TOMSK STATE UNIVERSITY

X-ray test of sapphire wafers and 4 channel sensors
Preliminary results.

Gamma-beam profiler for LUXE project

29-04-2024
Tomsk, Russia

History of R&D in field of sapphire sensor of ionizing radiation.

F. Wang et al., Electronic Charge Transport in Sapphire Studied by Optical-Pump/THz-Probe Spectroscopy. 2004

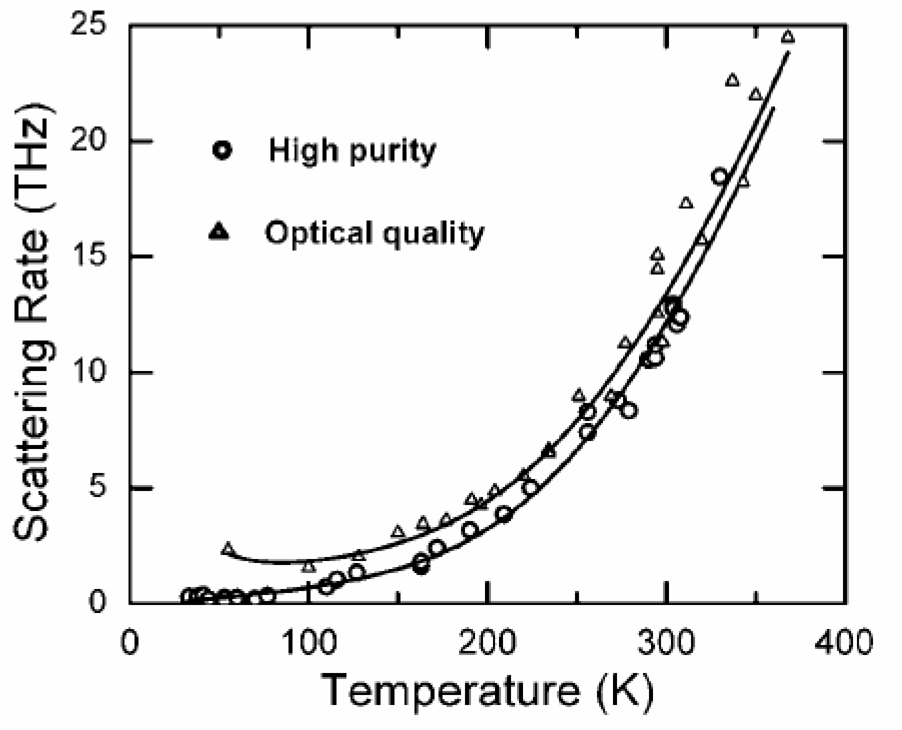
A. Ignatenko, Dissertation of Doctor of Science, Development of Beam Halo Monitors for the European XFEL using radiation hard sensors and Demonstration of the Technology at FLASH. 2014

O. Karacheban et al., Investigation of a direction sensitive sapphire detector stack at the 5 GeV electron beam at DESY-II, doi:10.1088/1748-0221/10/08/P08008. 2015

All sapphire sensor R&Ds in DESY were leaded by Sergej Schuwalow !

F. Wang et al., Electronic Charge Transport in Sapphire Studied by Optical-Pump/THz-Probe Spectroscopy. 2004

The method permits one to probe non-equilibrium systems with picosecond to sub-picosecond time resolution.

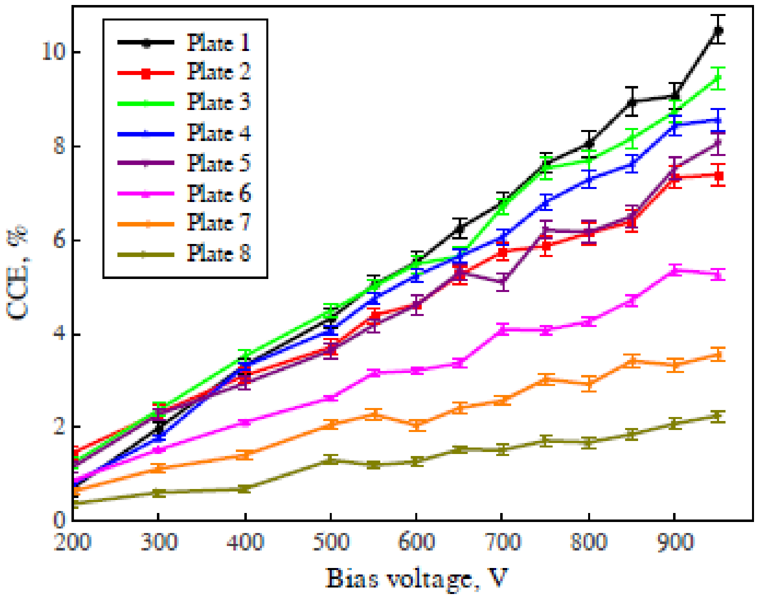


From time dependent THz probe measurements, we can determine the carrier lifetimes following photo-excitation. For the optical quality material, a typical carrier lifetime of 20 ps was observed; the lifetime in the high-purity sample was found to be close to 200 ps.

For the optical-quality sample of lower purity shown in Fig. 4, we estimated an impurity-limited mobility of ~ 4,000 cm^2/Vs at RT.

Carrier mobilities exceeding 10,000 cm^2/Vs can be achieved at 40 K

O. Karacheban et al., Investigation of a direction sensitive sapphire detector stack at the 5 GeV electron beam at DESY-II, doi:10.1088/1748-0221/10/08/P08008. 2015

