, it was commonly observed that the diode operated at 150-200 deg-°C.

Before a module is sold, it will have passed IEC 61215. The diodes will have a datasheet rating that is at least 1 degree beyond the 150-200 °C temperature observed during shading. But if 31 percent of the modules initially had trouble with the diode test before requiring a redesign, and the diodes are almost at the datasheet rating, these diodes will likely not survive 30 years in the field for all possible mission profiles.

In the course of investigating bypass diode failures, examination of forward operation over-heating, reverse bias thermal runaway, "shaded-to-unshaded" transition survivability, surge (lightning) survivability, and packaging fatigue were explored. Diodes that had failed in the field within a couple of years were examined. Controlled, “mildly” accelerated testing was conducted in the lab. Following is a summary of each of these examinations.

Forward Voltage Operation Over-Heating

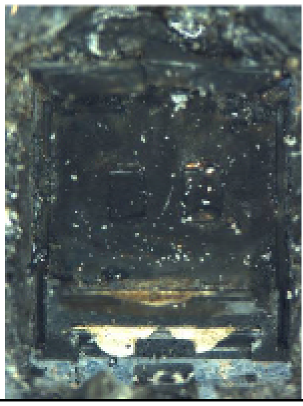
During shading events, bypass diodes have junction temperatures reaching upwards of 150 to 200 ºC. The junction box on the back of the module might peak at 90 ºC, but the diode has significant self-heating with virtually no air flow.

In an experiment with an oven controlled to +125 ºC (with air flow), 50 axial leaded diodes (rated at 12 amps/40 volts/150 ºC) were statically biased at 10 amps. One does not commonly think of a 125 ºC oven as a being a mechanism for cooling, but in this case, the air flow served to strip away much of the self-heating. Lacking airflow, the junction temperature would have been much hotter. After 1000 hours, 2 of 50 diodes had failed. Surprisingly, though, this did not seem to be the dominant mode of failure. One shortcoming of this experiment was that the oven had a fan equalizing the chamber temperature. It would have been more realistic to put the diodes in a sealed junction box with no internal airflow, and then put the junction boxes (under 10 amp bias) into the 125ºC oven for accelerated testing. Under that condition, it is likely that the self-heating of the diodes would behave more realistically, and the results of the experiment would be more pronounced. However, the material cost of accelerated-testing on diodes is far cheaper than that of fully assembled junction boxes, so tradeoffs were made.

There is evidence that prolonged over-heating is a culprit for failures, even though the controlled 125 ºC burn-in experiment only showed a few percent of the diodes failing. Diodes that failed in the field within two years were received from a well-respected, well-established module manufacturer. Failure analysis was performed on the 10 units that were received. Most of them had a failure signature that they were failing due to sustained over-heating over a long period of time. Some of the more interesting photos are shown below. It was not clear if this over-heating was due to forward or reverse operation.

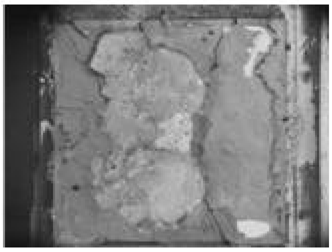
Failed Diode #1

This part was severely burned with the lid separated from the body of the package and with the die fractured. After decapping, analysis was performed.



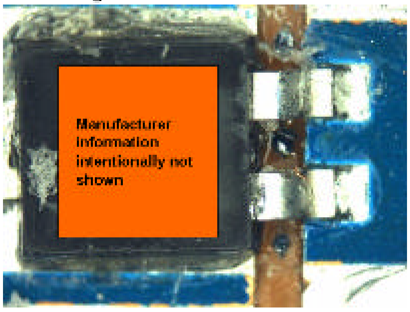
SEM Photo of the die. Molding compound has been burnt; die is fractured in multiple locations. This is symptomatic of a situation where there was excessive heat over a long period of time.

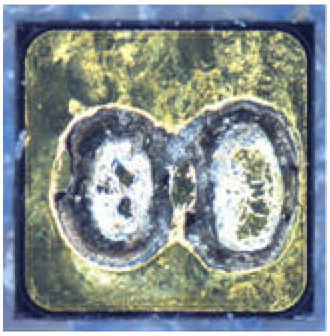
(Burnt) Molding Compound

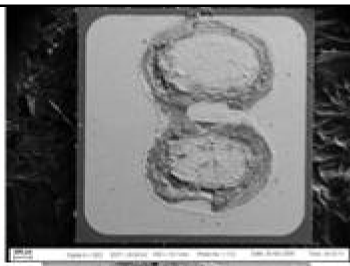


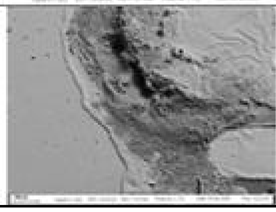
Failed Diode #2

This part was intact, with no sign of damage from the outside









Failed Diode #3

The plastic was etched away.

