US TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias
Diode ESD Characterization

Contains no confidential information.

Kent Whitfield

with thanks to Solaria for their support of this work

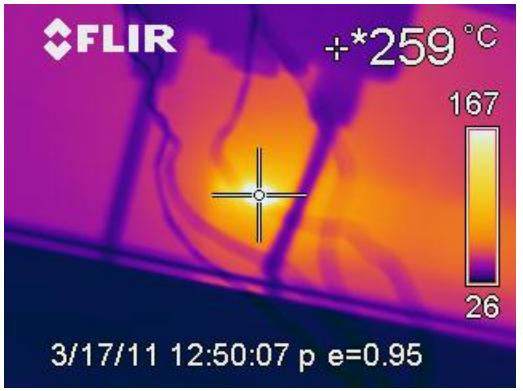
Overview of Presentation

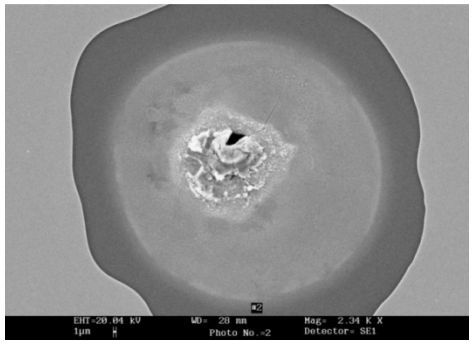
- ESD Surge Characterization of Schottky Diodes
  - Motivation – Why ESD characterization of diodes might be important
    - History
    - Case study
    - Observations from failed diodes
  - Methods to characterize a diode's ESD tolerance
    - Environment
    - Testing methods
    - Proposed procedure
    - Data analysis
    - Correlation to failures encountered
  - Next steps

A Completely Selective History

- 1985: General diode reliability guidelines based primarily on operational temperature.
- 1993: 20k modules had a 50% failure rate over ten years.
  - 90% of the failures were from common causes that included lack of adequate bypass diode protection (hot spot failures).
- 2011: Task Group 4 reviewed testing standards and identified potential gaps:
  - Accuracy of diode technical data sheet.
  - Qualification tests that ensure reliability.
  - *Electrostatic Discharge (ESD) susceptibility.*

Diode Type	Maximum Allowable Junction Temperature	Derated Temperature for Long-Term Reliability
p-n	175°C	125°C
Schottky	125°C	75°C



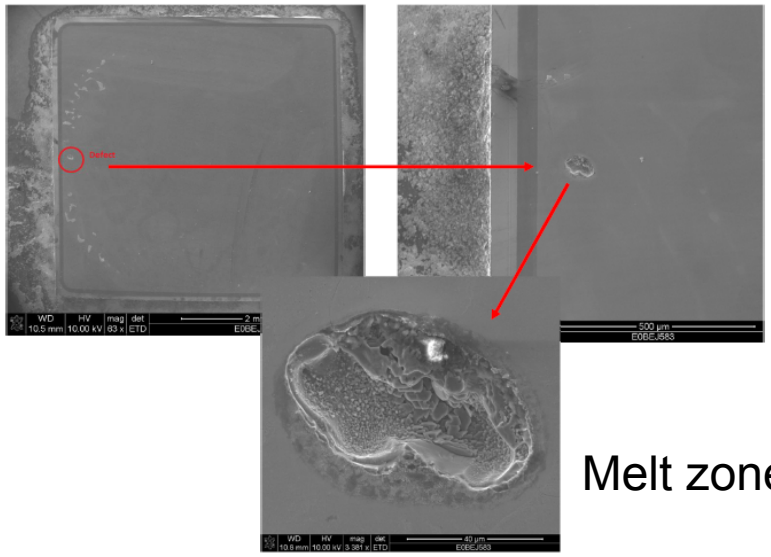


Case Study

- Field Failure Data: Anecdotal, mostly onesy-twosey, occasional large scale at *A* site. Suggests some batch/site-specific behavior.
- Undisputed: Schottky diodes are found to fail at a measurable rates in production – Final IV curve/EL.
  - 2011: Sudden onset of certification samples and production modules being found with shorted diodes.
  - No process or design change and some certification tests NOT related to diodes:
    - TC50, TC200, DH1000, Preconditioning???
  - Failure rate goes from 0.0% to 0.4% in one facility, but in another with ESDS 20.20 compliance, rates stays at 0.0%.

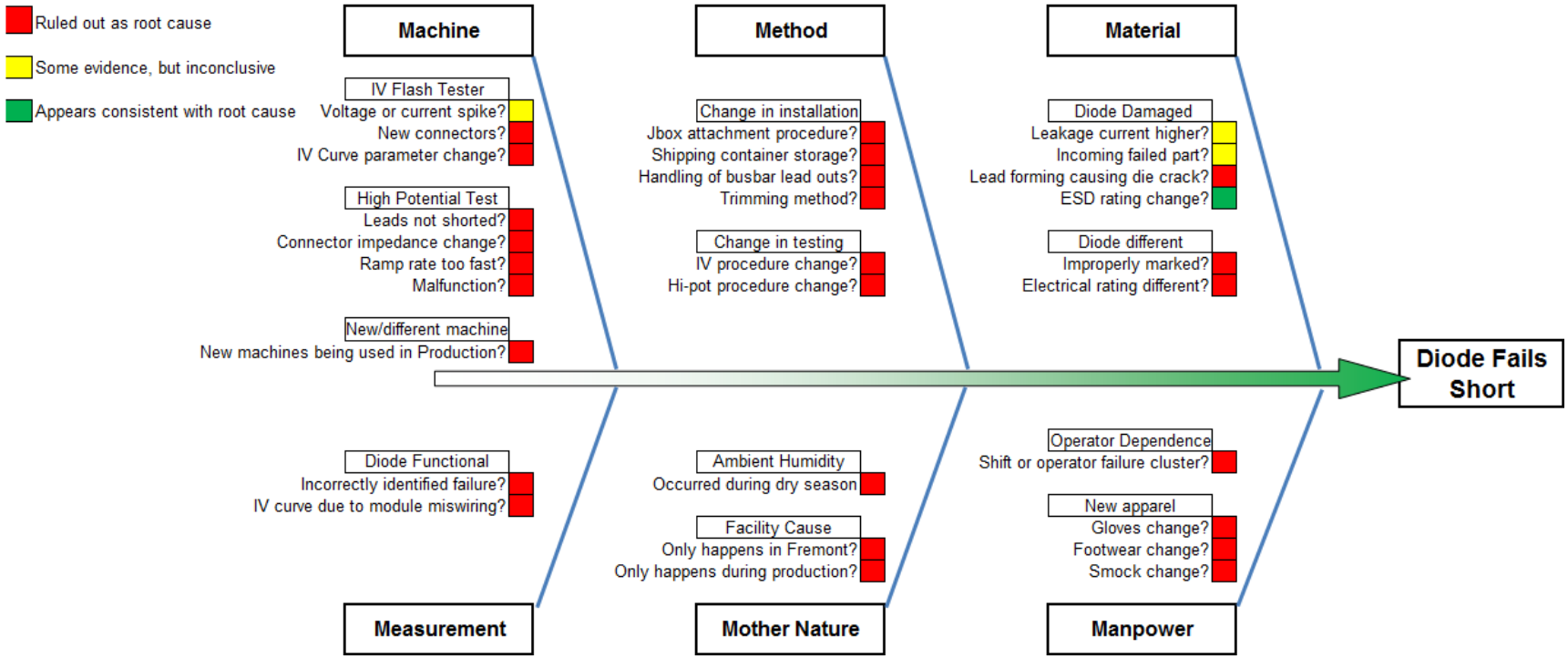
More Observations

- Decap and FA indicates all diodes of suffering from electrical overstress – but inconsistent from ESD alone due to presence of melted regions.
- Failed diodes happen to conform to a specific date code range.



Melt zone

Ye' Ol' Fishbone



- Evidence seems to point to ESD susceptibility change *in this case study only*.
- Bigger question is what is the susceptibility?

