

Investigation of Schottky bypass diodes from a faulty PV plant

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Abstract. Bypass diodes in photovoltaic modules are designed to prevent the solar cells and cell strings in the module from overheating if a module is operated incorrectly. Possible consequences of bypass diode failures are for example power loss, glass breakage or hot spot burns in PV modules. To avoid such situations, the key-role-playing bypass diode must be in good condition and the knowledge of the condition status is of high interest. For this reason, 36 Schottky diodes were randomly selected from the junction boxes of taken-back PV modules and examined using a variety of characterisation methods. These included electrical characterisation and imaging techniques. The investigation identified all three possible bypass diode states: (i) bypass diode functional and conducting in one direction and blocking in the other direction, (ii) bypass diode defective and conducting in both directions and (iii) bypass diode defective and no longer conducting in any direction. Defective bypass diodes that changed from failure state (ii) to failure state (iii) were found in different aged conditions. Conversely, only an abrupt transition was found for the state (i) to failure state (ii). The main objective of having a fast and suitable method for characterising Schottky bypass diodes in PV systems in the field, which is also in simple agreement with results from laboratory measurement technology, was found with the electrician's multimeter.

Keywords: Bypass diode, Schottky diode, Silicon solar PV, Bypass diode failure.

1 Introduction

When photovoltaic modules show reduced performance or failures (Figs. 1a and 1b), the question arises whether they can be discarded or used for another purpose - keyword "second life" [1–3]. However, to find the reason for the reduced performance, such modules must first be examined, which can be done efficiently with common methods like thermal imaging, electroluminescence, IV-curve analyser, visual inspection or a digital multimeter [4]. Very often, the bypass diode is a source of error in a PV module [5–15] which is why it can be worthwhile to check and replace it.

In this publication, all three known states (functional or fault states) of Schottky bypass diodes were demonstrably measured. This was done by analysing a random sample of accessible bypass diodes from declining PV modules that were declared as "defective". These diodes have been characterised to provide evidence and highlight the difficulties that technicians face in practice. Compared to other authors and literature, which generally deal with PV system faults [14], the danger to bypass diodes due to lightning strikes [12], other more suitable bypass diodes [16, 17],

operating conditions and reliability [5], conditions under shading [6, 9, 16]; modelling of bypass diodes [15], these authors pursue a different focus than in this article hence, it is closing a gap. However, two contributions were also found that address similar points but with a different main objective. Both, Xiao *et al.* [7] and Shin *et al.* [11] used the characterisation approach providing X-ray radiation pictures and cross-section analyses to show working and failed bypass diodes. Hence, the difference is that in this work, the failed bypass diodes are split into the subcategories (ii) defective diode but unproblematic and (iii) defective diode but problematic for the PV module and system operation. Xiao *et al.* focus more on scientific characterisation and analysis techniques like SEM/EDS among others, finding the reason for a bypass diode fault. Shin *et al.* focus more on the inspection and behaviour of diodes in the operating environment and temperature effects.

This work builds a bridge between other scientific work and applied scientific practice, where an analysis of bypass diodes with all three cases of diode operation modes has been performed. Since practical relevance is the main objective of this study, the work fits well with the research results of other authors who have described various details and

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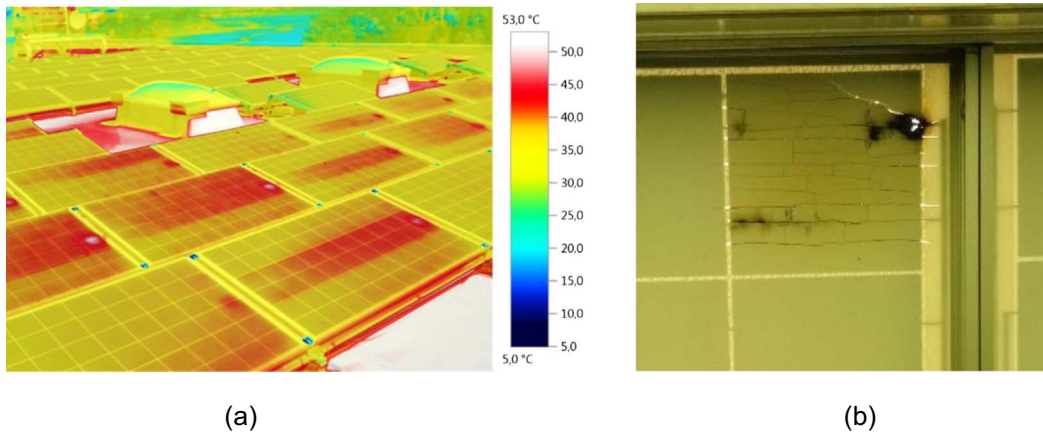


Fig. 1. a) Thermal image of PV modules showing inactive hotter areas connected with power loss due to active or defect bypass diodes and b) burn marks due to the lack of bypass function by defect bypass diode.

completed a missing important point in the bypass diode topic. The number of still-existing publications in the field of interest “bypass diode analyses” shows that the topic is of great interest.

