



CMS HGCAL Si sensors: radiation damage and annealing studies

Eva Fialová, Matteo M. Defranchis

14.10.2026



Outline



1

HGCAL silicon
sensors

2

Bulk radiation
damage

3

Surface damage
in SiO_2

4

Annealing
studies

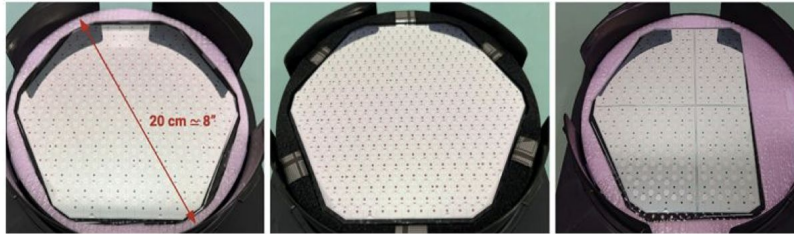
5

Summary and
outlook



HGCAL silicon sensors

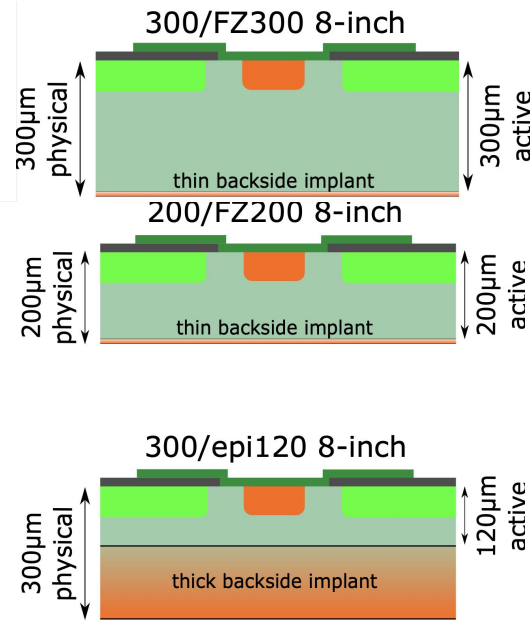
- 8" n-on-p hexagonal silicon sensors
- Common p-stop isolates neighbouring cells
- Three active thicknesses: 300 μm and 200 μm FZ, 120 μm EPI, 720 nm oxide on top
- LD (1.2cm²) and HD (0.5cm²) sensors
- Test structures on the wafer cut-offs, used for destructive testing



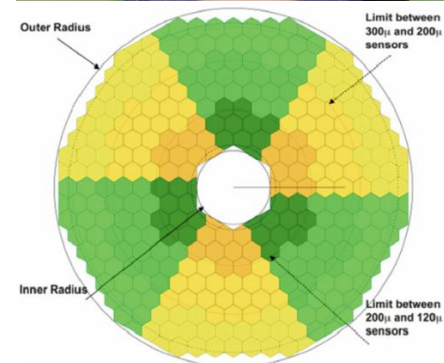
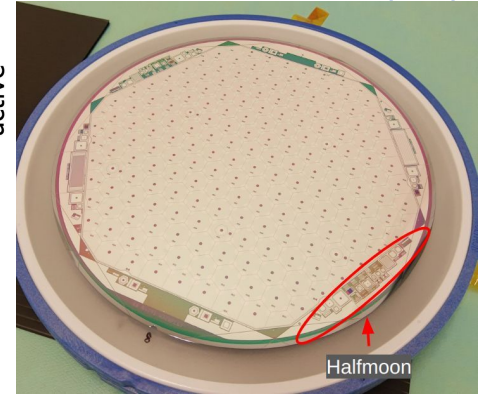
Low Density (LD)

High Density (HD)

Partial Sensor from
Multi Geometry Wafer
(MGW)



Figures by Peter Paulitsch

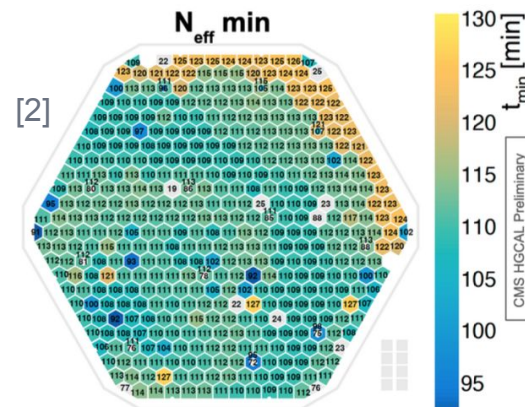
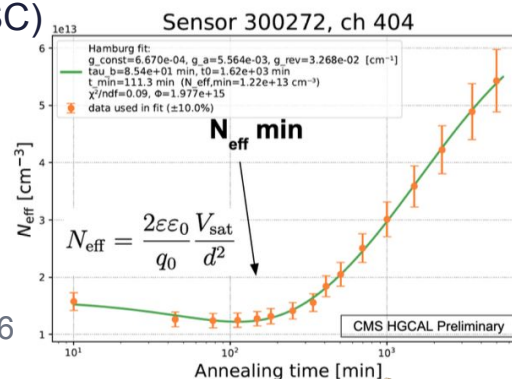
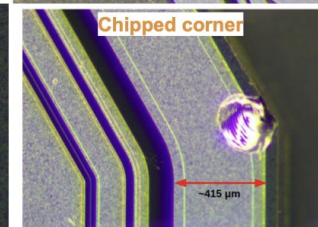
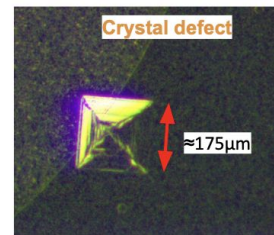
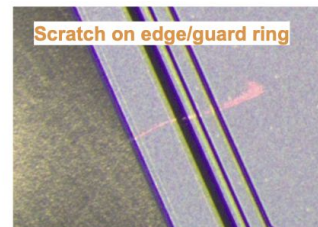