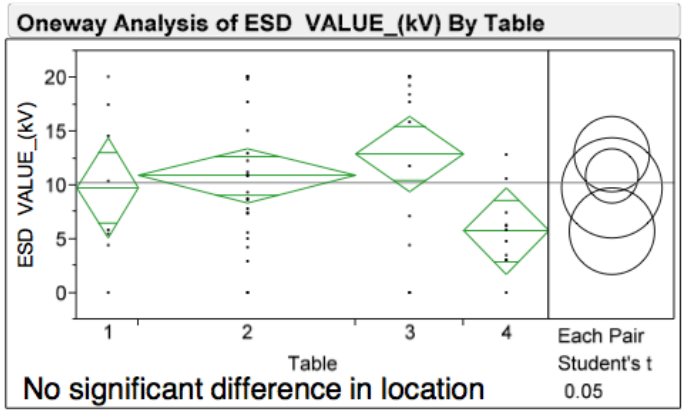
Characterization of Environment

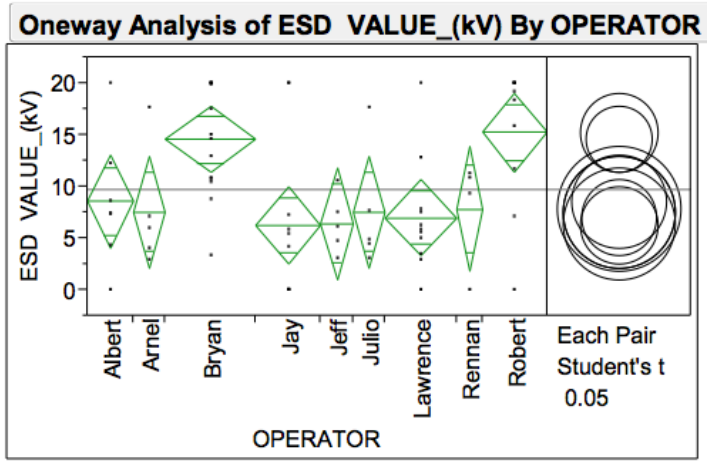
- Electrostatic voltage in the facility.
  - Simple, low-cost test equipment and fast to characterize.
  - Cannot gauge charge transfer which is critical to the ESD failure mode.
- ESD event meter.
  - Simple, but higher-costing test equipment.
  - Can gauge peak voltage stress associated with standard charge transfer models.

JBOX INSTALLATION STEP (measurement date 10 Oct 2011)	Measured Voltage (V)
Opening shipping container and measuring jbox potential while still in box	+1,260
Preparation table resting voltage	+90
Removal of Jbox from box and placement on table. Resulting jbox voltage.	+470
Placing two strips of double-sided tape on jbox. Max voltage.	+120
Jbox voltage after applying perimeter silicone adhesive.	+130
Jbox voltage after removing double-sided tape release liner. Max voltage.	+2500
Placing Jbox on laminate. Maximum box voltage.	+50
MODULE TESTING CONDITIONS	
Flash simulator curtain voltage. (NOT JBOX)	+200
Flash simulator structure voltage. (NOT JBOX)	+50
LAMINATE CONDITIONS	
Laminator outfeed belt voltage (NOT JBOX).	+250
Laminate on outfeed conveyer belt (NOT JBOX)	+110
Laminate on table post backsheet trimming operation	+110
SEPARATE WORK AREA KNOWN TO HAVE A HIGH STATIC POTENTIAL	
EVA Roll	-3500
Backsheet Roll	-56,000

Knowns

- Schottky diodes more susceptible to ESD damage.
- ESD events may occur from
  - human contact only, or
  - In-house charged-device/ operator interaction such as jbox installation, connecting to test equipment (hi-pot, IV, EL), or
  - 3rd party charged device interaction, or
  - In field installation.

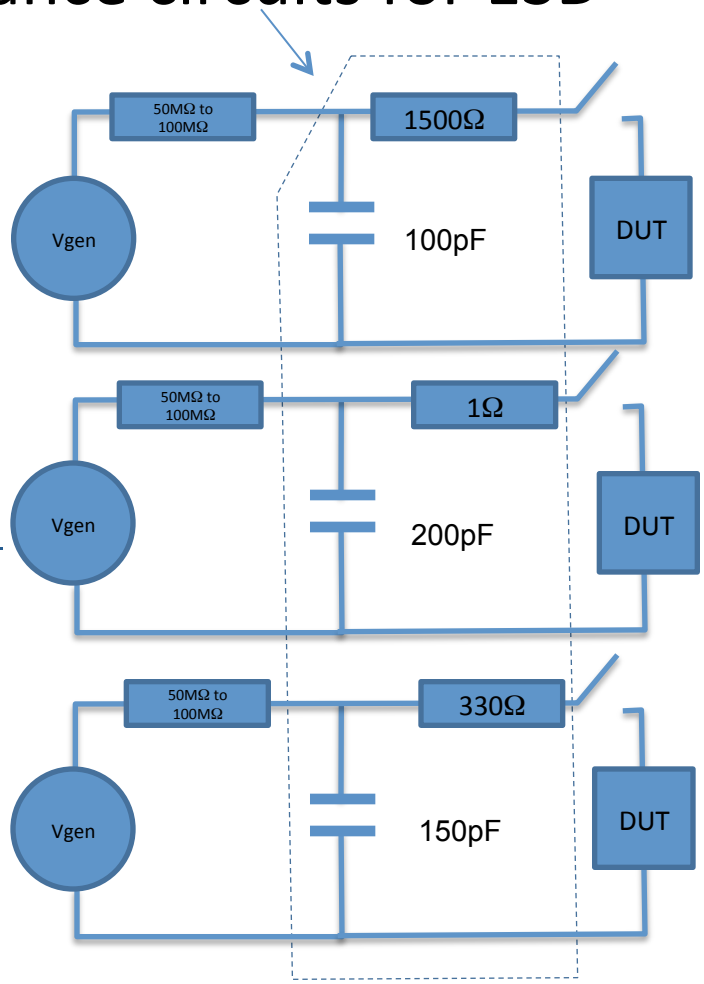




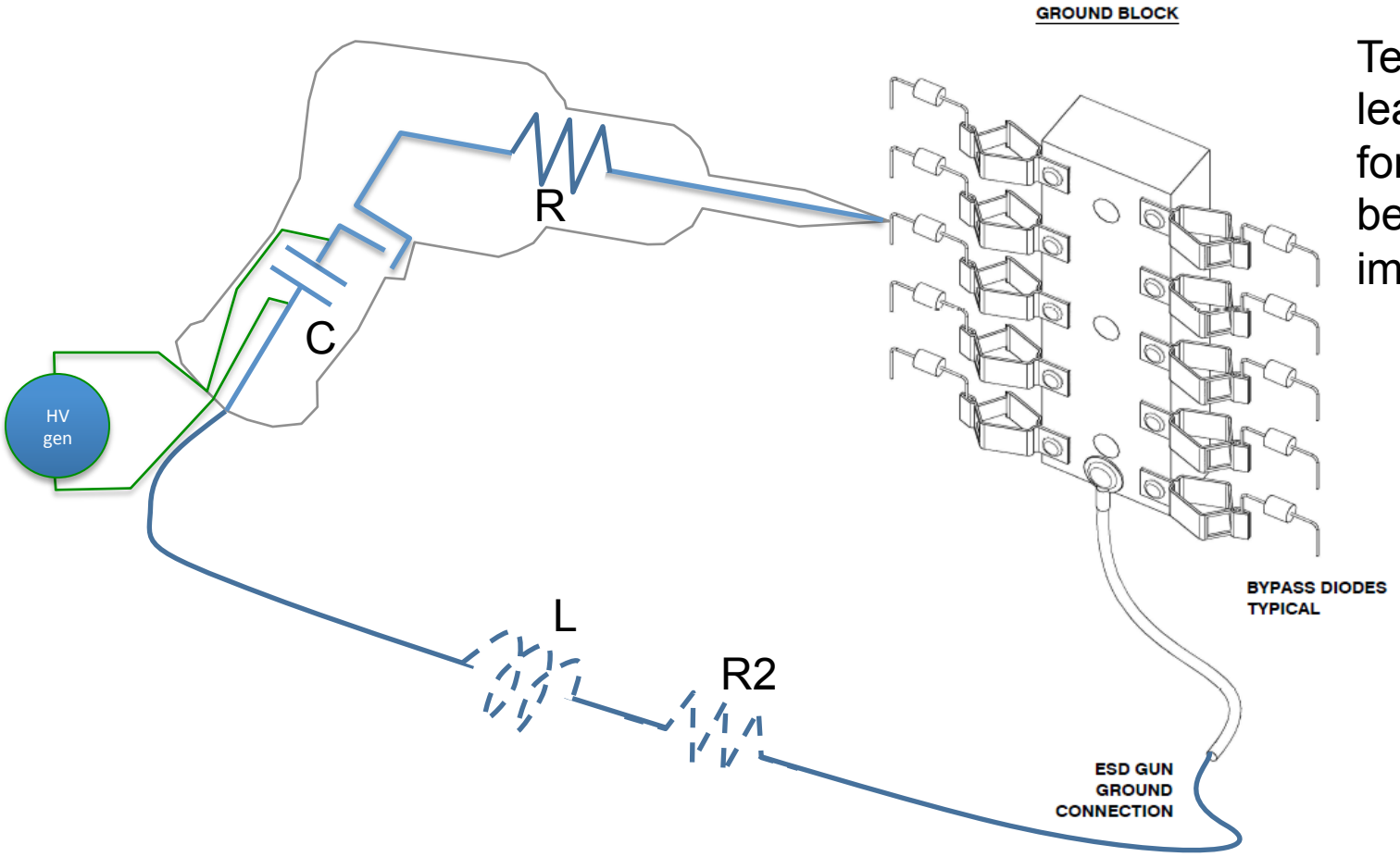
Some statistical difference between people

How to Characterize Susceptibility

- Most commonly used impedance circuits for ESD testing are:
  - Impedance Circuits:
    - ANSI/ESDA/JEDEC JS-001 – Human Body Model
      - Bare finger
    - JEDEC JESD22-A115C – Machine Model
      - Charged machine
    - IEC 61000-4-2 – ESD Immunity
      - Discharges from operators



