MC-PAD Closing Network Event

Project 2: Hybrid Pixel Detectors

(X-ray Radiation Damage Studies and Design of a Silicon Pixel Sensor for Science at the XFEL)

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Outline

Scientific work:

- Motivation: Radiation hard silicon sensors for the XFEL
- Selected topics in this talk:
  - Understanding of X-ray induced radiation damage
  - Characterization and determination of damage related parameters
  - Influence on electric properties of segmented sensors
- Review on other achievements

General aspects:

- Benefits from MC-PAD framework
- Suggestions

Motivation

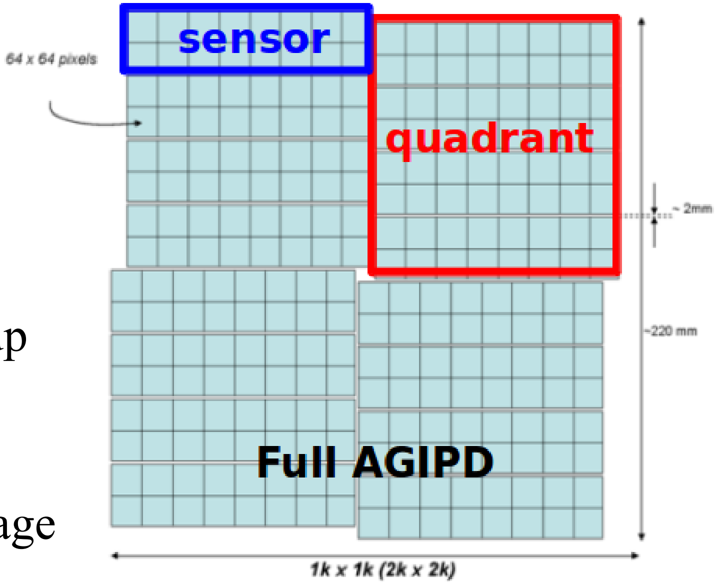
Motivation: Development of radiation hard (**0 - 1 GGy!**) silicon pixel sensors for experiments with hard X-rays (3 keV – 25 keV) at the European XFEL - work done within AGIPD collaboration

Method (collaboration with J. Schwandt, PhD student, Hamburg University):

- Extract microscopic parameters related to X-ray irradiation
- Understand the influence of X-ray irradiation on electrical properties of segmented sensors
- Implement the extracted parameters in TCAD simulation and verify results with measurements on segmented sensors
- Optimize sensor design using TCAD simulation
- Sensor layout design based on optimized parameters

Main effects in silicon sensors @ XFEL:

- No bulk damage for $E_{x\text{-rays}} < 300$ keV
- Surface damage: **oxide charges** and **interface traps** build up
  - → increase leakage current (noise + power dissipation)
  - → reduce breakdown voltage
  - → increase inter-pixel capacitance and full depletion voltage
  - → charge losses below the $Si\text{-}SiO_2$ interface



X-ray induced defects in silicon sensors

Formation of defects induced by X-ray ionizing radiation:

- X-rays produce electron-hole pairs in SiO_2 [~ 18 eV/pair]
- Fraction of electron-hole pairs recombine:
  → field dependent yield of e-h pairs
- Remaining electrons escape from SiO_2 [$\mu_e \sim 20\ cm^2/(V\cdot s)$]
- Holes trapped in vacancies near Si-SiO_2 interface
  [$\mu_h < 10^{-5}\ cm^2/(V\cdot s)$]

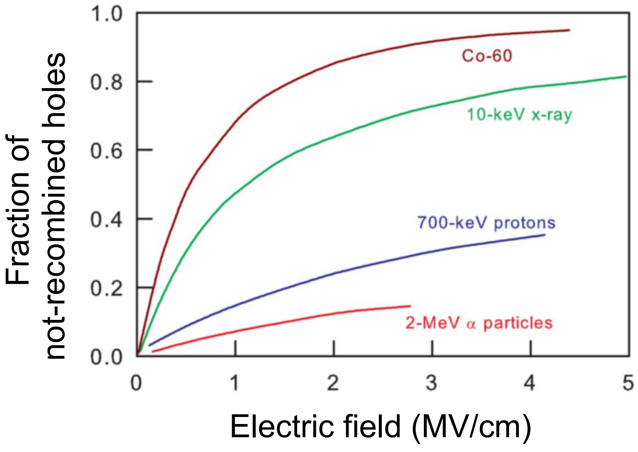
  e.g., $V_{ox} + h^+ \rightarrow V_{ox}^+$ ⇒ **oxide charges (*N_{ox}*)**
- Protons get released and react with passivated dangling bonds at the interface:

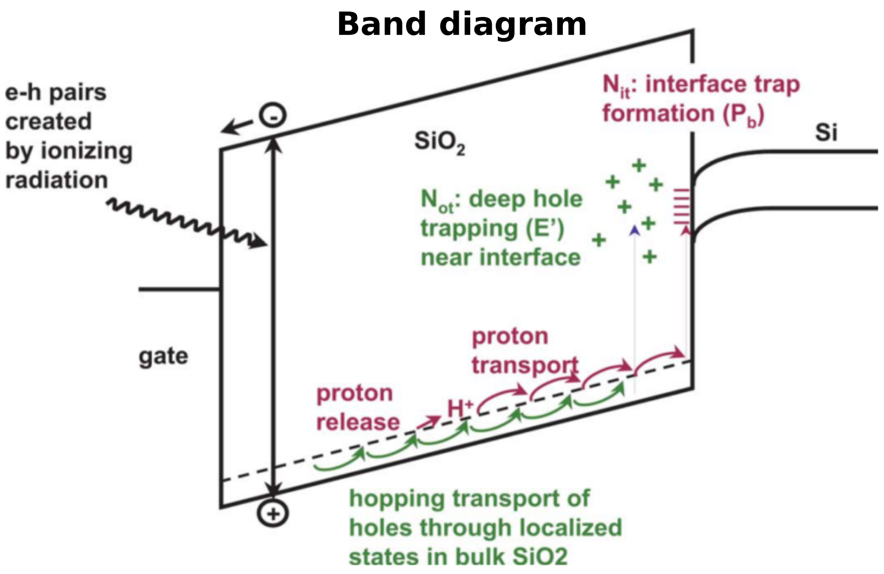
  e.g., $V_{ox}H_2 + h^+ \rightarrow V_{ox}H_2^+ \rightarrow V_{ox}H + H^+$

  $H^+ + SiH_{int} \rightarrow Si\bullet + H_2$

  ⇓

  interface traps (*N_{it}*)