HGCAL Si sensors

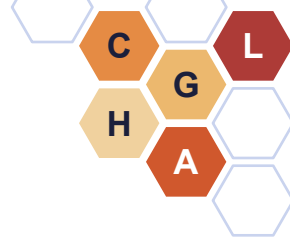
- Sensor manufacturer HPK, production 2023 - 2025
- ~24 000 sensors produced, 8% tested at 5 CMS institutes
- HGCAL test diodes and also full sensors used for bulk damage studies [1,2]
- Irradiated with reactor neutrons (JSI, RINSC) up to $1.5 \cdot 10^{16}$ neq/cm² to emulate HL-LHC
- Isothermal annealing from 5.5 to 60 °C → **reverse annealing not expected to dominate during HGCAL operation**

[1] L. Diehl et al., JINST 21 (2026) P03034

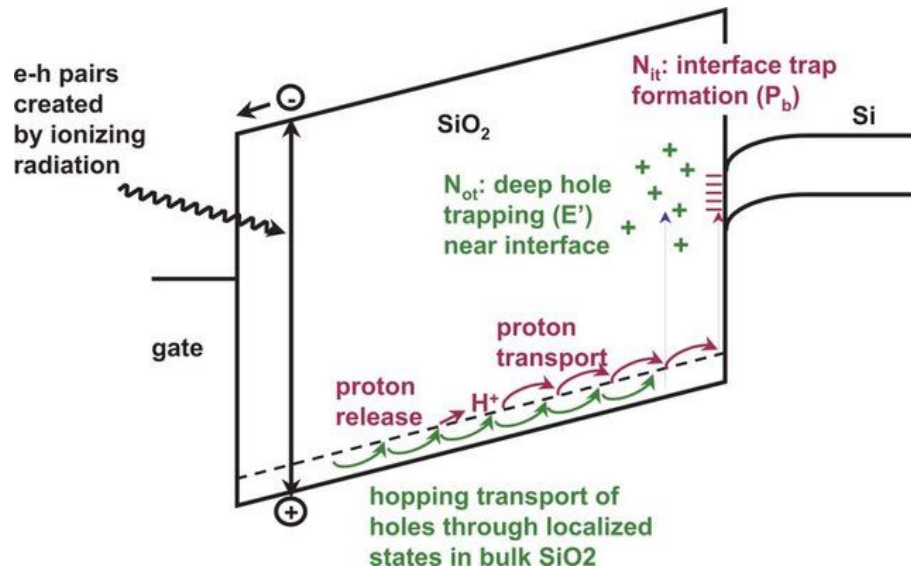
[2] G. G. Dincer (CMS HGCAL), JINST 21 (2026) C07006



Surface radiation damage



- Unlike the bulk (NIEL), the oxide is damaged by **ionizing energy loss** (IEL)
- Damage in SiO_2 alters the electric field and degrades cell isolation
- Mechanism:
 - Radiation creates e-h pairs in SiO_2 , part of them recombine
 - Electrons are collected quickly, holes drift slowly and can be trapped
 - Border traps** (E' centres, O vacancies) $\rightarrow$ positive oxide charge
 - Interface traps** (Pb centres): H^+ -passivated dangling bonds, depassivated by radiation

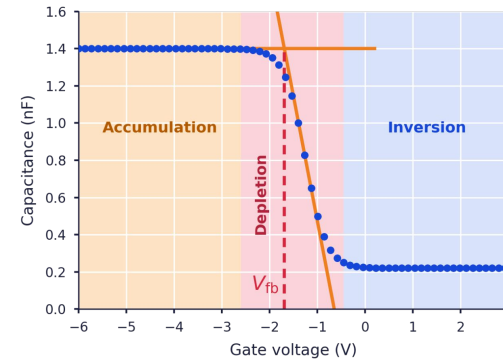
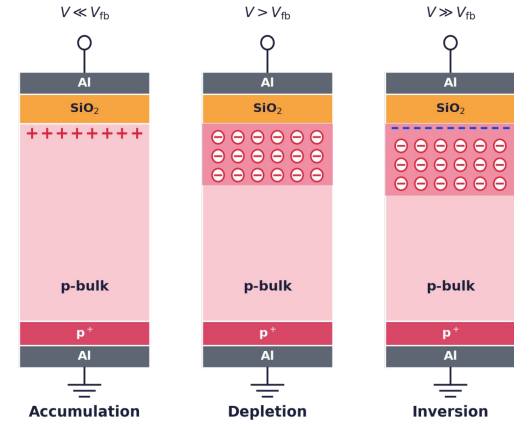


