Surface Damage
in Silicon Devices

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Outline

- Introduction
- Properties of SiO_2 and SiO_2-Si interface
- Experimental Techniques
- Radiation Damage
  - MOS and Gate-Controlled Diodes
  - Strip sensors
  - MOSFET

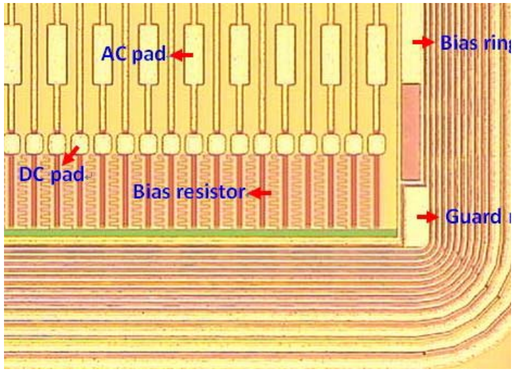
Introduction

- **What means surface damage?**
  Damage effects induced in silicon-oxide layers grown on silicon wafers and at the SiO_2-Si interface by ionizing radiation (charged particles, X-rays)
- **Where one has to take into account?**
  - Silicon tracker in HEP Collider-Experiments (LHC, S-LHC, ILC,…), damage effects in sensors and electronics
  - Silicon Detector-Arrays in X-ray Free Electron Laser (XFEL) experiments – sensors and electronics
  - Space experiments
- **Typical dose values in different areas**
  S-LHC: ~ 4.2 MGy at r = 4 cm for an integrated luminosity of 2500 fb^{-1}
  XFEL: up to 1 GGy in about 3 years of continuous operation

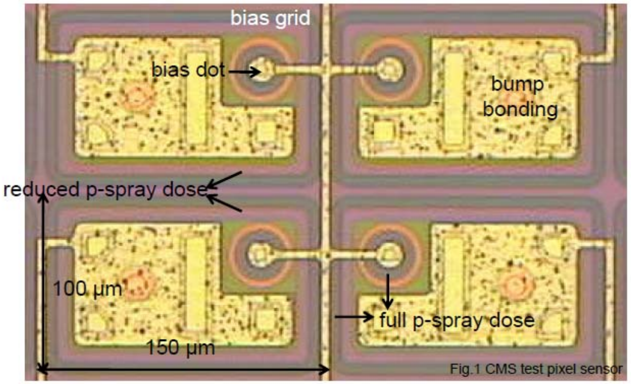
Typical Devices under Study

MOS test-field

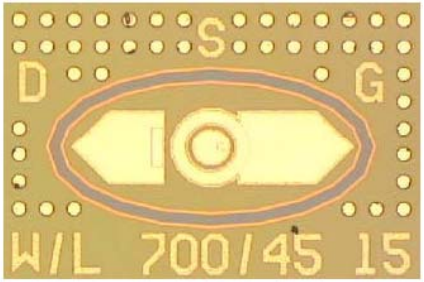
Strip Sensor



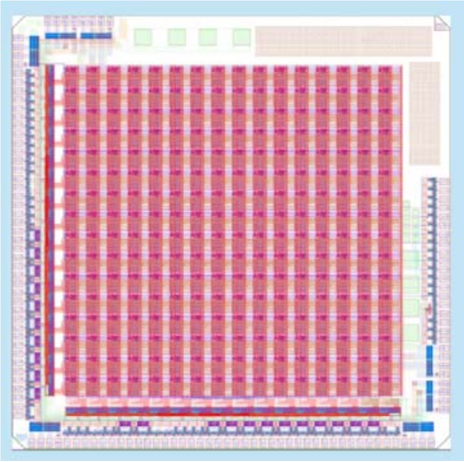
CMS Pixel sensor



N-channel MOSFET



AGIPD readout chip in 130 nm IBM CMOS



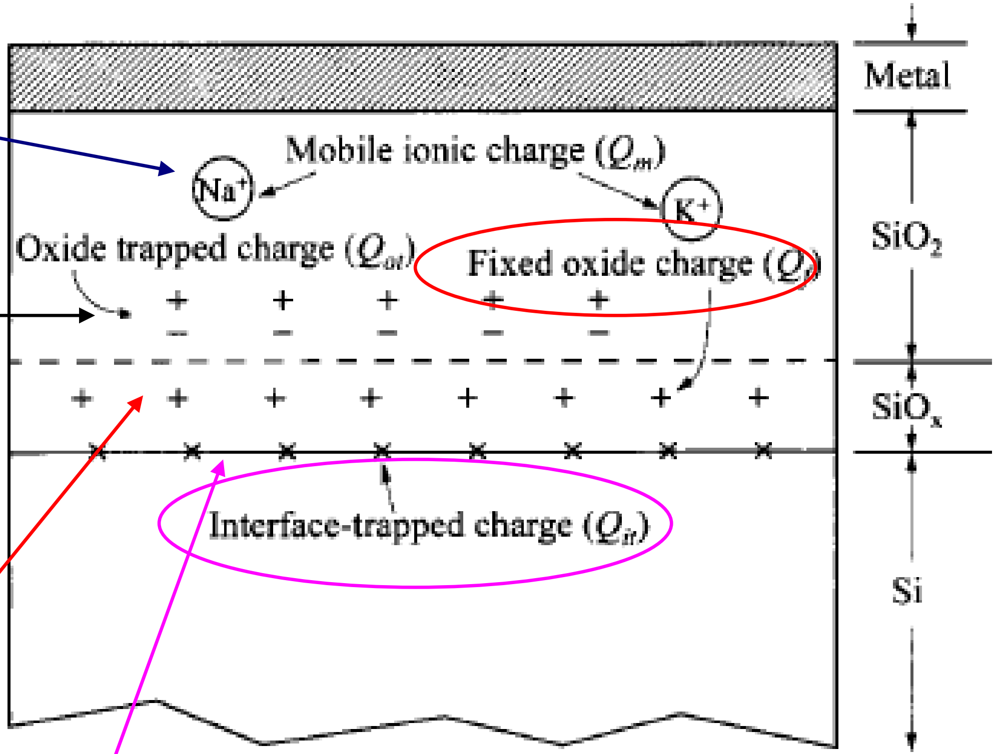
Properties of thermally grown SiO_2

Property	Value
Density	2.27 g/cm^3
Dielectric constant	3.4 (dry), 3.9 (H_20 ambient)
Refractive index	1.46
Dielectric strength	$5 - 10\times10^6$ V/cm
Energy gap	8.8 eV
Linear expansion coeff.	5×10^{-7} cm/K
Specific heat	10^{-3} J/(kgK)

Defects/Impurities in SiO_2

Mobile Ionic Charge Q_m
affected early stage MOS structures, not an issue today

Oxide Trapped Charge Q_{ot}
defects in the SiO_2 network, but difficult to communicate with free carriers

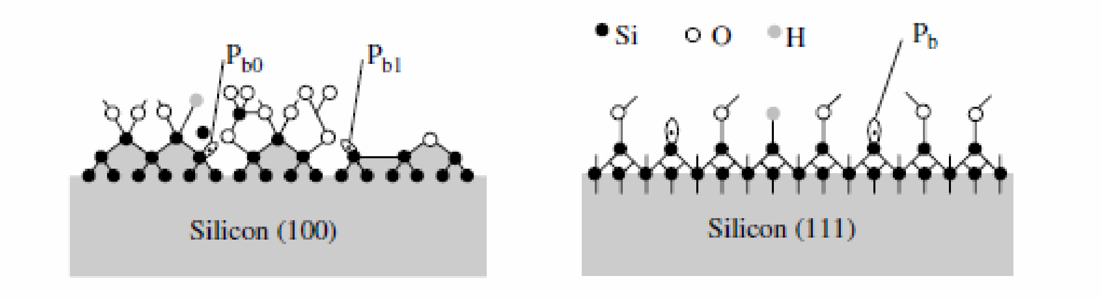


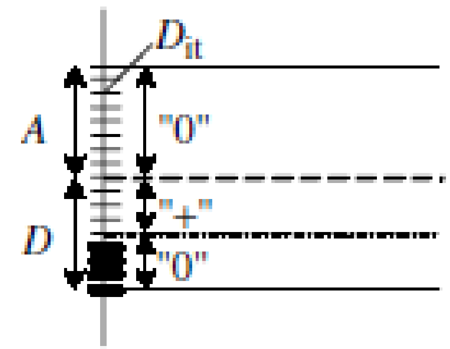
Fixed Oxide Charge Q_f
due to the hole trapping, ~ nm from interface, highly disordered region

Interface trap Q_{it}
due to dangling Si-O bonds with energy states in the forbidden band

SiO_2-Si interface

Structural imperfections between Si bulk and SiO_2 layer → interface states D_{it}





A: Acceptors, D: Donors

Example for structural model of (100) and (111) Si interface

P_b center on (111) Si surface (detected by ESR):
interface trivalent Si atom with dangling bond aimed into a vacancy in the oxide

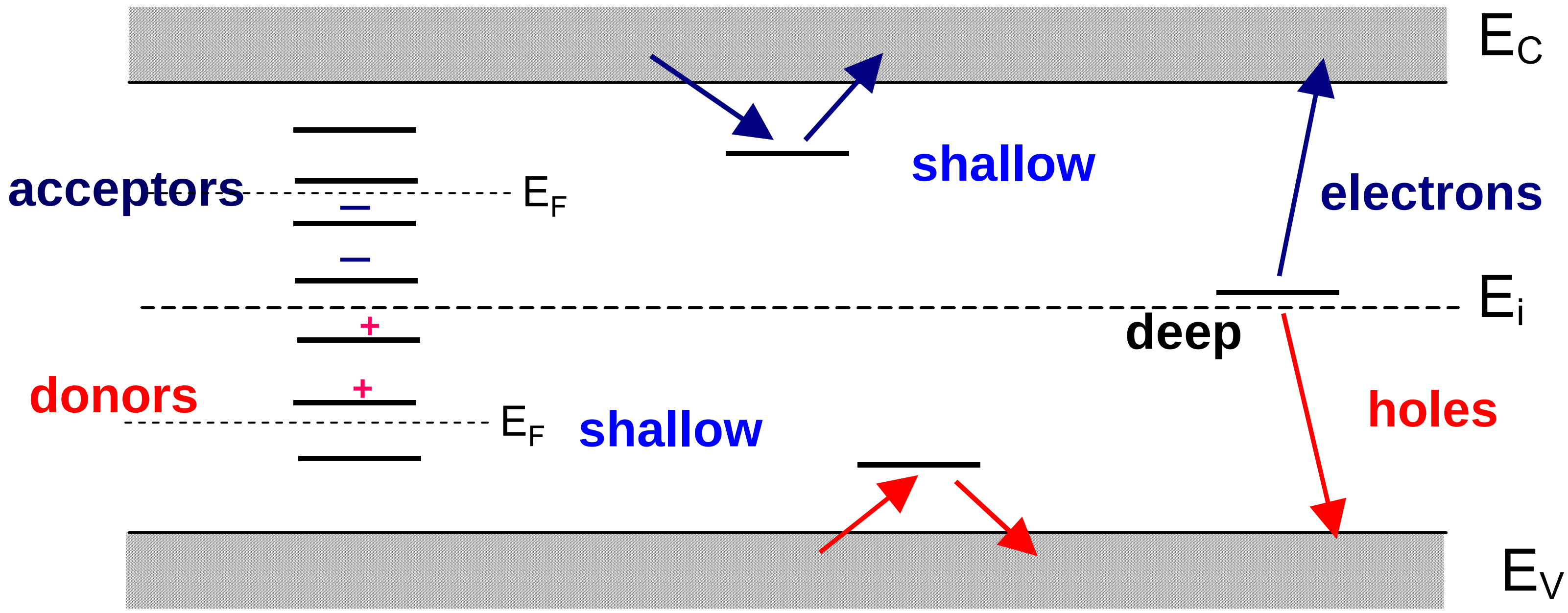
P_{b0} and P_{b1} on (100) Si surface:
chemically identical to Pb center but different configurations

D_{it} represent a continuum of states in the band gap and is given in units $(eVcm^2)^{-1}$

D.K. Schroder, Semiconductor Material and Device Characterization, Jon Wiley & Sons, Inc., 2006

Classification of Interface Traps

Capture/emission of charge carriers → Schockley-Read-Hall statistics



acceptors negatively charged if below E_F, otherwise neutral

donors positively charged if above E_F, otherwise neutral

Shallow traps → "fast" traps, responsible for frequency dependence of MOS C-V

Deep traps → generation/recombination centers, responsible for surface current

Summary Oxide - Interface Charges

- Mobile oxide charge Q_m : positive ions e.g. Na^+ (*negligible*)
- Trapped oxide charge Q_{ot}: defects in SiO_2 network (+ or -)
- Fixed oxide charge Q_f: traps near to the interface (trapped holes, Q_f positive)
- Interface-trapped charge Q_{it}: interface states with acceptor- or donor-character, occupation with electrons/holes depends on Fermi-level E_F at the interface

Experimental Techniques

- **MOS capacitor**

  Capacitance-Voltage characteristics (**C-V**) at different frequencies
  → information: flat band voltage V_{FB}, Q_f (N_f), Q_{it} (N_{it})
  Thermally Dielectric Relaxation Current (**TDRC**) for different bias voltage
  → information: $D_{it}(E_t)$ distribution in the band gap

