Four-quadrant Si and SiC Photodiodes for Beam Position and Monitor Applications

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CERN 28/11-1/12/2023

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- Beam position and monitor applications

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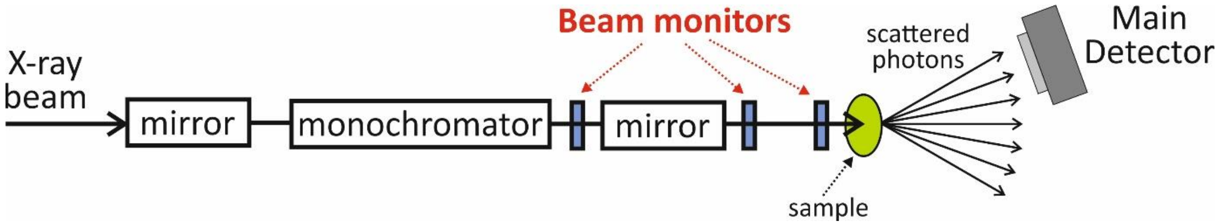
- Radiation detection: transient current technique
- Radiation detection: synchrotron X-rays testbeam

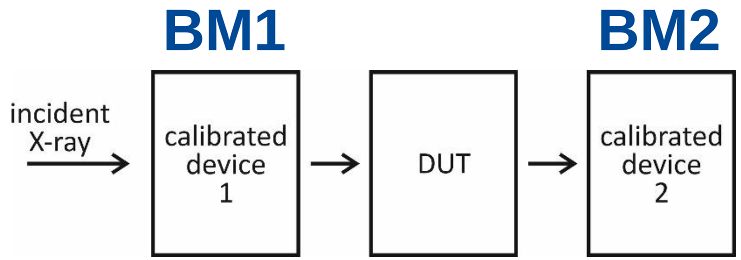
Conclusions

Introduction and motivation

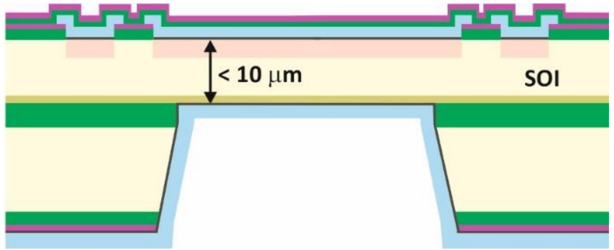
Beam position monitors

- **X-ray beam monitors** (beam intensity) for synchrotron applications **(transmissive mode)**





- **Currently diamond: transparency ☺, radiation hardness ☺, cost ☹, area ☹, process ☹**
- **Interest** also in WBG **SiC: dark current ☺, visible light-proof ☺, "Temperature-proof" ☺**
- **Silicon?: ~x7 lower transparency ☹** (10 keV X-Ray) => >90% transmission => **≤ 10 μm Si**



Collaboration:

Thin Si photodiodes

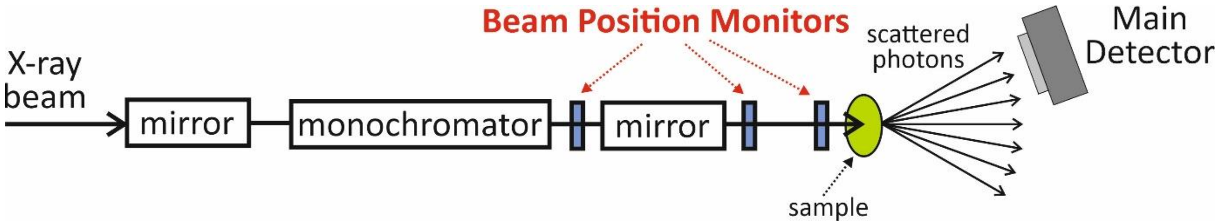
Some existing results

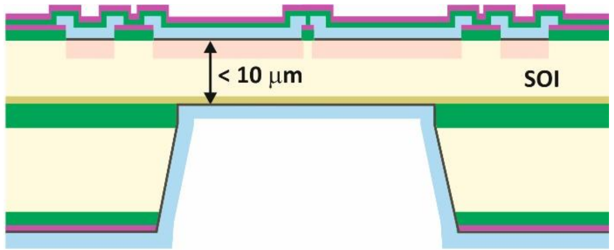
10-5 μm Si

M.R. Fuchs, et al., Rev. Sci. Instrum., 2008, v. 79, 063103 | C. Cruz, et al. J. Instrum., 2015, v. 10, C03005 | J.M. Rafí, et al., J. Instrum., 2017, v. 12, C01004

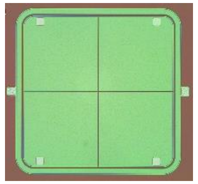
Beam position monitors

- **X-ray beam position monitors** for synchrotron applications





Thin Si 4-quadrant photodiodes useful for **beam alignment**

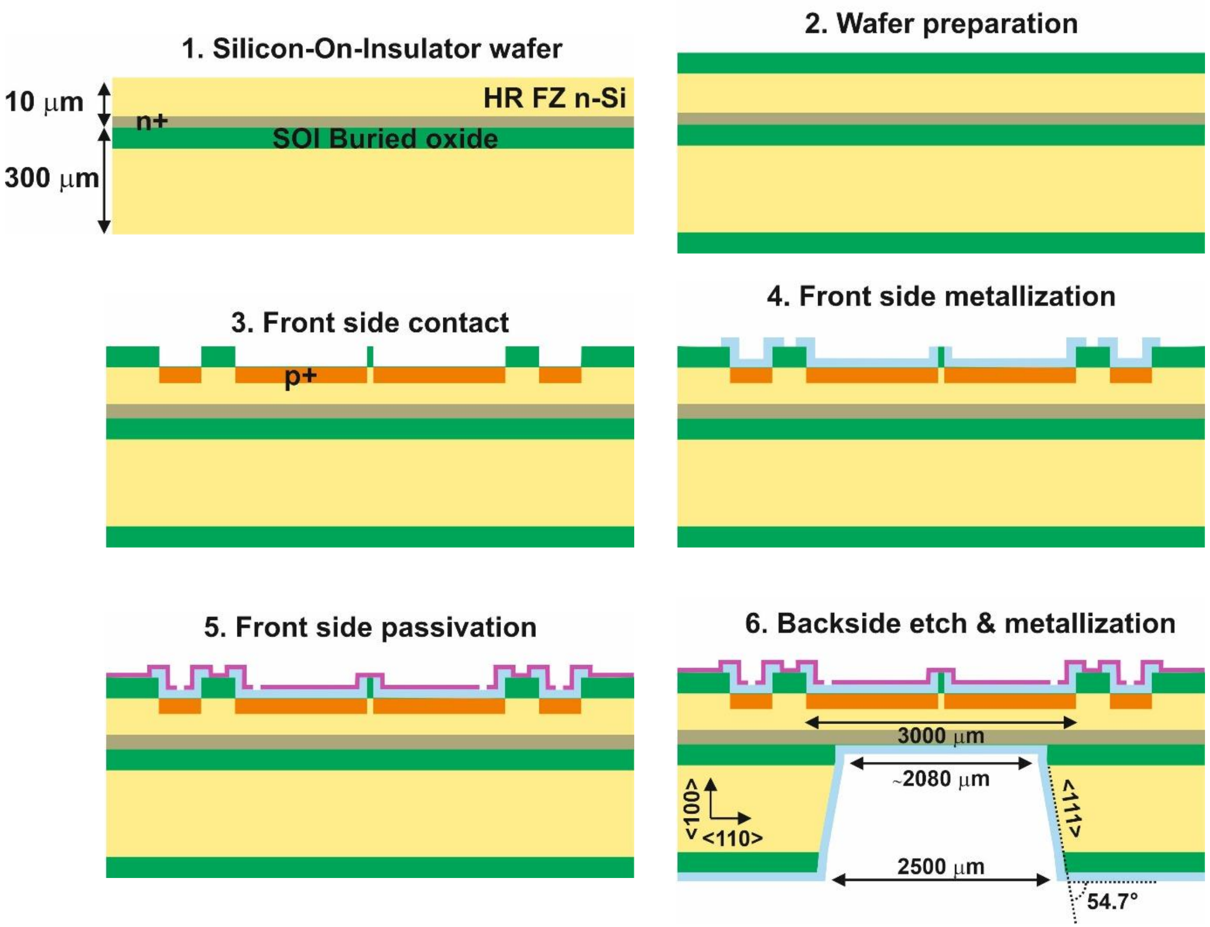


Other applications:

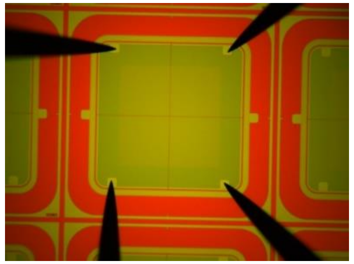
- **Real time monitoring** and **dosimetry** in **particle therapy medical applications**
- **Beam diagnostic** in **microprobe technique IBIC** (Ion Beam Induced Charge)
- **Solar tracking systems** for **space applications** (bulk Si)…

Experimental

Fabricated devices: Si film 10 μm, 5 μm & 3 μm on SOI substrates



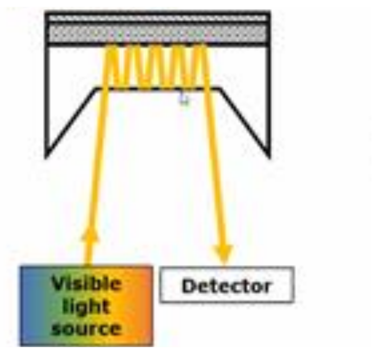
- IMB-CNM-CSIC cleanroom
- p-on-n diode process
- 4 mask levels (p+, metal, passivation, back etch)
- <10μm => different impl. + metals + thermal budget
- **Single diodes** + **4-quadrant diodes**
- **Full metal** or **“No metal”** (20 μm perimeter ring)
- Different interquadrant distance (100 μm to 4 μm)
- **MOS caps** (interquadrant isolation, no back-etch)
- 100 mm wafers: **4 of 10 μm**, **5 of 5 μm**, **2 of 3 μm**
- + Other substrates:
- **HR FZ bulk Si** and **4H-SiC 5 μm-thick n^- epilayer**



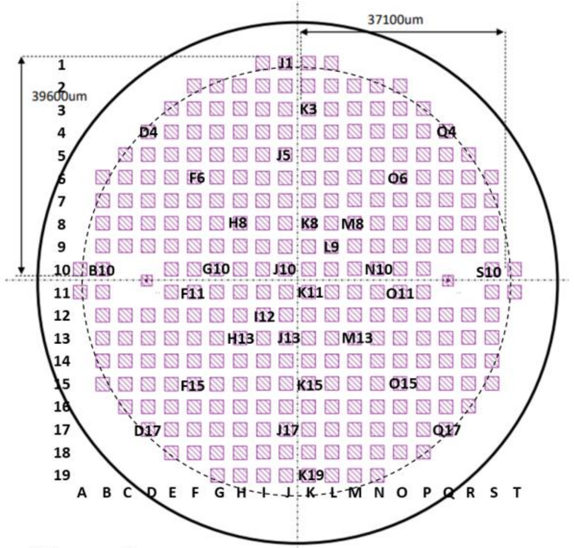
4Q-diode
3 μm-thick Si
“no metal”

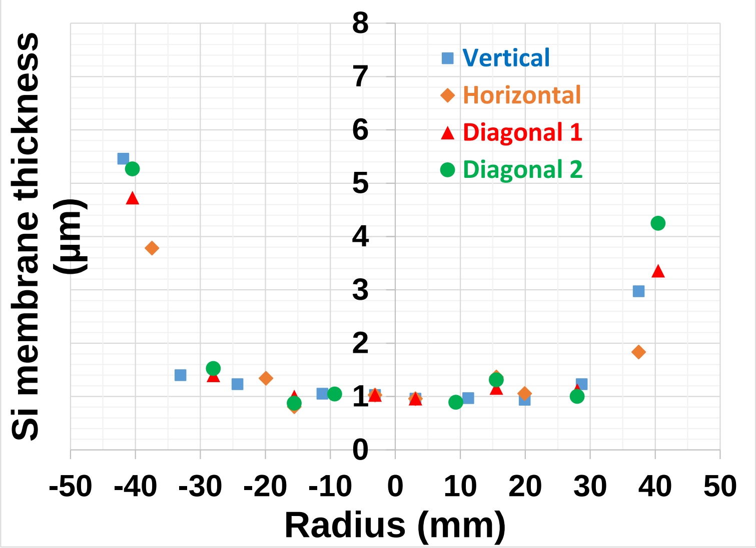
J.M. Rafí, et al., Solid-State Electronics, 2023, v. 209, 108756 https://doi.org/10.1016/j.sse.2023.108756

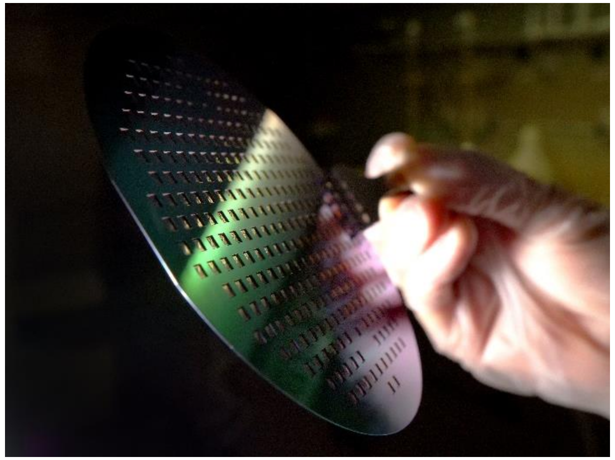
Fabricated devices: 1-2 μm Si on HR FZ bulk Si + back etch

