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STS Sensor's Leakage Current at their End-of-Lifetime*

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Abstract

This document aims to narrow down the leakage current, and thereby power dissipation behaviour of STS sensors at their end-of-lifetime fluence. This is done by stitching together estimates from the widely used empirical Hamburg Model and previous STS irradiation campaigns with miniature and prototype sensors from 2014-15 and 2018-19, respectively. All estimates were found to be consistent with each other and result in sensor power dissipation values of 6 mW/cm^2 at -10°C, when sensors are exposed to non-ionising fluence of 10^{14}n$_{eq}$(1 MeV)/cm^2.

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Table of Contents

1 Hamburg Model Expectations 1

2 STS Irradiation Campaign 2014-15 2

3 STS Irradiation Campaign 2018-19 3

4 Summary and Conclusion 4

References 5

1 Hamburg Model Expectations

Due to the high-multiplicity operating environment of CBM, the silicon sensors in STS are foreseen to be exposed to high non-ionising fluence (Φ_{eq}) of up to 1×10^{14}n$_{eq}$(1 MeV)/cm^2, thereby defining the detector's end-of-lifetime (EOL) fluence [1]. This fluence results in development of damages in the lattice structure of the silicon bulk populating new band gap levels [2, 3]. This leads to changes in sensor's global properties within rising fluence, such as its Leakage Current ($I_{Leakage}$), as shown in Eq. 1.1 and Fig. 1.

$$\frac{\Delta I_{Leakage}}{A} = \alpha \cdot \Phi_{eq} \cdot d \tag{1.1}$$

where α is the damage coefficient, which varies between 4...7 $\times10^{17}$ A/cm depending on the annealing conditions (see Fig. 1 and 2). d and A are the thickness and area of the sensor, respectively. The sensor leakage current also exhibits strong dependence on the its operation temperature (T_{Sensor}), as shown in Eq. 1.2.

$$I_{Leakage} \propto T^2_{Sensor} \cdot e^{-\frac{E_{gap}}{2 \cdot T_{Sensor} \cdot k_B}} \tag{1.2}$$

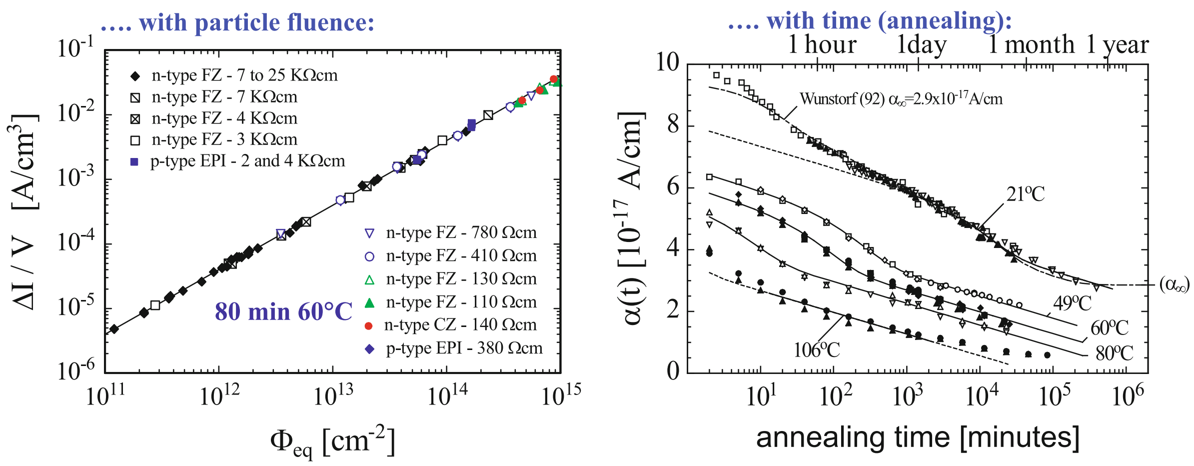

Figure 1: Variation of leakage current with fluence and annealing time [2, 3] (figure from [4]).

Annealing temperature in °C	21	40	60	80
α_0 in 10^{-17} A/cm	7	6	5	4
τ_I in min	140000	260	94	9

Figure 2: Change of damage coefficient α and annealing time constant τ_I with temperature (figure from [4]).

