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EUROPEAN SPACE AGENCY
CONTRACT REPORT
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Survey of Total Ionising Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE

TN5.10
TID Test Report for
SiC Schottky Diode
C4D40120D

Manufacturer:
Cree

Date code/Lot code: W13714

Report no.	**Version**	**Date**	**NEO no.**
023/2017	1.0	2018-12-10	NEO-14-086
Author	**Coauthors**	**Checked by**	**Project**
Michael Steffens +49 2251 18-222 michael.steffens@int.fraunhofer.de	--	Paschkowski	Survey of Total Ionising Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE (AO/1-7859/14/NL/SW)

Customer	**Project management**
European Space Agency (ESA), contract number 4000113976/15/NL/RA	Project Coordinator: Stefan Höffgen (INT) ESA Technical Project Officer: Marc Poizat (ESA/ESTEC)

Document approval

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Version history

Table 1: Revision history

Version	Date	Changed by	Changes
1.0	2018-12-10	Steffens	Initial release
2.0	-	-	
	-	-	

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1 Introduction

1.1 Scope

The Fraunhofer Institute for Technological Trend Analysis (INT) carried out a series of Co-60 irradiations on SiC Schottky Diode C4D40120D from Cree for the ESA project "Survey of Total Ionizing Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE" (ESA-TOPSIDE, AO/1-8148/14/NL/SFe) under contract number 4000113976/15/NL/RA.

This reports documents the preparation, execution and the results of these tests.

1.2 Applicable Documents

[AD1] ITT/AO/1-8148/14/NL/SFe "Statement of work: Survey of Total Ionizing Dose Tolerance of Power Bipolar Transistors and Silicon Carbide Devices for JUICE"

[AD2] Proposal for ITT/AO/1-8148/14/NL/SFe, Fraunhofer INT

1.3 Reference Documents

[1] Website of Fraunhofer INT: http://www.int.fraunhofer.de

[2] Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, B.N. Taylor and C.E. Kuyatt, NIST Technical Note 1297, 1994, http://www.nist.gov/pml/pubs/tn1297/index.cfm.

[3] ESCC Basic Specification No. 22900, issue 5, June 2016

[4] Datasheet of SiC Schottky Diode C4D40120D, "C4D40120D Silicon Carbide Schottky Diode Z-Rec® Rectifier", Cree, Rev. E

[5] TN2.10 "TID Test Plan C4D40120D (Schottky Diode)", Issue 1, Revision 1, 2017-02-13

[6] MIL-STD-883K w/CHANGE 2, Method 1019.9, "Ionizing Radiation (Total Dose) Test Procedure", 2017

2 Summary

Table 2: Summary

Test Report Number	023/2017
Project (INT)	NEO-14-086
Customer	European Space Agency (ESA), contract number 4000113976/15/NL/RA
Contact	Project Coordinator: Stefan Höffgen (INT) ESA Technical Project Officer: Marc Poizat (ESA/ESTEC)
ESA project / contract number	AO/1-8148/14/NL/SFe 4000113976/15/NL/RA
Device under test	C4D40120D
Family	SiC Schottky Diode
Technology	1.2kV Schottky Rectifier
Package	TO247-3
Date code / Wafer lot	W13714
SN	Biased (5x): # 1, 2, 3, 4, 5 Unbiased (5x): # 6, 7, 8, 9, 10 Reference (1x): # 0
Manufacturer	Cree
Irradiation test house	Fraunhofer INT
Radiation source	Co-60
Irradiation facility	TK1000B
Generic specification	ESCC 22900 Iss. 5
Detail specification	ESCC 22900 Iss. 5
Test plan	TN2.10 "TID Test Plan C4D40120D (Schottky Diode)", Issue 1, Revision 1, 2017-02-13
Max. test level	1 Mrad(Si)
Dose steps	Multiple: 30, 50, 100, 300, 500, 1000 krad(Si)
Dose rate	8.6 krad(Si)/h
Start of irradiation	2016-11-30 04:04:21
Stop of irradiation	2016-12-05 07:31:57
Non-Homogeneity in DUT	9.5%

Annealing	24h @RT, 168h @ 100°C
Electrical measurements/ Parameters tested	V_{F1}, V_{F2}, I_{R1}, I_{R2}

2.1 Overview of results

Figure 1: Overview of results

Pass/Fail		Total Dose [krad (Si)]							Annealing	
		0	30	50	100	300	500	1000	24h @RT	.68h @ 100°C
VF1	On									
	Off									
VF2	On									
	Off									
IR1	On									
	Off									
IR2	On									
	Off									

2.2 Comments

- Due to a limited number of samples, some DUTs were used for other tests after conduction of this TID campaign (see Table 4).
- The TID tests of SiC Schottky Diode IDW10G120C5B of the same project were performed simultaneously at the same facility TK1000B.
- During the conduction of the test campaign, a deviation from the requirements of ESCC 22900 occurred due to maintenance work at the facility: the time gap between the end of the 30 krad(Si) step and the 50 krad(Si) step was nearly one hour longer than allowed.
- **V_{F1} and V_{F2}:** Measured values are corrected for the setup by approx. 0.2 V. Displayed in this report are the already corrected values.

3 Sample preparations

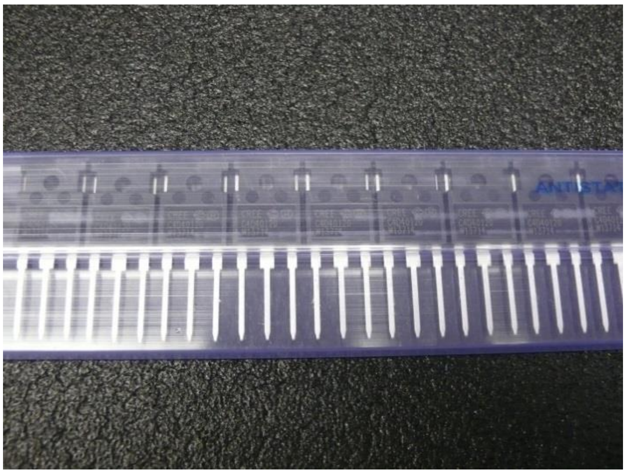
3.1 Sample shipment

A total of 30 Samples were procured by INT at a commercial supplier (Mouser Electronics) for the conduction of these tests for ESA. The parcel contained devices with one identification code (W13714). Due to the devices being so-called "commercial-off-the-shelf" (COTS) devices, it is not clear whether this identifies the wafer or just the packaging).

Table 3: Sample shipment

Samples ordered	Samples received	Samples sent back
December 2015	December 2015	still at INT (partially used for other tests in this project)

Figure 2: The ESD package with the samples

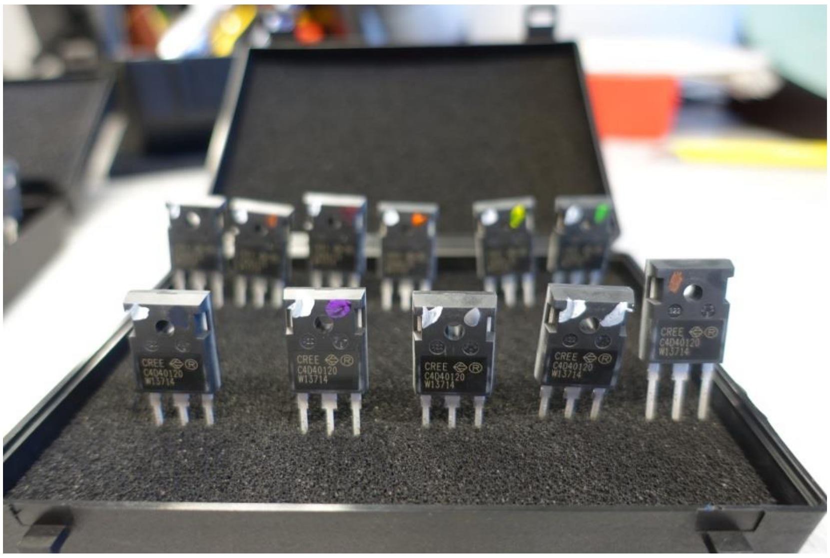


3.2 Sample identification/ marking

The samples were soldered to adapter pins, to ease the mounting to the board, exchanging, plugging and storage of the samples.

The samples were colour marked to differentiate the samples between each other and to separate the samples of the different campaigns or types.

Figure 3: Sample marking



3.3 Sample safekeeping

The samples were stored in an Electro-Static Discharge (ESD) box (Figure 3) to handle them safely during the test, the interim storage after the last measurement and the final shipment.