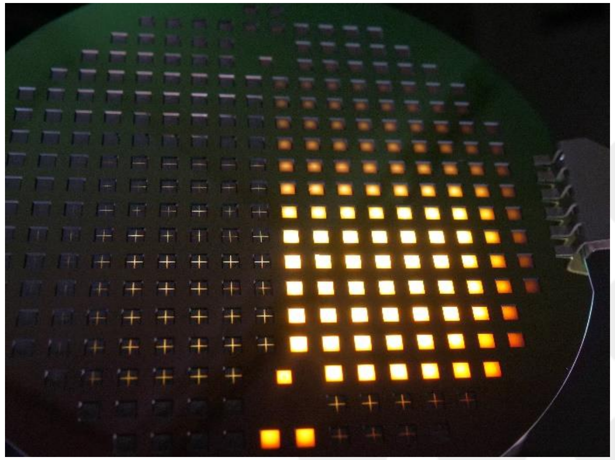


Reflectance spectrometer









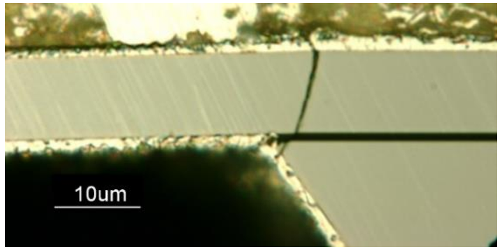
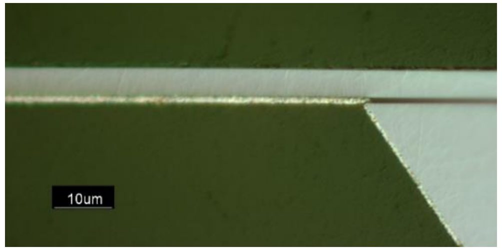
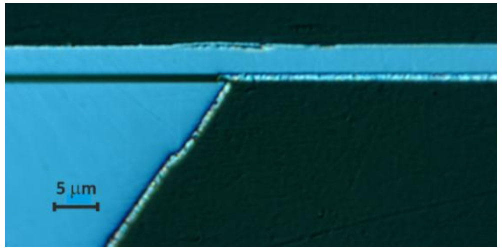
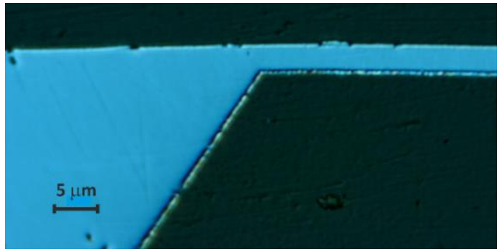
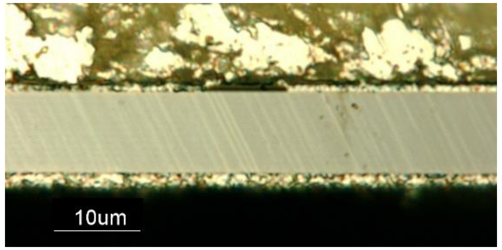
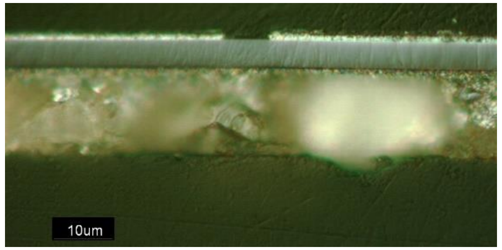
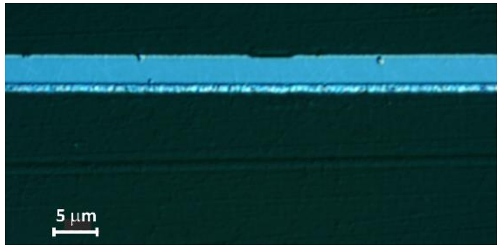
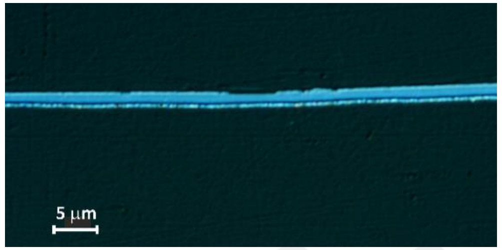
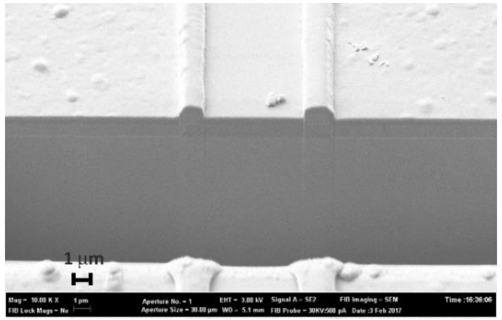
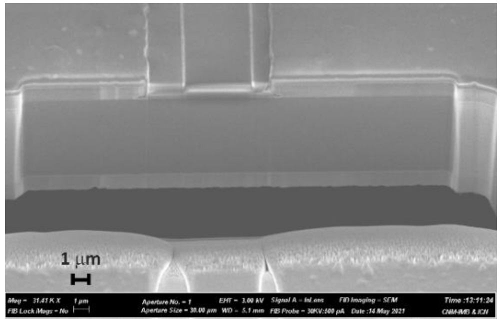
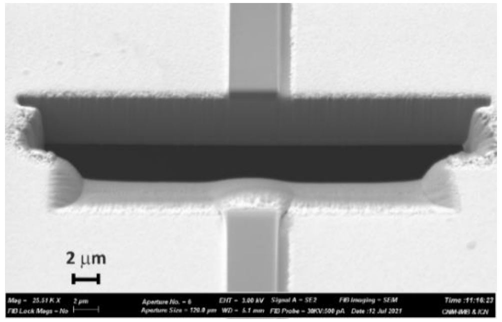
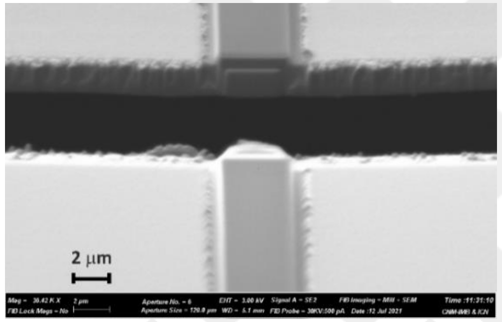
- 2 **High resistivity** (10 kΩ·cm) **Float Zone** (FZ) **bulk Si** wafers
- Carefully-controlled **back-etching process**
- **Final membrane thickness 1-2 μm**
- **Observed** some **thickness non-uniformity** (wafer radial dependence)

10 µm Si unbiased irradiations (terminals left floating)

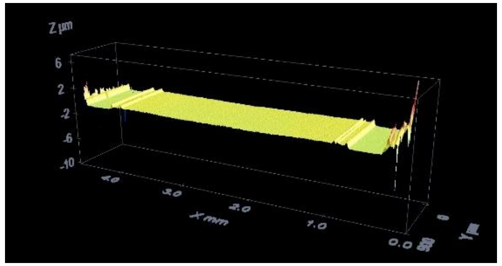
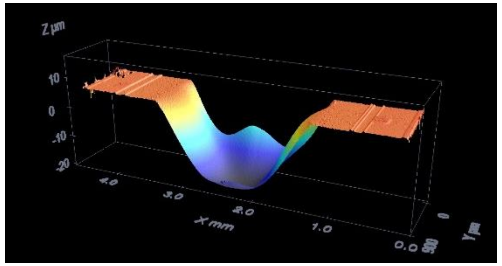
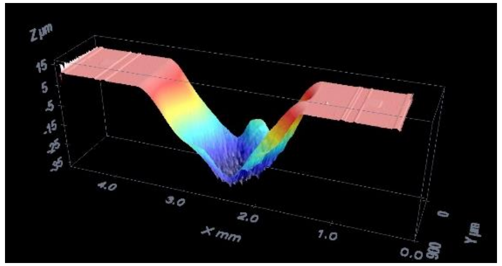
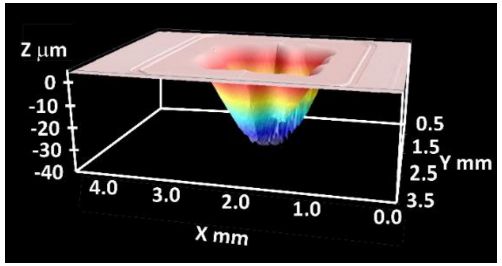
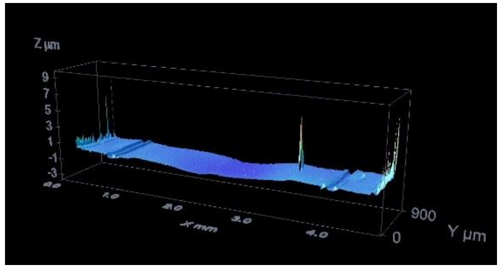
- **2 MeV e-** @Takasaki-QST, Takasaki, Japan
  $\Phi = 1x10^{14}, 1x10^{15}, 1x10^{16}$ e/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.0249
- **Neutron** @JSI TRIGA, Ljubljana, Slovenia
  $\Phi = 5x10^{13}, 1x10^{14}, 5x10^{14}, 1x10^{15}, 2x10^{15}$
  NIEL hardness factor (Si-1MeV n) ~ 0.9
- **24 GeV/c p+** @PS-IRRAD CERN, Geneva, Switzerland
  $\Phi = 8.6x10^{13}, 1.5x10^{14}, 1.0x10^{15}, 1.7x10^{15}, 2.5x10^{15}$ p/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.56
- **Gamma rays** @Sandia National Laboratory, Los Alamos, USA
  10 Mrad, 30 Mrad, 100 Mrad
  (J.M. Rafí, et al., J. Instr., 2017, v. 12, C01004, doi: 10.1088/1748-0221/12/01/C01004)

Characterization, radiation effects and **radiation detection**

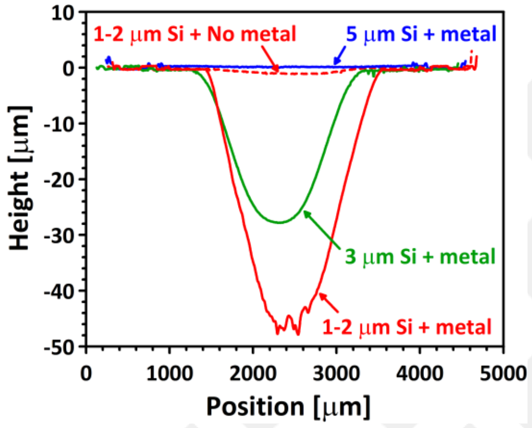
Physical characterization: cross sections