Bypass diodes can be checked quickly using a standard electrician’s multimeter if these components in the junction box are freely accessible and the boxes are not filled out. Schottky diodes, which are considered passive components, have been used as standard protection diodes in the photovoltaic sector for years. In contrast, there are also actively switching bypass diodes [16, 17] which are, however, not so widespread or are rather integrated into module optimisers. The name “protective diode” is derived from the fact that in the event of partial shading of a PV module, this component diverts the current from an affected and shaded solar cell substring in the module *via* the diode. This prevents solar cells from operating as loads and becoming so hot that the module glass can crack or burn marks can appear on the back foil. However, not only shading but also broken cells due to micro-cracks or soldering defects are problematic due to the increased internal resistance, as a bypass diode must then work permanently. A bypass diode also works permanently if it is “shot through” and conducts in both directions. However, if a bypass diode is always operated by a high-flowing current and heat, it is likely to age more quickly and even fail prematurely [7, 9–11]. Therefore, a correct function of the bypass diode is enormously important for a safe and profitable system operation. Although it has often been described in theory that there can also be bypass diodes that no longer conduct in “any direction”, *i.e.* are open in the circuit, until recently the author only encountered defective bypass diodes in practice that were short-circuited and conducted in both directions.

In general, a diode is an electronic passive component based on semiconductors that conducts a current in one direction but blocks it in the other direction. Schottky diodes are made using the metal-semiconductor principle and the junction region is formed by the contact between a metal and a semiconductor and are not made using the principle of forming a p - n junction between a p -type and n -type semiconductor [18]. In photovoltaic modules,

Schottky diodes are used as reverse current protection. Also, these have a smaller threshold voltage and thus generate less voltage drop and heat output than other diode types.

The structure of this work is such that it begins with the approach, continues with the results, and ends with a discussion and conclusion. The parts that are numbered in the approach are also numbered in the results part so they can easily be found.

2 Approach

From a pile of taken-back crystalline silicon photovoltaic modules, which had been in operation for about 10 years, 36 bypass diodes were sampled from the junction boxes and examined. The aim was to find out how many of these Schottky bypass diodes (SB 1540 TL) have a defect, which one it is and how to measure it correctly. In principle, three possibilities for a bypass diode condition are described and mentioned in the literature. Case (i): The diode functions normally and conducts in the forward direction and blocks in the reverse direction. Case (ii): The diode is “blown” and conducts in both directions, which corresponds to a short circuit. Case (iii): The diode does not conduct in either the forward or reverse direction, which corresponds to an open contact.

As the bypass diodes differed optically with partially oxidized contacts and discoloured housings, they were divided into three groups (Fig. 2). In group A, samples of 14 diodes were assigned, which did not show anomalies and had bright contacts and shiny plastic housings. Group B was assigned to 14 diodes with discoloured contacts and discoloured housings. Group C with 8 samples contained diodes showing discoloured contacts as well as discoloured and broken housings. A commercial electrician’s multimeter with a diode test function was used for the examination of the electrical characteristics, as well as a professional laboratory analysis device for comparison. In addition to the electrical characterisation, an X-ray analysis was performed on two bypass diodes of each case to identify anomalies and