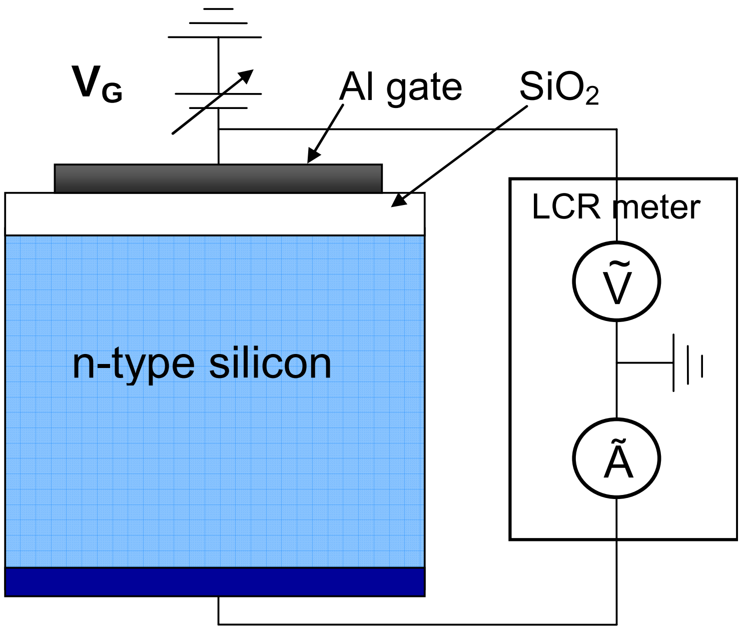
  Other techniques not presented here:
  Conductance method G(ω), quasi-static C-V, Deep Level Transient Spectroscopy (DLTS), Electron Spin Resonance (ESR or EPR)

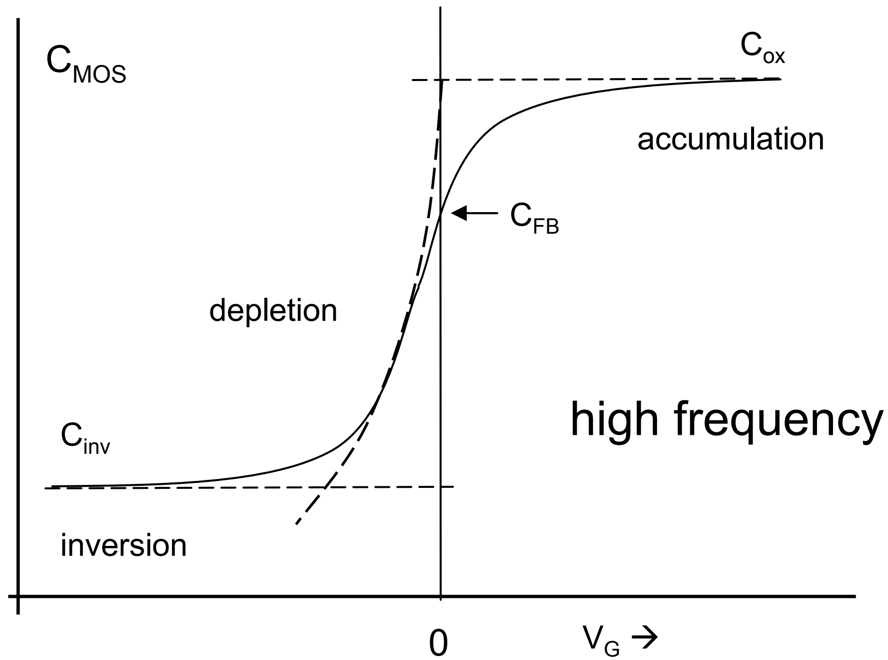
- **Gate controlled – Diode**

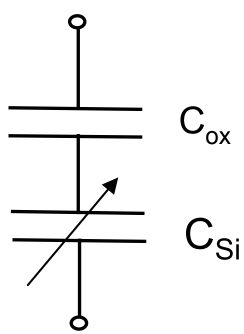
  Current-Gate Voltage characteristics for different junction bias voltage
  → information: surface recombination velocity S_0 or D_{it} at mid gap

MOS Capacitor (ideal)

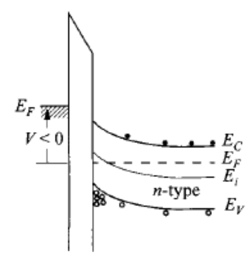
n-type silicon



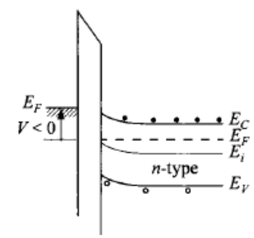




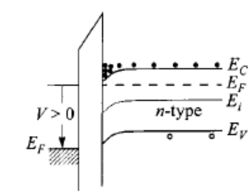
$$C_{MOS} = \frac{C_{ox} \cdot C_{Si}}{C_{ox} + C_{Si}}$$



inversion
(holes)



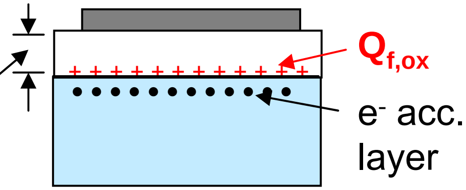
depletion
(Si space charge region)



accumulation
(electrons)

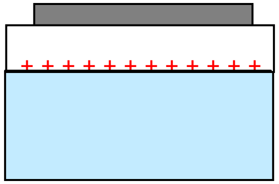
MOS Capacitor (real)

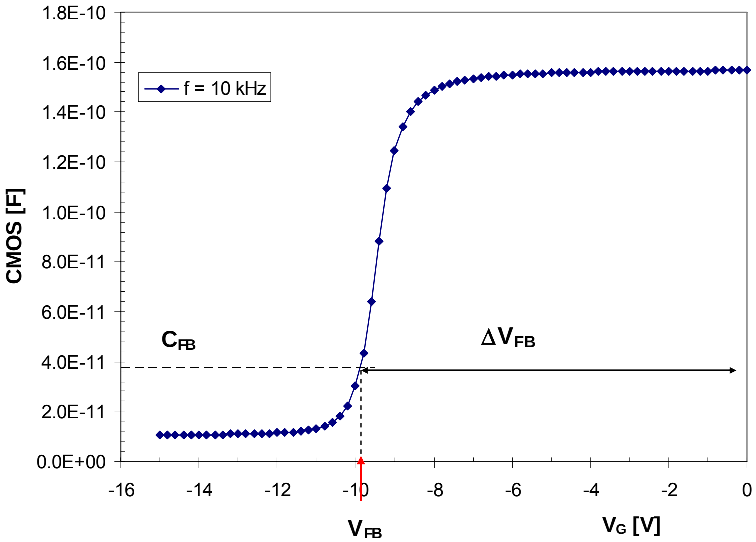
Accumulation: $C_{MOS} = C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$



Flat band: $C_{MOS,FB} = \frac{C_{ox} \cdot C_{FB,S}}{C_{ox} + C_{FB,S}}$

$C_{FB,S} = \frac{\varepsilon_S}{L_D}$ $\quad L_D = \sqrt{\frac{\varepsilon_S k_B T}{q_0^2 N_D}}$

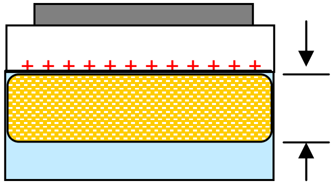




L_D = Debey length, N_D = Donor concentration

Flat band voltage shift $\quad -\Delta V_{FB} = \frac{Q_{f,ox}}{C_{ox}}, Q_{f,ox} > 0$

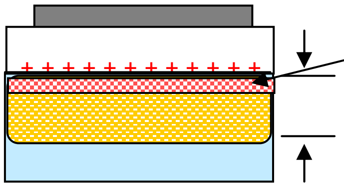
Depletion: $C_{MOS,D} = \frac{C_{ox} \cdot C_D}{C_{ox} + C_D}, \; C_D = \frac{\varepsilon_S}{w} \propto \frac{\varepsilon_S}{\sqrt{V}}$



Deep inversion: $C_{MOS,inv} = \frac{C_{ox} \cdot C_{inv}}{C_{ox} + C_{inv}}, \; C_{inv} = \frac{\varepsilon_S}{w_{\max}}$

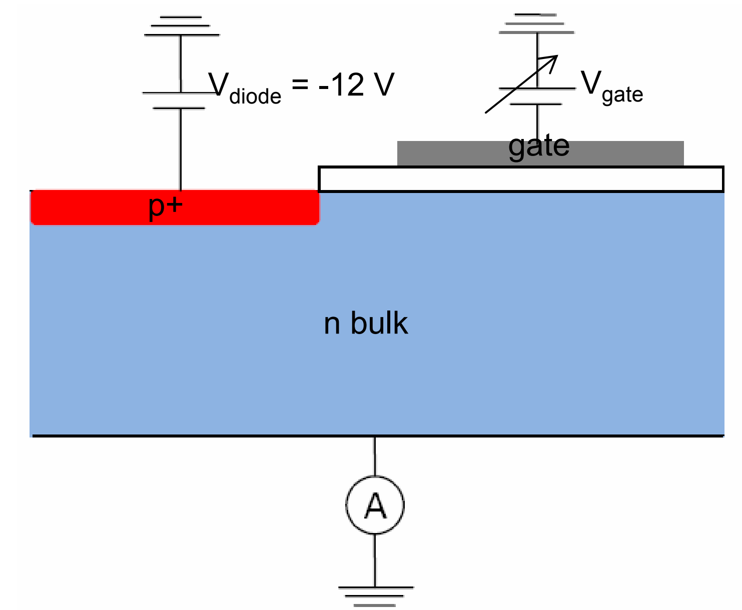
$$w_{\max} \propto \left(\frac{\ln(N_D / n_i)}{N_D} \right)^{1/2},$$