	10 μm Si film SOI	5 μm Si film SOI	3 μm Si film SOI	1-2 μm Si HR FZ
Reverse engineering optical **back etch corner**				 Thickness non-uniformity thicker corners vs. central
Reverse engineering optical **central membrane interquadrant**				
FIB slice SEM **central membrane interquadrant**				

Physical characterization: thin membrane bending with metal stress

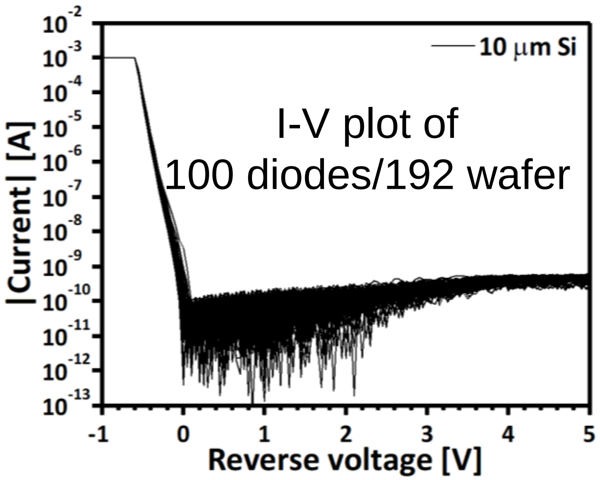
	5 μm Si film SOI 30 nm Ti + 700 nm Al	**3 μm Si film SOI** 200 nm W	**1-2 μm Si HR FZ** 200 nm W
3D Optical Profiler **Full metal**			 
3D Optical Profiler **“No metal”**			

- ➡ **Increasing membrane bending** for **≤ 3 μm Si** devices **fully metallized** (stress)
- ➡ **Higher membrane bending** in **central** (thinner) diodes of **1-2 μm Si wafers**
- ➡ No significant membrane bending differences between single and 4Q devices
- ➡ **No clear influence** of **wafer dicing** in **membrane bending**

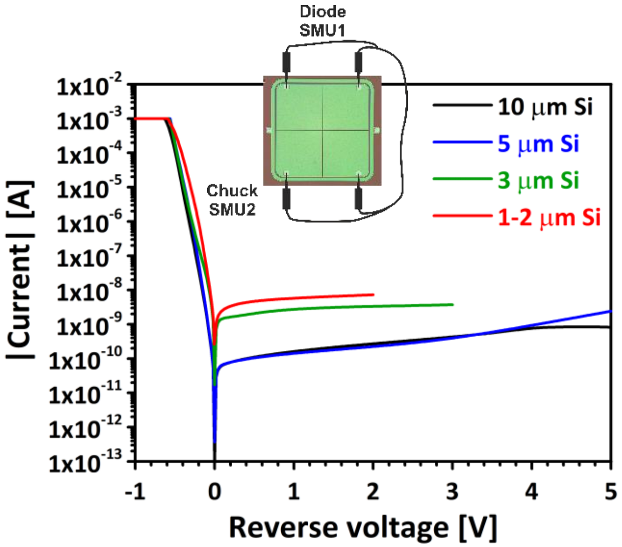


Electrical characterization

10 μm Si film SOI

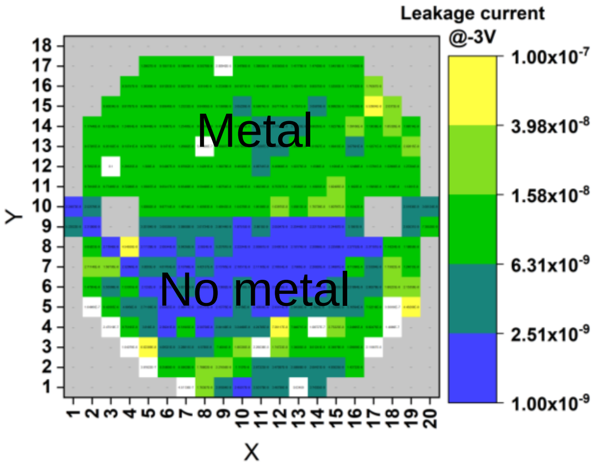


10 μm, 5 μm, 3 μm, 1-2 μm

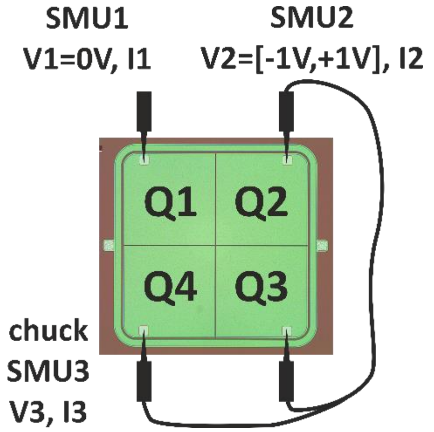


3 μm Si film SOI

Wafermap leakage @ -3V



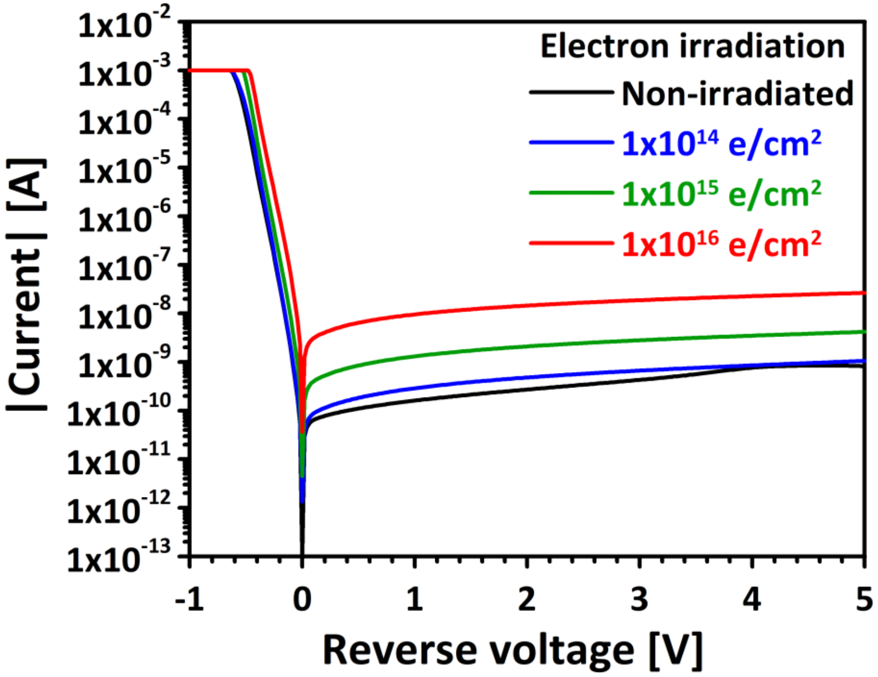
Interquadrant resistance

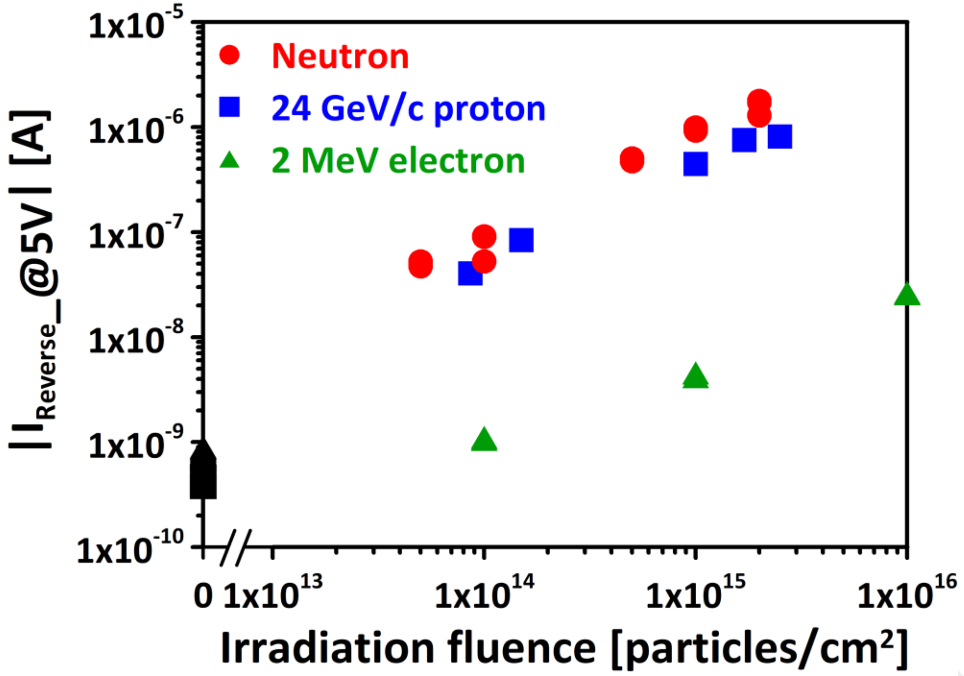


$$R_{interquadrant} \equiv \frac{1}{\frac{dI_1}{dV_2}}$$

- I-V characteristics single diodes and 4Q with shorted quadrants
- **I-V wafermaps** for **10 μm, 5 μm** and **3 μm** Si film SOI devices
- **Good functional characteristics** with **reasonable yield**
- Slightly higher leakage current in bended metallized membranes
- **High interquadrant resistance values ($R_{interquadrant}$)**

