Radiation Damage

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1. **Irradiation of segmented sensors and comparison to simulations with parameters derived from (compatible with) test structures**
2. **Annealing behaviour and progress in microscopic understanding**
3. **Summary and next steps**

1) has left to industry

2) PhD student since July 09 – supported by EU (Marie Curie-ITN: MC-PAD)

Parameters from irradiated test structures

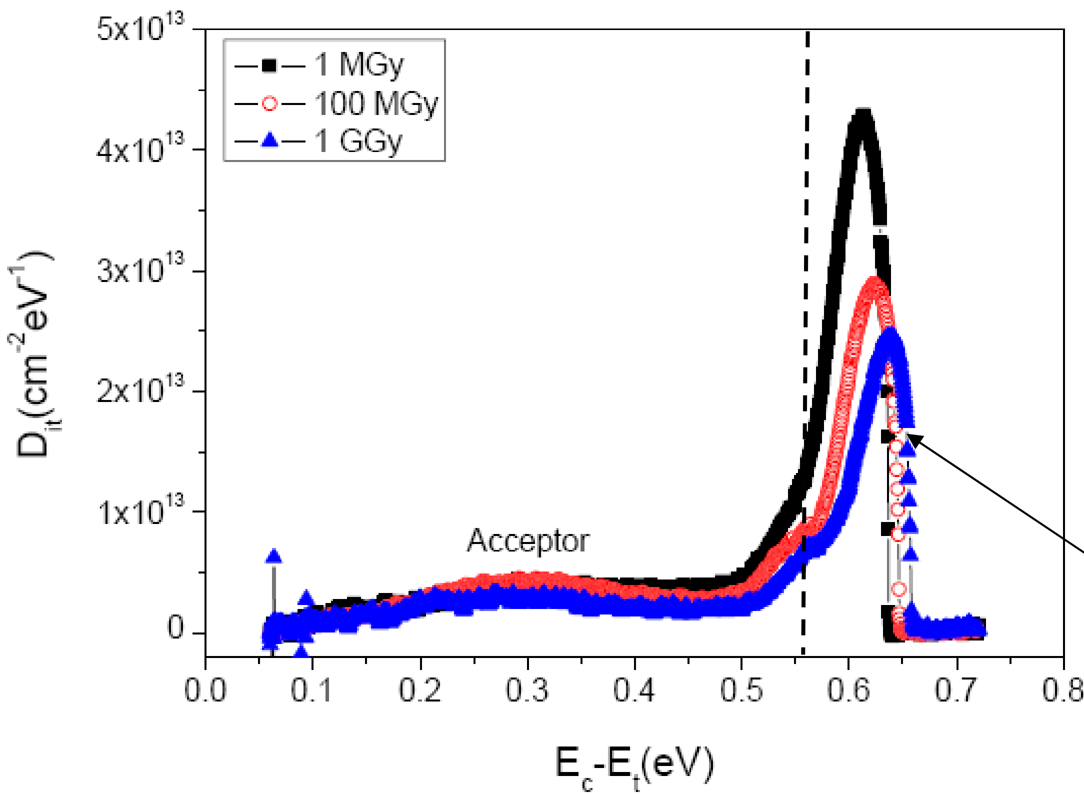
Strategy: Irradiation of test structures: CMOS capacitors + gated diodes

→ relevant microscopic parameters for SYNOPSIS-TCAD sensor simulations

→ predict (explain) properties of irradiated sensors → optimize sensor design

Thermally Stimulated Current (TSC) measurement of CMOS capacitors:

→ interface trap density D_{it} [$cm^{-2} \cdot eV^{-1}$]



dominant interface states*) :

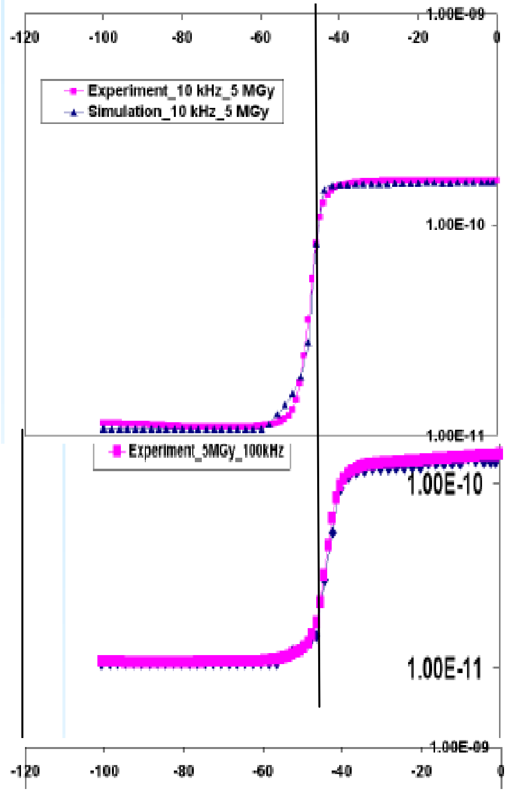
- E_c-E_t=0.35eV (acceptor)
  - Gauss with rms=0.068 eV
  - $\sigma_{eff}=4 \cdot 10^{-16} cm^2$
  - $N_{it}(1MGy) = 4.2 \cdot 10^{12} cm^{-2}$
  - $N_{it}(10MGy) = 4 \cdot 10^{12} cm^{-2}$
- E_c-E_t=0.6eV (acceptor) !
  - Gauss with rms=0.0065 eV
  - $\sigma_{eff}=8 \cdot 10^{-15} cm^2$
  - $N_{it}(1MGy) = 1.0 \cdot 10^{13} cm^{-2}$
  - $N_{it}(10MGy) = 6.5 \cdot 10^{12} cm^{-2}$

(+ injection of oxide charges close to SiO_2 interface if biased in strong inversion)

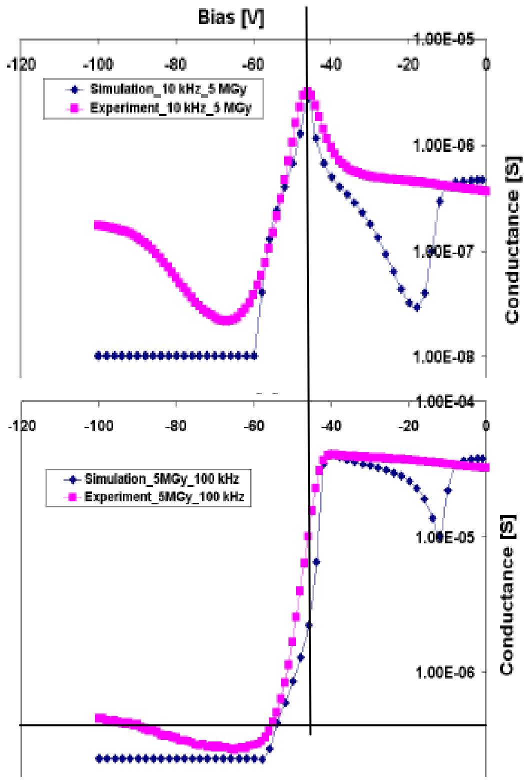
*) preliminary parameters for simulation

C/V-G/V characteristics of CMOS capacitance vs frequency

C/V of CMOS capacitor annealed at 80°C for 60 min



G/V of CMOS capacitor annealed at 80°C for 60 min



C/V:

- from frequency dependence of → N_{it}
- once Nit known → N_{ox}

$N_{ox}(0MGy) = 2.0 \cdot 10^{10}\ cm^{-2}$

$N_{ox}(1MGy) = 2.1 \cdot 10^{12}\ cm^{-2}$

$N_{ox}(10MGy) = 2.3 \cdot 10^{12}\ cm^{-2}$

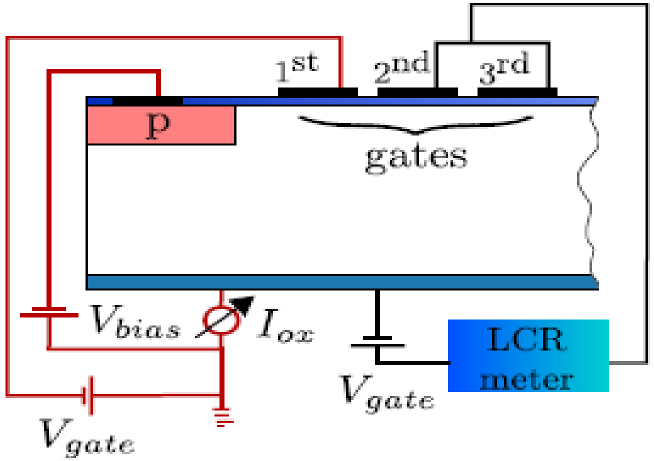
- good description of data
- N_{it}: consistency check with results from TSC

G/V:

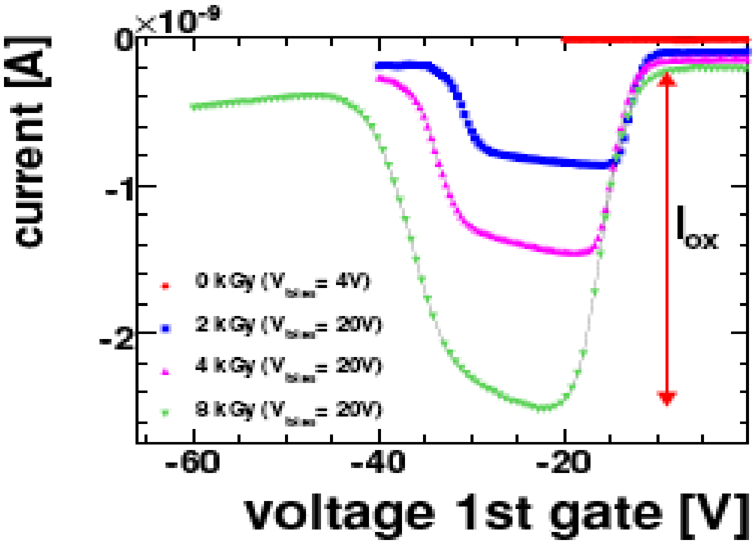
- peak (sensitive to N_{it}) reasonably described
- problems in particular in accumulation (reason unclear)

Surface recombination velocity S_0 (due to deep interface traps) from I/V-measurement on gated diode

I/V



C/V



→ surface recombination velocity *)

S_0(0 MGy) = 2.4 cm/s

S_0(1 MGy) = $7.7 \cdot 10^3$ cm/s

S_0(10MGy) = $6.6 \cdot 10^3$ cm/s

*) $S_0 = \sigma_{eff} \cdot v_{thermal} \cdot kT \cdot D_{it}(midgap)$

(taken from simulation, but consistent with measurements from test structures)

Question:

Can we predict the properties of irradiated segmented sensors with these "microscopic" parameters ?

Strip sensor (p^+on n-n^+) – fabricated by CIS

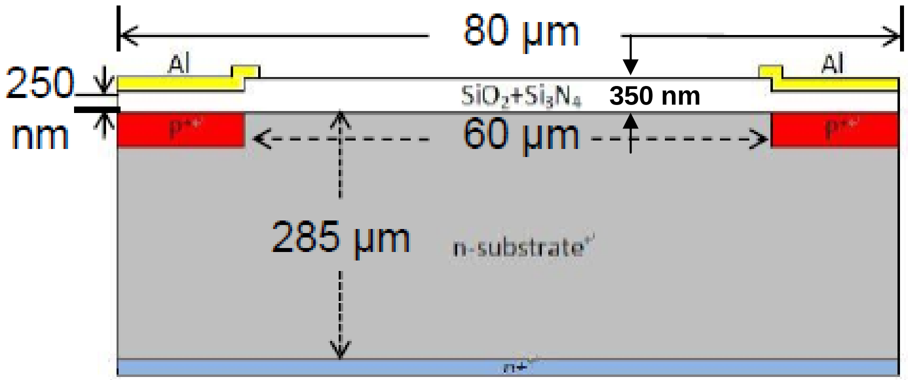


Fig 1. Side view of the test sensor

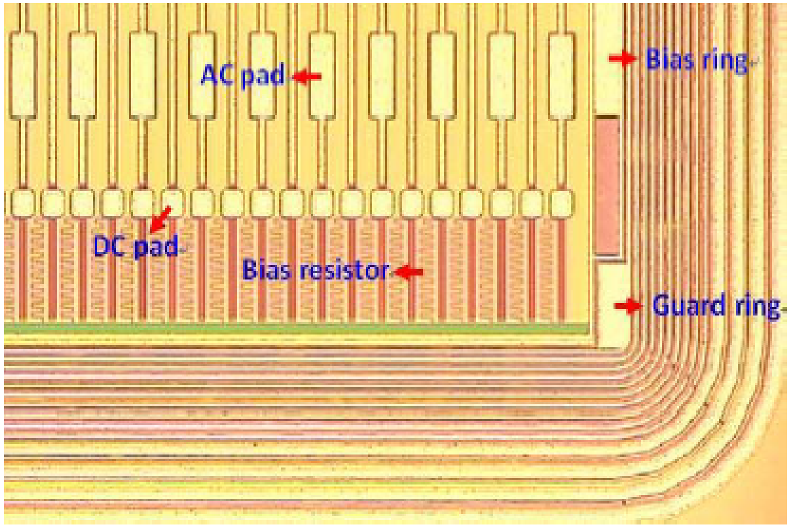


Fig 2. Top view of the test sensor

p^+ on n Si strip sensor:

- <100> n-substrate
- High resistivity: 2 - 5 kΩ·cm
- Thickness: 285 ±10 µm
- Active area: 0.62 cm^2
- "Oxide": 200 nm SiO_2+50 nm Si_3N_4
- Strip length: 7.8 mm
- Strip pitch: 80 µm
- Strip number: 98

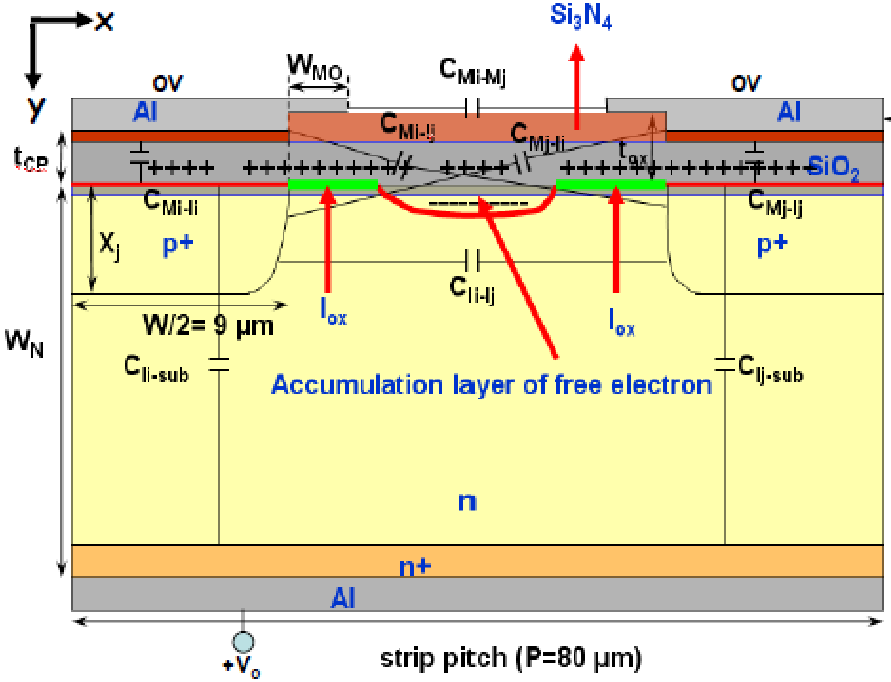
Photon irradiation:

- @DESY DORIS III beamline F4
- *Typical energy is 12 keV* (Γ ~10 keV)
- Dose rate in SiO_2: 200 kGy/s
- *Results for doses:*

1 MGy, 10 MGy, 100 MGy

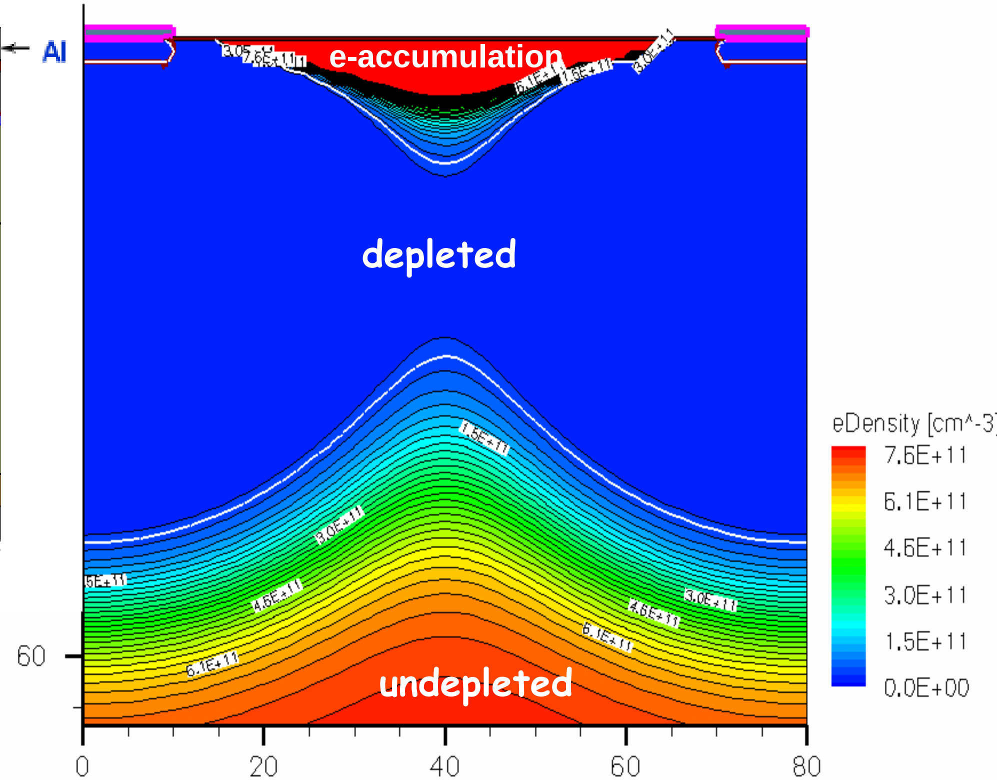
*) results only shown for 1 and 10 MGy (problems with bias resistor at 100 MGy)

Simulation: Synopsis-TCAD



Electron density for V_{bias}= 5 V

(doping: $8.1 \cdot 10^{11}$ cm^{-3}; V_{dep}(pad diode)~50 V)



Physical model:

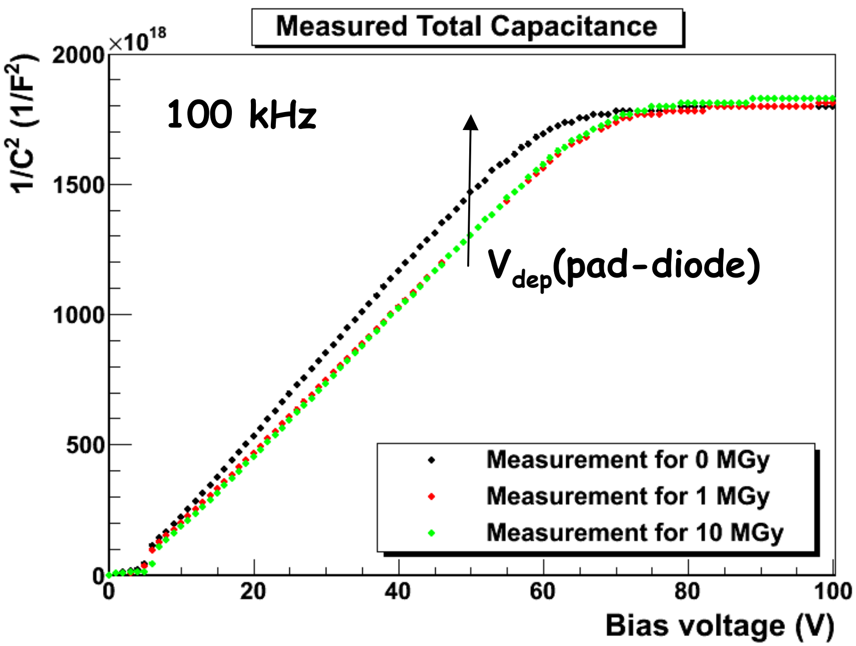
- SRH (Shockley-Read-Hall) recombination
- Auger recombination
- Impact ionization (for avalanche breakdown)
- Surface recombination (I_{ox})
- Gate current (Lucky) model (for CMOS capacitors)
- Trap models (Si-SiO_2 interface)
  - → Solving Poisson, electron, and hole current continuity equations
  - → Dependence of life time of charge carrier (τ) on interface trap density (Nit) taken into account
- Doping dependent mobility, high field saturation model, and band to band tunneling

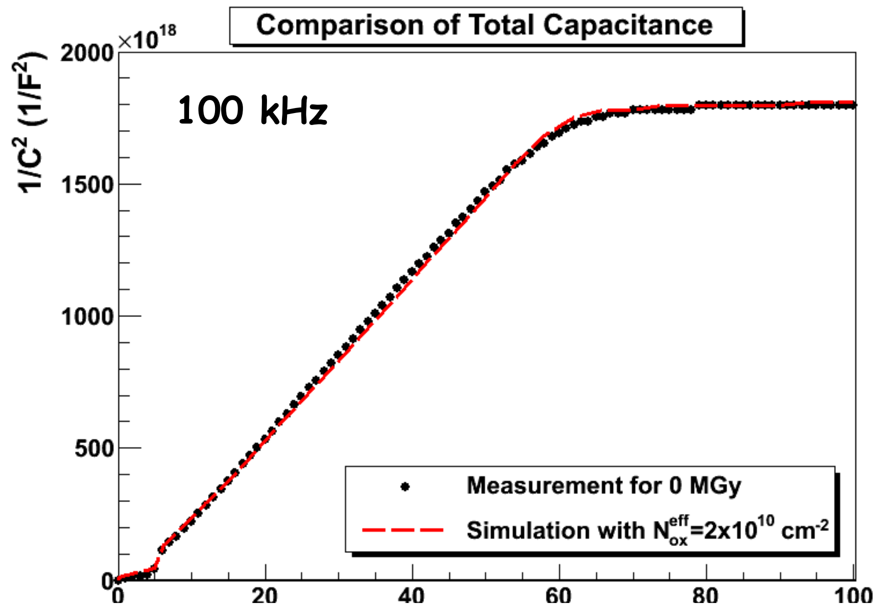
NB. Details at Si-SiO_2-interface also depend on surface boundary conditions (Neumann or Dirichlet) which may depend on time (under study)