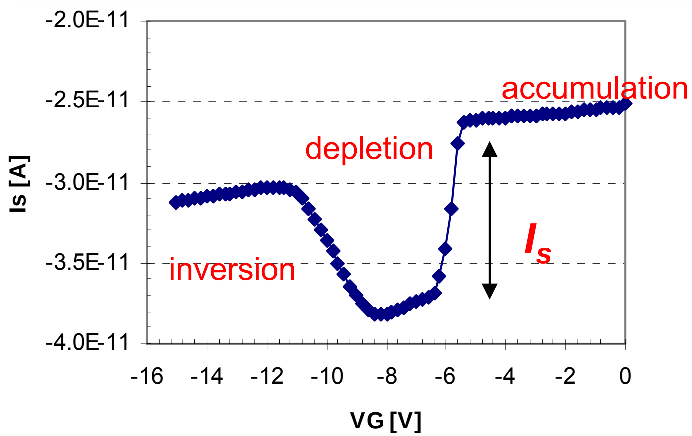
n_i = intrinsic carrier concentration

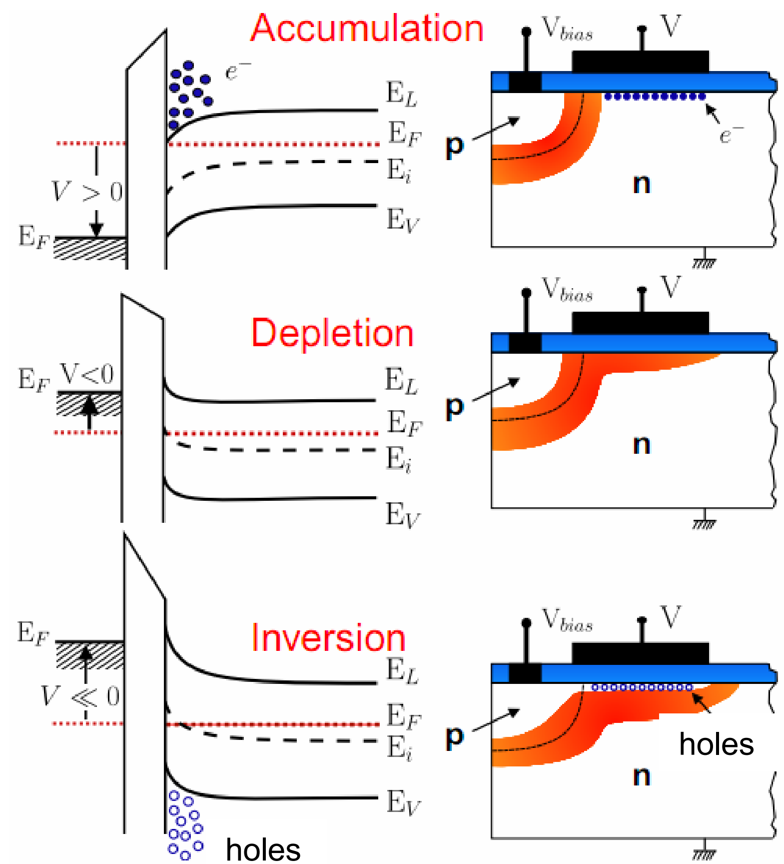


Gate Controlled Diode

Surface current density J_s due to deep interface states N_{it}

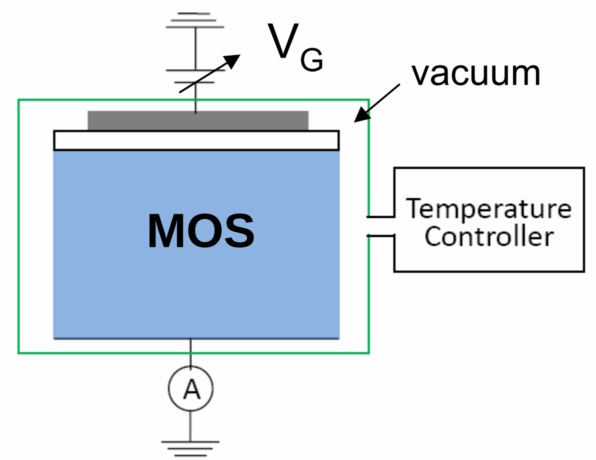






Surface recombination velocity: $$S_0 = \frac{I_s / A_{gate}}{q_0 \cdot n_i}$$

Thermally Dielectric Relaxation Current TDRC

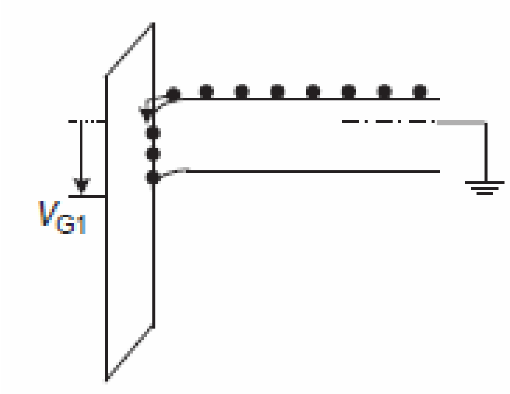


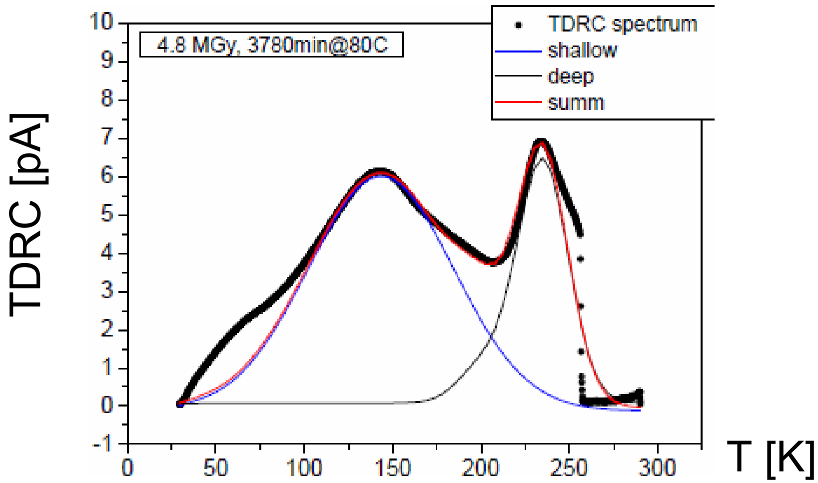
<u>Cooling down</u>:

$V_{G1} \geq 0$ V

Electron accumulation

Interface traps filled with electrons

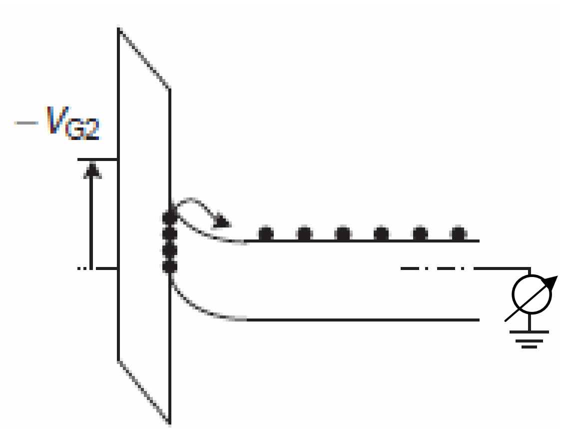




<u>At T = 30 K</u>:

$V_{G2} < 0$ V, depletion

Heating up with constant rate → trapped electrons will be emitted, depending on $D_{it}(E_t)$ and T → $I_{TDRC}(T)$



Radiation Damage

Basic effects induced by ionizing radiation (X-rays, charged particles)

(1) e-h pair creation

(2) hole transport

- most e-h pairs recombine
- electrons escape
- holes are much slower and get finally trapped

depends on E-field in SiO_2

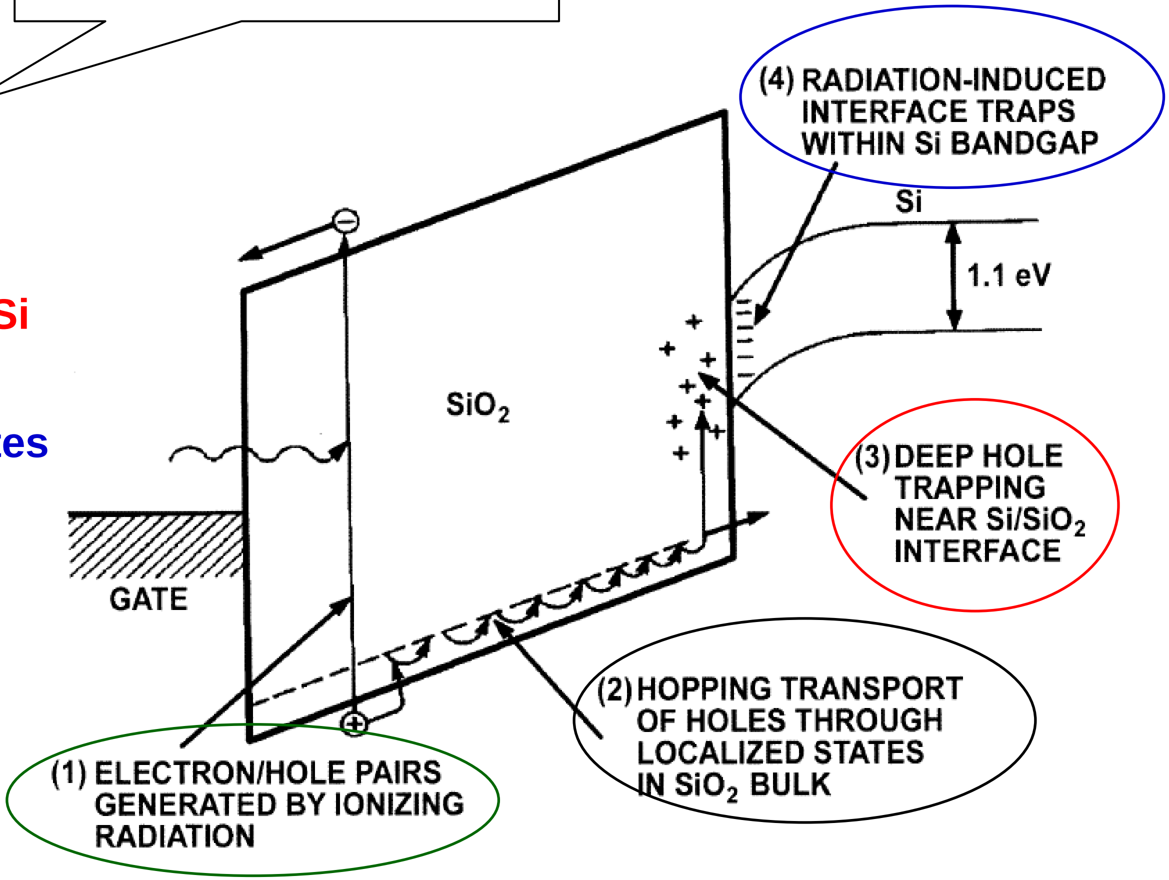
(3) hole trapping near SiO_2-Si interface Q_f

(4) Build up of interface states N_{it}

SiO_2

$\mu_e \approx 20\ cm^2/(Vs)$

$\mu_h \approx 5 \times 10^{-5}\ cm^2/(Vs)$



T.R. Oldham, Ionizing Radiation Effects in MOS Oxides, World Scientific, 1999

Unrecombined holes

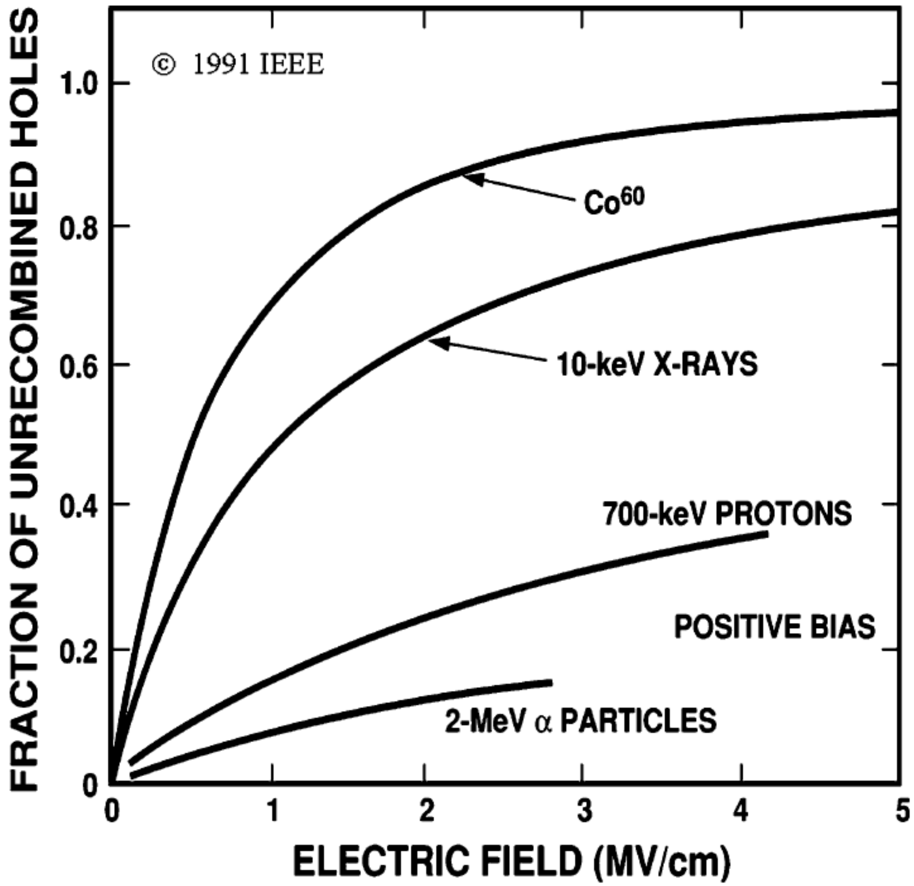
Buildup of $N_{f,ox}$

$$\Delta N_{f,ox} = D\,\kappa_g\,f_y\,f_{t,h}\,t_{ox}$$

D = *total dose*
κ_g = *e-h pair density per dose unit*
f_y = *fractional e-h yield*
$f_{t,h}$ = *hole trapping efficiency*
t_{ox} = *oxide thickness*

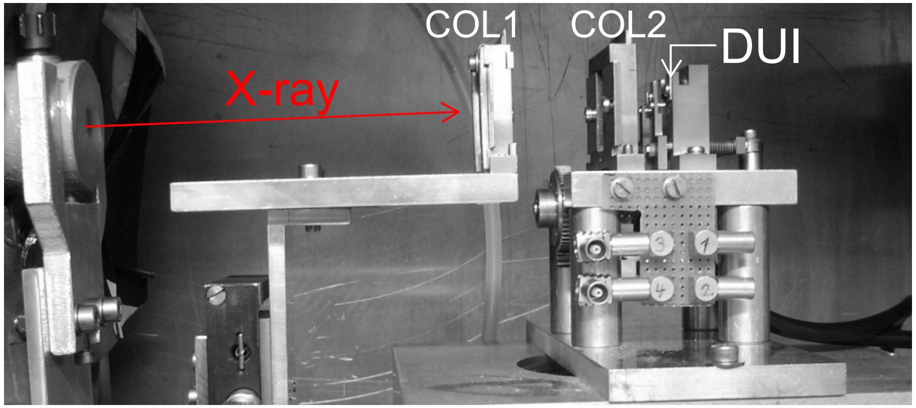
Buildup of ΔV_{FB}

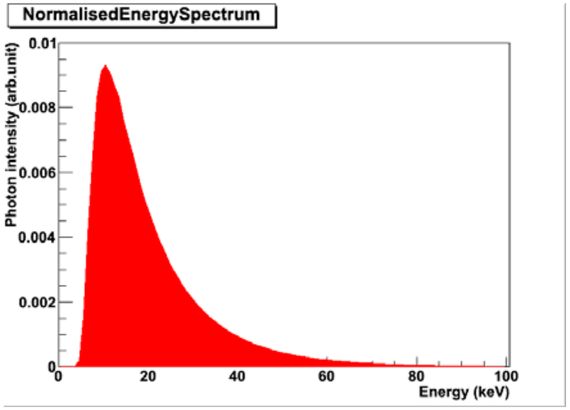
$$\Delta V_{FB} \propto t_{ox}\,\Delta N_{f,ox} \propto t^2_{ox}$$