Radiation effects: 10 μm Si diode I-V





Φ

- **Progressive increase** in **leakage current** with **irradiation fluence**
- **Generation-recombination centers ➔ $I_{reverse}$ ↑**
- α **values** in the range of published results for irradiated bulk Si detectors **(NIEL hardness factor n 0.9 > p+ 0.56)**

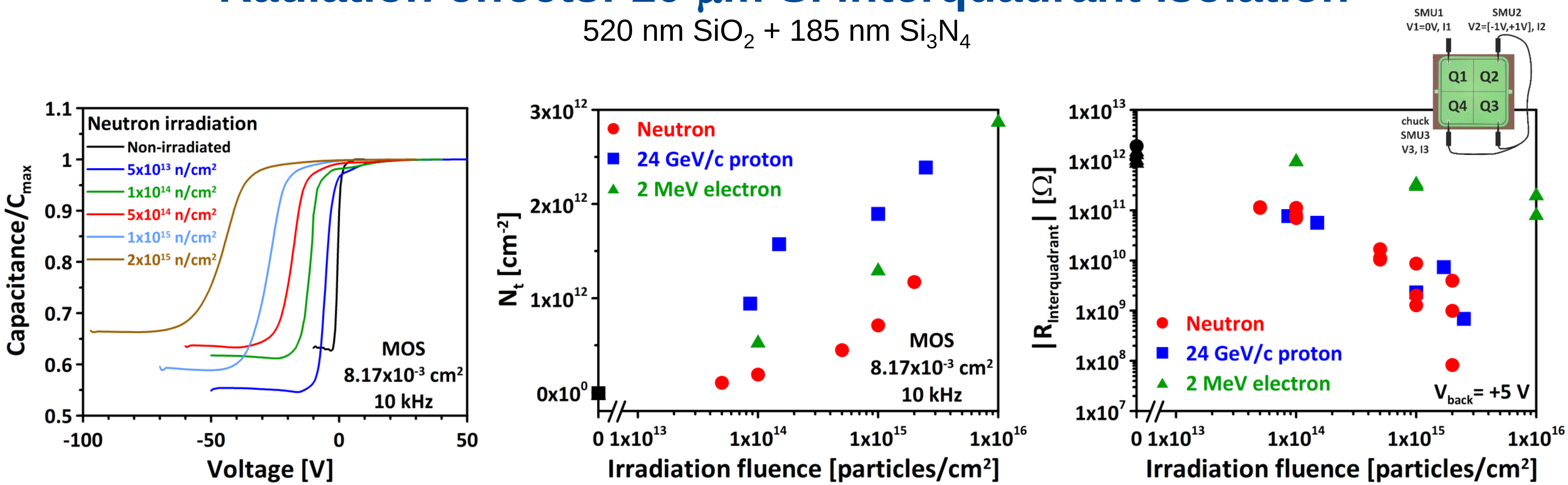
$$I_{vol} = \alpha \cdot \Phi$$

$\alpha \sim 1.3 \; x \; 10^{-17} \; A/cm$ (neutrons)
$\alpha \sim 0.6 \; x \; 10^{-17} \; A/cm$ (24 GeV/c protons)

$$I_{vol} \equiv \frac{I_{reverse}}{Area \cdot W_{depletion}}$$

Radiation effects: 10 μm Si interquadrant isolation

520 nm SiO_2 + 185 nm Si_3N_4



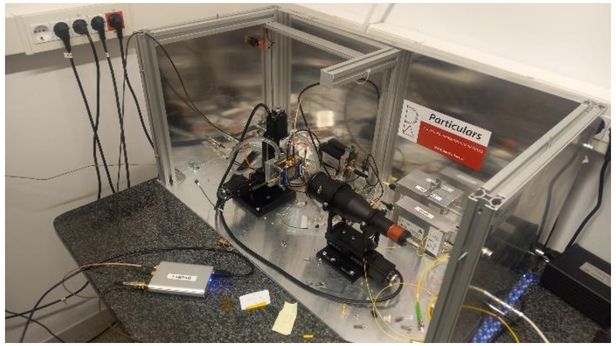
➡ **Progressive positive charge trapping** in the dielectric with **irradiation fluence**

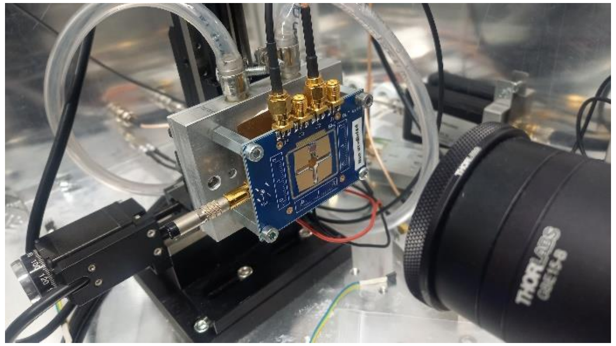
➡ **Trapped charges densities** up to a **few times 10^{12} cm^{-2}**

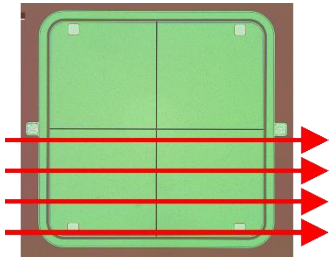
➡ **Progressive reduction** of **$R_{interquadrant}$** with **irradiation fluence**, however, **electrical isolation between quadrants still preserved** (still high $R_{interquadrant}$ values)

Radiation detection: Transient Current Technique (TCT)

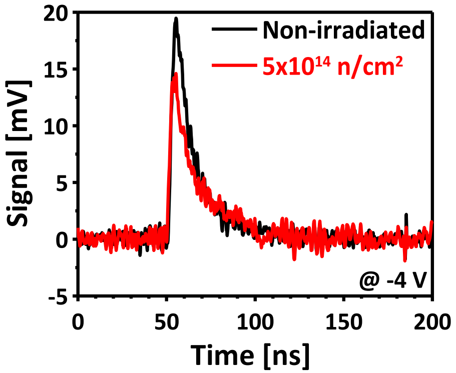
TCT set-up







Pulse peak

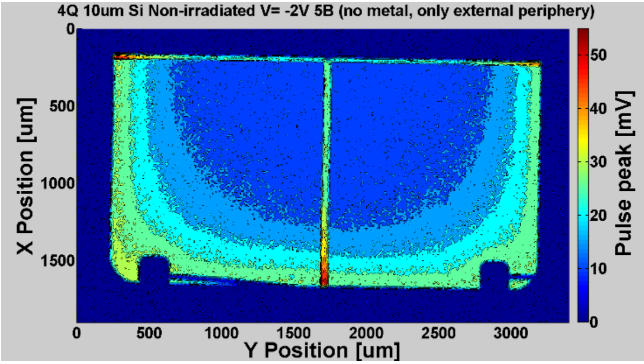


Pulse area
(collected charge)

