Surface effects in segmented silicon sensors

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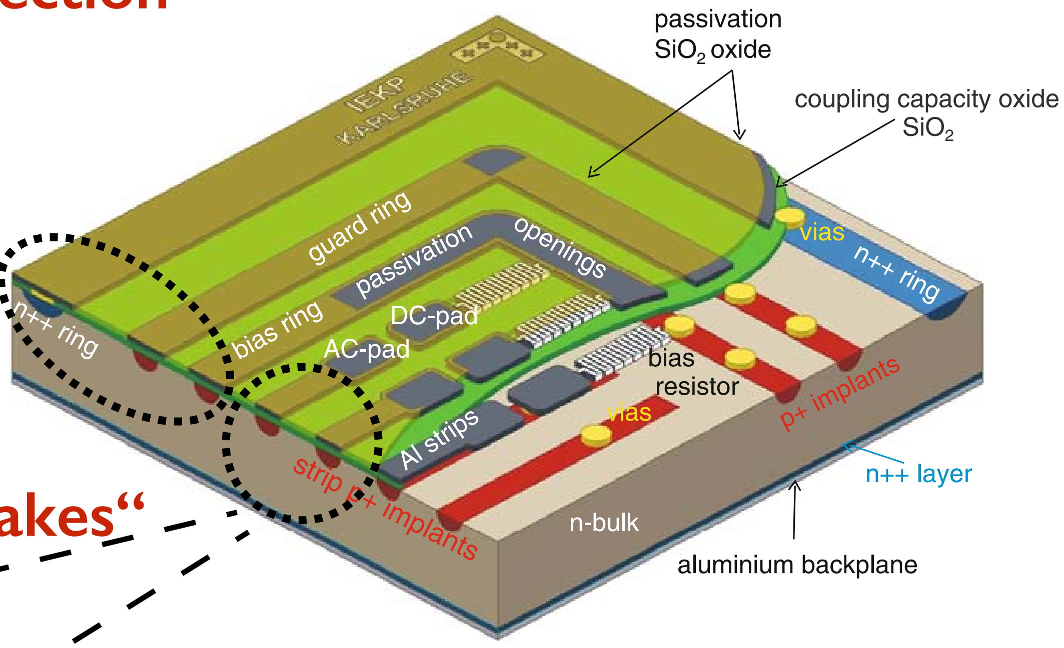
VCI2016
The 14th Vienna Conference on Instrumentation
15 -19 February 2016

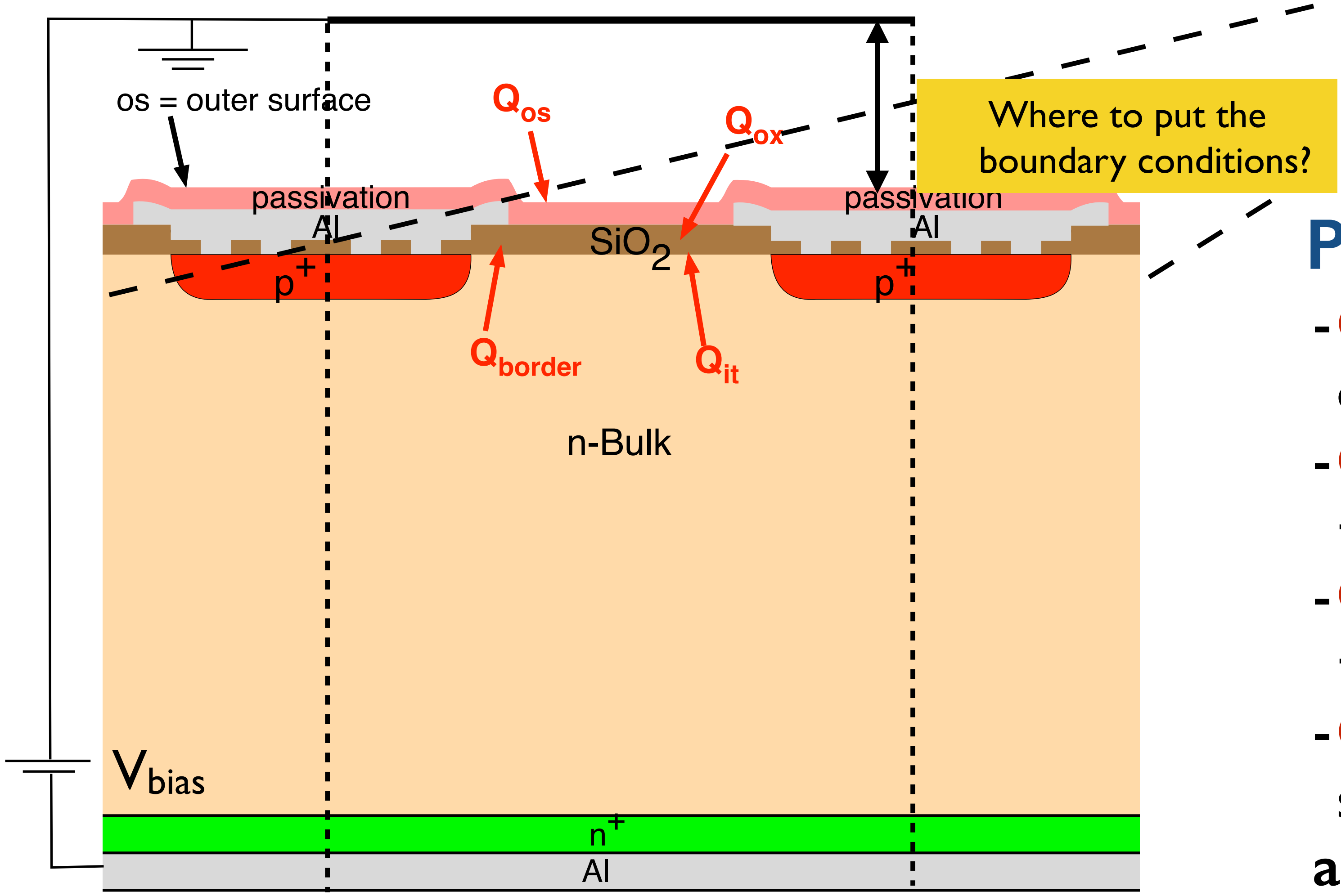
Outline

1. Introduction
2. Surface damage effects
3. Boundary conditions + humidity effects
4. Surface damage measurements during irradiation and with E-field
5. Summary

Introduction

- Surface effects influence the **stability** and the **charge collection** properties of segmented Si sensors
- Understanding and simulation of surface effects requires knowledge of **many parameters**
  → Methods have been developed to measure them
  → Parameter depend on technology (vendor)
    → needs characterization
- Simulation can help to **optimize designs** and avoid **„mistakes“**





Parameter determining the effects?

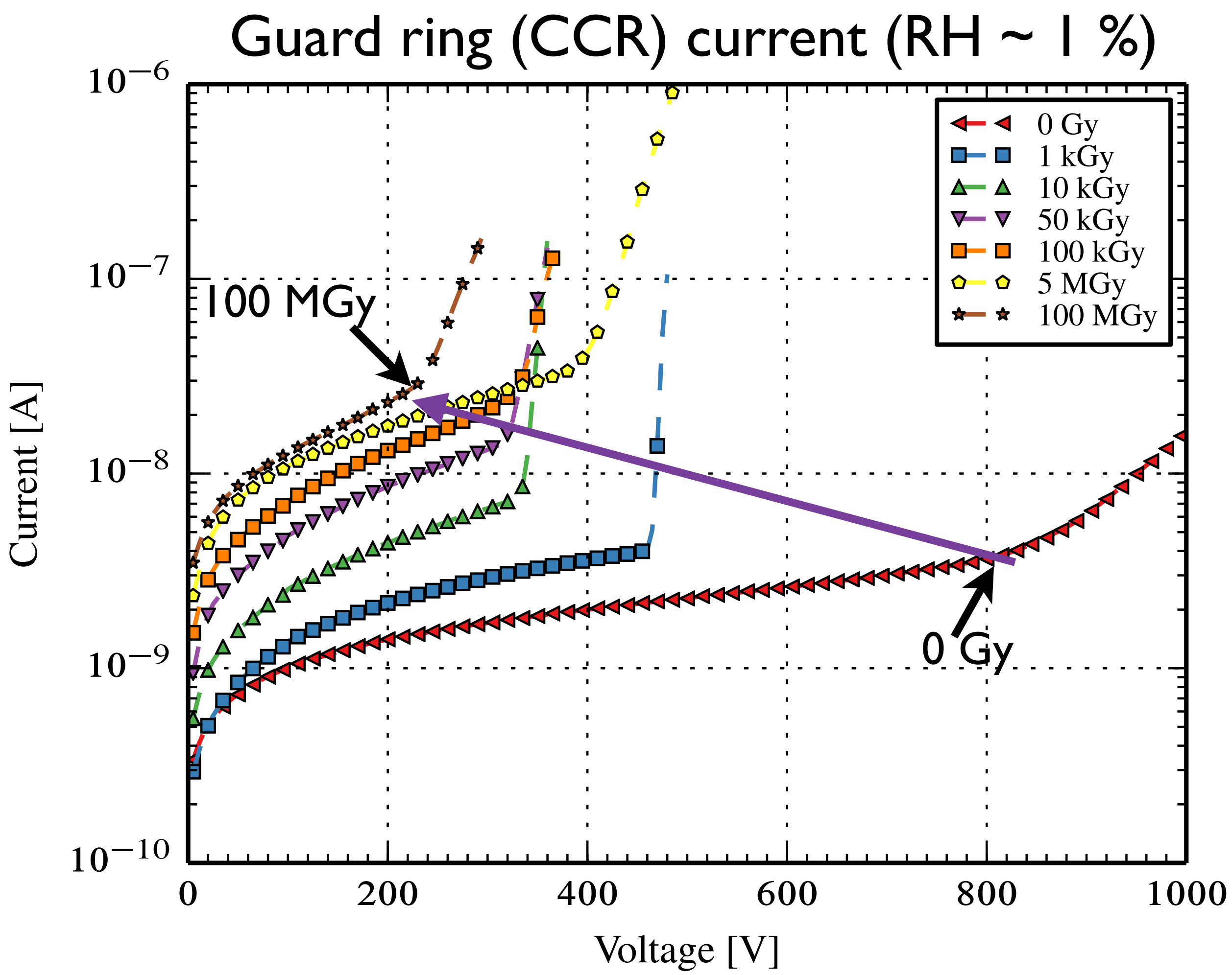
- Q_{os}: outer surface charge distribution → o.s. resistivity R_{sq} → time dependence
- Q_{ox}: “oxide” charge density → technology + surf. damage + time dependence
- Q_{border}: border trap density → technology + surf. damage + E-field + time
- Q_{it}: interface trap density → technology + surf. damage + E_{Fermi}@interface

and **boundary conditions** for simulations

Surface damage effects

Example:

- **Breakdown voltage** of a Sintef p^+-n guard ring decreases with X-ray dose from 800 V at 0 Gy to 200 V at 100 MGy



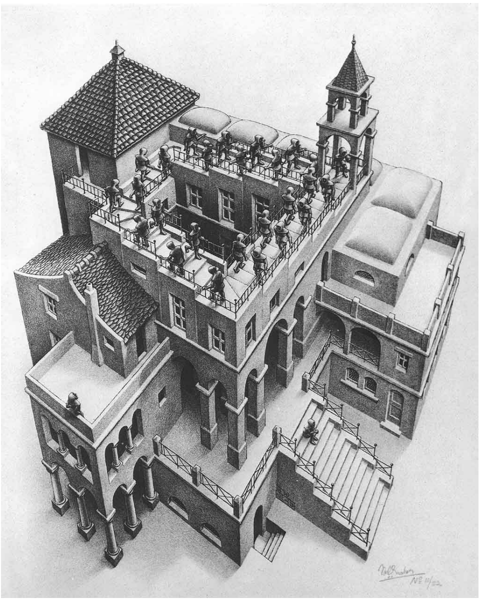
Problem:

- AGIPD p^+-n pixel sensor for the European XFEL requires operation in vacuum and a **breakdown voltage** of **above 900 V** for doses between 0 G and **1 GGy**

Strategy of the optimization for radiation hardness:

- Measure parameter using test structures
- Simulate impact on sensors
- Verify simulations with measurements on sensors
- Use simulations to optimize the sensor design

(an infinite loop ?)

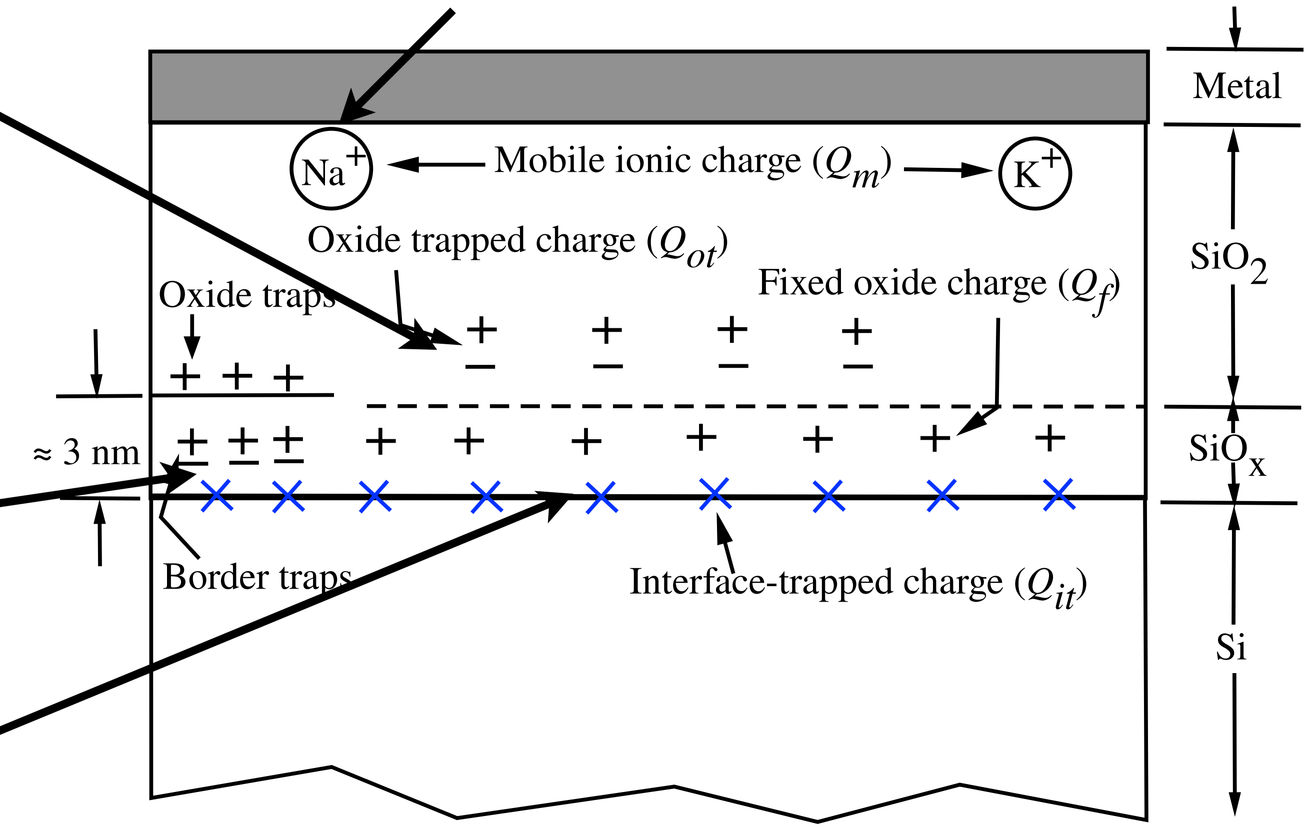


Can such an approach converge?