Table 4: Sample marking: Due to a limited number of samples, some DUTs were used for other tests after conduction of this TID campaign

Condition	Label	S/N	Color Code	Comment
Control sample	REF#1	0		
Biased	ON#1	1		further used for proton SEE tests
	ON#2	2		further used for proton SEE tests
	ON#3	3		further used for decapsulation tests
	ON#4	4		further used for decapsulation tests
	ON#5	5		further used for decapsulation tests
Unbiased	OFF#1	6		further used for decapsulation tests
	OFF#2	7		further used for decapsulation tests
	OFF#3	8		
	OFF#4	9		

	OFF#5	10			

4 Irradiation conditions

4.1 Irradiation steps

Table 5: Irradiation steps

	Step [krad(Si)]	Total [krad (Si)]	Doserate [krad(Si)/h]	Start Irr.	Stop Irr.	Duration [d h:m:s]	Start Tests	Stop Tests	Dur. [h:m]
0	0.00	0		-	-	--	29.11.2016 17:01	29.11.2016 17:39	0:38
1	30.00	30	8.61	30. 11.2016 04:04:21	30. 11.2016 07:33:23	0d 03:29:02	30.11.2016 08:55	30.11.2016 09:35	0:40
2	20.00	50	8.61	**30. 11.2016 10:21:21**	30. 11.2016 12:40:41	0d 02:19:20	30.11.2016 12:55	30.11.2016 13:17	0:22
3	50.00	100	8.61	30. 11.2016 13:24:52	30. 11.2016 19:13:10	0d 05:48:18	30.11.2016 19:26	30.11.2016 19:40	0:14
4	200.00	300	8.61	30. 11.2016 20:05:55	01. 12.2016 19:19:14	0d 23:13:19	01.12.2016 19:26	01.12.2016 19:57	0:31
5	200.00	500	8.61	01. 12.2016 20:48:09	02. 12.2016 20:01:27	0d 23:13:18	02.12.2016 20:19	02.12.2016 20:34	0:15
6	500.00	1000	8.61	02. 12.2016 21:28:48	05. 12.2016 07:31:57	2d 10:03:09	05.12.2016 07:53	05.12.2016 08:14	0:21
7	24 h @ RT			05. 12.2016 08:30:00	06. 12.2016 11:10:00	1d 02:40	06.12.2016 11:20	06.12.2016 11:44	0:24
8	168 h @100°C			06. 12.2016 12:00:00	14. 12.2016 09:00:00	7d 21:00	14.12.2016 09:20	14.12.2016 09:36	0:16

The TID tests of SiC Schottky Diode IDW10G120C5B of the same project were performed simulateously at the same facility TK1000B.

During the conduction of the test campaign, a deviation from the requirements of ESCC 22900 occurred due to maintenance work at the facility: the time gap between the end of the 30 krad(Si) step and the 50 krad(Si) step was nearly one hour longer than allowed.

4.2 Sample holder

A custom-build printed-circuit board (Figure 4) was manufactured to

- bias the samples according to the circuit-layout of the irradiation test plan [5] (see also chapter 4.3)
- fix the samples under the radiation source (see also chapter 4.3 Geometry)
- irradiate the samples homogeneously.

4.3 Geometry

The irradiation parameters correspond to a sample-distance of 16.5 cm from the TK1000B source (Figure 5) to the object minimum.

In each test a PMMA layer of 5 mm was placed over the DUTs to achieve charge equilibrium.

Figure 4: Bias board

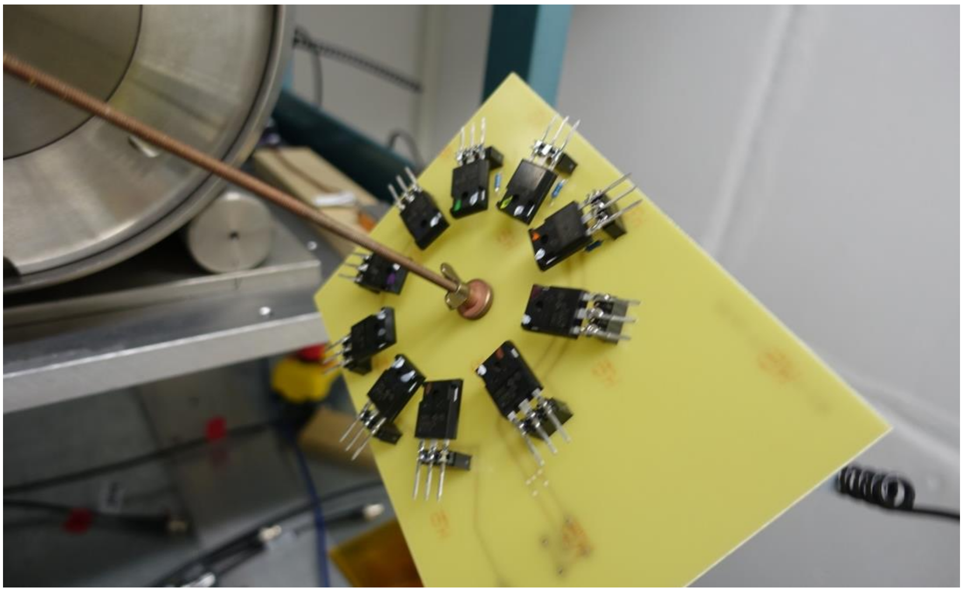
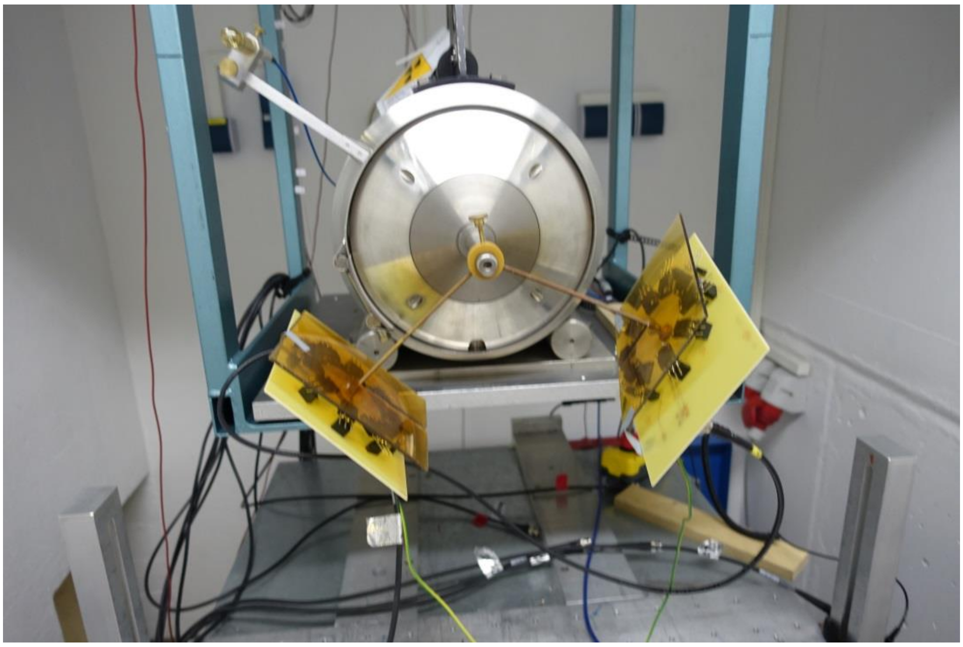


Figure 5: Board fixture at TK1000B



4.4 Bias conditions

During the irradiation and the subsequent annealing the samples were biased or operated according to the circuit-description of the irradiation test plan [5] (see Figure 6).

A single fug HCE 35-1250 voltage supply (Eq.Id E-PS1-032, Figure 7) was used for biasing of both the C4D40120D and the SiC Schottky Diode IDW10G120C5BFKSA1 of the same project. The supply was not calibrated but the voltage was checked with a calibrated voltmeter.

During transport from the irradiation site to the electrical measurement site and back again all terminals were shorted.

Figure 6: Bias conditions

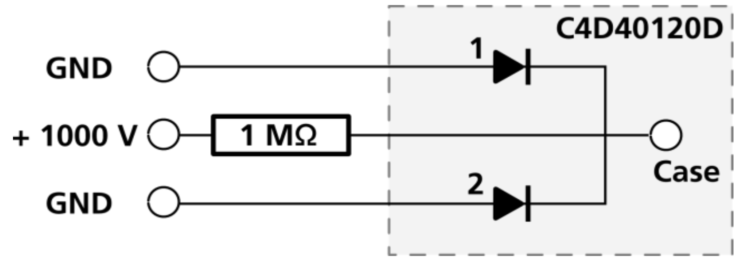
ON-Mode	OFF-Mode
 V_{Bias} = 1000 V (≥ 80% V_{RRM})	All pins were short circuited and grounded.