H.J. Barnaby, IEEE TNS 53, NO.6, 3103, 2006

X-ray irradiation at DESY DORIS III



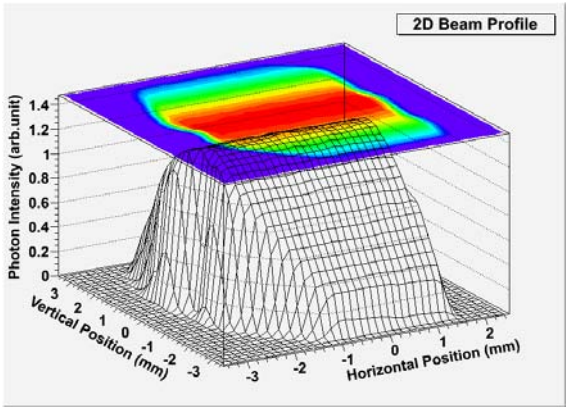


X-ray energy spectrum

Energy spectrum of photons:
- ***Typical energy: 12 keV***
- ***Flux density: 1.08 × 10^{14} /(s ·mm^2)***

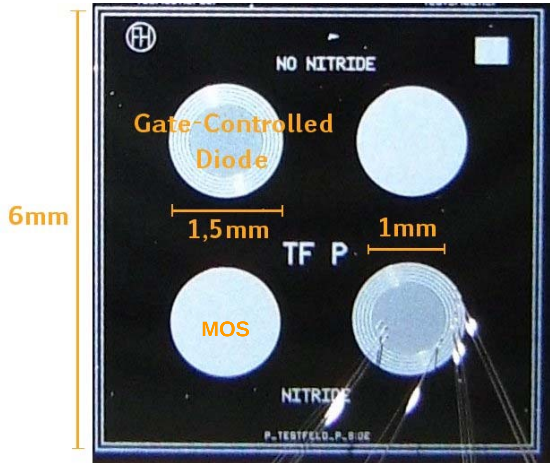
Beam profile:
- ***Beam spot: 4 mm × 6 mm***

Dose rate:
- ***Beam centre: 200 kGy/s***
- *2D scan: 500 kGy/scan*

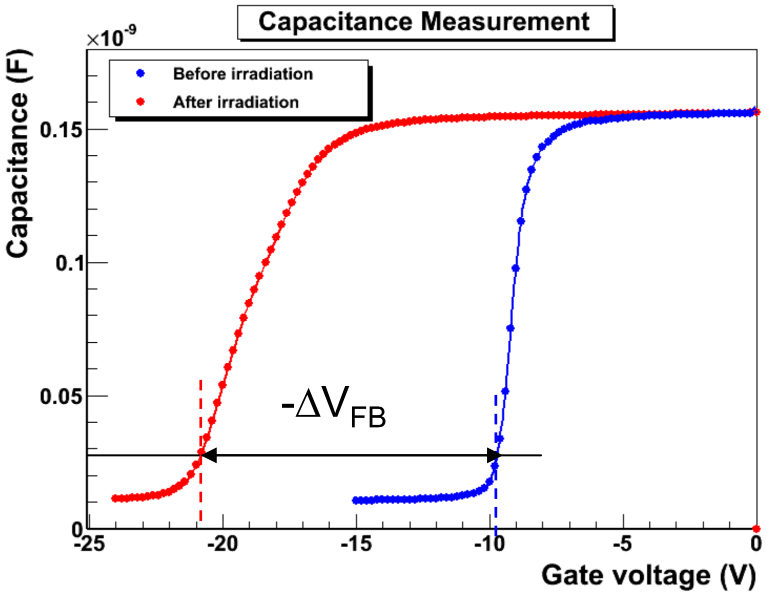


Beam profile at beamline F4

Flat Band Voltage Shift



Test field

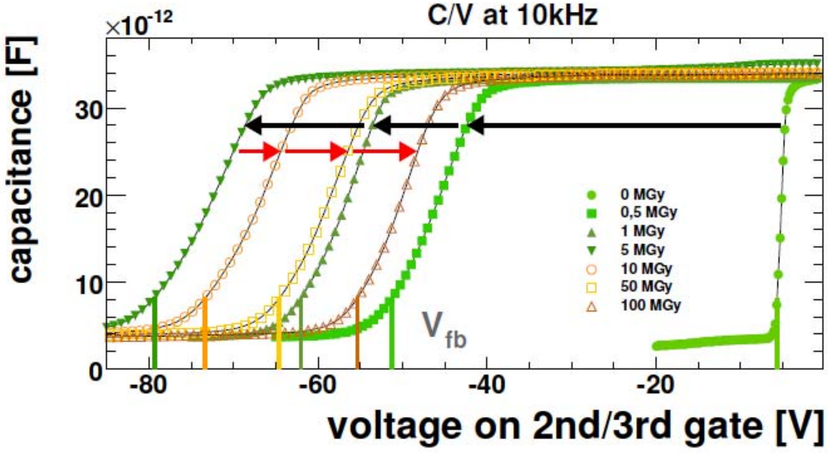


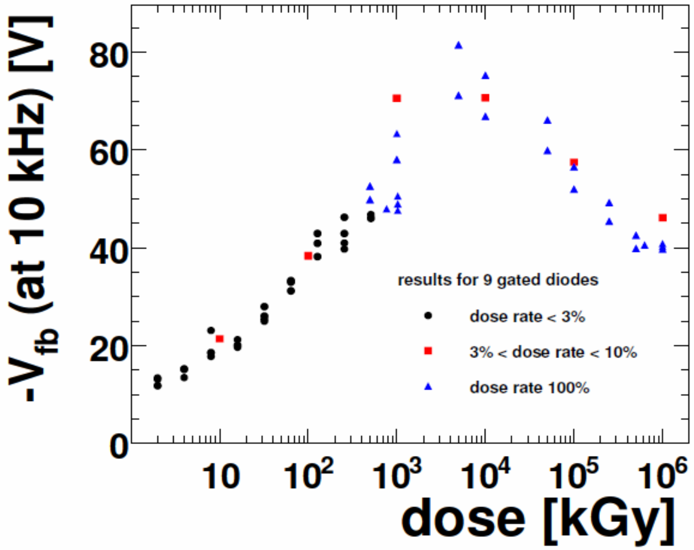
$$-\Delta V_{FB} = \frac{Q_f}{C_{ox}} + \frac{Q_{it}^{donor}}{C_{ox}} - \frac{Q_{it}^{acceptor}}{C_{ox}}$$

Flat band voltage shift:

- Buildup of fixed oxide charge Q_f and interface charge Q_{it} with dose
- $Q_f > 0$, trapped holes, shift to more negative V_G
- $Q_{it} > 0$, if interface states donors → larger V_{FB} shift
- $Q_{it} < 0$, if interface states acceptors → less V_{FB} shift
- C-V stretch out caused by Q_{it} (depends on D_{it}-distribution in the band gap and the surface potential

ΔV_{FB} Dose Dependence



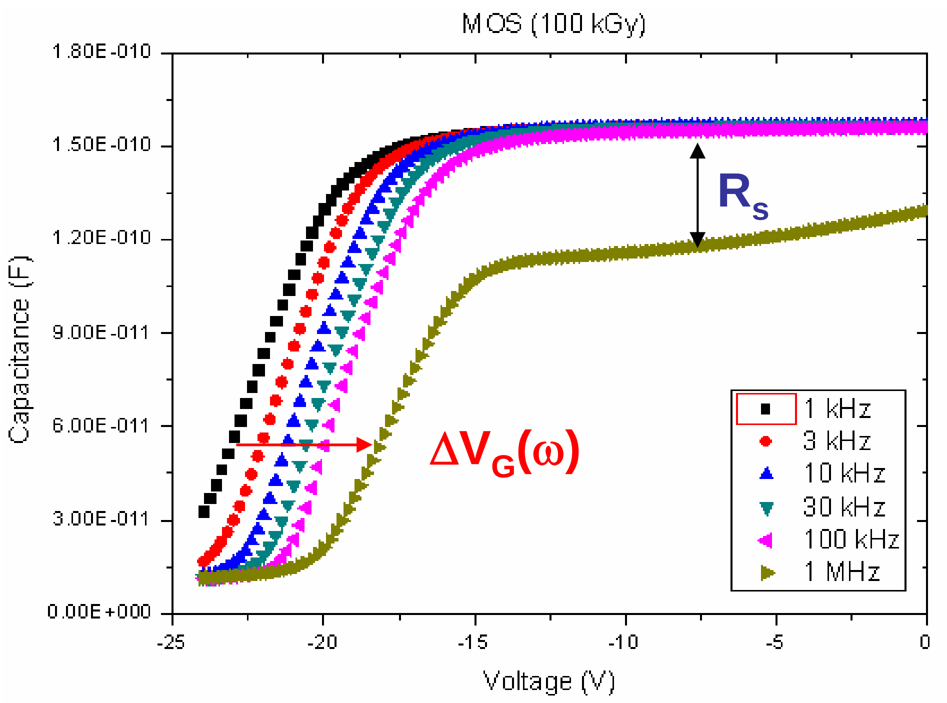


Flat band voltage shift with accumulated dose of 12 keV X-rays

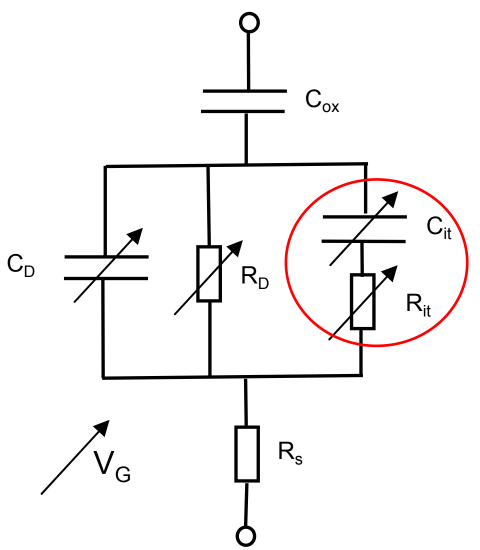
- Strong increase up to about 1 MGy
- Maximal value between 1-10 MGy
- Decrease by about a factor of 2 at 1 GGy

How to disentangle fixed oxide charge and interface charge from measured MOS C-V

C-V Frequency Dependence



Equivalent circuit for depletion (simplified)



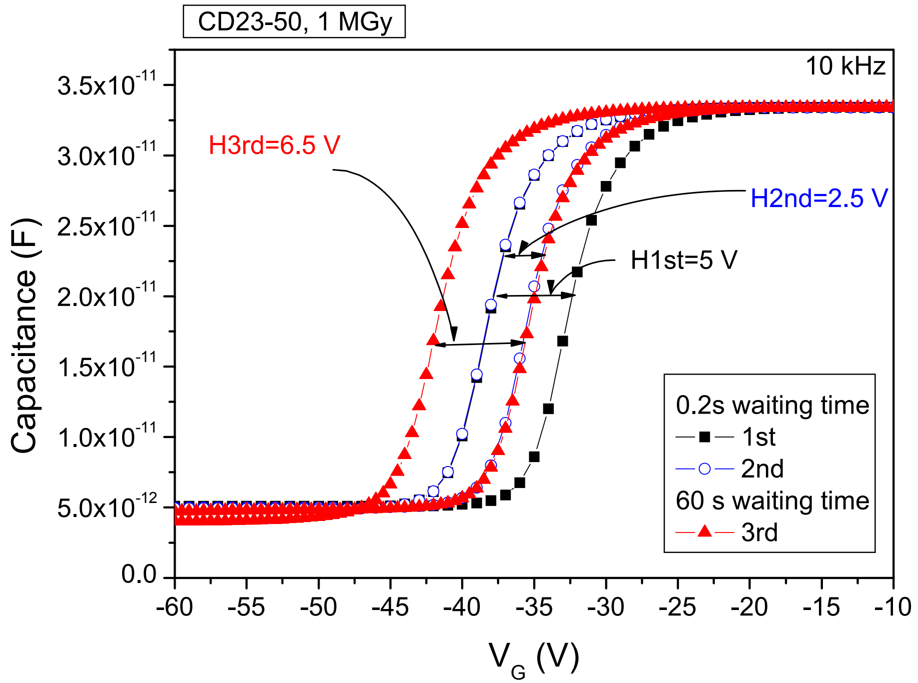
C_{it} and R_{it} depend on $D_{it}(E_t,\psi_s)$ and frequency ω, ψ_s = surface potential

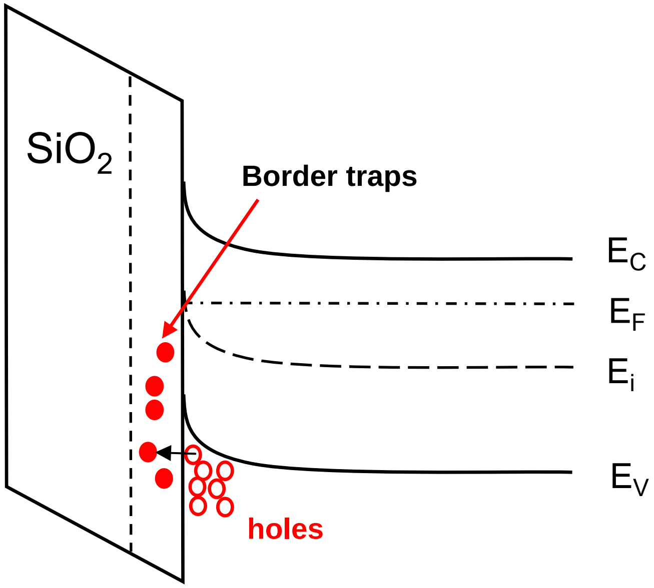
$C_{it} \times R_{it}$ represent a time constant of the continuum of the interface traps
→ capture and emission of majority carriers of trap levels