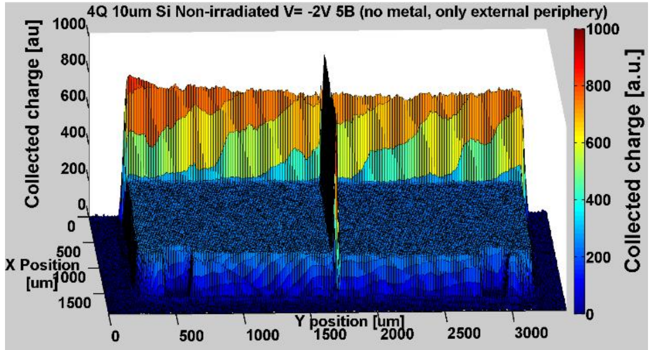
- **Pulsed laser scanning**
- 10 μm-narrow beam, violet 404 nm
- **Record detector pulse signal** (10 μm steps)

10 μm Si - No metal

Non-irradiated

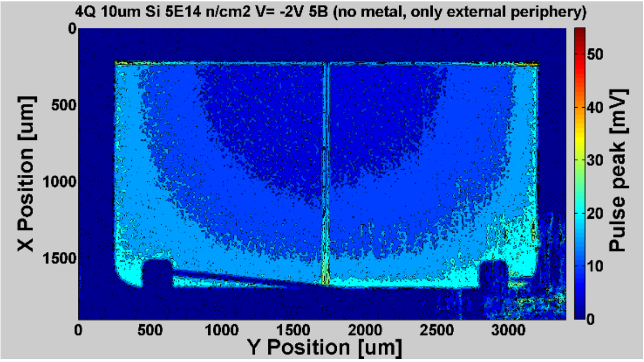


Peak↑ near metal perimeter

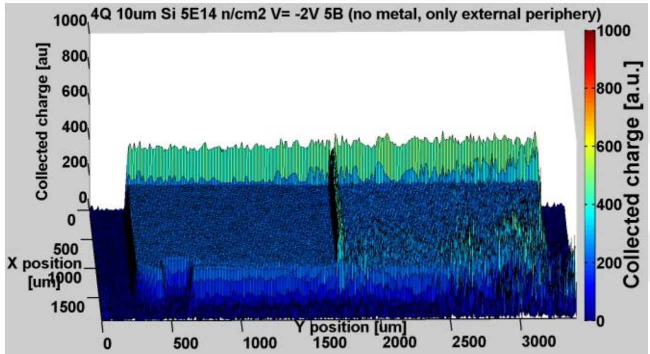


Uniform collected charge

$5x10^{14}$ neutron/cm²



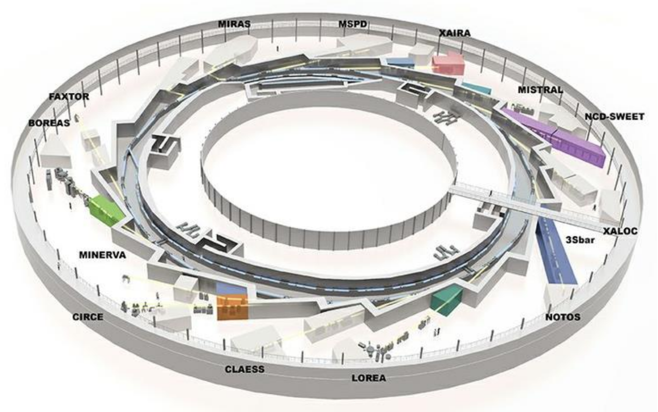
Peak↓



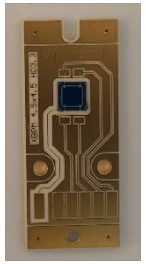
Collected charge↓

Radiation detection: synchrotron X-rays testbeam

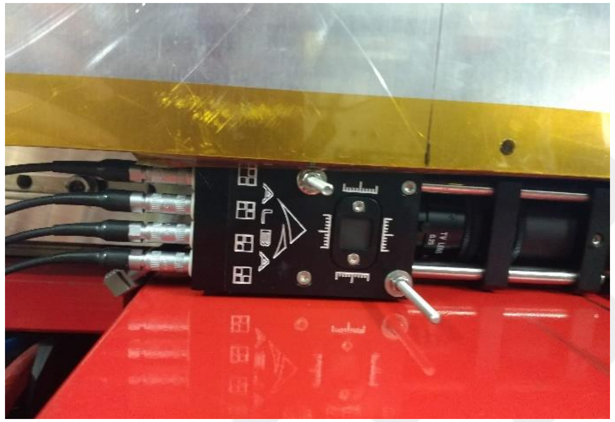
ALBA synchrotron (Cerdanyola del Vallès, Barcelona) (close to UAB campus/IMB-CNM-CSIC)



XALOC beamline



4Q-diode mounted in ALBA pcb



ALBA granted access: ID 2020084426, 30/11-2/12/**2021**, ID 2022086978, 20/10-22/10/**2023**

Radiation detection: synchrotron X-rays testbeam **3 μm Si film SOI**

Requirements for **X-ray Beam Position Monitors**

☑ **Linearity:** response signal proportional to beam intensity

☑ **Energy response sensitivity:** X-ray energy from 4.7 keV to 20 keV

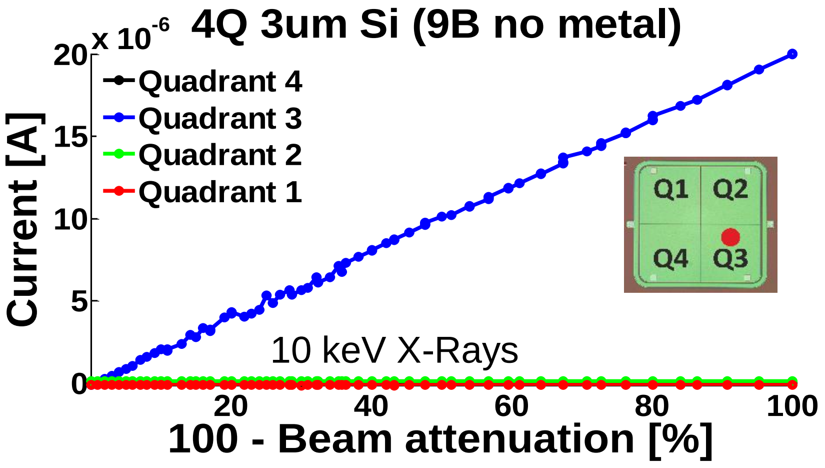
☑ **Spatial uniformity:** 2D flat response

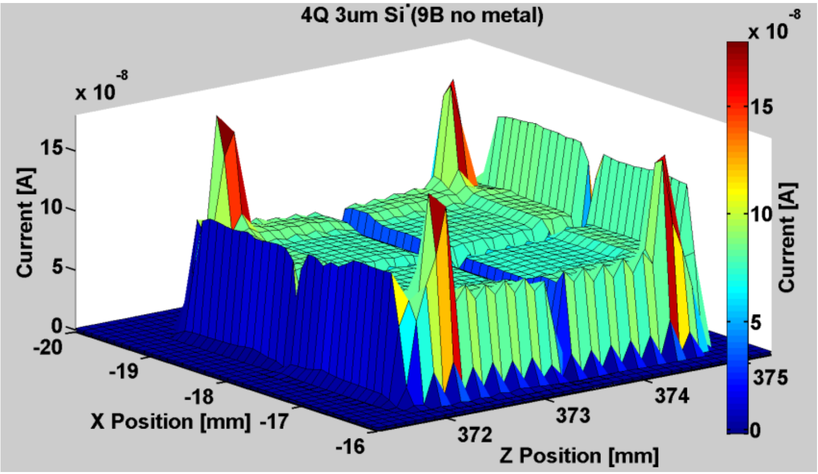
☑ **Spatial resolution:** 1D quadrant transition

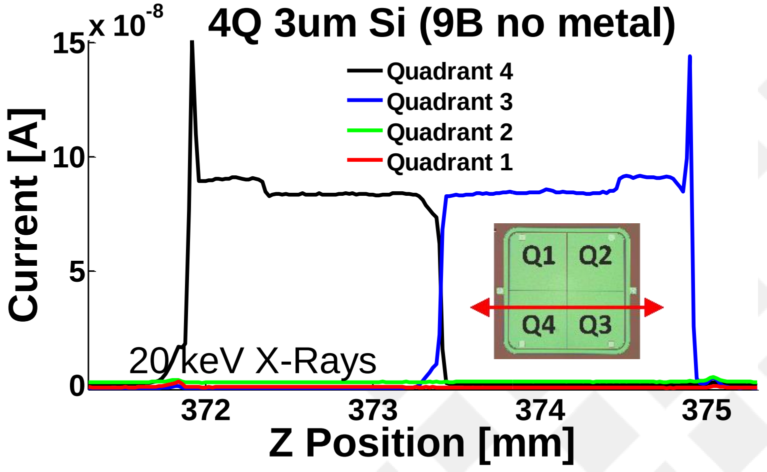
☑ **Transmission:** >90-95%, using front/end calibrated diodes

