Surface effects in segmented silicon sensors

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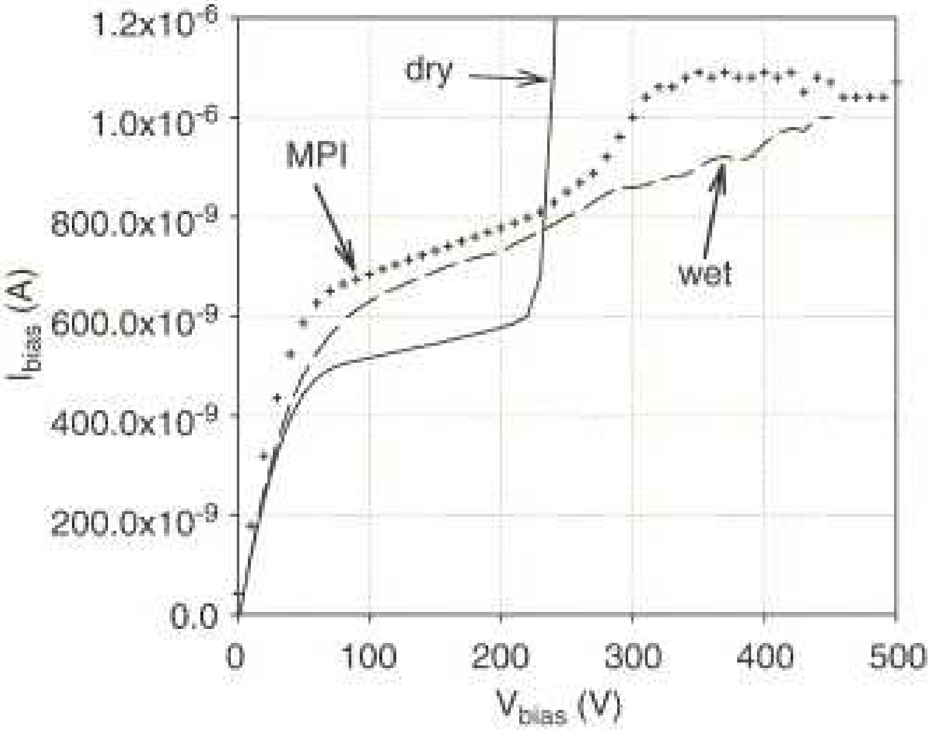
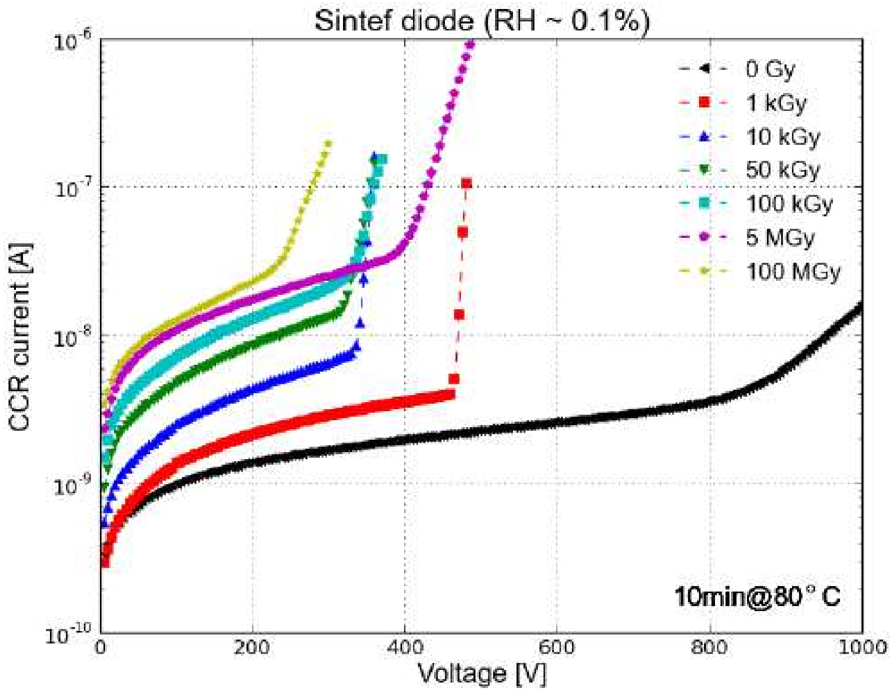
Introduction: Some experimental observations

F.G.Hartjes, NIM-A552(2005)168



Breakdown voltage of a CiS p^+n strip sensor depends on humidity

R.Klanner et al., NIM-A732(2013)117



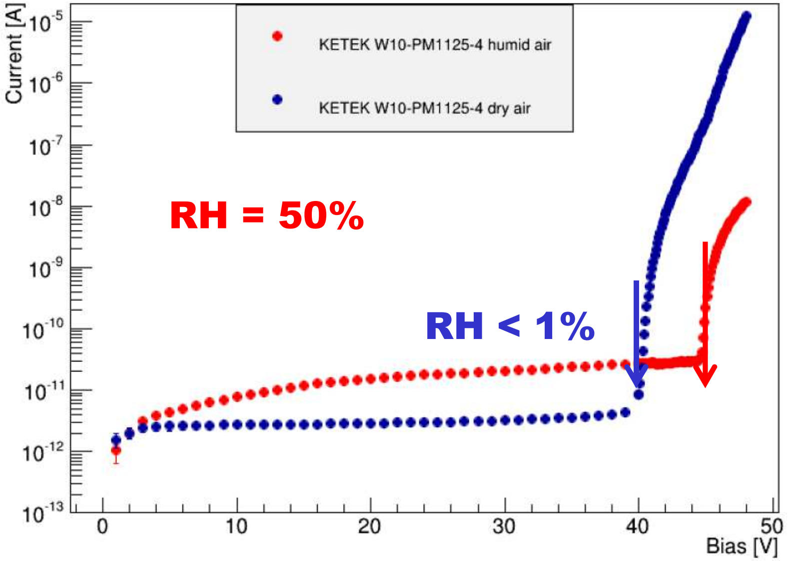
Breakdown voltage of a SINTEF p^+n strip sensor decreases with X-ray dose

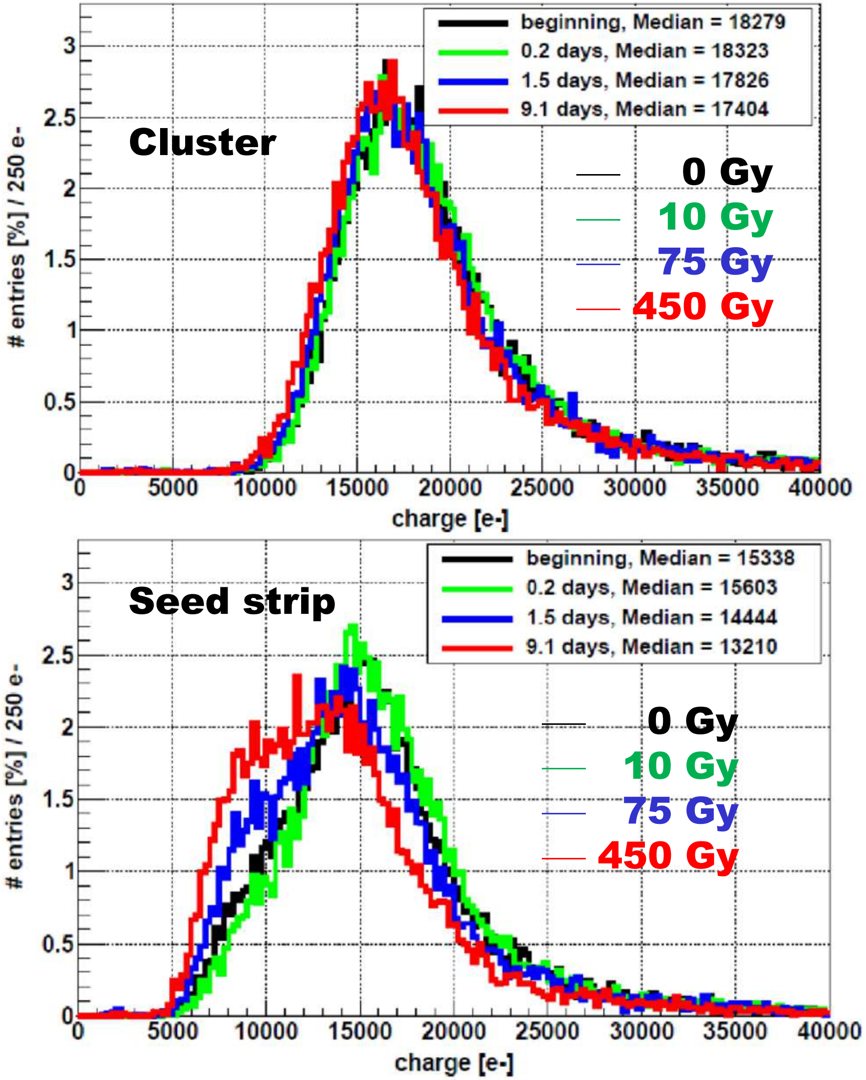
Can we understand these observations + avoid them ?

Introduction: Some experimental observations

S.Jaster-Merz, Characterization of SiPMs a function of humidity, BSC-thesis, Hamburg University 2014

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



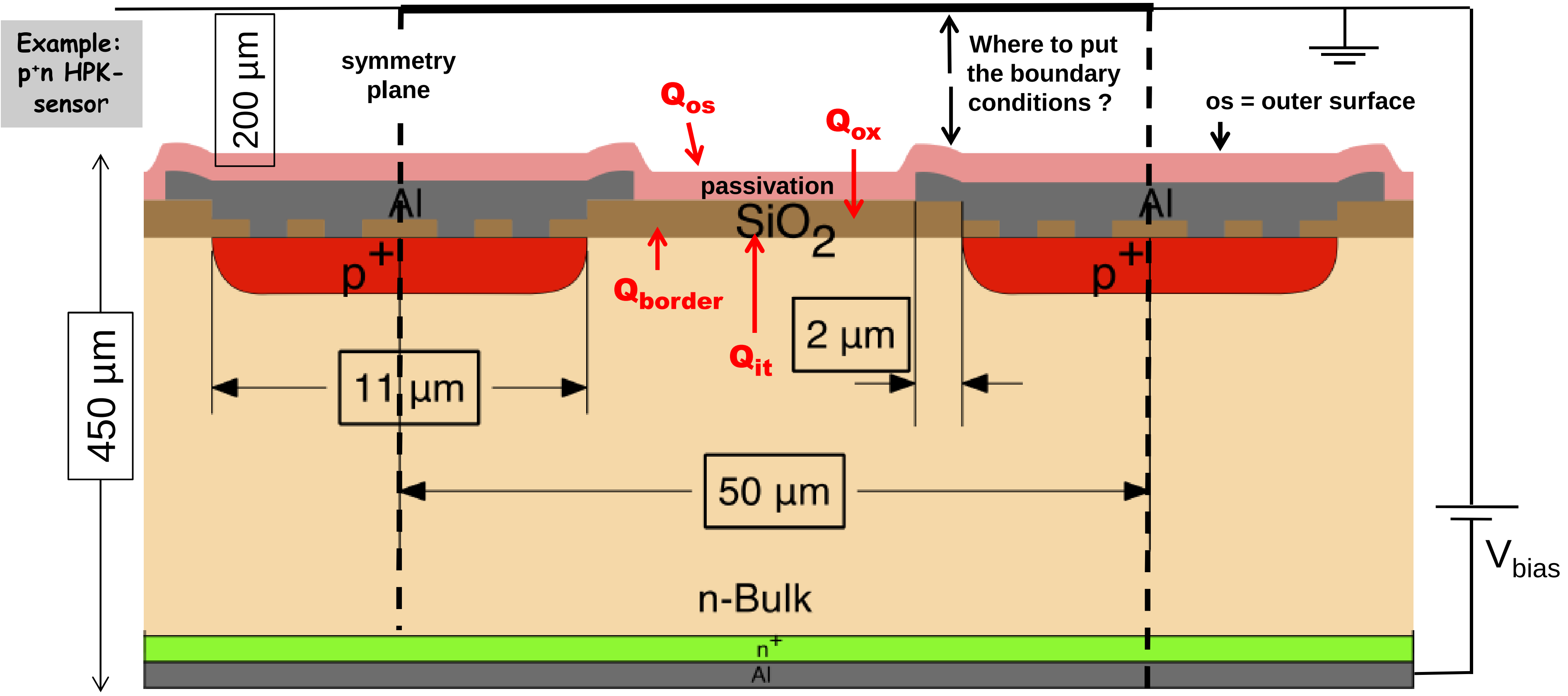


Breakdown voltage of a KETEK SiPM at RT depends on humidity

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

Can we understand this ?

Simulations and relevant parameters



- Q_{os}: outer surface charge distribution → o.s. resistivity R□ → time depend.
- 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

→ Program of determining the relevant parameters

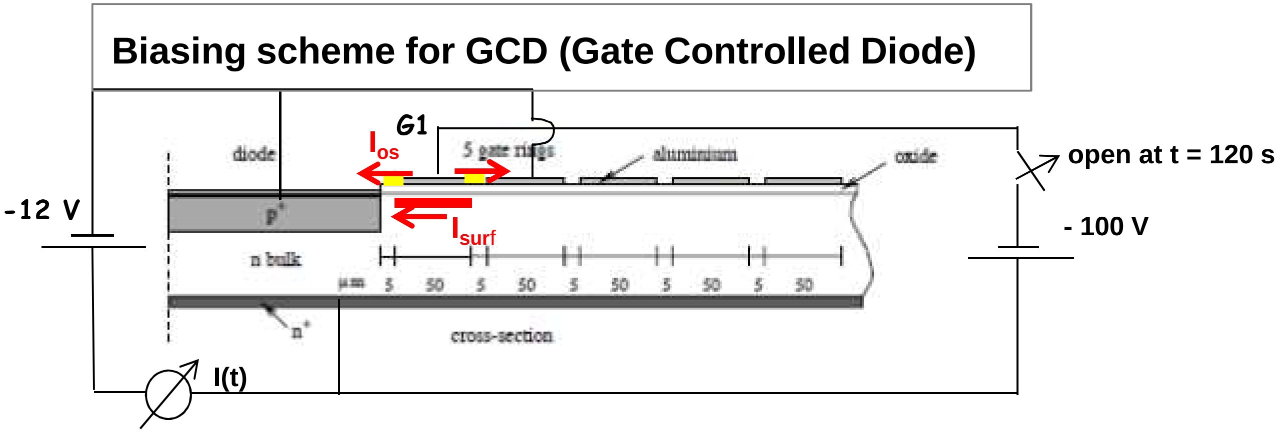
Outer surface charges and resistivity R□

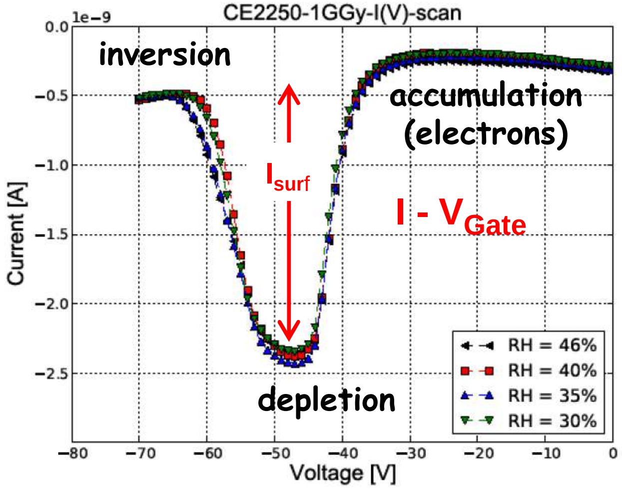
- Q_{os}: bias detector → E_L-field on o.s. → rearrangement of o.s. charges