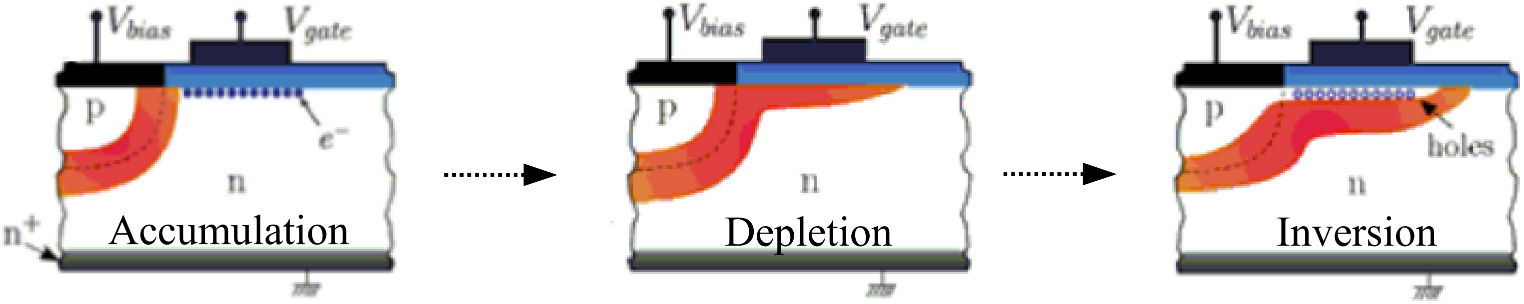


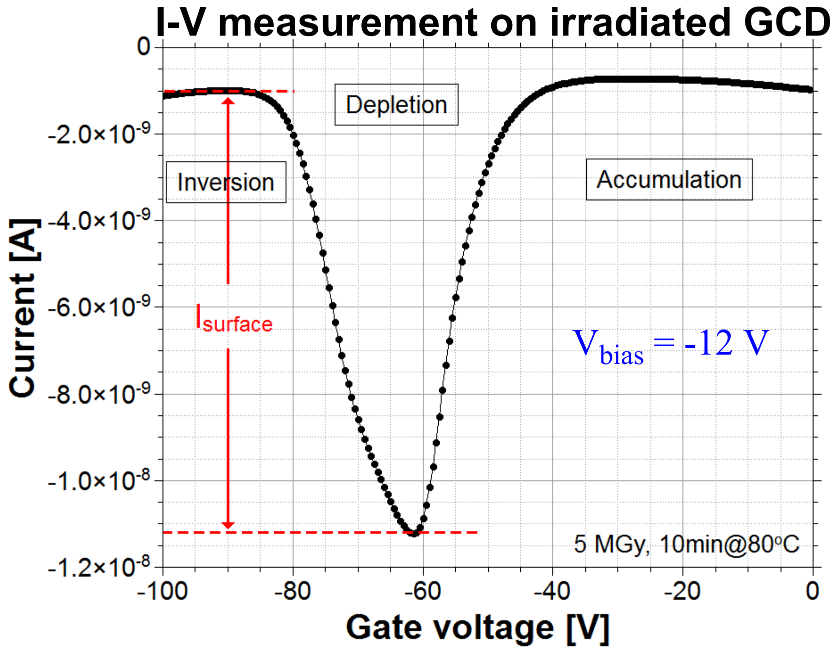
* from J.R. Schwank, 2008

Defect characterization: I-V, TDRC & C/G-V

Current-Voltage (I-V) measurement on Gate-Controlled Diode (GCD) for J_{surf} (µA/cm^2):

- Increase of surface current density $J_{surf} \leftarrow D_{it}^{mid\text{-}gap}$ (eV^{-1}cm^{-2})





Accumulation: $I_{bulk,diode} + I_{diff}$

Depletion: $I_{bulk,diode} + I_{diff} + I_{surface} + I_{bulk,gate}$

Inversion: $I_{bulk,diode} + I_{diff} + I_{bulk,gate}$

$\rightarrow I_{surface} = |I_{depletion} - I_{inversion}|$

$\rightarrow J_{surf} = I_{surface}/A_{gate}$

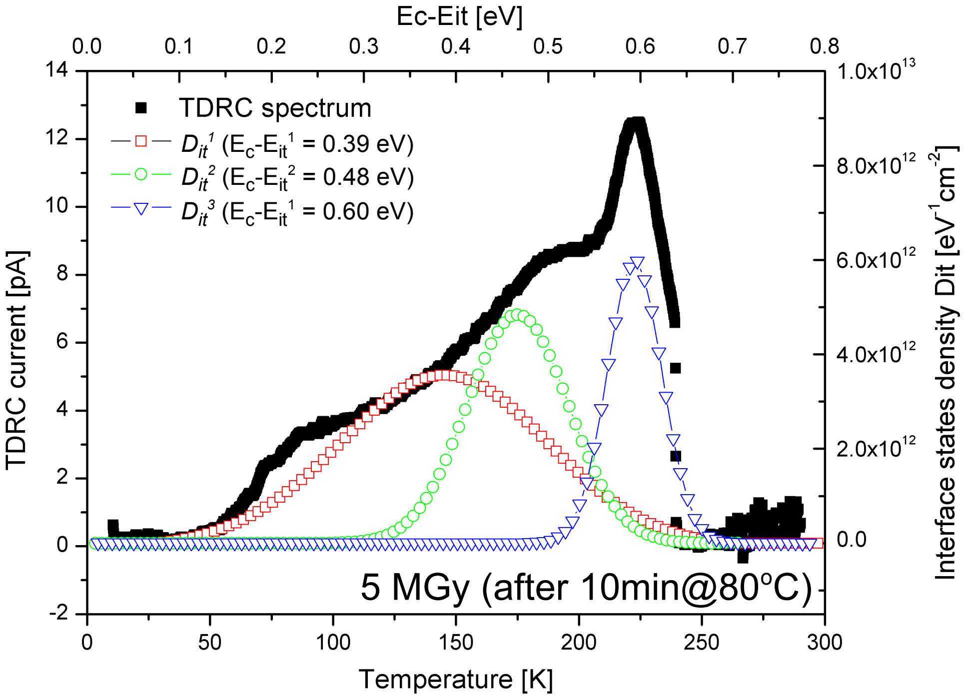
Defect characterization: I-V, TDRC & C/G-V

Thermal Dielectric Relaxation Current (TDRC) measurement on MOS capacitor for $N_{it}^{(i)}$ (cm^{-2}):

- Measurement technique: Thermal Dielectric Relaxation Current (TDRC)
  - (1) Bias the MOS capacitor to accumulation → fill interface traps with electrons
  - (2) Cool down to 10 K → freeze traps
  - (3) Bias to deep depletion and heat up to 290 K → trapped charges at the Si-SiO$_2$ interface get released

Temperature [K] → E_c-E_{it} [eV]
TDRC signal [pA] → D_{it} [eV^{-1}cm^{-2}]

$$N_{it}^{(i)} = \int_{E_v}^{E_c} D_{it}^{(i)}(E_{it})dE_{it}$$



- Properties of 3 dominant interface traps in silicon band gap after X-ray irradiation:

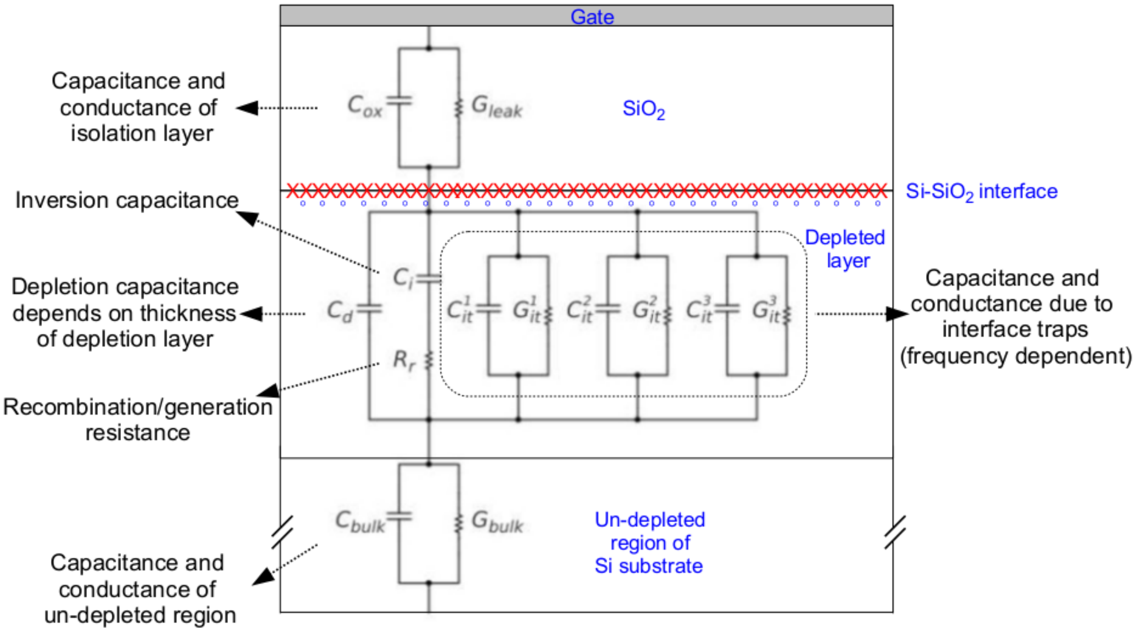
	D_{it}^{1}	D_{it}^{2}	D_{it}^{3}
E_c-E_{it} [eV]	0.39	0.48	0.60
FWHM [eV]	0.26	0.13	0.071
σ_{eff} [cm^2]	1.2×10^{-15}	5.0×10^{-17}	1.0×10^{-15}