Positive oxide charge

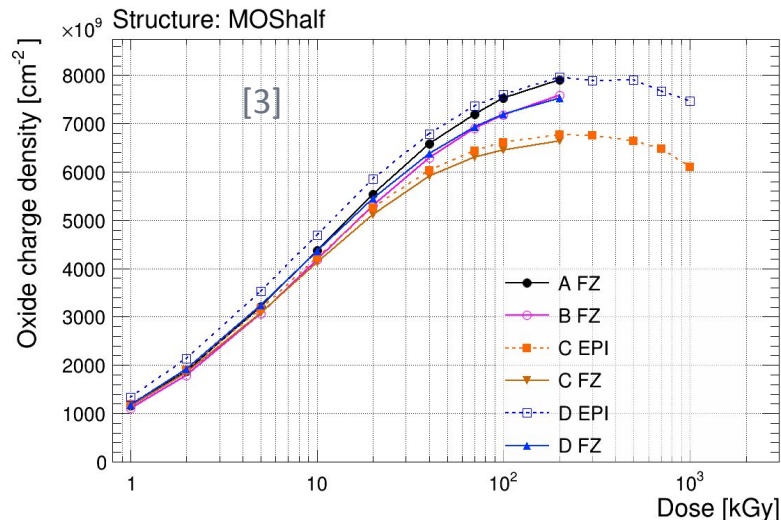
- MOS capacitors** are used to measure the oxide charge N_{ox}
- N_{ox} is estimated from the flat-band voltage V_{FB} of the CV curve:

$$N_{ox} = \frac{C_{ox}}{q A_{gate}} (\phi_{ms} - V_{FB})$$

- Surface current related to interface traps is measured with gate-controlled diodes (backup)

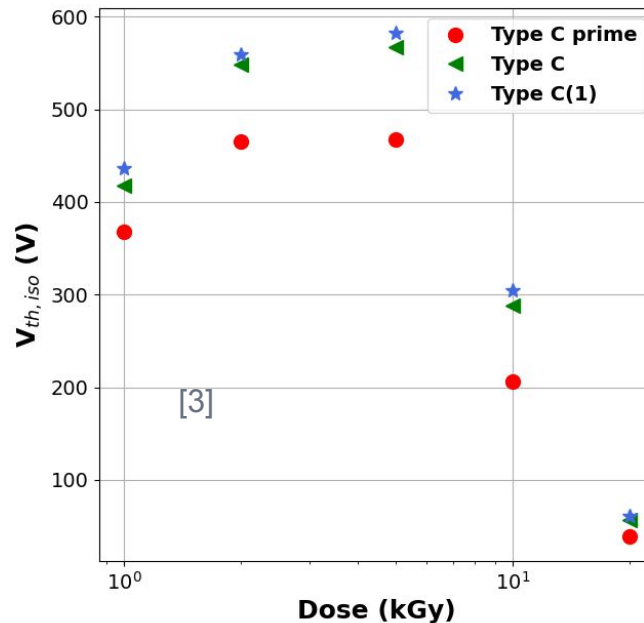


SiO₂ for HGICAL



- New 8" production for HPK → a new oxide process was needed
- Several oxide variants offered; **type C** chosen based on MOS measurements
- After production started **new variant C'** offered, closer to the tracker oxide

CMS HGICAL · Si sensors radiation damage and annealing



- Diode measurements of threshold voltage of inter-electrode isolation ($V_{th,iso}$) confirm C' is higher quality → promising for future applications
- **$V_{th,iso}$ new method of estimating the oxide quality**

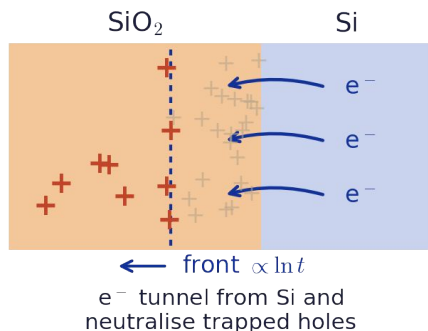
[3] M. Defranchis, <https://indico.cern.ch/event/1096847/contributions/4743792/>