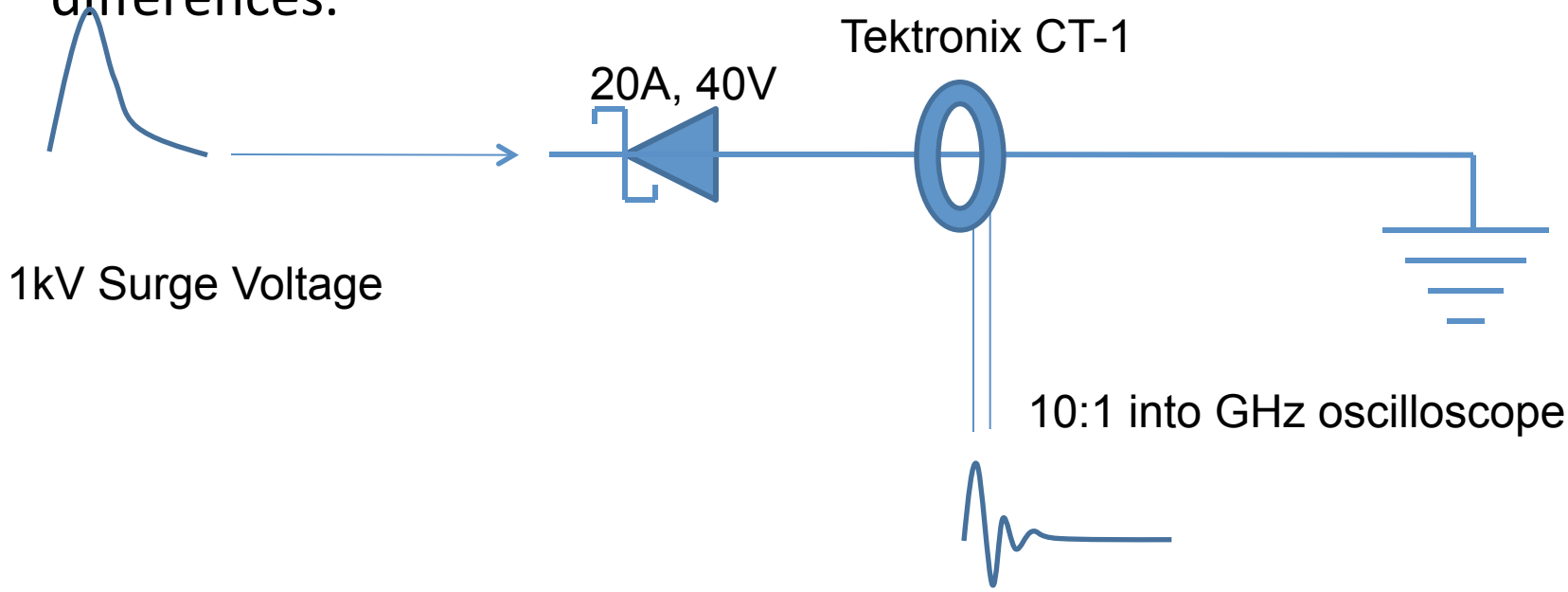
Set Up



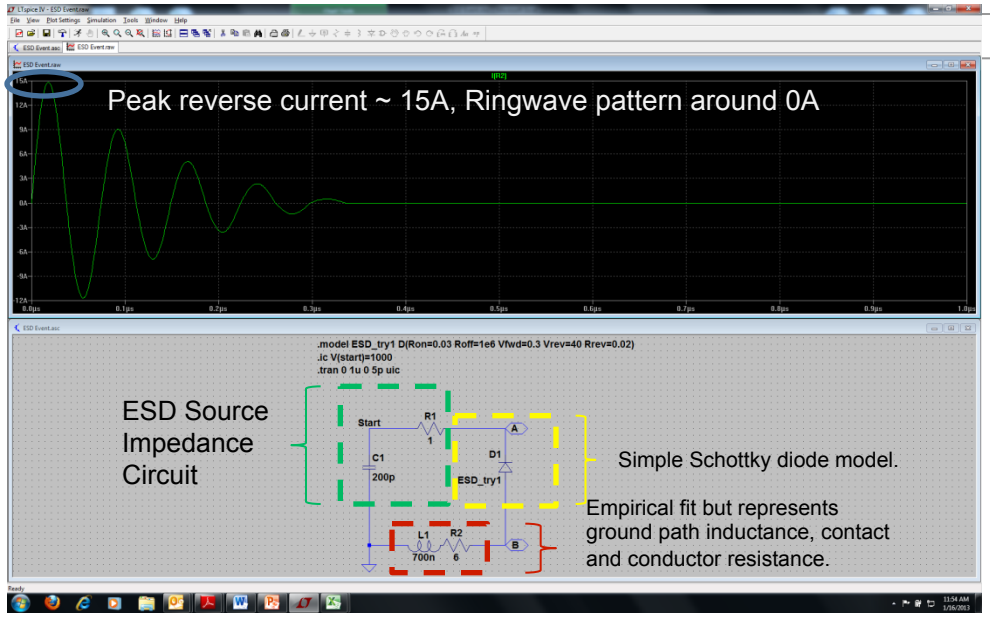
Testing with leads already formed for jbox believed to be important.

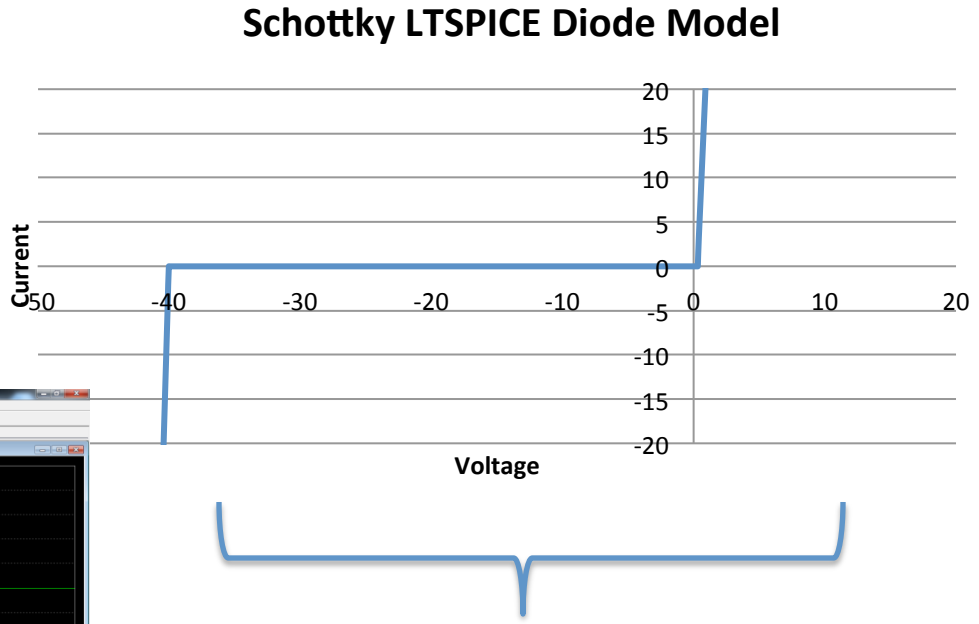
Differences in the Impedance Circuits

- Hard to measure voltage and current during actual test without affecting results.
- Contact repeatability issues also occur.
- So, validate a LTSpice model against real current waveforms and use model to improve understanding of surge differences.