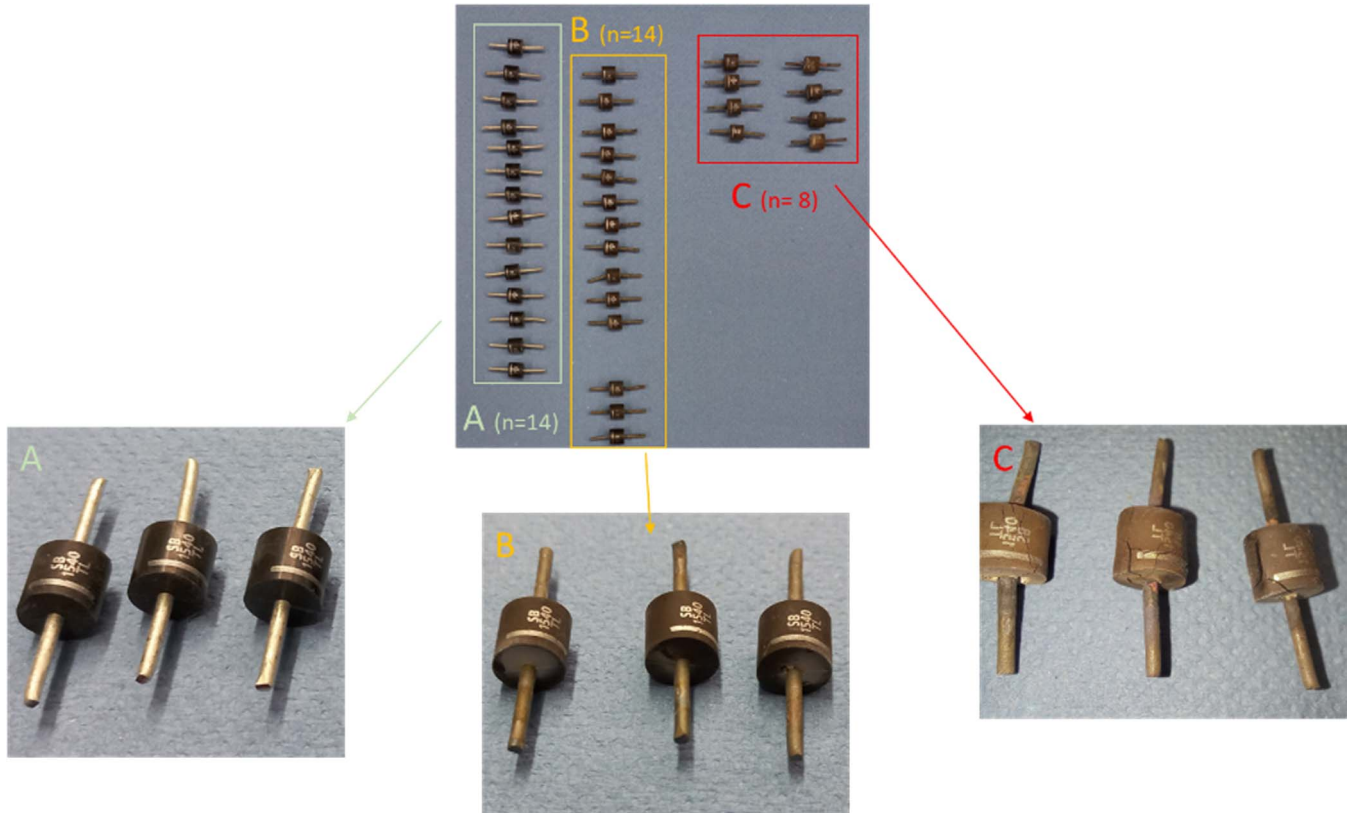


Fig. 2. Visible inspection and sorting in groups.

differences. A comparison was also made under the microscope of an open functioning diode to a completely defective one. In the end, all measurements and data were analysed and compared.

During the visual inspection, it was noticed that the bypass diodes were visually very different. Many looked good and like new with shiny contacts and shiny black housings (Fig. 2 – group A). Others showed oxidised contacts and matt housings, with white plastic discolouration only on the contact side of the negative pole (Fig. 2 – group B). There were a few diodes with very corroded contacts, cracked and burst-open housings, as well as brown discolouration and a smelly housing (Fig. 2 – group C). In some cases, it was critical to touch the cracked parts, as any small bend could cause the housing to crumble and expose the contacts.

2.1 Measurement procedure with handheld multimeter

The hand-held multimeter measurement (measuring device: Voltcraft VC190 SE) was carried out in the laboratory at ambient conditions of 21 °C once in the “diode test” mode and once in the “resistance test” mode. Using 2-point contacting, the measuring cable and diode were connected once in the forward direction and once in the reverse direction using crocodile clips to ensure good contact. The measurement range for resistance is 0.1–60 MOhms. According to the manual, the device creates a test voltage of about 3 V. A good diode is expected to show values in the range

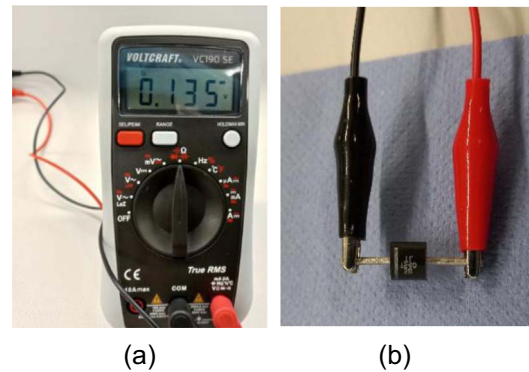


Fig. 3. a) Measuring with an electrician's handheld multimeter and b) connected Schottky diode 2-wire method.

of 0.1–0.4 V in the forward direction whereas OverLoad (OL) would be seen in the case of reverse direction connection and diode's blocking behaviour (Figs. 3a and 3b).