Oxide charges, interface traps and border traps

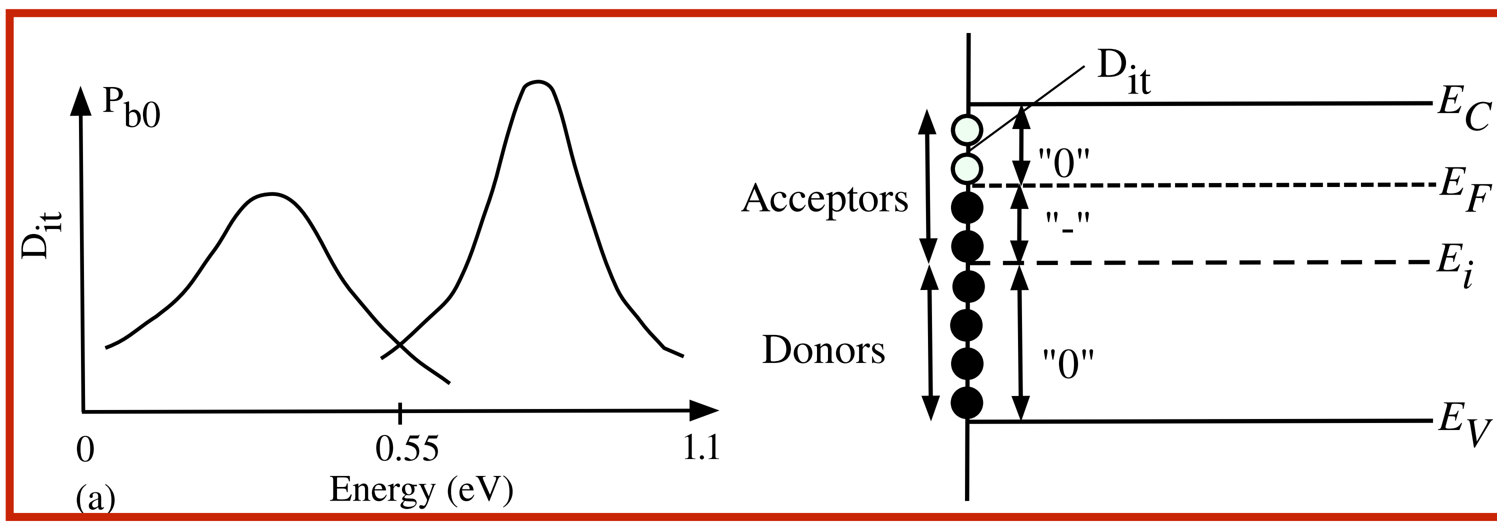
- **Oxide trapped charges (N_{ox}):**
  - Mainly positive oxygen-vacancy defects (one shallow trap → hole transport, + one deep trap E'$_\gamma$ @~3 eV) saturation: h-trapping = eh- recombination

Mobile Ionic Charge: usually not an issue anymore



- **Border traps ("+/-" to N_{ox}):**
  - E'$_\gamma$ defect can exchange
  - charge with Si depending on Fermi-level on time scales > 0.01 s to seconds

- **Interface traps (D_{it}*)):**
  - Traps at interface (no barrier !) dangling bond defects (P_b)
  - No. limited by no. of dangling bonds
  - Charge state dep. on surface potential



*) Distribution of traps in the Si bandgap:
D_{it} [(eV · cm^2)$^{-1}$]

A complex many parameter problem

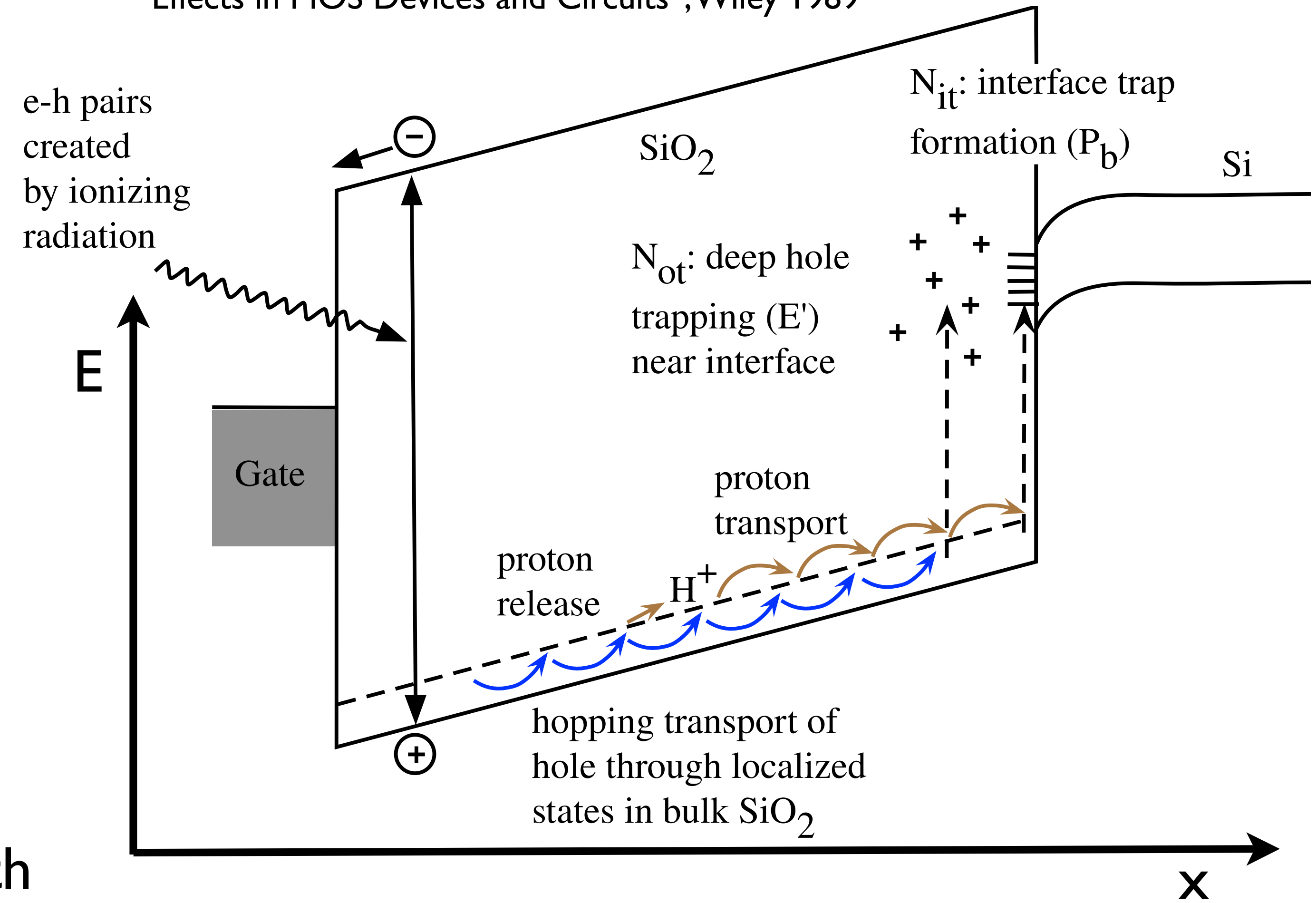
Defects by ionizing radiation

Simplified model of formation:

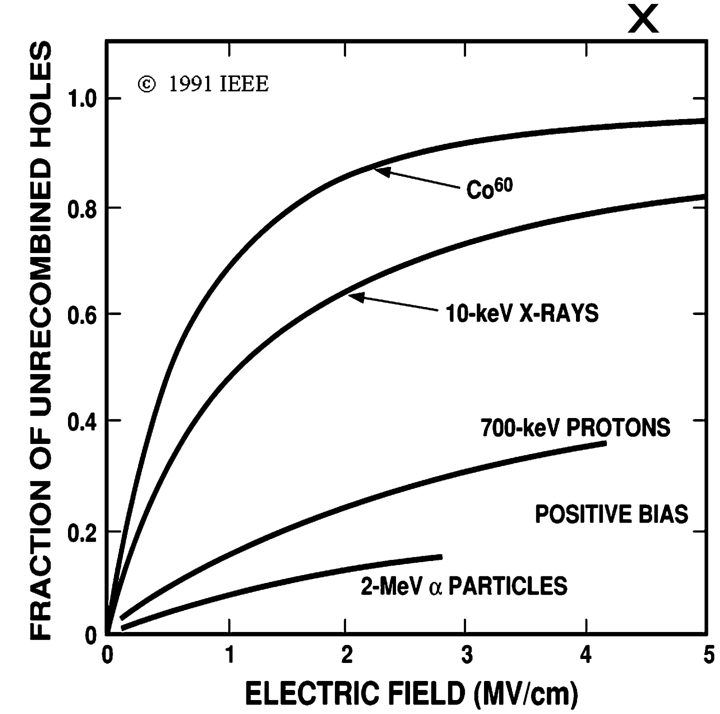
- Ionizing radiation produces electron-hole pairs in SiO_2
- Fraction of electron-hole pairs recombine
- Remaining electrons escape from SiO_2 [$\mu_e \sim 20\ cm^2/(V\bullet s)$]
- Remaining holes will move toward the Si-SiO_2 interface [$\mu_h \leq 5\bullet 10^{-5}\ cm^2/(V\bullet s)$]

1. Oxide trapped charges: N_{ox}
2. Interface traps: $D_{it}(E)$
   ➡ Surface current

from T.P. Ma and Paul V. Dressendorfer, „Ionizing Radiation Effects in MOS Devices and Circuits", Wiley 1989



- Details depend on: Oxide thickness, growth and annealing, dose, dose rate, electrical field temperature, crystal orientation
- Also electron can be trapped (cross-section ≈ $10^{-17}\ cm^2$)



For simulations frequently used:

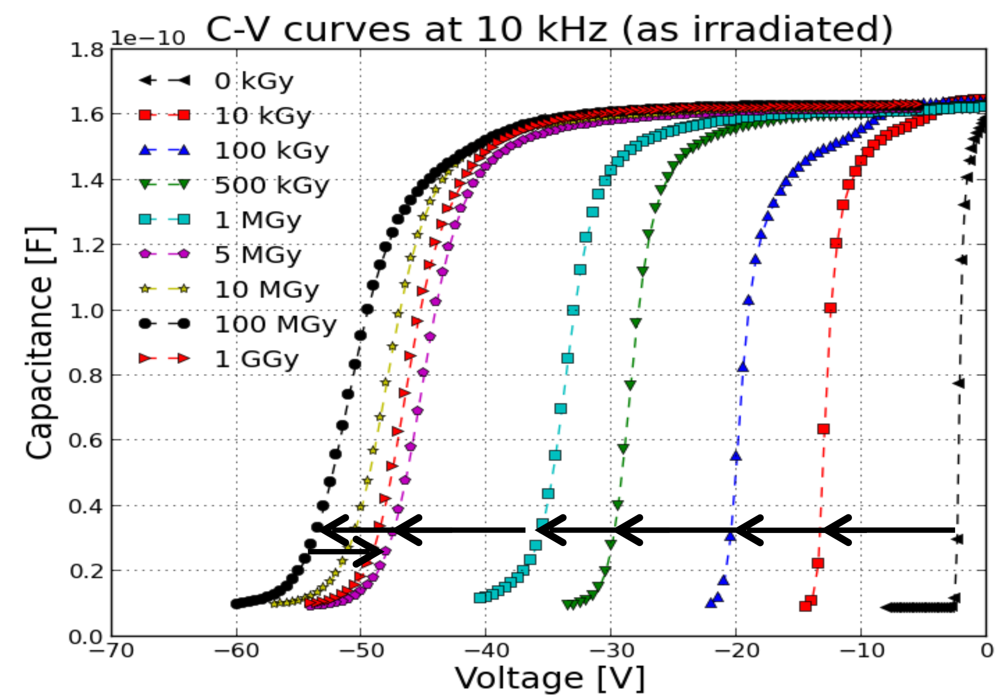
- Position-independent effective oxide charge density N_{ox}^{eff} [cm^{-2}]
- Position-independent surface recombination velocity s_0[cm/s] (or J_{surf} [A/cm^2] where Si-SiO_2 interface is depleted)

Measurement: Oxide-charge density (N_{ox})

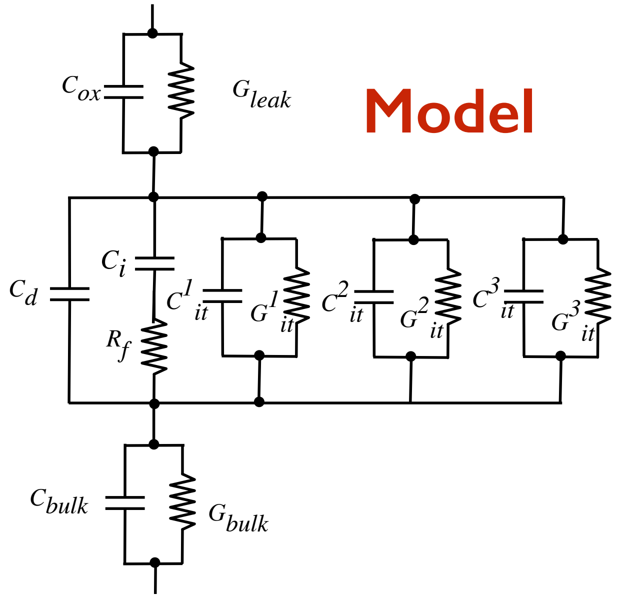
C/G-V+TDRC for MOS-C (from 4 vendors, <100> and <111>, surface damage by X-rays (0 - 1 GGy), no E-field)

How to obtain reproducible results ?
(1) Annealing at 80°C for 10 min
(2) Stop voltage scan before strong inversion

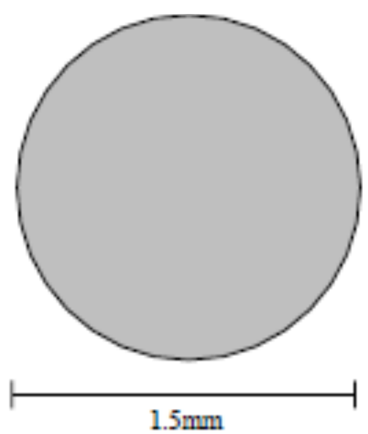
Analysis method:
- TDRC spectra → N_{it}^{i}
- Electric model → shape C/G (V,f)
- Shift along voltage axis → N_{ox}

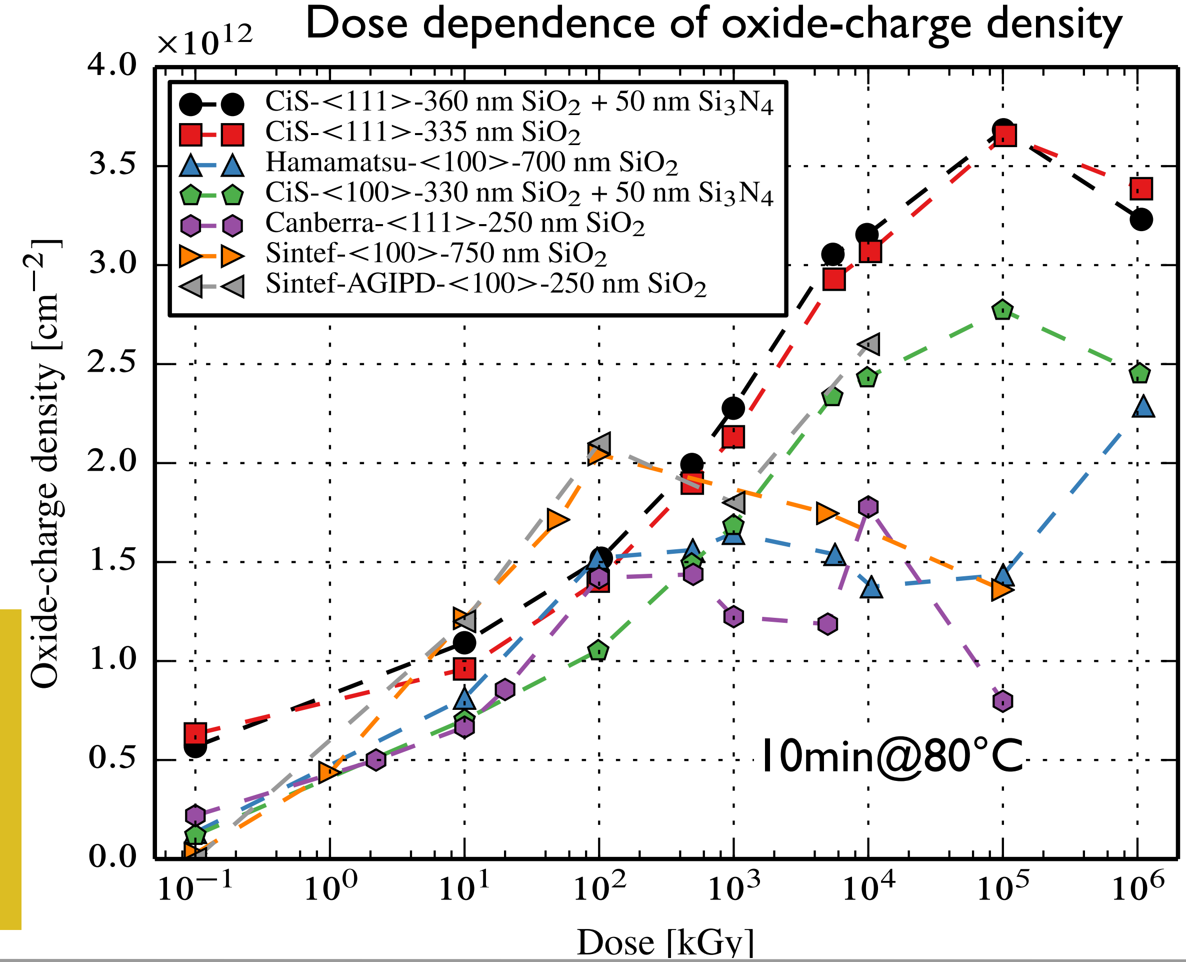


Model



MOS Capacitor

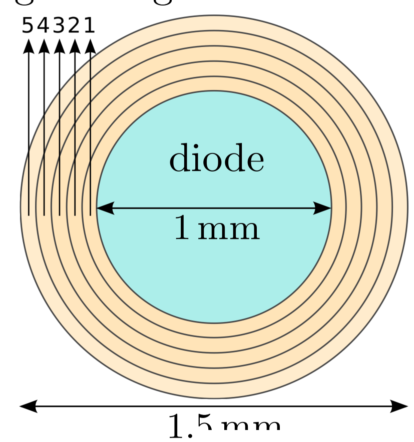




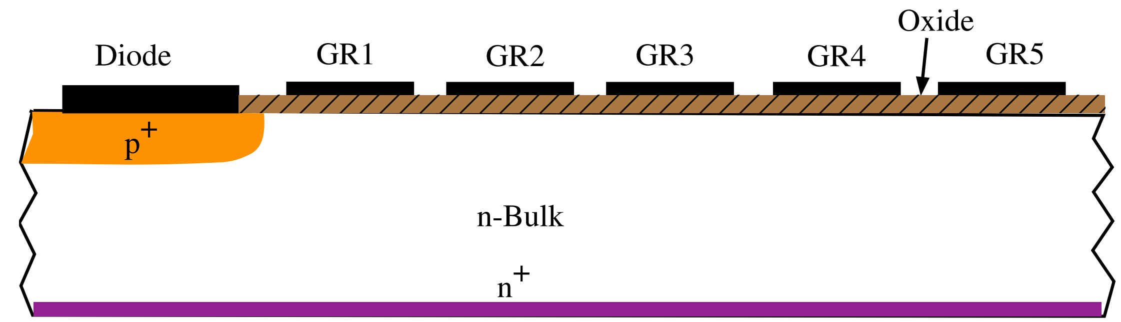
- X-ray radiation damage of N_{ox} saturates at high dose
- 0 Gy: N_{ox} for <111> » than for <100>
  higher dose values: difference is getting smaller
- For different vendors the values are within a factor ±2

Measurement: Surface-current (J_{surf})