LTSPICE Model Machine Model Impedance

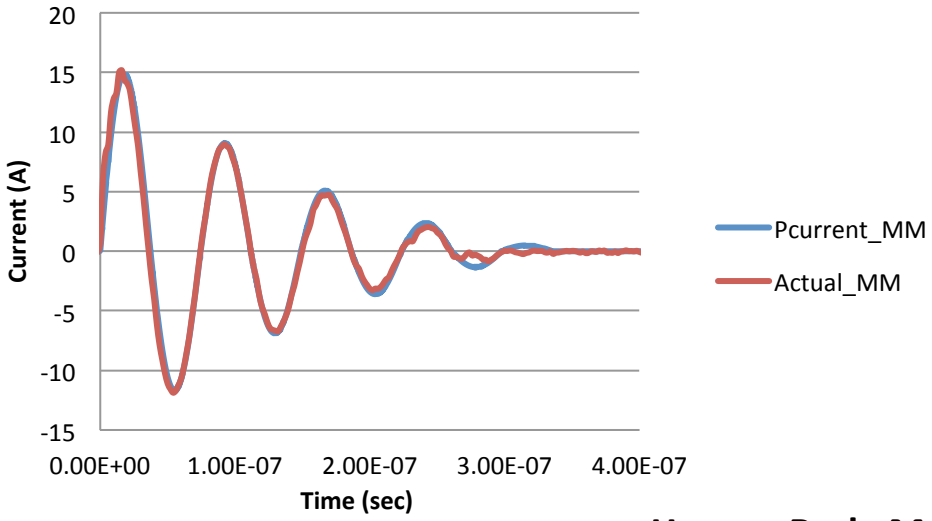




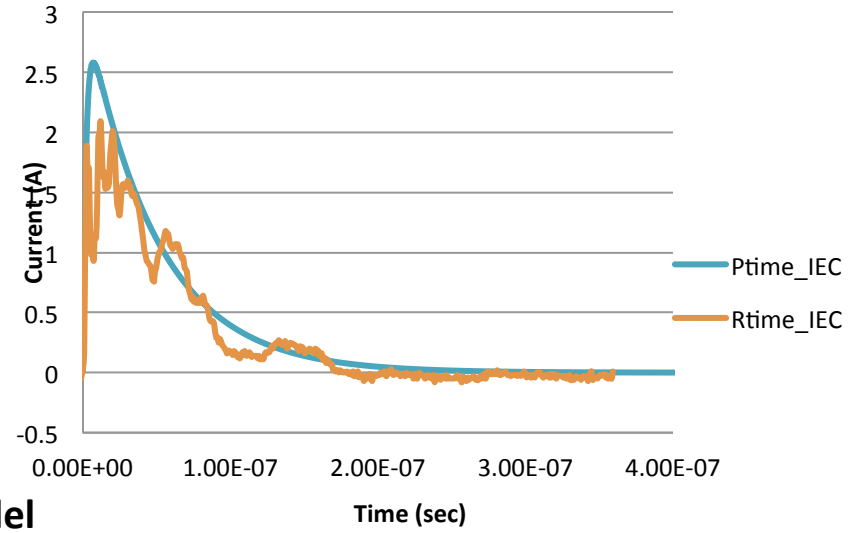
Key Consideration – This model diode is fully recoverable in the breakdown region regardless of current. Actual diodes are also fully recoverable in breakdown below a specific current threshold at a specific temperature.

Comparison to Actual

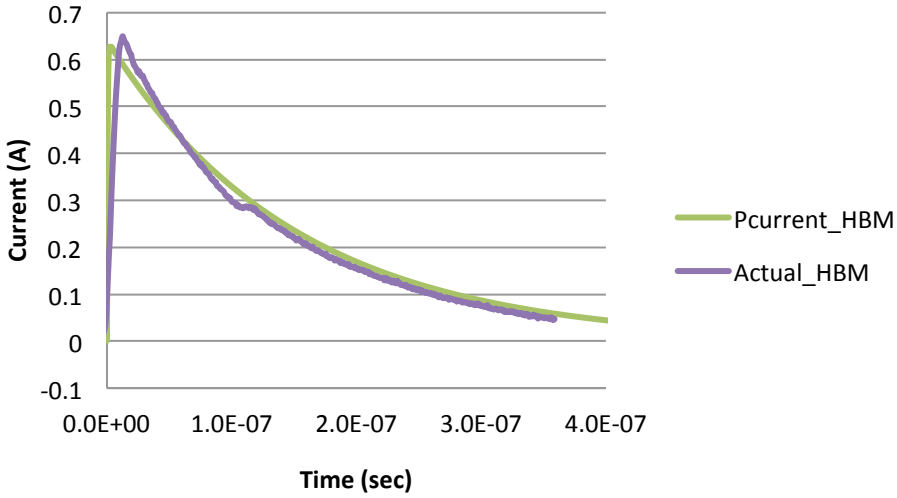
Machine Model



IEC 61000-4-2

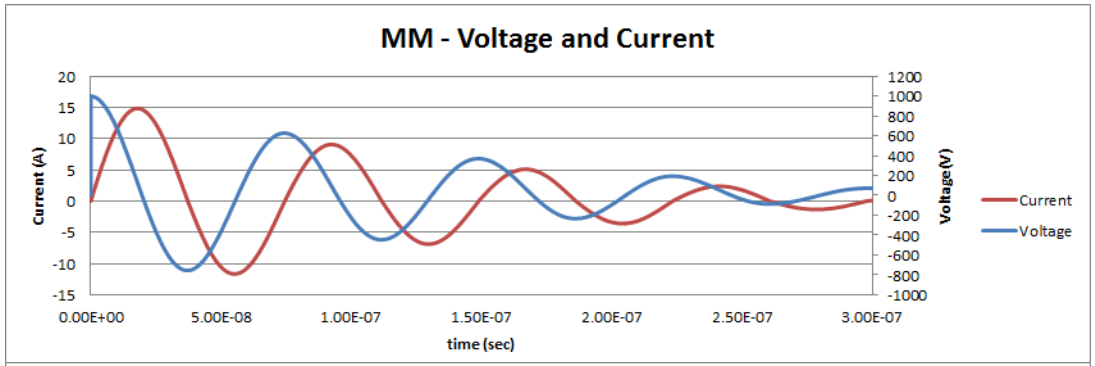


Human Body Model

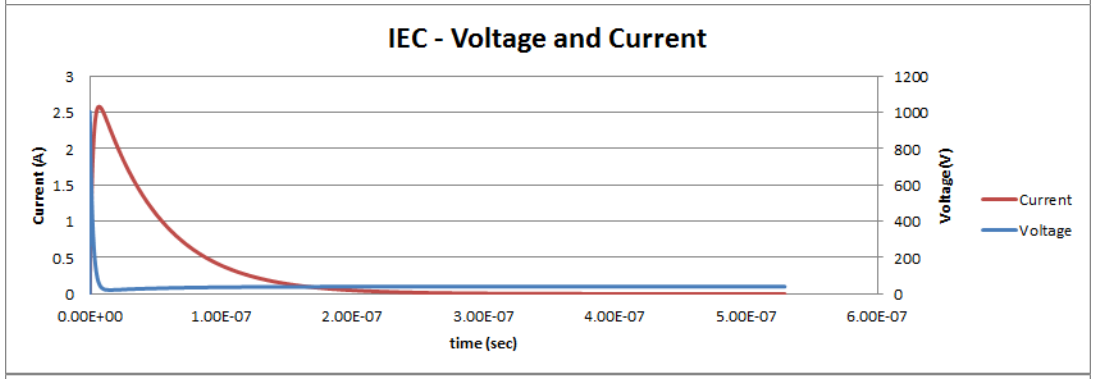


One model matches real current waveform quite well!

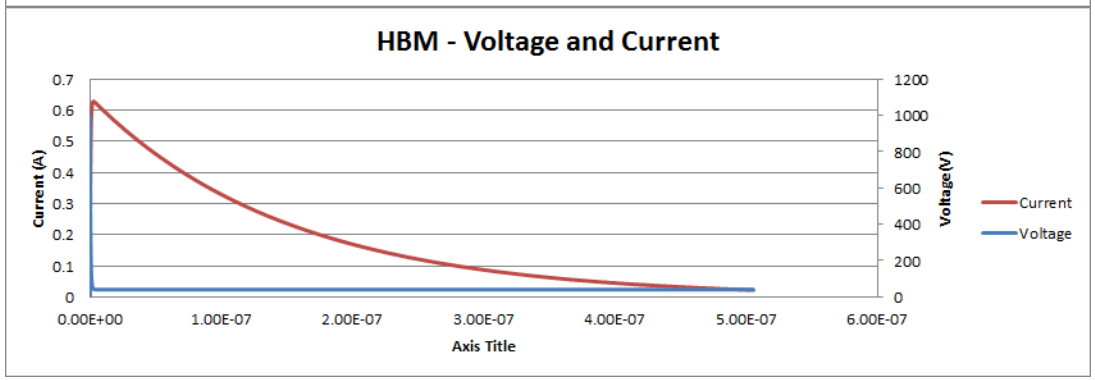
LTSPICE Voltage and Current



Numerically integrated surge energy ~0.4 mJ



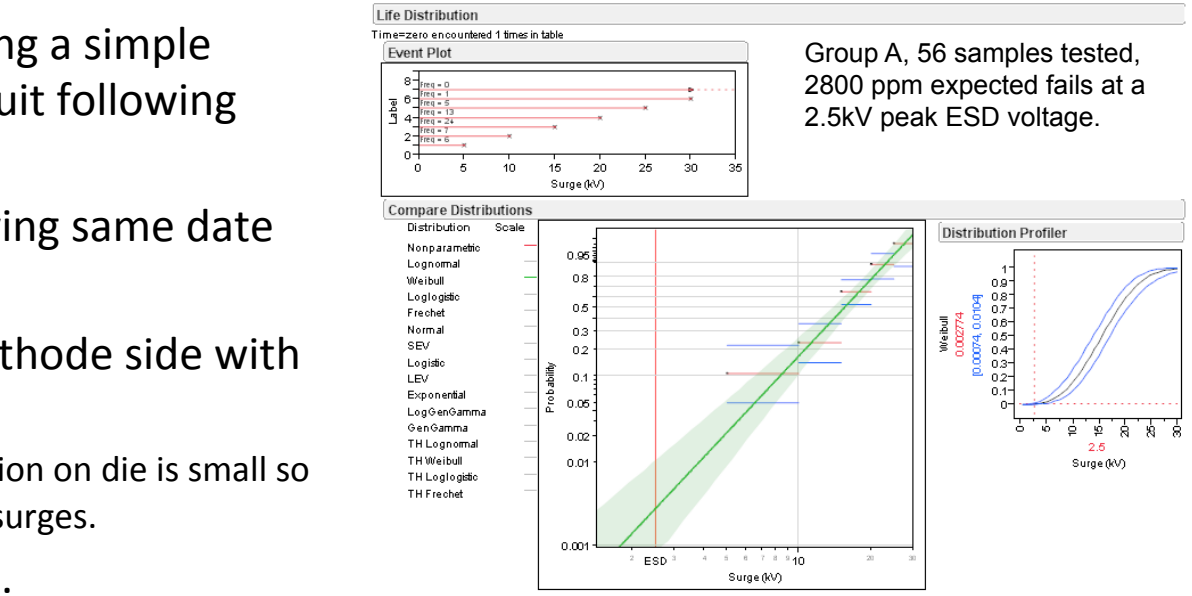
Numerically integrated surge energy ~7 μJ