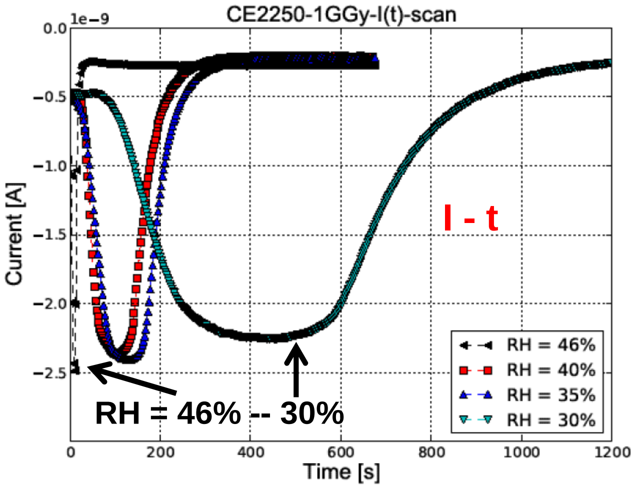
surface resistivity R□ → time-dependent surface charge distribution:

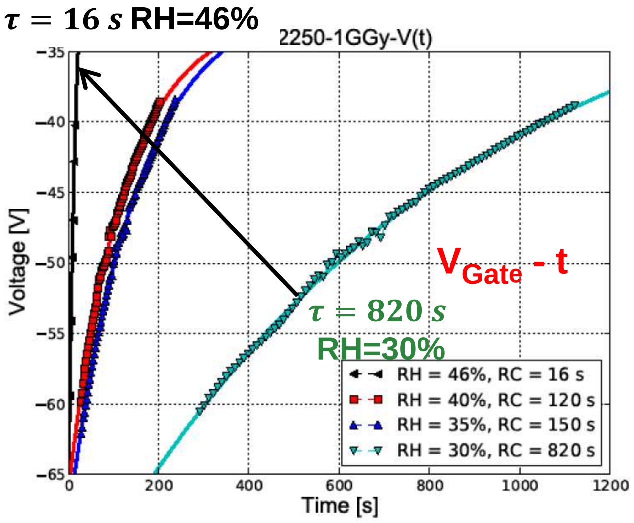
Measurement of R□ over 5 µm SiO_2 by Si-SiO_2 interface current in GCD

Biasing scheme for GCD (Gate Controlled Diode)





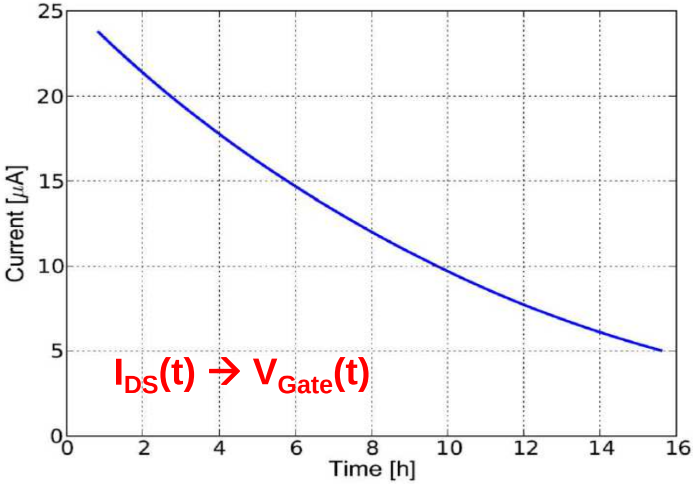




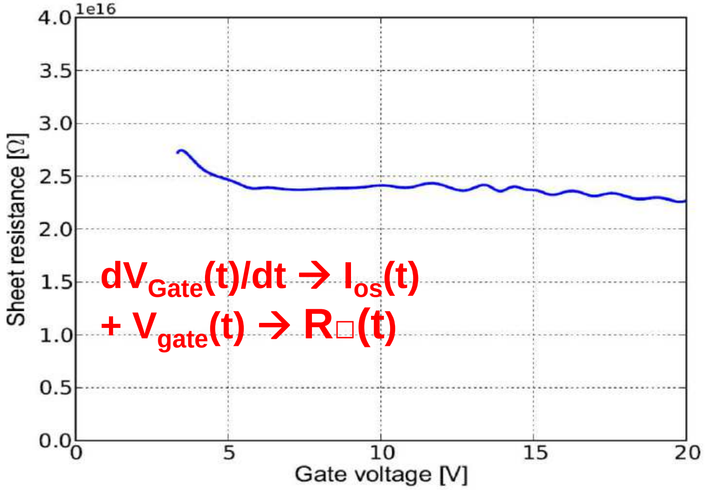
Time constants change by factor 50 for RH 46% → 30%

Outer surface charges and resistivity R□

Measurement of R□ with MOSFET FGT (Floating Gate Technique) :

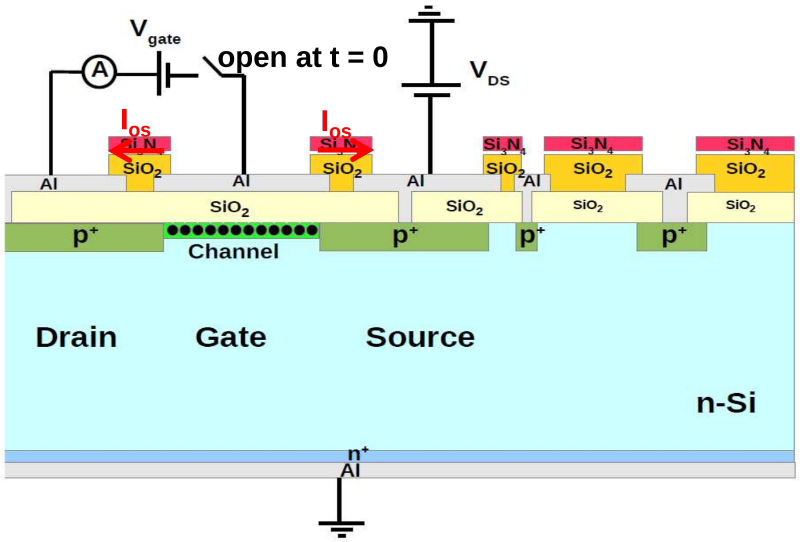


$I_{DS}(t) \rightarrow V_{Gate}(t)$



$dV_{Gate}(t)/dt \rightarrow I_{os}(t)$
$+ V_{gate}(t) \rightarrow R_\square(t)$

FGT biasing scheme for MOSFET



Relative humidity RH [%]	30	35	40	46
Discharge time [s]	820	150	120	16
$R_\square(RH)/R_\square(RH = 46\,\%)$	52	9.4	7.5	1
R_{os} $[10^{12}\,\Omega]$	50	9.1	7.3	0.97
$R_\square$ $[10^{15}\,\Omega]$	66	12	9.7	1.3

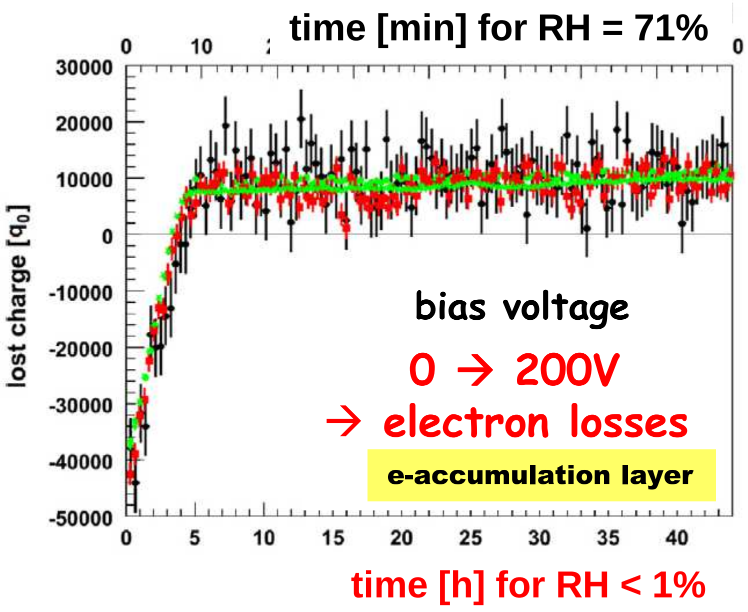
R□ shows ohmic behaviour

$R_\square \sim 10^{17}\Omega$ @ RH = 30%
(difficult to measure for lower RH!)

Outer surface charges and resistivity $R_{\square}$

Time-dependent charge collection close to Si-SiO_2 in p^+n strip sensor

T.Poehlsen et al., NIM-A731(2013)172
T.Poehlsen DESY-THESIS-2013-025

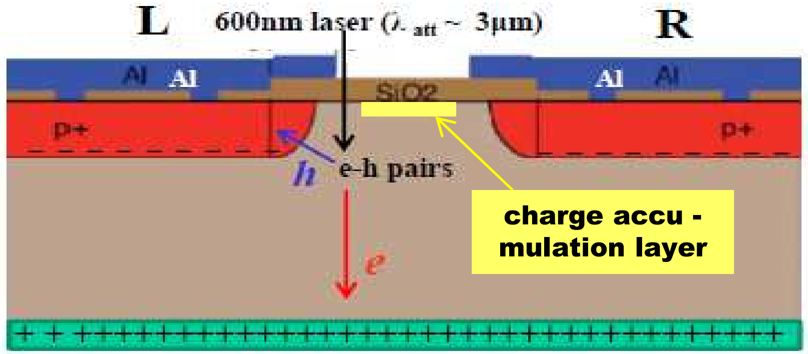


bias voltage

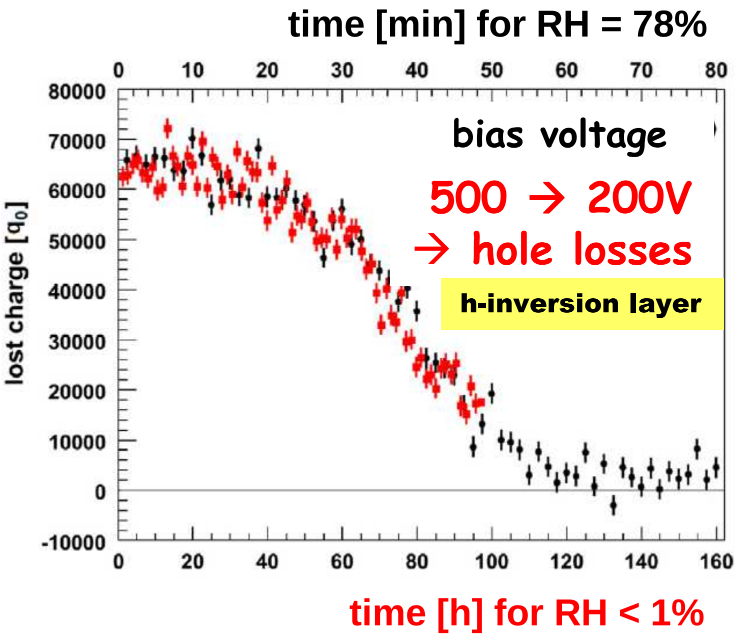
0 → 200V

→ electron losses

e-accumulation layer



charge accu - mulation layer



bias voltage

500 → 200V

→ hole losses

h-inversion layer

E-field + charge layers @ Si-SiO_2
interface depend on biasing history + RH
→ τ ~ many days for low RH !

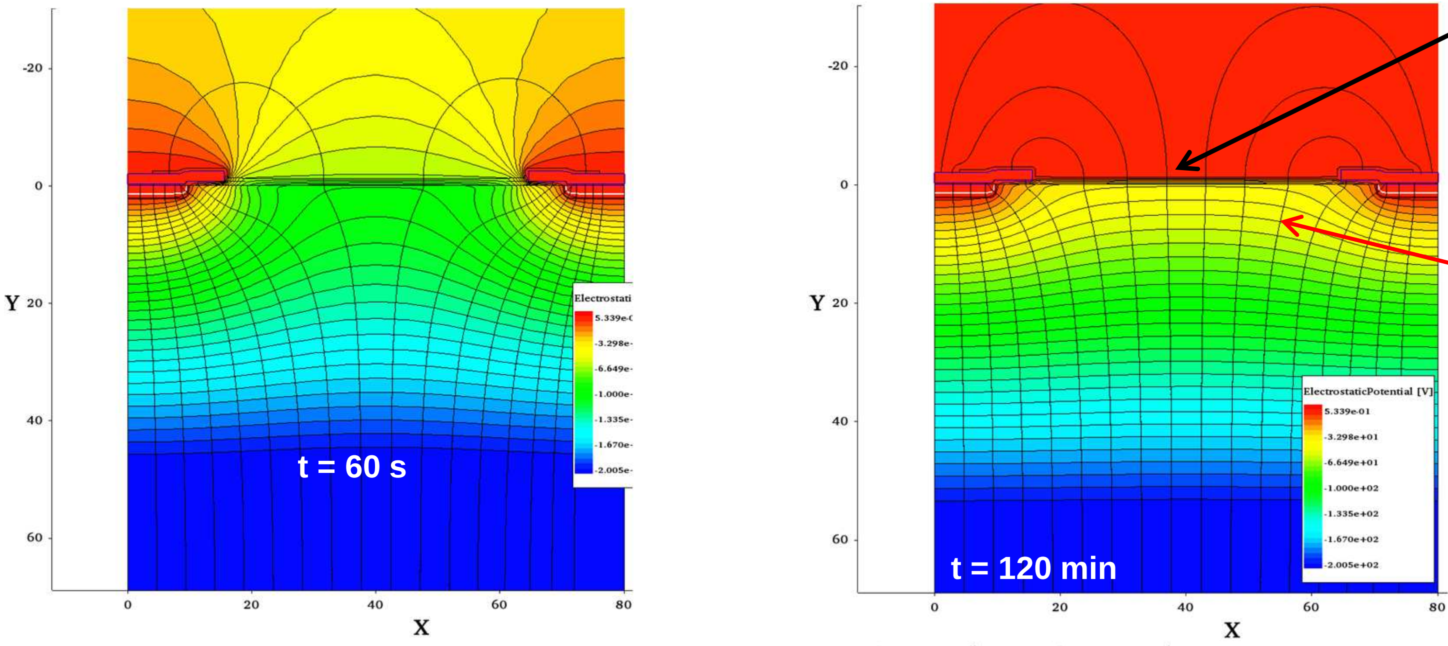
Outer surface charges and resistivity R□

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□, which changes by many orders of magnitude with humidity (+T)

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

Simulation: Outer surface layer with high resistivity for t dependence



watch potential here

and field lines here

Summary outer surface resistivity R□

Outer surface charge distribution influences E-field in Si close to the Si-SiO_2 interface

→ influences the presence/size of inversion/accumulation layers
→ can cause high-field regions → possible breakdowns
→ can cause changes in charge collection

After biasing, the o.s. charge distribution is not in equilibrium

→ Time constants to reach equilibrium are related to o.s. surface resistivity and can be many days → high initial currents + long-term instabilities

Proper boundary conditions and mesh sizes in simulations are essential

→ Default TCAD boundary conditions are typically not the ones to use; make simulations with different boundary conditions

Avoid instabilities by high-resistivity layer on top of passivation ?