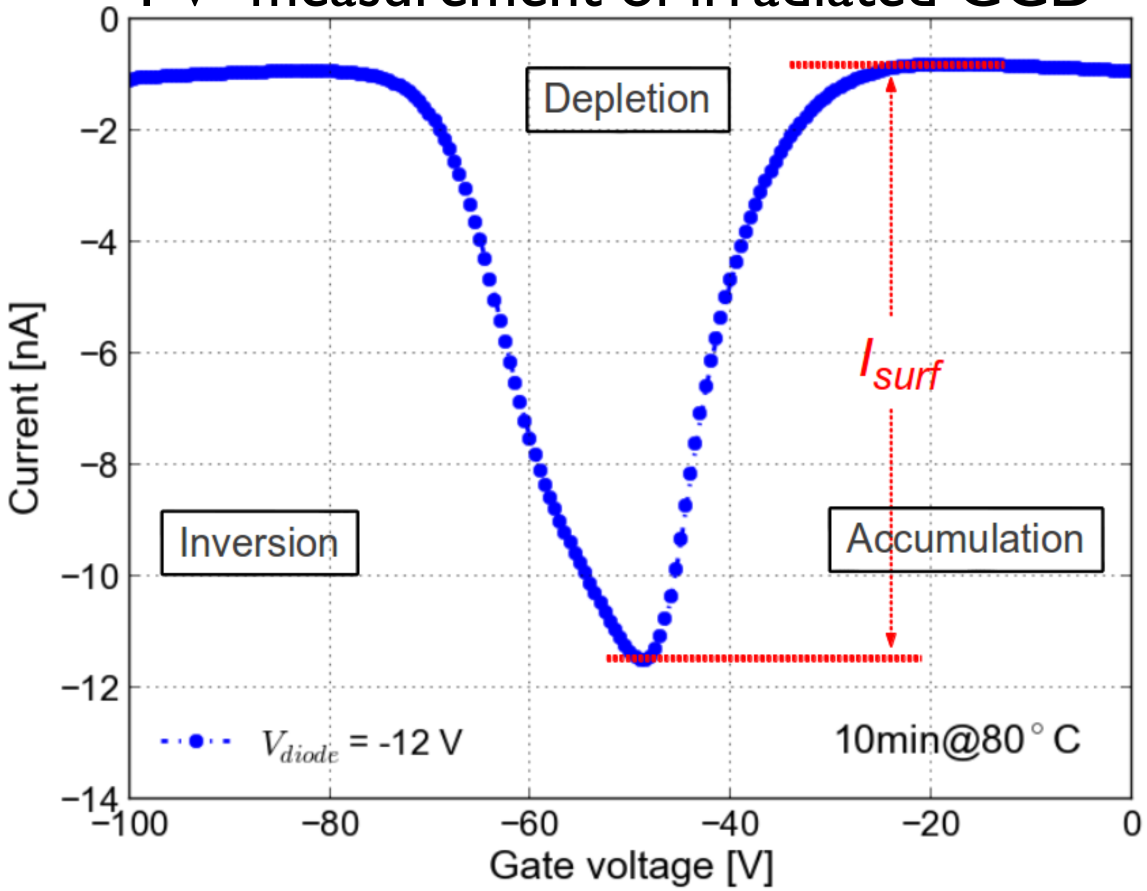
I-V for Gate Controlled diodes (GCD) (from 4 vendors, <100> and <111>, surface damage by X-rays (0 - 1 GGy), no E-field)



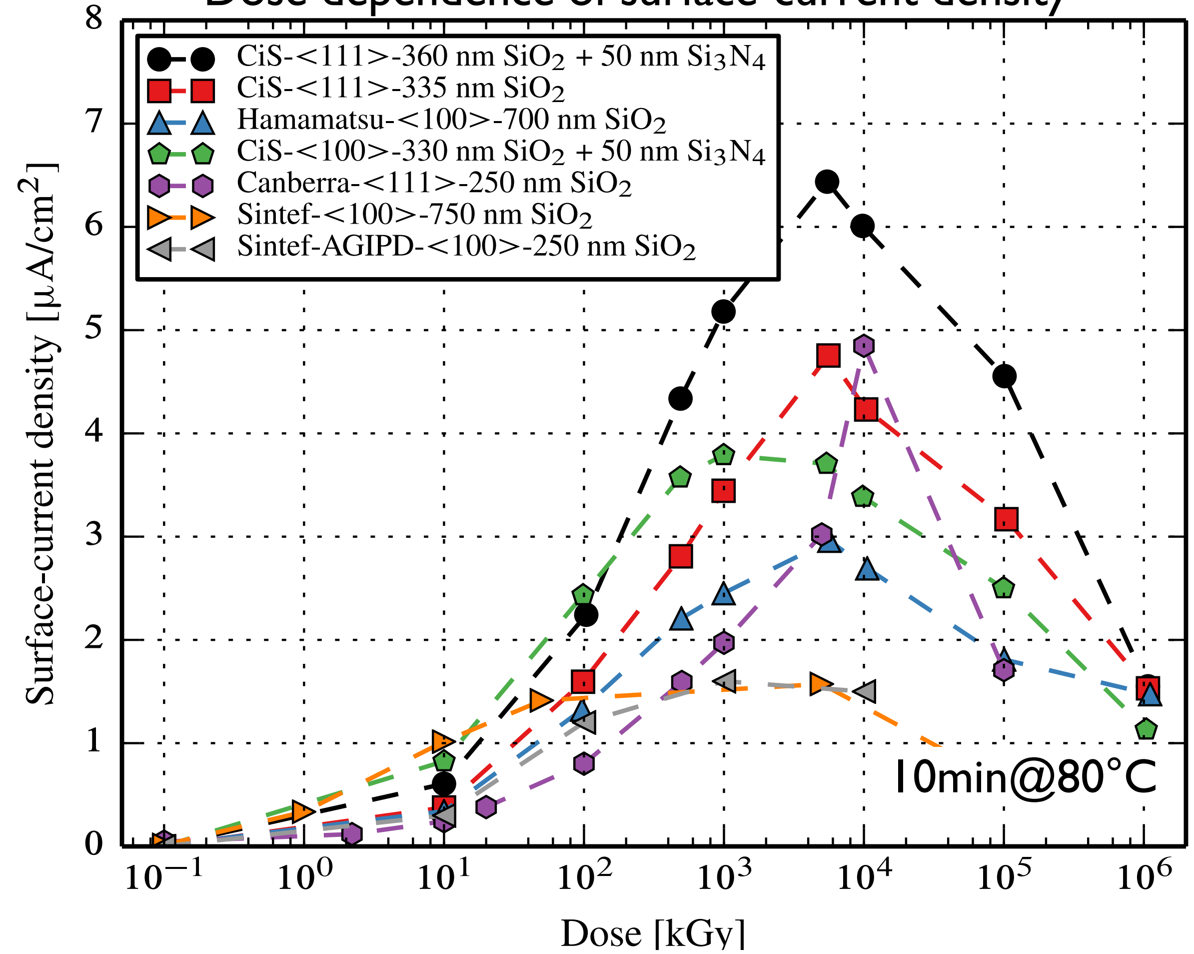
Gate controlled diode „GCD“



I-V measurement of irradiated GCD



Dose dependence of surface-current density

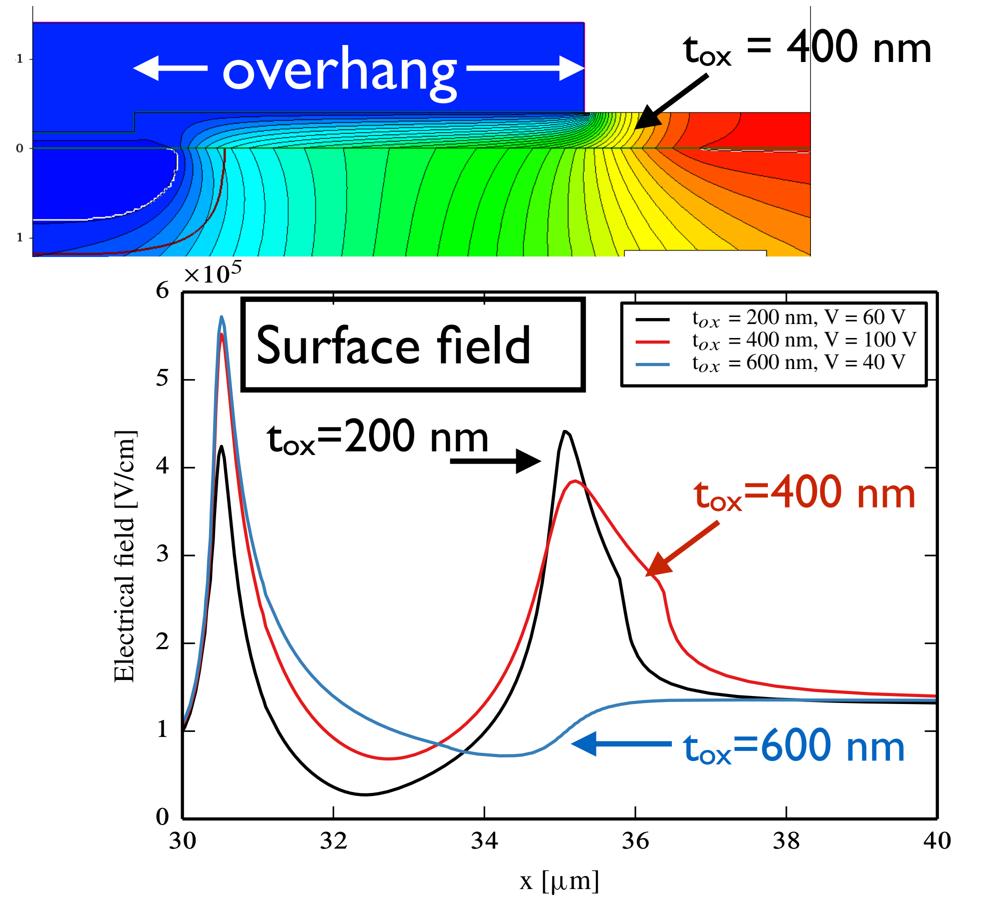


Surface-current densities peaks at 1- 10 MGy and then decrease
(max. value: J_{surf} = 1.5 - 6 µA/cm²)

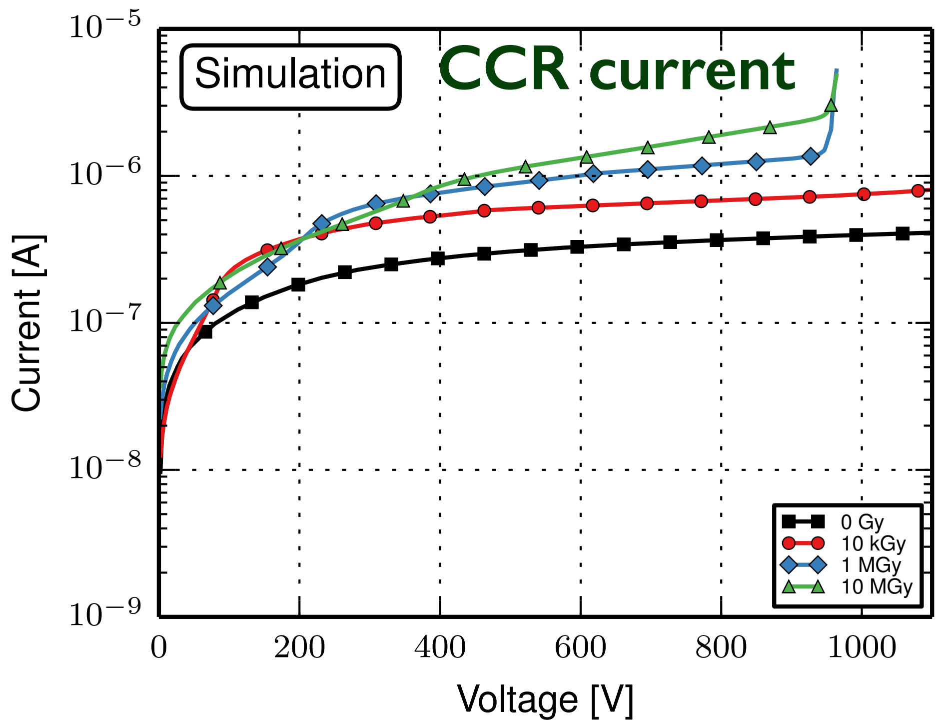
AGIPD guard ring optimization

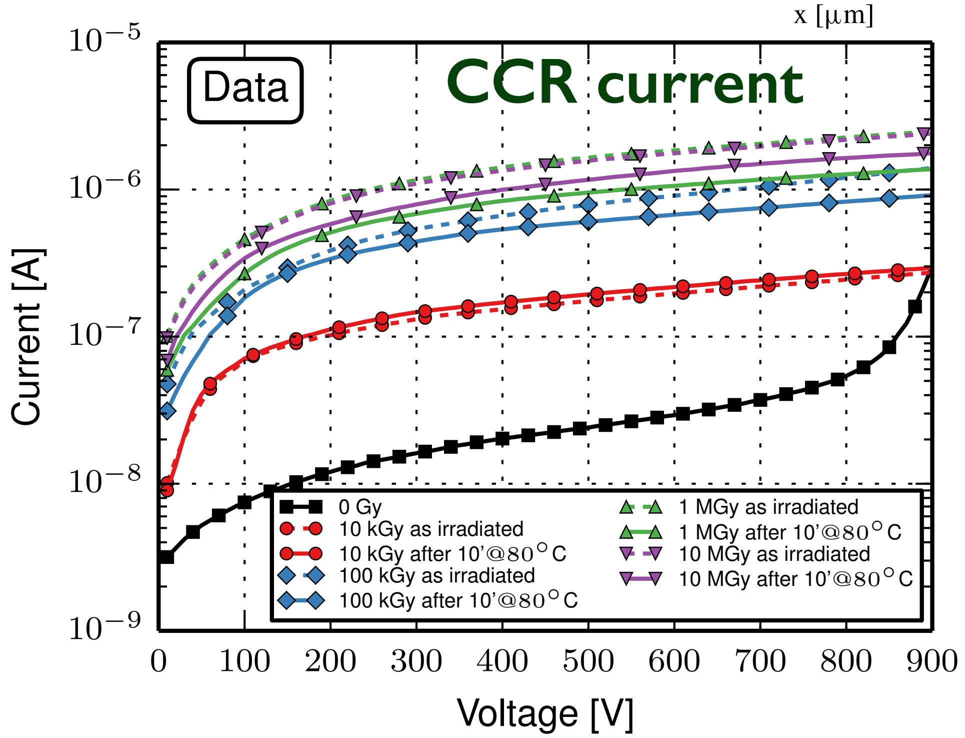
Strategy of guard-ring (GR) optimization:

- Use measured N_{ox} and s_0
- Study breakdown behavior of 0 GR (CCR only) as function of junction depth, oxide thickness and Al overhang
- Estimate number of floating GRs for 1000 V
- Vary spacing between rings, implant width and overhang to achieve maximum V_{bd}
  →max E-field between individual GRs the same
- Minimize space



Optimized GR design:





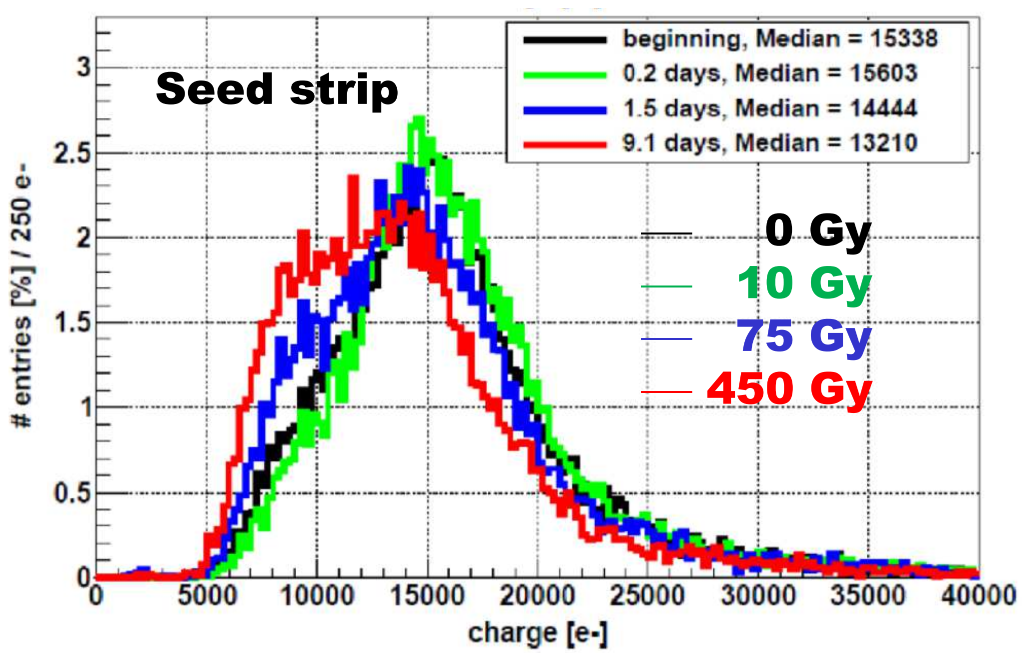
Radiation hard design needs dedicated optimization based on proper simulation