Defect characterization: I-V, TDRC & C/G-V

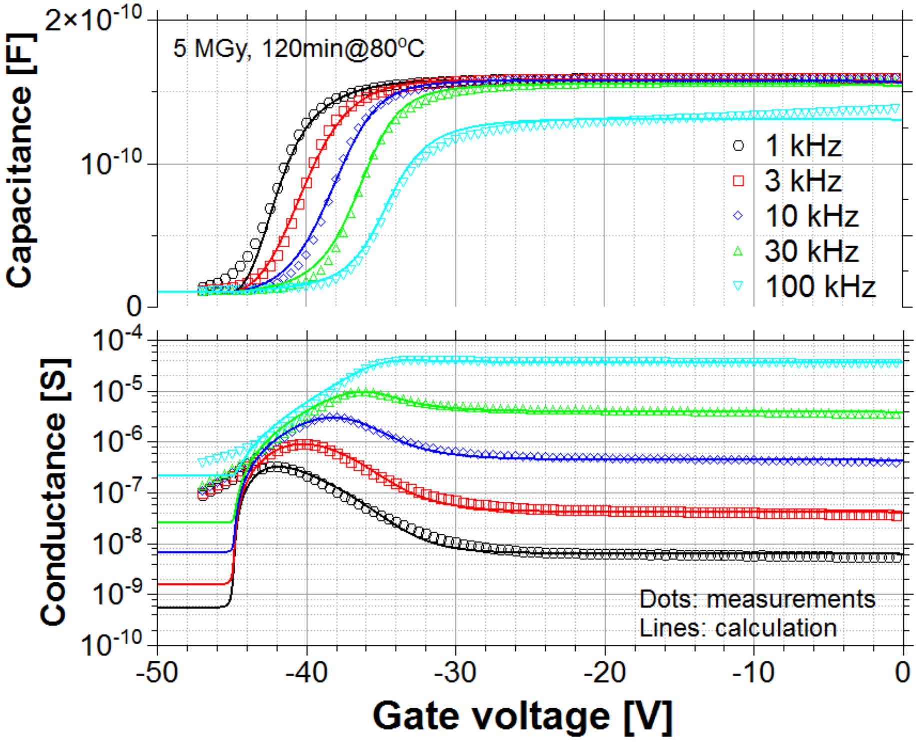
Capacitance/Conductance-Voltage (C/G-V) measurement on MOS capacitor + model calculation for N_{ox} (cm^{-2}):

- Frequency shift of C/G-V curves ← $N_{it}^{(i)}$
- Shift in gate voltage ← $N_{ox} + N_{it}^{(i)}$
- TDRC spectra + model → reproduce measured C/G-V curves → N_{ox}

Model for MOS capacitor



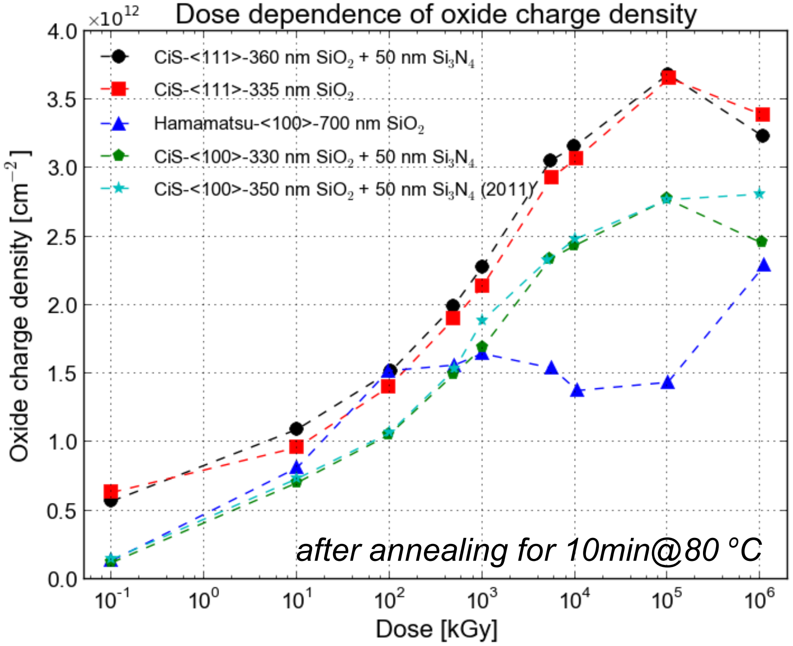
C/G-V measurement on irradiated MOS capacitor



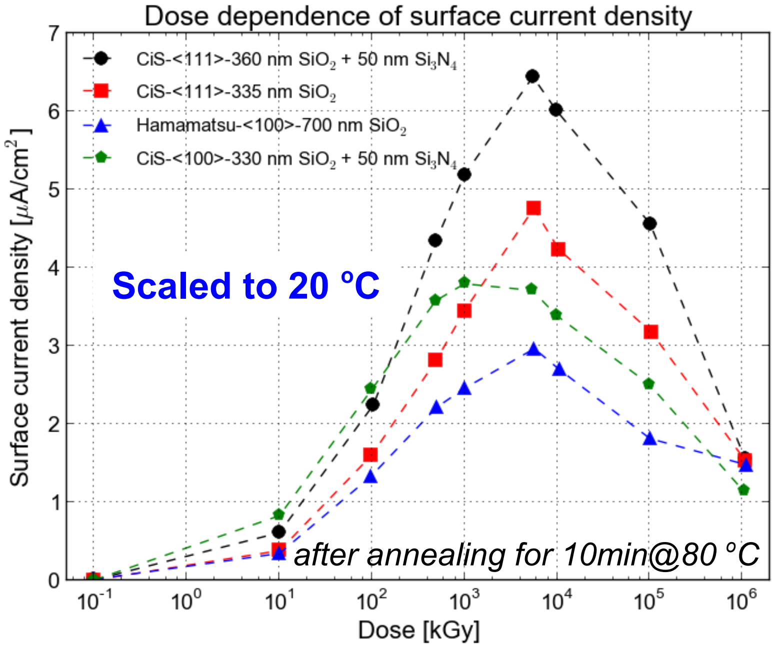
Results: N_{ox} & J_{surf} vs. dose

Investigations:

- Orientation: <111> and <100>
- Vendor: CiS and Hamamatsu
- Insulator: SiO_2 and $SiO_2 + Si_3N_4$
- Unbiased during irradiation


Dose dependence of oxide charge density

after annealing for 10min@80 °C


Dose dependence of surface current density

Scaled to 20 °C

after annealing for 10min@80 °C

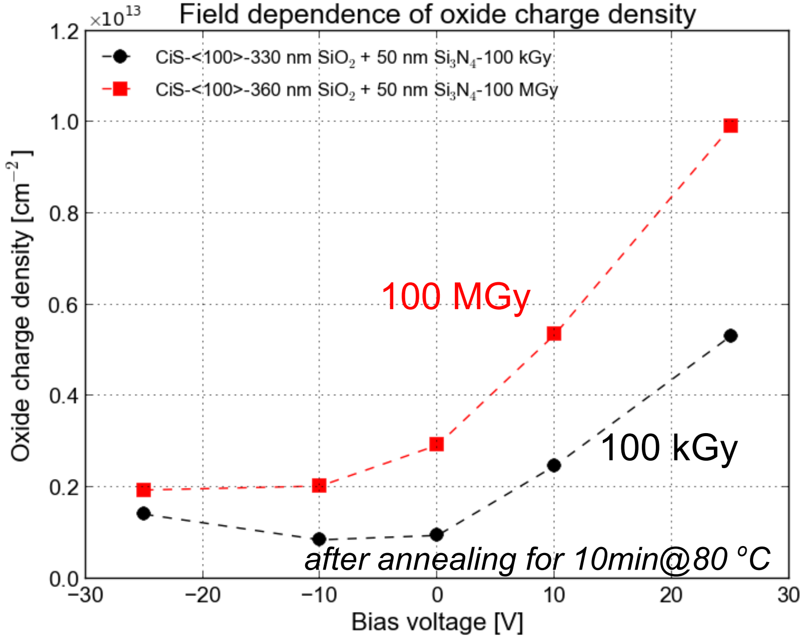
Conclusions:

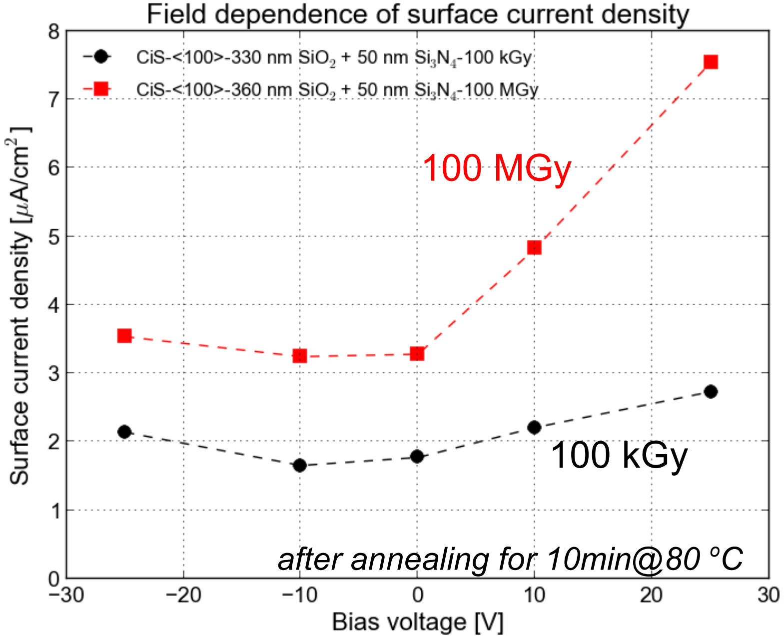
- N_{ox} and J_{surf} saturate with dose: typically $N_{ox} \sim (1.5 - 4.0) \times 10^{12}$ cm^{-2}, $J_{surf} \sim (3 - 7)$ μA/cm^2
- Differences observed for orientations, SiO_2 vs. SiO_2+Si_3N_4, vendors
- Saturation mechanism of N_{ox}: equilibrium between hole trapping and electron recombination

Results: N_{ox} & J_{surf} vs. E_{ox}

Investigations:

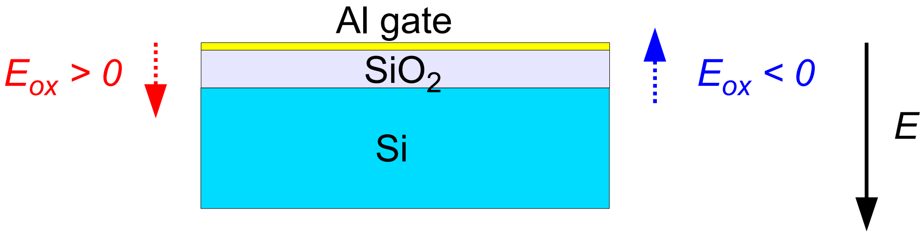
- CiS <100> MOS capacitor and Gate-Controlled Diode (~ 350 nm SiO_2 + 50 nm Si_3N_4)
- Electric field in the oxide E_{ox}: ~ (0 - 0.7) MV/cm [oxide breakdown: ~ 10 MV/cm]





Conclusions:

- N_{ox} and J_{surf} increase for $E_{ox} > 0$
- No strong E_{ox} dependence for $E_{ox} < 0$
- p^+n sensor: $E_{ox} < 0$ → not a problem!



Al gate

$E_{ox} > 0$

SiO_2

$E_{ox} < 0$

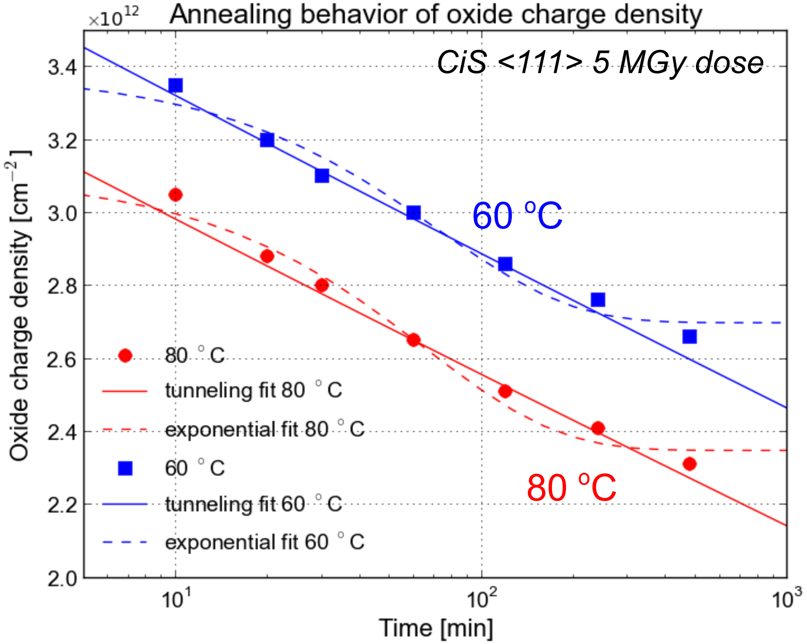
Si

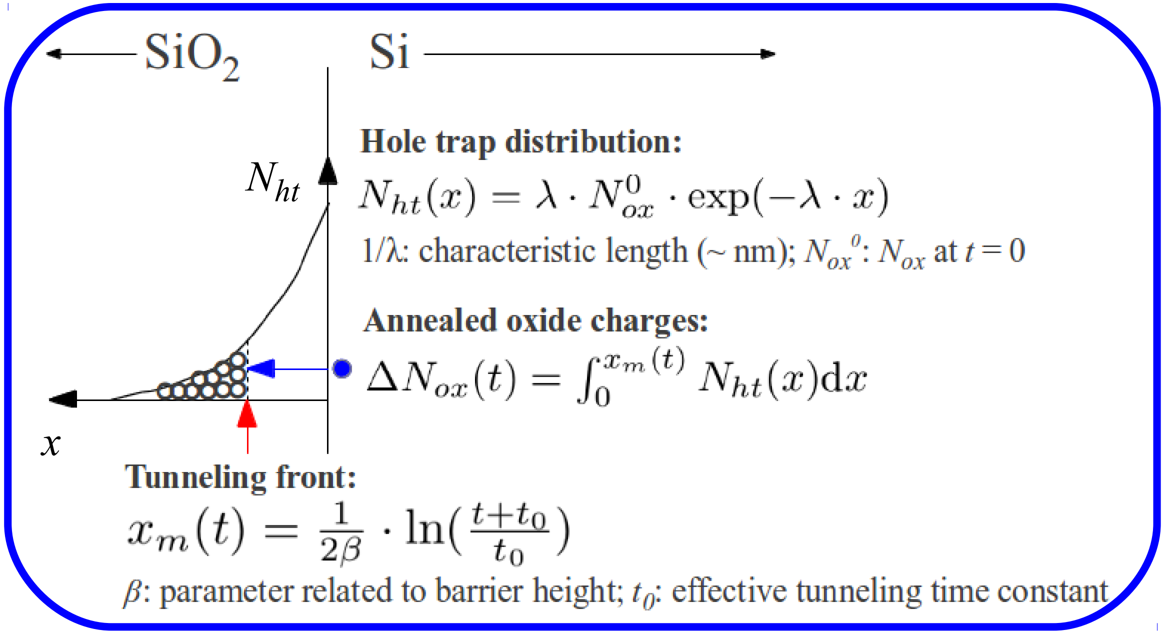
E

Results of annealing: N_{ox} vs. *time*

Annealing of N_{ox}:

- Exponential decay: $N_{ox}(t) = A \cdot \exp(-\frac{t}{\tau}) + \boxed{y_0}$ → description inadequate





Hole trap distribution:

$$N_{ht}(x) = \lambda \cdot N_{ox}^0 \cdot \exp(-\lambda \cdot x)$$

1/λ: characteristic length (~ nm); $N_{ox}{}^0$: N_{ox} at $t = 0$

Annealed oxide charges:

$$\Delta N_{ox}(t) = \int_0^{x_m(t)} N_{ht}(x)\mathrm{d}x$$

Tunneling front:

$$x_m(t) = \frac{1}{2\beta} \cdot \ln(\frac{t+t_0}{t_0})$$

β: parameter related to barrier height; t_0: effective tunneling time constant

- "Tunnel anneal" model [T. R. Oldham et al., 1986]:

$$N_{ox}(t) = N_{ox}^0 \cdot (1 + t/t_0)^{-\frac{\lambda}{2\beta}} \quad \text{with} \quad t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$$

{ t_0*: tunneling time constant
ΔE: energy difference between trap level and silicon Fermi level

$N_{ox}{}^0$ [cm^{-2}]	λ/2β	$t_0{}^*$ [s]	ΔE [eV]
3.6 x 10^{12}	0.070	5.4 x 10^{-12}	0.91

T [°C]	80	60	20
t_0 [s]	48	290	22000

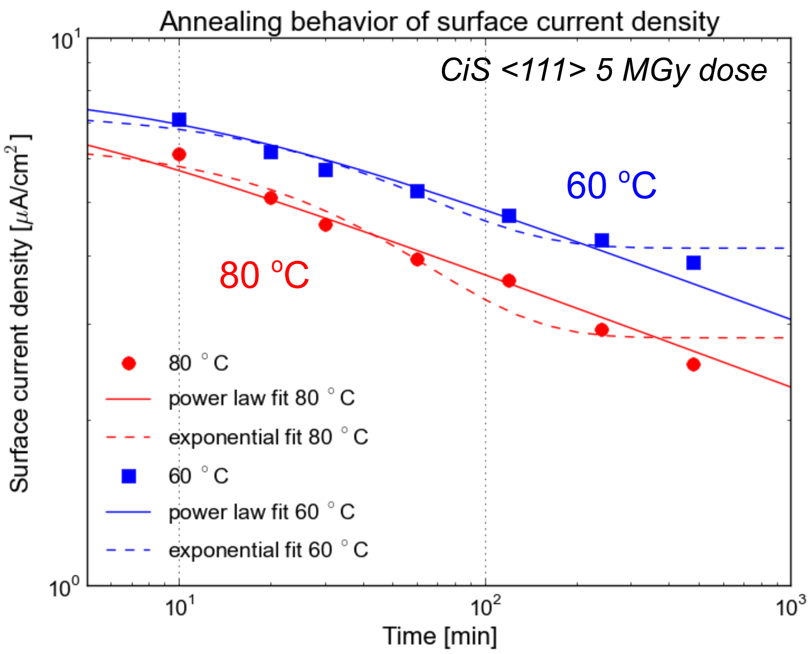
ΔE = $E_t(SiO_2)$ - $E_F(Si)$→ $E_t(SiO_2)$ ~ 6.0 eV, compatible with existing data

Results of annealing: J_{surf} vs. *time*

Annealing of J_{surf} ($I_{surface}$):

- Exponential decay: $I_{surface}(t) = A \cdot \exp(-\frac{t}{\tau}) + \boxed{y_0}$ → description inadequate
- "Two-reaction model":

$$I_{surface}(t) = I^0_{surface} \cdot (1 + t/t_1)^{-\eta} \quad \text{with} \quad t_1(T) = t_1^* \cdot \exp\left(\frac{E_\alpha}{k_B T}\right) \quad \text{and} \quad \eta = \frac{k_1}{2k_2}$$



Two-reaction model (M. L. Reed 1987):

→ Dangling bonds: $\frac{d}{dt}[\mathrm{Si}\cdot] = -k_1[\mathrm{Si}\cdot][\mathrm{H}]$

→ Hydrogen: $\frac{d}{dt}[\mathrm{H}] = -2k_2[\mathrm{H}][\mathrm{H}]$

k_1& k_2: reaction rate

J_{surf}^0 [μA/cm²]	η	t_1^* [s]	E_α [eV]
8.1	0.21	1.4 x 10^{-8}	0.70

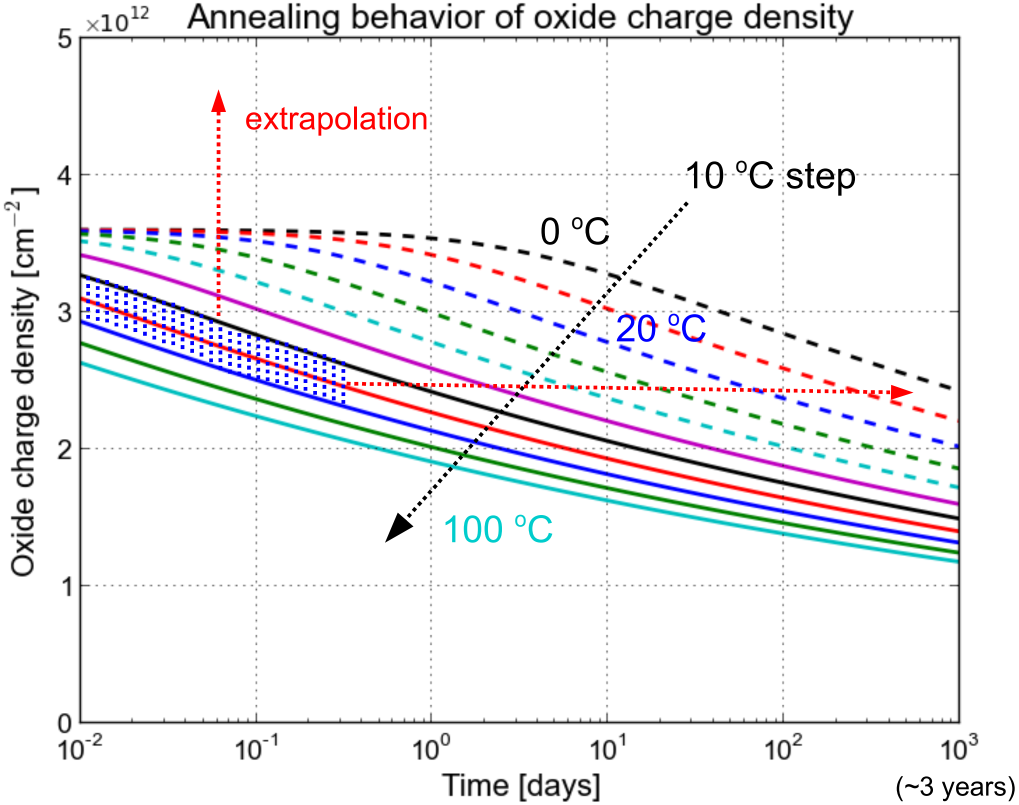
T [°C]	80	60	20
t_1 [s]	140	550	15000

- Data described by power law predicted by "two-reaction model"
- Data show that same function with different parameters for the different traps $N_{it}^{(i)}$ describes data