(General rule: make sure that the potential is defined everywhere)

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'_γ @~3 eV) saturation:

h-trapping = eh- recombination

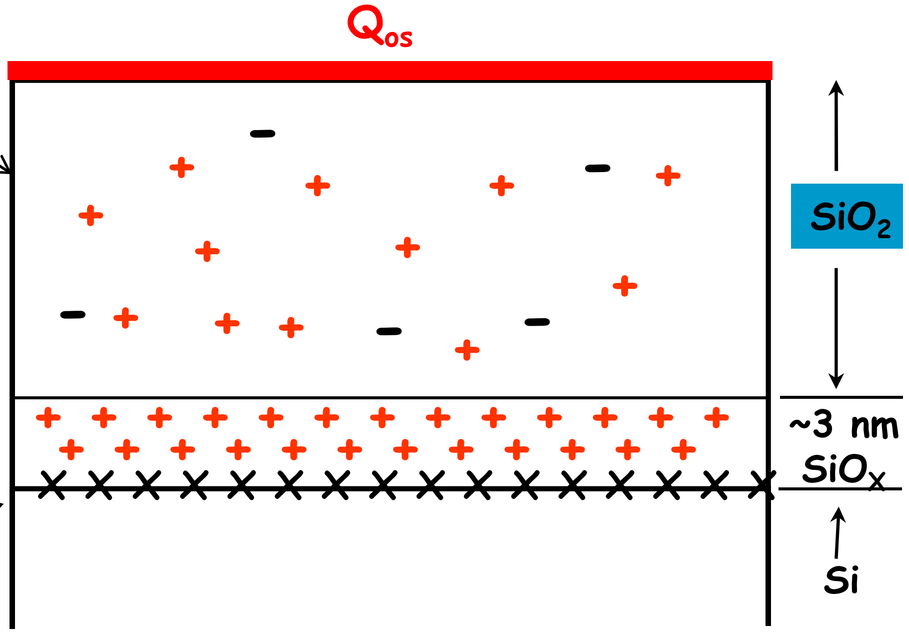
⊕ Border oxide traps ("add" to N_{ox}):

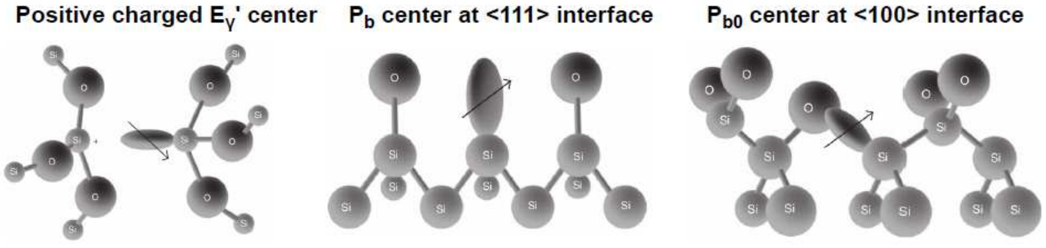
Positive E'_γ defect can exchange charge with Si depending on Fermi-level on time scales > 0.01 s to seconds

⊗ Interface traps (D_{it}*)):

Traps at interface (no barrier !)
dangling bond defects (P_b) –
H^+ released when *h* captured:
$SiH + H^+ \rightarrow (Interface\ Trap)^+ + H_2$
No. limited by no. of dangling bonds

Mobile ions: not an issue anymore





* from D. M. Fleetwood's book "Defects in Microelectronic Materials and Devices"

A complex many parameter problem

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*) Distribution of traps in the Si bandgap:
D_{it} [(eV·cm²)⁻¹]

Oxide charges, interface traps and border traps

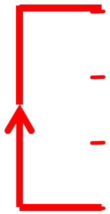
Complex many parameter problem → simplifications are needed:

For simulations frequently used:

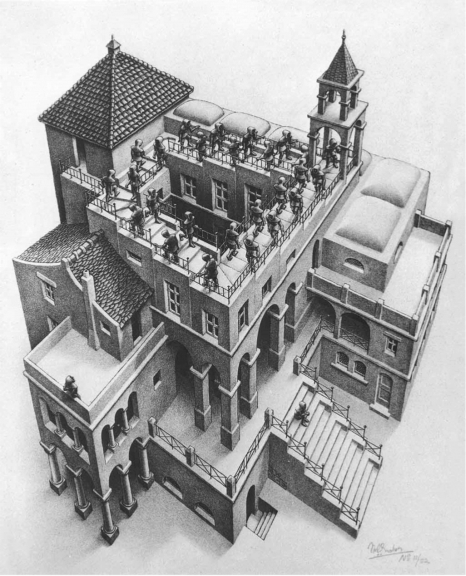
- Position-independent effective oxide charge density N_{ox}^{eff} [cm^{-2}]
- Position-independent surface recombination velocity s[cm/s] (or J_{surf} [A/cm^2] where Si-SiO_2 interface is depleted)

Experimental determination of parameters (which depend on technology, crystal orientation, radiation damage, etc.) using test structures is a major effort !

Strategy followed (an infinite loop ? – needs excellent + dedicated students !):



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



Can such an approach converge?

I have been warned by experienced colleagues !

and now understand why !

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

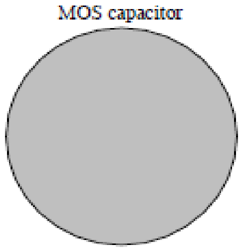
C/G-V+TDRC for MOS-C (from 4 vendors, <100> and <111>, surface damage by X-rays (0 → 1 GGY), E-field during irradiation, annealing)

How to obtain reproducible results ?

(1) Annealing at 80°C for 10 min

(2) Stop voltage scan before strong inversion → no injection of border traps

MOS-C on n-Si



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
  → $I_{TDRC}(T) \rightarrow D_{it}(E)$ *)

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

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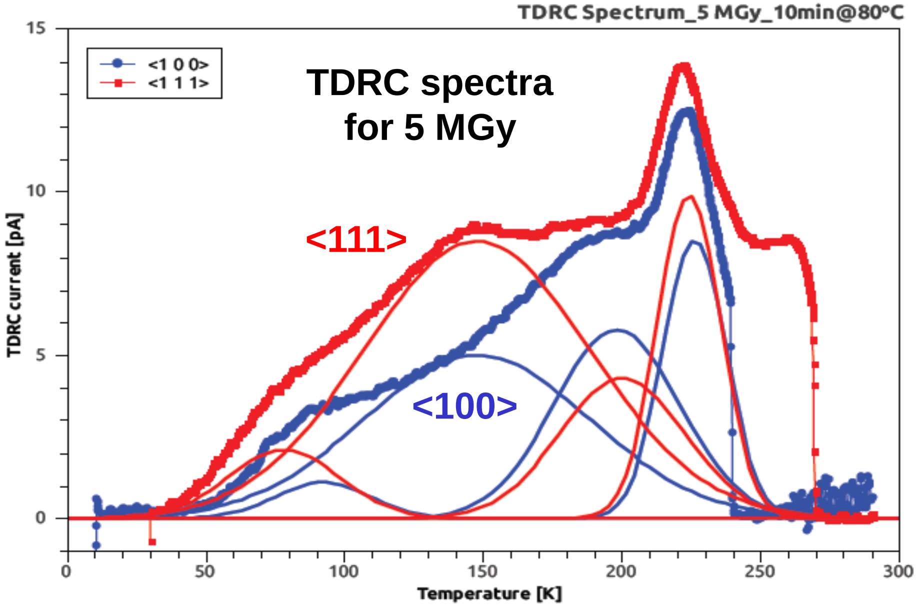
*) Temperature T → $E_c - E_{it}$ (T dependence of Fermi level)

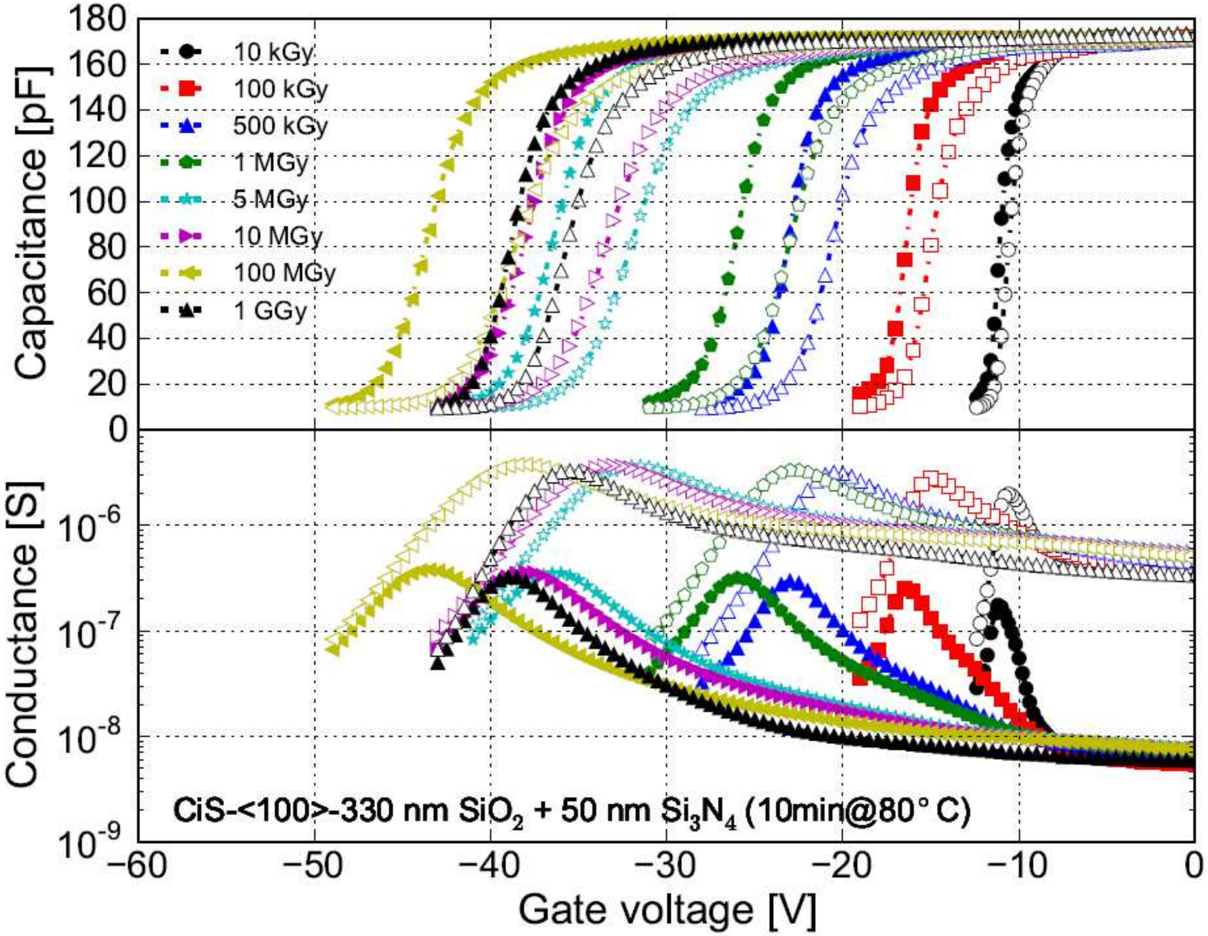


Parameterize by 4 states - not unambiguous !

J.Zhang et al., JSR 19(2013)340
J.Zhang DESY-THESIS-2013-018

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

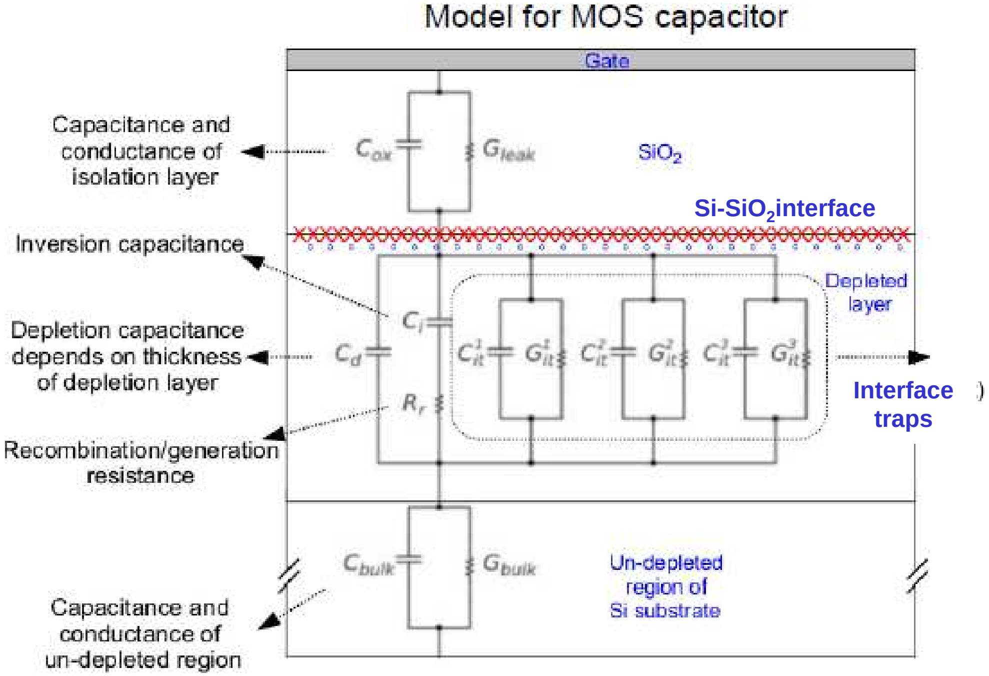
C/G-V curves vs dose for MOS-C (10 kHz and 100 kHz only)

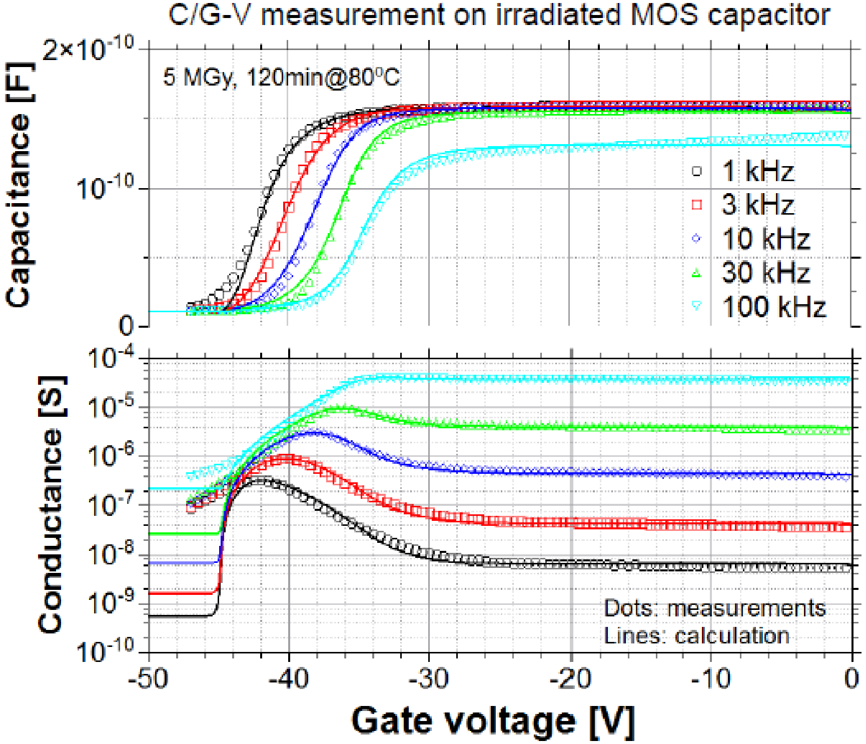


Oxide charges N_{ox} + interface traps D_{it}

Analysis of TDRC + *C*/*G*-*V*/*f* data:

J.Zhang, DESY-THESIS-2013-018





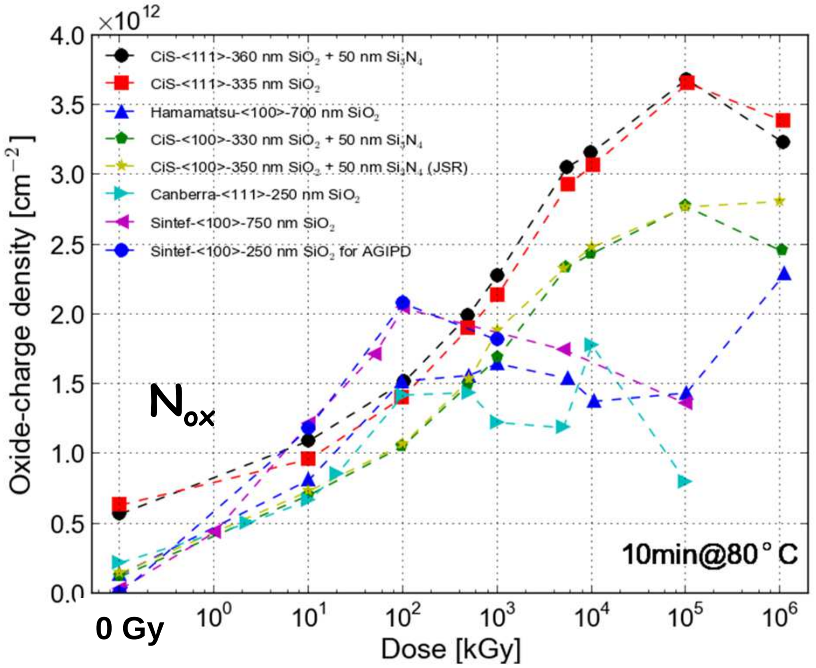
Analysis method:

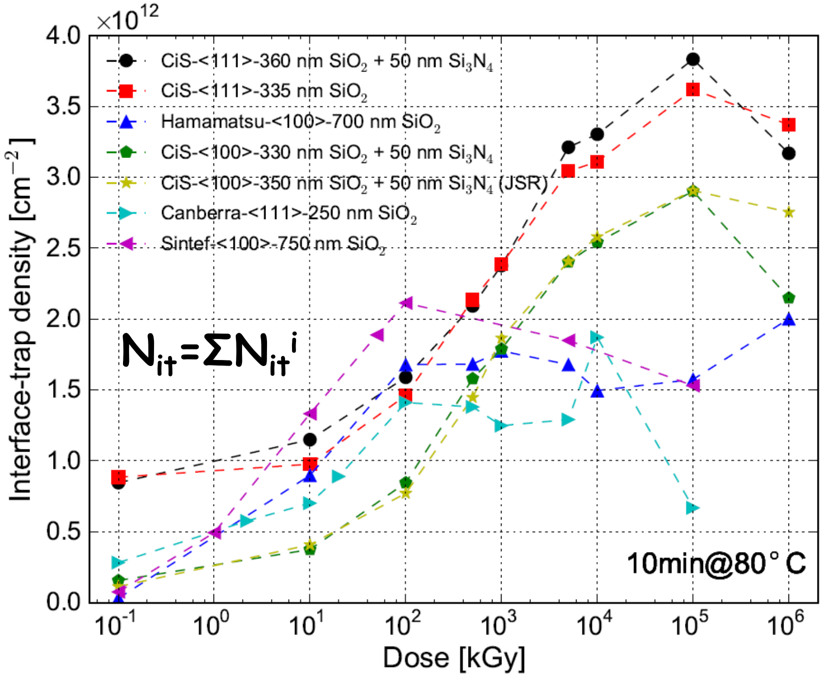
- TDRC spectra → N_{it}^{i}
- Electric model → shape *C*/*G* (*V*, *f*)
- Shift along voltage axis → N_{ox}

Good description of a large amount of data; but is it unique?

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

Results of analysis of TDRC + C/G-V data





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

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

Problems of N_{it} analysis: (→ J.Schwandt DESY THESIS-2014-029)

- We are not sure if all border traps have been filled in accumulation
- In mid-gap region current due to empty interface traps contributes
- For the given T range only sensitive to traps above mid-gap
- Dominant electron emission assumed ($e_n \gg e_p$)
- I_{TDRC} (T) → D_{it} (E) transformation assumes $\sigma_{capture}$ ~$1/T^2$ + linearized formula
- Acceptor states only have been assumed

→ **Unable to explain $J_{surface}$ measured with GCD** (Gate-Controlled-Diode)

(However: method used typically gives higher values for N_{ox})

→ **Give up, and use N_{ox}^{eff} from C/V(1 kHz) and measured $J_{surface}$ *)**

More work + different techniques required for reliable separation of N_{ox} and N_{it} !

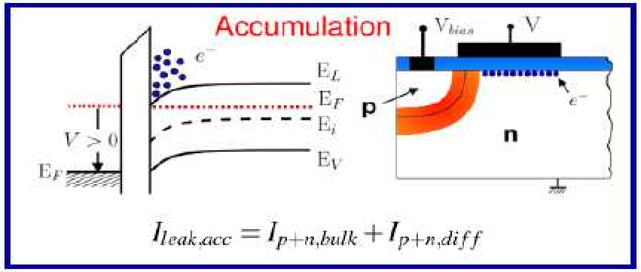
*) Surface recombination rate: $$R_{surf} = \int_{E_V}^{E_C} \frac{n_s p_s - n_i^2}{(n_s + n_1)/c_{ps} + (p_s + p_1)/c_{ns}} D_{it}(E_{it})\,\mathrm{d}E_{it}.$$

Surface recombination velocity and current density for const. D_{it}: $s_0 = \frac{\pi}{2}\sigma_s v_{th} D_{it} k_B T \qquad J_{surf} = q n_i s_0.$

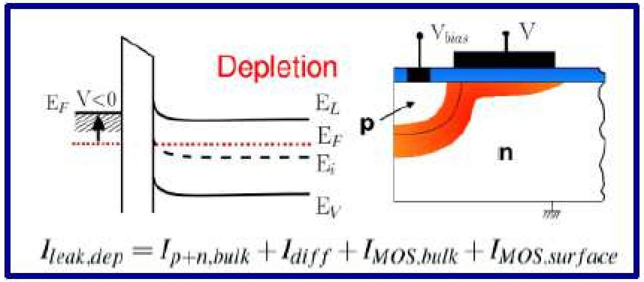
Surface-generation current density: J_{surf}

Surface current density from GCD:

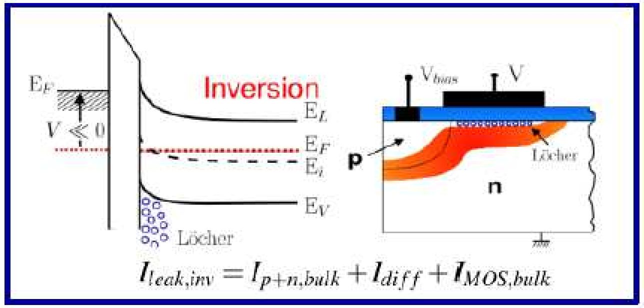
- **Measure I-V curve**
- **J_{surf} dominated by mid-gap traps**



$$I_{leak,acc} = I_{p+n,bulk} + I_{p+n,diff}$$



$$I_{leak,dep} = I_{p+n,bulk} + I_{diff} + I_{MOS,bulk} + I_{MOS,surface}$$



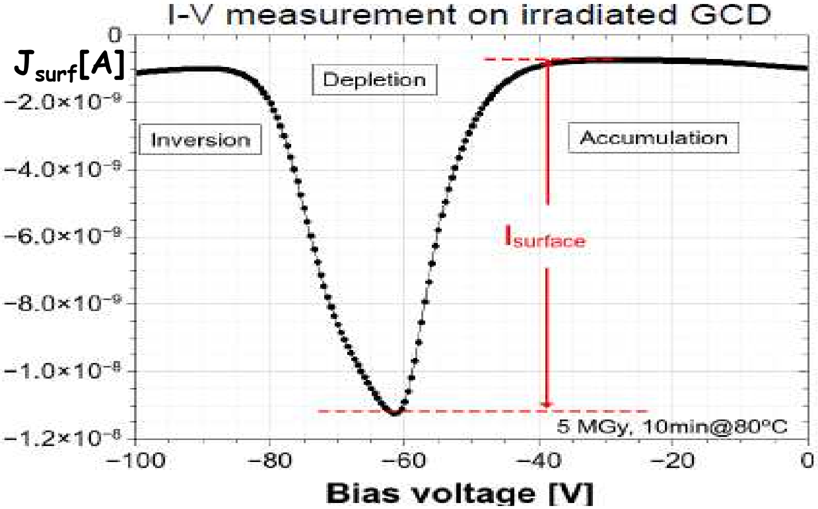
$$I_{leak,inv} = I_{p+n,bulk} + I_{diff} + I_{MOS,bulk}$$

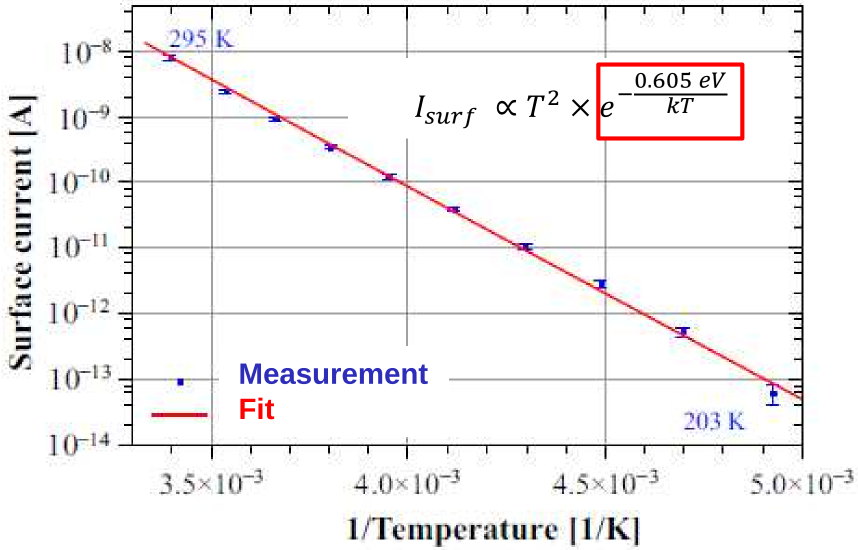
Si-SiO_2 interface:

electrons
→ $I_{surf} = 0$

depleted
→ $I_{surf} \neq 0$

holes
→ $I_{surf} = 0$



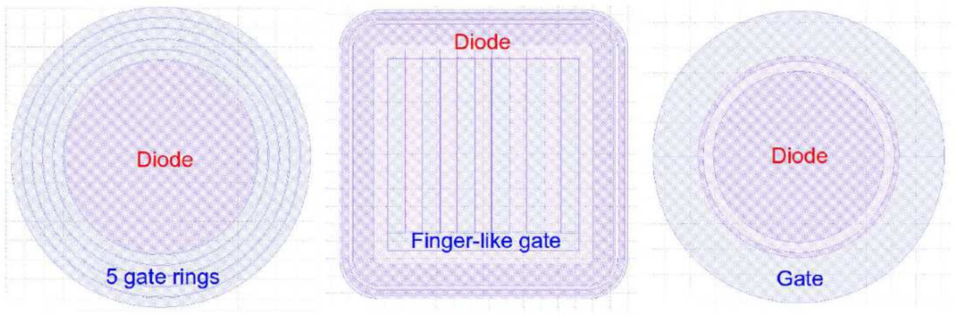


Same exponent as for I_{bulk} !

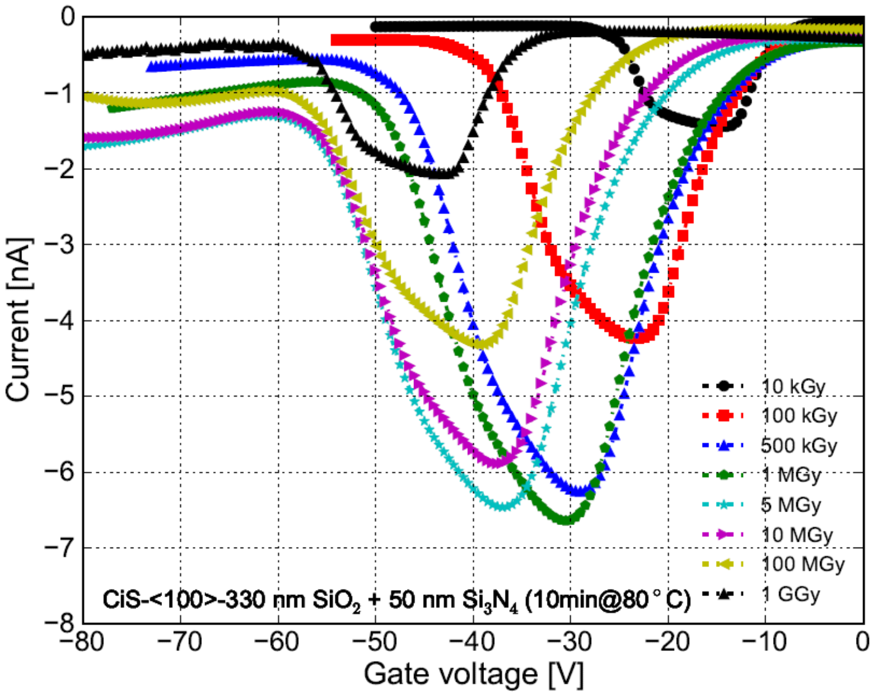
Surface-generation current density: J_{surf}

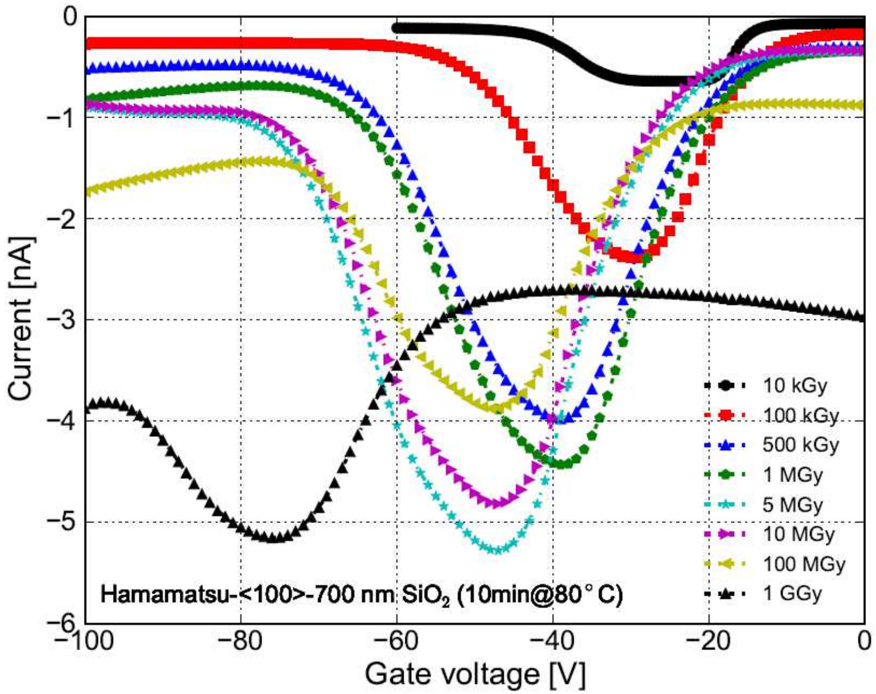
Examples of measurement results (2 out of ~∞ → J.Zhang DESY THESIS-2013-018):

I-V vs. X-ray dose for CIS <100> and HPK <100> Gate-Controlled Diodes on n-Si



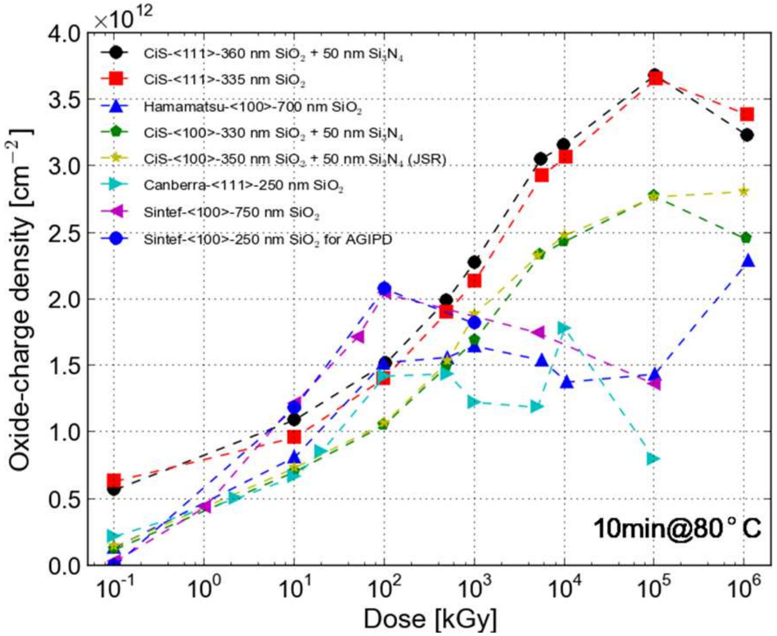
(a) CiS and Hamamatsu (b) Canberra (c) Sintef