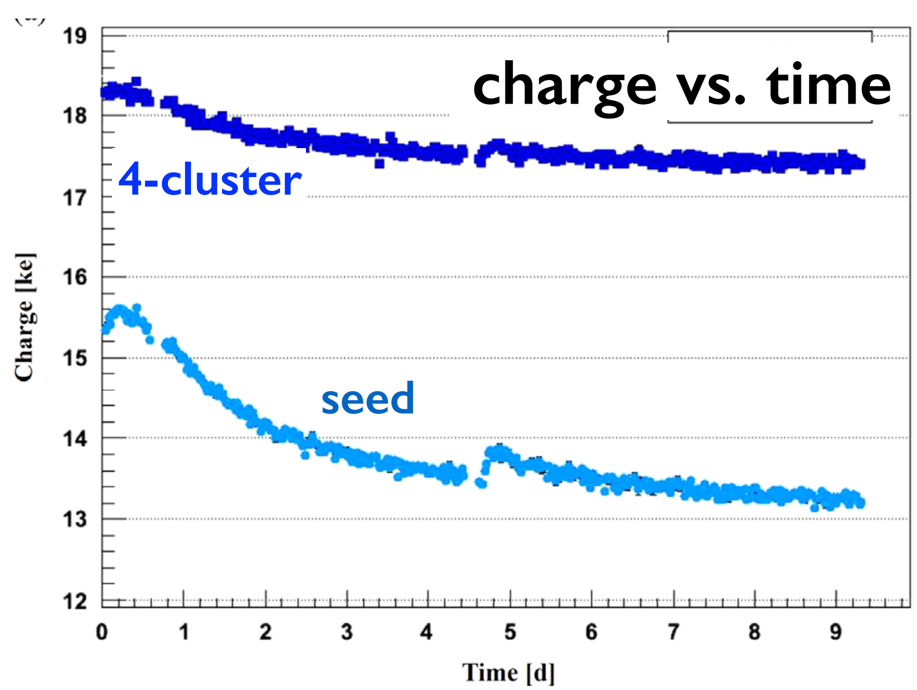
Boundary conditions + humidity effects

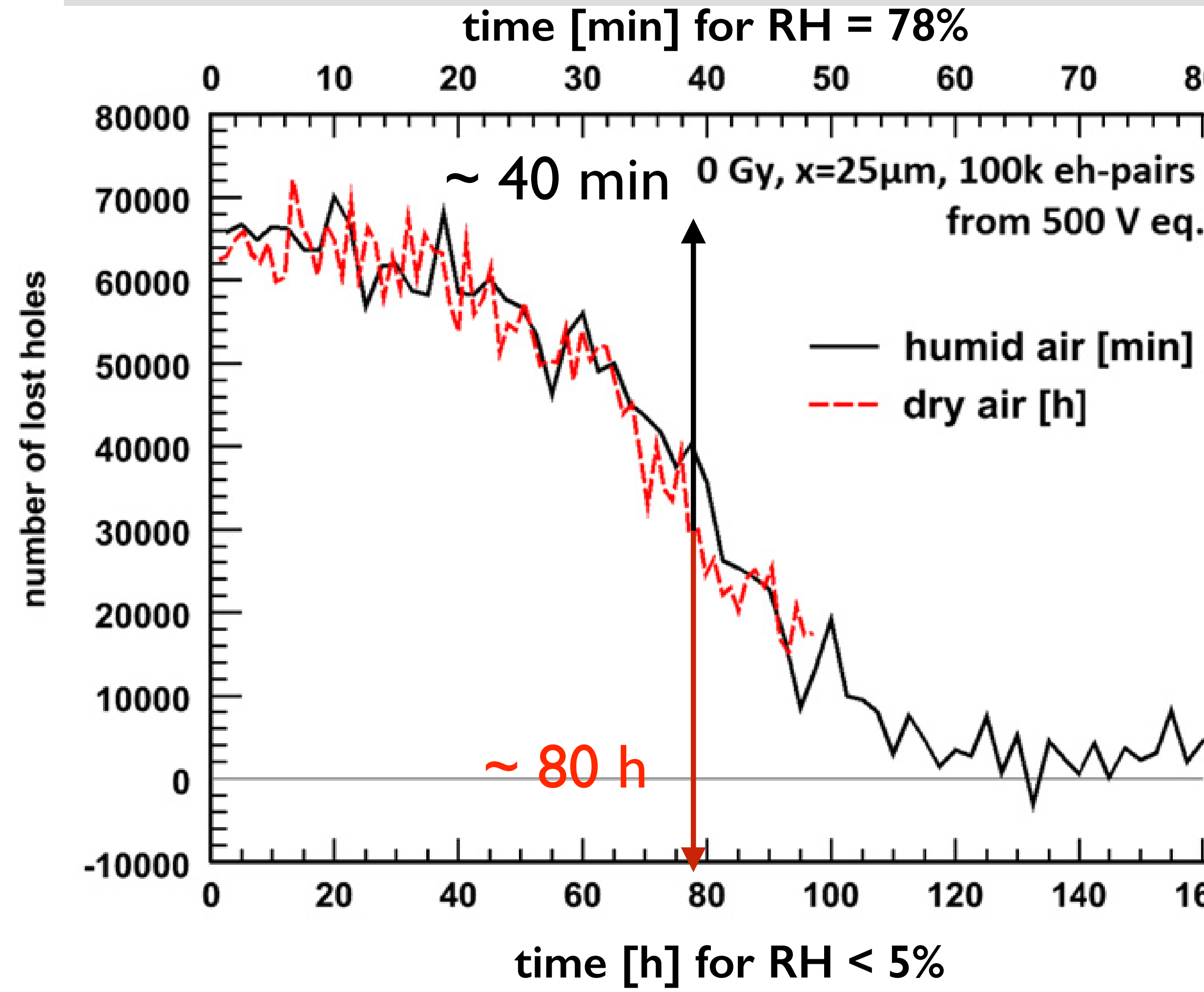
- **Charge collection** of a HPK n⁺-p strip sensor is **sensitive** to doses of a few tens of Gy from a ^{90}Sr β-source

- **Hole losses** vs. time after changing bias voltage from 500 V to 200 V of a HPK p⁺-n strip sensor (670nm laser)

R. Klanner et al., POS(TIPP2014)040







(T. Pöhlsen, DESY-THESIS-2013-025)

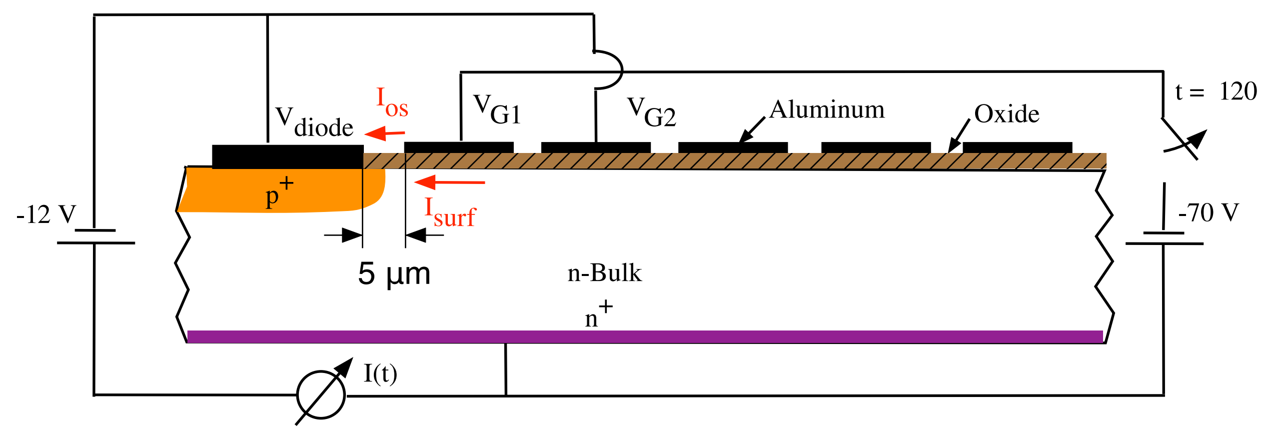
Steps for understanding

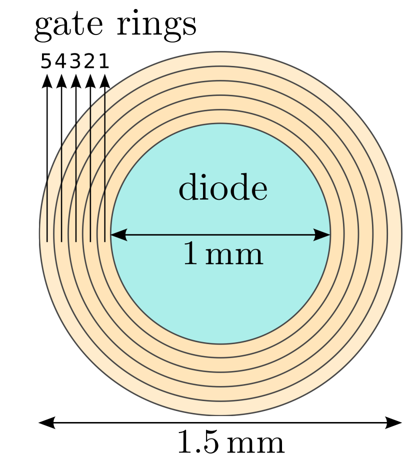
- Measurement of R_{sq} for different humidities using test structures
- TCAD simulation with proper implementation of boundary conditions

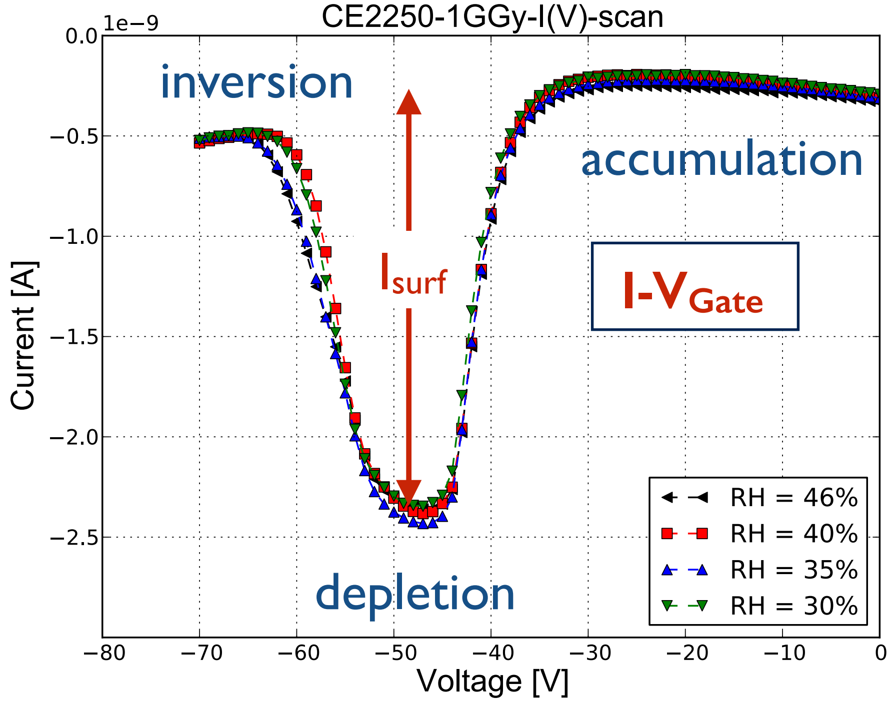
Outer surface charges and resistivity R_{sq}

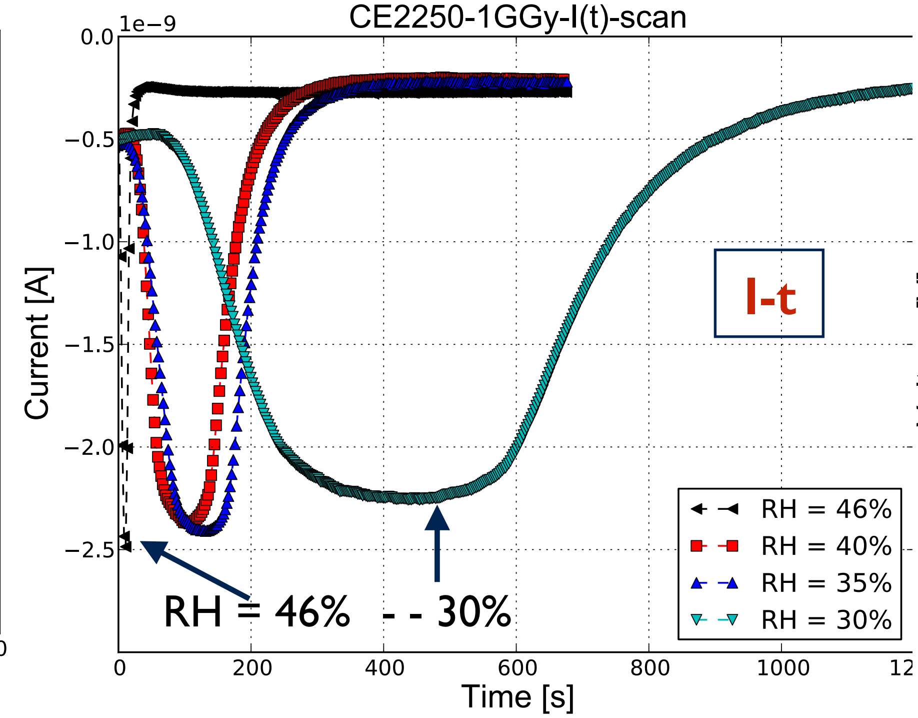
Measurement of $R_{\square}$ over 5 µm SiO_2 by Si-SiO_2 interface current in GCD

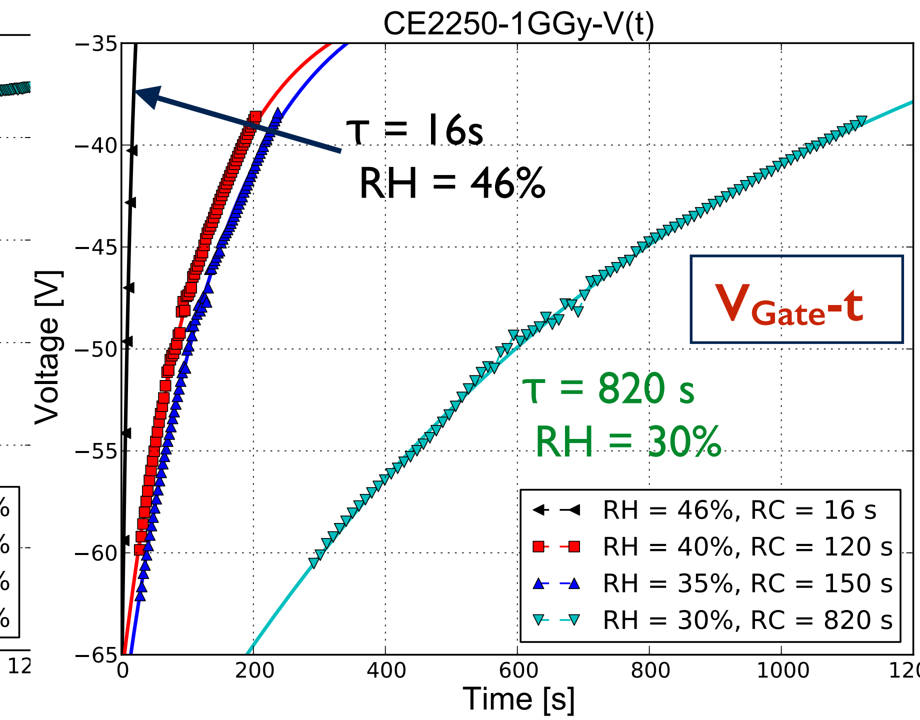
Biasing scheme for GCD (Gate Controlled Diode)











Relative humidity *RH* [%]	30	35	40	46
Discharge time [s]	820	150	120	16
R_{surf} [10^{12} Ω]	50	9.1	7.3	0.97
R_{sq} [10^{15} Ω]	66	12	9.7	1.3

Time constants change by factor 50 for RH 46% → 30%
R_{sq} ~10^{17}Ω @ RH = 30%
(difficult to measure for lower RH!)

N.B. Measurement of R_{sq} with MOSFET Floating Gate Technique are also possible

Outer surface charges and resistivity R_{sq}

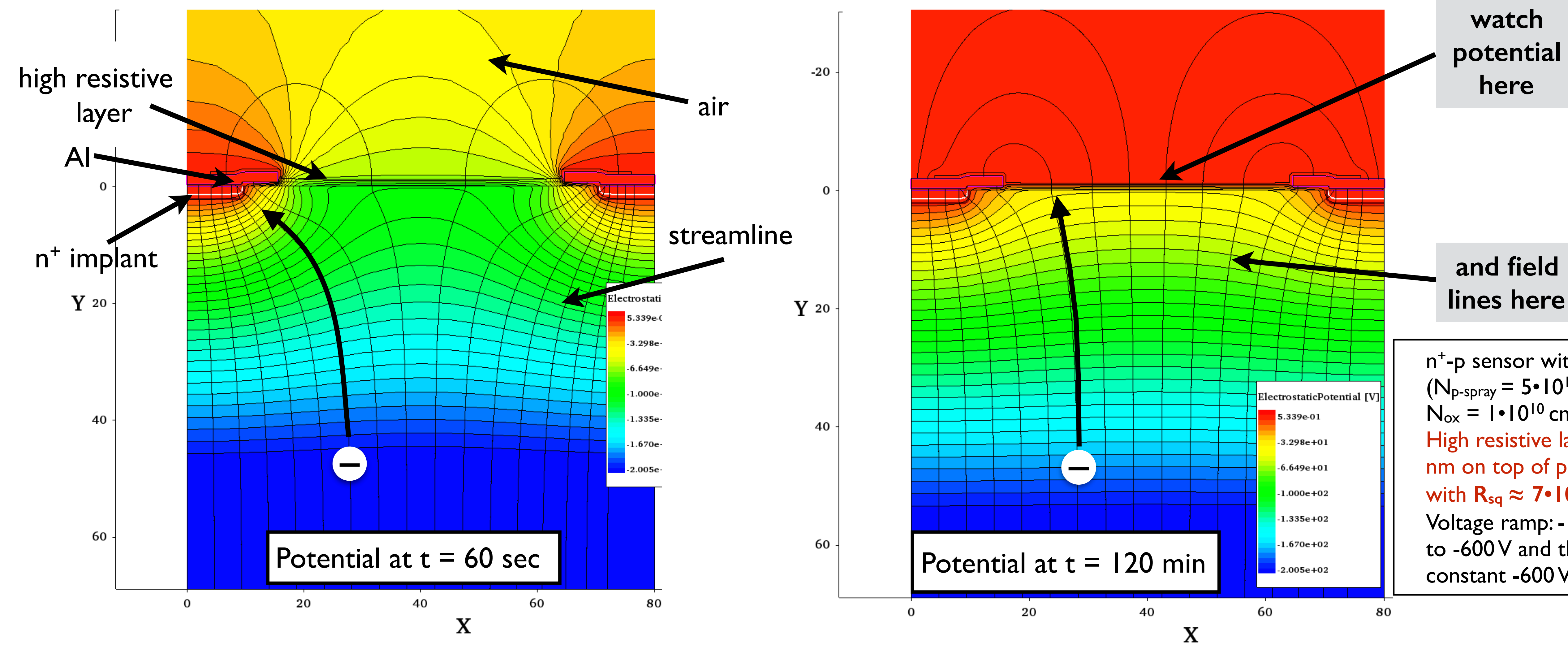
Explanation of long-term changes (w.o. radiation damage)*):

Biasing → longitudinal E-field component on o.s. → rearrangement of Q_{os} until $E_{long} = 0$ and V_{os} = const → time constant depends R_{sq}, which changes by many orders of magnitude with humidity (and T)

*) already discussed by A.Longoni et al., NIM-A288(1990)35

Simulation of boundary conditions:

- Outer surface layer with high resistivity for time dependence



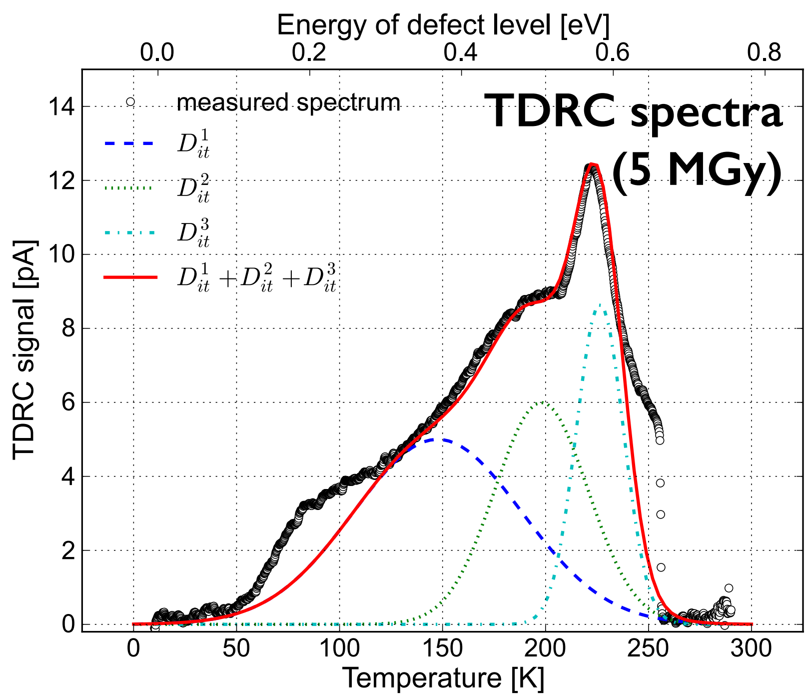
n+-p sensor with p-spray ($N_{p\text{-}spray} = 5{\bullet}10^{11}$ cm^{-2}), $N_{ox} = 1{\bullet}10^{10}$ cm^{-2}
High resistive layer of 10 nm on top of passivation with $R_{sq} \approx 7{\bullet}10^{14}\ \Omega$
Voltage ramp: -10 V/s up to -600 V and than constant -600 V

Changes of potential leads to different charge collection

What is missing - under study

Accurate determination of D_{it} from MOS-C:

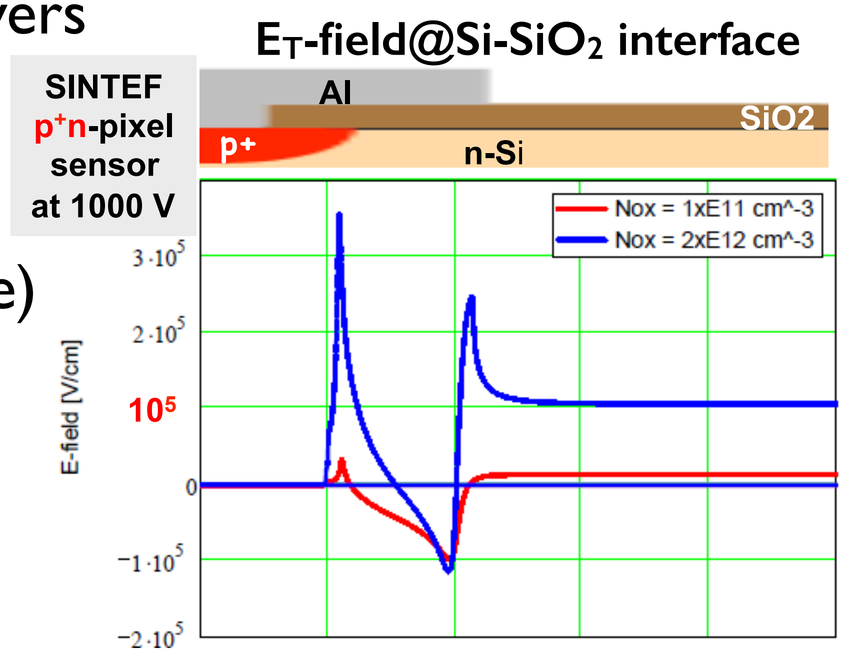
- Interface traps are continuously distr. in energy
- High-ohmic substrate + irradiation
  → Standards methods are not applicable
- TDRC spectra difficult to interpret
- Further investigations are required



So far assumed that N_{ox} is independent of E-field during irradiation or biasing condition

➡ Crude approximation because
  1) N_{ox} depends on E-field
  2) Charge of interface traps depends on surface potential
  3) Surface currents depends on presence/absences of charge layers
  4) Charging up oxide during irradiation (ignored)

➡ Needed for understanding of sensor performance:
  - Irradiation under bias (i.e. different E-fields at Si-SiO$_2$ interface)
  - Parameters during and shortly after irradiations under bias
  - Annealing



Relevant E-field from simulation of sensors 3 nm from SiO$_2$

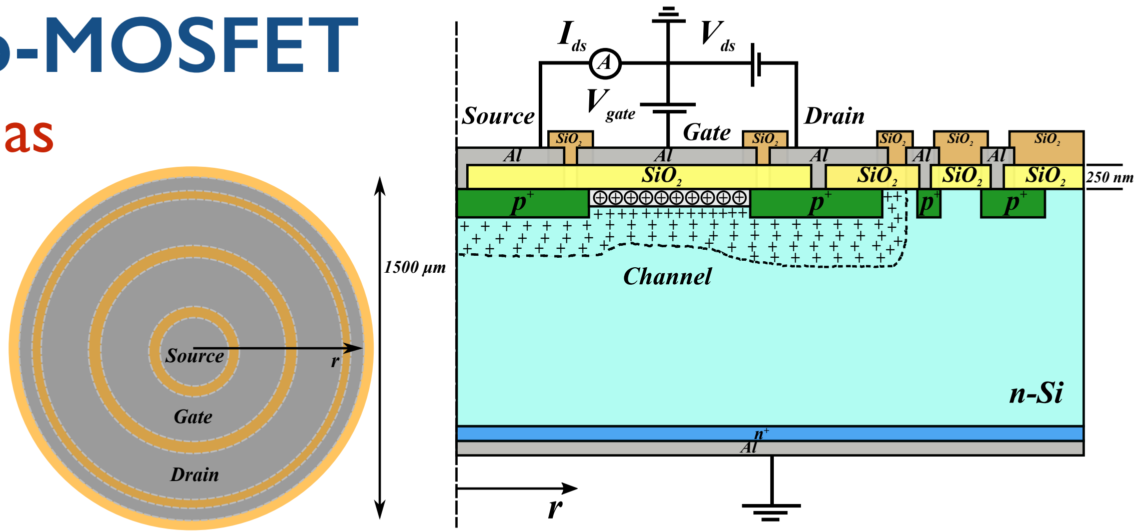
➡ local transverse fields up to ~300 kV/cm with both directions

Field-enhanced N_{ox}^{eff} before/during/after irradiation

Experimental investigation using n- and p-MOSFET

➡ Allows to study of oxide **during irradiation with bias**

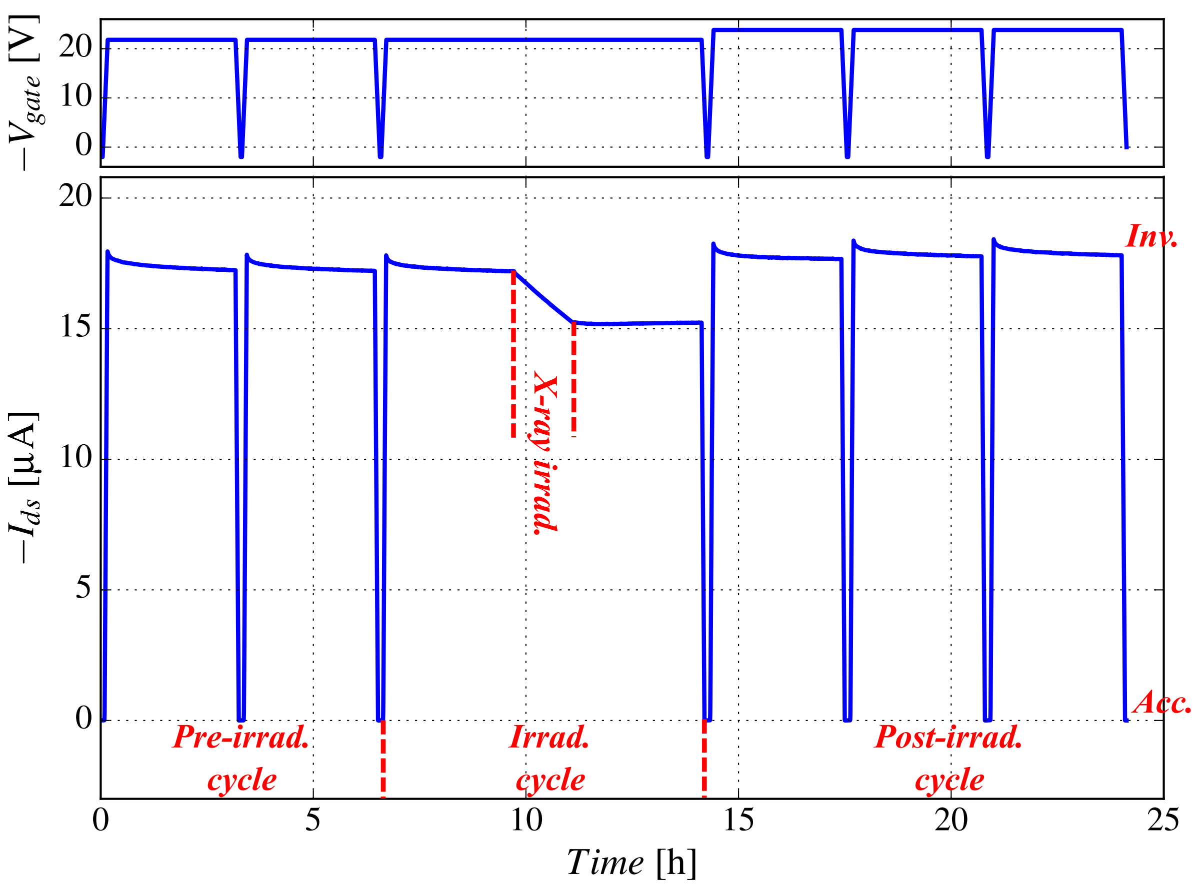
$$I_{ds} = \frac{\mu_0^p}{1 + (V_{gate} - V_{th})/V_{1/2}} C_{ox} \frac{W}{L} V_{ds} (V_{gate} - V_{th})$$

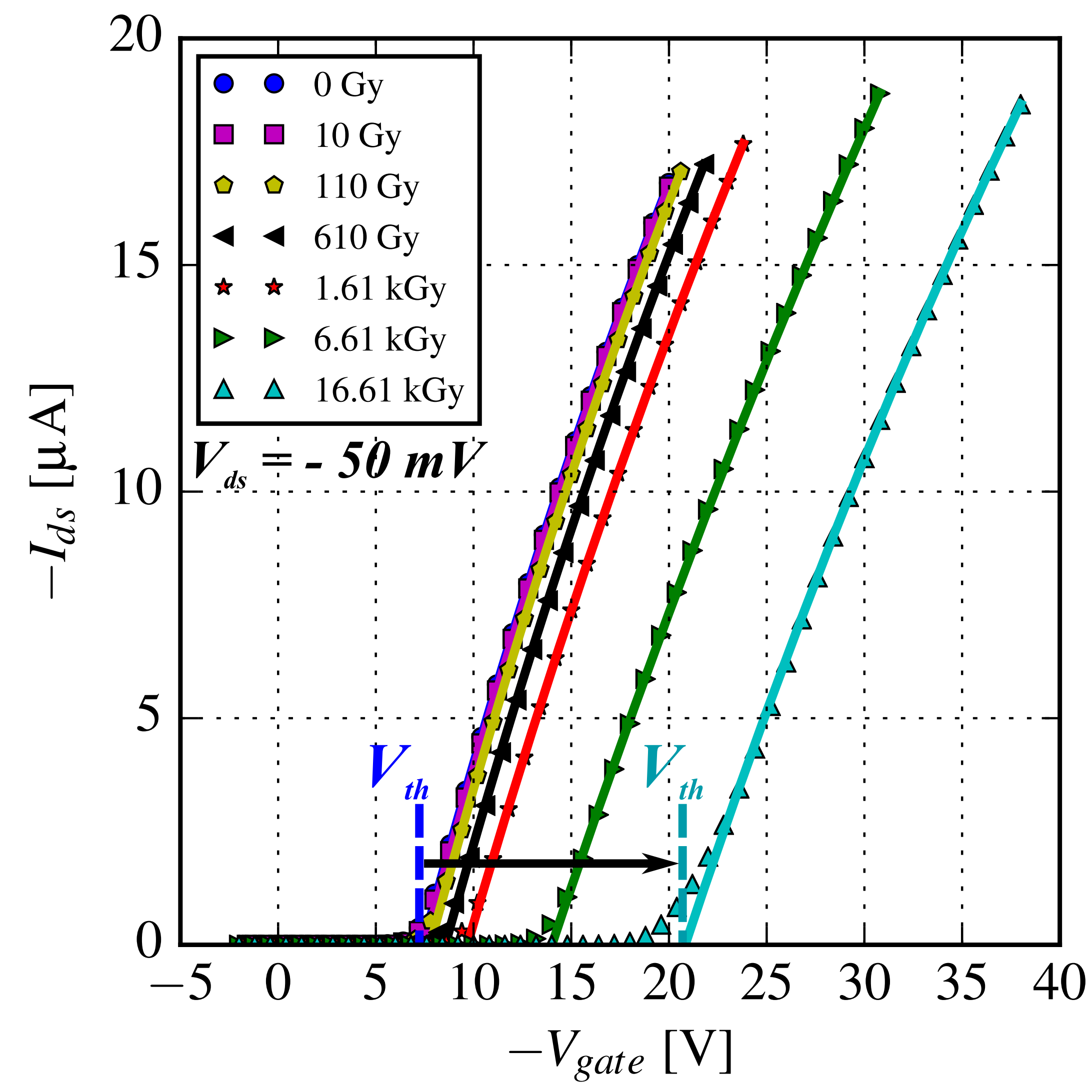


1. Calibrate $I_{DS}(V_{gate})$ for const. V_{DS}
2. Fix V_{gate} and measure $I_{DS}(t)$ and calculate $V_{th}(t)$
3. Calculate $N_{ox}(t)$ from $V_{th}(t)$

Difficulty: $\mu_0(N_{ox})$ and $V_{1/2}(N_{ox})$

(→ several calibrations before/after irr.)