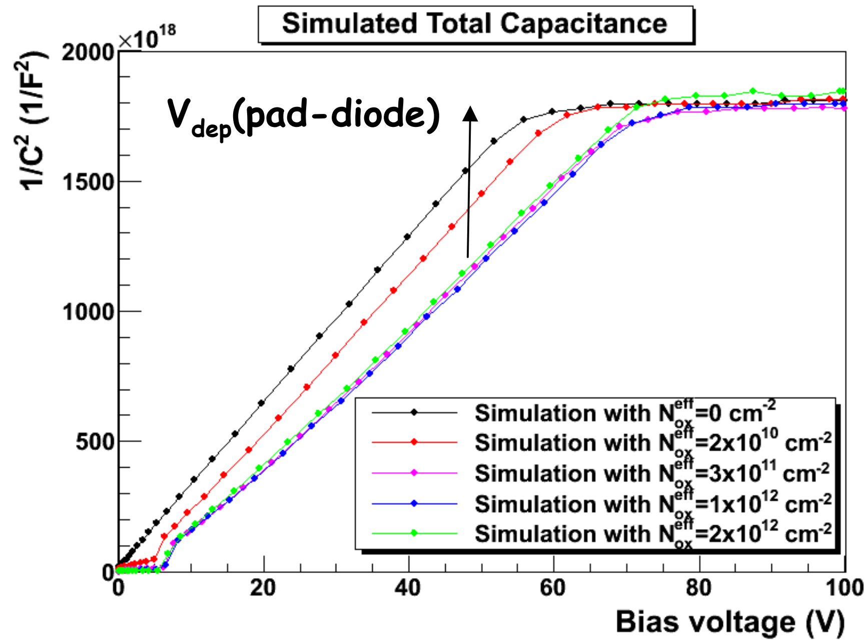
C-V for segmented sensors

C-V characteristic vs irradiation dose

($\Delta V_{depletion}$ due to surface charges)







Simulation describes data well:

- ΔV_{dep} by ~ 10V due to surface charges
- change of $1/C^2$-slope
- at ~ 6V jump in C: depletion regions from adjacent strips join
- effect of N_{ox} saturates at few$\cdot 10^{11}$cm^{-2}

C-V of segmented sensors

C-V characteristic vs irradiation dose

(frequency dependence due to interface states)

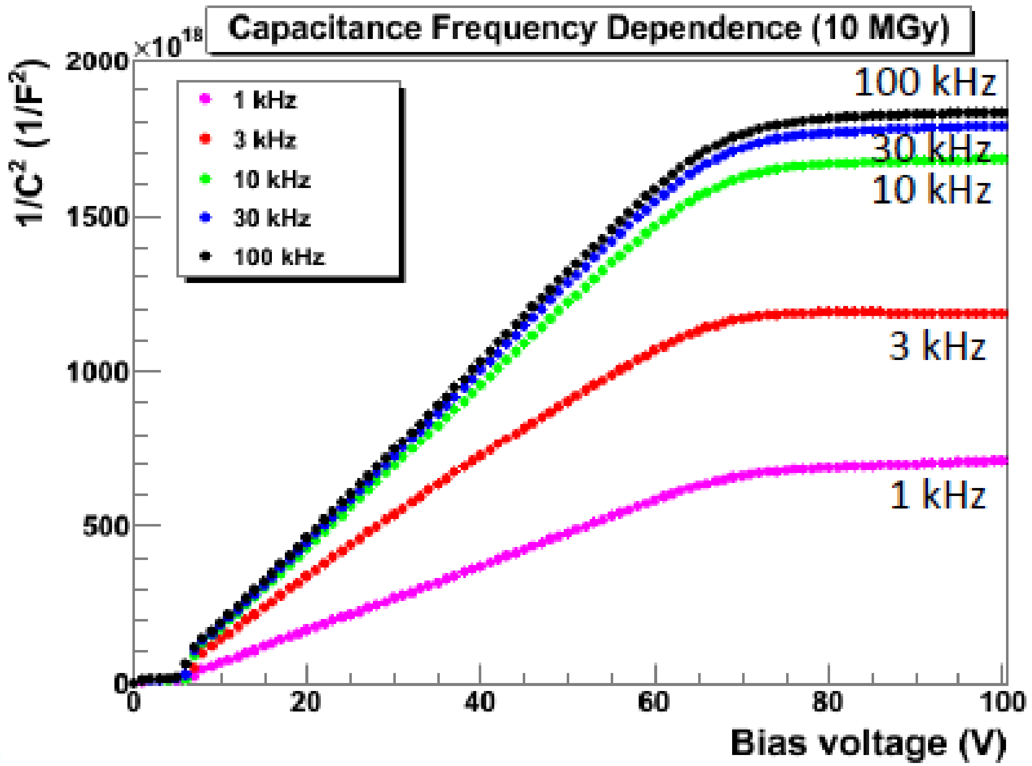


Fig 6. Measured CV curves frequency response

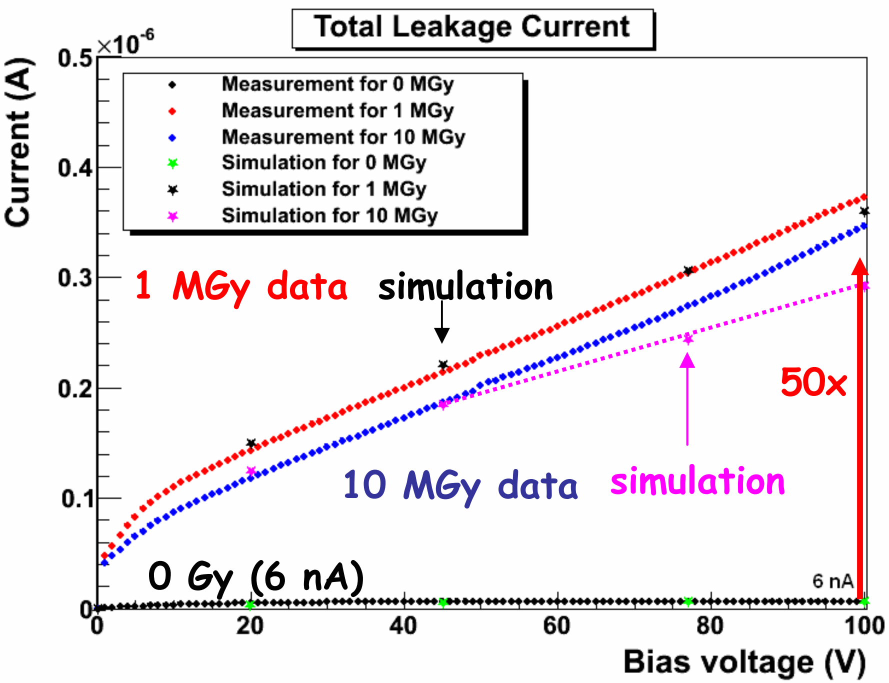
Strong dependence of C on frequency due to interface traps