Figure 7: Biasing equipment

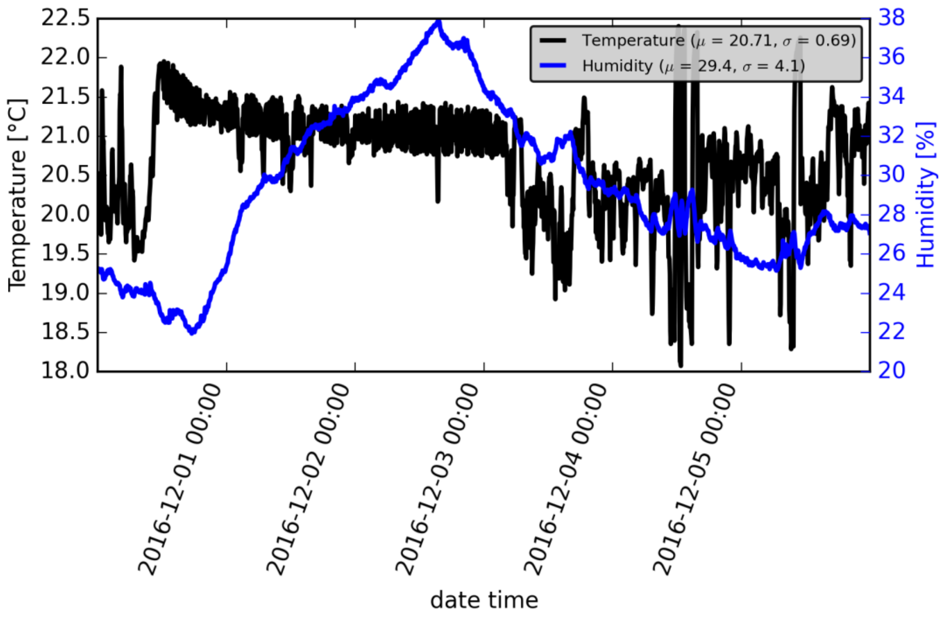
4.5 Environmental variables

All irradiation steps were done in air. The samples at TK1000B were irradiated in ambient light. The parameters of the humidity and the temperature are given in the following tables and figures.

Table 6: LDR: Environmental variables during irradiation

Parameter	Value and Unit	Remarks
Humidity	29.4% ± 4.1%	Non-condensing, during irradiation and first annealing (24 h)
Temperature	20.7 °C ± 0.7 °C	During irradiation and first annealing (24 h)
Temperature	100.0 ± 3.0 °C	During second annealing at 100°C.

Figure 8: Environment variables during irradiation.



5 Measurement parameters

The measurement of the electrical parameters was done by Fraunhofer INT in accordance with the measurements standards and test methods of ESA, MIL and IEC.

The test plan based on the ESA Basic Specification No. 22900 [3] in general and the irradiation test plan [5] in particular.

Parameters listed in the following Table 7 were measured before and after each irradiation step and each annealing step.

5.1 Measurement parameters

Table 7: Measurement parameters. Based on [4], taken from [5]

No.	Characteristics	Symbol	MIL-STD-750 Test Method	Test Conditions
1	Forward Voltage	V_{F1}	4011	Diode 1, $I_F = 20$ A
2		V_{F2}		Diode 2, $I_F = 20$ A
3	Reverse Current	I_{R1}	4016	Diode 1, $V_R = 1200$ V
4		I_{R2}		Diode 2, $V_R = 1200$ V

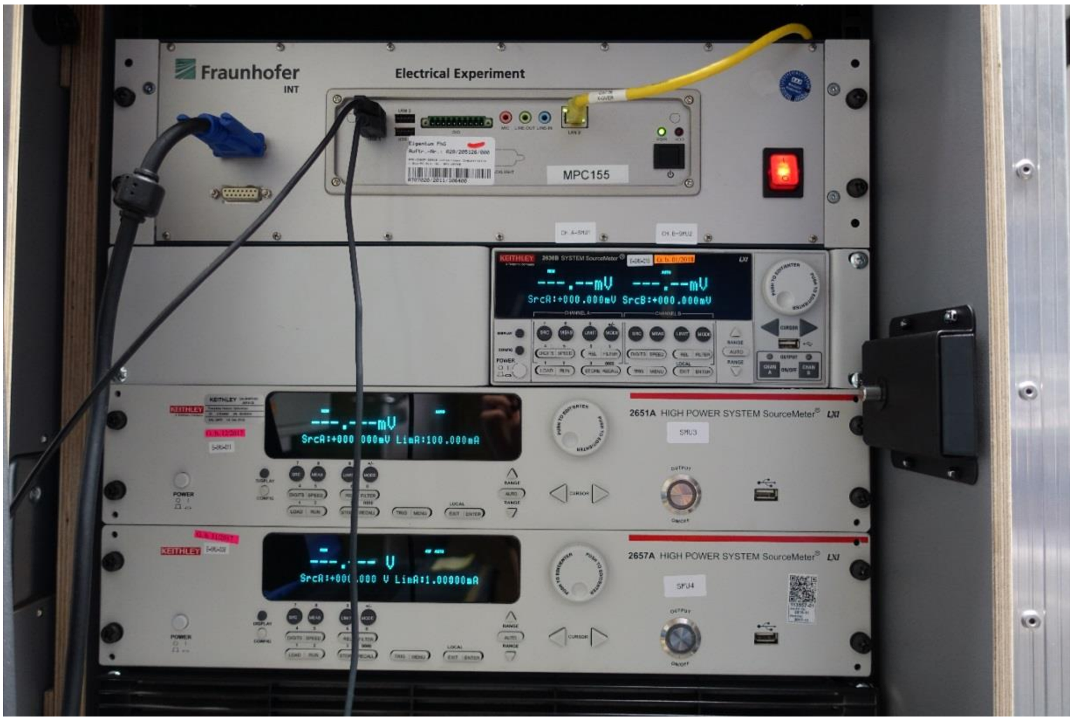
5.2 Measurement equipment

Table 8: Measurement equipment

Equipment	Manufacturer	Model	INT-Code	Calibr. due	Measurement
System Source Meter	Keithley	2651A	E-SMU-011	11/2017	V_{F1}, V_{F2}
High Power System Source-Meter	Keithley	2657A	E-SMU-008	11/2017	I_{R1}, I_{R2}
Test Fixture	Keithley	8010	E-SPAT-004	--	all

Figure 9: Measurement equipment/setup

Figure 10: Test setup: SMUs



5.3 Measurement procedures

Procedures according to the MIL test methods given in Table 7 and Notes 1+2.

Measurements were programmed using the software Keithley ASC Basic allowing timed operation of the SMUs during pulses (e.g. using a fixed delay between pulse rise and parameter readout times).

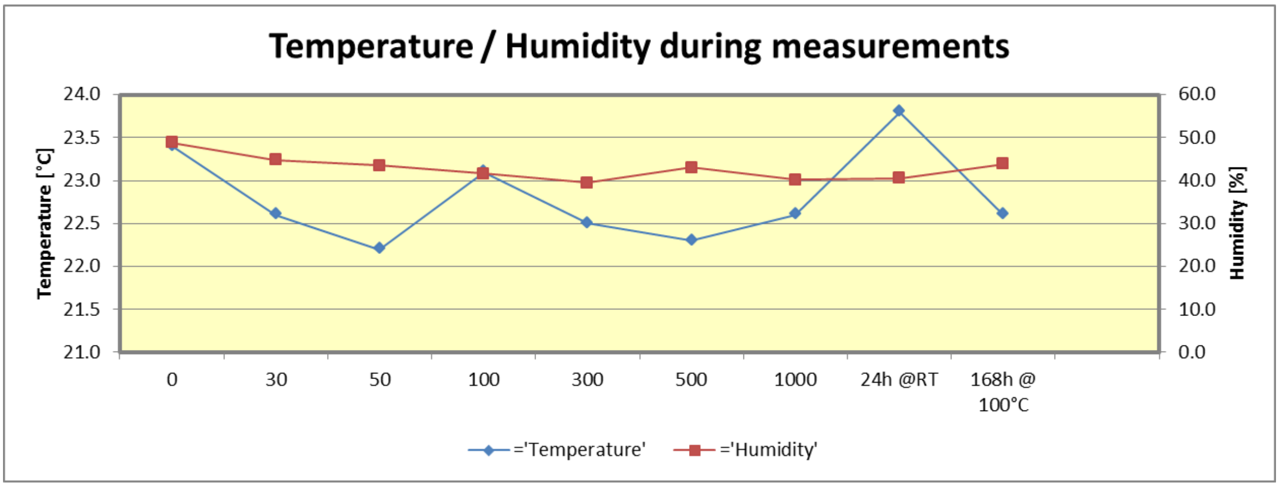
5.4 Environmental variables

All measurement and annealing steps were done in air. The samples are measured in a lightproof measuring-case. The parameters of the humidity and the temperature during the tests in the ESD area are given in the following table and figure.

Table 9: Environment variables during measurements

Test cond.	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	.68h @ 100°C
Temperature [°C]	23.4E+0	22.6E+0	22.2E+0	23.1E+0	22.5E+0	22.3E+0	22.6E+0	23.8E+0	22.6E+0
Humidity [%]	48.8E+0	44.8E+0	43.5E+0	41.6E+0	39.5E+0	43.1E+0	40.2E+0	40.5E+0	43.9E+0

Figure 11: Environment variables during measurements



6 Results

6.1 Overview: Pass/Fail

Pass/Fail		Total Dose [krad (Si)]							Annealing	
		0	30	50	100	300	500	1000	24h @RT	.68h @ 100°C
VF1	On									
	Off									
VF2	On									
	Off									
IR1	On									
	Off									
IR2	On									
	Off									

- **V_{F1} and V_{F2}:** Measured values are corrected for the setup by approx. 0.2 V. Displayed in this report are the already corrected values.