2.2 Measurement procedure with laboratory source meter

With the source meter (measuring device: Keithley 2450), the measurement of a diode was carried out in 4-point contacting, which compensates for the influence of leads and transition contact resistances (Figs. 4a and 4b).

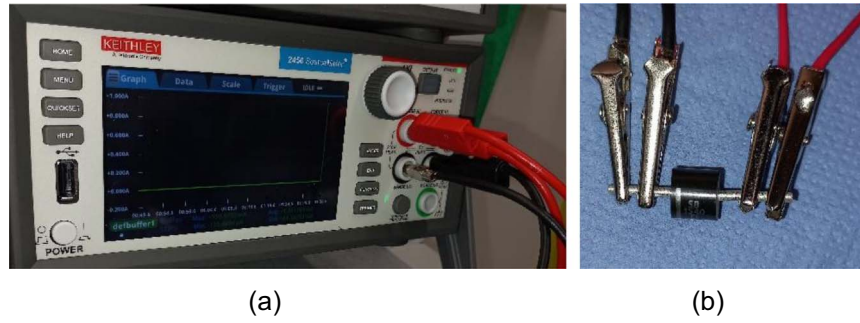


Fig. 4. a) Measuring with a professional laboratory diode IV-characteristic curve device and b) connected Schottky diode 4-wire method.

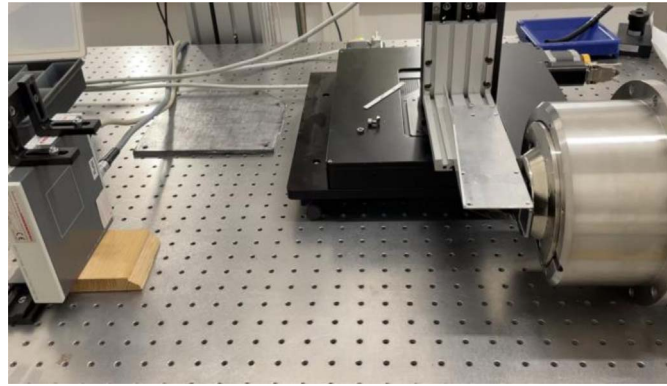


Fig. 5. X-ray measurement system setup.

As there was the possibility, strongly oxidised contacts were additionally made shiny with sandpaper to avoid the influence of strongly varying contact resistances and measurement artefacts. For the characterisation of the characteristic curve, a voltage range of -40 V to $+1\text{ V}$ was run through, with a current limit of 1 A on the device side. With this measurement, both the current in the reverse direction (leakage current) and the current in the forward direction could be accurately determined over the voltage range.

2.3 Measurement procedure with X-ray tube

For the X-ray examination, a Hamamatsu Photonics X-ray source and a CMOS flat panel detector C7921SK were used with a voltage-, current setting of 90 kV , $50\text{ }\mu\text{A}$, and a detector exposure time of 2 s . In this method, the target is irradiated through the thickness of the material and an image is generated at the detector (Fig. 5). It should be noted that due to the cumulative mapping of a volume shown on a surface photo, small error spots in the volume of the diode material cannot always be mapped due to the sensitivity limit.

2.4 Measuring procedure with microscope

A profilometer measuring system (measuring device: Keyence VHX) with magnification levels of $20\times$, $30\times$, $100\times$ and $300\times$ (Figs. 6a–6e) was used to take microscope images. The samples were held on a carrier during the

measuring time of 10 s to be able to produce a depth-focused image.

3 Results

3.1 Measurement by hand-held multimeter

Table 1 lists the 36 bypass diode samples by group, consecutive diode number, forward direction diode test, reverse direction diode test, forward direction resistance, reverse direction resistance, and defect status. The functioning bypass diodes (case (i) – status “I” – green coloured) from group A showed consistent behaviour in both the diode and resistance tests, despite minor deviations. For diodes that conduct in both directions (case (ii) – status “X” – coloured orange) and for those that no longer conduct in any direction (case (iii) – status “o” – coloured red), the results of the diode and resistor tests are not always complementary in a direct comparison.