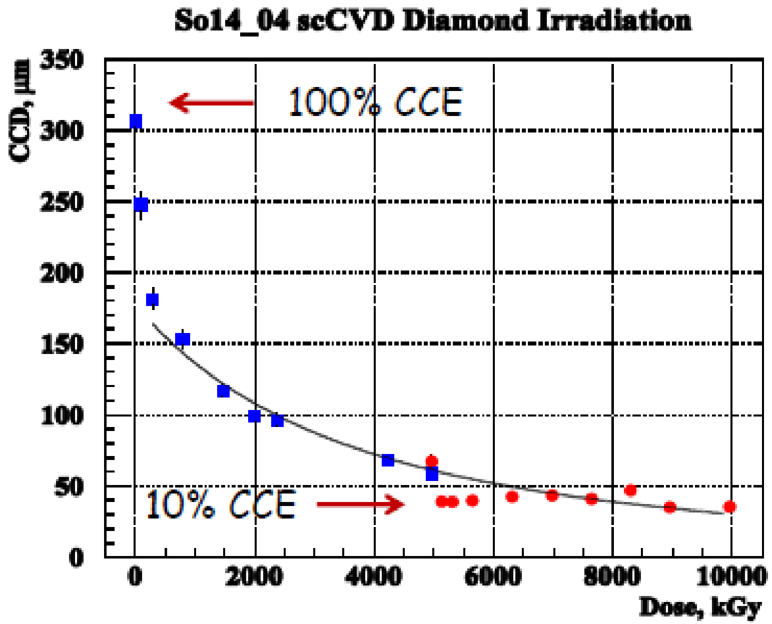


The measured CCE at the highest applied bias voltage of 950 V

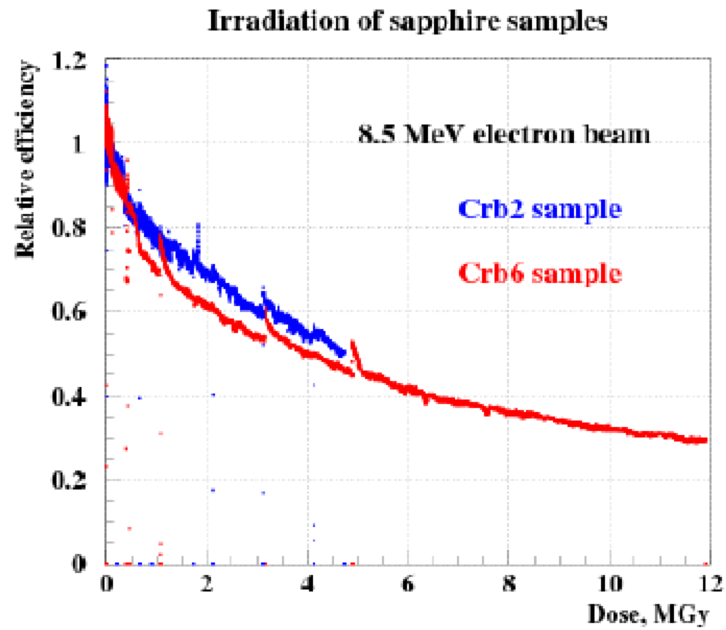
Plate number	1	2	3	4	5	6	7	8
CCE, %	10.5	7.4	9.5	8.6	8.1	5.3	3.6	2.2
Stat. error	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Syst. error	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
<CCE>, %	9.9	7.2	9.0	8.5	7.5	5.3	3.7	2.1
RMS	1.7	0.9	0.9	0.8	0.6	0.5	0.9	0.7

Irradiation of sapphire and diamond sensors at ~10 MeV electron beam (TU Darmstadt)

Single crystal CVD diamond



Single crystal sapphire



Leakage current after irradiation is still at few pA level

10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL,Summers)

Presented on 33rd FCAL workshop by Sergej Schuwalow

A. Ignatenko, Dissertation of Doctor of Science, Development of Beam Halo Monitors fo
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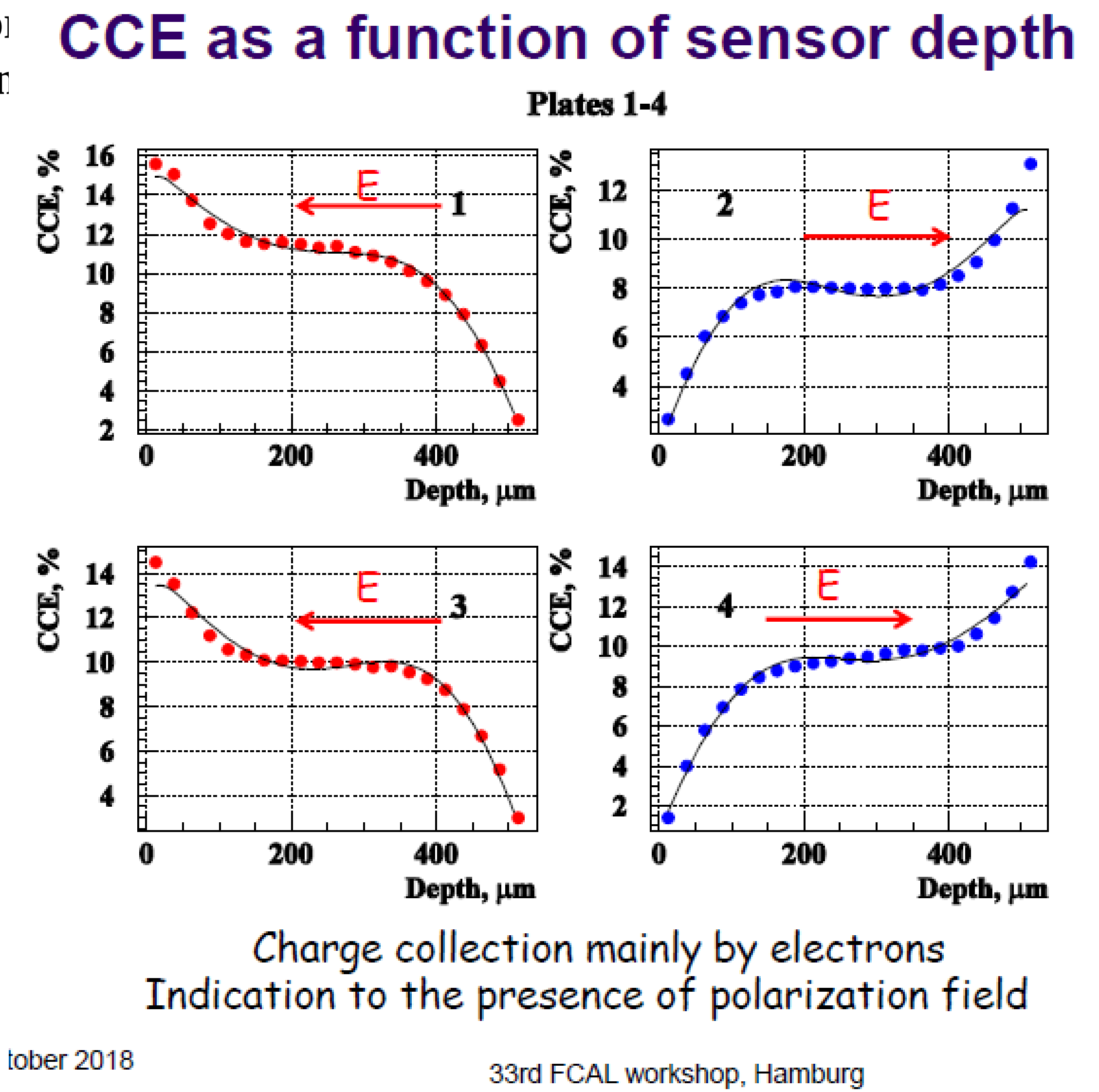