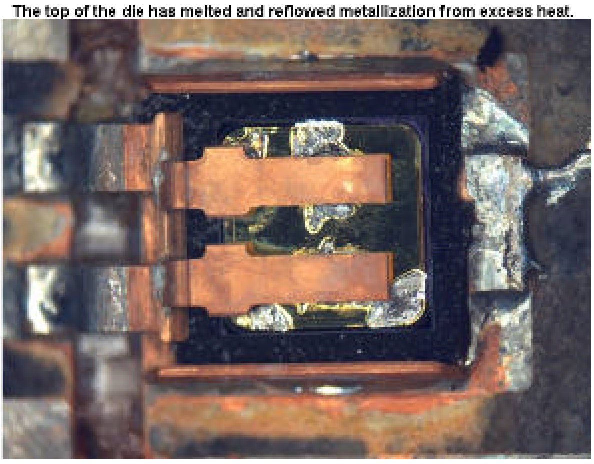
The die had melted metallization on top.

Failed Diode #4

The part was curve traced and found to be shorted.

The part was decapsulated.

The top of the die has melted and reflowed metallization from excess heat.



All engineers are familiar with Arrhenius's Equation. Assuming standard activation energies ("Ea") for silicon devices, a good rule of thumb is that for every additional 10 ºC rise in temperature, the expected time to intrinsic failure is cut in half. IEC 61215 tests the module at 85 ºC, and as a by-product drives the bypass diode temperature up to 150-200 ºC during the bypass diode test. Many diode manufacturers optimistically rate their datasheets based on survivability of 1000 diodes in a controlled-temperature oven for 2000 hours. This test condition might be 125 or 150 ºC with good air flow to maintain the overall oven temperature. The presence of this air flow, unfortunately, strips away excess heat due to self-heating. A typical solar module warranty might be for 30 years. Is there really enough guard-band in the operating temperature of these diodes? If Svante Arrhenius's equation is studied, it would suggest the answer is "no."

The same effect applies to the diode packaging. An interesting study relating to temperature effects on plastic encapsulated devices was published in 1997 by John Devaney, et al. ("Thermal wear-out of plastic encapsulated devices") showing that high temperature significantly shortens the lifetime of the packaging. (See Fig. 4).

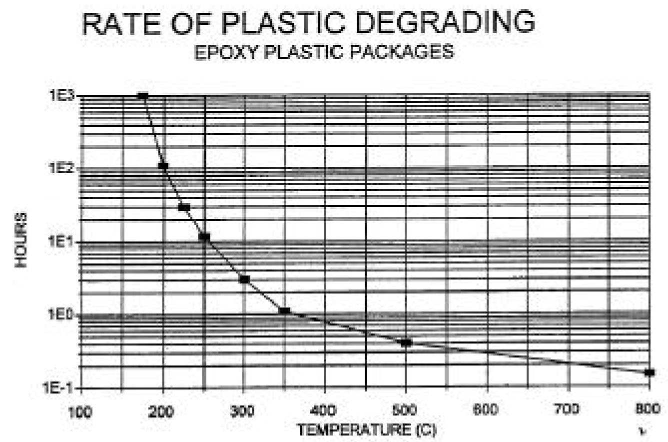


Fig. 4.

Reverse Bias Thermal Runaway

An unexpected result occurred when testing 50 of the same 12-amp/40-volt solar bypass diodes at 105 degrees with -15 volts statically applied. At approximately 500 hours, about 20 percent of the diodes self-destructed. In a well-designed installation the diodes are in standby mode for the majority of the time with perhaps -10 volts bias. A test condition of 105 ºC and -15 volts is not that much acceleration. It is hard to believe that the thermal runaway observed after 500 hours of mild acceleration would not occur at some point within 30 years given normal mission profiles.

After observing this thermal runaway, a closer look was given to reverse leakage. A common mistake that manufacturers make when rating their diodes is to only consider the leakage at +85 or +95 ºC. It will be shown why this is a bad design choice.

For the axial-leaded 12A/40V Schottky diodes used during the 500 hour thermal runaway events, the leakage doubles every 10 ºC. This is typical of all classical diodes (but not including "lossless" diodes). The measured results are shown (see Fig. 5).

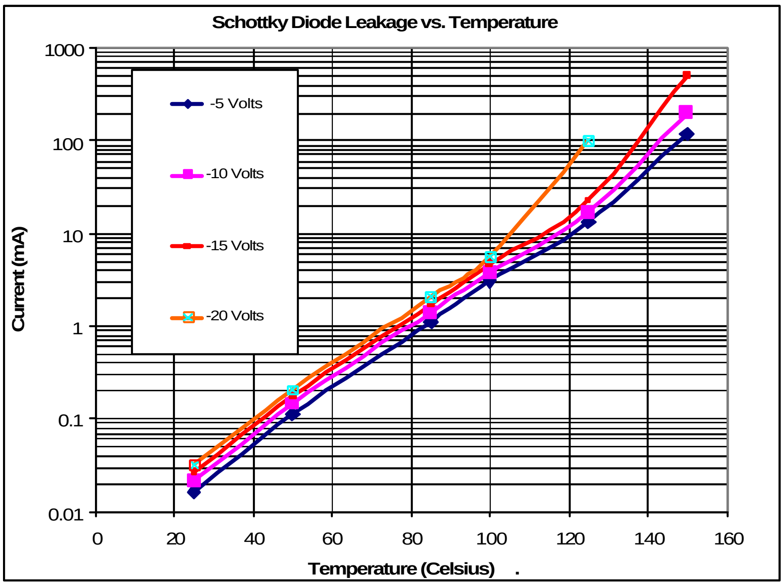


Fig. 5.