☐ **Radiation hardness:** degradation/stability over time

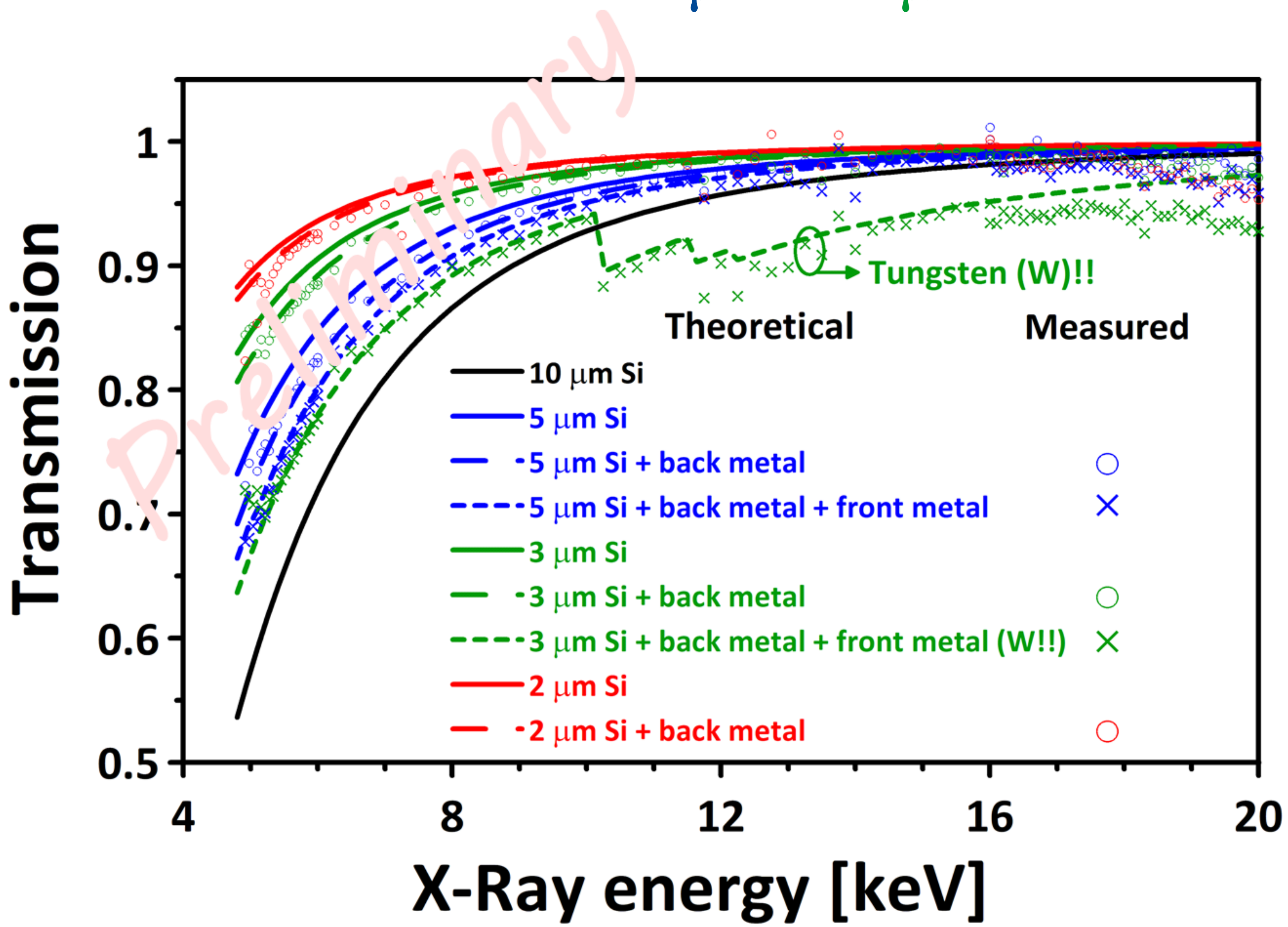
☐ **Dynamic/time response: Si/SiC/diamond…C**

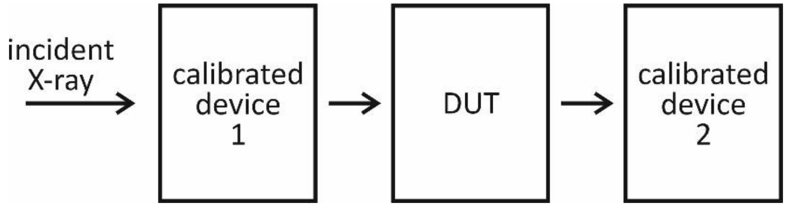






Transmission: 5 μm & 3 μm on SOI and 1-2 μm Si HR FZ

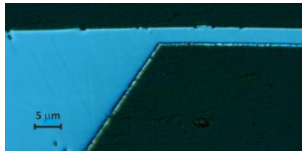




Preliminary results analysis

Good agreement theoretical / measured

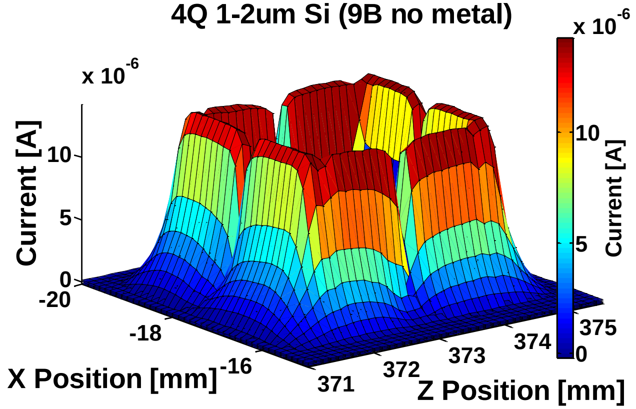
Radiation detection: synchrotron X-rays testbeam 1-2 μm Si HR FZ

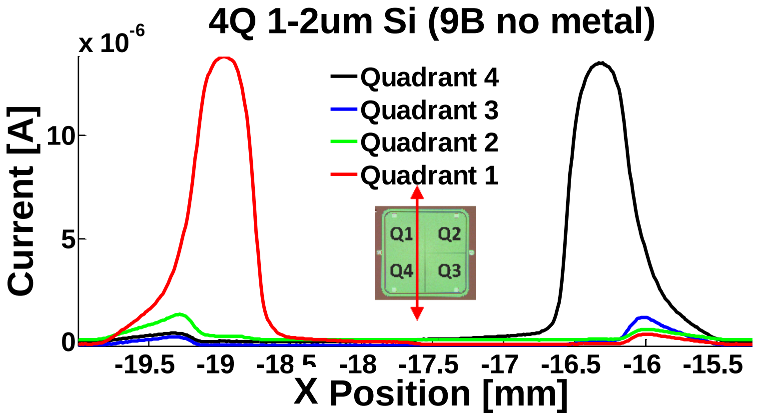


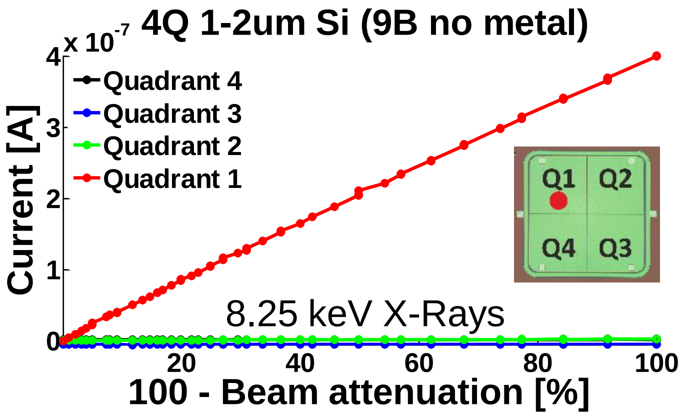
Requirements for X-ray Beam Position Monitors