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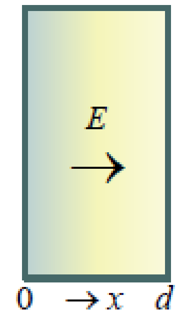
Charge transport in sapphire



Space charge creation due to the trapped carriers

Space charge is a linear function of depth: $\rho = p(2x - d)$

Parabolic electric field $E(x) = A\left(x - \frac{d}{2}\right)^2 + B$

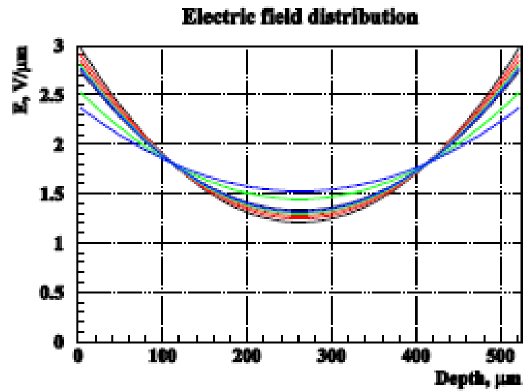
$$\int_0^d E\,dx = \frac{Ad^3}{12} + Bd = V$$ boundary condition

$x_0 \rightarrow d$ charge drift

Collected charge for one carrier type:

$$Q = \frac{N_0}{d} e^{\frac{\arctan\left(\left(x_0 - \frac{d}{2}\right)\sqrt{\frac{A}{B}}\right)}{\mu\tau\sqrt{AB}}} \int_{x_0}^{d} e^{-\frac{\arctan\left(\left(x - \frac{d}{2}\right)\sqrt{\frac{A}{B}}\right)}{\mu\tau\sqrt{AB}}} dx$$

Plate number	$B,\ V/\mu m$	$\mu\tau(e),\ \mu m^2/V$	$Norm,\ \%$	$\mu\tau(h),\ \mu m^2/V$	χ^2
1	1.328±0.011	79.4±1.0	52.4±0.4	4.7±0.2	18
2	1.207±0.011	62.0±1.0	47.0±0.5	5.7±0.2	59
3	1.274±0.009	66.7±0.9	53.2±0.5	6.1±0.2	35
4	1.243±0.010	76.6±1.0	48.6±0.5	2.3±0.2	35
5	1.441±0.010	61.0±1.0	48.6±0.8	2.4±0.3	16
6	1.297±0.011	40.5±0.9	44.2±0.9	4.2±0.3	67
7	1.521±0.006	18.7±0.3	60.4±1.4	2.3±0.2	17
8	1.314±0.009	14.2±0.5	46.3±1.9	1.9±0.3	46



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Sensor material properties

	Sapphire	Diamond	GaAs	Si
Density, g/cm^3	3.98	3.52	5.32	2.33
Dielectric constant	9.3 - 11.5	5.7	10.9	11.7
Breakdown field, V/cm	$\sim 10^6$ *	10^7	$4 \cdot 10^5$	$3 \cdot 10^5$
Resistivity, $\Omega \cdot cm$	$>10^{14}$	$>10^{11}$	10^7	10^5
Band gap, eV	9.9	5.45	1.42	1.12
El. mobility, $cm^2/(V \cdot s)$	>600 **	1800	~8500	1360
Hole mobility, $cm^2/(V \cdot s)$	-	1200	-	460
MIP eh pairs created, eh/μm	22	36	150	73