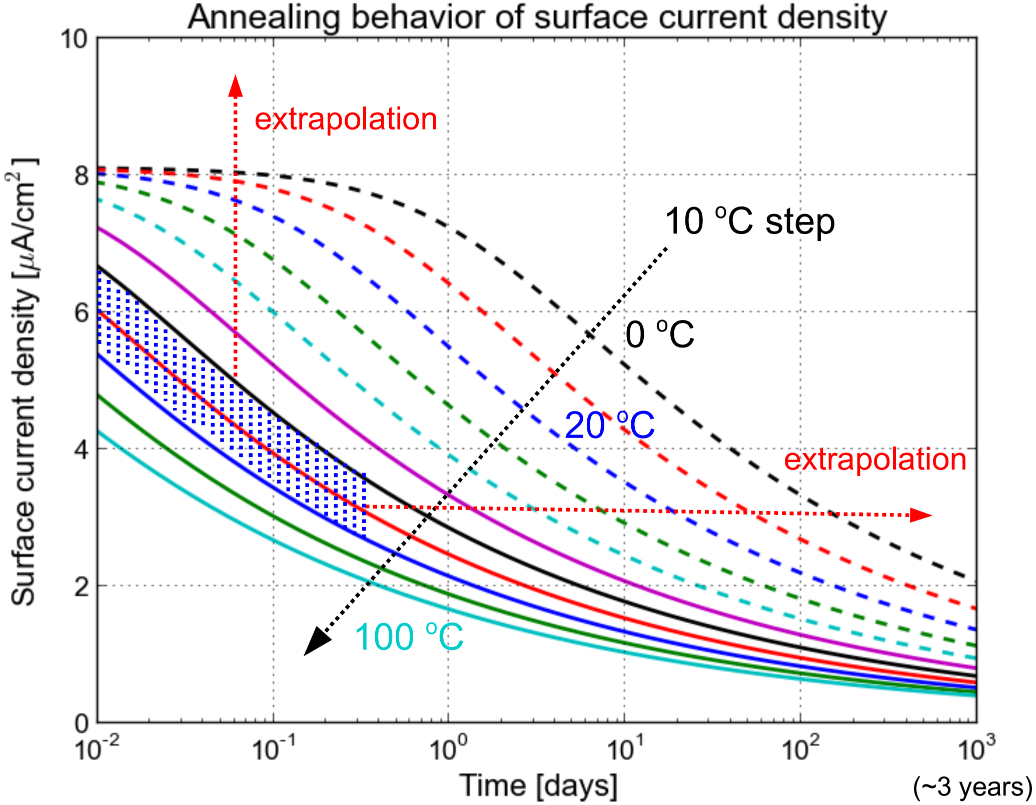
Long term behavior of N_{ox} & J_{surf}

Results based on calculation for 5 MGy dose (results scalable to other doses):

- Slow annealing for N_{ox}: e.g., at 20 ºC, $\Delta N_{ox}/N_{ox}$ by less than 50% in <u>3 years</u> (but...)
- Reduction of J_{surf} in days: e.g., at 20 ºC, $\Delta J_{surf}/J_{surf}$ by 50% just in <u>5 days</u>!

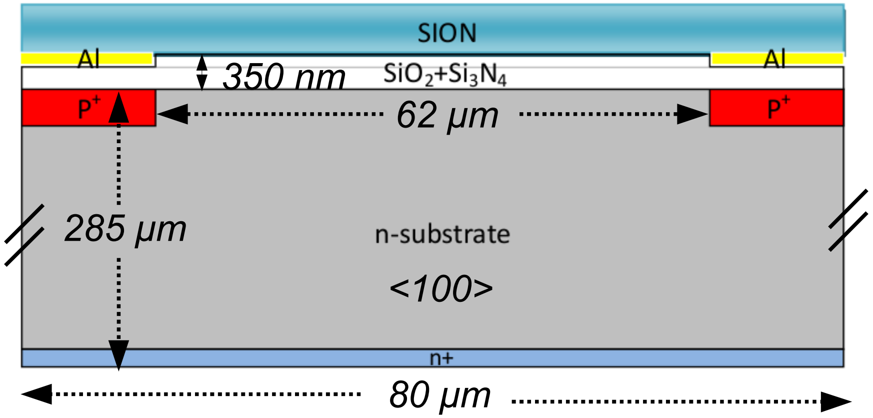


Annealing behavior of oxide charge density



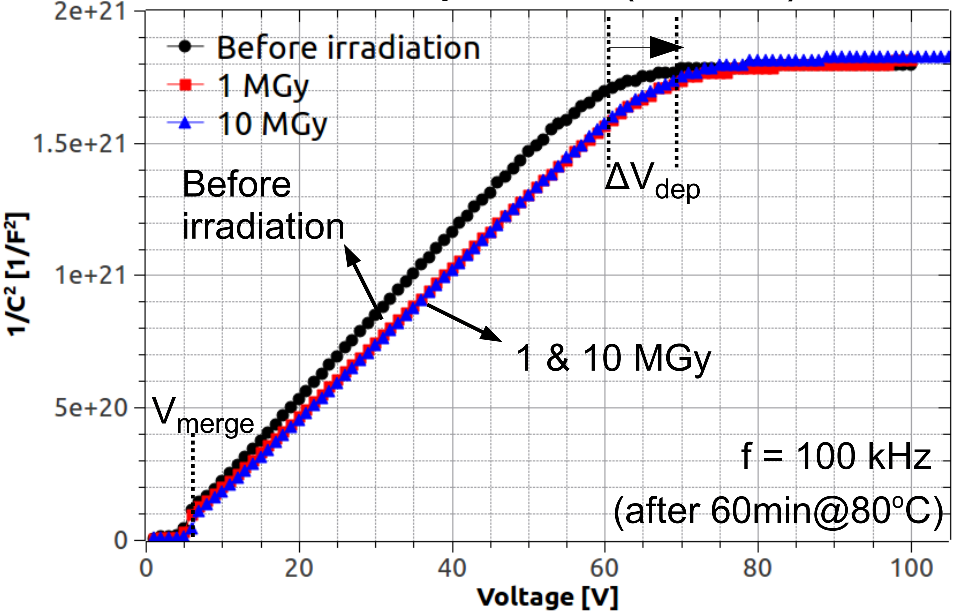
Annealing behavior of surface current density

C-V curves of p$^+$n strip sensor

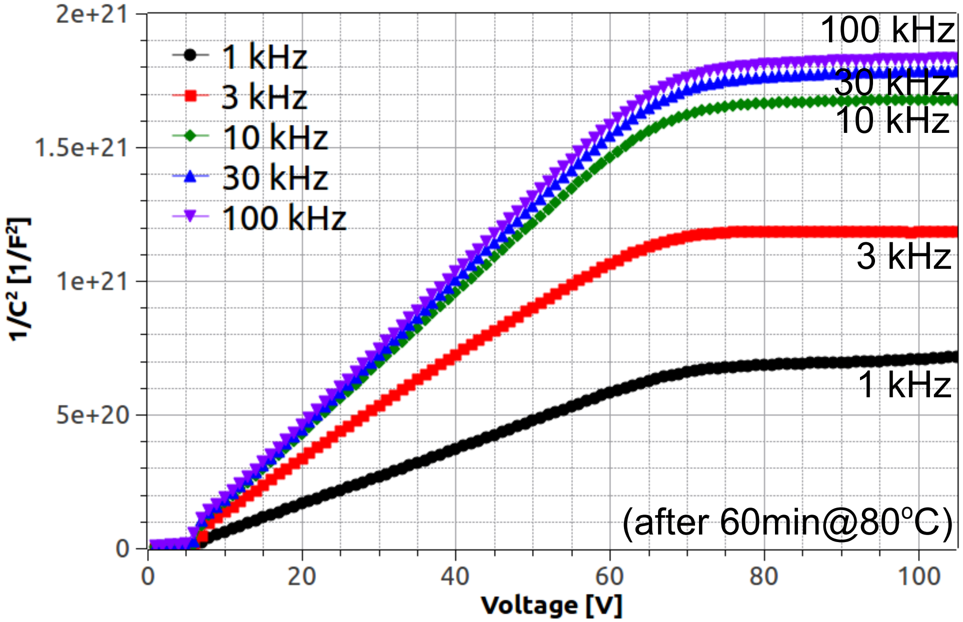


- V_{dep} increases ~10 V after irradiation due to the presence of surface charges (not due to change of doping concentration)
- Strong frequency dependence of total capacitance observed for $V_{bias} < 300$ V