[4] E. Fialova et al., JINST 20 (2025) C07061



Annealing of SiO₂

- As for the bulk, oxide damage anneals with time and temperature
- MOS capacitors → oxide charge N_{ox} (GCD → surface current)
- Expected time/temperature dependence not yet extensively tested**



$$N_{\text{ox}}(t) = N_{\text{ox}}^0 (1 + t/t_0)^{-\lambda/2\beta}$$

$$t_0(T) = t_0^* \exp\left(\frac{\Delta E}{k_B T}\right)$$

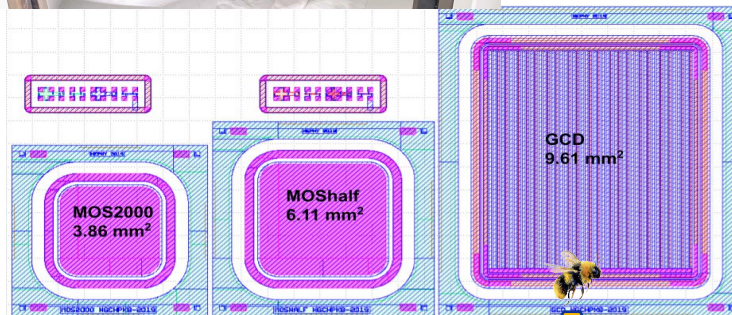
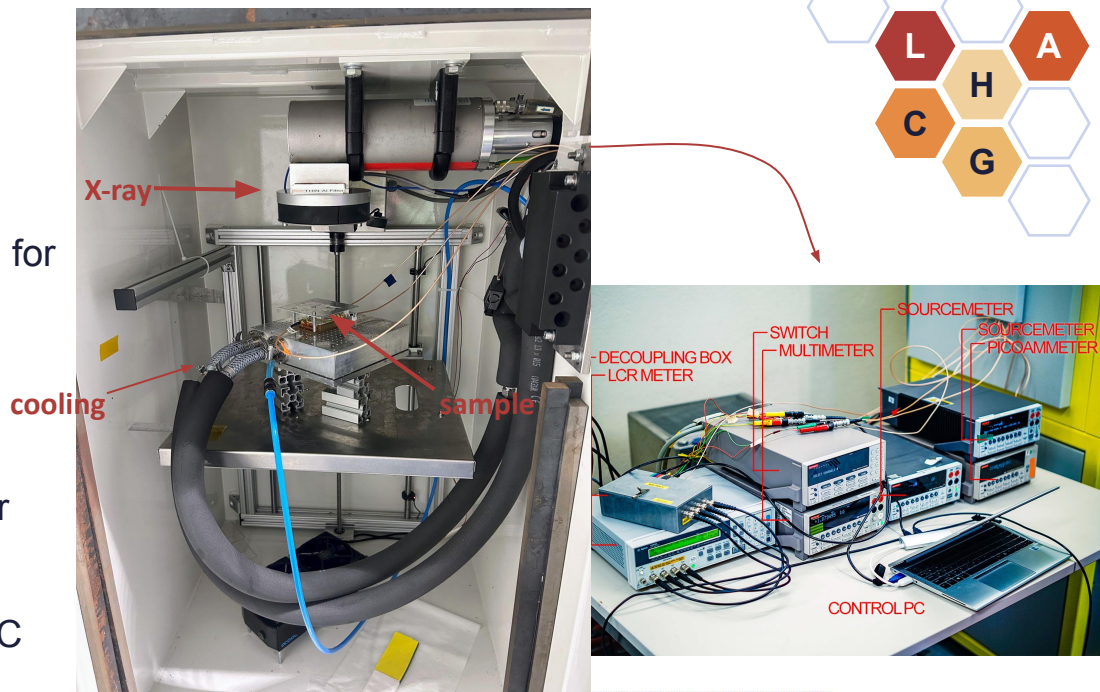
- N_{ox}^0 : surface density of oxide charges at $t = 0$
- t_0 : effective tunnelling time constant, t_0^* : tunnelling time constant
- $1/\lambda$: characteristic depth of the oxide-charge distribution in the SiO₂
- β : parameter related to the barrier height
- ΔE : energy of the SiO₂ defects relative to the Si Fermi level

[5] M. Schmidt and H. Köster, Phys. Status Solidi B 174 (1992) 53



Annealing studies

- First extensive annealing study, crucial for operation together with bulk annealing
- Automated setup (AXIOM): high level of measurement reproducibility
- All irradiations with X-rays (ATLAS tracker group X-ray machine)[4]
- Shown results: 25kGy, 11.1kGy/h, at -14°C
- Irradiated samples: 2 MOS and GCD, measurements directly after irradiation
- Smaller MOS biased during irradiation to study damage with el. field present