* Typical operation field $\sim 1\text{-}2 \cdot 10^4$ V cm^{-1}

** at 20°C, ~30000 at 40°K

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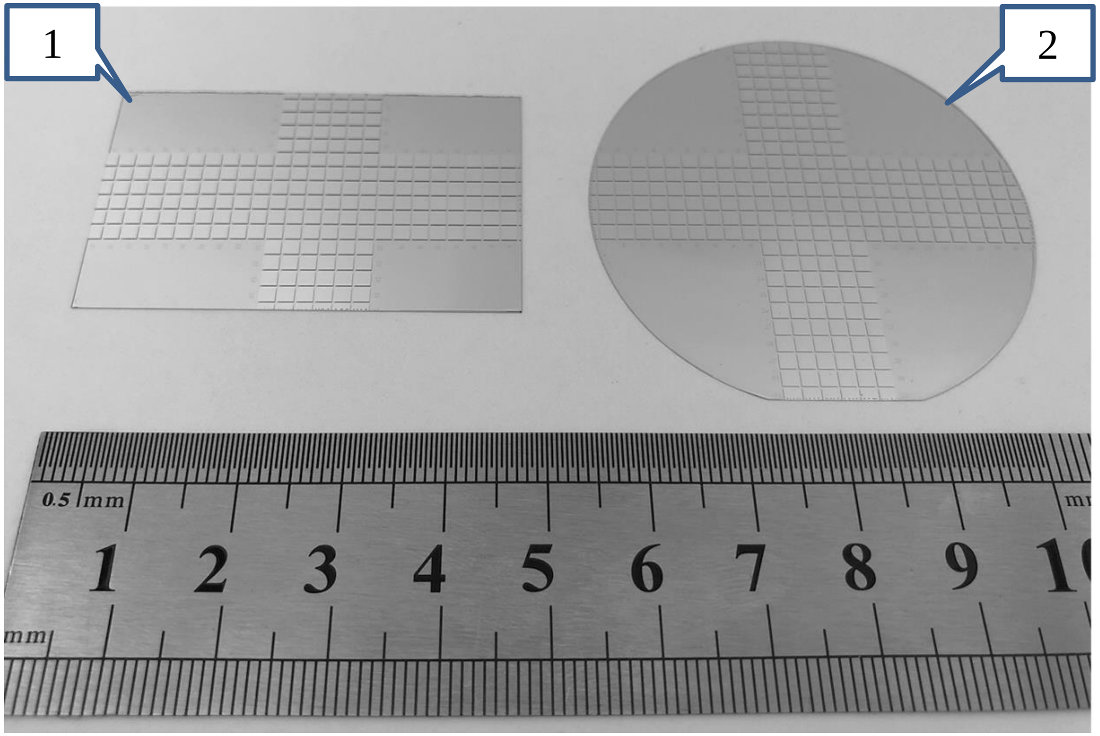
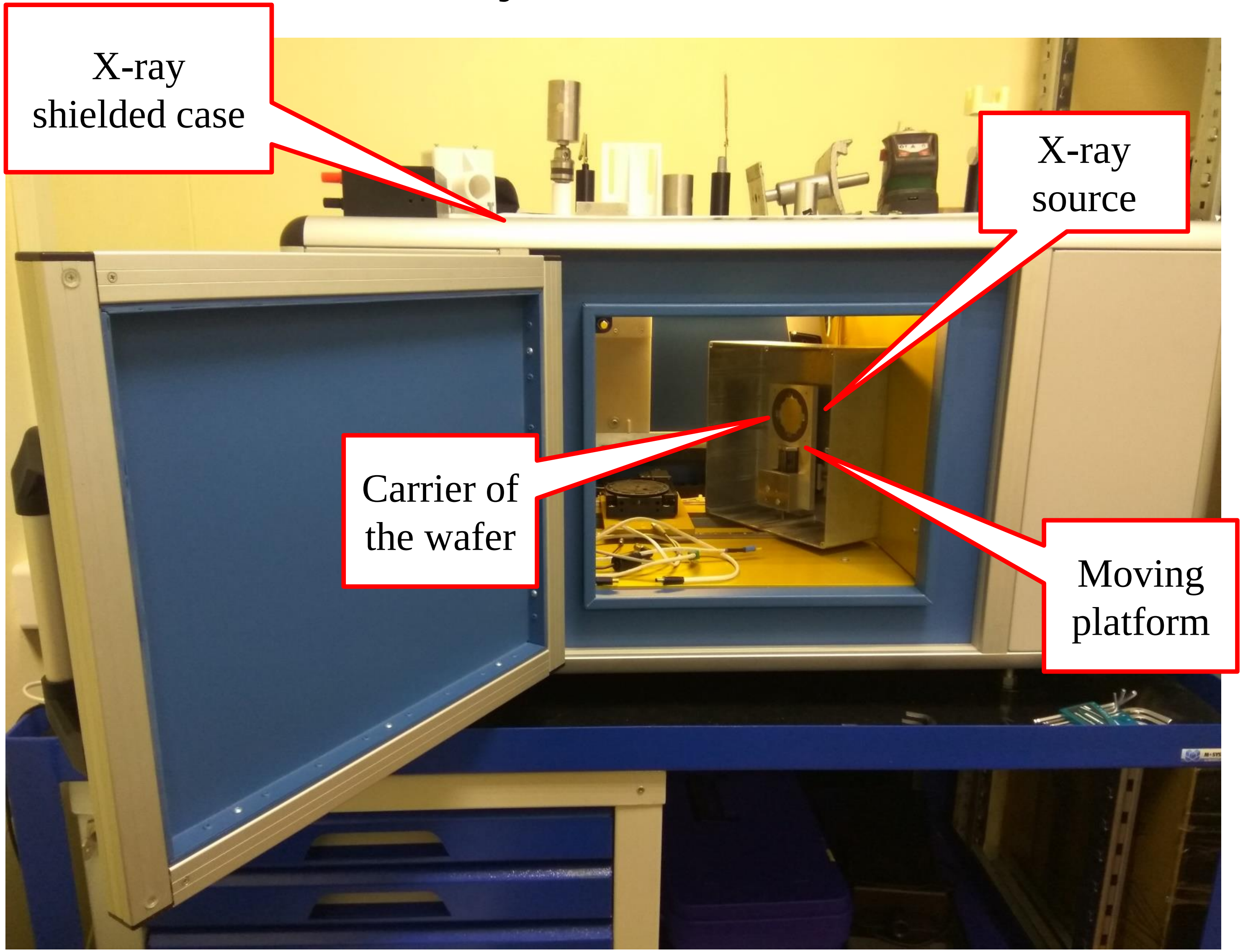
Pixelated sapphire wafers produced by TSU