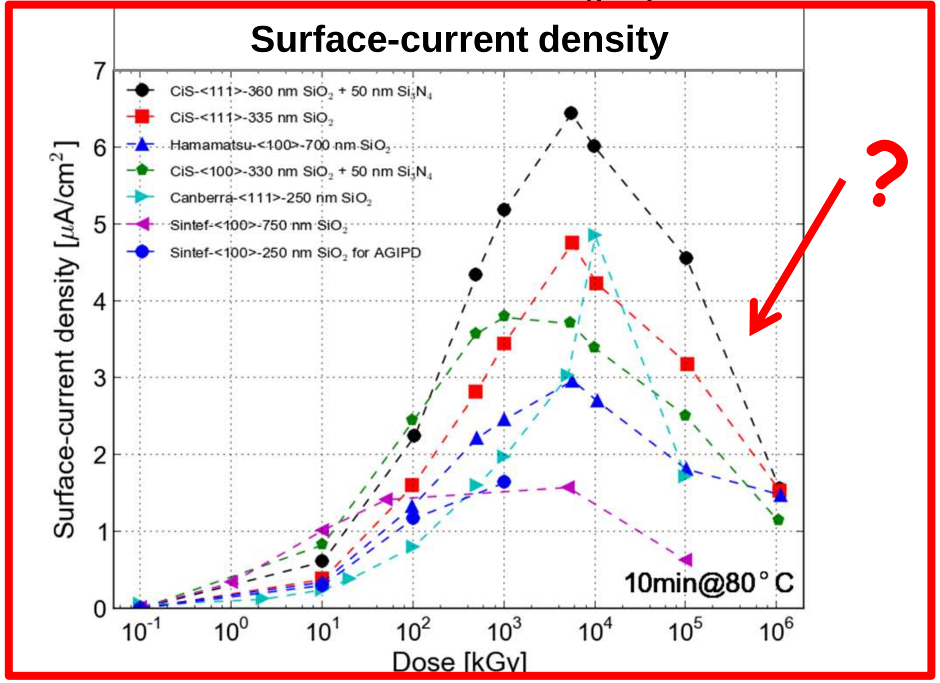




Summary: Dose Dependence of N_{ox}^{eff} and J_{surf}

Vendors: CiS, Hamamatsu, Canberra, Sintef; **Crystal orientations**: <111>,<100>
Insulator: SiO_2 (335-700 nm), with and without additional 50 nm Si_3N_4





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

- Results reproducible (after some annealing)
- Spread of about a factor 2
- N_{ox}^{eff} saturates for ~1 – 10 MGy
- J_{surf} peaks at 1-10 MGy, then decreases

- Equilibrium h-trapping and eh-recombination ?
- E-field effects due to oxide charges ?

→ Understanding needs more studies

X-ray radiation damage saturates (decreases) at high dose !!!
Surface-radiation damage data available for simulations

More on N_{ox}^{eff} and J_{surf}

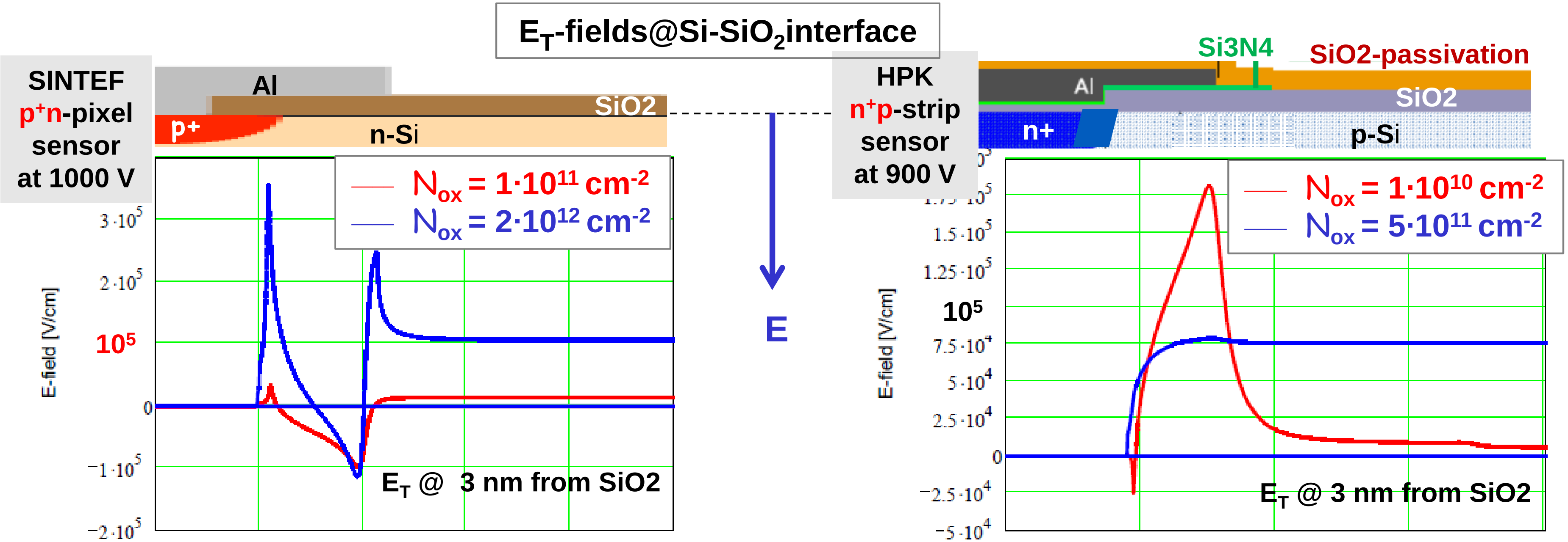
So far: Irradiation without bias + measurements after some annealing

Needed for understanding of sensor performance:

- Irradiation under bias (i.e. different E-fields at Si-SiO_2 inteface)
- Parameters during and shortly after irradiations under bias
- Annealing

Relevant E-field from simulation of p^+n and n^+p strip sensors 3 nm from SiO_2

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



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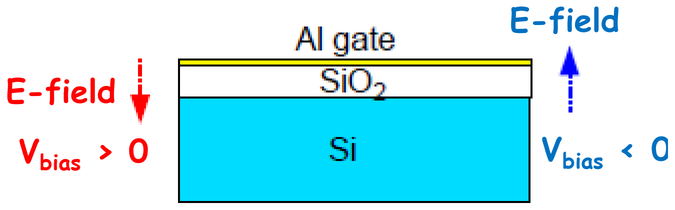
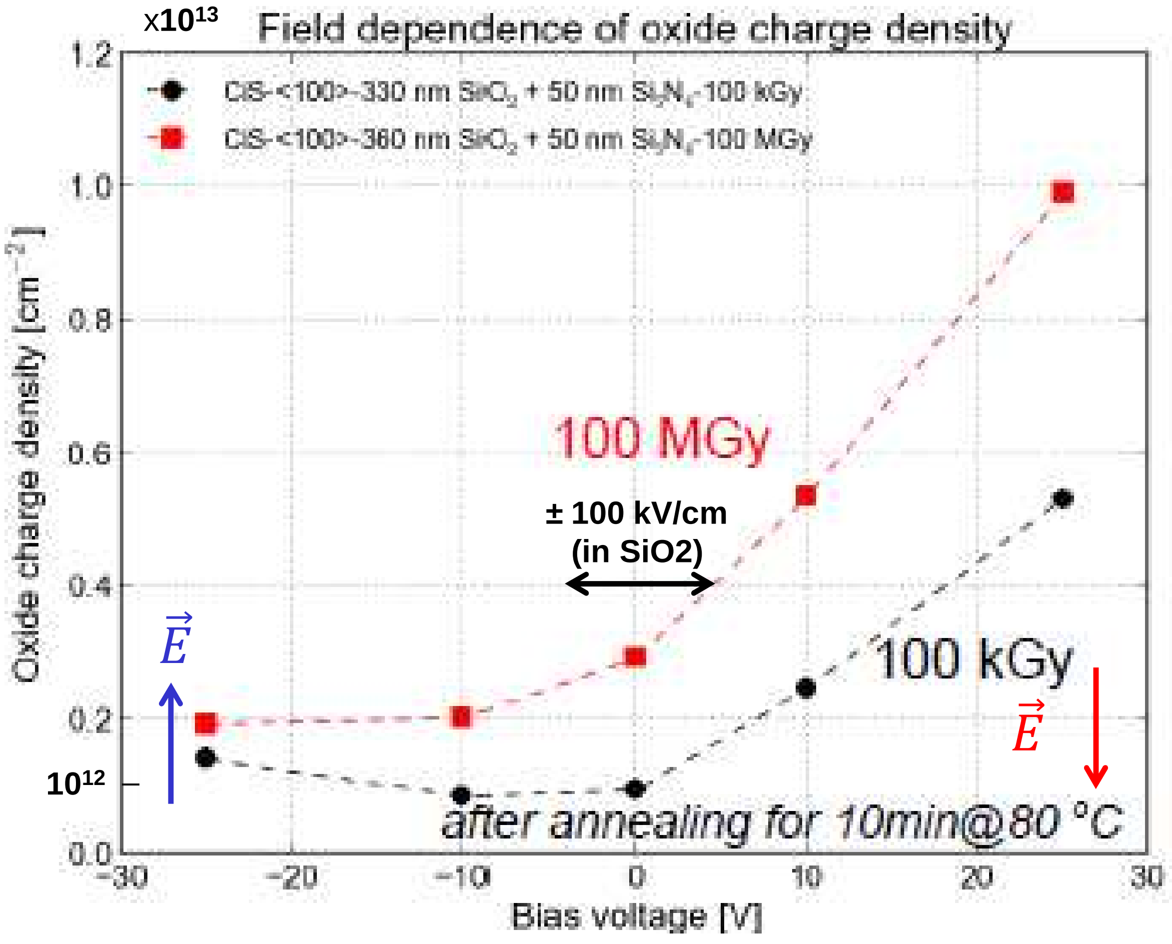
N_{ox}^{eff} with E-field during irradiation

Irradiation MOS-C and GCD with bias applied

- CiS <100> with ~350 nm SiO_2 + 50 nm Si_3N_4





E-field dependence:

V_{bias}>0: increase of N_{ox}

V_{bias}≤0: weak dependence

→ Significant effect not considered in simulations !

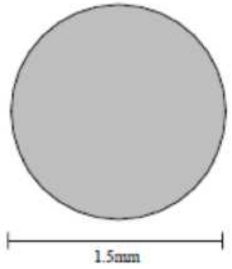
Field-enhanced oxide charges N_{ox}^{eff} before/after irr.

Border traps charged/discharged by h/e in E_T-field at Si-SiO_2 interface

→ position-dependent N_{ox}^{eff}

→ time dependence + saturation values

Circular MOS-C from CIS (350 nm SiO_2 + 50 nm Si_3N_4) on <100> and <111> n-Si for 0 and 1 GGy X-ray dose



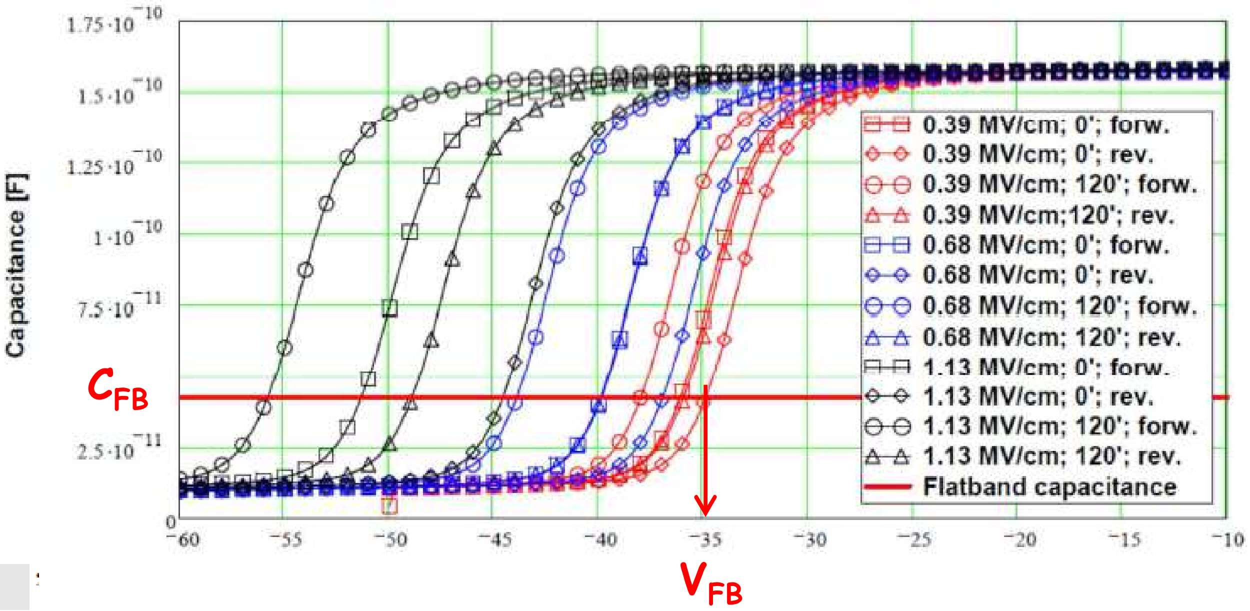
D.Brüske, BSC Thesis 2014

Biasing cycle C-V_{Gate}:

1. V_{gate} in accumulation
2. V_{gate} to inversion $E_{ox} = (V_{inv}-V_{FB})/d_{ox}$ (=forw. C-V curve)
3. V_{inv} for t = t_{bias}
4. V_{gate} to accumulation (=rev. C-V curve)

→ V_{FB} for 2. and 4.

→ Calculate N_{ox}

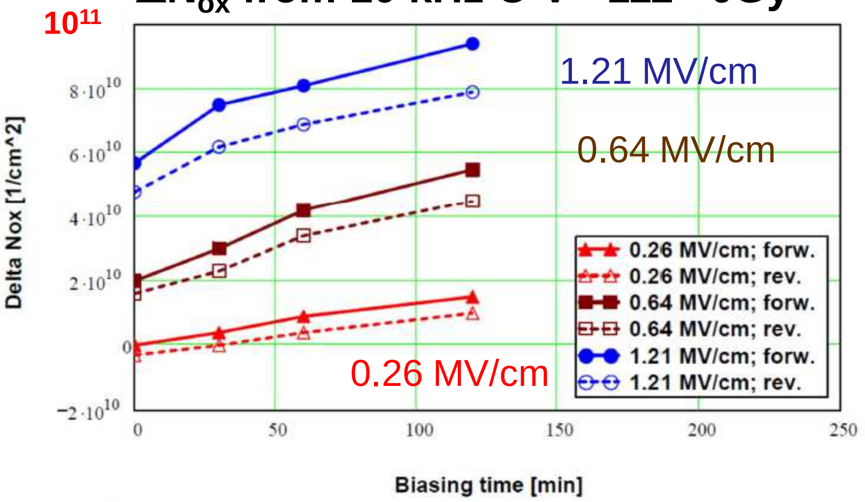


3.: $\Delta N_{ox} > 0$ → Field-enhanced injection (charging of border traps by h-inv. layer)

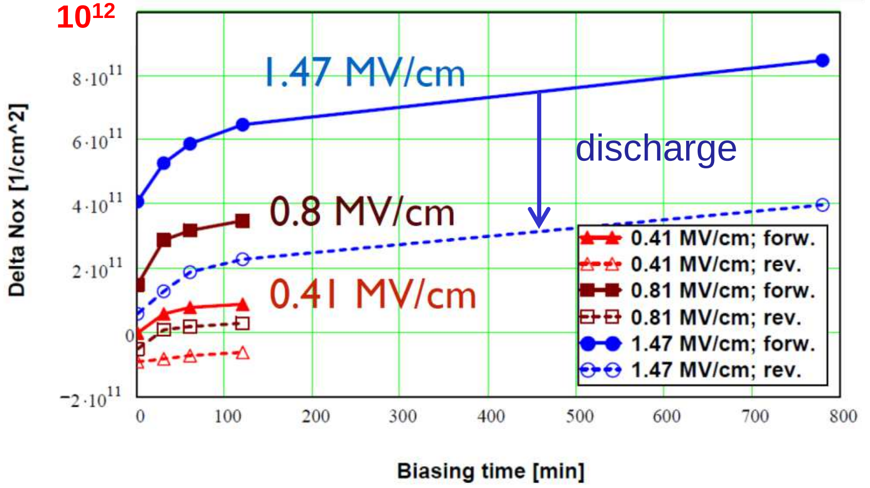
4.: $\Delta N_{ox} < 0$ → Discharging of border traps by e-accumulation layer

Field-enhanced oxide charges N_{ox}^{eff} before/after irr.