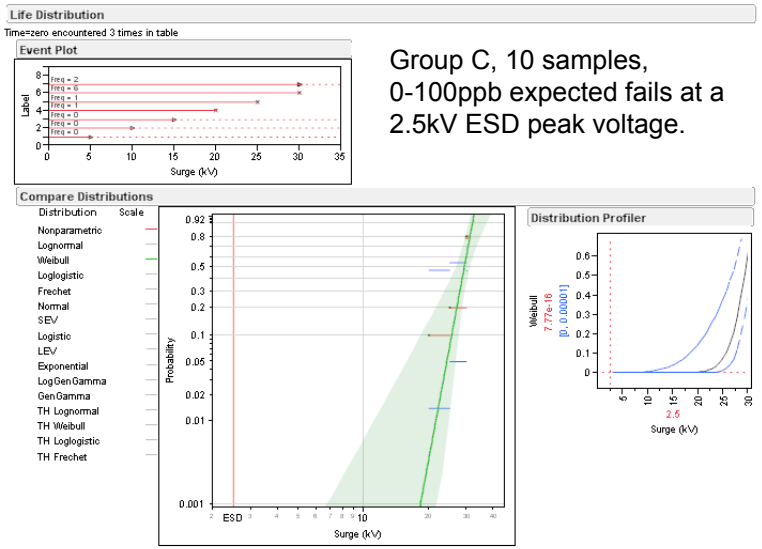
Numerically integrated surge energy ~4 μJ

Arrived at ESD Testing Method

- 5kV steps from 5kV to 30kV using a simple multimeter check for short-circuit following surge application.
- Sample size of 10 diodes all having same date code.
- 10 positive surges applied to cathode side with 10 seconds between surges.
  - Literature suggests breakdown region on die is small so relaxation time required between surges.
- A Weibull curve used to fit data.
  - Where we have substituted surge voltage for time.
  - The CDF is thus interpreted to mean fraction of all units in the population which will fail by V peak voltage having a voltage and current waveform given by the IEC model.
  - Shaded region indicates a 95% confidence interval around the median line.



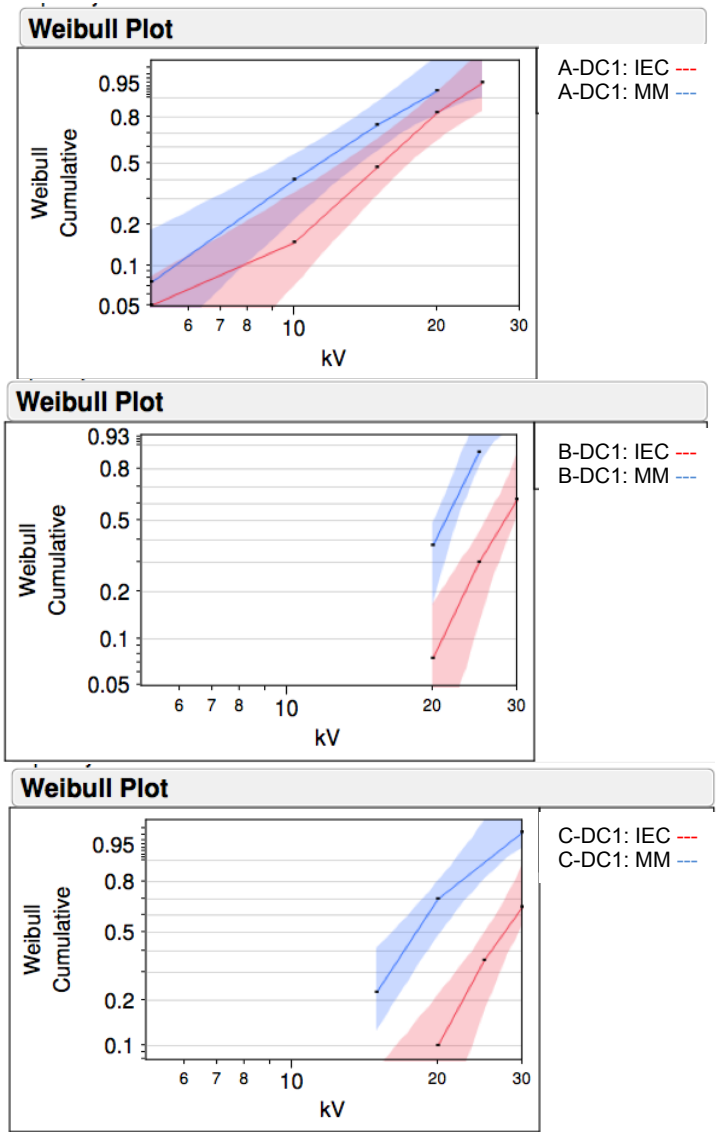
Group A, 56 samples tested, 2800 ppm expected fails at a 2.5kV peak ESD voltage.



Group C, 10 samples, 0-100ppb expected fails at a 2.5kV ESD peak voltage.

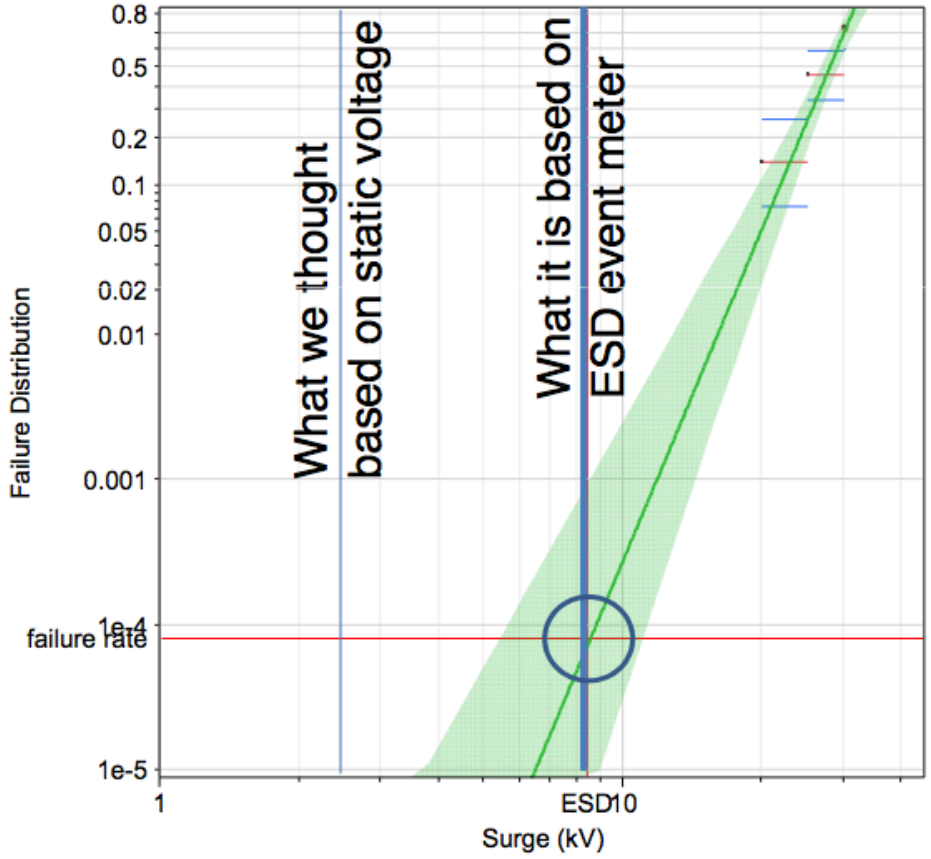
ESD Surge Testing

- Basis of ESD Test – IEC 61000-4-2
- Surge-to-Failure, Step-Stress Program. Considered following variables:
  - Impact to reverse leakage current at room temperature
    - No correlation below failure threshold.
  - Impact to reverse leakage current when diode is at 60C
    - No correlation below failure threshold.
  - Impact of positive surges against anode side of diode
    - No failures observed.
  - Impact of positive surges against cathode side
    - Resulted in failures.
  - Impact of sample size
    - Similarity of failure distributions exists with samples sizes from 10 to 60 at 95% confidence,
  - Impact of number of surges applied per stress step
    - Similarity of failure distributions exist with 5 to 50 surges at 95% confidence.
  - Compared results using IEC model with Machine Model
    - Failure distributions are similar in Weibull space, but shifted to lower voltages in the Machine Model.