Assuming the highest damage coefficient of 7 $\times10^{17}$ A/cm, for a 320 μm thick sensor irradiated at Φ_{eq} of 1×10^{14}n$_{eq}$(1 MeV)/cm^2, the leakage current and power surface density is approximately 224 μA/cm^2 and 112 mW/cm^2, respectively at +20°C and 500 V[1]. This corresponds to power dissipation of less than 7 mW/cm^2 at -10°C.

[1]In Eq. 1.1, the initial leakage current of the sensor plays a negligible role as the post-irradiation leakage current is completely driven by $\alpha \cdot \Phi_{eq} \cdot d$. Nevertheless, based on the electrical inspection of 1200 HPK sensors for STS, the pre-irradiation leakage at +20°C and 500 V is less than 0.04 μA/cm^2.

2 STS Irradiation Campaign 2014-15

Irradiation studies with neutrons were performed at the Jozef Stefan Institute in Ljubljana, Slovenia, with reactor neutrons from the TRIGA type nuclear reactor. Miniature sensors (1.2×1.2 cm^2; 290 μm thick) from CiS were fabricated with the same wafers as the CBM05 prototype sensors. Properties of the irradiated sensors along with their IDs are summarised in Fig. 3. Additionally, the leakage current variation with bias voltage of these irradiated sensors at -5°C is shown in Fig. 4. Further details of this irradiation campaign along with measurement details are mentioned in [5].

Given that the end-of-lifetime fluence expected for STS sensors is $1{\times}10^{14}$n$_{eq}$(1 MeV)/cm^2, the miniature sensors *w1sn2* and *w2sn1* are considered (see sensors marked in red in Fig. 3). Therefore, the corresponding leakage current measured at -5°C and 500 V is approximately 20 μA (see Fig. 4). This corresponds to the leakage current and power surface density of approximately 14 μA/cm^2 and 7 mW/cm^2, respectively at -5°C and 500 V.

Acronym	Vendor	Thickness [µm]	Size [cm^2]	V$_{fd,0}$ [V]	Strip pitch [µm]	Fluence [n$_{eq}$/ cm^2]
Irradiated batch A: miniature STS sensors irradiated with neutrons						
w06				85		0
w1sn5				88		3×10^{13}
w2sn5				82		3×10^{13}
w2sn3				82		5×10^{13}
w8sn2				83		5×10^{13}
w7sn1	CiS	290	1.2× 1.2	85	50	8×10^{13}
w7sn4				80		8×10^{13}
w1sn2				**90**		$\mathbf{1\times 10^{14}}$
w2sn1				**85**		$\mathbf{1\times 10^{14}}$
w2sn2				85		2×10^{14}
w8sn1				80		2×10^{14}

Figure 3: Properties of the CiS miniature sensors studied for neutron irradiation during 2014-15. The considered sensors are marked in red (figure adapted from [5]).

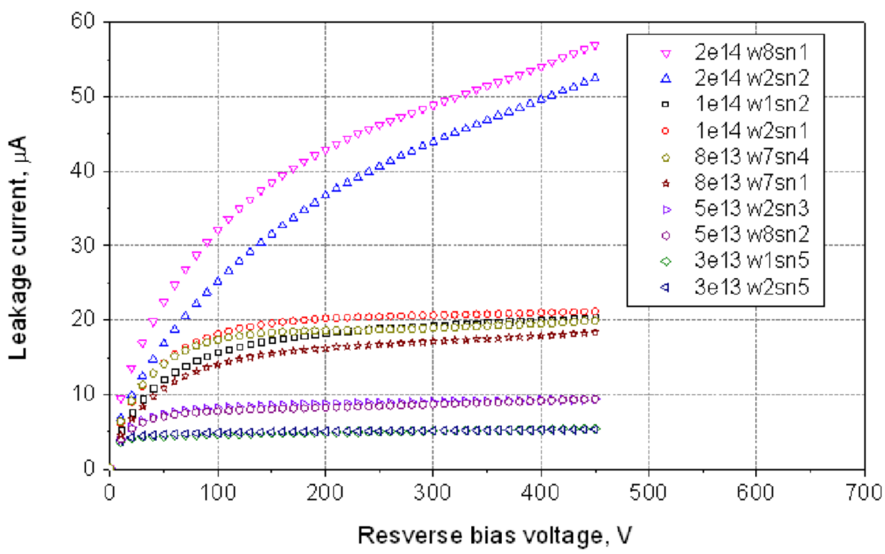

Figure 4: Leakage current variation with reverse bias voltage of the irradiated CBM05 miniature sensors (batch A) measured at -5°C (figure from [5]).