ΔN_{ox} from 10 kHz C-V <111> 0Gy



ΔN_{ox} from 10 kHz C-V <100> 1GGy

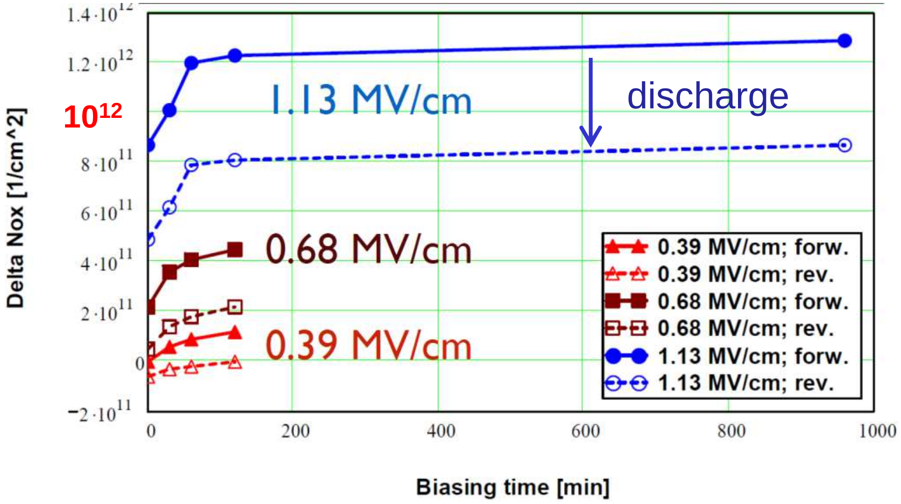


- Field-enhanced charge injection (FeCI) + discharge in accumulation observed
- Saturation reached after ~ 2 h
- 0 Gy: FeCI < 20% N_{ox}^0
- 1 GGy: FeCI up to 50% N_{ox}^0

  FeCI(<111>) > FiCI(<100>)

→Simulation for irradiated sensors to be done to see if relevant for surface-damaged sensors

ΔN_{ox} from 10 kHz C-V <100> 1GGy



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

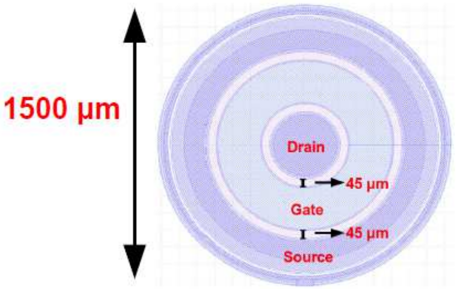
Idea: MOSFET characteristics

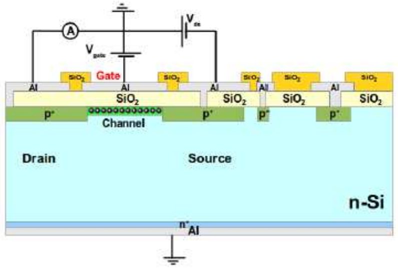
$$\underbrace{I_{ds}(V)}_{\text{measure}} = \underbrace{\frac{C_{ox}}{A_{gate}} \cdot \frac{W}{L}}_{\text{geometry}} \cdot \underbrace{\frac{\mu_0}{1+(V-V_{th})/V_{1/2}}}_{\text{mobility}} \cdot \underbrace{V_{ds}}_{\text{fix}} \cdot (\underbrace{V}_{\text{Vary } V_{gate}} - V_{th})$$

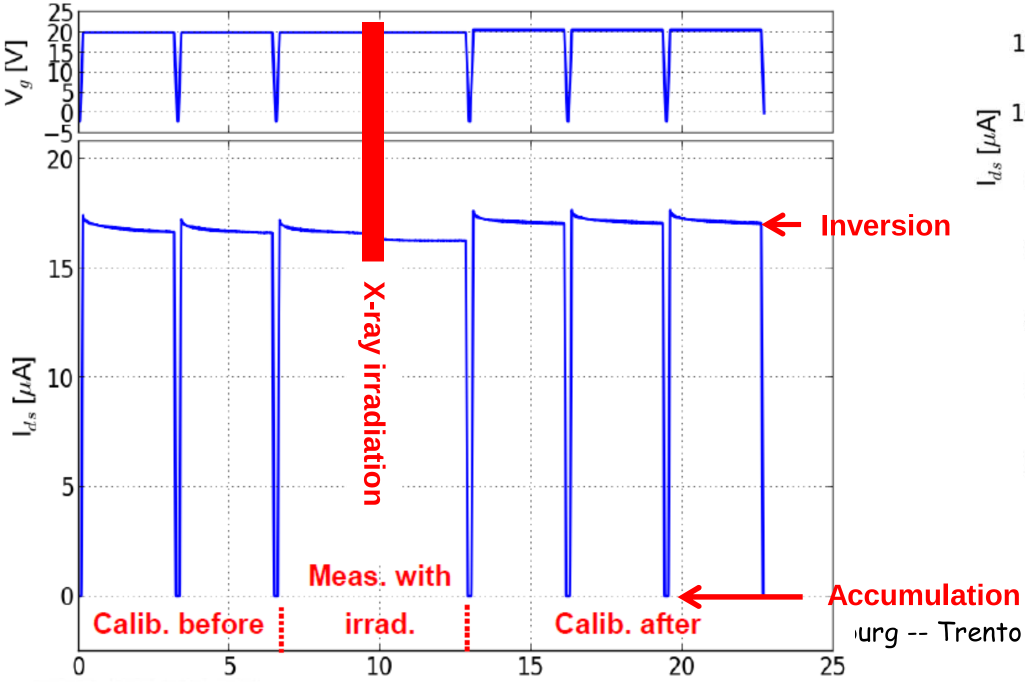
1. Calibrate $I_{DS}(V_{gate})$ for const. V_{DS}
2. Fix V_{gate} and measure $I_{DS}(t)$ and calculate $V_{th}(t)$
3. Calculate $N_{ox}(t)$ from $V_{th}(t)$

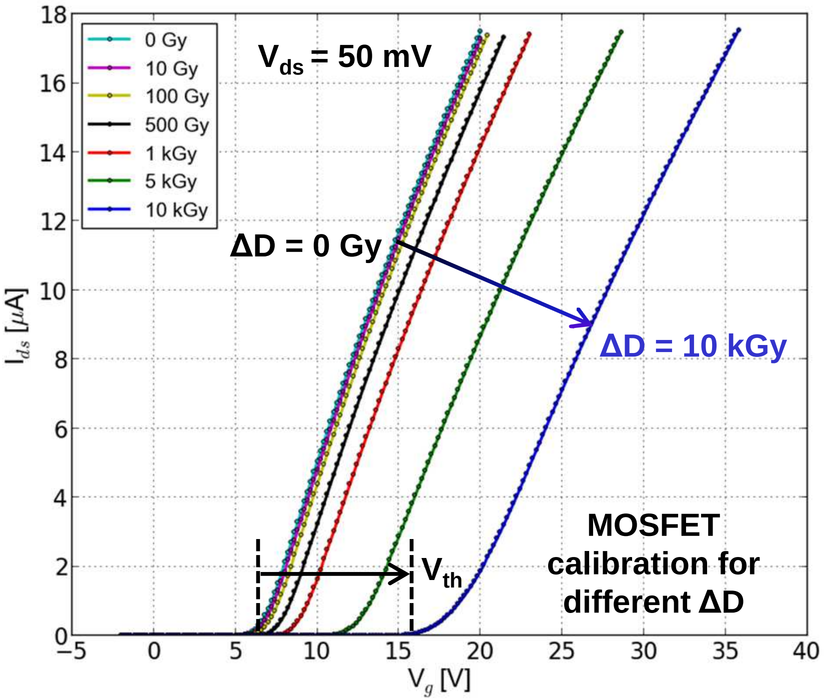
Difficulty: $\mu_0(N_{ox})$ and $V_{1/2}(N_{ox})$

(→ several calibrations before/after irr.)









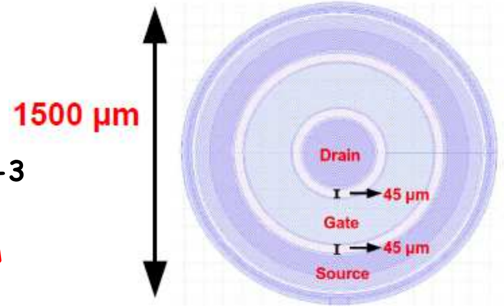
MOSFET calibration for different ΔD

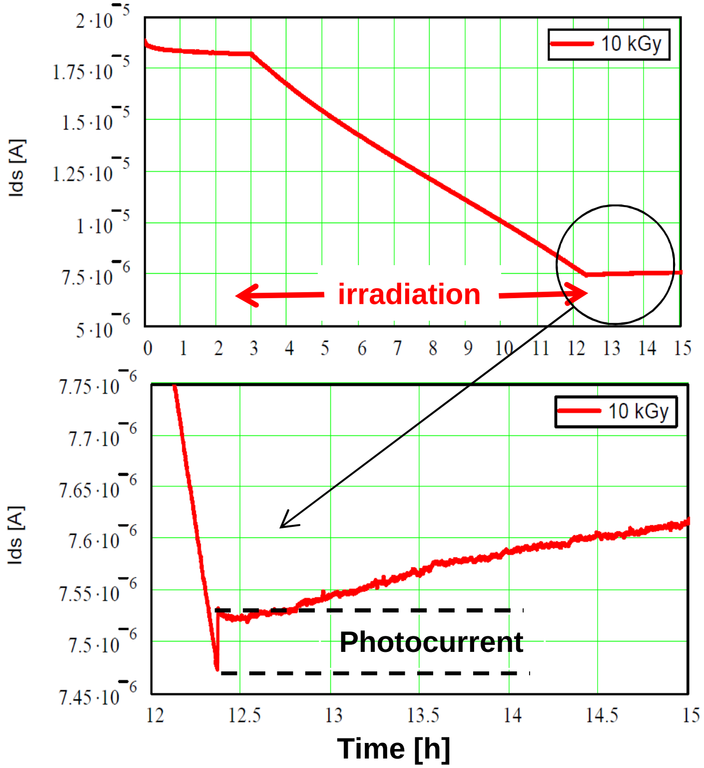
Field-enhanced N_{ox}^{eff} before/during/after irradiation

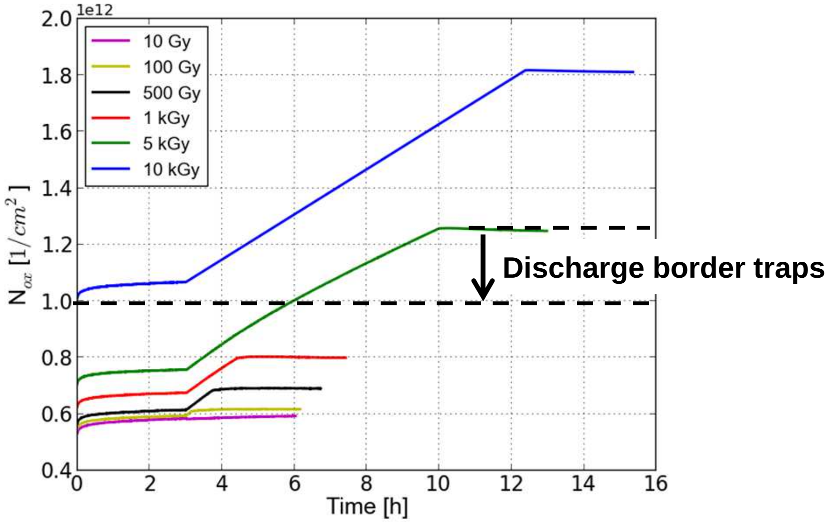
X-ray irradiations:

- 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=10 kGy irradiation for E ≈ 500 kV/cm







Significant reduction of $Q_{border\ traps}$ in accumulation

E-field does not cause anomalous short-term effects during or after X-ray irradiation

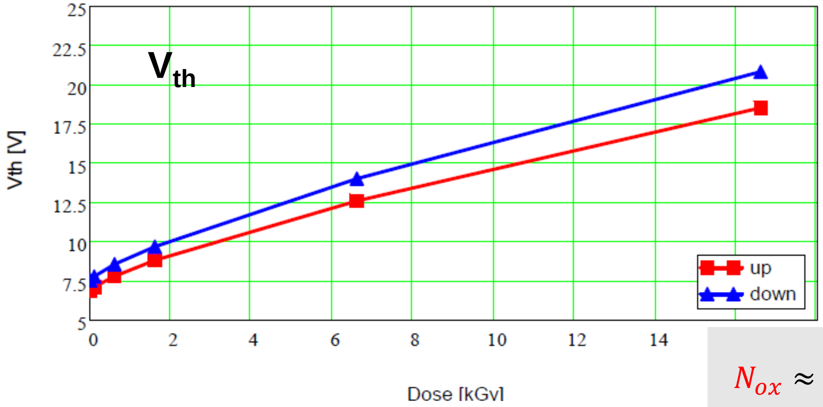
X-ray damage and hole mobility at interface

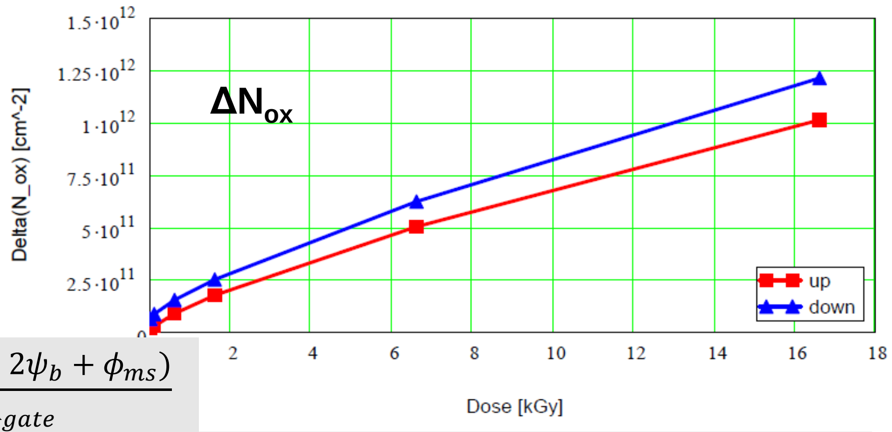
p-MOSFET allows to determine N_{ox}^{eff} + μ_p(Dose, E-field, time,…)

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

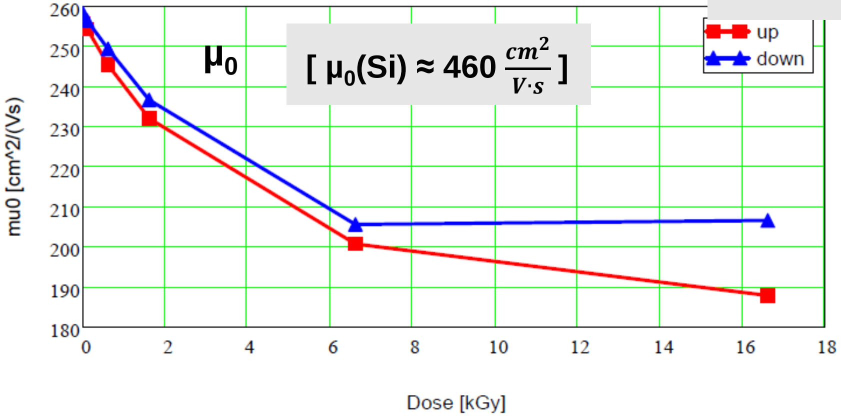
μ_0 … mobility at interface for $E_T = 0$