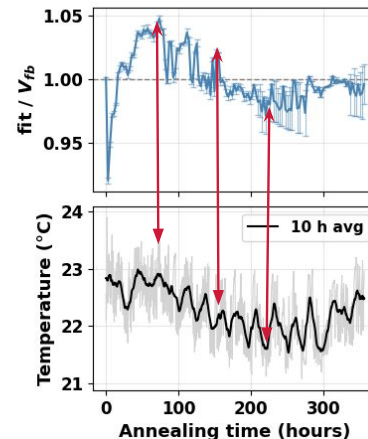
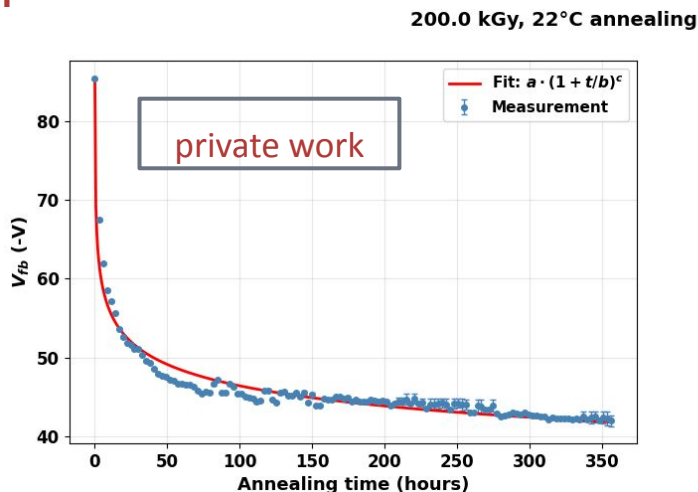
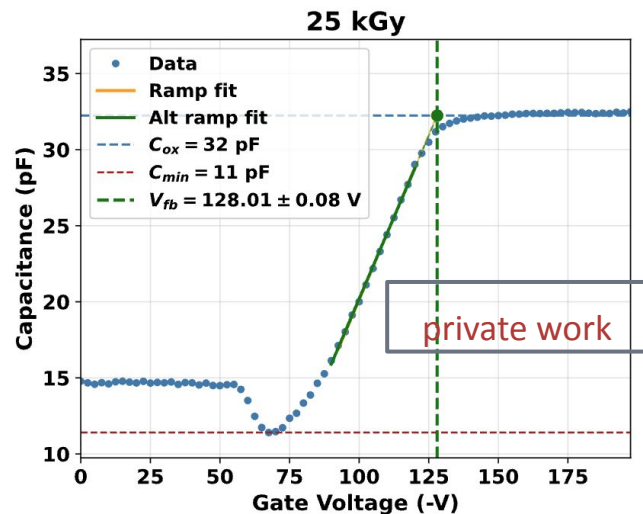


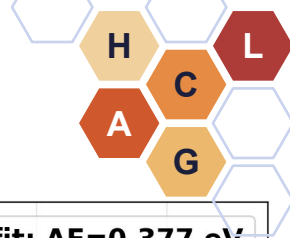
[4]<https://ade-pixel-group.web.cern.ch/xray/>

CMS HGCALE · Si sensors radiation damage and annealing

Annealing studies

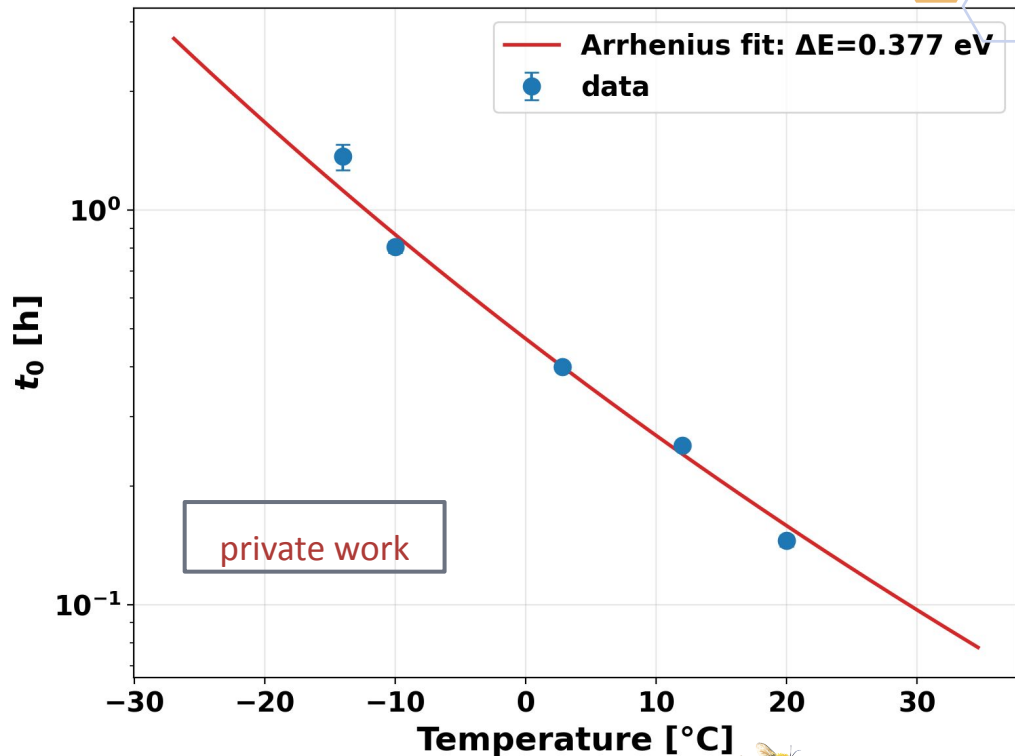
- Flat-band voltage V_{fb} extracted from MOS CV curves
- Annealing followed in fixed time steps → with AXIOM long scans possible
- Extremely temperature sensitive** → best scenario is to start annealing directly after irradiation in temperature controlled environment, moving the sample adds uncertainties
- N_{ox} follows expected physical model**