Some Confirmation of Technique

- Static voltage measurement indicated a 2500V risk in area of jbox installation.
- Tested a group of diodes using IEC model and selected one that SHOULD result in a 7.2ppb failure rate of at this level of ESD voltage.
- Actual failure rate in production found to be 82ppm!
- Changed in-house measurement from static voltage to actual ESD event detection.
- Measured 47 ESD events and mean found to be 8.2kV *NOT 2.5kV*.
- This mean correlated well with the observed production failure rate.



Conclusion and Next Steps

- ESD found to damage Schottky diodes.
- ESD events triggered when there is an interaction between charged devices during installation or testing although there appears to also be some operator interaction.
- Failure rates differ from diode-to-diode even when ratings are the same.
- A test procedure based IEC surge standard seems to be useful in characterizing diode ESD susceptibility.
- NEED other manufacturers to corroborate findings.
- PROPOSE a test method in IEC TC82, WG2 but without pass/ fail criteria.

Thank you!

On the occurrence of thermal runaway in Diode in the J-box

J-TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias

Feb. 26-27, 2013 ***@ Denver, USA***

Y. Uchida / JET (Japan Electrical & Environment Technology Laboratories)

Y. Konishi / ONAMBA CO.,LTD.

T. Okura / SOMA OPTICS, LTD.

J-TG4 Activity Report

J-TG4 activities had been reported in the following events ;

1. Dec.08, 2011 — 2nd. QA Forum Tokyo
2. Feb. 28, 2012 — NREL PV Module Reliability Work-shop
3. May 07, 2012 — WG2 STRESA meeting
4. Oct.01, 2012 — WG2 Oslo meeting
5. Nov.27, 2012 — 3rd. QA Forum Tokyo
6. **Feb.26,27, 2013 — NREL PV Module Reliability Work-shop**

Background

→ Trend of Bypass diode from P/N Si diode to SBD

■ This trend is because of the addition of “Bypass diode thermal test” in IEC 61215 Ed2. (2005-04),

①When applying current of Isc at 75℃, diode junction temperature shall not exceed max. rated Tj.

②When applying current of "1.25XIsc" at 75 ℃, the function of diode shall not be impaired.

On top of the above requirements, due to the pressure of the price reduction of diode and suppression of heat-up, the bypass diode has switched to the SBD with low Vf .

Test reports

Test① Continuous current test for J-box

①-1 for Diode-A

①-2 for J-box-A

Test② Intermittent current test for Diode

②-1 for Diode-A

②-2 for Diode-B

Reported at WG2 Oslo meeting.

Test③ Reverse bias test at high temperature (Thermal runaway test)

③-1 for J-box-A / with potting

③-2 for J-box-B-1 / without potting

for J-box-B-2 / without potting

③-3 for J-box-C / without potting

Contents of this report

1. **Thermal runaway test results of J-boxes**

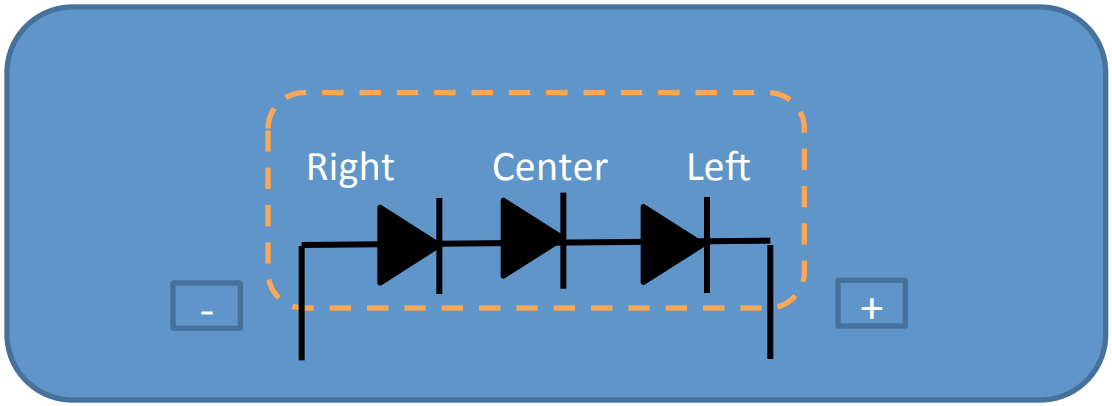
2. Tj measurement method for Bypass diode

J-boxes for Thermal-runaway tests

J-box-A

J-box-B

J-box-C



Summary of “Reverse bias test at high temperature” ;

Test ③-1 ; J-box-A / with potting (Test sequence : ①center→②right→ ③left)

■ Chamber temp. : 90℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	9A	1. Center ○	2. Center ○	3. Center ○	
	11A	4. Center ○	5. Center ○	6. Center ×	
	12A	7. Right ○	8. Right×		
	13A	9. Left ×			

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

Summary of "Reverse bias test at high temperature" :

Test ③-2 ; J-box-B-1 / without potting

■Chamber temp. : 75℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○	10. Center ○		
	11A	9. Center ○	11. Center ×		
	12A				

Summary of "Reverse bias test at high temperature" :

Test ③-2 ; J-box-B-2 #3 / without potting (Test sequence : ①center→②right→ ③left)

		Left diode		Center diode		Right diode	
VR; reverse voltage		15VR	20VR	15VR	20VR	15VR	20VR
■ Chamber temp. : 75C							
If	8A	Not done	Not done	1. ○	3. ○	1. ○	3. ○
	9A	Not done	Not done	2. ○	5. ○	2. ○	5. ○
	11A	Not done	Not done	4. ○	Not done	4. ○	Not done
■ Chamber temp. : 90C							
If	8A	Not done	Not done	6. ○	8. ○	6. ○	9. ○
	9A	Not done	1. ○	7. ○	—	7. ○	10. ○
	11A	2. ○	3. ×	9. ×	—	8. ○	11. ○
	12A	—	—	—	—	12. ○	13. ×

Summary of “Reverse bias test at high temperature” ;

Test ③-3 ; J-box-C / without potting

■Chamber temp. : 75℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○			
	11A	9. Center×			
	12A				

Temperature of each diode in J-box under the forward current

J-box-A-3 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	130.2	131.2	129.2

J-box-B-1 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	160.1	173.3	158.7
11A	178.7	192.7	176.8
12A	187.5	201.5	184.5
13A	195.5	212.1	193.7

J-box-B-1 / Chamber temp. ; 90℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	171.0	182.6	169.8
11A	189.2	201.4	186.4
12A	197.2	211.3	194.3
13A	205.3	220.1	203.7

The temperature of the center diode is affected by the left and right diodes and becomes the highest.

Note ;
The Tj was obtained from the Vf value using Vf-Tj relation.

Results of the study -1

1. We were able to confirm the thermal runaway of the SBD during high-temperature reverse bias.

2. As for the thermal runaway, the timing of switching from forward to reverse is important.

3. We have confirmed that the conditions for the thermal runaway was different according to the type of J-box (ex. ; J-box shape and with or without the potting materials).

   → We are planning to perform the thermal runaway test for some more J-boxes with different diodes.

4. In case of typical J-box with 3 diodes in the box, the temperature of the center diode is affected by the left and right side diodes and becomes the highest.

Contents of this report

1. Thermal runaway test results of J-boxes

2. Tj measurement method for Bypass diode

T_{lead} method vs Vf-Tj method

From our experiment,

As for Diode Tj, the difference was confirmed in "Vf-Tj method" and "T_{lead} method".

→ with experimental data on the next page.

Test sample ; J-box-B-2

[Chamber temp. ; 75℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	158.1	160.1	165.0	173.3	143.1	158.7
	11A	175.2	178.7	183.4	192.7	156.9	176.8
	12A	183.5	187.5	192.4	201.5	164.0	184.5
	13A	192.0	195.5	201.2	212.1	170.7	193.7

[Chamber temp. ; 90℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	168.8	171	175.2	182.6	154.2	169.8
	11A	185.4	189.2	192.8	201.4	168.1	186.4
	12A	193.7	197.2	201.9	211.3	174.7	194.3
	13A	201.7	205.3	210.4	220.1	181.3	203.7

Note 1. : Tlead ; Tj by "Tlead method"
Tj = Tlead + (Rth × Vf × If), Rth= 2.5℃/W provided by diode maker
Note 2. : Vf-Tj ; Tj by "Vf-Tj method"
in accordance with "IEC61646 Ed.2 10.18 Btpass diode thermal test / Procedure 2"

Why always
Tlead < Vf-Tj ?

Tlead method

The correct Tj can not be obtained by Tlead method.

Because, the thermal resistance (Rth) could vary.

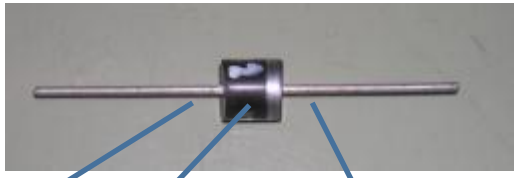
$$Tj = Tlead + (Rth \times If \times Vf)$$

The reason that thermal resistance varies is as follows;

there is a difference in heat radiation conditions because diodes are installed in various J-box.