3 STS Irradiation Campaign 2018-19

An extensive irradiation campaign with realistic sensor dimensions (6.2×2.2 cm^2, 6.2×4.2 cm^2 and 6.2×6.2 cm^2) fabricated by CiS and HPK were carried out with protons at the Irradiation Center Karlsruhe. The properties of the irradiated sensors along with their IDs and leakage current properties at -10°C[2]are summarised in Fig. 5. Further details of this irradiation campaign along with measurement details are mentioned in [6, 7].

Please note that the sensors considered for power dissipation estimates are the ones which will be comprised in the final STS, i.e., HPK-type irradiated at the end-of-lifetime fluence of $1\times10^{14} n_{eq}(1\ \mathrm{MeV})/\mathrm{cm}^2$ (see sensors marked in red in Fig. 5)[3]. Therefore, the corresponding leakage current and power surface density measured at -10°C and 500 V[4] is between 10...16 μA/cm^2 and 5...8 mW/cm^2.

Size	Vendor and gen.	Batch #	Wafer #	Fluence, $10^{14} n_{eq}/\mathrm{cm}^2$	Current at 500 V, μA/cm^2	Operation voltage, V
62×62 mm^2	CiS 06	350191	09	0.0	0.253	150
			03	1.0	5.7	350
			08	1.0	14.3	350
			01	2.0	8.7	≥ 500
			10	2.0	9.7	≥ 500
	HPK 06	**S10938-4440**	72	0.0	0.012	150
			65	**1.0**	**12.7**	**400**
			71	**1.0**	**10.2**	**400**
			59	2.0	20.1	≥ 500
			79	2.0	14.1	≥ 500
62×42 mm^2	CiS 08	351135	05	0.0	0.124	150
		351135	02	0.1	1.7	150
		351139	01	0.1	1.9	150
		351135	11	0.5	11.8	300
		351135	06	1.0	16.2	350
		351139	08	2.0	22.7	≥ 500
	HPK 06	**S10938-5552**	84	0.0	0.006	150
			33	0.5	7.0	300
			32	**1.0**	**15.4**	**400**
			31	2.0	28.2	≥ 500
62×22 mm^2	CiS 07	350714	22-3	0.5	8.0	300
			23-1	0.5	9.6	300
			21-3	1.0	24.2	350
			23-2	1.0	12.4	350
			17-3	2.0	29.5	≥ 500
			23-3	2.0	29.1	≥ 500
	HPK 06	**S10938-4723**	06	0.5	4.7	300
			04	0.5	5.1	300
			08	**1.0**	**11.4**	**400**
			01	1.0	54.2	400
			02	2.0	25.1	≥ 500
			05	2.0	22.7	≥ 500

Figure 5: Properties of the prototype sensors studied for proton irradiation during 2018-19. The considered sensors are marked in red (figure adapted from [6]).

[2]The temperatures for the resulting plots quoted in [6, 7] are +20°C, but this is in fact -10°C. Therefore, all plots, figures and data from [6, 7] should be referenced at +20°C.

[3]CBM06HPK2-w1 isn't considered here because it was mechanically damaged during the measurements

[4]Although the measurements for the considered sensors were conducted at 400 V, it's assumed that the leakage current at 400 V and 500 V is the same as the leakage current is expected to plateau after full-depletion.

4 Summary and Conclusion

All estimates for STS sensor's end-of-lifetime behaviour, as introduced in previous sub-sections, are collectively plotted in Fig. 6 by using Eq. 1.2. They are represented as the variation of power density with sensor temperature, with the underlying values at -10°C and +20°C also summarised in Tab. 1.