→ still to be checked if reproduced quantitatively by simulations

(should have no impact on signal)

I-V characteristic vs irradiation dose

($I_{surface}$ due to interface traps)



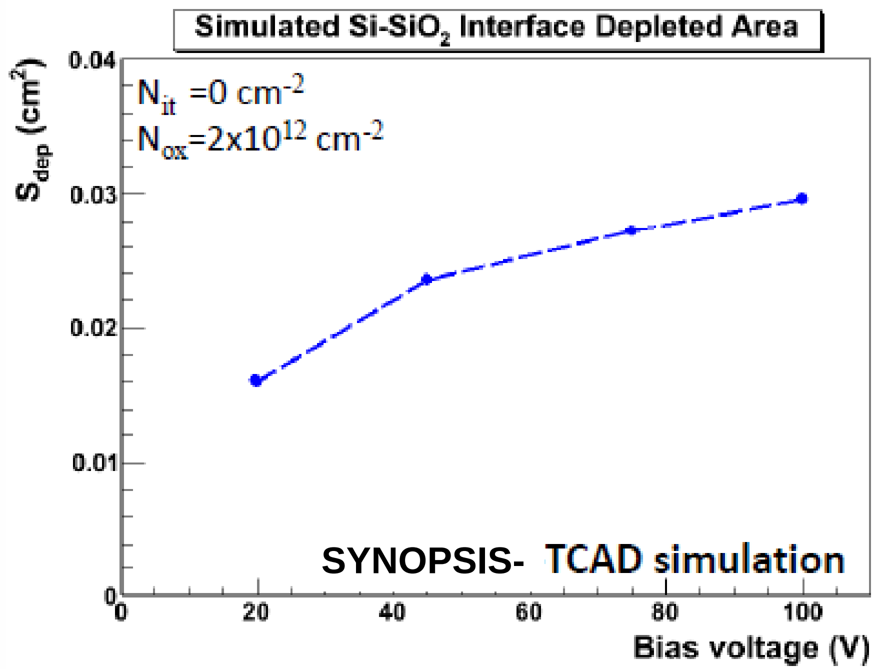


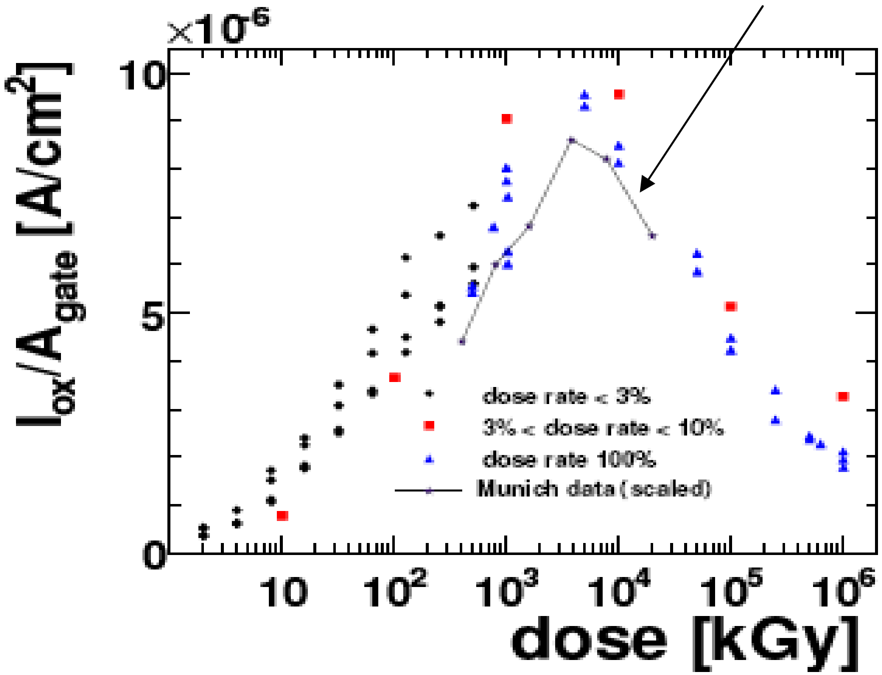
Fig 8. Simulated Si-SiO_2 interface depleted area

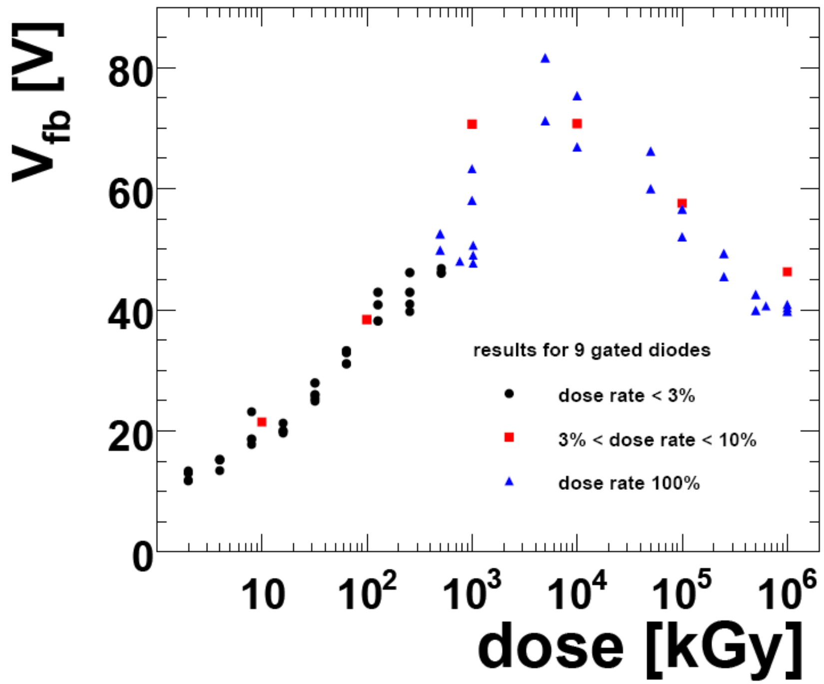
- Simulation describes voltage dependence of current
- current proportional to depleted interface area
- saturation (decrease) of current for doses > few MGy
- normalized to a 200x200 μm² pixel: I ~ 0.2 nA (depends on design!)
  [I_{sensor}~0.5μA/cm² ⇔ $I_{surface}$ (sensor depl. region) ~9 μA/cm²
  ⇔ $I_{surface}$ (from gated diode) ~8 μA/cm²] ☺

1. Parameters extracted from test structures x TCAD simulations describe radiation effects in segmented p^+-n(-n^+) sensors
2. Saturation of N_{it}, N_{ox} and $I_{surface}$ confirmed
3. Next a) Irradiate n^+-n(p^+) sensors + similar measurements
   b) Verify charge collection in irradiated sensors

Reminder: First irradiation results from measurements on gated diodes ☺
(no annealing –immediately after irradiation)