→ We are now measuring in order to obtain the support data.

Heat flow from Diode chip



Rc-1 < Ra-1 << Rb-1

Cathode

Rc-1 — C — Rc-2

Cc : heat flow on the cathode side

Ca : heat flow on the anode side

Ra-1 — A — Ra-2

Anode

Cb : heat flow on the diode body

Rb-1 — B — Rb-2

Body

Ambient

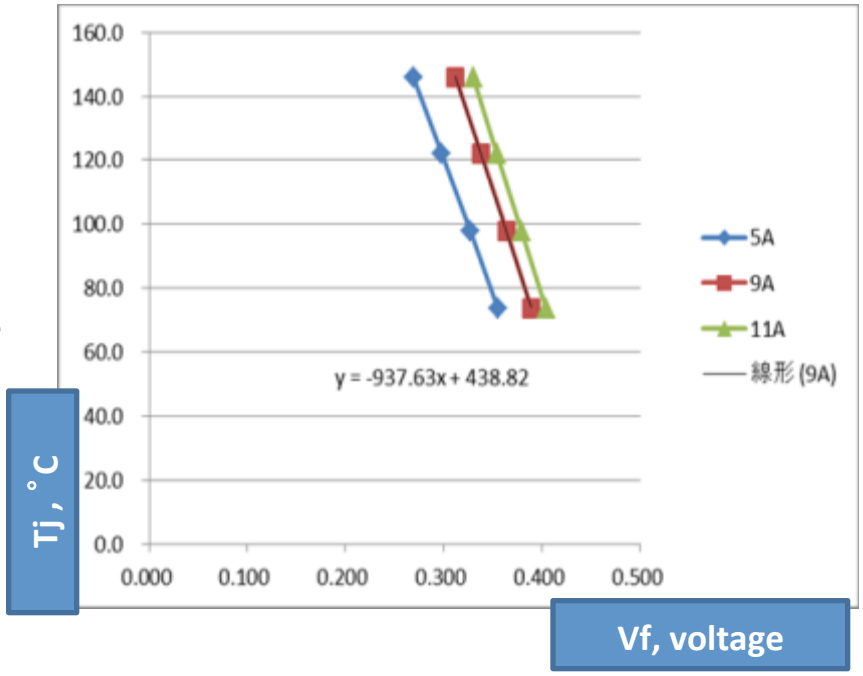
Thermal source
(Diode chip)
P = Vf X If

Heat flow varies with the radiation conditions !!!!!

Tj = Tlead + Vf×If × Cc × Rth (→ real Rth) → **apparent Rth**

Vf – Tj method

- **Once Vf-Tj relation is obtained,**
  Tj is easily decided from the value of Vf.
  Vf-Tj relation can be acquired by measuring the temperature of the lead and the voltage across the diode in thermal equilibrium condition.



Results of the study -2 (1/2)

From this experiment, the difference was confirmed in Vf-Tj method and Tlead method as for Tj of diode.

Regarding the thermal resistance (Rth) by Tlead method, Rth is provided by Diode maker.

When it is assembled into the J-box, an apparent Rth will vary because of the influence of wiring left and right side diodes, including Heat-sink.

$$Tj = Tlead + (Rth \times If \times Vf)$$

Results of the study -2 (2/2)

Therefore, we should use the Vf-Tj method in accordance with "paragraph 10.18 Bypass diode thermal test / procedure 2 specified in IEC61646".

In order to continue accumulating technical data for Tj of diodes, we would like to propose a Vf-Tj method.

Next activities

1. Establishment of a method of thermal design verification test for J-box, and preparation of a draft standard

2. Development and manufacturing of thermal runaway test equipment

3. Suggestions for improvement of Diode Tj measurement method

4. In order to discuss the rating system, we have to confirm the changes of the characteristics of reverse bias after long term reliability test.

Thank you for your attention.

Acknowledgment ;
I would like to thank those who have helped us i.e. SHARP, Onamba, Nihon Inter Electronics, Sanken Electronic and SOMA Optics.

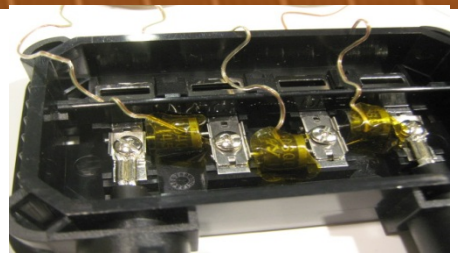
Posters

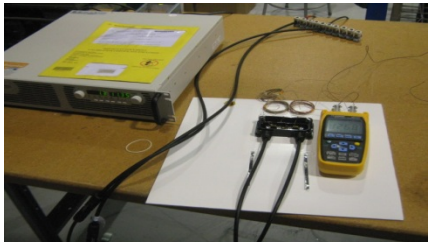
International PV Module Quality Assurance Forum

Task-4 Region US

Problem Description

- By-pass diodes generally get “activated” during a shading occurrence in the field.
- For a 72-cell module with 3 by-pass diodes per module, the diodes are typically of the Schottky type and rated 40 to 45 V for maximum reverse voltage and 10 to 20 A for maximum forward current and maximum junction temperature of 150°C.
- Right after a shading occurrence and while the diode is still at high temperature, the diode goes into the normal mode where it sees the operating voltage of 24 cells or roughly 8 to 12 V and that induces a reverse leakage current that can exceed the diode reverse current rating at that temperature with the destruction of that diode most likely in the open mode, although shorted diodes have also been seen.
- We developed a very simple method to test diodes in a j-box or individually in the lab without the need for a sophisticated thermal chamber.

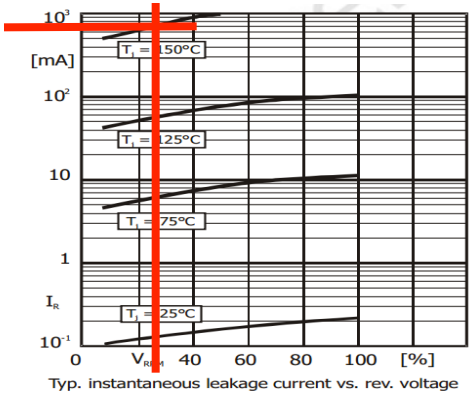




Simple Test Procedure

- 30 A 60 V power supply
- Thermo-couples and Fluke meter
- Connect diodes in forward mode and pass 12 to 15 A (note that the central diode always heats up faster)
- Wait until diodes temperature reaches 150°C
- Quickly reverse polarities and apply 10V per diode while reading the reverse current
- High current diodes fail quickly in a “ run-away” mode; i.e. the hotter they get the more current they pass and so forth until the junction melts
- Lower current diodes cool down and stabilize safely at relatively low current.
- Tests were also done on individual diodes as well, outside the j-box with similar results

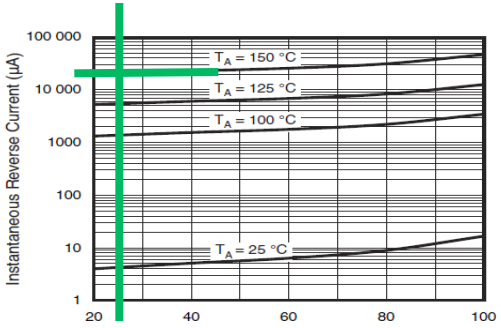
High Reverse Current Diode



Typ. instantaneous leakage current vs. rev. voltage

- Vr = 10V or 25% or Vrmax
- Ir is then 700 mA at 150°C
- P reverse is 7 W
- Diode exceeds 200°C and fails within seconds in the open mode (most of the time)
- A dozen diodes were tested under these conditions and all failed open

Low Reverse Current Diode



Typical Reverse Leakage Characteristics

- Vr = 10V or 25% or Vrmax
- Ir is then 20 mA
- P reverse is 0.2 W
- Diode cools down to less than 100°C within seconds and further down
- No problem with this type of diode

Standards and Certification

- **Field failures of by-pass diodes are most concerning when the diode(s) fail open due to shading conditions as the upcoming shading incident will undermine the cell(s) involved and may lead to cell(s) failure and other related safety problems**
- **An official test procedure needs to be incorporated into the international standards (performance, reliability and safety) and pass/fail criteria included**
- **At a minimum, choose the diodes that have the appropriate reverse characteristics**

The thermal reliability study of bypass diodes in photovoltaic modules

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Introduction

Bypass diodes are a standard addition to PV (photovoltaic) modules. The bypass diodes' function is to eliminate the reverse bias hot-spot phenomena which can damage PV cells and even cause fire if the light hitting the surface of the PV cells in a module is not uniform. The design and qualification of a reliable bypass diode device is of primary importance for the solar module. To study the detail of the thermal design and relative long-term reliability of the bypass diodes used to limit the detrimental effects of module hot-spot susceptibility; this paper presents the result of high temperature durability and thermal cycling testing and analysis for the seleceted diodes. During both the high temperature durability and the thermal cycle testing, there were some diodes with obvious performance degradation or failure in J-box 1 with bad thermal design. Restricted heat dissipation causes the diode to operate at elevated temperatures which could lower its current handling capability and cause premature failure. Thermal cycle with forward biased current to the diode, is representative of hot spot conditions, can impose a strong thermal stress to diode, and may cause failure for bypass diodes in some PV module that may be able to pass the present criteria of IEC 61215.