6.2 Forward Voltage (1)

Forward Voltage (1)
VF1 in V
Corrected data: x-0.1935872
Limit: x < 1.8

C4D40120D
Date-/Lotcode: W13714

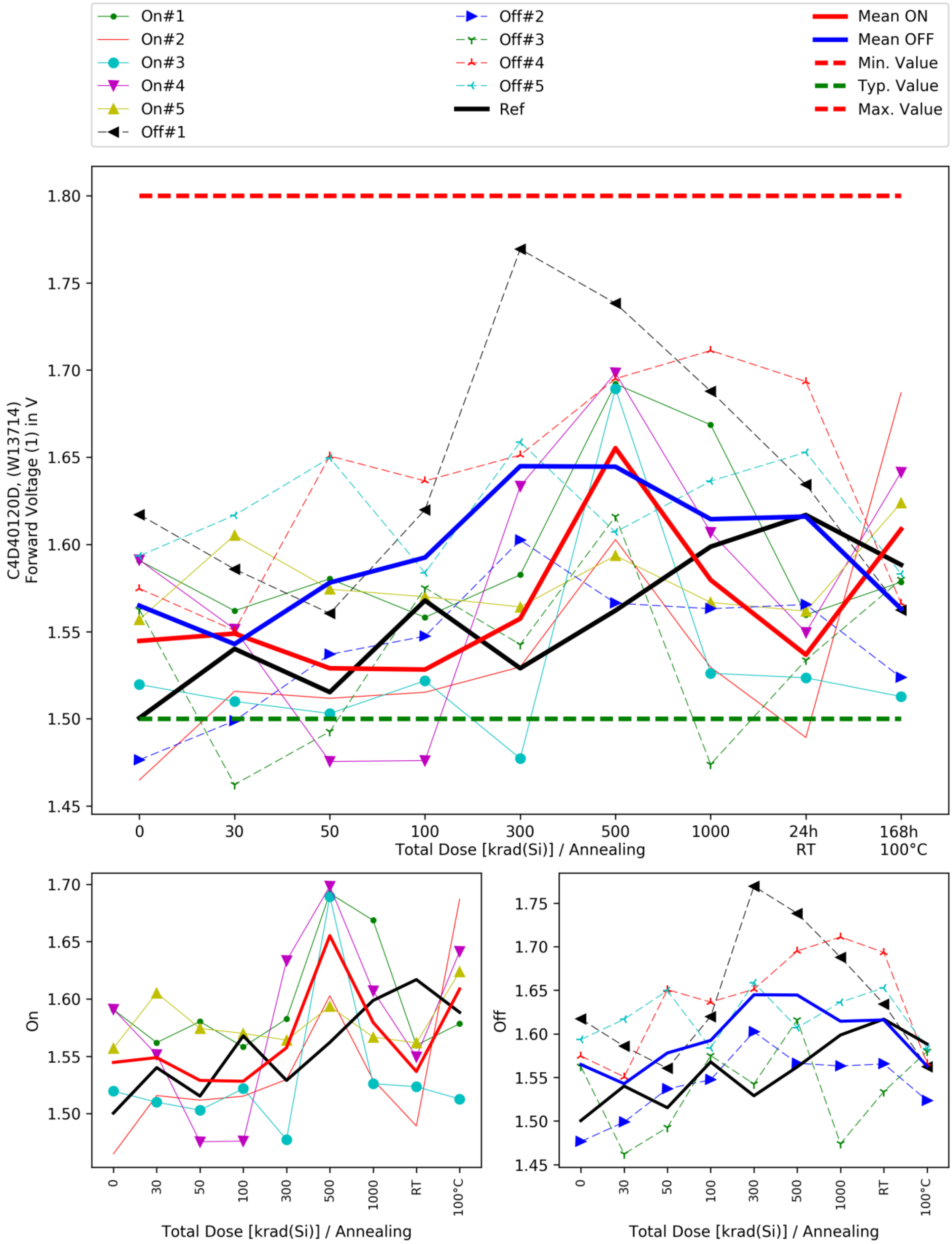
ON-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
On#1	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.7E+0	1.6E+0	1.6E+0
On#2	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.5E+0	1.5E+0	1.7E+0
On#3	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.7E+0	1.5E+0	1.5E+0	1.5E+0
On#4	1.6E+0	1.6E+0	1.5E+0	1.5E+0	1.6E+0	1.7E+0	1.6E+0	1.5E+0	1.6E+0
On#5	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0
Radiation-Mean ON	**1.5E+0**	**1.5E+0**	**1.5E+0**	**1.5E+0**	**1.6E+0**	**1.7E+0**	**1.6E+0**	**1.5E+0**	**1.6E+0**
Standarddeviation	53.4E-3	38.6E-3	46.1E-3	37.3E-3	58.4E-3	52.3E-3	59.6E-3	30.6E-3	66.3E-3
Mean + kσ	**1.7E+0**	**1.7E+0**	**1.7E+0**	**1.6E+0**	**1.7E+0**	**1.8E+0**	**1.7E+0**	**1.6E+0**	**1.8E+0**
Mean - kσ	**1.4E+0**	**1.4E+0**	**1.4E+0**	**1.4E+0**	**1.4E+0**	**1.5E+0**	**1.4E+0**	**1.5E+0**	**1.4E+0**

OFF-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Off#1	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.8E+0	1.7E+0	1.7E+0	1.6E+0	1.6E+0
Off#2	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.5E+0
Off#3	1.6E+0	1.5E+0	1.5E+0	1.6E+0	1.5E+0	1.6E+0	1.5E+0	1.5E+0	1.6E+0
Off#4	1.6E+0	1.6E+0	1.7E+0	1.6E+0	1.7E+0	1.7E+0	1.7E+0	1.7E+0	1.6E+0
Off#5	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.6E+0	1.6E+0	1.7E+0	1.6E+0
Radiation-Mean OFF	**1.6E+0**	**1.5E+0**	**1.6E+0**	**1.6E+0**	**1.6E+0**	**1.6E+0**	**1.6E+0**	**1.6E+0**	**1.6E+0**
Standarddeviation	53.5E-3	62.8E-3	70.2E-3	35.7E-3	83.7E-3	70.1E-3	97.0E-3	65.2E-3	23.7E-3
Mean + kσ	**1.7E+0**	**1.7E+0**	**1.8E+0**	**1.7E+0**	**1.9E+0**	**1.8E+0**	**1.9E+0**	**1.8E+0**	**1.6E+0**
Mean - kσ	**1.4E+0**	**1.4E+0**	**1.4E+0**	**1.5E+0**	**1.4E+0**	**1.5E+0**	**1.3E+0**	**1.4E+0**	**1.5E+0**

Reference	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Ref1	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0

Typ. Value	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Max. Value	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0

- **V_{F1} and V_{F2}:** Measured values are corrected for the setup by approx. 0.2 V. Displayed in this report are the already corrected values.


On#1
On#2
On#3
On#4
On#5
Off#1
Off#2
Off#3
Off#4
Off#5
Ref
Mean ON
Mean OFF
Min. Value
Typ. Value
Max. Value
C4D40120D, (W13714)
Forward Voltage (1) in V
Total Dose [krad(Si)] / Annealing
24h RT
168h 100°C
On
Off
Total Dose [krad(Si)] / Annealing
Total Dose [krad(Si)] / Annealing

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6.3 Forward Voltage (2)