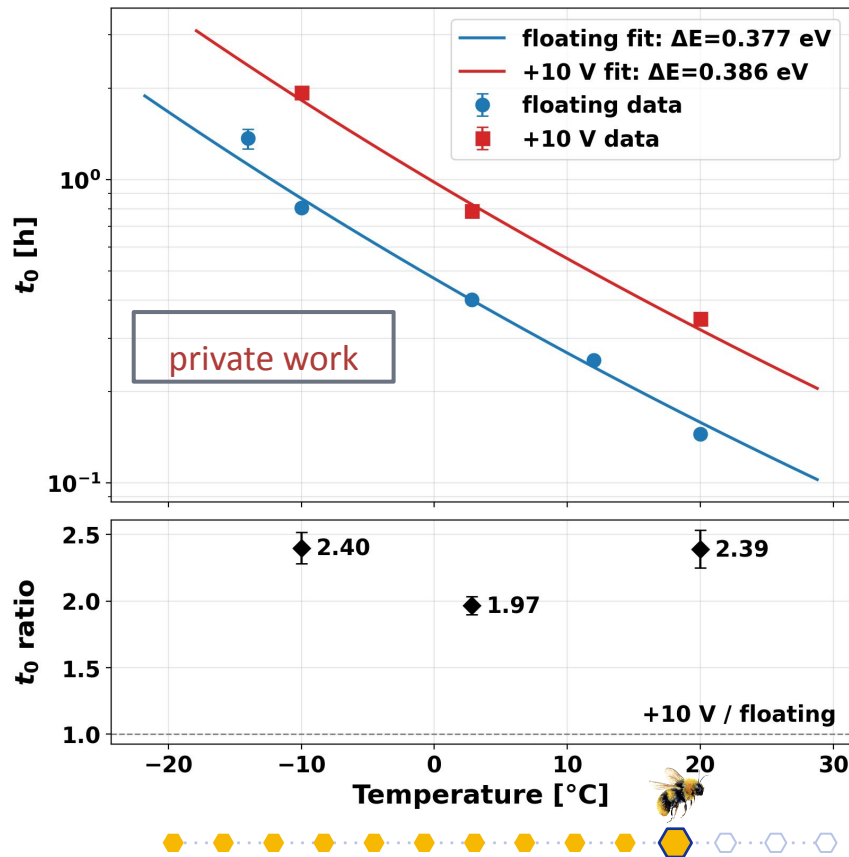
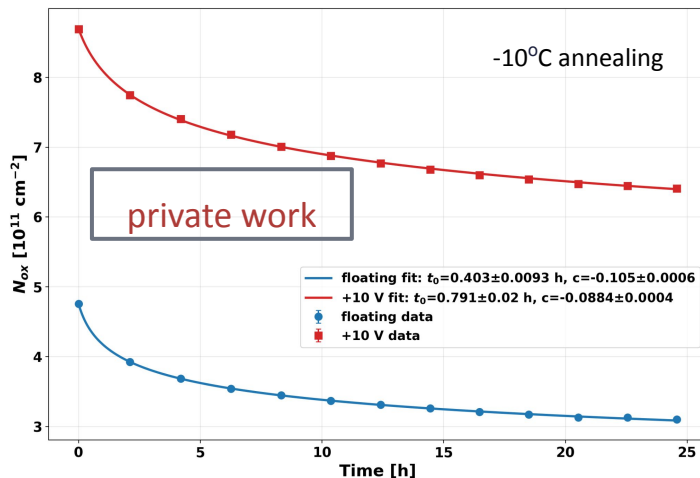
Annealing studies: temperature dependence

- One dose point (25 kGy), samples annealed at several temperatures
- Fit of each annealing curve $\rightarrow$ parameters t_0 and $-1/2\beta$
- Arrhenius fit of t_0 temperature dependence $\rightarrow$ extraction of activation energy ΔE
- Follows well the Arrhenius fit**
- Parameter $-1/2\beta$ is expected to be constant for all the temperatures - not what was observed $\rightarrow$ further investigations ongoing



Annealing studies: biased vs floating MOS

- MOS2000 biased at +10 V during irradiation - lower initial recombination
- Higher damage for the biased MOS2000
- Larger t_0 parameter for MOS2000 → slower annealing





Summary

- 🟡 **Production:** ~24 000 8" sensors by HPK (2023–2025), ~8 % tested at 5 CMS institutes
- 🟡 **Si bulk:** radiation hardness studied up to HL-LHC fluences, reverse annealing not a concern during operation
- 🟡 **Oxide annealing:** N_{ox} recovery follows the expected model, t_0 follows an Arrhenius law ($\Delta E \approx 0.38$ eV)