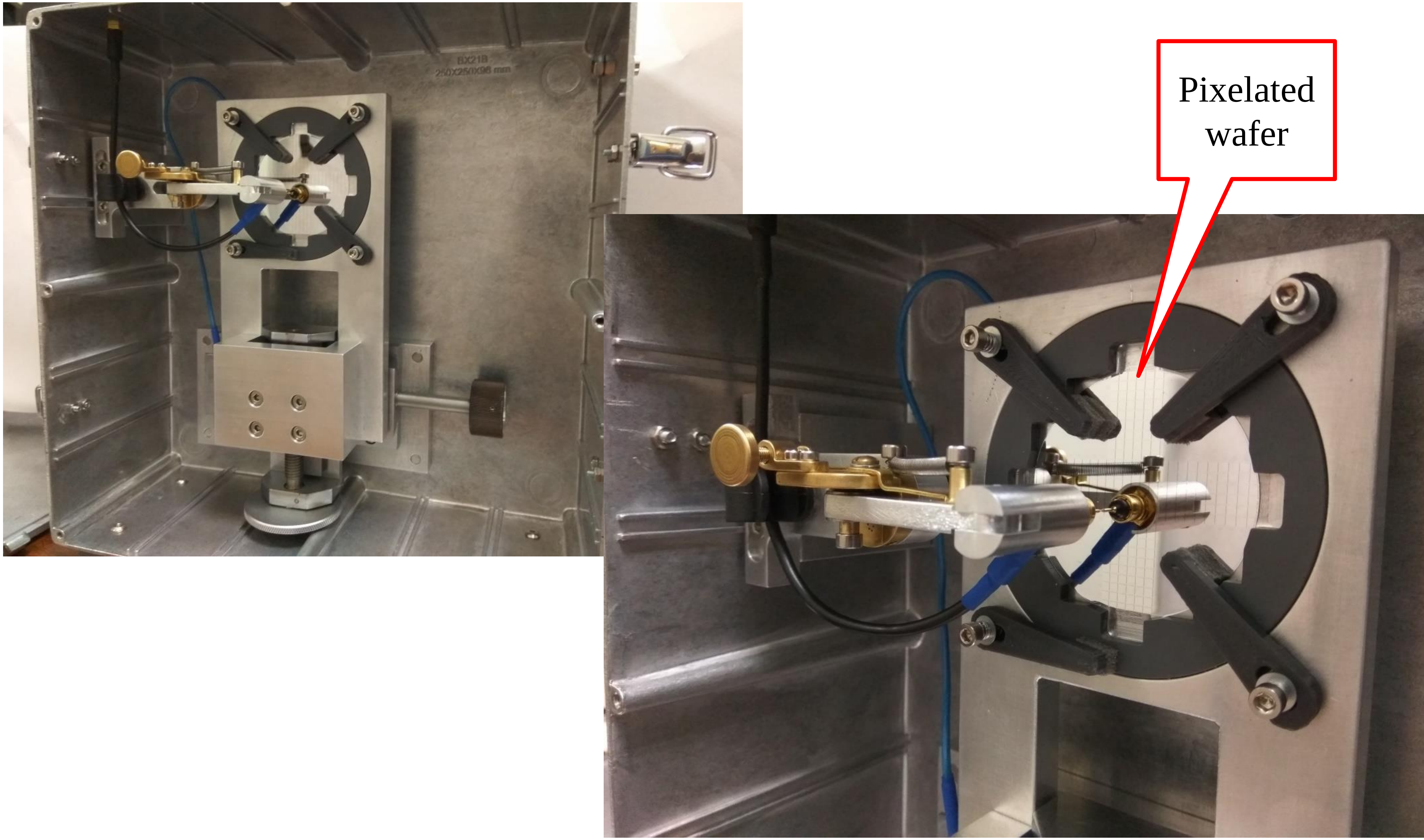
1 - Wafer # 1; 2 – Wafer # 2, 3

- Pixel and backside metal contacts are made of 0.2 um thick Al film. The film was deposited with magnetron sputtering.
- Pixel pitch is 2 mm and interpixel gap of 0.2 mm