Forward Voltage (2)
VF2 in V
Corrected data: x-0.1935872
Limit: x < 1.8

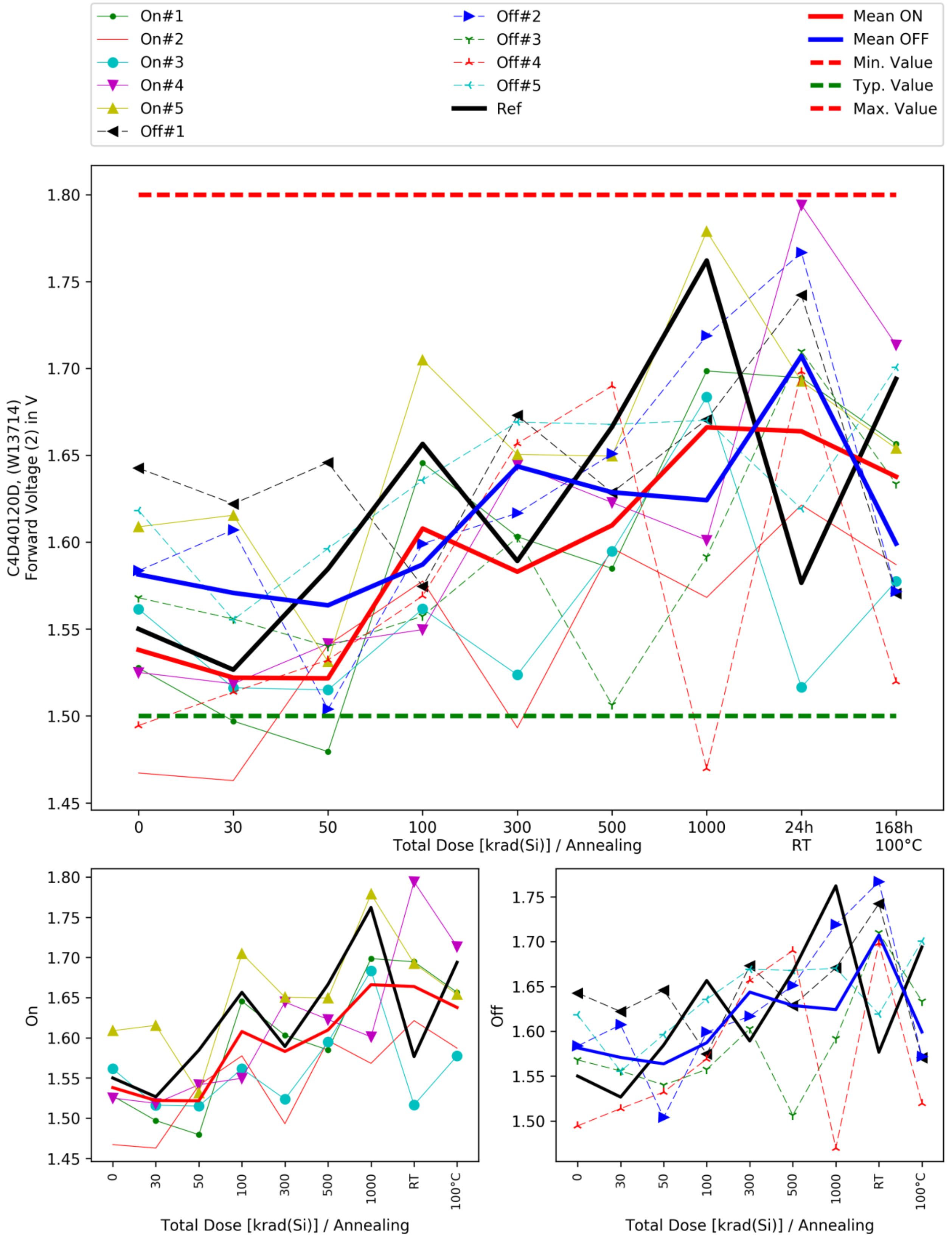
C4D40120D
Date-/Lotcode: W13714

ON-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
On#1	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.7E+0	1.7E+0
On#2	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0
On#3	1.6E+0	1.5E+0	1.5E+0	1.6E+0	1.5E+0	1.6E+0	1.7E+0	1.5E+0	1.6E+0
On#4	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.8E+0	1.7E+0
On#5	1.6E+0	1.6E+0	1.5E+0	1.7E+0	1.7E+0	1.6E+0	1.8E+0	1.7E+0	1.7E+0
Radiation-Mean ON	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.7E+0	1.6E+0
Standarddeviation	52.1E-3	56.8E-3	25.9E-3	65.7E-3	71.3E-3	26.3E-3	83.5E-3	102.8E-3	56.0E-3
Mean + kσ	1.7E+0	1.7E+0	1.6E+0	1.8E+0	1.8E+0	1.7E+0	1.9E+0	1.9E+0	1.8E+0
Mean - kσ	1.4E+0	1.4E+0	1.5E+0	1.4E+0	1.4E+0	1.5E+0	1.4E+0	1.4E+0	1.5E+0

OFF-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Off#1	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.6E+0	1.7E+0	1.7E+0	1.6E+0
Off#2	1.6E+0	1.6E+0	1.5E+0	1.6E+0	1.6E+0	1.7E+0	1.7E+0	1.8E+0	1.6E+0
Off#3	1.6E+0	1.6E+0	1.5E+0	1.6E+0	1.6E+0	1.5E+0	1.6E+0	1.7E+0	1.6E+0
Off#4	1.5E+0	1.5E+0	1.5E+0	1.6E+0	1.7E+0	1.7E+0	1.5E+0	1.7E+0	1.5E+0
Off#5	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.7E+0	1.7E+0	1.6E+0	1.7E+0
Radiation-Mean OFF	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.6E+0	1.7E+0	1.6E+0
Standarddeviation	56.7E-3	43.8E-3	56.9E-3	31.1E-3	32.0E-3	72.0E-3	97.7E-3	56.1E-3	69.6E-3
Mean + kσ	1.7E+0	1.7E+0	1.7E+0	1.7E+0	1.7E+0	1.8E+0	1.9E+0	1.9E+0	1.8E+0
Mean - kσ	1.4E+0	1.5E+0	1.4E+0	1.5E+0	1.6E+0	1.4E+0	1.4E+0	1.6E+0	1.4E+0

Reference	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Ref1	1.6E+0	1.5E+0	1.6E+0	1.7E+0	1.6E+0	1.7E+0	1.8E+0	1.6E+0	1.7E+0
Typ. Value	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0	1.5E+0
Max. Value	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0	1.8E+0

- **V_{F1} and V_{F2}:** Measured values are corrected for the setup by approx. 0.2 V. Displayed in this report are the already corrected values.


On#1
On#2
On#3
On#4
On#5
Off#1
Off#2
Off#3
Off#4
Off#5
Ref
Mean ON
Mean OFF
Min. Value
Typ. Value
Max. Value
C4D40120D, (W13714)
Forward Voltage (2) in V
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
0
30
50
100
300
500
1000
24h
RT
168h
100°C
Total Dose [krad(Si)] / Annealing
On
Off
RT
100°C
Total Dose [krad(Si)] / Annealing
Total Dose [krad(Si)] / Annealing

6.4 Reverse Current (1)

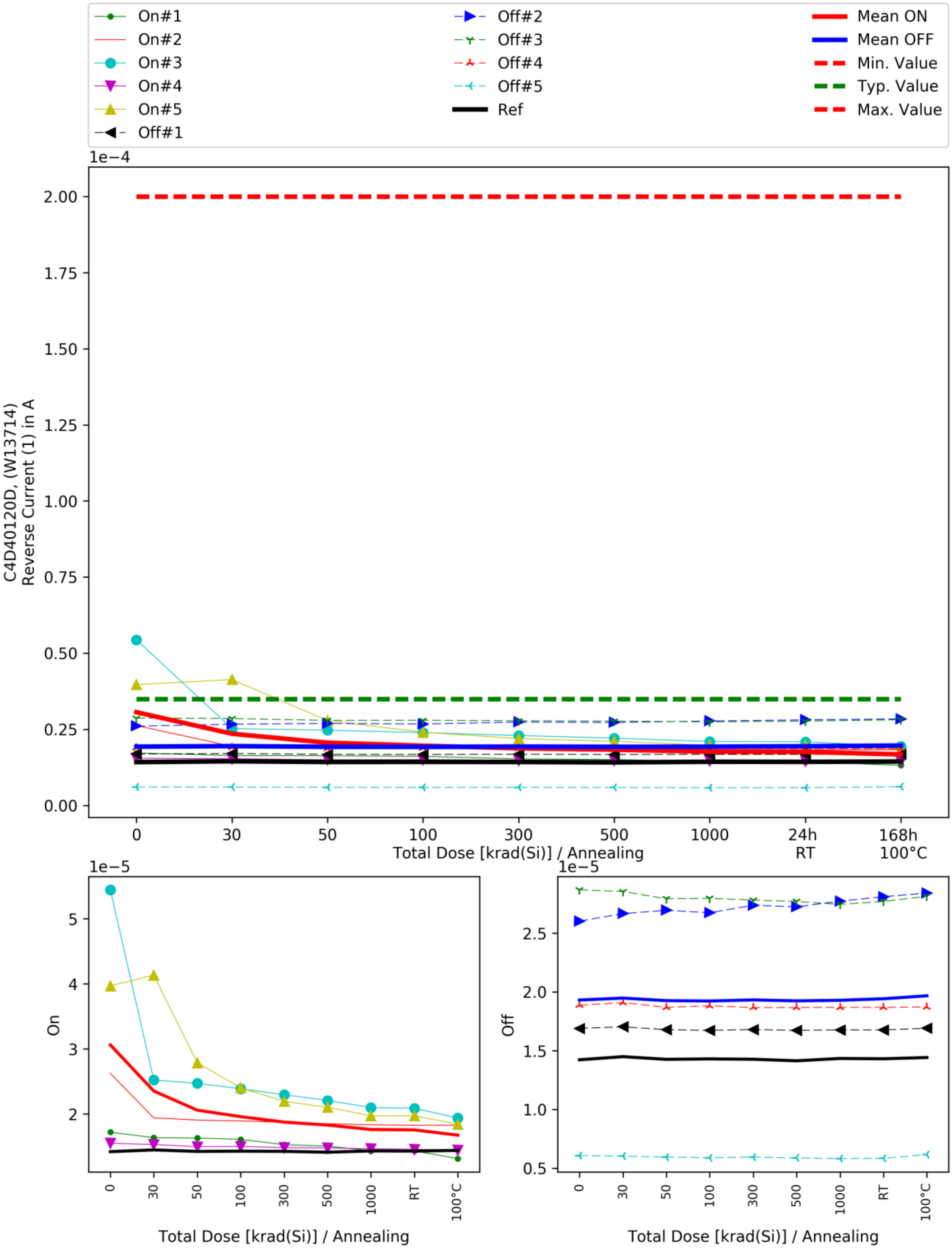
Reverse Current (1)
IR1 in A
Limit: x < 200.0