- ☑ Linearity
- ☑ Energy response sensitivity
- ☒ Spatial uniformity
- ☒ Spatial resolution
- ☑ Transmission
- ☐ Radiation hardness
- ☐ Dynamic/time response

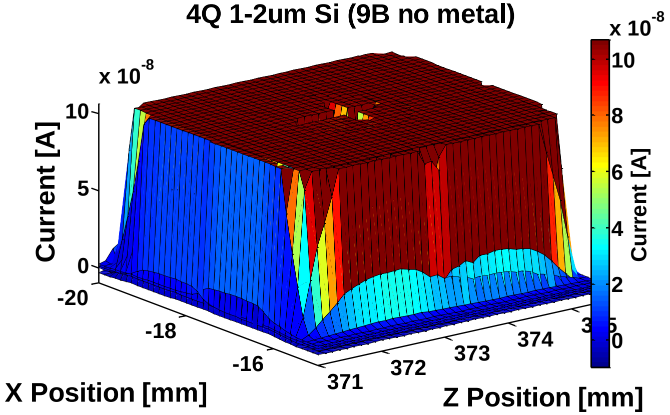
Electrometers range: 100 μA

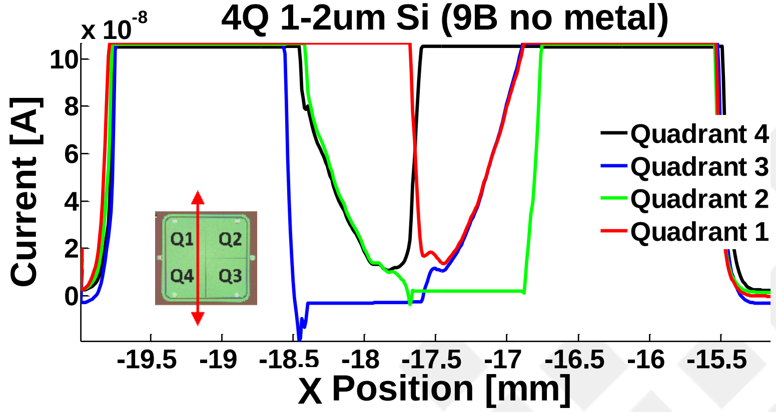






Electrometers range: 100 nA (saturated)



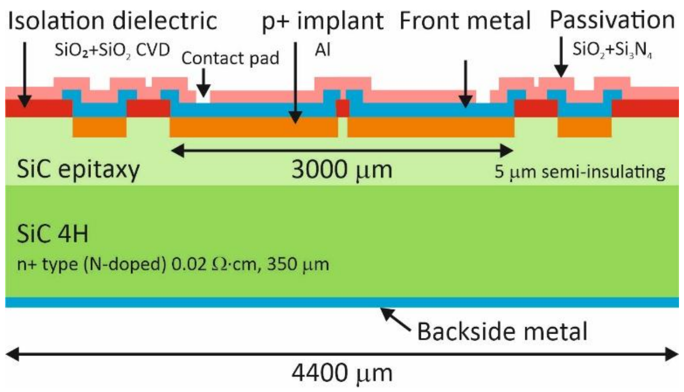


➡ **Non-uniform active thickness: back etch corner & membrane + crosstalk quadrants (@ Z=373 mm)**

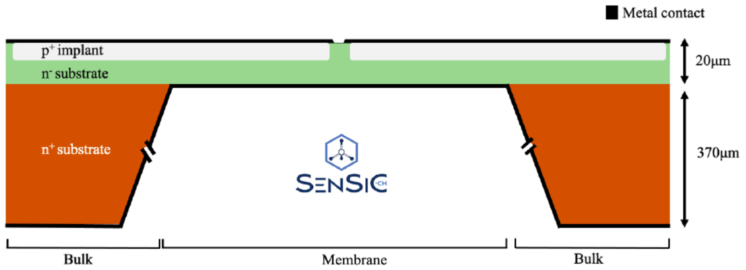
Radiation detection: synchrotron X-rays testbeam **5 μm SiC epilayer**

Requirements for **X-ray Beam Position Monitors**

- ☑ **Linearity**
- ☑ **Energy response sensitivity**
- ☐ **Spatial uniformity**
- ☑ **Spatial resolution**
- ☐ **Transmission**
- ☐ **Radiation hardness**
- ☐ **Dynamic/time response**



SiC Back-etch developed by SENSiC



E. Medina*, E. Sangregorio*,..., M. Camarda
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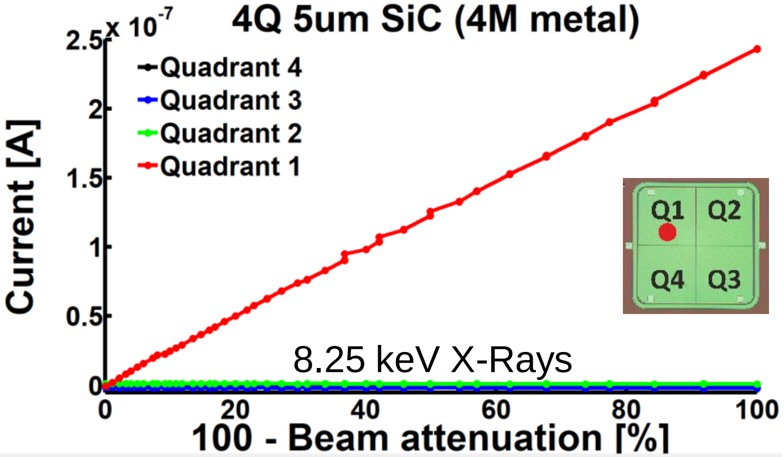
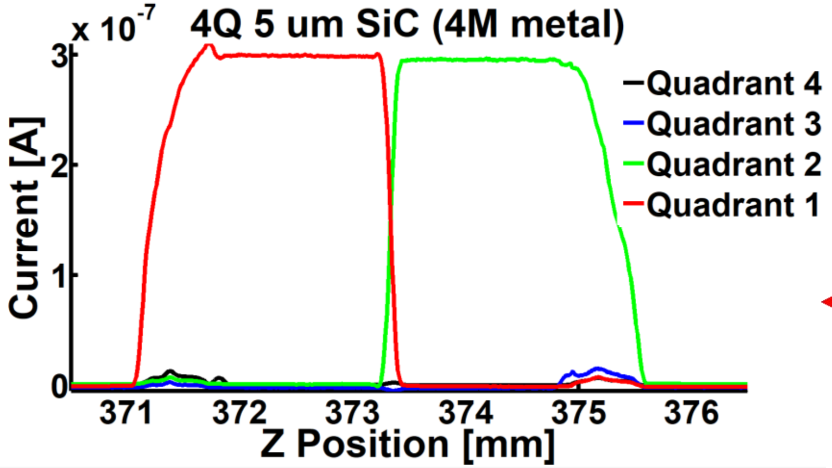
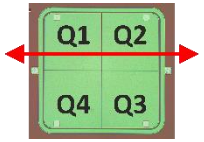
(* students on spring 2023 TCAD training at IMB-CNM)







Conclusions

Conclusions and future work

- **Thin single** and **4-quadrant photodiodes** for **beam position** and **monitor applications** have been fabricated on **10 μm, 5 μm** and **3 μm Si films** from **SOI substrates**, as well as on **1-2 μm Si membranes** from back etched **HR FZ Bulk Si** and **5 μm SiC epilayer**
- **Physical** and **electrical characterization** of different types of devices (interquadrant distances, metallization approaches (full metal and perimeter ring), etc…)
- **Impact of radiation** (**2 MeV electron**, **neutron** and **24 GeV/c proton**) on **electrical characteristics** and **interquadrant isolation** for 10 μm Si devices
- First results about operation as **radiation detectors** evaluated by means of **pulsed laser beam transient current technique (TCT):** impact of metallization approach and radiation effects on 10 μm Si devices
- First results characterization **synchrotron X-rays testbeam:** good for devices on **5 μm** and **3 μm Si films** from **SOI substrates** and **5 μm SiC epilayer**, not uniform for etched **1-2 μm Si membranes**
- To be studied: **analysis 2nd ALBA access**, **TCT** on **<10 μm devices, radiation hardness?**…

Thank you for your attention

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