3.2 Measurement with laboratory source meter

Without exception, the measurement data with the source meter show functioning bypass diodes for case (i) with a typical curve in both the blocking and conducting sections (Fig. 7). Nevertheless, and as already noticed in the hand-held multimeter measurement, small deviations can also be found in the characteristic curve behaviour, which

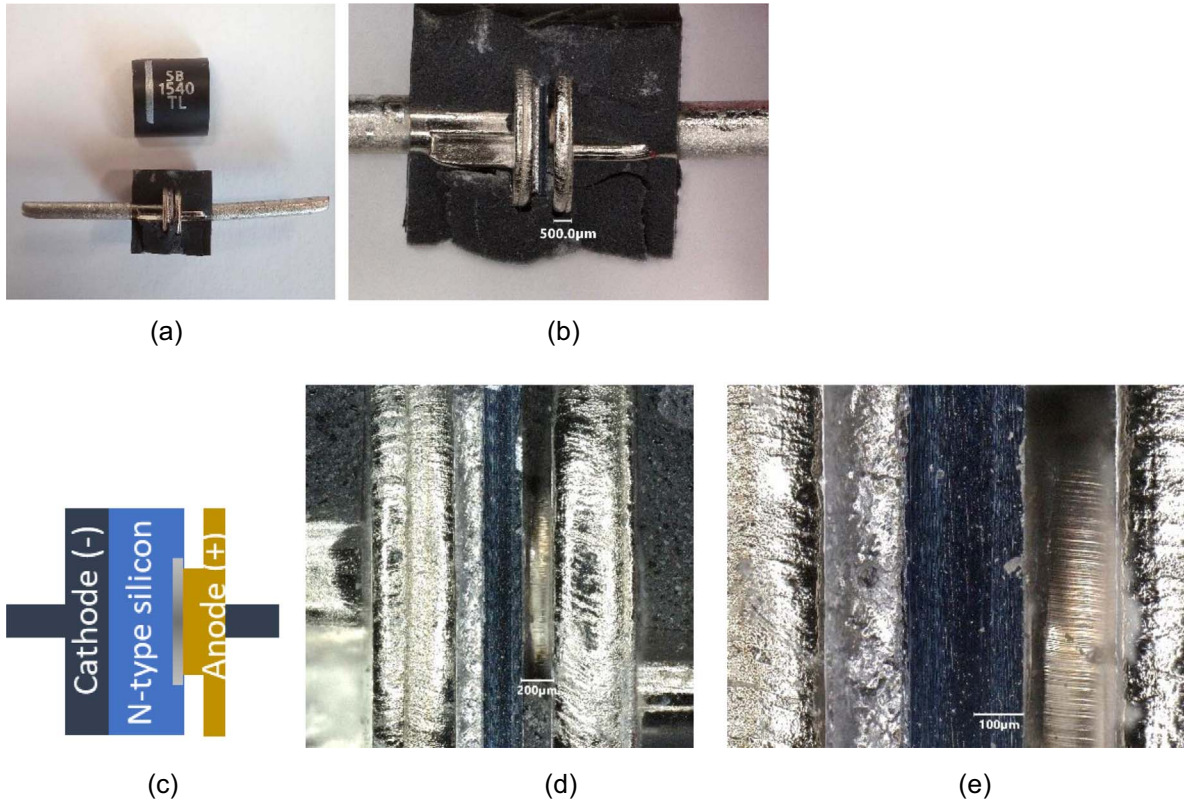


Fig. 6. a) Opened Schottky diode with 20× magnification, b) with 30× magnification, c) schematic sketch of diode setup, d) with 100× magnification and e) with 300× magnification.

corresponds to the statements of the hand-held multimeter. The measurements for the cases (ii) and (iii) are also consistent with the hand-held multimeter measurements. Note: The evaluation of the source meter measurements for the two defective diode cases (ii) and (iii) are not shown separately because no curves can be displayed.

3.3 Measurement with X-ray tube

The X-ray image in Figures 8a and 8b show the two samples with the numbers 6 and 7 from group A, as well as the diode status case (i). Apart from a homogeneous and light-coloured area, nothing else suspicious can be seen in the square chip surface, which is recognisable in white, to indicate melted areas or cracks. Shown in Figures 9a and 9b, the samples with the numbers 17 and 18 from group B and the diode status case (ii), inhomogeneity in the centre area is only faintly visible for sample 18. This means that only one of two defective diodes has been detected. Whereas the defects, depicted by black areas in Figures 10a and 10b, are clearly visible in the samples with the numbers 32 and 33 of group C and the diode status case (iii).

3.4 Measurement with microscope

Under the microscope, two samples (group A and case (i), group C and case (iii)) can be seen in comparison (Figs. 11a–11c and 12a–12c). In the case of the intact diode for group A, the individual areas and chips are clearly

visible. On the other hand, the defective diode from group C shows already detached areas with strong corrosion as well as strong signs of ageing.