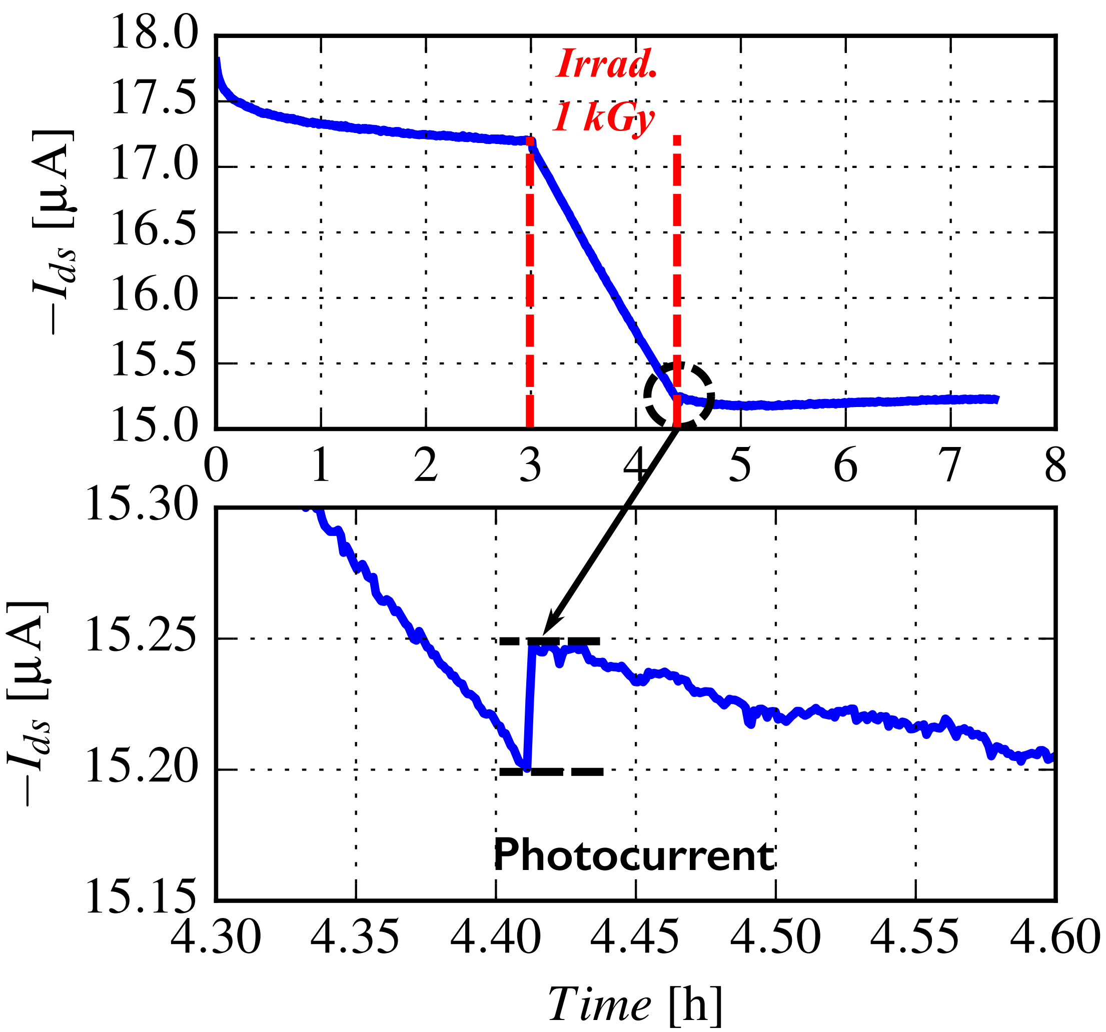


Field-enhanced N_{ox}^{eff} before/during/after irradiation

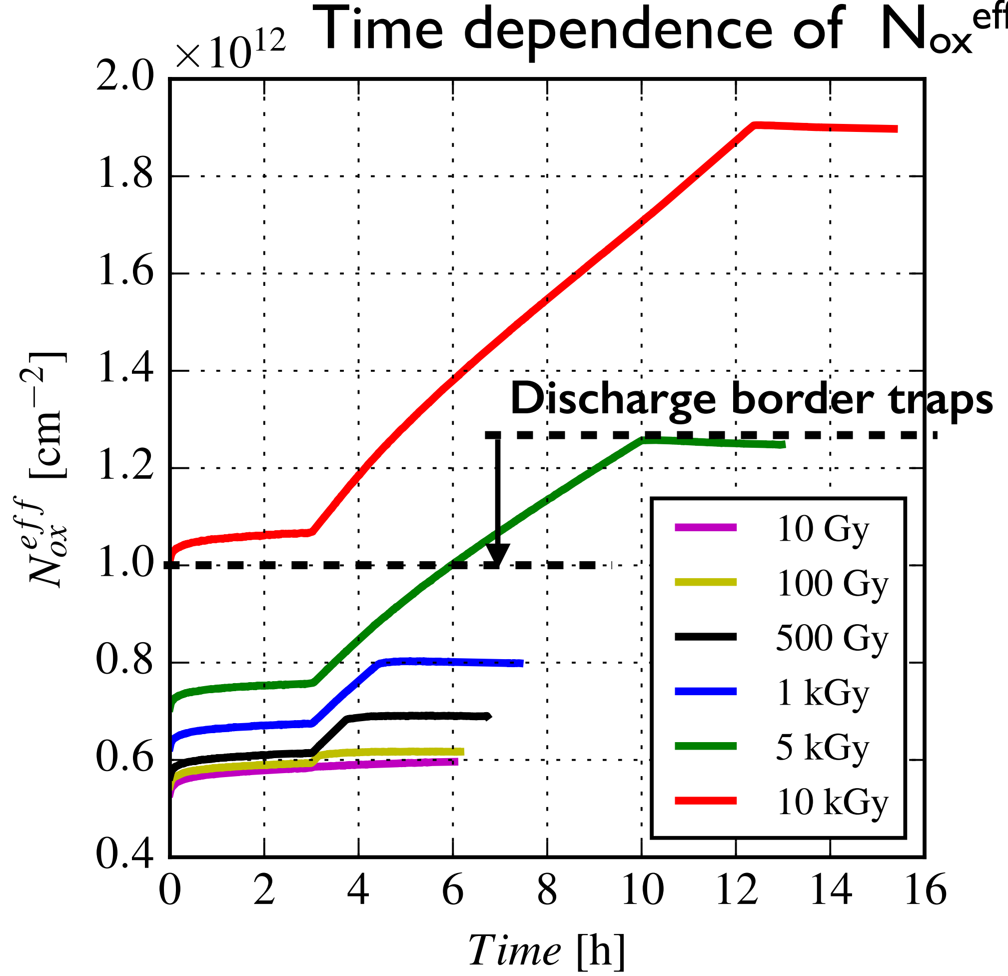
X-ray irradiations of p-MOSFET:

- ΔDose = 10, 100, 500 Gy, 1, 5, 10 kGy
- MOSFET Canberra 250 nm SiO_2, <111>, n-type $6 \cdot 10^{11}$ cm^{-3}

Example: ΔDose=1 kGy irradiation for E ≈ 500 kV/cm



Time dependence of N_{ox}^{eff}



- E-field does not cause anomalous short-term effects during or after irradiation
- observe charging and „de-charging" of border traps
- attempts to determine D_{it} using sub-threshold current (complementary to MOS-C)

➡ data available to put into simulation and study effects on sensors

Conclusions

1. Proper simulations of surface effects are complex and require a systematic approach
   - Parameter extraction on test structures
   - Simulate sensors + optimize
   - Verify simulations by measurements

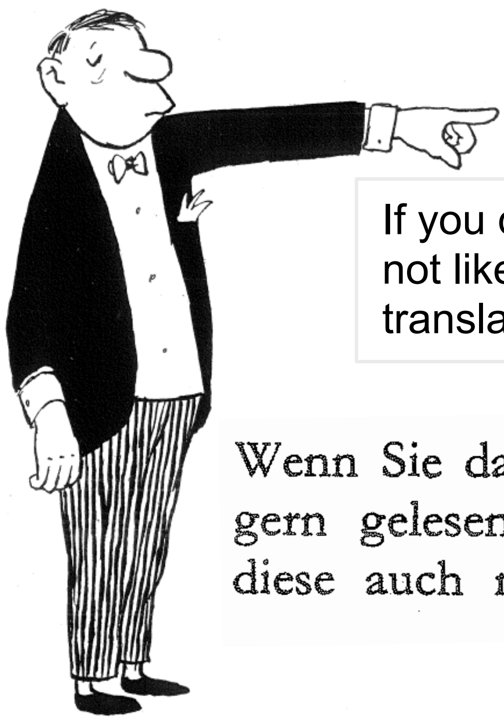
2. Methods for determination of parameters relevant for simulation of surface effects have been established, some data are available and further data are acquired

3. Methods of implementing proper boundary conditions and implementation of surface effects in TCAD have been established

4. Successful optimization + understanding of surprises have been demonstrated

Thank you for your attention!!!

References to work from UHH-Group



If you did not like this talk, you will also not like the following publications (free translation from V. von Bülow "Loriot")

Wenn Sie das vorliegende Buch ungern gelesen haben, werden Ihnen diese auch nicht so recht gefallen.

V. von Bülow "Loriot"

Low-dose effects in segmented Si sensors:

C. Henkel, Impact of low dose-rate electron irradiation on the charge collection of n^+p silicon strip sensors, BSC thesis, University of Hamburg, March 2014, unpublished

J. Erfle, Irradiation study of different silicon materials for the CMS tracker upgrade, PhD thesis, University of Hamburg, DESY-THESIS-2014-010

R. Klanner et al., Impact of low-dose electron irradiation on n+p silicon strip sensors, POS (TIPP 2014) , detailed paper in preparation

Surface resistivity and border traps:

J. Schwandt et al., Investigation of the insulator layers for segmented silicon sensors before and after X-ray irradiation, Talk presented at the IEEE Nuclear Science Symposium, Seattle 8-15. Nov, 2014

D. Brueske, Investigation of the field dependence of the injection of positive charges into the SiO2 at the Si-SiO2 interface, BSC thesis, University of Hamburg, 2014, unpublished

Charge trapping at the Si-SiO_2 interface - humidity:

T. Poehlsen et al., Study of the accumulation layer and charge losses at the Si–SiO2 interface in p+n-silicon strip sensors, NIM-A 721 (2013) 26; doi: 10.1016/j.nima.2013.04.026

T. Poehlsen et al., Time dependence of charge losses at the Si-SiO2 interface in p+n-silicon strip sensors, NIM-A 731 (2013) 172; doi: 10.1016/j.nima.2013.03.035

T. Poehlsen, Charge Losses in Silicon Sensors and Electric-Field Studies at the Si-SiO2 Interface, PhD thesis, University of Hamburg, DESY-THESIS-2013-025

X-ray radiation damage:

J. Zhang et al., Study of radiation damage induced by 12 keV X-rays in MOS structures built on high-resistivity n-type silicon, J. Synchrotron Rad. 19 (2012) 340; doi: 10.1107/S0909049512002384

R. Klanner et al., Study of high-dose X-ray radiation damage of silicon sensors, NIM-A; 732 (2013) 117, doi: 10.1016/j.numa.2013.05.131

J. Zhang et al., X-ray induced radiation damage in segmented p+n silicon sensors, PoS (Vertex 2012) 019

J. Zhang, X-ray Radiation Damage Studies and Design of a Silicon Pixel Sensor for Science at the XFEL, PhD thesis, University of Hamburg, DESY-THESIS-2013-018 (2013)

Sensor optimization for high X-ray doses:

J. Schwandt et al., Optimization of the radiation hardness of silicon pixel sensors for high x-ray doses using TCAD simulations, 2012 JINST 7 C01006; doi: 10.1088/1748-0221/7/01/C01006

J. Schwandt et al., Design of the AGIPD sensor for the European XFEL, 2013 JINST 8 C01015; doi: 10.1088/1748-0221/8/01/C01015

J. Schwandt et al., Design and First Tests of a Radiation-Hard Pixel Sensor for the European X-Ray Free-Electron Laser, IEEE TNS, doi: 10.1109/RADECS.2013.6937446 and arXiv-140213

J. Schwandt , Design of a radiation hard pixels sensor for X-ray science, PhD thesis, University of Hamburg, DESY-THESIS-2014-029

Backup

Oxide charges N_{ox} + interface traps D_{it}

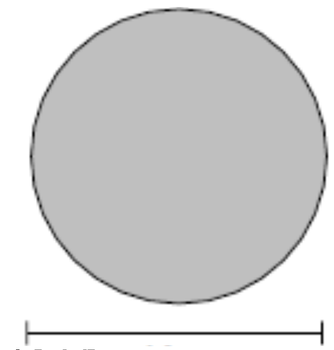
C/G-V+TDRC for MOS-C (from 4 vendors, <100> and <111>, surface damage by X-rays (0 - 1 GGy), no E-field during irradiation, annealing)

How to obtain reproducible results ?

(1) Annealing at 80°C for 10 min

(2) Stop voltage scan before strong in-version → no injection of border traps

MOS Capacitor MOS-C

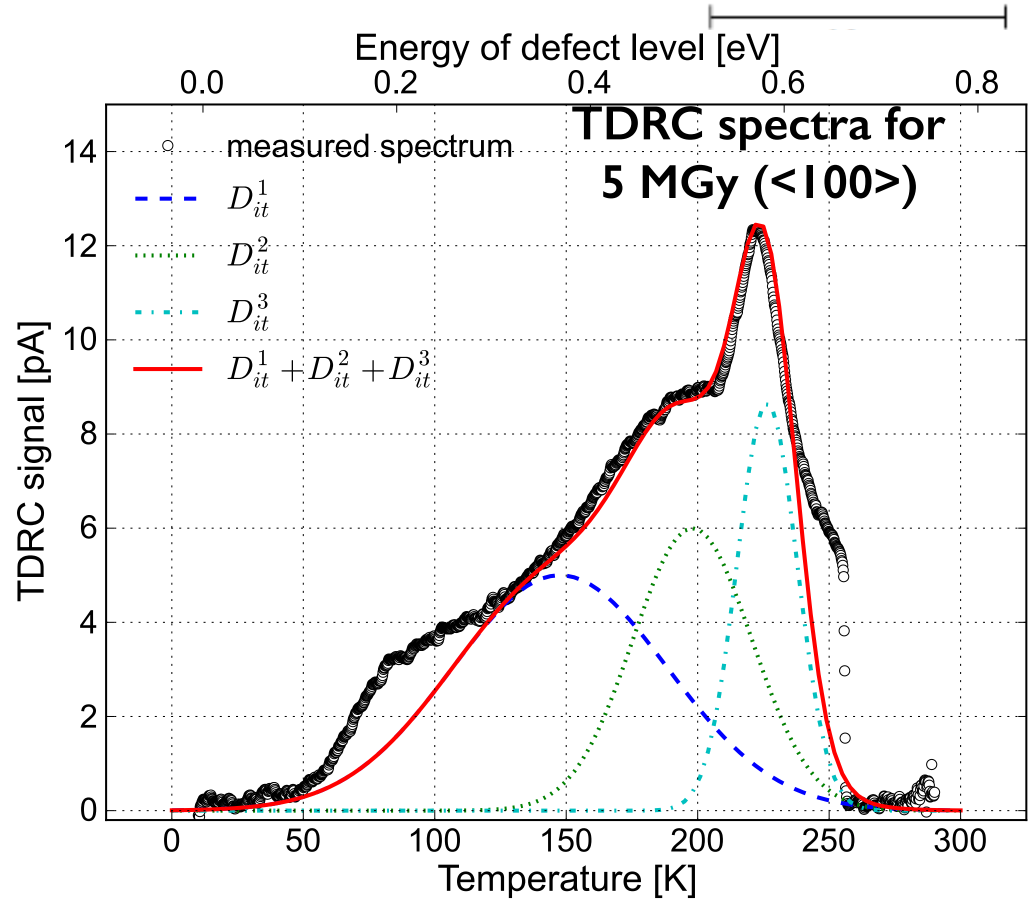


- TDRC: Properties of interface traps (Thermal Dielectric Relaxation Current)
  - Bias MOS-C in e-accumulation
    ➡fill interface traps with electrons
  - Cool to ~10 K
    ➡freeze e in traps
  - Bias to inversion and heat up to 290 K

➡I_{TDRC} due to release of trapped e's

$I_{TDRC}(T)$ → $D_{it}(E)$ *)

➡(Energy levels + widths + densities)$_{it}$

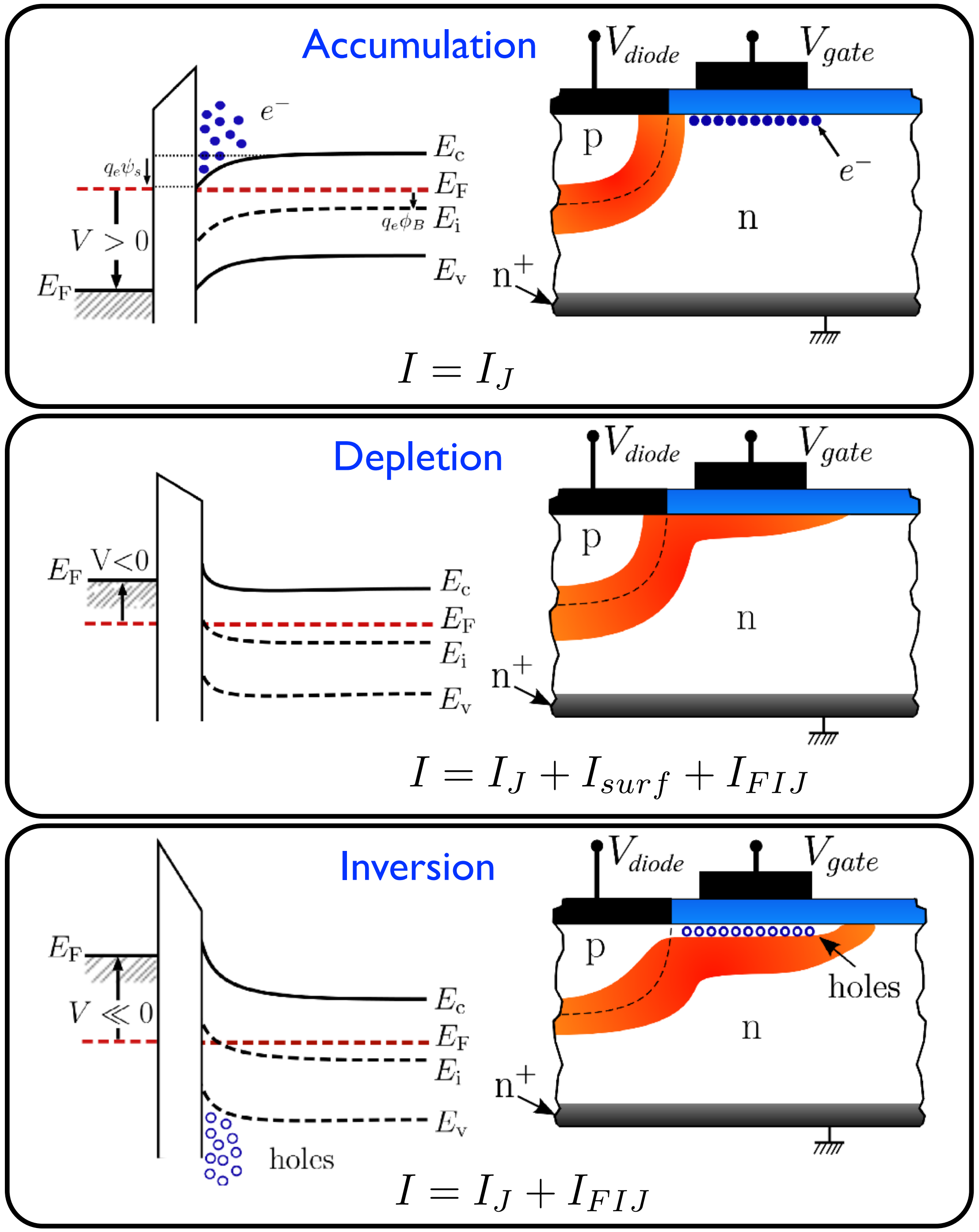


Parameterized by 3 states interpretation not unambiguous !