Bulk series resistance R_s has to be included (high ohmic material) → responsible for lowering C_{MOS} in accumulation at high frequencies

Depletion capacitance C_D and parallel conductance $1/R_D$ independent on ω if bulk traps can be neglected

C-V Hysteresis





Biasing into deep inversion

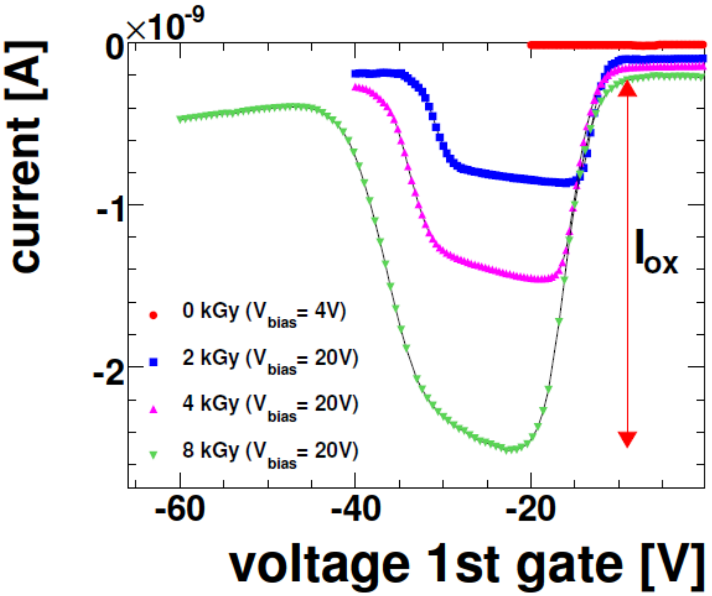
→ high concentration of holes at the interface

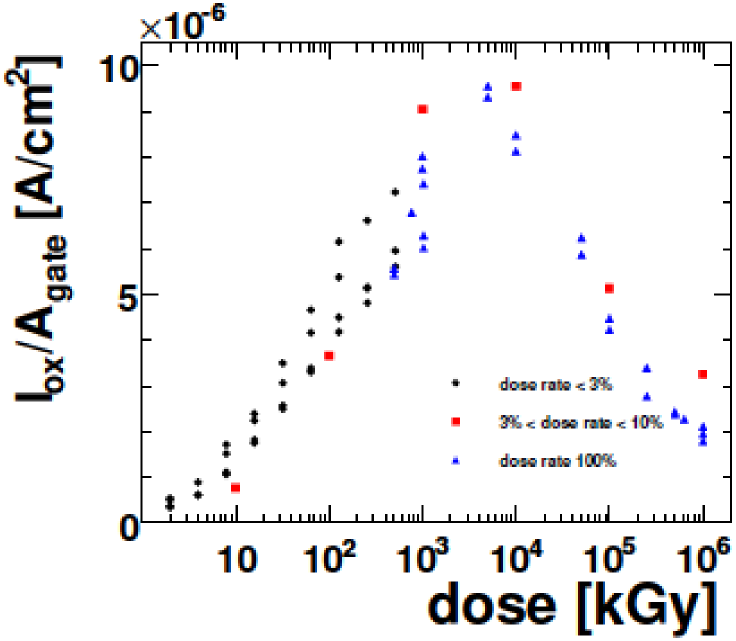
→ injection of holes into border traps

→ increase of positive oxide charge (depends on injection time)

→ increase of flat band voltage shift

Interface Current – Dose Dependence





Recombination velocity $S_0 \propto I_s/A_{gate} \propto D_{it,mid\ gap}$

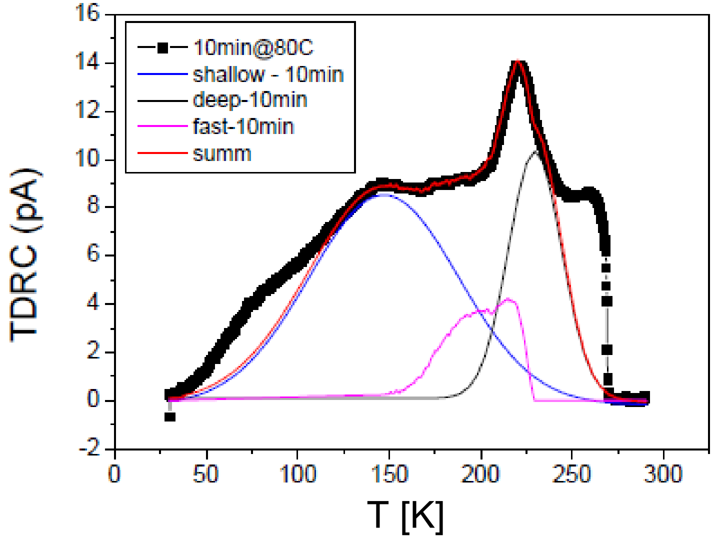
Near mid-gap interface states responsible for surface (interface) current

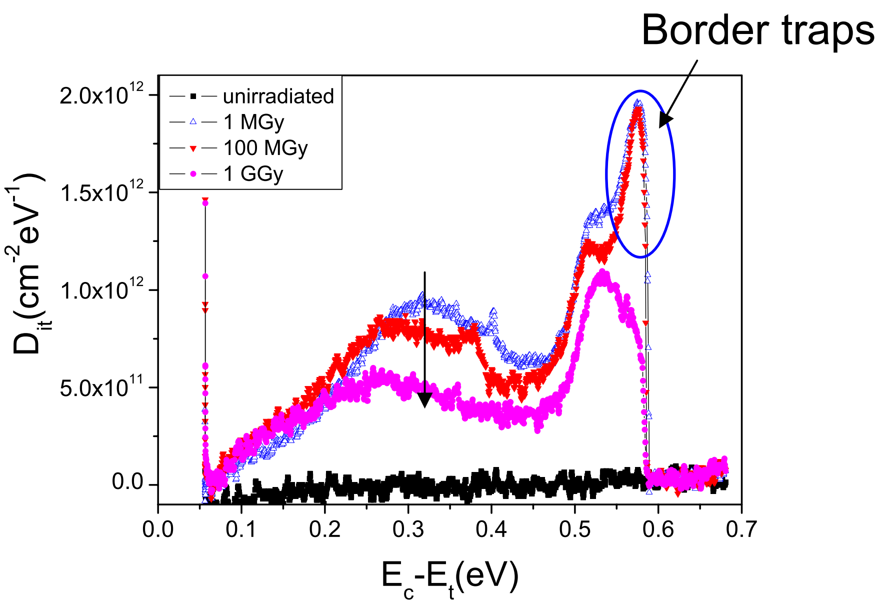
Strong increase up to 1 MGy

Maximum between 1-10 MGy

Extraordinary decrease for higher dose values, only ≈ 20-30 % of max. value

Interface States $D_{it}(E_t)$ from TDRC





TDR-current density $J_{TDR} = q_0 \cdot D_{it}(E_t) \cdot \beta \cdot f(T)$

β=heating rate, f(T) function of capture cross section σ, thermal velocity v_{th} and density of states in the conduction band N_C

Transformation T → energy E_C-E_t depends also on σ

D_{it} decreases between 1 MGy and 1 GGy

as expected from $I_{surface}$ and ΔV_{FB}

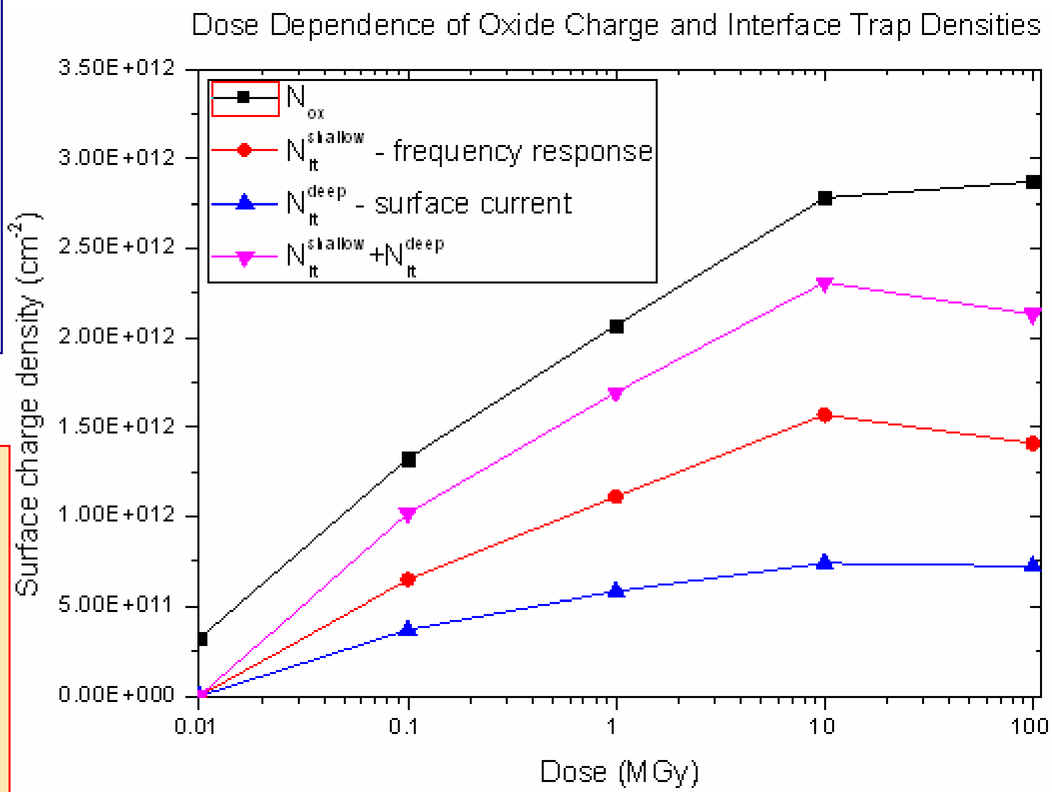
Summary for N_{ox} and N_{it}

Extraction of N_{ox} and N_{it}:

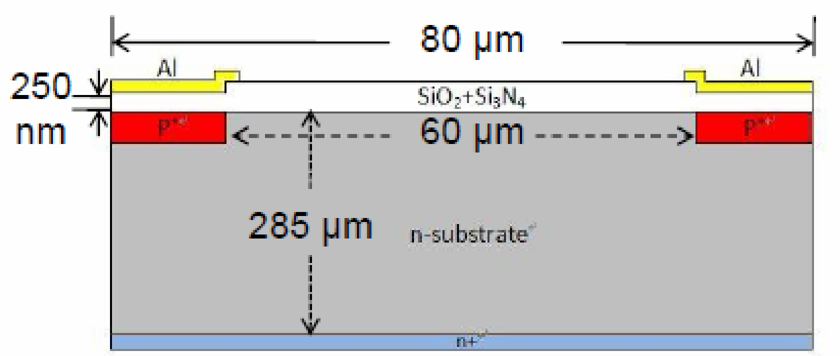
- D_{it} (N_{it}) from TDRC
- N_{ox} from V_{FB} of C-V at high frequency (first guess)
- Fit frequency shift of C-V with D_{it} and adjust N_{ox}
- Compare surface current I_s with $N_{it, deep}$

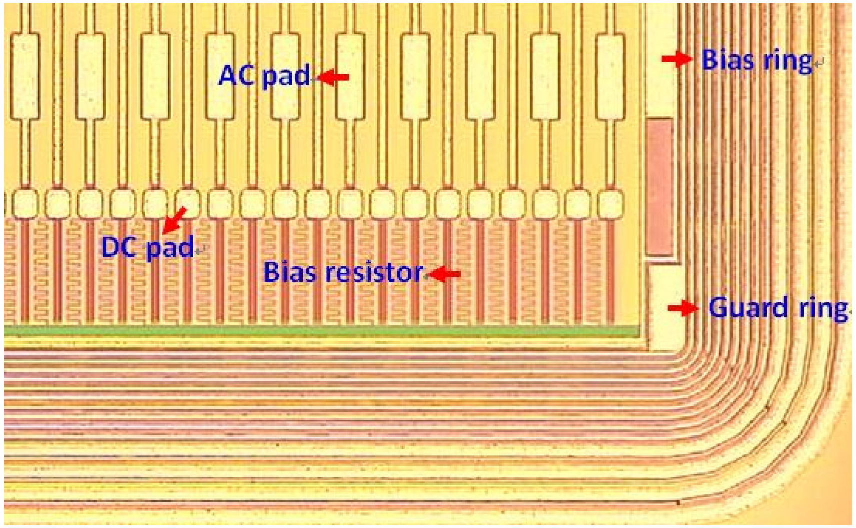
Results:

- **N_{ox}** saturates (2.8×10^{12} cm^{-2}), all oxide traps filled with holes
- **$N_{it,total}$** maximal at ≈10 MGy (2.3×10^{12} cm^{-2}), decrease D>10 MGy
- **$N_{it,deep}$** maximal at ≈10 MGy (5×10^{11} cm^{-2}), decrease D>10 MGy
- **$N_{it,shallow}$** maximal at ≈ 10 MGy (1.6×10^{12} cm^{-2}), decrease D>10MGy