4 Discussion

The characterisation of the bypass diodes of claimed photovoltaic modules, which were in use in the field for 10 years, has shown that it is not always possible to clearly distinguish between the status “defective – blown” and the status “defective – completely failed” using a hand-held multimeter. Since many different multimeters are used in practice, a cost-effective and simple hand-held multimeter was selected. If these measures are successful, it stands to reason that other, higher-quality devices can also accomplish this task. From the interpretation of the measured results, which are explained in more detail below, a summary of the conclusions drawn is shown at the end of this section. For example, with bypass diode numbers 23, 26, 29, and 30, the diode tester displays a voltage and tricks the user into believing that the diode behaviour has a higher threshold voltage. In contrast, the resistance tester displays more than 60 MOhms and therefore “OverLoad” (OL), which corresponds to a very high resistance and therefore no significant conductivity is measured in any direction. The situation is different with sample no. 36, where the diode test was not passed, but a very high resistance was still

Table 1. Handheld multimeter measurements and status.

Visual inspection group	Diode number	Forward diode test [V]	Reverse diode test [V]	Forward resistivity test [Ohm]	Reverse resistivity test [Ohm]	Defect status
A	1	0.137	OL	333	OL	I
A	2	0.135	OL	381	OL	I
A	3	0.134	OL	335	OL	I
A	4	0.134	OL	370	OL	I
A	5	0.122	OL	310	OL	I
A	6	0.138	OL	370	OL	I
A	7	0.138	OL	384	OL	I
A	8	0.138	OL	360	OL	I
A	9	0.131	OL	305	OL	I
A	10	0.167	OL	450	OL	I
A	11	0.133	OL	350	OL	I
A	12	0.112	OL	260	OL	I
A	13	0.137	OL	360	OL	I
A	14	0.135	OL	340	OL	I
B	15	0	0	0.5	0.5	x
B	16	0	0	0.5	0.4	x
B	17	0	0	1.7	1.7	x
B	18	0	0	1.2	1.2	x
B	19	0	0	1.6	1.6	x
B	20	0	0	3.1	3.2	x
B	21	0	0	0.8	0.8	x
B	22	0	0	0.8	0.8	x
B	23	1.64	2.67	OL	OL	o
B	24	OL	OL	OL	OL	o
B	25	OL	OL	OL	OL	o
B	26	2.006	2.42	OL	OL	o
B	27	0	0	1.8	1.8	x
B	28	0	0	1.4	1.4	x
C	29	2.58	2.58	OL	OL	o
C	30	2.83	2.98	OL	OL	o
C	31	0	0	1.2	1.2	x
C	32	0.75	1.1	OL	1800	o
C	33	OL	OL	OL	OL	o
C	34	OL	OL	OL	OL	o
C	35	1.25	1.27	2200	2200	x
C	36	OL	OL	3,800,000	4,900,000	o

measurable. Interesting is sample no. 32, which shows a diode behaviour in the diode test, but a not measurable high resistance in the resistance test in the forward direction, but 1800 Ohm in the resistance measurement in the reverse direction. The diodes with serial numbers 32, 35 and 36 are examples that show a gradual transition from still conducting (ii) to no longer conducting at all (iii), which is an indication of slow and progressive degradation up to complete failure. The measured values were in the

kilo- and megaohm range, *i.e.* between a short circuit and an open contact, which indicates the progressive deterioration, which was also initially detected using X-ray and microscope analyses.

This means that electricians in the field must be more careful with the hand-held multimeter when they receive measured values and better interpret them again. The exciting thing about the investigation, however, was that the random sample also included completely defective

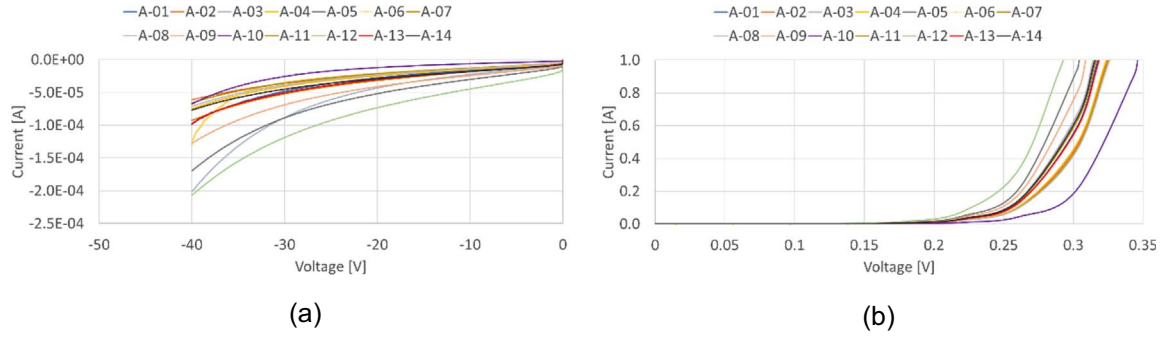


Fig. 7. a) Characteristic curve in blocking direction (leakage current) and b) in forward direction.