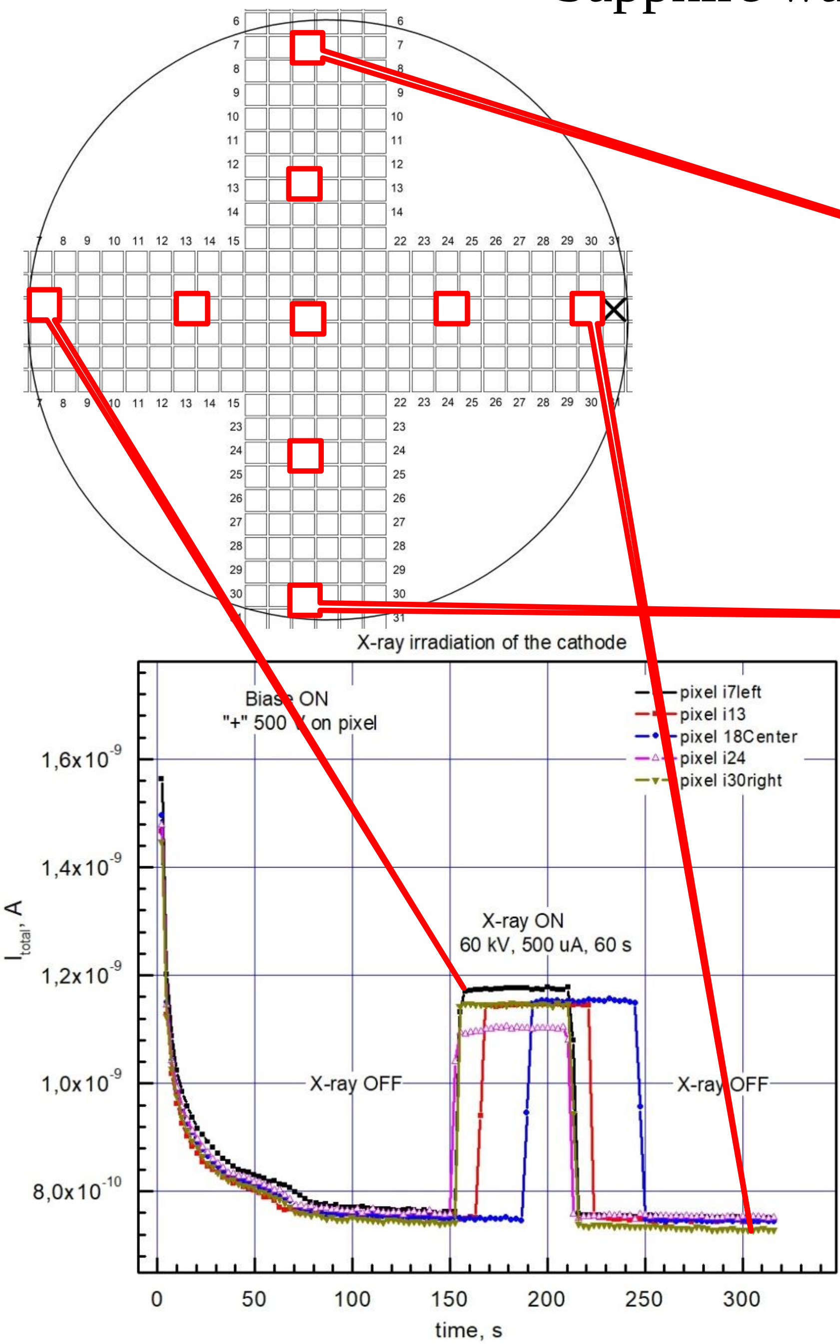
X-ray test bench

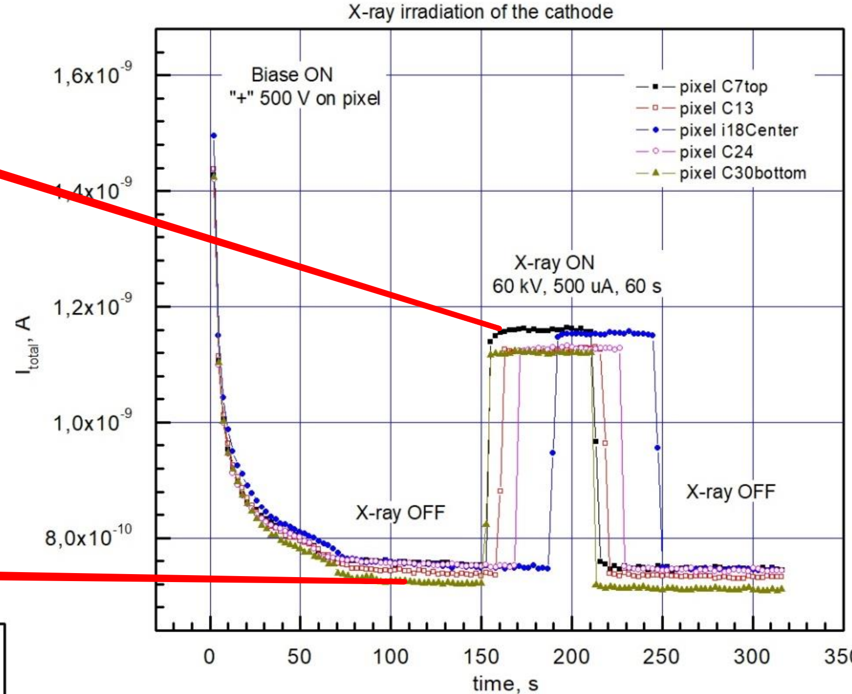


Moving platform with pixelated wafer



Sapphire wafer # 3. Test points location

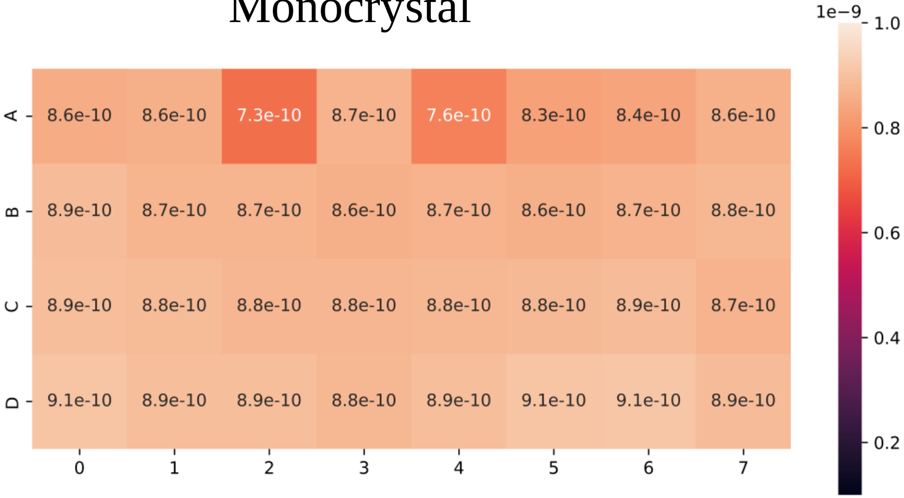




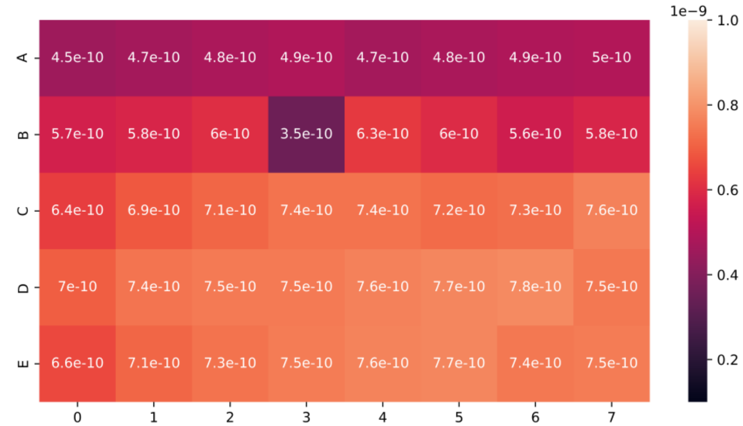
X- ray source:
W anode X-ray tube
60 kV, 500 uA
60 s x-ray pulse duration

Photocurrent mapping

Monocrystal



US



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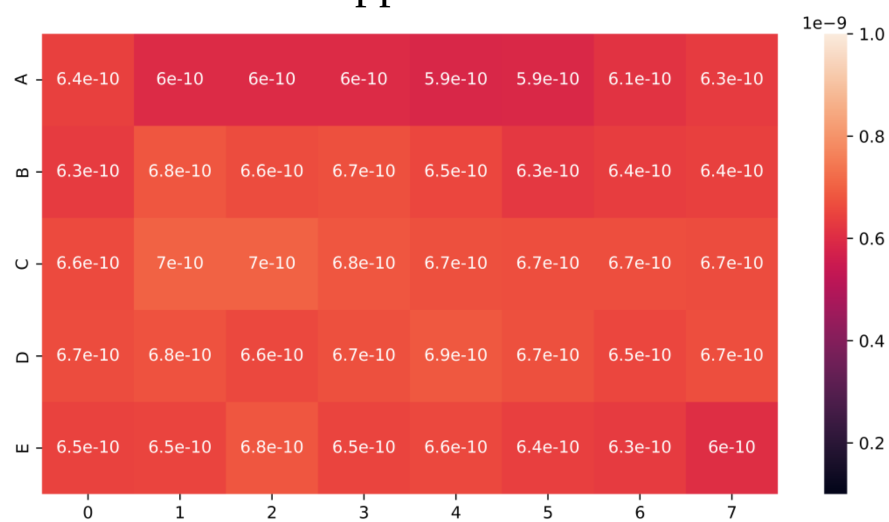
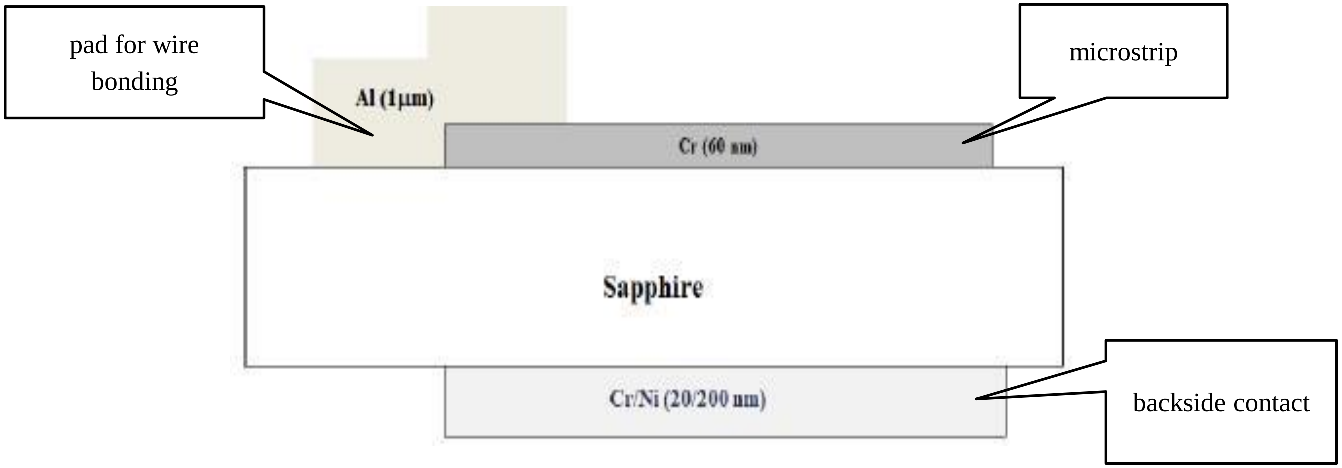
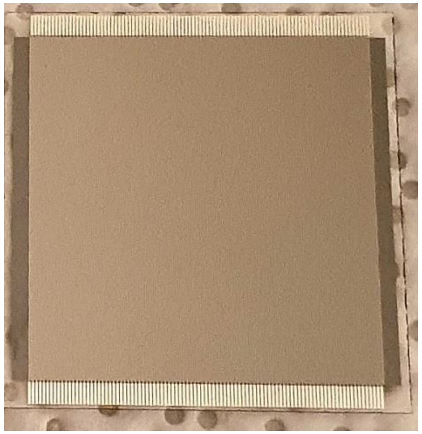