C4D40120D
Date-/Lotcode: W13714

ON-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
On#1	17.2E-6	16.4E-6	16.3E-6	16.1E-6	15.3E-6	15.1E-6	14.4E-6	14.3E-6	13.2E-6
On#2	26.2E-6	19.4E-6	19.1E-6	18.9E-6	18.7E-6	18.5E-6	18.4E-6	18.3E-6	18.3E-6
On#3	54.4E-6	25.2E-6	24.7E-6	23.9E-6	23.0E-6	22.1E-6	21.0E-6	20.9E-6	19.4E-6
On#4	15.5E-6	15.3E-6	15.0E-6	15.0E-6	14.8E-6	14.8E-6	14.7E-6	14.6E-6	14.5E-6
On#5	39.7E-6	41.3E-6	27.9E-6	24.0E-6	22.0E-6	21.0E-6	19.7E-6	19.7E-6	18.5E-6
Radiation-Mean ON	30.6E-6	23.5E-6	20.6E-6	19.6E-6	18.8E-6	18.3E-6	17.6E-6	17.6E-6	16.8E-6
Standarddeviation	16.4E-6	10.7E-6	5.5E-6	4.2E-6	3.7E-6	3.3E-6	3.0E-6	3.0E-6	2.7E-6
Mean + kσ	75.6E-6	52.8E-6	35.7E-6	31.2E-6	29.0E-6	27.5E-6	25.8E-6	25.8E-6	24.3E-6
Mean - kσ	-14.4E-6	-5.7E-6	5.4E-6	8.0E-6	8.6E-6	9.2E-6	9.4E-6	9.4E-6	9.2E-6

OFF-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Off#1	16.9E-6	17.0E-6	16.8E-6	16.7E-6	16.8E-6	16.7E-6	16.8E-6	16.8E-6	16.9E-6
Off#2	26.0E-6	26.7E-6	27.0E-6	26.7E-6	27.4E-6	27.2E-6	27.7E-6	28.1E-6	28.4E-6
Off#3	28.7E-6	28.6E-6	27.9E-6	28.0E-6	27.8E-6	27.7E-6	27.5E-6	27.7E-6	28.1E-6
Off#4	18.9E-6	19.1E-6	18.7E-6	18.8E-6	18.7E-6	18.7E-6	18.7E-6	18.7E-6	18.7E-6
Off#5	6.1E-6	6.0E-6	6.0E-6	5.9E-6	5.9E-6	5.9E-6	5.8E-6	5.8E-6	6.2E-6
Radiation-Mean OFF	19.3E-6	19.5E-6	19.3E-6	19.2E-6	19.3E-6	19.2E-6	19.3E-6	19.4E-6	19.7E-6
Standarddeviation	8.9E-6	9.0E-6	8.9E-6	8.9E-6	9.0E-6	9.0E-6	9.0E-6	9.2E-6	9.2E-6
Mean + kσ	43.6E-6	44.0E-6	43.7E-6	43.6E-6	44.0E-6	43.8E-6	44.0E-6	44.6E-6	44.9E-6
Mean - kσ	-5.0E-6	-5.1E-6	-5.2E-6	-5.2E-6	-5.3E-6	-5.3E-6	-5.5E-6	-5.7E-6	-5.6E-6

Reference	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Ref1	14.2E-6	14.5E-6	14.3E-6	14.3E-6	14.3E-6	14.1E-6	14.3E-6	14.3E-6	14.4E-6
Typ. Value	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6
Max. Value	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6


On#1
On#2
On#3
On#4
On#5
Off#1
Off#2
Off#3
Off#4
Off#5
Ref
Mean ON
Mean OFF
Min. Value
Typ. Value
Max. Value
1e−4
C4D40120D, (W13714)
Reverse Current (1) in A
Total Dose [krad(Si)] / Annealing
24h RT
168h 100°C
1e−5
On
Off
Total Dose [krad(Si)] / Annealing
Total Dose [krad(Si)] / Annealing

6.5 Reverse Current (2)

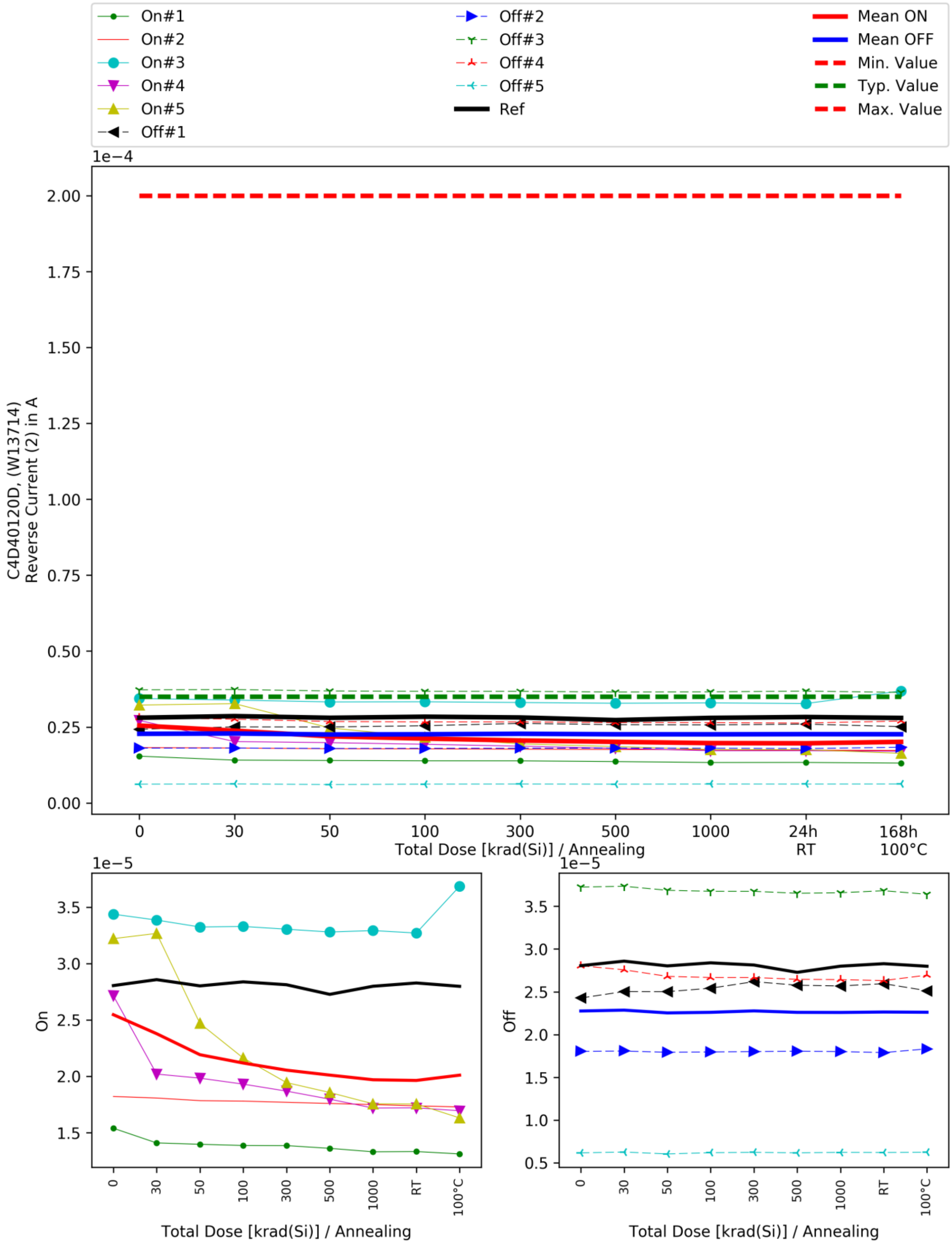
Reverse Current (2)
IR2 in A
Limit: x < 200.0