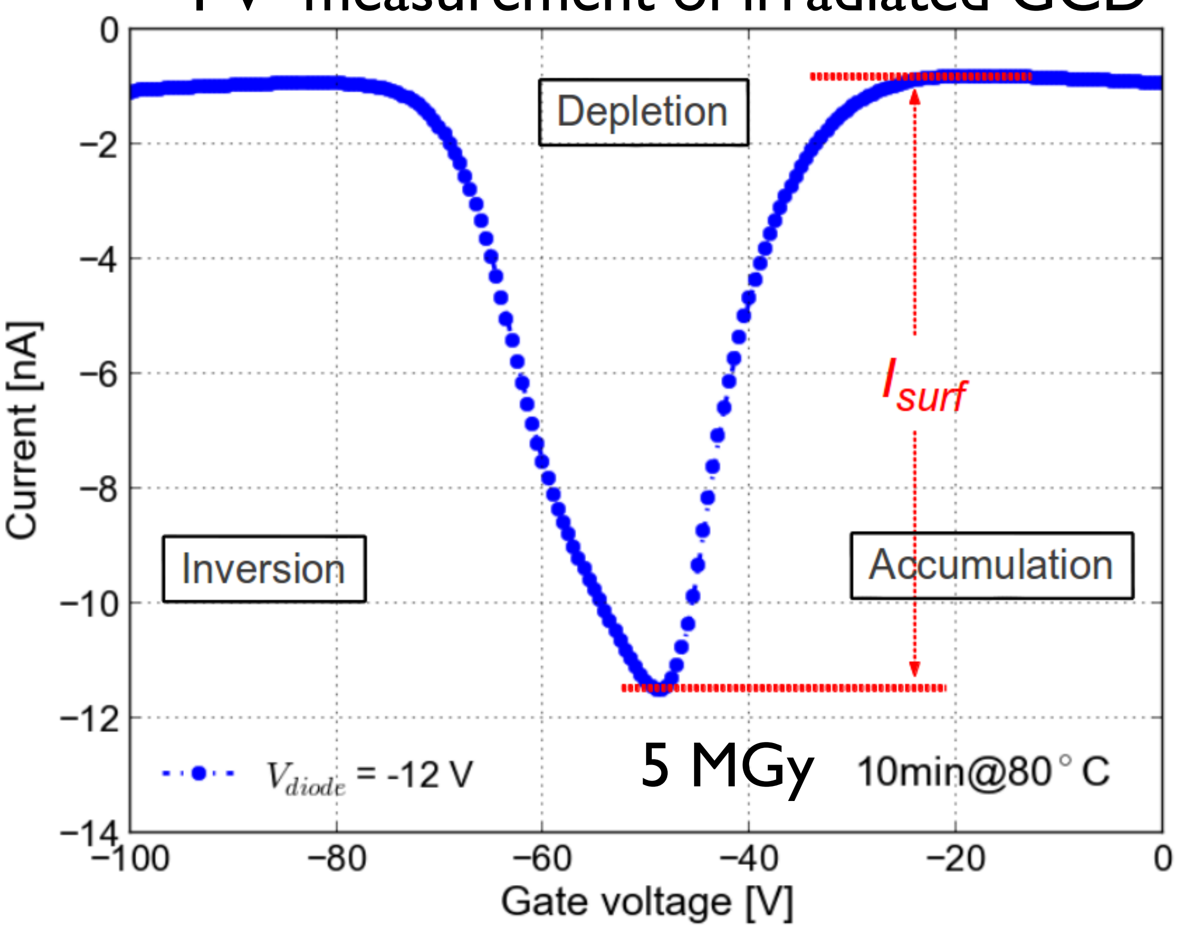
*) Temperature T → $E_c - E_{it}$ (T dependence of Fermi level)

X-Ray damage: J_{surf}

- Surface current density J_{surf} from GCD:
  - Measure I-V curve
  - J_{surf} dominated by mid-gap traps



I-V measurement of irradiated GCD

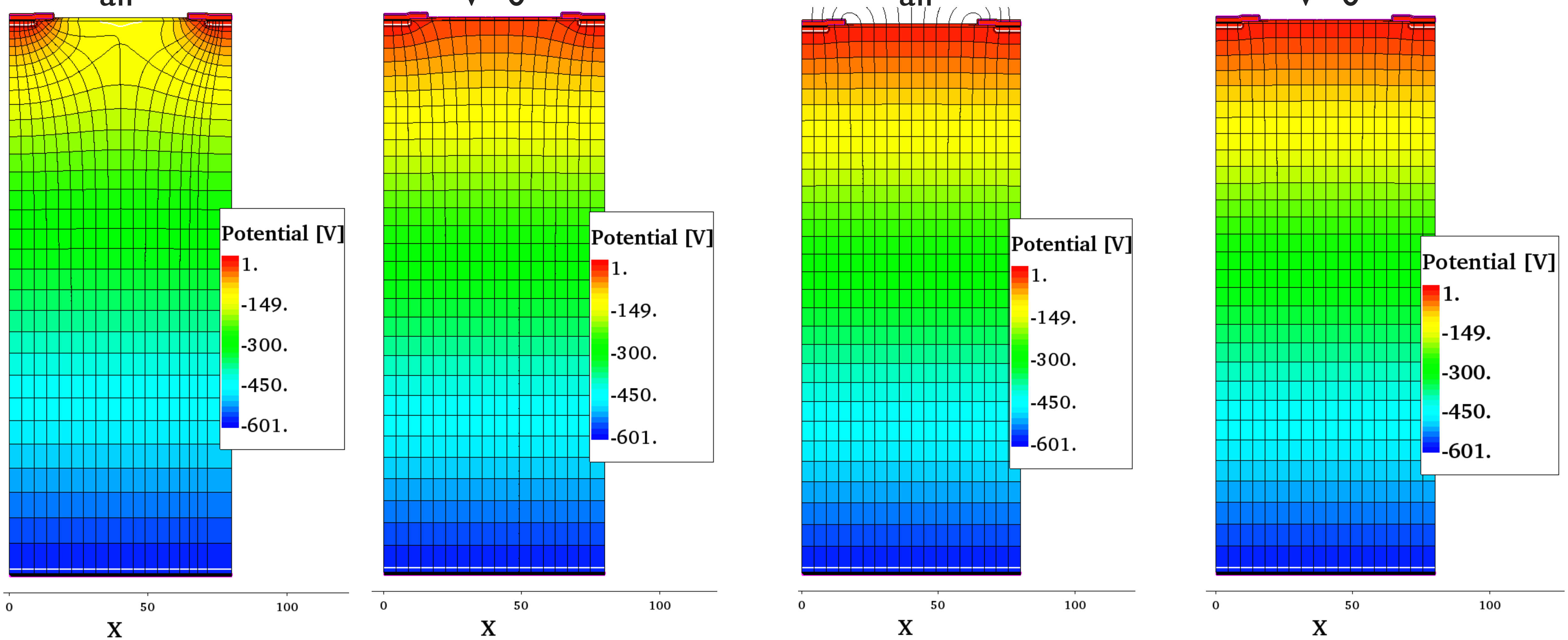


- Comments on J_{surf} measurements:
  - For high J_{surf} voltage drop along surface
    ➡Si-SiO_2 interface only partially depleted
  - Si-SiO_2 interface states decrease of mobility
  - We do not take into account these effects
    ➡Measured I_{surf} = lower limit of surface current

Simulation of p-spray vs. N_{ox}

- p-spray: peak doping conc. ~ $4 \cdot 10^{15}$ cm^{-3}; depth ~ 1.5 µm → $N_{p\text{-}spray}$ = $2.5 \cdot 10^{11}$ cm^{-2}
- Results depends on boundary conditions:
  - „Dirichlet“: SiO_2 surface on potential of readout strip (0 V)
  - „air“: 500 µm above strips Dirichlet with potential of readout strips

$N_{ox} = 1 \cdot 10^{10}$ cm^{-2} air | $N_{ox} = 1 \cdot 10^{10}$ cm^{-2} V=0 | $N_{ox} = 5 \cdot 10^{11}$ cm^{-2} air | $N_{ox} = 5 \cdot 10^{11}$ cm^{-2} V=0

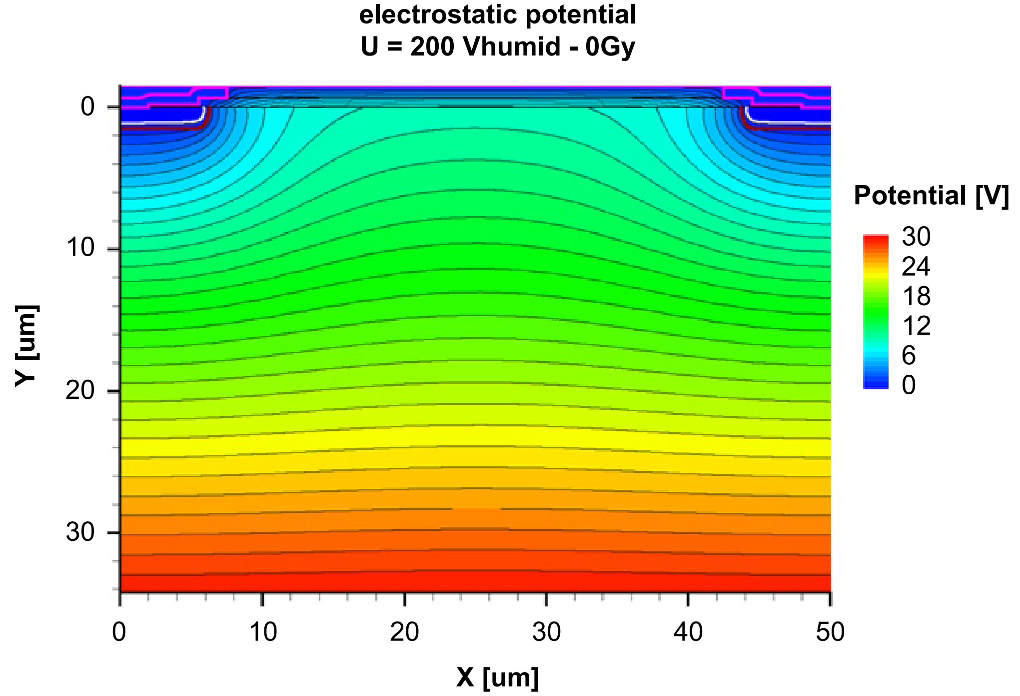


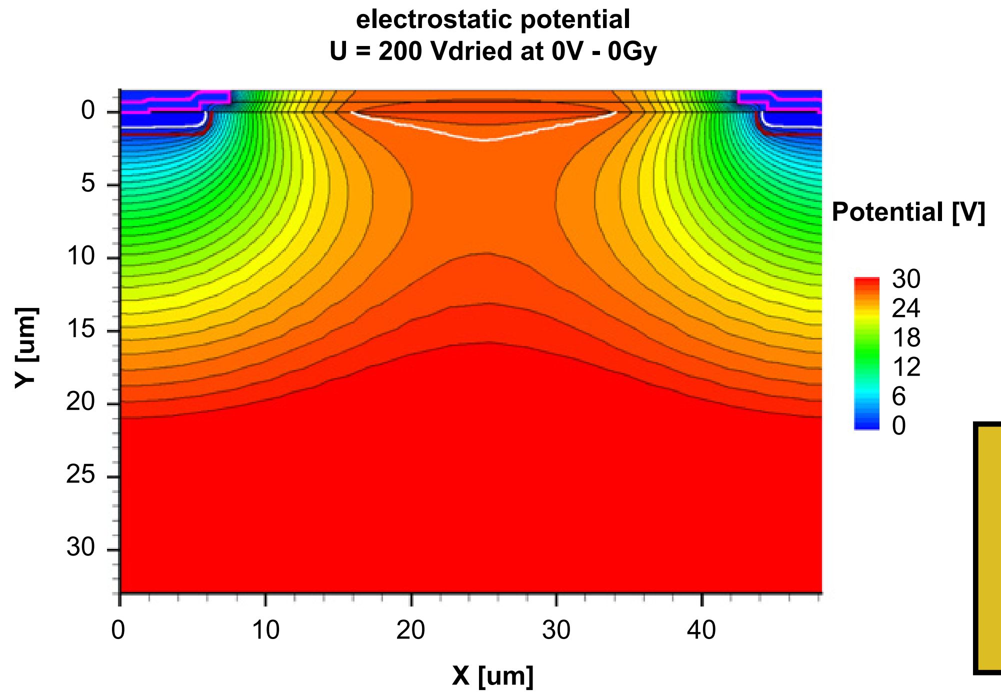
- $N_{ox} < N_{p\text{-}spray}$: E-field lines end at readout strips → no charge charing
- $N_{ox} > N_{p\text{-}spray}$: E-field lines end at Si-SiO_2 interface → charge charing

Increase of oxide charge density N_{ox} will change the charge sharing

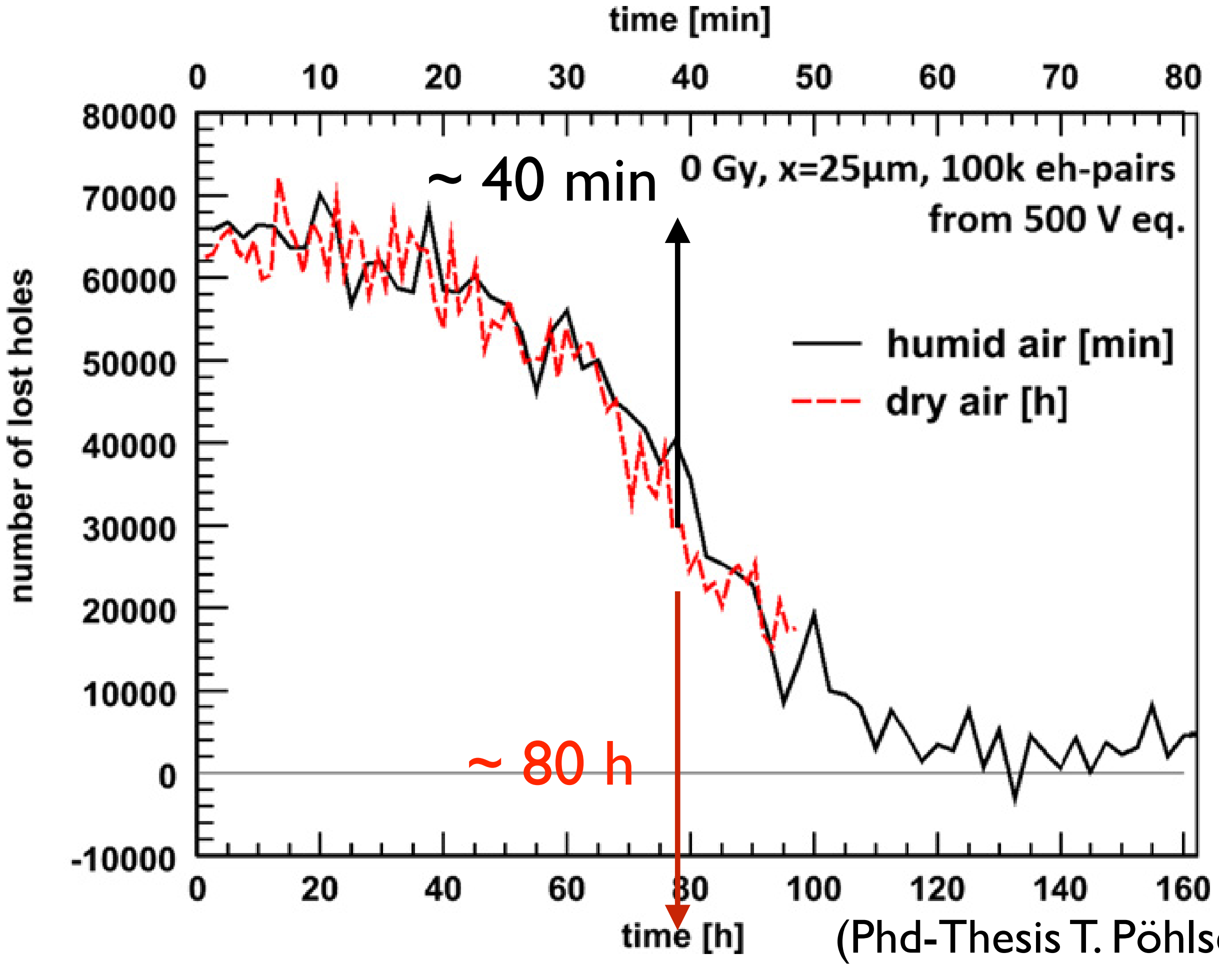
Charge losses in p^+n sensors

- DC coupled p^+-n sensor: pitch 50 µm,
- Losses limited to few µm below SiO_2
- Charges spread in ps over acc. layer
- Time to reach equilibrium after losses 10 - 100 µs ≫ 200 ns





Hole losses vs. time after changing bias voltage from 500 V to 200 V: 0 Gy, 600nm laser, 100k e-h paris injected



(Phd-Thesis T. Pöhlsen)

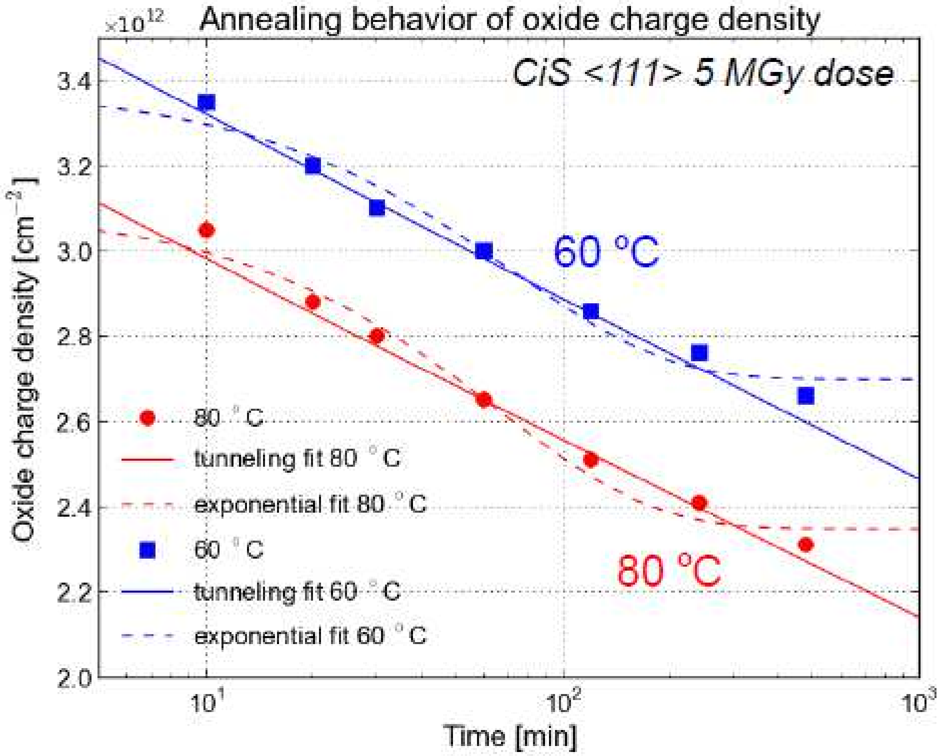
Using dedicated TCAD simulations observed losses of electrons (holes) can be qualitatively understood by formation of electron-accumulation (hole-inversion) layer