Microstrip sensors



4 channel sensor

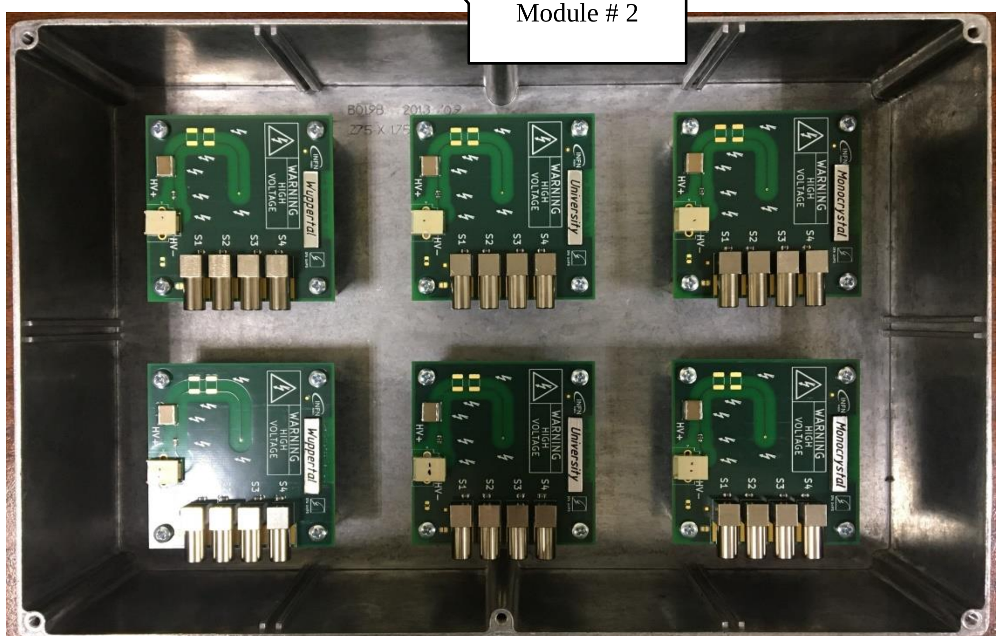


192 channel sensor

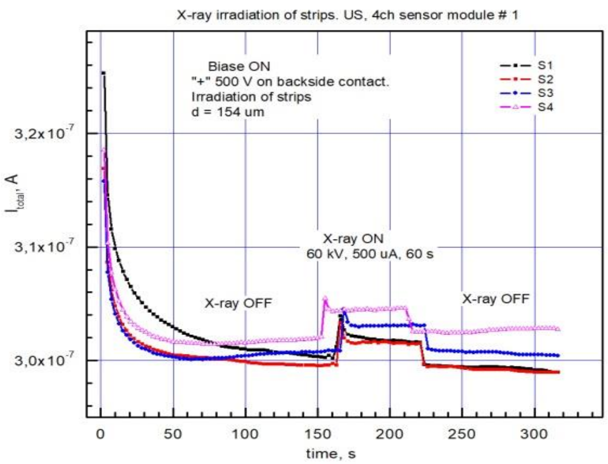
Review of 4 channel sensor

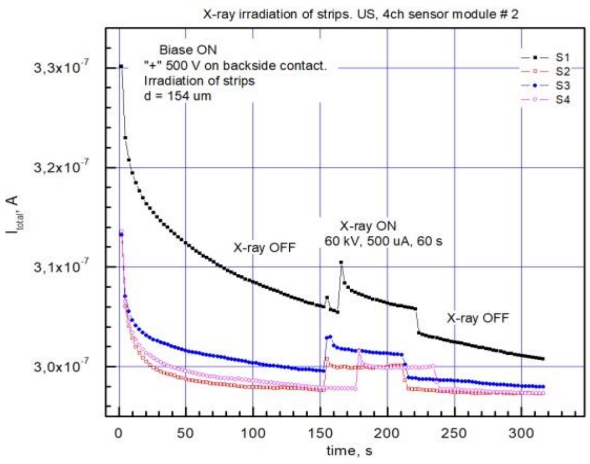
Module # 1

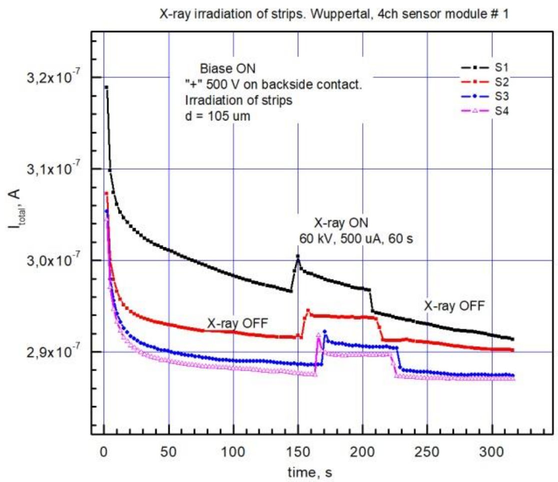
Module # 2

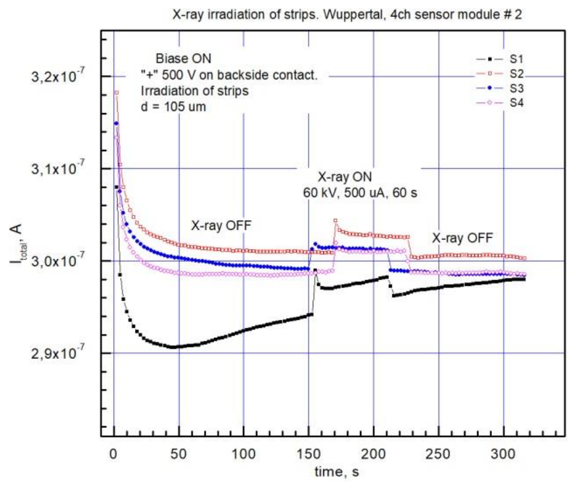


Review of 4 channel sensors
Photocurrent under X-ray irradiation



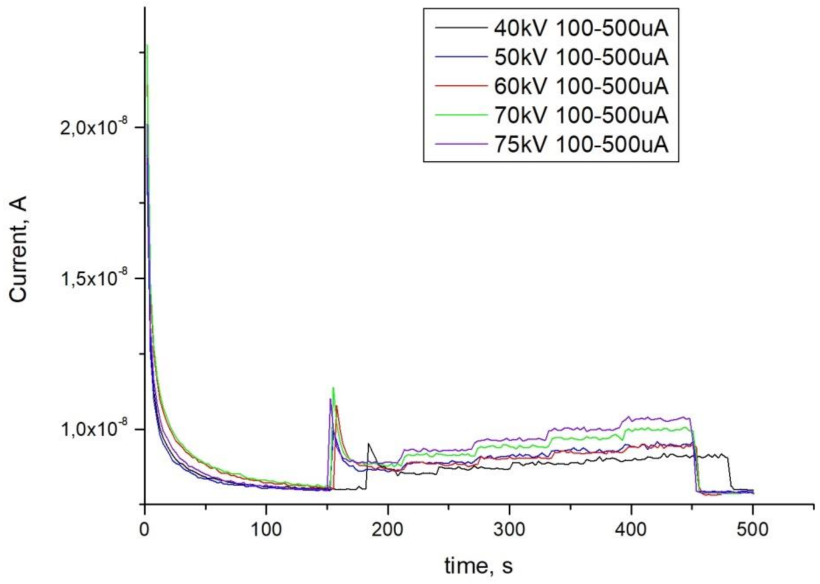


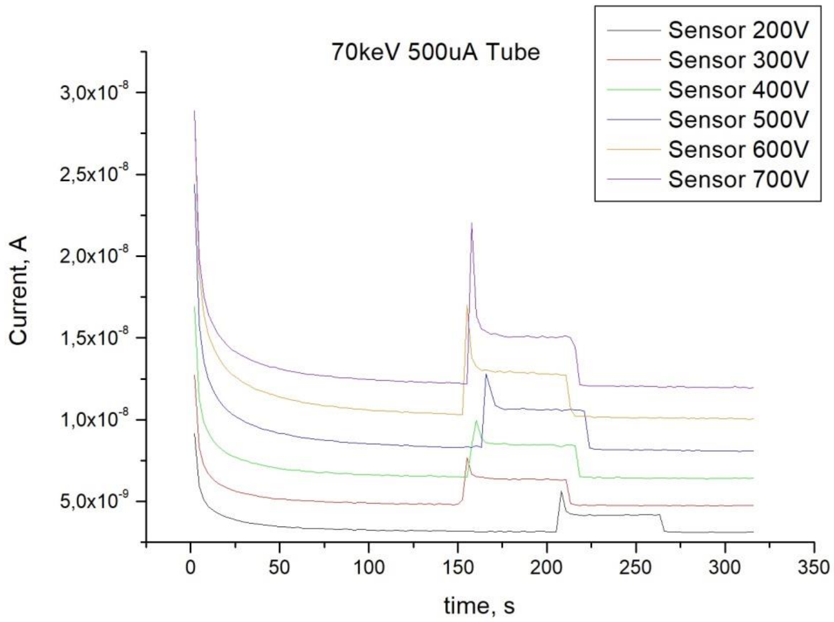


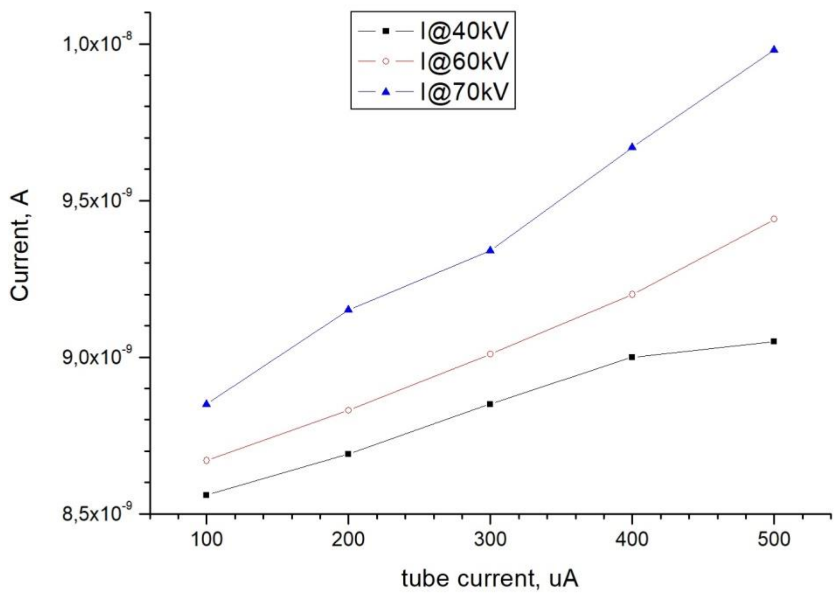


Testing of 4 channel sensor module

Wuppertal wafer







Thank you for your time !