$V_{1/2}$ … reduction of μ by factor 2

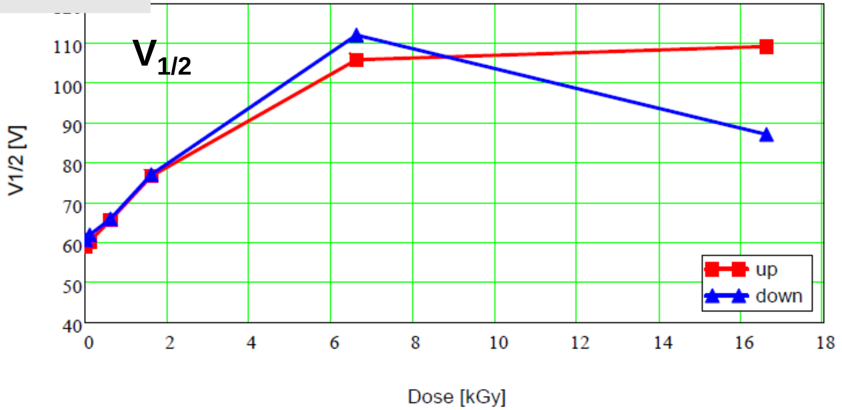




$$N_{ox} \approx \frac{C_{ox} \cdot (-V_{th} + 2\psi_b + \phi_{ms})}{q_0 \cdot A_{gate}}$$



[μ_0(Si) ≈ 460 $\frac{cm^2}{V \cdot s}$]



N_{ox} and ΔN_{ox} values compatible with previous determinations with E-field

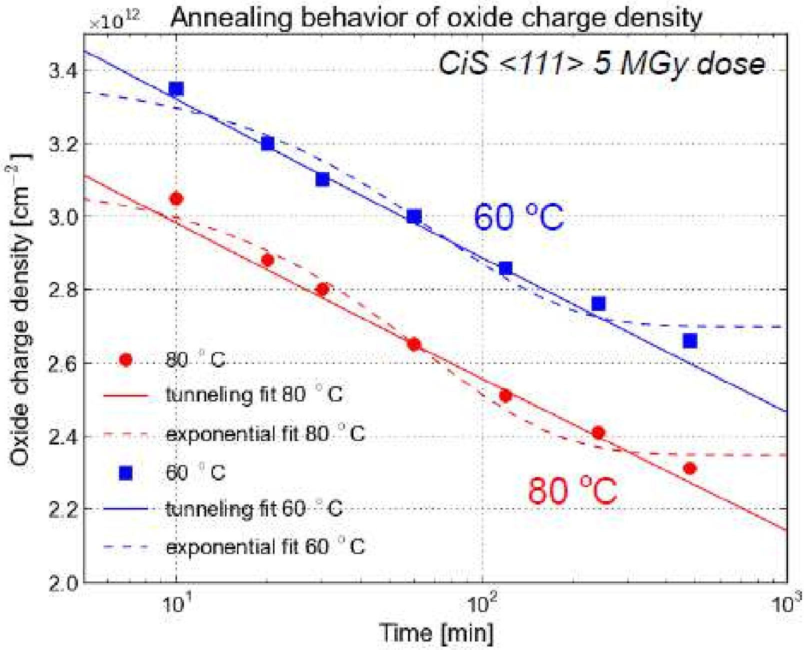
Values of μ (E_T, Dose) now available for simulations

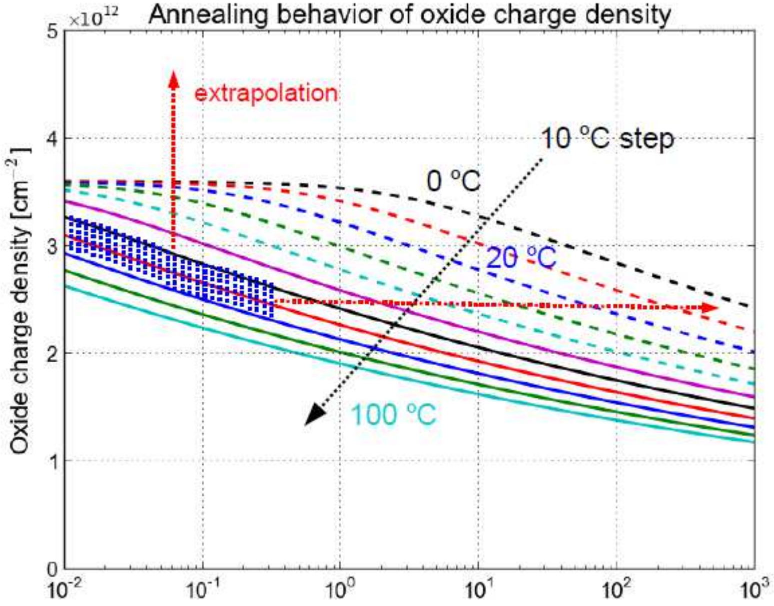
Annealing of N_{ox}^{eff}

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]

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

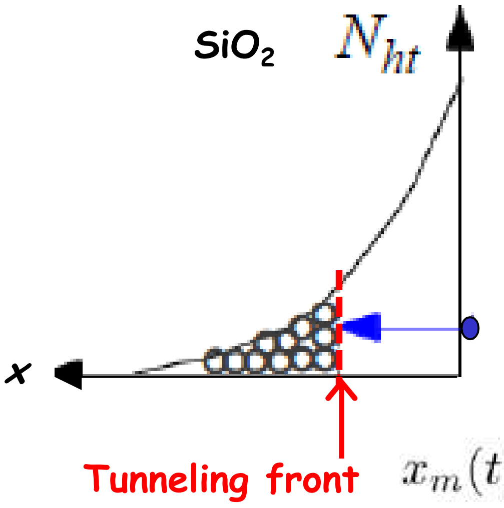
$1/\lambda$ … width of hole trap distr. in SiO_2
$t_0(T)$ … tunneling time constant
β … related to tunnel-barrier height
ΔE … $E_{trap} - E_{Fermi}$

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**

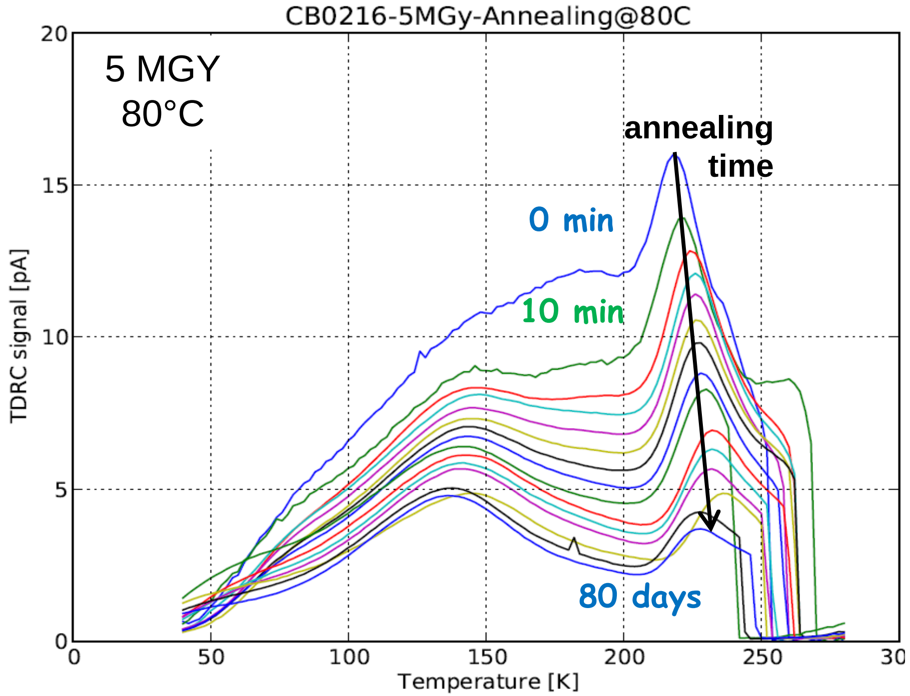
→ Slow N_{ox} annealing: At 20°C <50% annealing in 3 years (assuming model is correct!)

Annealing of N_{it} and J_{surf}

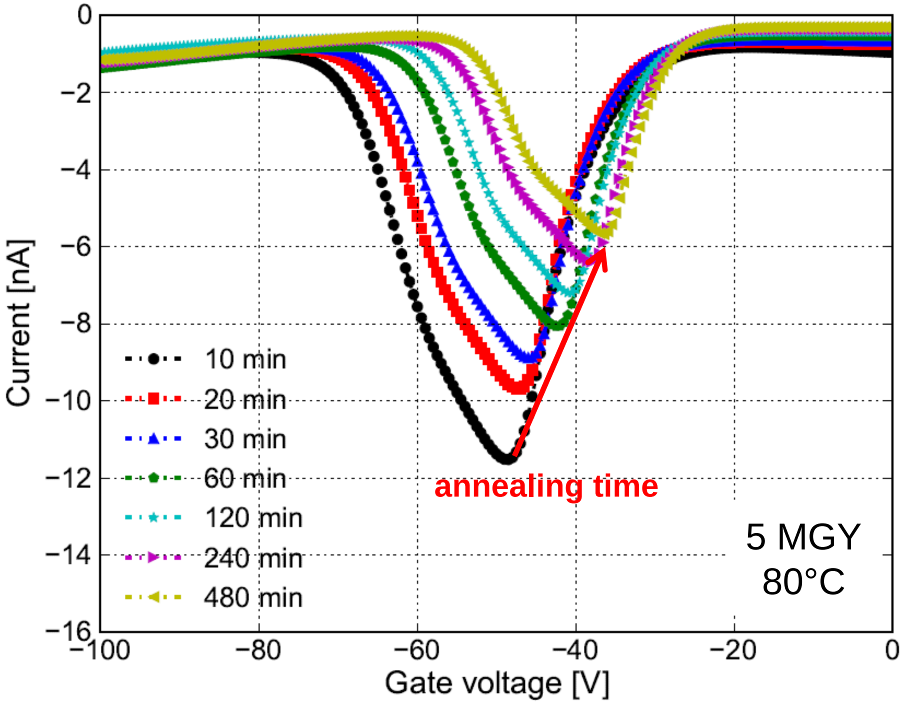
MOS-C + GCD irradiated to 5 MGy and annealed 80°C

- 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



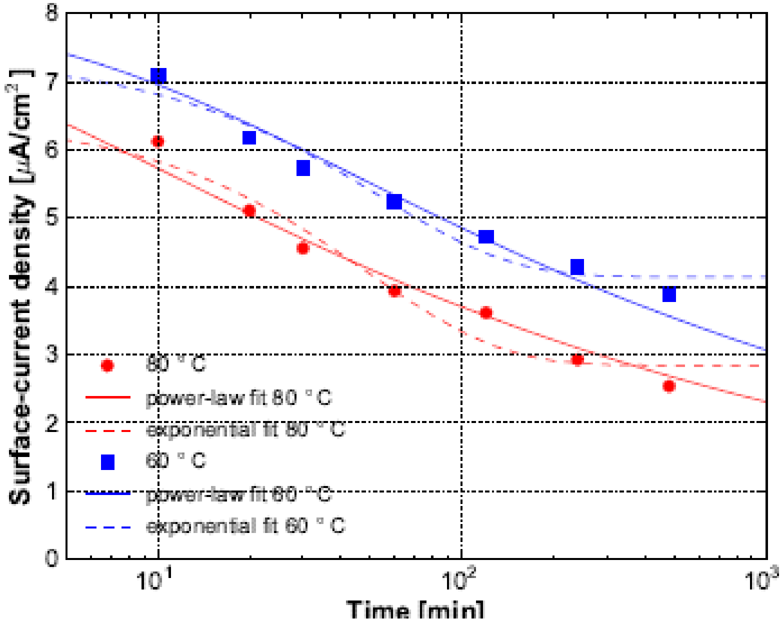
I_{surf} from GCD vs. annealing time at 80°C



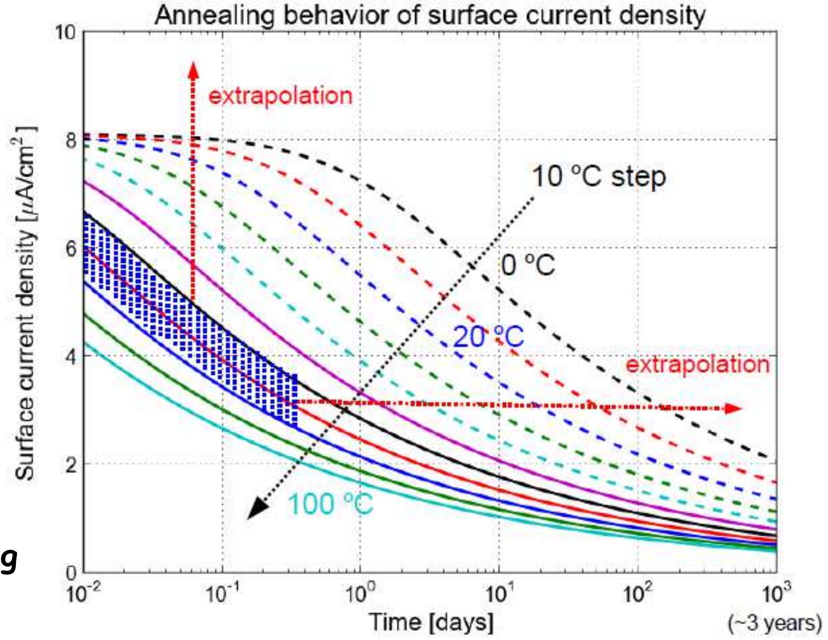
Annealing of J_{surf}

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]

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

η = $k_1/2k_2$
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})

Summary on N_{ox} and D_{it} vs ionizing dose

N_{ox} and D_{it} influences E-field in Si close to Si-SiO_2 interface

→ influences the presence/size of inversion/accumulation layers
→ can cause high-field regions → possible breakdowns
→ can cause changes in charge collection

Separate determination of N_{ox} and D_{it} not achieved → N_{ox}^{eff}, J_{surf}

→ values of N_{ox}^{eff} and J_{surf} for 0 to 1 GGy for <100>,<111> determined
  - saturation at ~ $(2\text{-}4)\cdot 10^{12}\,\mathrm{cm}^{-2}$ and $(3\text{-}6)\cdot \mu\mathrm{A/cm}^2$
  - increase in the presence of E-field
  - parameters for annealing (T,t) determined

Observe field-enhanced charging and discharging of border traps

→ for E-field + holes @ Si-SiO_2 interface (inversion for nMOS-C):
  - charging of border traps saturates in ~120 min
  - for <111> and high X-ray doses increase in N_{ox}^{eff} by up to 50 %
  - no bad surprises during and shortly after X-ray irradiation

→ for electrons @ Si-SiO_2 interface (accumulation for nMOS-C)
  - prompt discharging of a fraction of the border traps

Dependence of hole mobility at the Si-SiO_2 interface determined

Measurement and analysis methods + parameters for simulations

Comparisons of simulations and measurements

1. AGIPD pixel sensor – optimization for X-ray hardness:
   Pixel sensor for X-ray doses 0 – 1 GGy and V_{bd} > 900 V
   → J. Schwandt, PhD thesis
2. Breakdown in p^+n strip sensors after irradiation with ionizing radiation
   → J. Schwandt, PhD thesis
3. Observation of low dose effects in an HPK n^+p strip sensor
   → next (detailed paper under discussion in CMS Tracker Group)