Strip Sensors





p^+ on n Si strip sensor:

- <100> n-substrate
- High resistivity: 2 - 5 kΩ·cm
- Thickness: 285 $\pm$10 µm
- Active area: 0.62 cm^2
- "Oxide": 300 nm SiO_2+50 nm Si_3N_4
- Strip length: 7.8 mm
- Strip pitch: 80 µm
- Strip number: 98

X-ray irradiation environments:

- @DESY DORIS III beamline F4
- Typical energy is 12 keV
- Dose rate in SiO_2: 200 kGy/s
- ***Doses: 1 MGy***
- ***Irradiated sensors:***

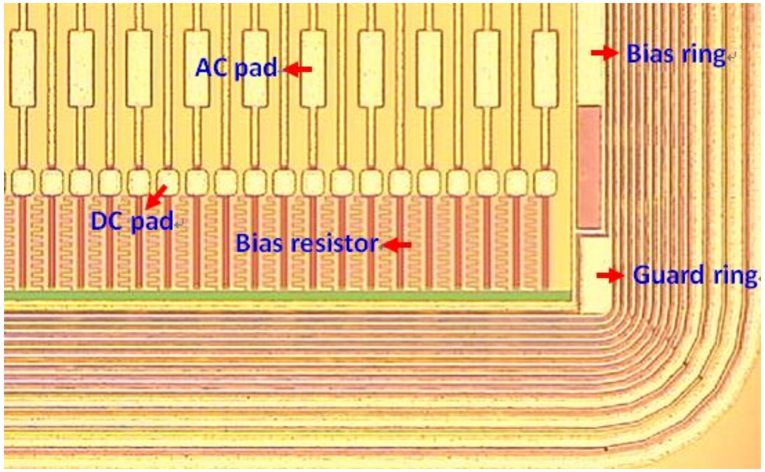
  sensor 1: irradiated without bias

  sensor 2: irradiated with 35 V bias

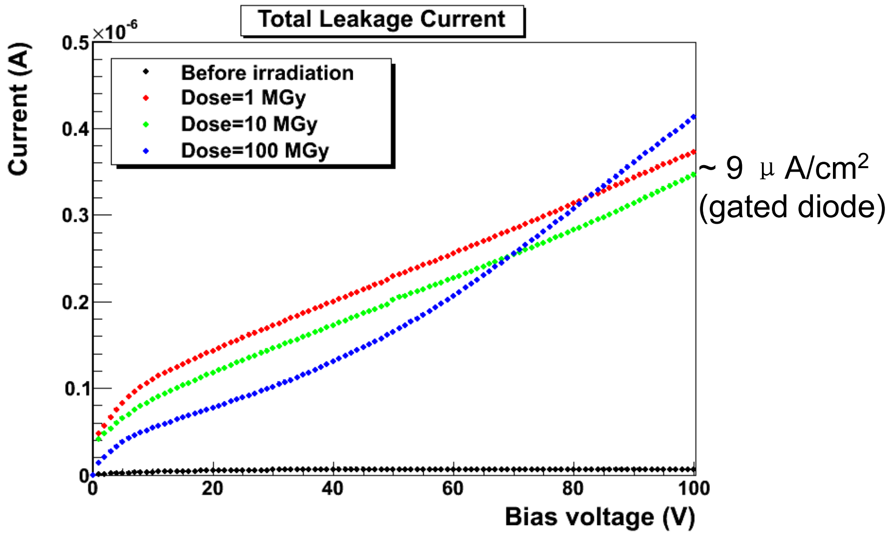
  (enough to depleted surface)

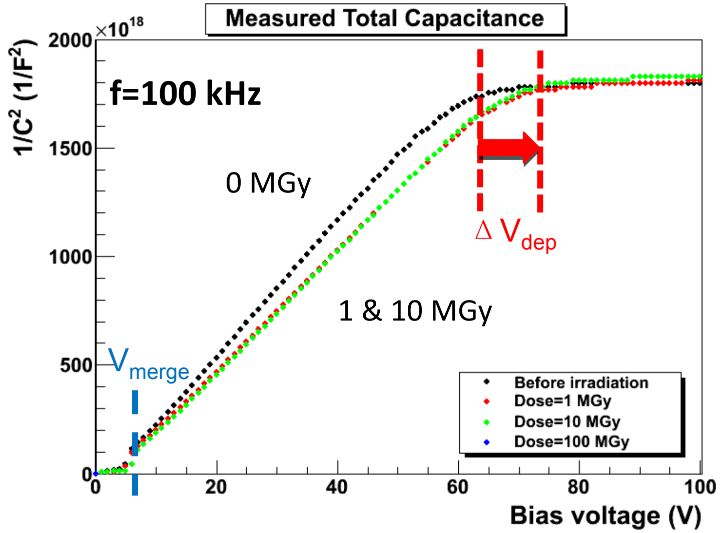
Strip Sensor

Characterization of p+ on n strip sensor up to 100 MGy:



p+ on n strip sensor

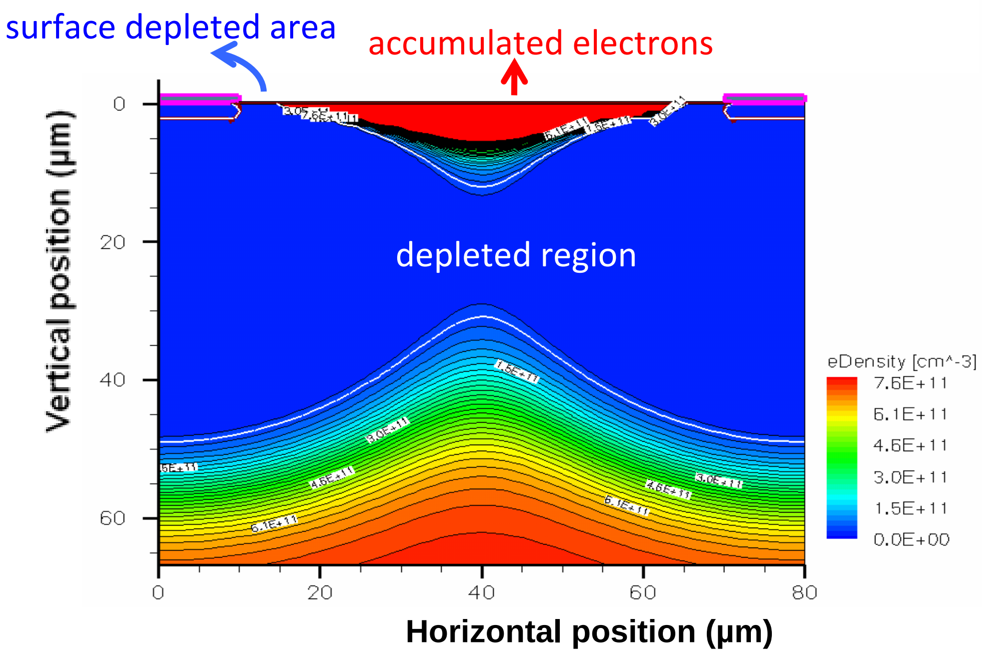


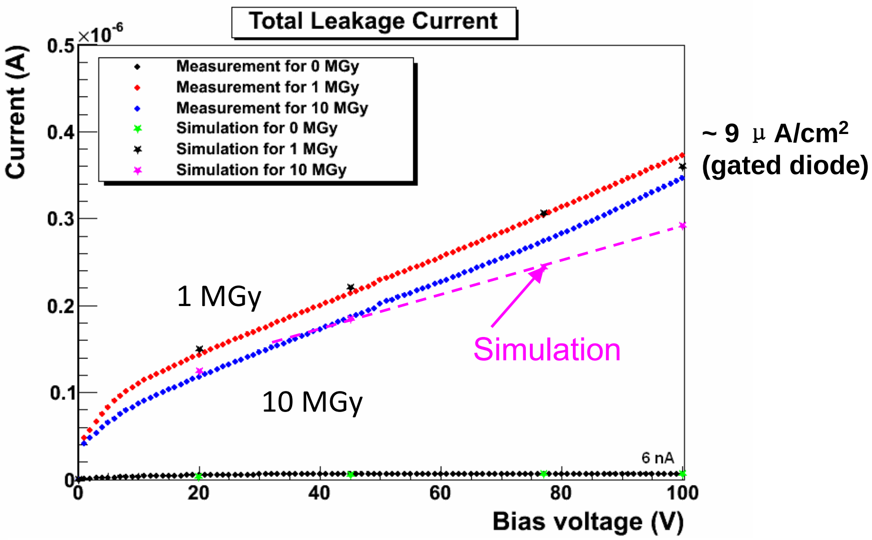


- **Non-saturating leakage current (I-V)**
  → surface depleted area S_{dep}
- **Change of full depletion voltage V_{dep}**
  → electron accumulation layer at the $Si\text{-}SiO_2$ interface

Simulation

Synopsis-TCAD simulation





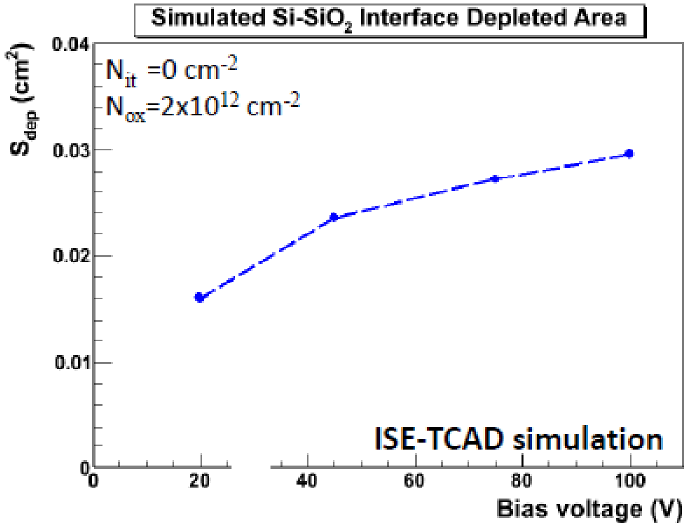


Fig 8. Simulated Si-SiO$_2$ interface depleted area

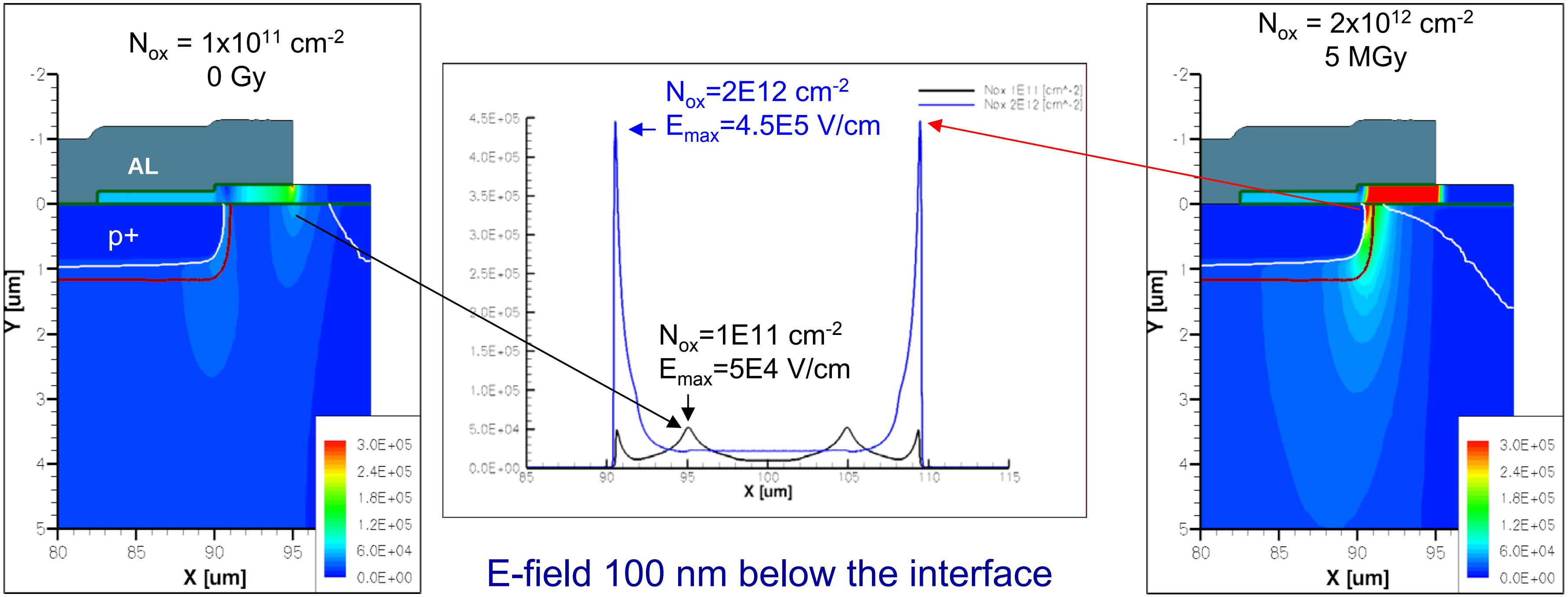
Simulation describes voltage dependence of current

- current proportional to depleted interface area
- Decrease of current (I-V) for doses > few MGy