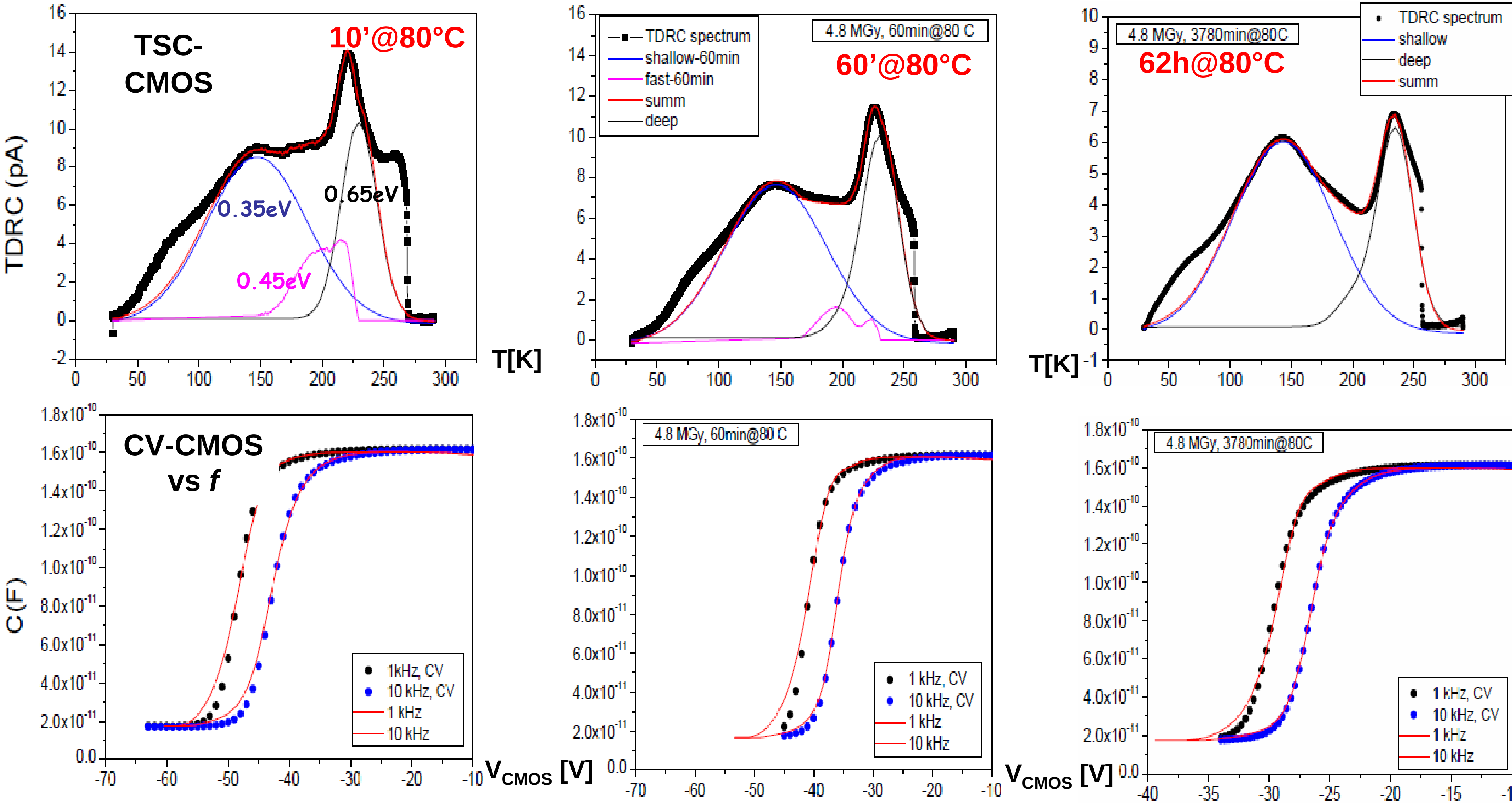
MPI-data scaled by 2





Annealing of radiation damage

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



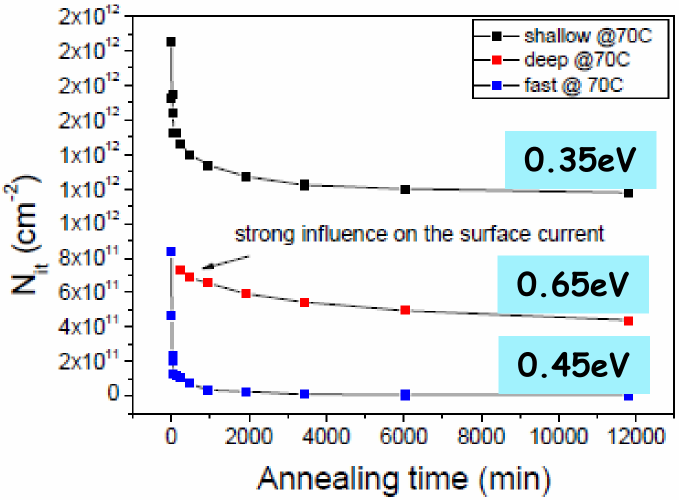
→ 3 dominant trap levels with different activation energies → τ_{anneal}

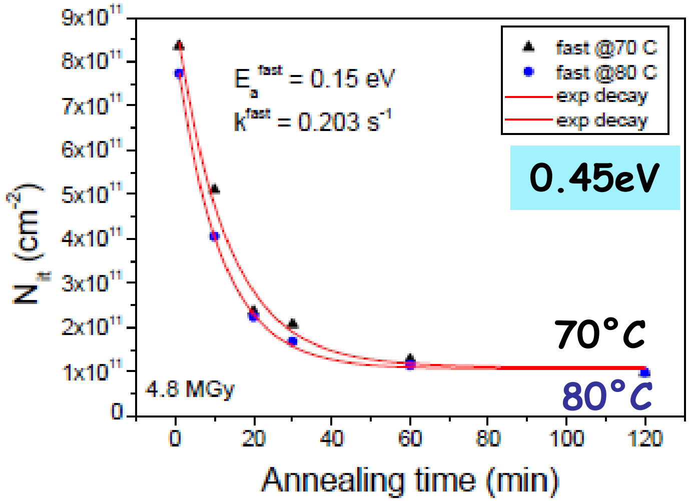
e.g interface trap at 0.45eV quickly anneals at room temperature

Annealing of radiation damage

Time dependence of annealing of 3 levels and N_{ox} at 70 and 80°C
→ activation energies E_a and frequency factor k

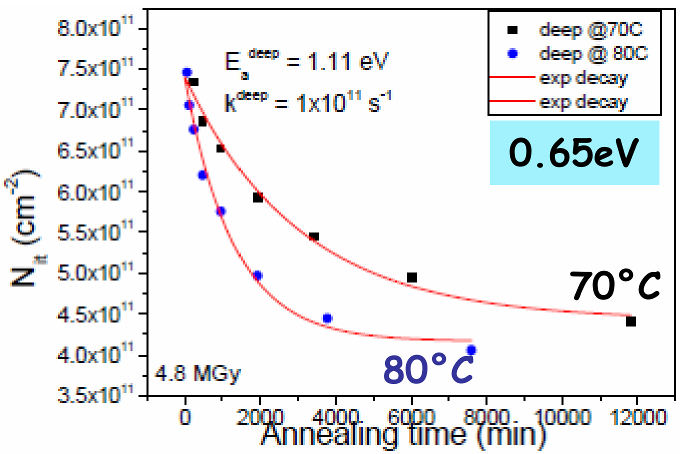
$N(t,T) = N_0 + N_1 e^{-\alpha(T)\cdot t}$ and $\alpha(T) = k \cdot e^{-(E_a/k_B T)}$ (Arrhenius-plot)

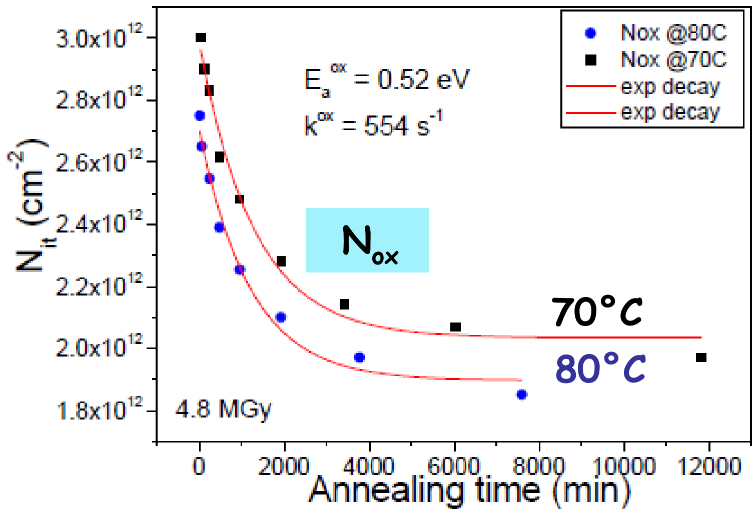




τ(25°C)
(large uncertainties !!)