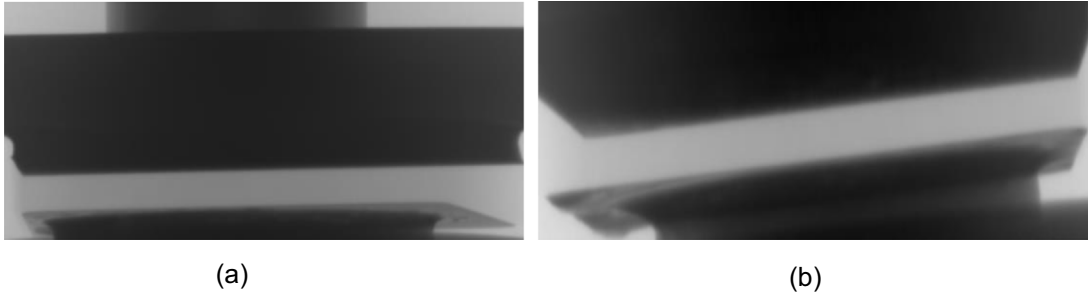


Fig. 8. a) X-rayed diode no. 6 and b) X-rayed diode no. 7, both from group A.

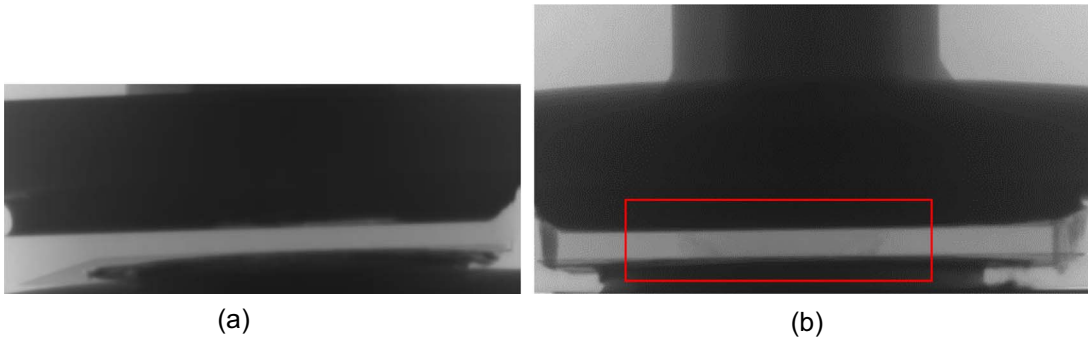


Fig. 9. a) X-rayed diode no. 17 and b) X-rayed diode no. 18, both from group B.

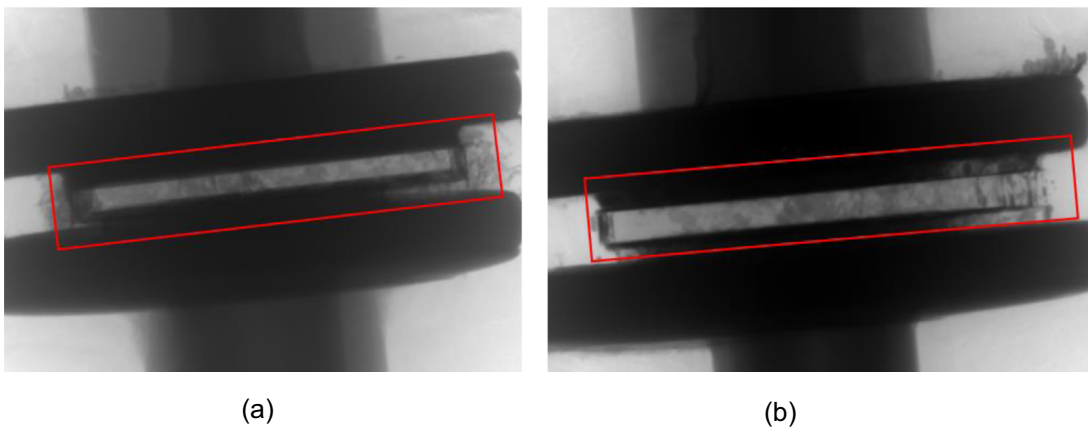


Fig. 10. a) X-rayed diode no. 32 and b) X-rayed diode no. 33, both from group C.