Experiments

Test samples(shown in fig.1 and fig.2) :
- 3 types of junction boxes for testing
- J-boxes were attached on mini laminate modules
- 3 diodes per j-box
- Diode rated current > 10A
- Thermocouples were bonded to diode cases

Data monitoring
- Measure forward and reverse characteristics of diodes before each thermal durability test
- Monitor current and voltage data of diodes and/or power supply
- Monitor case temperature of each diode

Test Procedure
- Test 1
  - Put the samples in chamber with controlled temperature of 50, 60, 75°C
  - Add forward current of 10A to bypass diodes
  - Monitor the bypass diode case temperature and forward voltage drop and current
  - 1000 hours
- Test 2
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add forward bias current of 10A to diodes when the chamber temperature is higher than 25°C
  - One power supply is used for one J-box (3 power supplies).
  - 100 cycles
- Test3
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add reverse bias voltage of 12V to diodes when the chamber temperature is higher than 25°C.
  - One power supply is used for one diode(9 power supplies).
  - 100 cycles
- Next step
  - Chamber temperature at 75°C
  - One hour of reversed bias (12 V) plus one hour of forward bias(10A) per cycle
  - 20 cycles

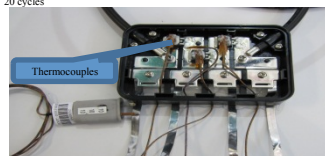

Fig. 1. Junction box sample for testing

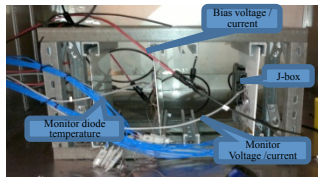

Fig. 2. Assembled testing samples in the chamber

Results

Test 1

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under long-term hot spot condition.

- Diodes temperature rise of 3 J-box during the testing(shown in fig.3 and fig.4) :
  - Box 1: Temperature rises of diodes 1-1 and 1-2 increased by 20°C . The highest diode case temperature reached 220°C when the chamber temperature was 60°C
  - Box 2: Temperature rises of diodes were very stable.
  - Box 3: Temperature rises of diodes 3-1, 3-2 and 3-3 increased slightly
  - Temperature rises of diodes decreased when ambient temperature increased.
  - Diode temperature rises of J-box 1 and 3 went up after restart testing.
- Diodes forward voltage of 3 J-box during the testing:
  - J-box 1: Voltages varied with testing time. Forward voltage of diodes 1-2 increased dramatically after restarted testing(Oct. 6), while voltage of diodes1-1, 1-3 decreased.
  - J-box 2: Voltages were stable
  - J-box 3: Voltages were stable
- No diode failed after the high temperature testing.

Note:
1.Temperature rise is the temperature difference between diode case and chamber
2.Diode 1-2, 2-2, 3-2 is the middle diodes of box 1, box 2 and box 3.
3.The temperature of middle one is highest in the box.

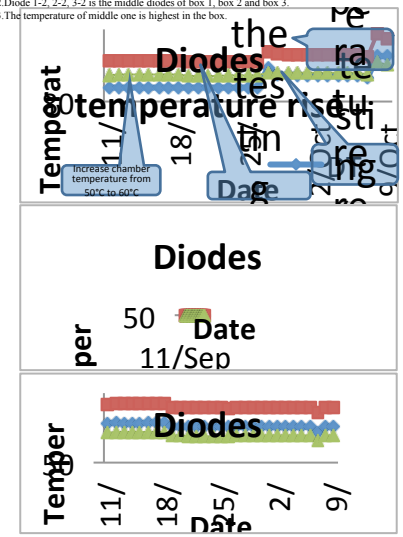

Fig. 3. Diode case temperature rise for 3 J-box during high temperature testing

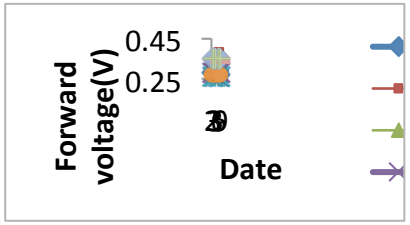

Fig. 4 Diodes forward voltage of 3 J-box during the high temperature testing

Test 2

Thermal cycle plus forward bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change combined with hot spot current flow.

Diodes case temperature during the testing :
- Box - 1: - 40 ~ 214°C
- Box - 2: - 40 ~ 158°C
- Box - 3: - 40 ~ 157°C

Diodes performance after the testing:
- Diodes forwards bias voltage of Box-1 increase dramatically after 40 cycles. Diodes of Box-1 totally failed after this testing.
- Reverse current(at reverse voltage of 10 - 16V) of diodes 3-2 (middle diode of box-3) and 2-2 increased by 10~20%.
- Diodes forward bias voltage of Box-2 remained steady
- Diodes forward bias voltage of Box-3 increased by 0.5V

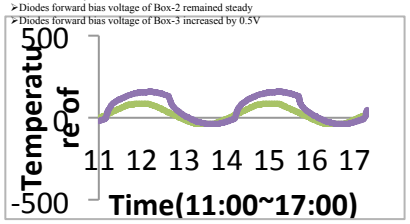

Fig. 5. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus forward bias testing

Test 3

Thermal cycle plus reverse bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change without hot spot.

Diodes case temperature are very close to chamber temperature during the testing

Diodes performance after the testing:
- 12V reverse biased voltage was applied to diodes when the chamber temperature is higher than 25°C.
- Diode case temperature was close to chamber temperature.
- No failure or obvious degradation of diodes were observed during or after the test.

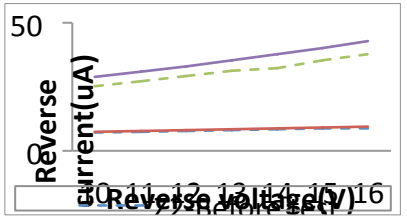

Fig. 6. Reverse characteristics of diodes 2-2(Q2) and diode 3-2(Z2) before and after diodes thermal cycle plus reverse bias testing

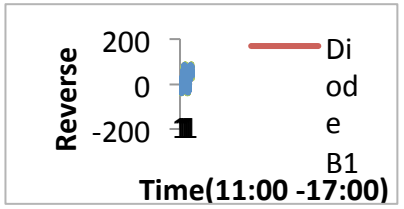

Fig. 7. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus reverse bias testing

Discussion

To assess diodes thermal reliability of PV modules, three indoor tests were designed to simulate 3 types of diodes operating condition. The related test results were shown in above section.

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under hot spot condition. Mini modules with three types of junction boxes were put in chamber with controlled temperature. Forward biased current of 10A was added to bypass diodes; and the bypass diode case temperature and forward voltage drop and current were monitored during the testing. After 1000 hours' testing, though there is no abnormal appearance of diode were found and no appreciable changes in terms of reverse diode characteristics were detected, the temperature rise of worst diodes in one J-box increased by 25°C. The temperature rises of diodes in J-box 1 and 3 went up by 2-15°C and their forward voltage increased dramatically after cool down the diodes and restart testing, while that of J-box 2 was stable. Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation in PV modules in hot spot condition. When the diodes is forward biased with hot spot current flow, the forward current may make the diode hot enough for the dopants that create the N- and P-type areas in the diode to diffuse across the junction, wrecking the semi-conducting behavior that we rely on, and cause performance degradation.

Two types of thermal cycle testing were processed to assess the diodes' durability of thermal cycling stress caused by ambient temperature change with or without hot spot in PV modules. Three types of J-boxes were tested in chamber with cycling temperature range from -40°C to 85°C. For the first 100 cycles, forward biased current of 10A was applied to diodes when the chamber temperature is higher than 25°C. One of diodes totally failed with open circuit after the first 100 thermal cycles testing. The high temperature combined with thermal cycling will cause the diodes resistance increase and damage the PN junctions. For the second 100 cycles, -12V reverse biased voltage was added to diodes during the chamber temperature is higher than 25°C. The diodes case and junction temperatures were close to ambient temperature during the second 100 cycles test. And there was no failure or obvious degradation of diodes were observed during or after the test. The diodes performance of PV module is stable if there is no hot spot issue.

The diode performance is stable if the diode is reverse-biased with low diode temperature. However, the leakage currents doubles every 10°C as the temperature increase, and eventually the current may reach a level where the heat dissipation within the junction is high enough for the junction temperature to run away. For the field operating condition, the PV modules may encounter momentary shading caused by cloud or bird, etc. The diodes in the modules will work under the condition of high temperature with hot spot current flow firstly when the shading is on the modules. Then the diodes will be reverse-biased in high temperature condition after the shading is gone. For next step, the experiments need be designed to access the diode thermal reliability under simulated the field condition of momentary shading .

Conclusions

Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation or failure in PV modules under hot spot condition. Thermal cycle condition with forward biased current to diode, really representative of hot spot conditions, can impose a strong thermal fatigue stress to diode, and may cause failure for bypass diodes of some PV module that may be able to pass present criteria of IEC 61215.

Acknowledgments

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