Influence of N_{ox} on Breakdown

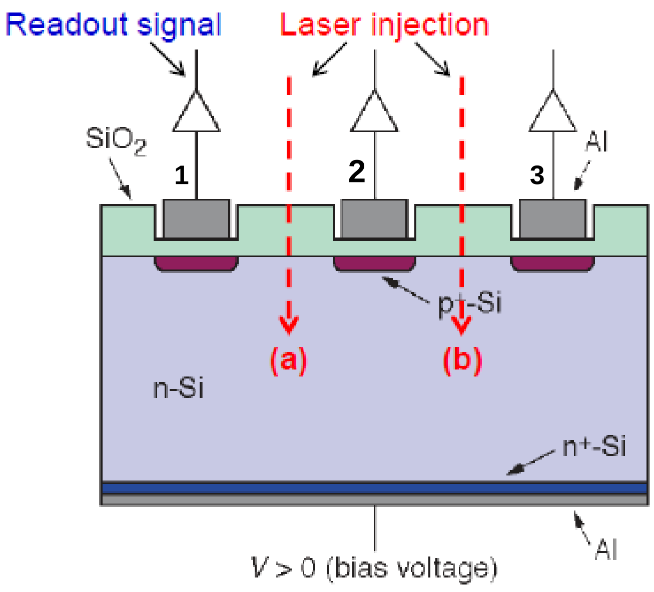
Strip sensor: 200 μm pitch, 20 μm gap, 5 μm Al overhang, 500 μm thick

2D TCAD – simulation of E-field



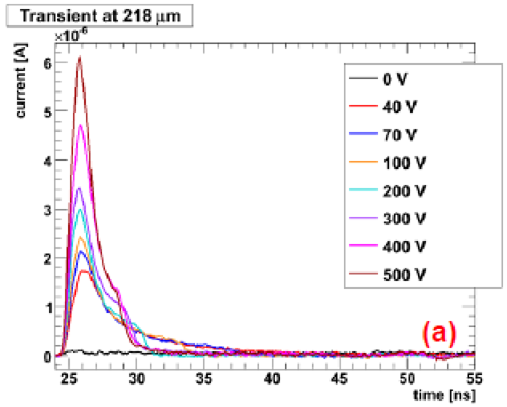
E-field 100 nm below the interface

Charge losses near to SiO_2-Si interface

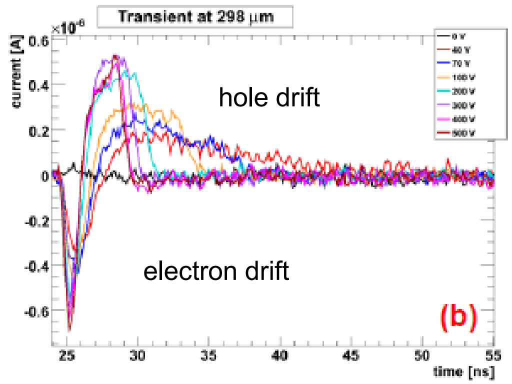


Laser:
λ = 660 nm
3 μm absorption length
~ 3 μm focus
Pulse width ~ 60 ps

Laser between strip 1,2
readout strip 1



Laser between strip 2,3
readout strip 1



Weighting filed — Weighting potential

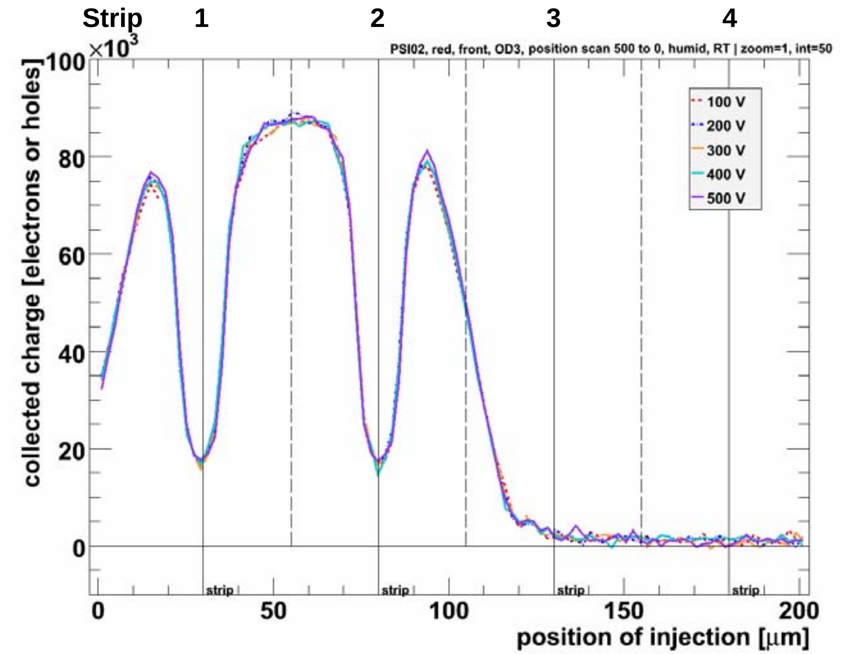
$$I_i = -q \cdot \vec{v} \cdot \frac{\vec{E}_i(\vec{r})}{V_i} = -q \cdot \vec{v} \cdot \frac{1}{V_i} \cdot \vec{\nabla}\Phi_i(\vec{r})$$

Ramo's theorem

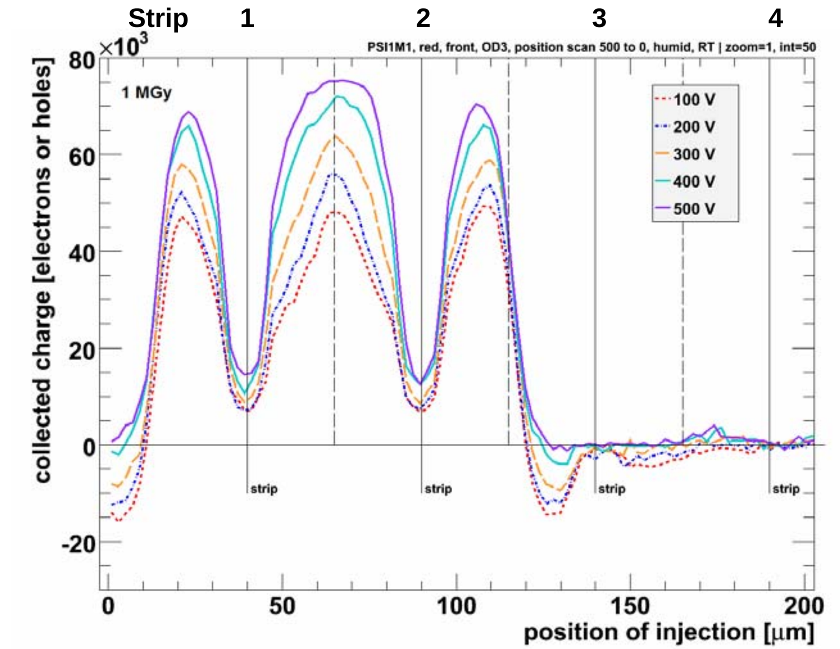
Virtual voltage applied to electrode i (while the other electrodes grounded)

Collected Charge versus Position

Non-irradiated sensor



Irradiated sensor, D = 1 MGy



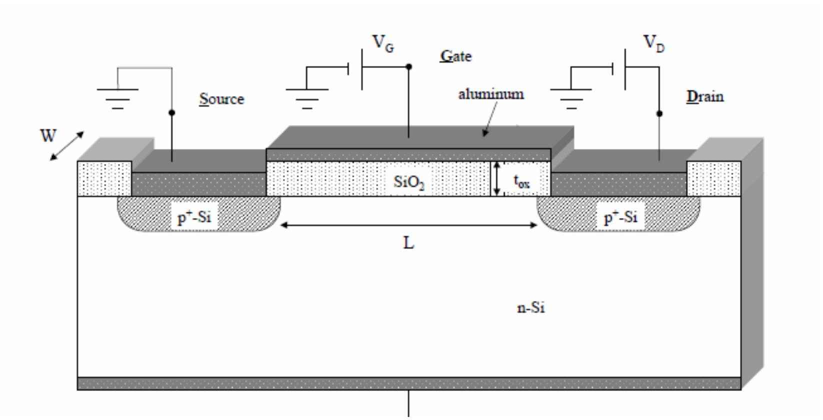
Charge collected at strip 1 and 2 summed up

Full charge collection
independent on bias voltage
if sensor in steady state → humidity ≈ 45 %
in dry condition → electron or hole losses
depending on V_{bias} ramping up or down

Full charge collection only for V_{bias}>500 V
V_{bias}<500 V → strong electron losses
if sensor in steady state
otherwise electron losses lager

Physics origin of this effect so far unclear

P-Channel MOS-FET



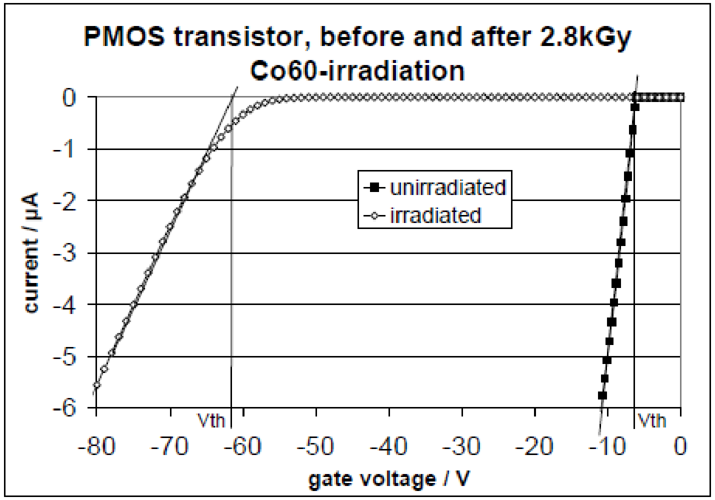
Parameter:

W/L = 5.7

V_D = 0.1 V

$t_{ox} \approx$ 600 nm

$N_D \approx 1 \times 10^{12}$ cm^{-3} for bulk



$$I_{DS} = \mu_h \cdot \frac{W}{L} \cdot \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox}} \cdot V_D \cdot (V_G - V_{th})$$

In sub-micron CMOS-technology:

t_{ox} (Gate) $\approx$ 2-3 nm

→ small V_{th} shift due to $\Delta V_{th} \propto t^2_{ox}$

but also degradation of channel conductivity

→ decrease of gain factor

→ increase of noise

Threshold voltage shift (~V_{FB}):

V_{th} = - 6.5 V before

V_{th} = - 62 V after 2.8 kGy ^{60}Co

Summary

Surface damage effects:

- **Increase of oxide charge Q_{ox} (N_{ox}, V_{FB}, V_{th})**
  - saturation at few MGy, depends on t_{ox}
  - impact on interstrip-capacitance due to e^- accumulation layer
  - charge losses near surface (low E-Field between strips)
  - breakdown

- **Increase of interface charge Q_{it} (N_{it}, D_{it})**
  - maximal value reached between 1-10 MGy, decreases for D > 10 MGy
  - impact on surface leakage current and noise
  - frequency shift in MOS C-V
  - gain-factor degradation in MOSFETs, etc…

Acknowledgements

Many thanks to all group members involved in “surface damage”