Note that the leakage at 105 ºC was only about 5mA. Further, notice that at 150 ºC, the diode leakage is now above 100mA and can only be applied for a very short time (1-2 seconds) before thermal runaway occurs. For the case of -20 volts, thermal runaway occurred earlier. The implications of this thermal runaway will become apparent in the next section.

Transitioning from the "Shaded" to the "Unshaded" condition

Lacking airflow in the junction box, the forward biased diode during shading can reach 150-200 ºC. When the bypass diode returns to its normal reverse-biased condition, the temperature of the diode will cool down. But this cooling does not happen right away. This is a critical point to understand. During this transition, the diode leakage will be very high due to the residual forward-biased self-heating (as high as 0.1 to 0.5 amps) and, in turn, can easily maintain self-heating due to high leakage current multiplied by the 10 volts of reverse bias.

With the reverse biased diodes tested at 105 ºC, 20 percent failed at 500 hours. Increase the temperature to 155 ºC and expect 20% failures at 31 hours (by Arrhenius's equation).

In instances of frequent shading, the accumulated effect of the “shaded-to-unshaded” transition periods will degrade the lifetime of the diode.

This was observed in the lab under controlled conditions. The same diode was placed in a pre-heated oven at 85 ºC with no air flow (important: no air flow). A forward current of 4.75 A was applied until reasonable self-heating occurred. When the current was shut off and -10 volt bias was applied, the leakage current immediately increased to 125mA and then entered thermal runaway, and ultimately, tripped the safety clamp of the current supply. With 4.5 A, the result was just short of a thermal runaway event. At the lab-replicated “shaded-to-unshaded” transition, the leakage current shot to 75mA and then slowly decayed back to 2mA approximately following:

$$I_{LEAKAGE}(t) = 75 milliAmps * e^{\frac{-t}{40\sec}}.$$

Although some heat sinking was used in the above experiment, it apparently was not enough.

To the best of this author’s knowledge, this potential failure mode has not been investigated. But considering that it was created fairly easily in the lab, it is very possible that it is occasionally occurring.

Two possible solutions are possible for the problem of over-heating. Add an infinite heat sink to prevent the bypass diode’s junction temperature from ever getting above 100 ºC during forward conduction. Alternately, migrate to a new technology node and use lossless diodes with negligible self-heating. A “lossless” diode with a 40-50mV forward voltage at 10 amperes will only generate a 5 to 10 ºC rise over ambient.

Lightning/Surge Current Survivability

Solar systems are fully exposed to outdoor conditions and must endure at least some transient energy induced by nearby lightning storms. The frequency of lightning strikes per Megawatt of installed power varies by region, but it is not a negligible number.

A very good study was performed in 2007 by Professor Haeberlin of Berne University (“Damages at Bypass Diodes by Induced Voltages and Currents in PV Modules Caused by Nearby Lightning Currents”). The reported failure mode for the diode was interesting. The majority of the transient energy stressing the bypass diode was not coupled in via the “mains.” It was actually coupled in via a local magnetic loop antenna. This local loop was comprised of the bypass grouping of 12 to 24 cells with a return path through the bypass diode. This magnetic loop antenna area depends on the module’s cell layout. As the lightning surge strikes nearby with 250kA/µs, the magnetic field couples into the local loop antenna. This in turn induces 100’s to 1000’s of amperes of transient current that the bypass diode must endure.

IEC 61000-4-5 gives a standardized IEC method for examining this effect. A capacitor bank is pre-charged to some level (i.e., 600 volts) and then discharged through an inductor into a design under test. Schottky diodes can withstand about 0.05 to 0.1 Joules of this energy when injected into the cathode before permanent damage occurs. By comparison, "Lossless" diodes can survive about 1.4 Joules (or more).

Many module warranties today do not cover lightning damage. Lacking a direct strike, however, there will not be a "tell-tale" that lightning made the diode leaky. As a result, the manufacturer may have to honor the warranty. It is difficult for a failure analysis effort to say, definitively, what caused a diode to be leaky once it is removed from the field.

Conclusion

Solar installation owners are chasing every Joule of harvestable energy and will demand higher performance if they detect that their operational profit margins are at risk. Tracking bypass diode failures has traditionally been a challenge, but now, with the advent of Individual Module Monitoring solutions, the incidence of detected failure will likely rise. It may be time for the bypass function to move to a new technology node of "lossless" diodes.

About the author

Shawn Fahrenbruch is an analog integrated circuit design engineer employed by Microsemi Corporation and can be contacted at sfahrenbruch@microsemi.com. He received is BSEE/MSEE from Montana State University in 1993/1995. Most recently, he designed Microsemi's LX2400 lossless "CoolRUN™" solar bypass active diode.