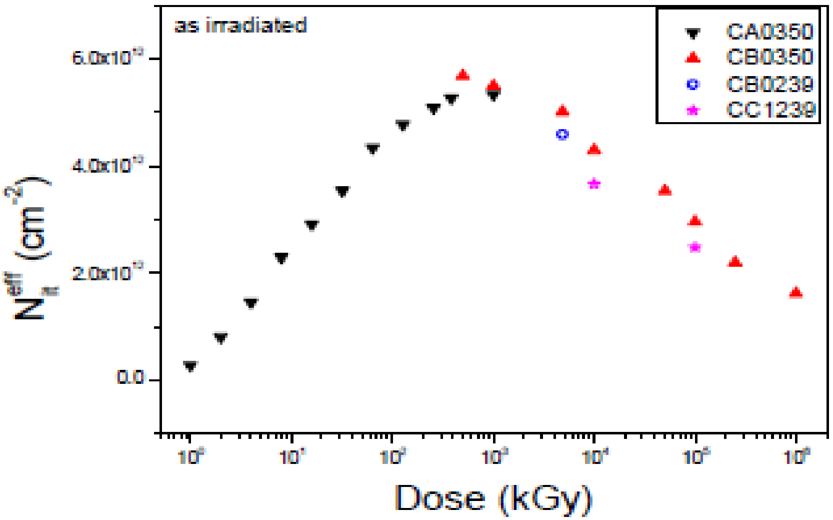
0.45eV: 35'
0.65eV: 3000d
N_{ox}: 25d

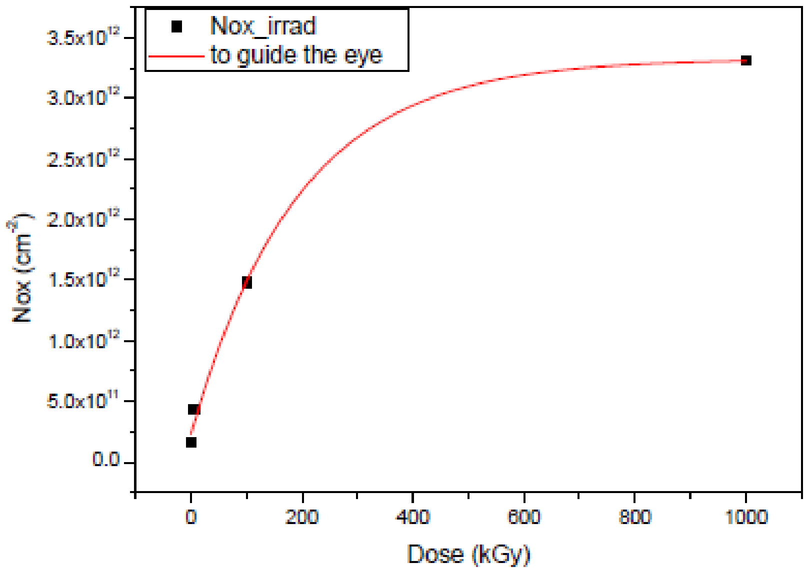




significant room temperature annealing !

Dose dependence of N_{it}(eff) and N_{ox}:





→ confirms first results (2008 !!!):

- radiation damage (N_{it}) reaches a maximum at a few MGy and then decreases
- N_{ox} saturates (slow further in-crease?) around same value
- at deep inversion injection of oxide charges close to Si-SiO_2-interface: of no relevance for detectors? but makes interpretation of CV-measure-ments on CMOS capacitors and determination of N_{ox} difficult

Summary and next steps

Summary:

- Surface radiation damage is a complex business
- Parameters extracted from test structures x TCAD allow to "predict" macroscopic effects for segmented p^+n sensors
- Preliminary determination of activation energies (annealing behaviour) of dominant trap levels
- Saturation (decrease) of N_{ox}, N_{it} and $I_{surface}$ confirmed

→ Radiation damage does not to appear to be a show-stopper

→ Input for sensor design + performance prediction available

Next:

1. Check radiation damage effects on segmented n^+n sensors
2. Check signal collection on irradiated p^+n and n^+n sensors (multi TCT setup
3. Verify technology dependence (test structure + sensors under fabrication by Hamamatsu for CEC (Central European Consortium – studies for sLHC detector within CMS Collaboration)