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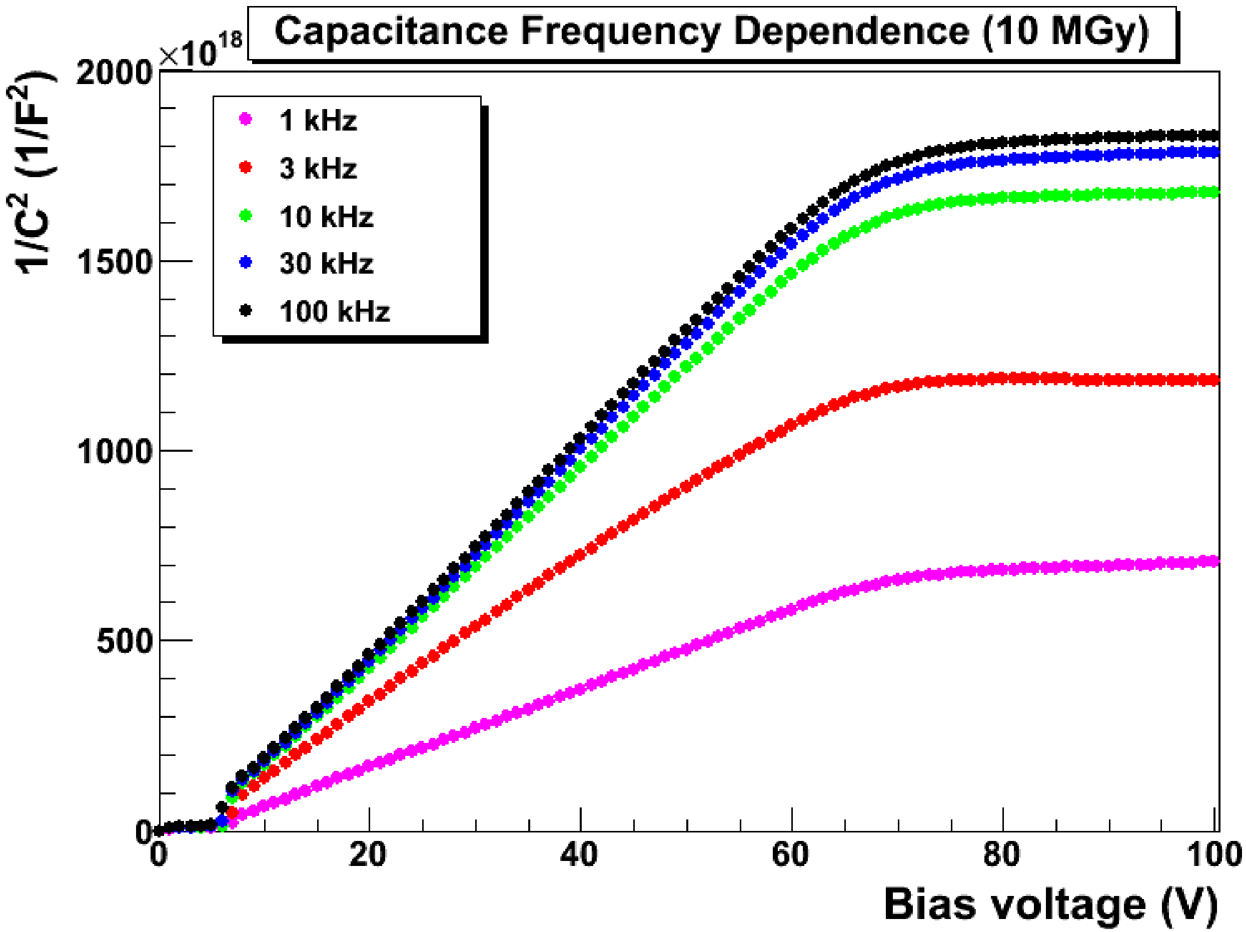
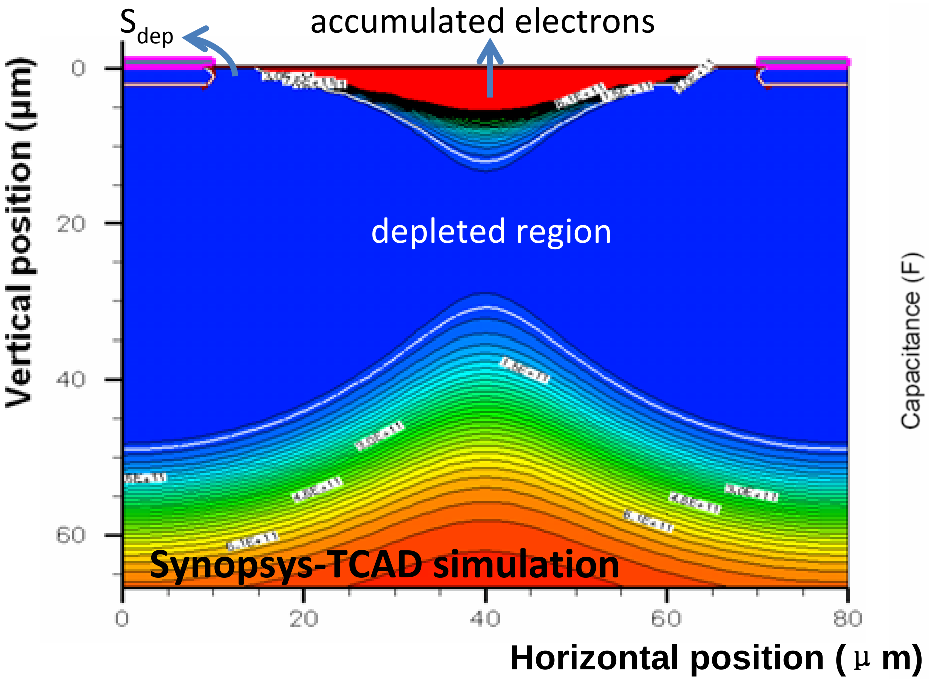
A. Srivastava, T. Theedt, J. Zhang

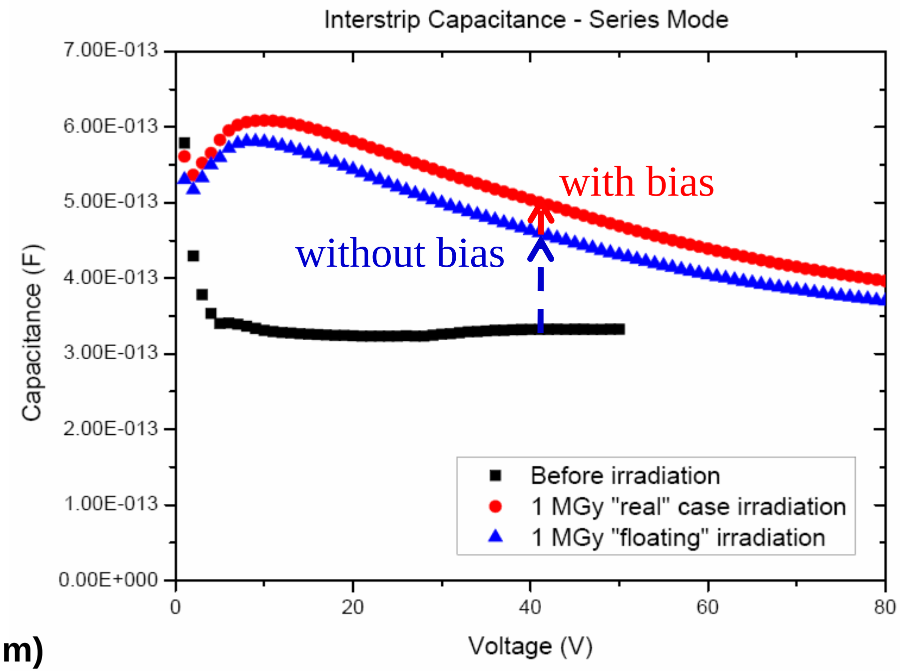
C-V Frequency Dependence



Inter-strip Capacitance

Results comparison for irradiations with and without bias:





- Interstrip capacitance C_{int}

C_{int} decrease with surface depleted area S_{dep}

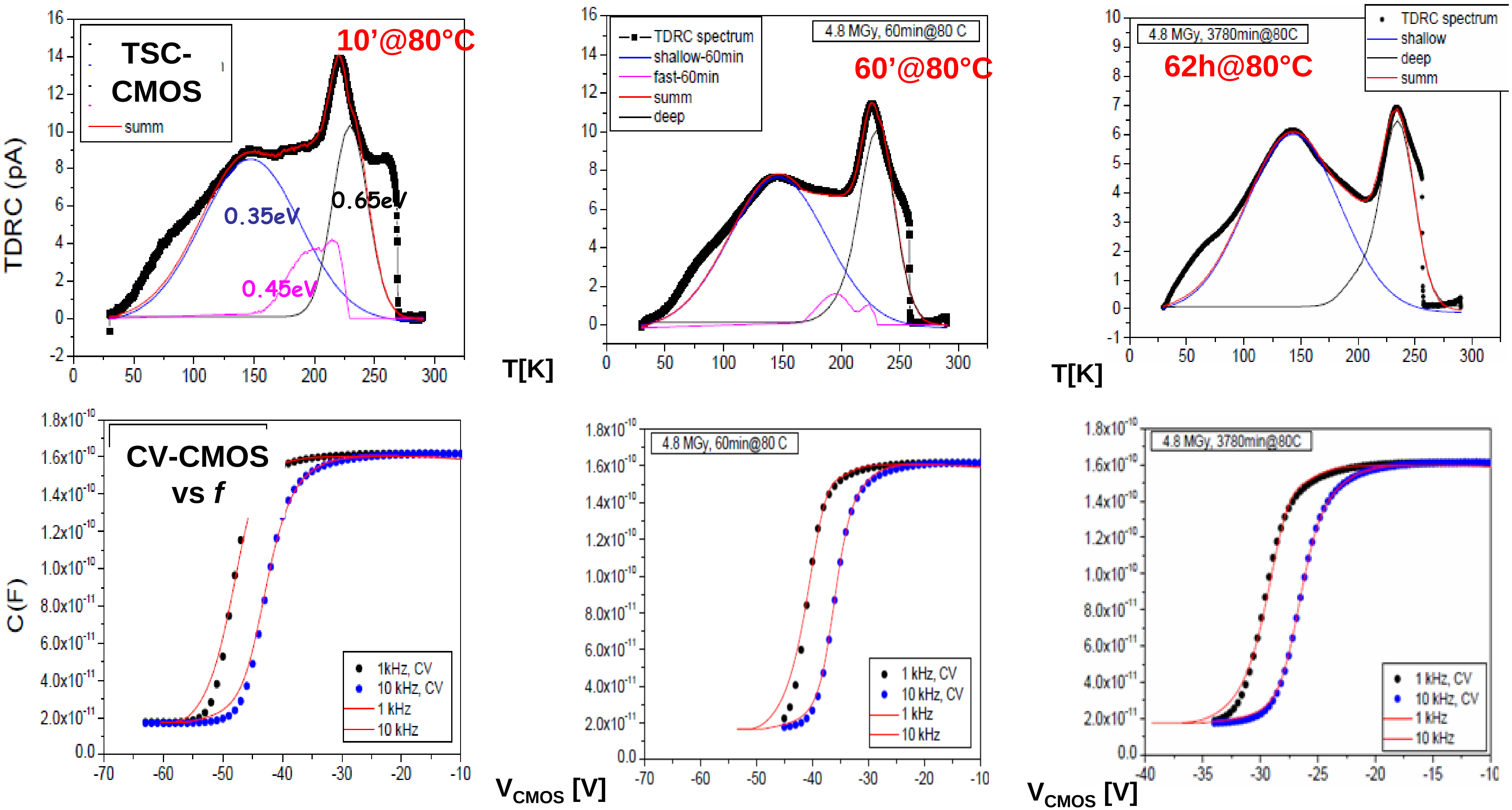
- **Irradiation with bias → larger leakage current and inter-pixel capacitance!**
- Tentative conclusion: more interface traps in the mid-gap were generated!

 (oxide charges and interface traps close to conductance band need to be confirm)

Surface charges depend on electric field during irradiation!

Annealing

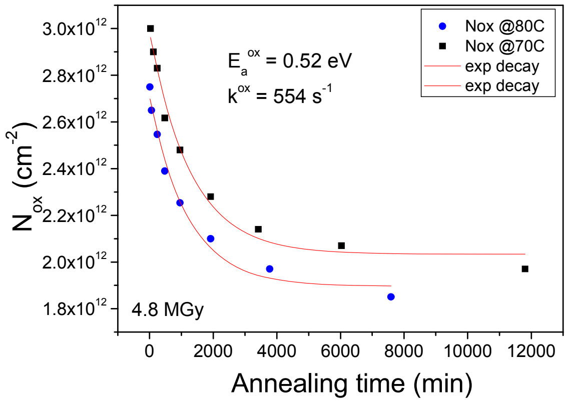
Annealing: **Relevant for long-term behaviour (+ to understanding test measurements !) + help to understand physics of radiation damage**

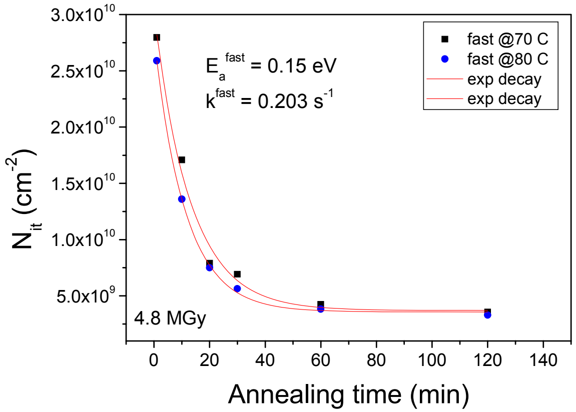


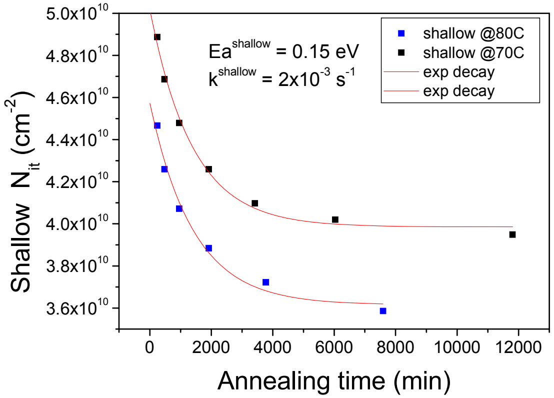
→ 3 dominant trap levels with different activation energies → t_{anneal}

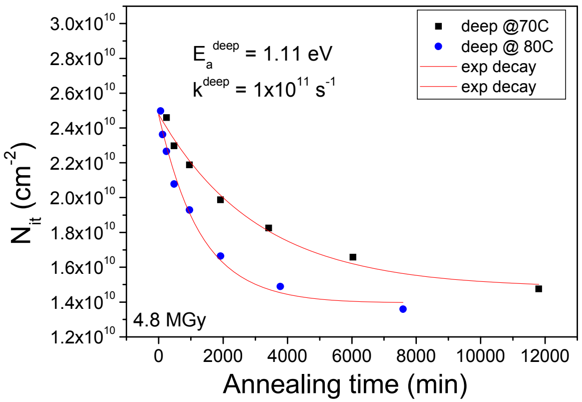
e.g interface trap at 0.45eV quickly anneals at room temperature

Activation energy and frequency-factor









LC dry→ humid→dry