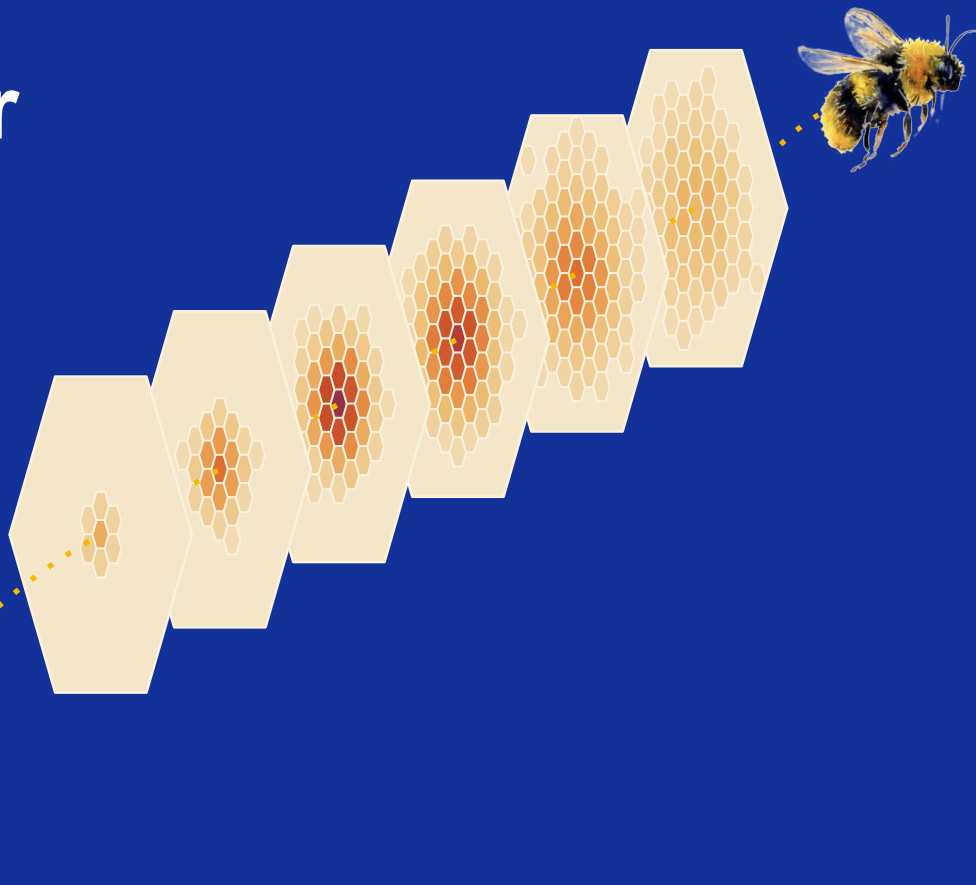
Outlook

- 🟡 Multiple dose steps and dose rates for annealing studies
- 🟡 TCAD implementation → predict oxide annealing for HGCal operation and shutdowns



Thank you for your attention!

Questions?



ATLAS X-ray machine

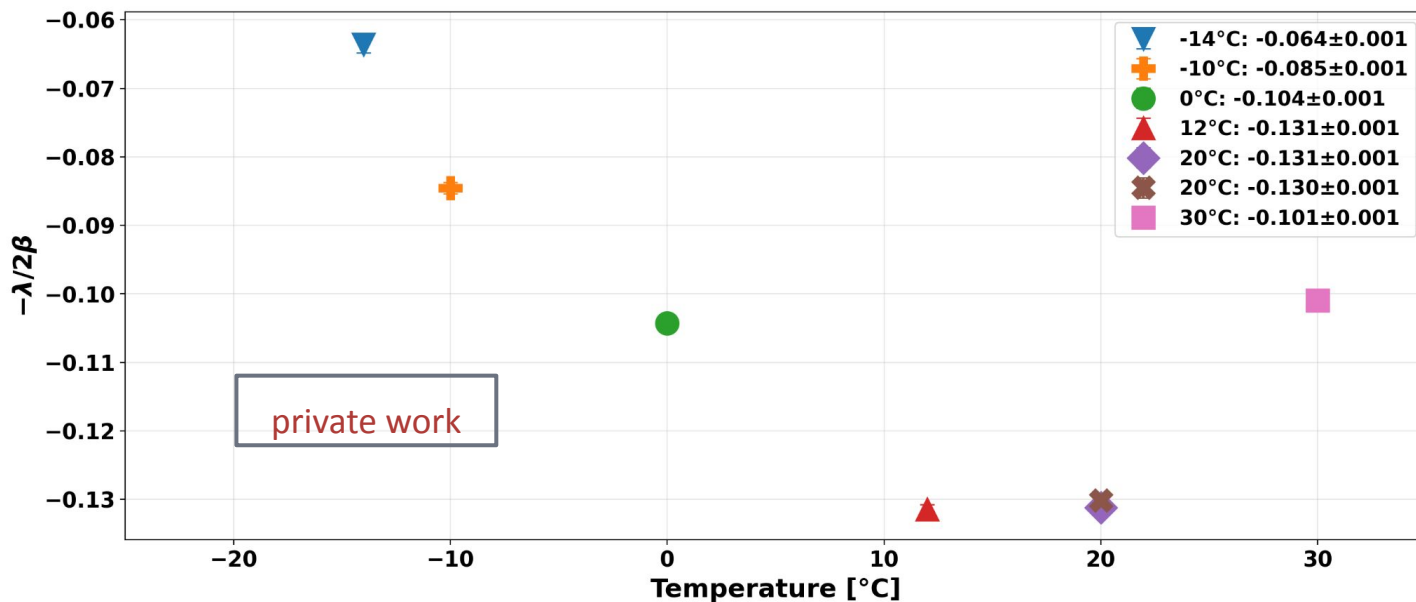
- Machine is Precision X-Ray X-RAD iR160 biological irradiator
- Cooling of the sample via cold chuck connected to a chiller
- Machine does not have cooling for X-ray -> stable sample cooling only up to $\sim -15^{\circ}\text{C}$, dry air is also not cooled
- No possibility of precise distance measurement