C4D40120D
Date-/Lotcode: W13714

ON-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
On#1	15.4E-6	14.1E-6	14.0E-6	13.9E-6	13.9E-6	13.6E-6	13.3E-6	13.3E-6	13.1E-6
On#2	18.2E-6	18.1E-6	17.8E-6	17.8E-6	17.7E-6	17.6E-6	17.5E-6	17.4E-6	17.3E-6
On#3	34.4E-6	33.9E-6	33.3E-6	33.3E-6	33.1E-6	32.8E-6	32.9E-6	32.7E-6	36.9E-6
On#4	27.2E-6	20.2E-6	19.8E-6	19.3E-6	18.7E-6	18.0E-6	17.2E-6	17.2E-6	16.9E-6
On#5	32.2E-6	32.7E-6	24.7E-6	21.6E-6	19.4E-6	18.6E-6	17.6E-6	17.5E-6	16.3E-6
Radiation-Mean ON	25.5E-6	23.8E-6	21.9E-6	21.2E-6	20.5E-6	20.1E-6	19.7E-6	19.6E-6	20.1E-6
Standarddeviation	8.4E-6	9.0E-6	7.4E-6	7.3E-6	7.3E-6	7.4E-6	7.6E-6	7.5E-6	9.5E-6
Mean + kσ	48.5E-6	48.3E-6	42.3E-6	41.3E-6	40.6E-6	40.3E-6	40.6E-6	40.3E-6	46.2E-6
Mean - kσ	2.4E-6	-761.2E-9	1.6E-6	1.0E-6	478.7E-9	-84.2E-9	-1.2E-6	-995.0E-9	-6.0E-6

OFF-Mode	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Off#1	24.3E-6	25.0E-6	25.0E-6	25.4E-6	26.2E-6	25.8E-6	25.7E-6	25.9E-6	25.1E-6
Off#2	18.0E-6	18.1E-6	17.9E-6	18.0E-6	18.0E-6	18.1E-6	18.0E-6	17.9E-6	18.3E-6
Off#3	37.2E-6	37.3E-6	36.9E-6	36.8E-6	36.7E-6	36.5E-6	36.6E-6	36.8E-6	36.4E-6
Off#4	28.0E-6	27.6E-6	26.8E-6	26.7E-6	26.7E-6	26.5E-6	26.4E-6	26.3E-6	27.0E-6
Off#5	6.2E-6	6.3E-6	6.0E-6	6.2E-6	6.2E-6	6.2E-6	6.2E-6	6.2E-6	6.2E-6
Radiation-Mean OFF	22.8E-6	22.9E-6	22.5E-6	22.6E-6	22.8E-6	22.6E-6	22.6E-6	22.6E-6	22.6E-6
Standarddeviation	11.6E-6	11.6E-6	11.4E-6	11.4E-6	11.4E-6	11.3E-6	11.3E-6	11.4E-6	11.2E-6
Mean + kσ	54.5E-6	54.6E-6	53.9E-6	53.7E-6	54.0E-6	53.5E-6	53.5E-6	53.8E-6	53.3E-6
Mean - kσ	-9.0E-6	-8.9E-6	-8.8E-6	-8.5E-6	-8.5E-6	-8.3E-6	-8.3E-6	-8.6E-6	-8.1E-6

Reference	Total Dose [krad (Si)]							Annealing	
	0	30	50	100	300	500	1000	24h @RT	68h @ 100°(
Ref1	28.1E-6	28.6E-6	28.0E-6	28.4E-6	28.1E-6	27.3E-6	28.0E-6	28.3E-6	28.0E-6
Typ. Value	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6	35.0E-6
Max. Value	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6	200.0E-6


On#1
On#2
On#3
On#4
On#5
Off#1
Off#2
Off#3
Off#4
Off#5
Ref
Mean ON
Mean OFF
Min. Value
Typ. Value
Max. Value
1e−4
C4D40120D, (W13714)
Reverse Current (2) in A
Total Dose [krad(Si)] / Annealing
24h RT
168h 100°C
1e−5
On
Off
Total Dose [krad(Si)] / Annealing

A Fraunhofer INT

A.1. About the institute

The Fraunhofer Institute for Technological Trend Analysis INT provides scientifically sound assessments and counselling on the entire spectrum of technological developments. On this basis, the Institute conducts Technology Forecasting, making possible a long-term approach to strategic research planning. Fraunhofer INT constantly applies this competence in projects tailor-made for our clients.

Over and above these skills, we run our own experimental and theoretical research on the effects of ionizing and electromagnetic radiation on electronic components, as well as on radiation detection systems. To this end, INT is equipped with the latest measurement technology. Our main laboratory and large-scale appliances are radiation sources, electromagnetic simulation facilities and detector systems that cannot be found in this combination in any other civilian body in Germany.

For more than 40 years, INT has been a reliable partner for the Federal German Ministry of Defence, which it advises in close cooperation and for which it carries out research in technology analysis and strategic planning as well as radiation effects. INT also successfully advises and conducts research for domestic and international civilian clients: both public bodies and industry, from SMEs to DAX 30 companies.

Further information can be found on the website [1].

A.2. Business unit Nuclear Effects in Electronics and Optics

The Business Unit „Nuclear Effects in Electronic and Optics (NEO)" at Fraunhofer INT investigates the effects of ionizing radiation on electronic, optoelectronic, and photonic components and systems. Its work is based on more than 40 years of experience in that field.

NEO performs irradiation tests based on international standards and advises companies regarding radiation qualification and hardening of components and systems. The knowledge obtained in years of radiation testing is also used for the development of new radiation sensor systems. These activities are performed either at irradiation facilities installed at INT or at partner institutions to which our scientists have regular access.

A multitude of modern equipment to measure electrical and optical parameters is available. Furthermore our institute runs a precision mechanical workshop and an electronic laboratory. This enables us to conduct most of the irradiation tests without help or equipment of the customer.

The activities within NEO are:

- Investigations of the effects in all kinds of radiation environments
- Performance, analysis, and evaluation of irradiation tests done at Fraunhofer INT and external facilities

- Ensuring the operability of components and systems in typical radiation environments, such as space, nuclear facilities, medicine, or accelerators
- Consulting users and manufacturers on the use of products in radiation environments by selecting, optimizing and hardening
- Measurement of the radiation effects on optical fibers and fiber Bragg gratings (FBG)
- Development of radiation sensors based on optical fibers, FBGs, oscillating crystals, UV-EPROMs, and SRAMs
- Participation in the development of international test procedures for IEC, IEEE, NATO, and IAEA
- Since 2013 all services of the business unit are certified according to ISO 9001

A.3. Irradiation facilities

Fraunhofer INT operates several irradiation facilities on site that are dedicated to perform irradiation tests. For that purpose the design and operation characteristics are highly optimised from many decades of experience and to comply with all relevant standards and test procedures.

Furthermore Fraunhofer INT accesses regularly external facilities, partly with dedicated irradiation spots for exclusive use to Fraunhofer INT.

These irradiation facilities are:

- Co-60 irradiation sources on site to simulate the effect of total dose
- Neutron generators on site to simulate the displacement damage of heavy particles
- 450 keV X-ray irradiation facility on site
- Laser induced single event test system on site
- Dedicated proton irradiation spot at the injector cyclotron of FZ Jülich to simulate the effects of solar and trapped protons
- External Co-60 irradiation sources for high dose and high dose rate irradiations

The facilities used in the context of this work will be described in detail in the following sections.

A.4. QM-Certificate

DNV·GL

MANAGEMENT SYSTEM CERTIFICATE

Certificate No: 126306-2012-AQ-GER-DAkkS
Initial certification date: 13. February 2013
Valid: 29. March 2018 - 12. February 2019

This is to certify that the management system of

Fraunhofer INT

Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen INT
Appelsgarten 2, 53879 Euskirchen, Germany

has been found to conform to the Quality Management System standard:

ISO 9001:2015

This certificate is valid for the following scope:

Scientific research on the effects of nuclear and electromagnetic radiation as well as application and development of methods for their characterization

Place and date:
Essen, 29. March 2018

DAkkS Deutsche Akkreditierungsstelle D-ZM-18453-01-00

For the issuing office:
DNV GL - Business Assurance
Schnieringshof 14, 45329 Essen, Germany

Thomas Beck
Technical Manager

Lack of fulfilment of conditions as set out in the Certification Agreement may render this Certificate invalid.
ACCREDITED UNIT: DNV GL Business Assurance Zertifizierung und Umweltgutachter GmbH, Schnieringshof 14, 45329 Essen, Germany.
TEL:+49 201 7296-222. www.dnvgl.de/assurance