Total Capacitance (in series)

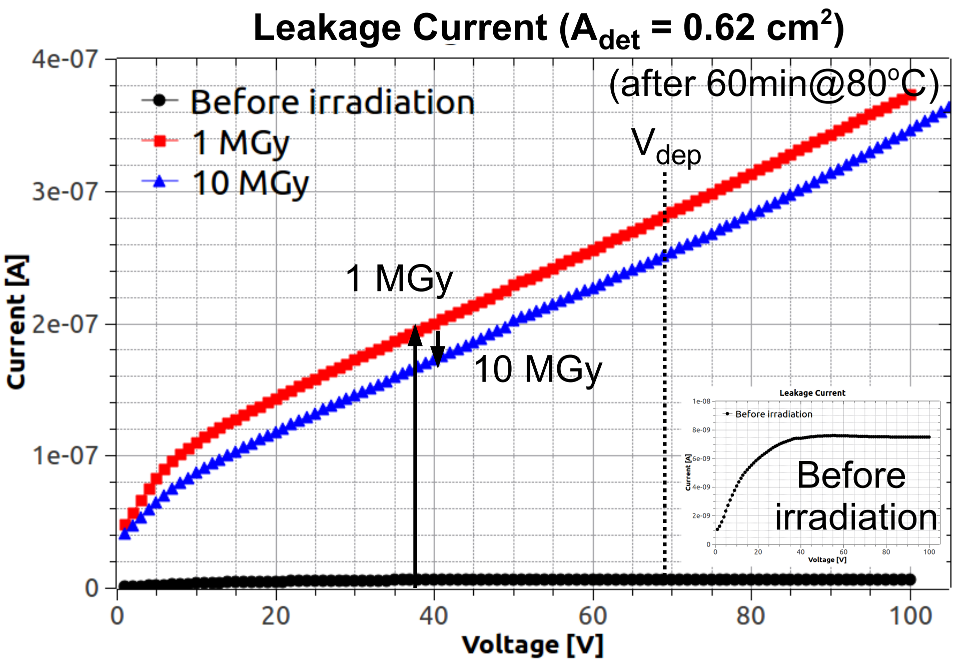


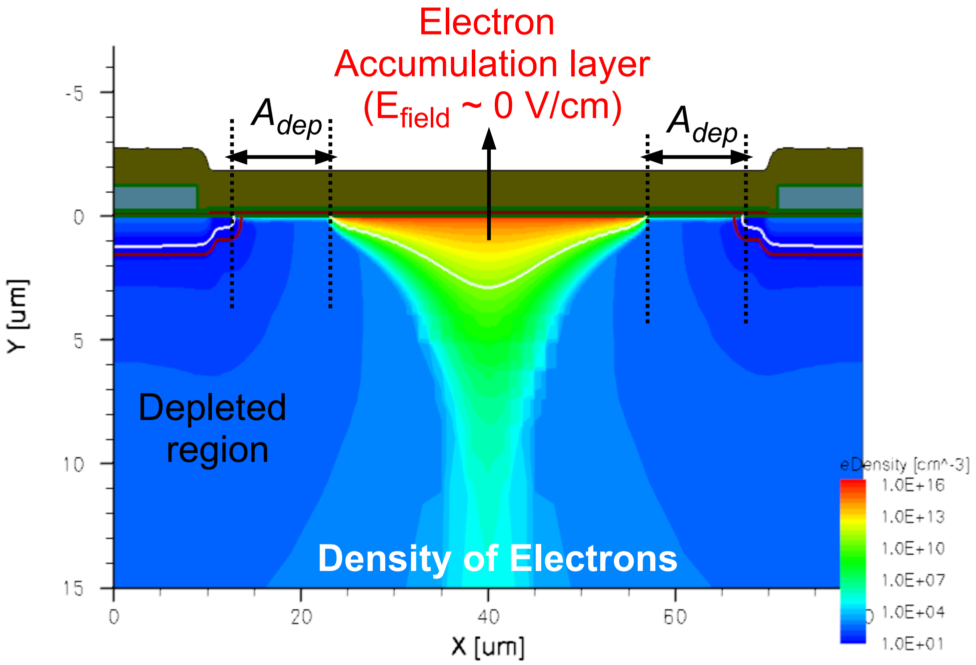
Total Capacitance after 10 MGy (in series)



I-V curves of p^+n strip sensor

- Leakage current: $I_{leakage} = I_{bulk} + I_{surface}$, where $I_{surface} = J_{surf} \cdot A_{dep}$





- Increase of $I_{leakage}$ after irradiation ← surface current density J_{surf} ← N_{it}
- "Linear" increase of $I_{leakage}$ with bias voltage ← depleted area A_{dep} at Si-SiO$_2$ interface
- Decrease of $I_{leakage}$ with irradiation dose ← result of competition between N_{it} and A_{dep}

- For irradiation under bias, $I_{leakage}$ larger by ~ 100 nA

Review on other achievements

Other work done and experiences:

- Dose calibration and operation of irradiation setup at the DESY DORIS III synchrotron light source
- Helped colleagues from other labs with irradiation set-up
- Model development for irradiated MOS capacitors
- SPICE simulation for non-irradiated p^+ on n microstrip sensors
- Test beam experiment at CERN SPS with T. Rohe, J. Sibille, et al.
- Response of PMOSFET and NMOSFET to irradiation dose
- Characterization of electrical properties of n^+ on n pixel sensors with X-ray irradiation
- Mask design of the AGIPD sensor for the European XFEL
- Supervision of a summer student from National Technical University of Athens

Review on other achievements

Talks given:

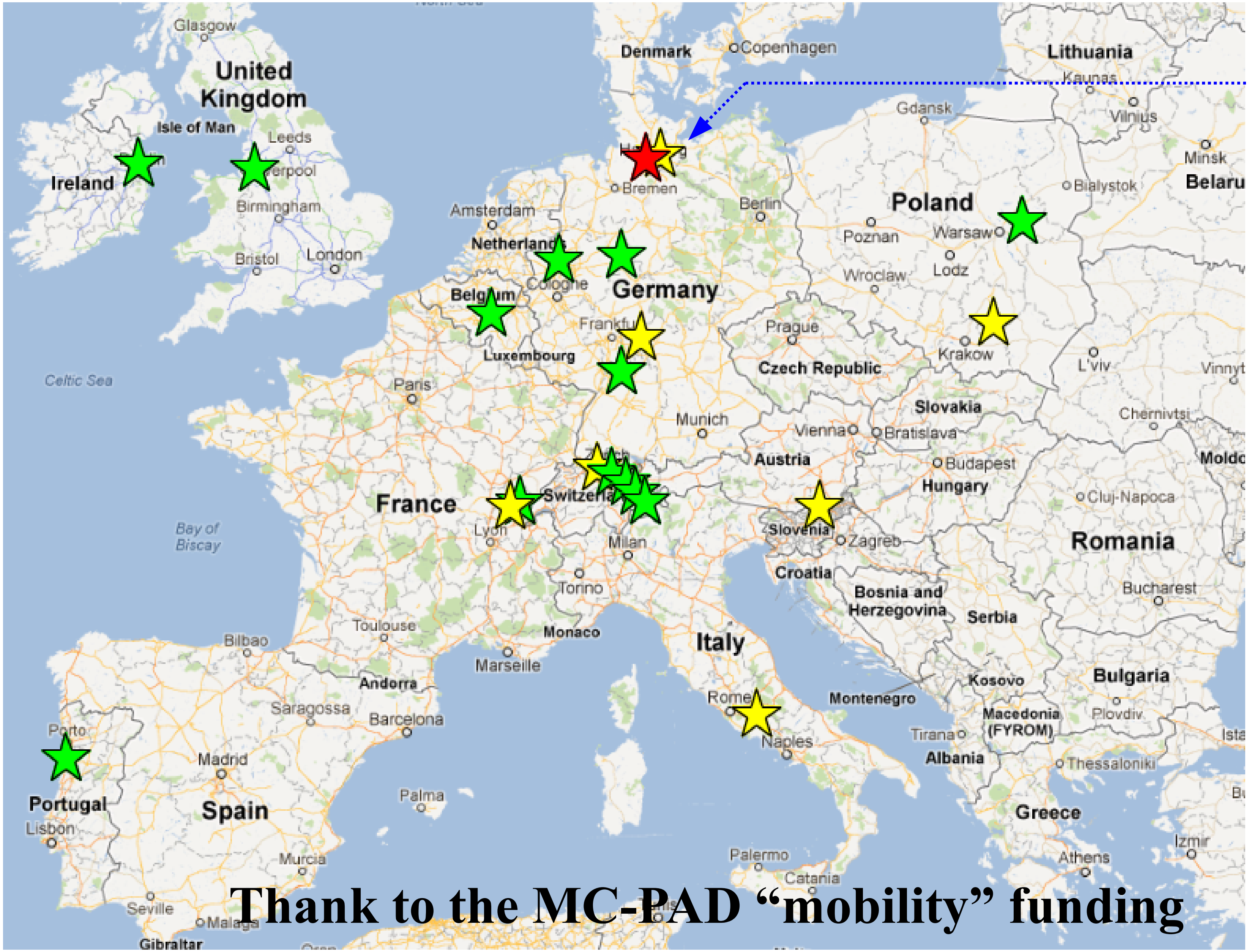
- "Investigation of X-ray induced radiation damage at the Si-SiO_2 interface of silicon pixel sensors for the European XFEL" at 14th iWoRID, July 2012, Figueira da Foz, Coimbra, Portugal
- "Status report: Radiation damage and sensors" at 10th XDAC Meeting, October 2011, XFEL GmbH-Hamburg
- "Study of X-ray radiation damage in silicon sensors" at 13th iWoRID, July 2011, ETH-Zurich and PSI-Villingen
- "Study of surface radiation damage in silicon sensors" at 18th RD50 Workshop, May 2011, Liverpool

Review on other achievements

Work results in:

- **J. Zhang**, et al., "Investigation of X-ray induced radiation damage at the Si-SiO_2 interface of silicon pixel sensors for the European XFEL", to be published by *Journal of Instrumentation*.
- T. Poehlsen, et al., "Charge losses in segmented silicon sensors at the Si-SiO_2 interface", to be published by *Nuclear of Instruments and Methods* A.
- **J. Zhang**, et al., "Study of radiation damage induced by 12 keV X-rays in MOS structures built on high resistivity n-type silicon", *Journal of Synchrotron Radiation*, Vol.19, Issue 3, 340-346 (2012).
- J. Schwandt, et al., "Optimization of the radiation hardness of silicon pixel sensors for high X-ray doses using TCAD simulations", *Journal of Instrumentation*, Vol.7, C01006 (2012).
- **J. Zhang**, et al., "Study of X-ray radiation damage in silicon sensors", *Journal of Instrumentation*, Vol.6, C11013 (2011).

Benefits from MC-PAD framework



Thank to the MC-PAD "mobility" funding

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Currently, I am in Hamburg writing and finalizing the PhD thesis.

Future: Postdoc

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MC-PAD training

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Conferences, meetings and workshops

Suggestion:

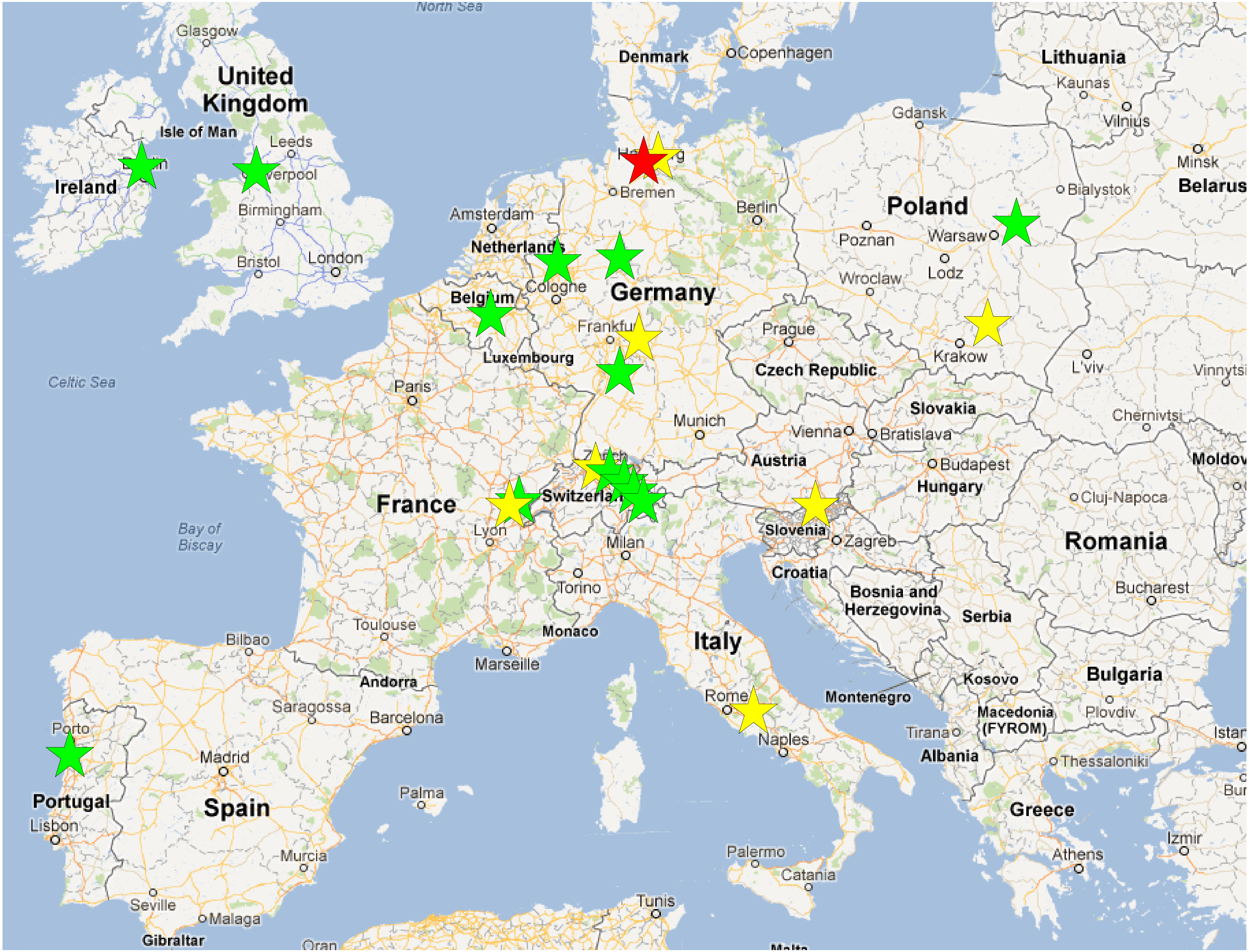
Exchange between researchers from different institutes

Special thanks go to:

- MC-PAD program
- Christian Joram
- All fellows within the MC-PAD
- Prof. Robert Klanner
- All those I worked with: Eckhart Fretwurst, Ioana Pintilie, Tilman Rohe, Joern Schwandt, Monica Turcato, Thomas Poehlsen, Jennifer Sibille, Thorben Theedt, Hanno Perrey, ...

Thanks for your attention,

and good luck for your future!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Results: N_{it} vs. E_{ox}

TDRC spectra and N_{it}:

- Dependence on E_{ox} similar to J_{surf}
- TDRC spectra:

  100 kGy → change of amplitude

  100 MGy → change of shape and amplitude