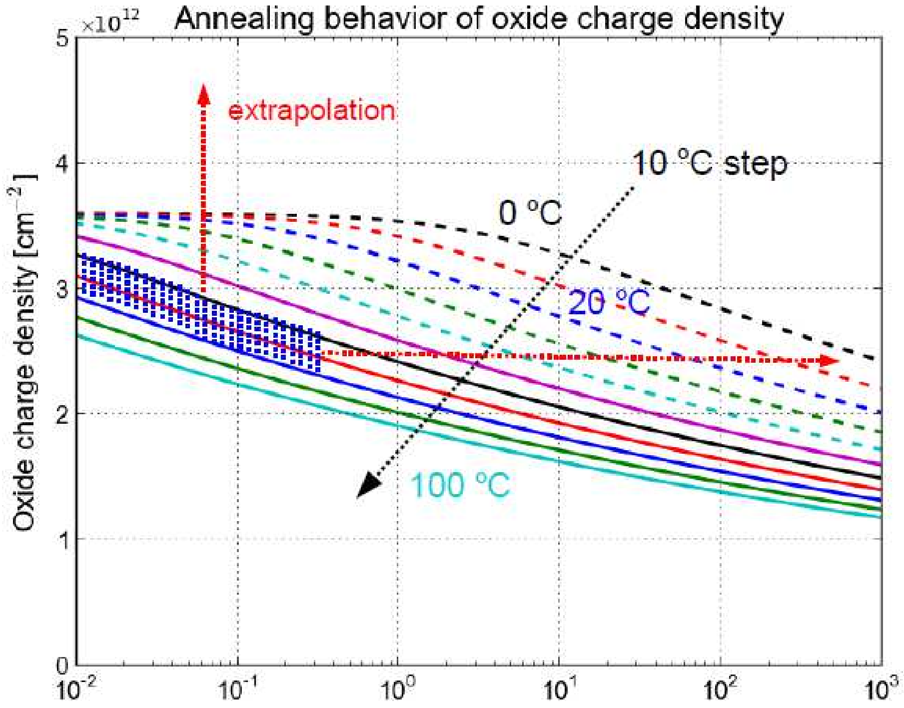
Annealing of N_{ox}^{eff}

MOS-C and GCD irradiated to 5 MGy and annealed at 60 and 80°C

- CiS <111> with ~350 nm SiO_2 + 50 nm Si_3N_4

J.Zhang et al., arXiv:1210.0427(2012)





- Described by modified "tunnel anneal model" [T.R. Oldham et al., 1988]

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

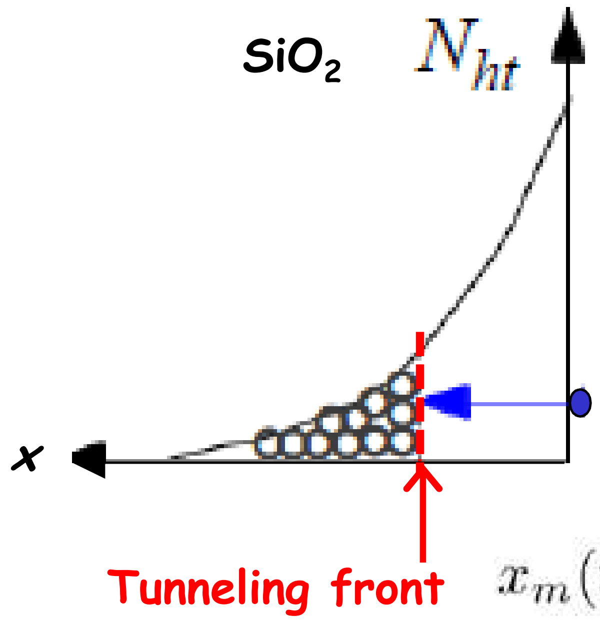
1/λ … width of hole trap distr. in SiO_2
$t_0(T)$ … tunneling time constant
β … related to tunnel-barrier height
ΔE … E_{trap} - E_{Fermi}

Slow N_{ox} annealing: at 20°C <50% annealing in 3 years (assuming model correct!)

Model for annealing of N_{ox}^{eff}

"Tunnel anneal" model: How to obtain a non-exponential t-dependence?

T.R.Oldham et al., IEEE Trans.NS-33/6(1986)1203 – (with some modification by J.Zhang/R.Klanner)



Hole trap distribution:

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

Electrons tunnel and anneal hole traps

→ Annealed oxide charges: $\Delta N_{ox}(t) = \int_0^{x_m(t)} N_{ht}(x) \mathrm{d}x$

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

t_0: effective tunneling time constant

$t_0(T) = t_0^* \cdot \exp\left(\frac{\Delta E}{k_B T}\right)$ ΔE ... distance trap level to E_{Fermi}

β: parameter related to barrier height

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

N_{ox}^0 [cm^{-2}]	$\lambda/2\beta$	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	21710

$\Delta E = E_{ht}(\mathrm{SiO_2}) - E_{Fermi}(\mathrm{Si})$ = 0.91 eV ➡ $E_{ht}(\mathrm{SiO_2}) \sim 6$ eV – compatible with existing data

→ Slow N_{ox} annealing: At 20°C <50% annealing in 3 years (assuming model is correct!)

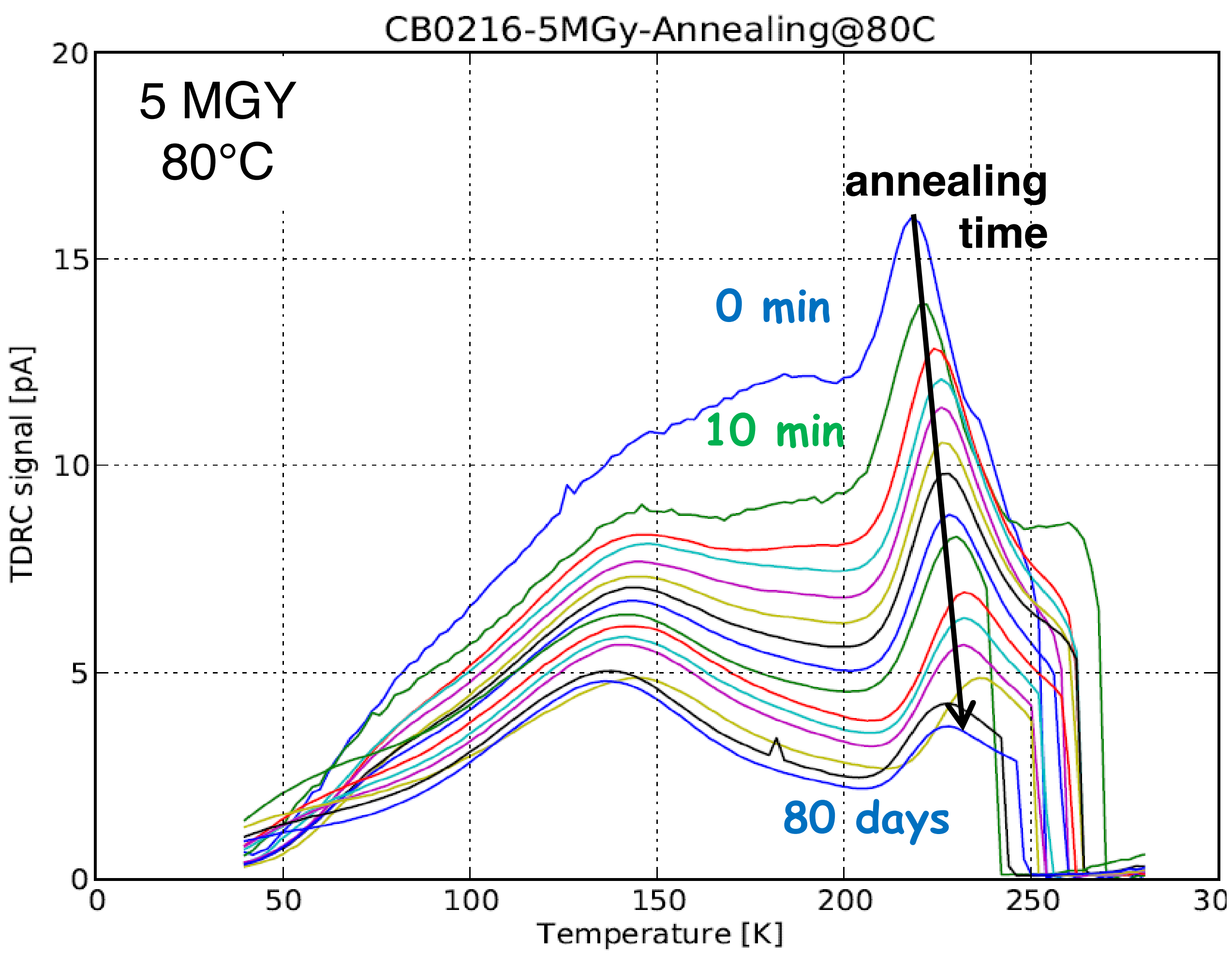
Annealing of N_{it} and J_{surf}

MOS-C + GCD irradiated to 5 MGy and annealed 80°C

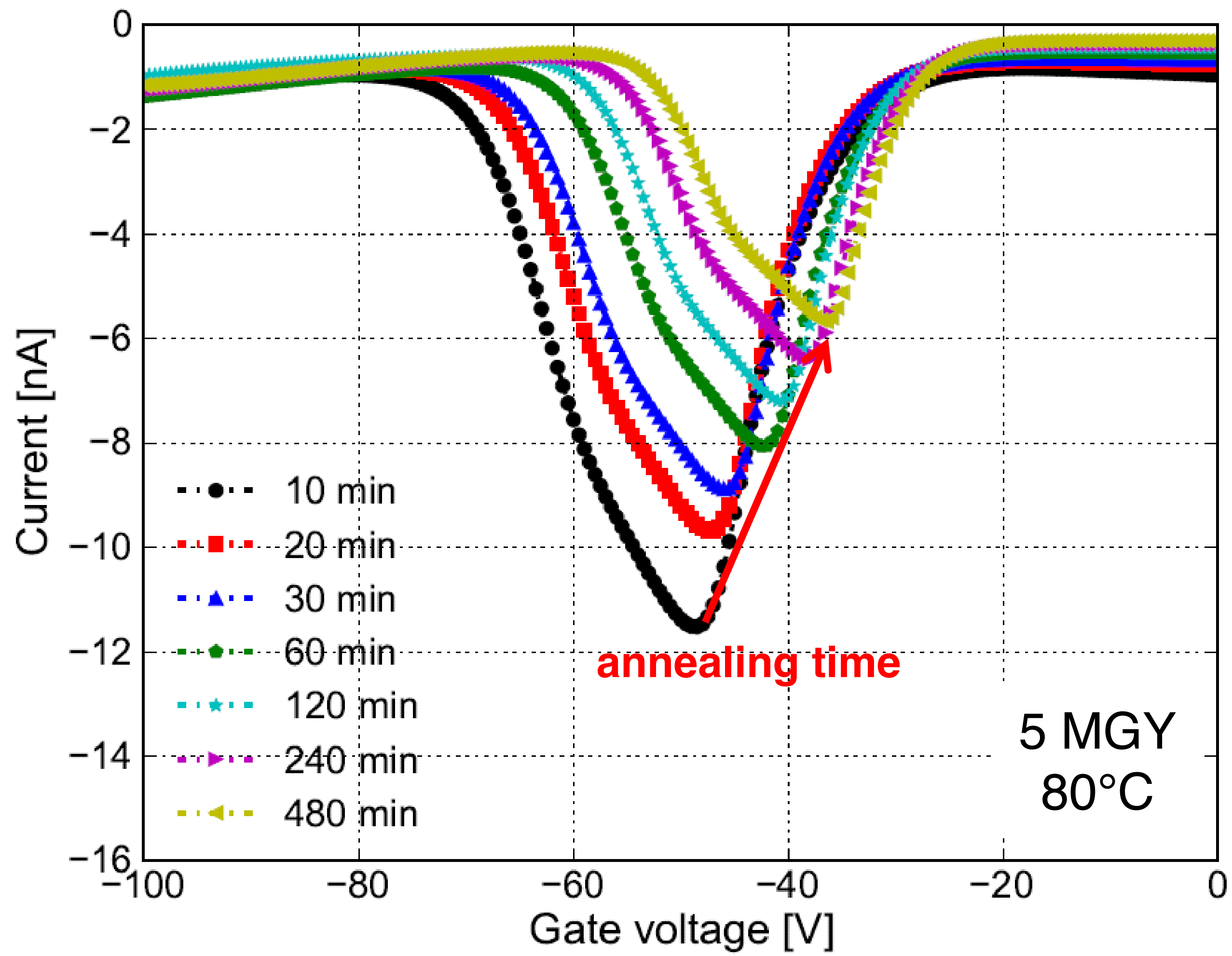
- CiS <111> with ~350 nm SiO_2 + 50 nm Si_3N_4

J.Zhang, DESY-THESIS-2012-018

TDRC spectrum from MOS-C vs annealing time at 80°C



I_{surf} from GCD vs. annealing time at 80°C

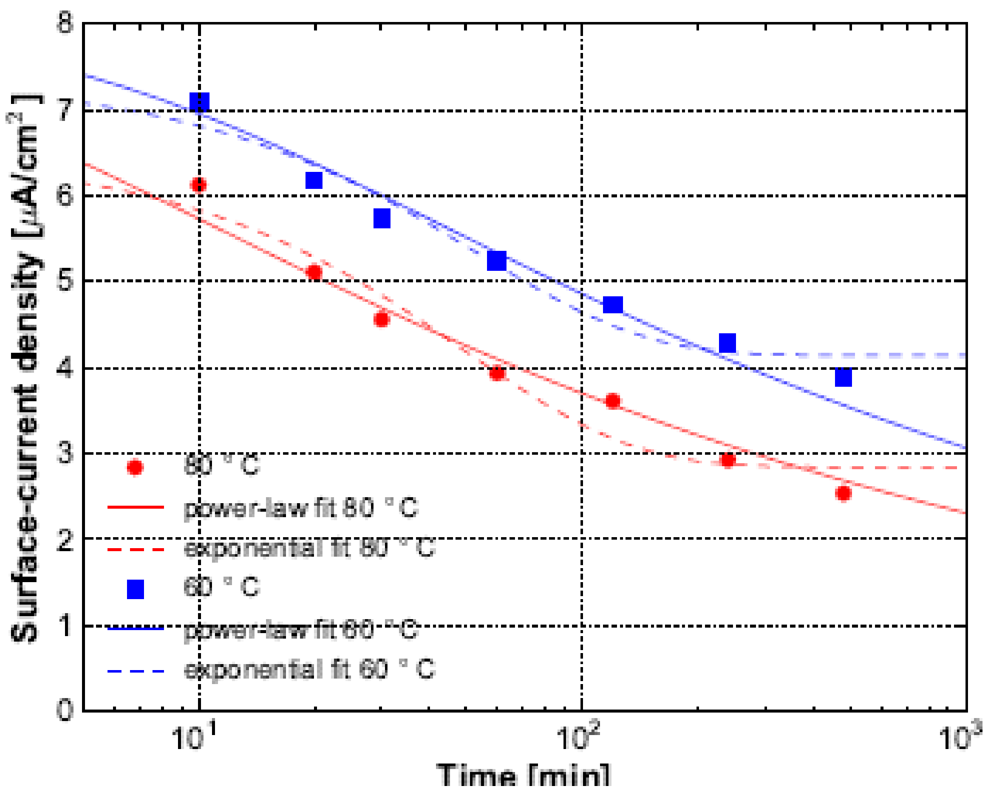


Annealing of J_{surf}

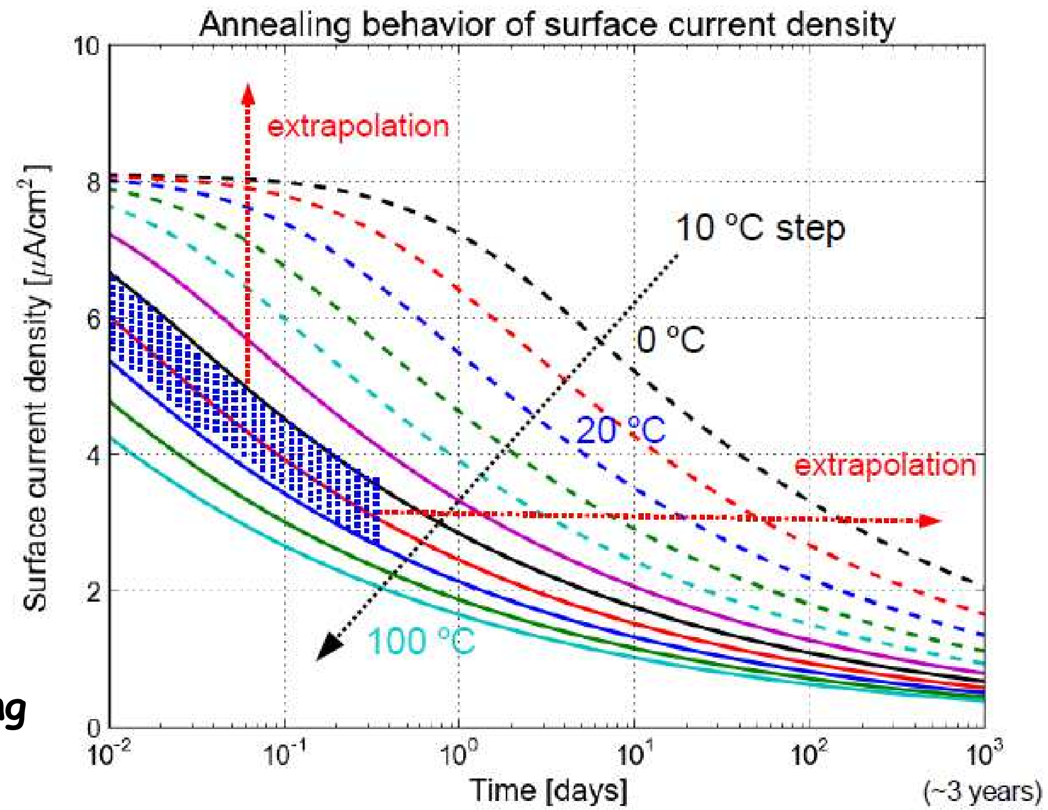
MOS-C and GCD irradiated to 5 MGy and annealed at 60 and 80°C

- CiS <111> with ~350 nm SiO_2 + 50 nm Si_3N_4

J.Zhang, DESY-THESIS-2012-018



J.Zhang



- Described by "two reaction model" [M.L. Reed 1987]

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

$\eta = k_1/2k_2$
Dangl. bonds: $\frac{d}{dt}[\mathrm{Si}\cdot] = -k_1[\mathrm{Si}\cdot][\mathrm{H}]$
H_2 formation: $\frac{d}{dt}[\mathrm{H}] = -2k_2[\mathrm{H}][\mathrm{H}]$
$t_1(T)$ … characteristic time constant
E_a … activation energy

→ **Fast annealing:** At 20°C ~50% annealing in 5 days (assuming model is correct!)

Fast J_{surf} annealing (D_{it})