B Irradiation details

B.1. Irradiation facility TK1000B

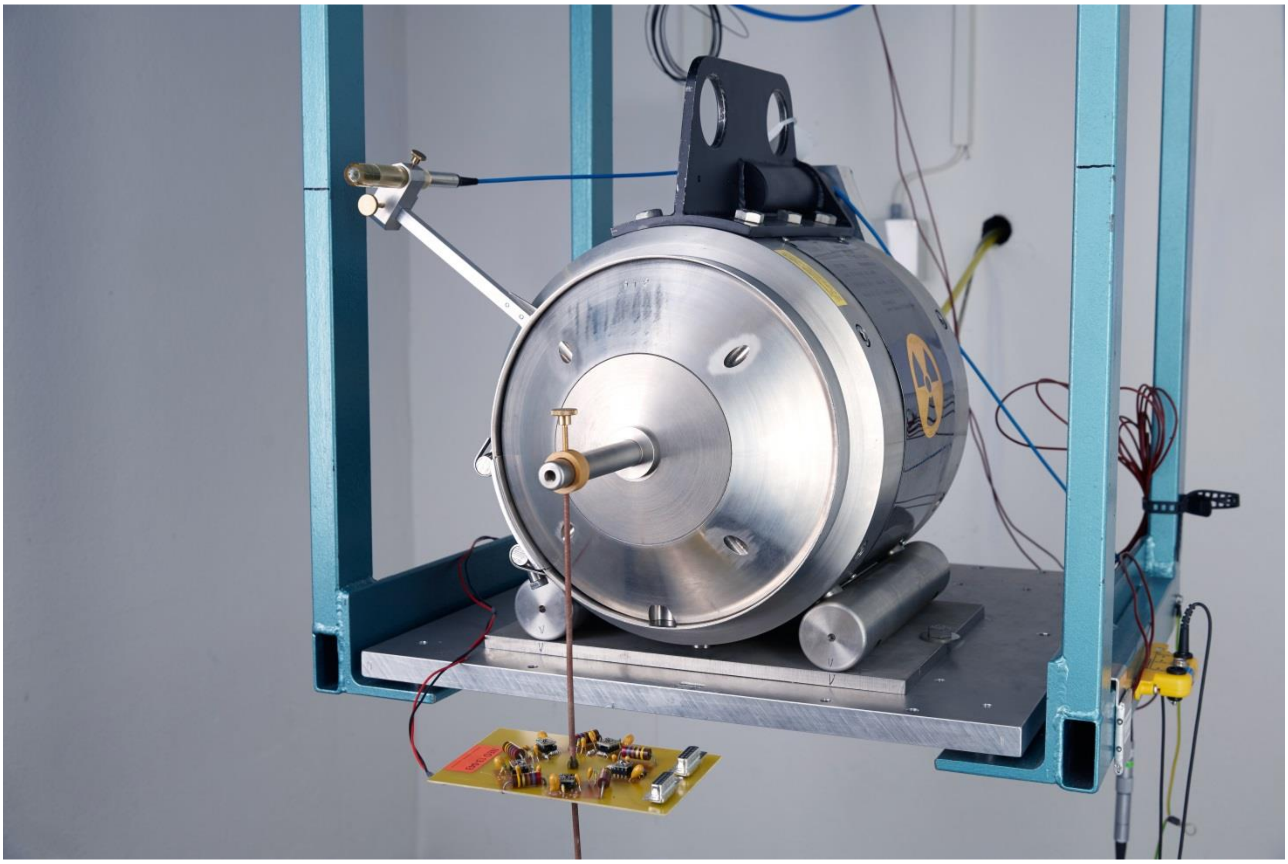
The TK1000B is a Co-60 gamma irradiator manufactured by Sauerwein Isotopentechnik, Germany. Inside the shielding container is a small radioactive pellet with a diameter of 7 mm and a length of 10.4 mm. The activity decreases with a physical half-life of 5.27 years. The current radioactive pellet was installed in the irradiator at 2012-01-25. The activity at that time was 16526 GBq.

In deactivated state the radioactive pellet is stored inside the shielding container allowing the operator to install the samples and conduct measurements without getting exposed to ionizing radiation.

On activation, the radioactive source is pushed into the source guiding tube in less than a second irradiating the surrounding volume.

The certificate of the radioactive source can be found in Appendix B.4.

Figure 12: TK1000B irradiation facility



B.2. Radiation properties of TK1000B

The samples are irradiated with Co-60 gamma radiation. The radioactive Co 60 isotope decays by emitting beta radiation (i.e. electrons) into a highly excited Ni-60 isotope which emits two gamma photons to reach the stable ground state. The gamma radiation has two energy levels of 1.172 MeV and 1.332 MeV.

The gamma radiation of around 1 MeV is a penetrating radiation, so the samples are irradiated completely. The shielding of the sample holder and other surrounding material between the source and the sample is negligible.

The radiation is emitted from a point-like source. Thus the dose rate $\dot{D}$ falls off with $1/r^2$ where r is the distance from the source.

$$\dot{D}(r) = \dot{D}_0 \cdot \frac{r_0^2}{r^2}$$

B.3. Dosimetry at TK1000B

The dosimetry is done regularly with calibrated ionisation chambers manufactured by IBA, Germany, and PTW Freiburg, Germany.

The dose rates obtained at varying distances between 2 cm and 50 cm and in different directions relative to the source are used to develop a model of the dose rate distribution around the source as a function of distance and direction. The dose rate of an individual measurement is scaled to a reference date taking the half-life of the radioactive isotope into account. This model is constantly checked and improved with each additional measurement of dose rates.

As a result a reliable description of the dose rates inside a specific volume arranged in a given geometry in the vicinity of the irradiation source is available.

The uncertainties of the reported dose rates are given by an uncertainty evaluation according to [2] and mainly result from the uncertainties of the dosimetry and positioning of the samples.

The uncertainty evaluation for this irradiation can be found in Appendix C.

B.4. Certificate of TK1000B irradiation source

IT-Service Leipzig

Ingenieur-Technischer Geräte- und Produktservice für Werkstoffprüfung und Medizintechnik

Qualitätszertifikat
für umschlossene Strahlenquelle

TK 1000 B

Prüfungszeugnis - Nr.:	12061
Kunde:	Frauenhofer Institut
Strahler/HRQ Ident. Nr.:	**001-2010(GK60R01**
Kapsel Typ:	GK60R01
ISO Code:	ISO/99/E 65546
AFNOR Code:	NF/99/E 65546
Zertifikat Nr.:	RUS/5614/S-96 (Rev. 0)
Radionuklid:	**Co-60**
Physikalische Form:	**fest, umschlossen**
Chemische Form:	**metallisch**
Brennfleck in mm x mm:	7,0x10,4 mm
Herstellungsaktivität:	20102,1 GBq (543,3 Ci)
Herstellungsdatum:	30.07.2010

Dichtheitsbescheinigung

Oberflächenkontaminationstest:		ohne Beanstandung
Datum:	30.07.2010	Ergebnis: < 185 Bq
Lecktest:		ohne Beanstandung
Datum:	30.07.2010	Ergebnis: dicht

Die Qualitätskontrolle wurde vom Hersteller in unserem Namen durchgeführt.
Es wird bescheinigt, daß die umschlossene radioaktive Strahlenquelle den Anforderungen nach NF / ISO 9978 (1992), ISO 2919 (1999) und NF M61002 (1984) entspricht.

Der oben genannte Strahler wurde in einem neuen bzw. entsprechend DIN 54115 Teil 6 überprüften und zugelassenen Strahlerhalter Nr.: eingebaut.

Datum: 25.01.2012 Signum IT-Service:

i.A. [illegible]

IT-Service Leipzig GmbH, BS Haan, Bergische Straße 16, 42781 Haan Tel.: 02129 / 377595 Fax: 02129 / 378794

C Irradiation documentation

Irradiation Test Documentation

Fraunhofer INT

Irradiation Source	TK1000B (2012)	Date	30.11.2016
Responsible Employee	MS		
Project Description	NEO-14-086 TOPSIDE SiC Run#2		

Reference Data for Dose Rate Calculation

Reference Activity	8.74 TBq ± *10.0%*	Standard uncertainty[1]
Reference Dose Rate	2.35 Gy/s ± *2.5%*	Standard uncertainty[1]
Reference Distance	10 cm ± *0.5%*	Standard uncertainty[1]
Reference Date	01.01.1990	

Geometry of Irradiated Object (As defined or measured):

Inner Diameter	8.40 cm ± *0.05* cm	Standard uncertainty[1]
Outer Diameter	10.80 cm ± *0.05* cm	Standard uncertainty[1]
Height	0.45 cm ± *0.05* cm	Standard uncertainty[1]

Distances of Point Source:

Surface of Object	16.00 cm ± *0.05* cm	Standard uncertainty[1]
Object Minimum	16.53 cm ± 0.05 cm	Standard uncertainty[2]
Object Maximum	17.33 cm ± 0.07 cm	Standard uncertainty[2]
Mean Distance	**16.92 cm ± 0.11 cm**	*Expanded uncertainty*[3]

Dose Rates in Object

Minimum	0.0229 Gy/s ± 2.8%	Standard uncertainty[2]
Mean	**0.0240 Gy/s ± 2.8%**	Standard uncertainty[2]
Maximum	0.0252 Gy/s ± 2.8%	Standard uncertainty[2]

Irradiation Time	**416399 s ± *1* s**	Standard uncertainty[1]
in DD HH:MM:SS	04 19:39:59 ± *1* s	Standard uncertainty[1]

Dose in Object

Minimum	9536 Gy ± 2.8%	Standard uncertainty[2]
Maximum	10485 Gy ± 2.8%	Standard uncertainty[2]
Mean	**10000 Gy ± 5.5%**	*Expanded uncertainty*[3]
Homogeneity	9.5%	

[1] Experience or statistics based estimation of standard uncertainty with a coverage factor k=1
[2] Combined standard uncertainty with a coverage factor k=1
[3] Determined from a combined standard uncertainty (i.e., estimated standard deviations of values above) and a coverage factor k = 2. Since it can be assumed that the possible estimated values of the dose are approximately normally distributed with approximate standard deviation, the unknown value of the dose is believed to lie in the interval given with a level of confidence of approximately 95 %.

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