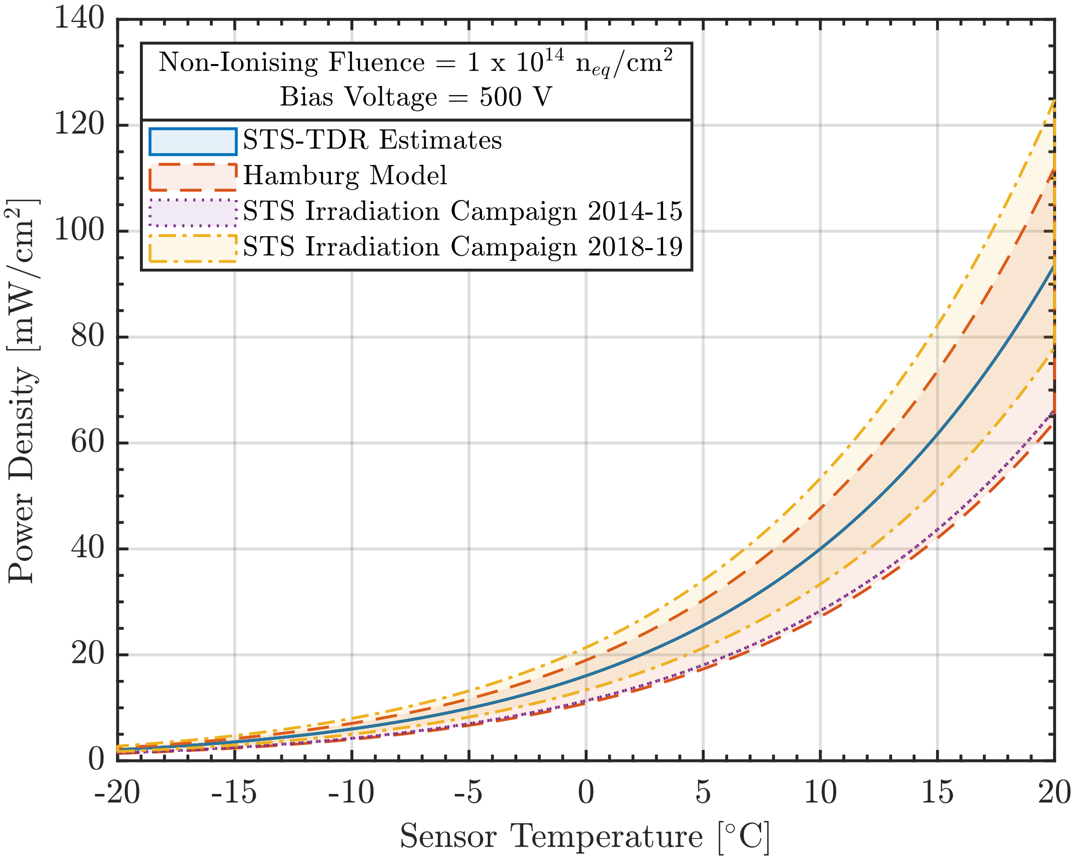

Figure 6: Variation of sensor power density with temperature at the end-of-lifetime conditions for different estimates.

Sensor Power Dissipation [mW/cm^2] Non-Ionising Fluence = $10^{14}n_{eq}$(1 MeV)/cm^2 and Bias Voltage = 500V		
	-10°C	+20°C
STS-Technical Design Report	6.00	93.62
Hamburg Model	4.04 ... 7.06	64.02 ... 112.02
STS Irradiation Campaign 2014-15	4.24	66.32
STS Irradiation Campaign 2018-19	5.00 ... 8.00	78.01 ... 124.82

Table 1: Sensor power dissipation at end-of-lifetime conditions for different estimates at different sensor temperatures.

Therefore, all estimates, both theoretical and experimental, are coherent with each other and STS sensors are foreseen to dissipate ≈ 6 mW/cm^2 at -10°C at end-of-lifetime fluence of $1{\times}10^{14}n_{eq}$(1 MeV)/cm^2.

References

[1] J. Heuser et al., eds. *Technical Design Report for the CBM Silicon Tracking System (STS)*. Darmstadt: GSI Report 2013-4, 2013, 167 p. URL: https://repository.gsi.de/record/54798.

[2] M. Moll. “Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties”. PhD thesis. Hamburg U., 1999.

[3] R. Wunstorf. “A Systematic investigation of the radiation hardness of silicon detectors for high-energy physics experiments”. PhD thesis. Oct. 1992.

[4] Frank Hartmann. *Evolution of Silicon Sensor Technology in Particle Physics*. Vol. 275. Springer Tracts in Modern Physics. Springer, 2017. ISBN: 978-3-319-64434-9, 978-3-319-64436-3. DOI: 10.1007/978-3-319-64436-3.

[5] P. Larionov. “Systematic irradiation studies and Quality Assurance of silicon strip sensors for the CBM Silicon Tracking System”. PhD thesis. Frankfurt U., 2016.

[6] I. Momot. “Characterization and radiation hardness studies of the silicon microstrip sensors for the CBM experiment”. PhD thesis. Frankfurt U., 2019.

[7] I. Momot et al. *Evaluation of the STS sensor prototypes irradiated with 23 MeV proton beam using relativistic β-electrons*. Technical Note CBM-TN-18015. GSI, 2018.