$-\lambda/2\beta$ parameter

- ✦ $-\lambda/2\beta$ is expected to be temperature independent, but varies from -0.06 to -0.13 , beyond the statistical uncertainties
- ✦ Studies with different oxide variants can be done in future to observe difference between those



GCD and surface current

- Interface traps are studied with gate-controlled diodes (GCD) via the surface current I_{surf} :

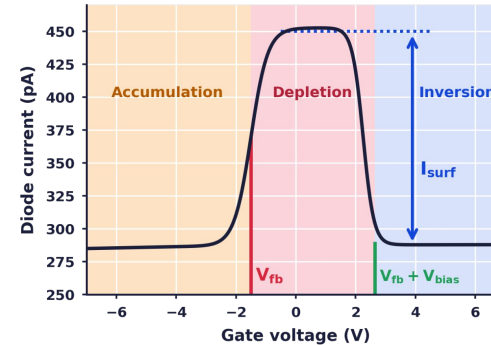
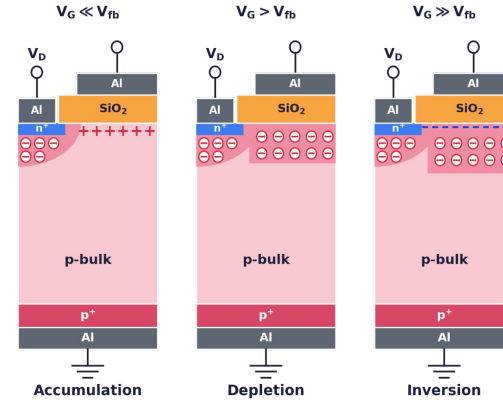
$$s_0 = \frac{I_{\text{surf}}}{q n_i A_{\text{gate}}}$$

- Expected annealing of the surface current:

$$J_{\text{surf}}(t) = J_{\text{surf}}^0 (1 + t/t_1)^{-\eta}$$

$$t_1(T) = t_1^* \exp\left(\frac{E_\alpha}{k_B T}\right)$$

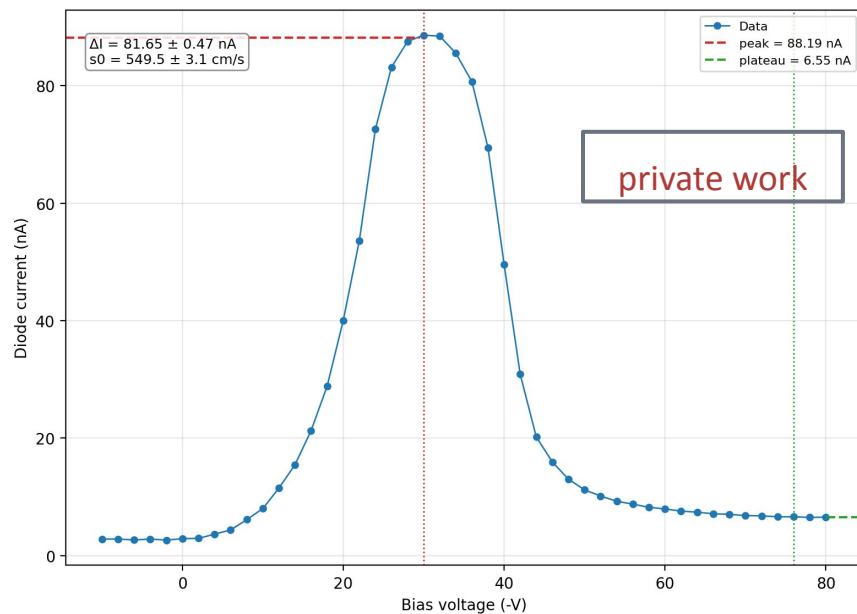
- J_{surf}^0 : surface-current density at $t = 0$; η : related to the ratio of the two reaction rates
- $1/t_1^*$: frequency factor; E_α : activation energy



Backup: GCD annealing



- We don't observe much of annealing for temperatures below 60°C - contrary to N_{ox}



Backup