Sensors + irradiation

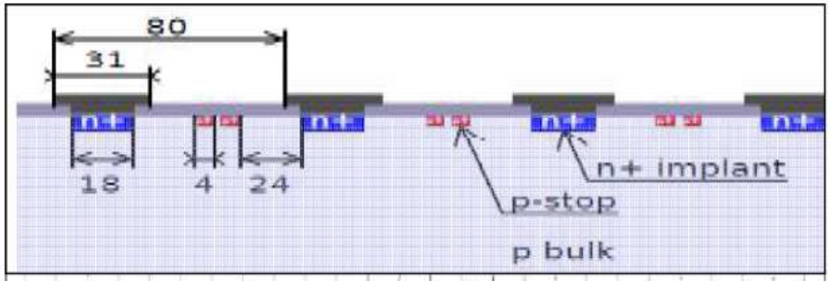
"Baby add. from HPKCampaign"

- FZ p-doping: $3.7 \cdot 10^{12}$ cm^{-3}
- [O]: ~$5 \cdot 10^{16}$ cm^{-3}
- ➢ p-spray: ~$5 \cdot 10^{10}$ cm^{-2}
- ➢ p-stop: ~$2 \cdot 10^{11}$ cm^{-2}
- 64 AC-coupled strips
- Strip length: 25 mm
- Pitch: 80 µm
- Implant width: 19 µm
- Al overhang: 5 µm
- d_{Si}: 200 µm
- d_{SiO2}: 650 nm + 130 nm
- d_{Si3N4}: 50 nm

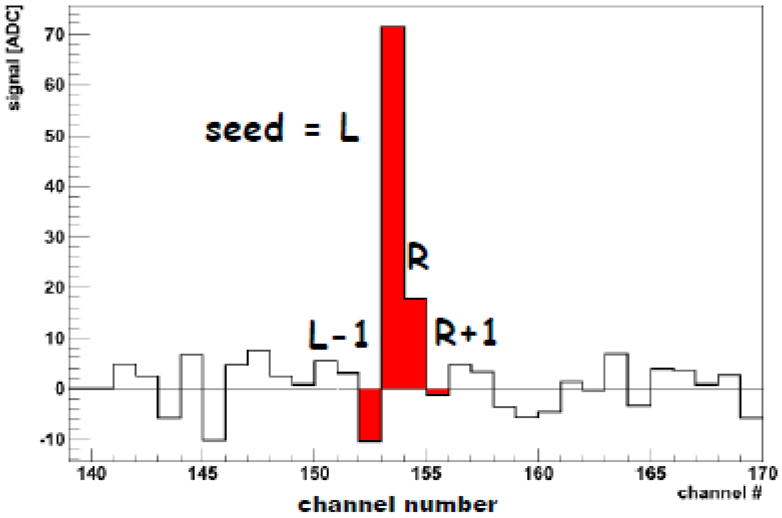
Measurement+irradiations:

- ^{90}Sr electrons 50 Gy/day, 2mm Ø
- Trigger: 2 scintillators
- Readout: ALiBaVa 40 MHz
- Vbias=600 V; T = -20°C

Details of sensor layout (p-stop):



Strip pulse heights for single event

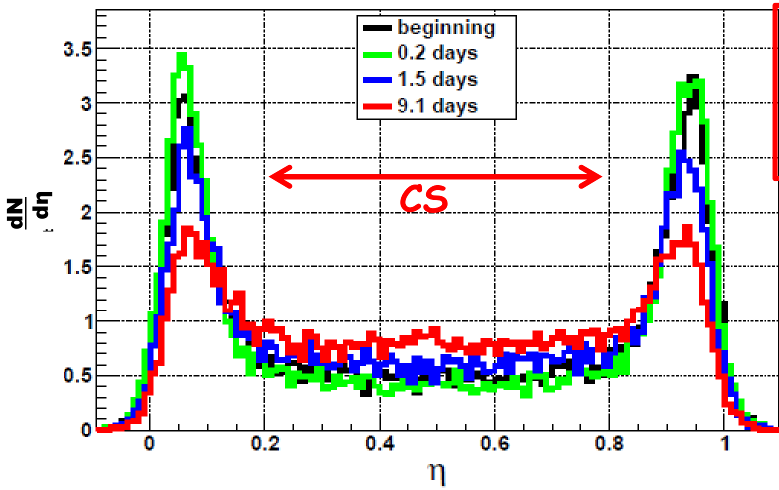


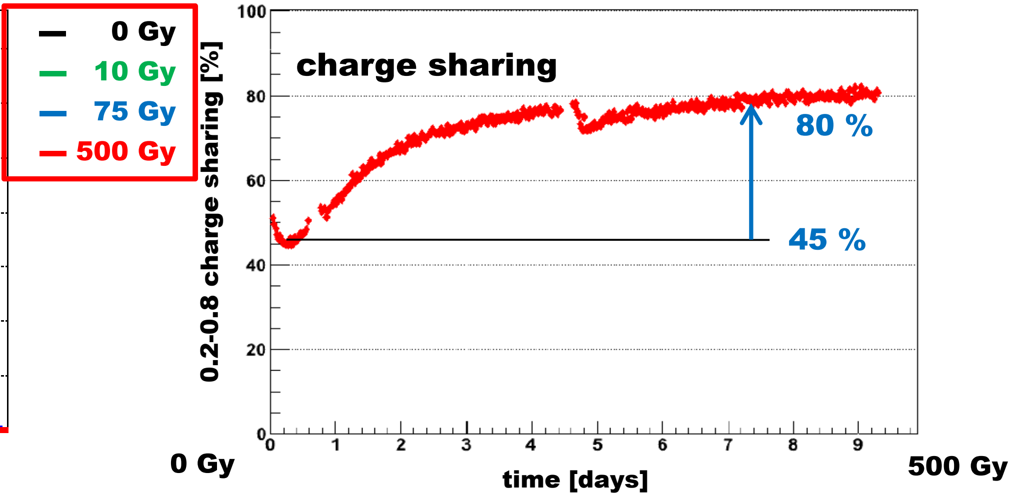
Analysis:

4-cluster = ΣPH(L-1,L,R,R+1)

η = R/(R + L)

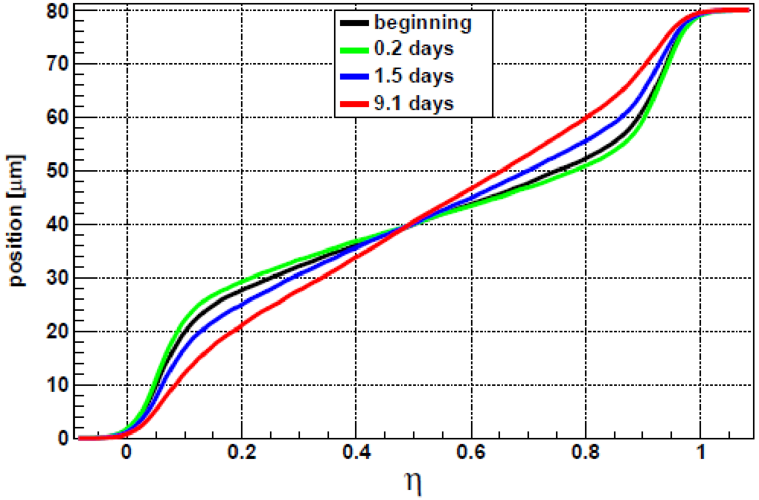
Observations for V_{bias} = 600 V (p-stop sensor)

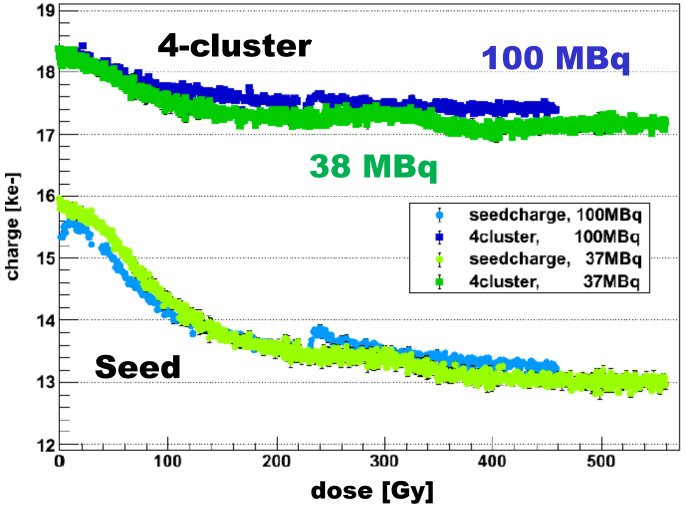




Significant increase in charge sharing@low dose

Increase in charge sharing





Change of η vs. position relation

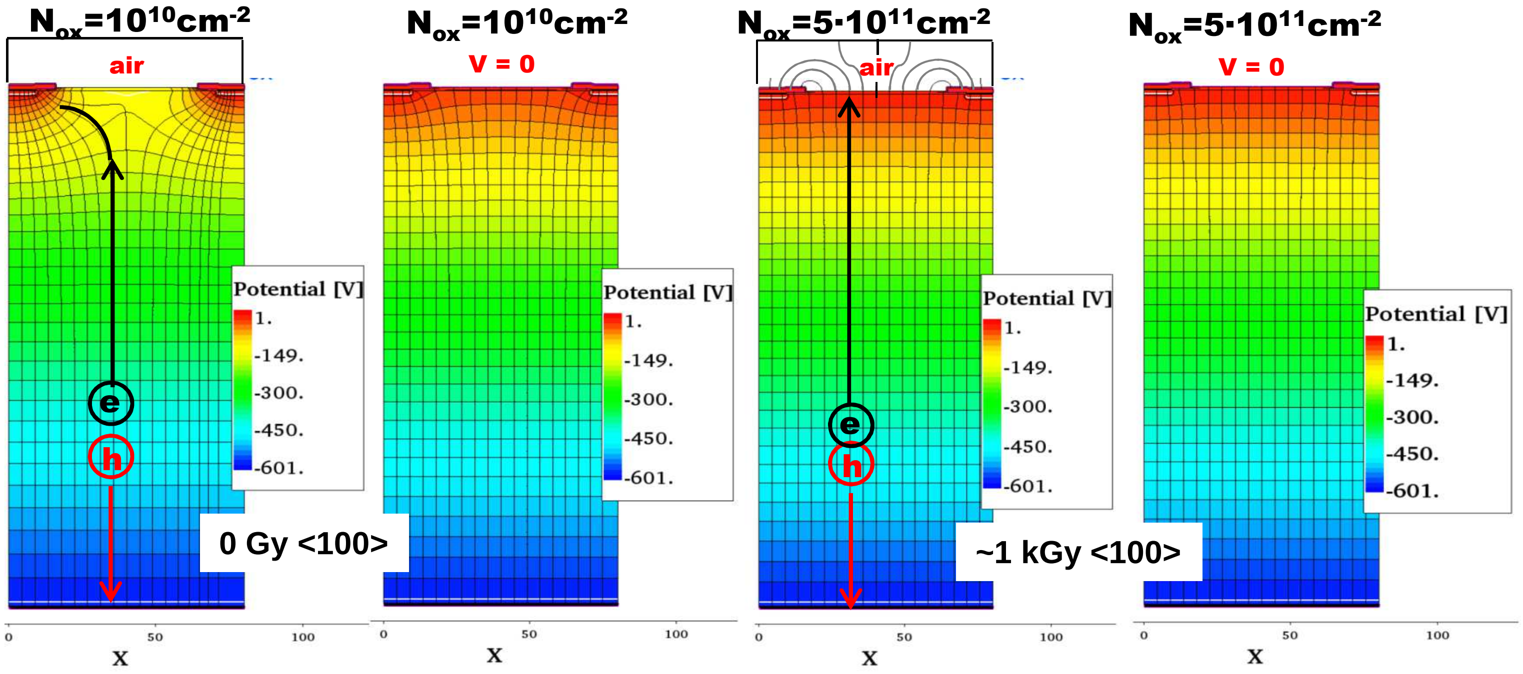
Change depends on dose – not on dose rate

Synopsys TCAD simulation of p-spray sensor vs. N_{ox}

Results of simulations depend also on boundary conditions:

1. "Dirichlet": SiO_2 surface on potential of readout strips (0 V)
2. "Air": 500 μm above strips Dirichlet with potential of readout strips

$N_{pspray} \sim 2.5 \cdot 10^{11} cm^{-2}$



Similar simulations by Y.Unno et al., NIM-A(2013)183

$N_{ox} < N_{p\text{-}spray}$: E-field lines end at readout strips → no charge sharing

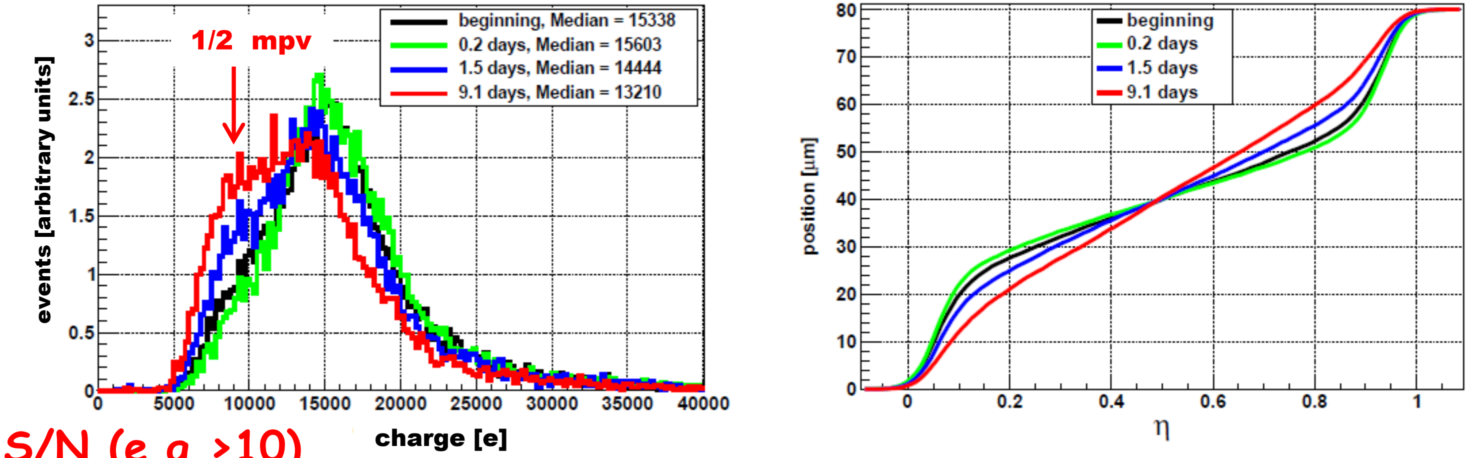
$N_{ox} > N_{p\text{-}spray}$: E-field lines end at Si-SiO_2 interface → charge sharing

Increase of oxide charge density N_{ox} → Change of charge sharing

Relevance for sensor design

Impact depends on S/N, readout scheme, track angle, dose, etc.

Here only qualitative discussion – needs quantitative estimation for a specific design



Good S/N (e.g.>10)

- **analog readout**: **C**harge **S**haring improves the position resolution (δ ~ 1/(dx/dη))
- **binary readout**: **CS** improves the resolution and worsens the track separation

Poor S/N (e.g.<10)

- **analog readout**: as long as low signal pulses are red out, **CS** improves the position resolution
- **binary readout**: unless low threshold, loss in efficiency; threshold < 0.4·mpv → for 3σ noise cut S(cluster)/N > 7.5 required

Charge Sharing important for design of efficient sensor of similar importance as Charge Collection Efficiency

Summary and conclusions

Surface effects influence stability and performance of sensors

Methods established to measure relevant parameters R□, N_{ox}, J_{surf} (D_{it}), charging/discharging of border traps on test structures

Parameter values have been determined (technology dependence !!!), which are available for simulations

Special care with respect to boundary conditions and mesh has to be taken when implementing surface effects in TCAD simulations

Several puzzling observations could be explained

Your comments and suggestions are welcome

Can we understand these observations + avoid them ?

Yes we can - if we work hard !

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