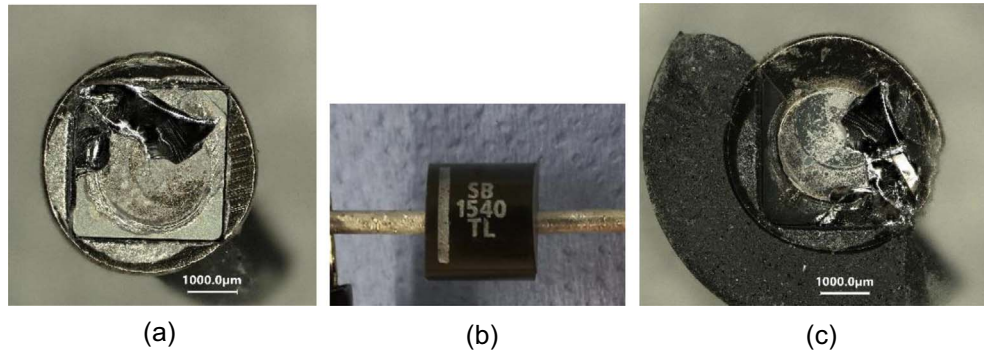


Fig. 11. Diode from group A – a) cathode side; b) diode before opening; c) anode side.

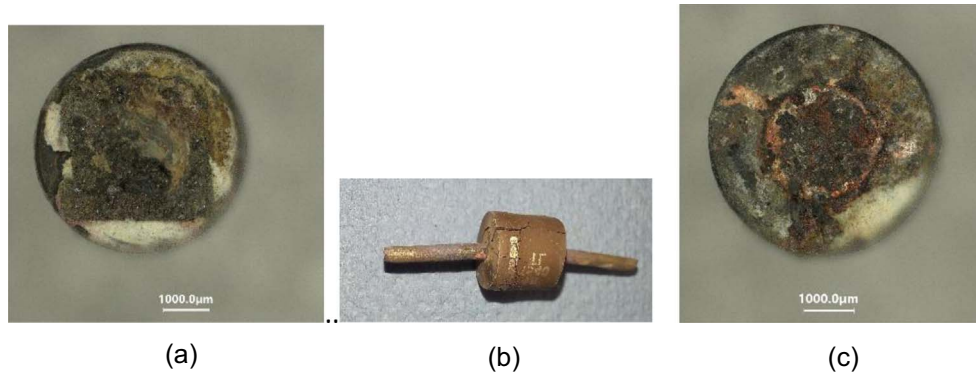


Fig. 12. Diode from group C – a) cathode side; b) diode before opening; c) anode side.

diodes that had not previously been found in many system investigations. It is not the defective diodes, which are conductive in both directions, that are a problem for a PV module and a system, but the further ageing of these to total failure and no longer being conductive in any direction including losing the bypass function of a PV module completely. This would correspond to an open contact, and in the event of a fault, a complete module string could be interrupted, resulting in a loss of yield. Another issue would be the lost protection capability and the higher risk of hot spots and burn marks.

With the findings and indications from the investigation, likely, that the process from defective diodes conducting in both directions to defective diodes conducting in neither direction takes place over a longer period of time. This could be in turn an advantage for maintenance as there is still time if defective diodes are found, to replace them before the problems increase with further time and further ageing of defective diodes.

Compared to other literature in the field of Schottky bypass diode investigations, no one used an electrician's handheld multimeter to make investigations and comparisons to laboratory and scientific measurement equipment including providing measurement data for all three possible function conditions. Nevertheless, handheld multimeters are certainly one of the common devices used by service personnel on-site in PV parks and should not be missing in research tasks. Our own measurements and those of other

authors for X-ray analyses, characteristic curve measurements or microscopy images show similar results and therefore complement each other.

5 Conclusion

Schottky bypass diodes, which are used in photovoltaic modules, can become defective, for example, due to indirect lightning strikes, overvoltage, overheating or a batch problem with higher susceptibility. Starting from an unknown reason for the defect, all three possible bypass diode states: a) functioning bypass diode, b) defective in short-circuit operation and c) defective in the non-conductive operating state, were detected in this investigation from 36 random samples of recommissioned PV field modules. Visual inspection is helpful in identifying defective diodes on the basis of discolouration, whereby the external appearance can only serve as an indication. Microscopic or X-ray examinations provide information about the structure of the diode and the localisation of a defect. The electrician's hand-held multimeter can serve well on site and is the first choice due to its wide range of uses. However, it provides similar, but not as detailed, information as the more scientific characteristic curve analyser in the laboratory, which is not necessary in the field. During the measurement process and the evaluation of the display values, a double check should be carried out by switching between the “diode

tester” and the “resistance tester” function in order to avoid measurement artefacts and misinterpretations. Based on the measurement results and findings, defective bypass diodes should be replaced at one of the next service intervals to avoid loss of yield.

Acknowledgments

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