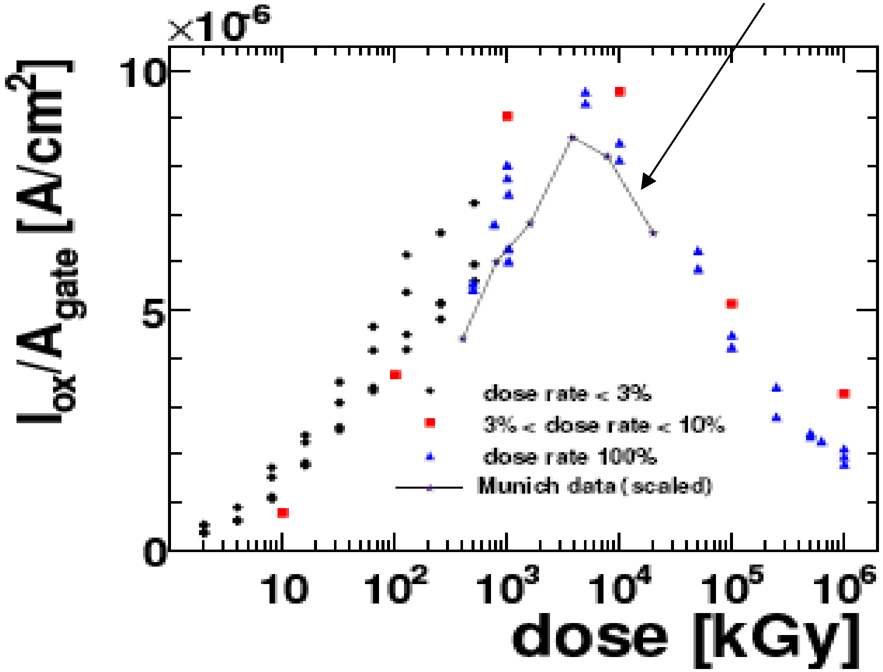
Spare

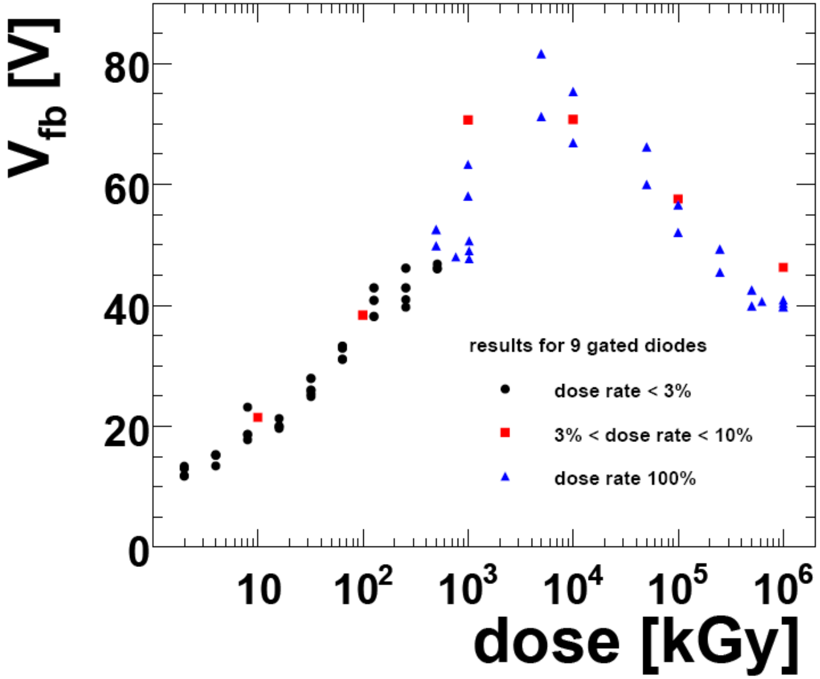
bla-bla:

1. Summary of radiation damage measurements and parameter extraction for simulation (from gated diode measurements)

Surface generation current vs dose + "Flat-band voltage" vs dose (immediately after irradiation)

MPI-data scaled by 2



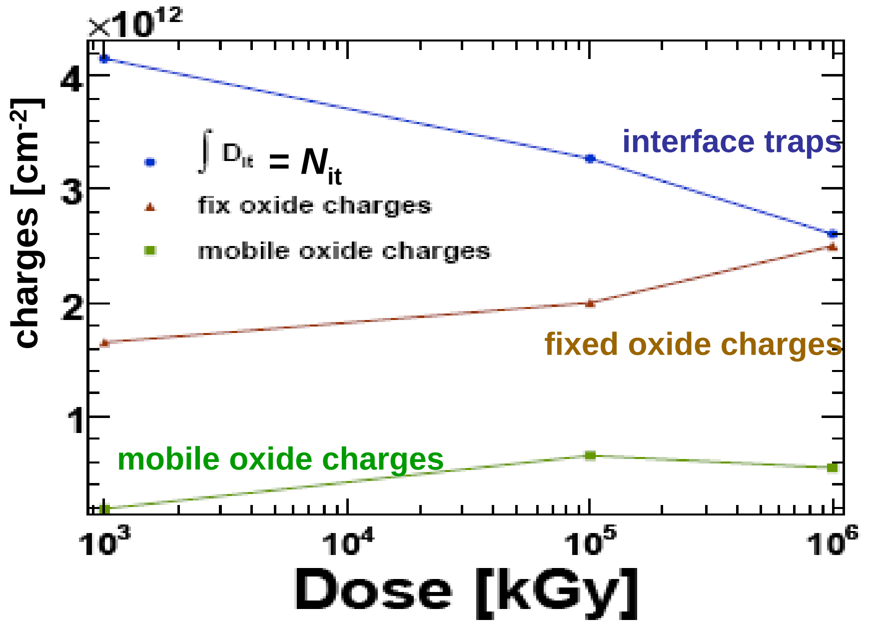


→V_{fb} [N_{Ox}+N_{it}] and I_{Ox} [N_{it}] reach maximum at few MGy – then decrease (tentative conclusion: decrease due to N_{it} at high doses – reason not clear)

Summary Radiation Damage

Relevant parameters:

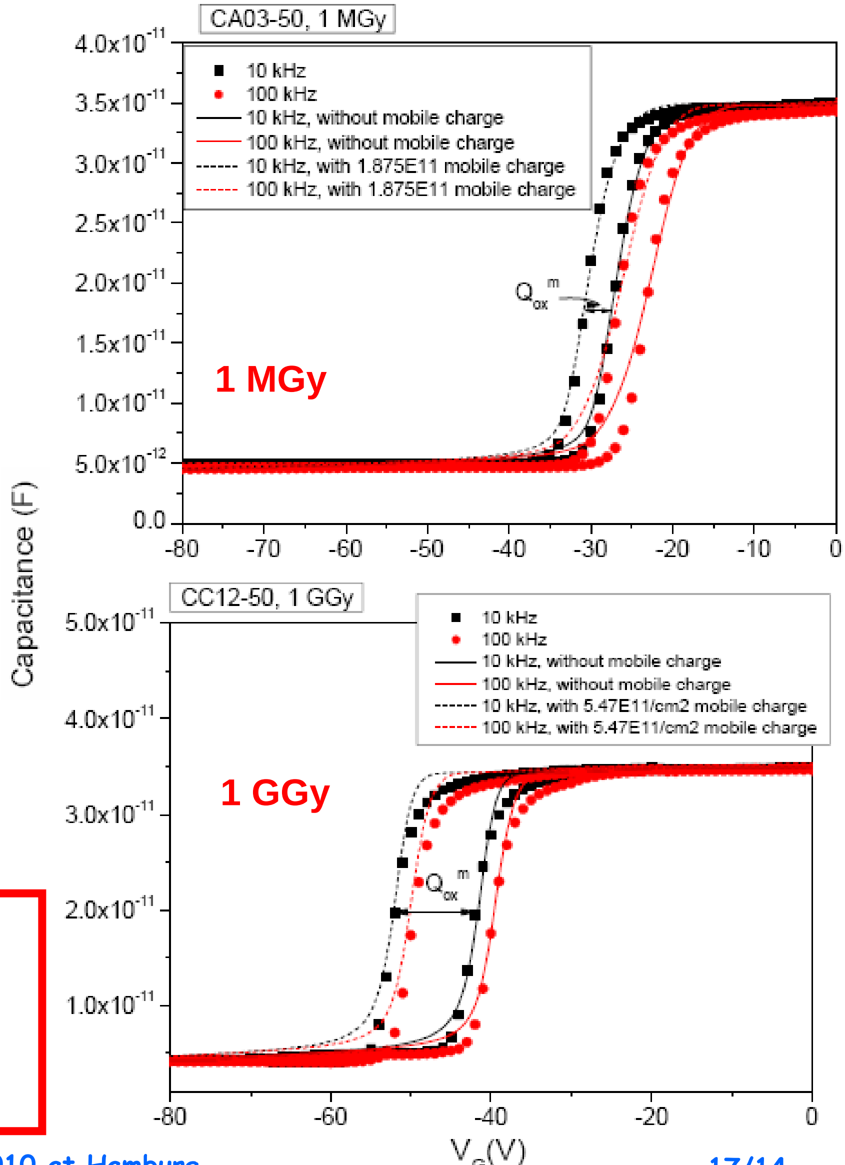
1. N_{Ox}(fix) fixed oxide charges
2. N_{Ox}(mob) mobile oxide charges - recent studies show introduction under biasing with long (hours) introduction time const.
3. D_{it}[$cm^{-2} \cdot eV^{-1}$] interface trap density



→ summary:

→ data can be described by microscopic model → parameter extraction → → for use in simulations

Comparison to measurements



Program used: ISE-TCAD from Synopsis

Physical models used:

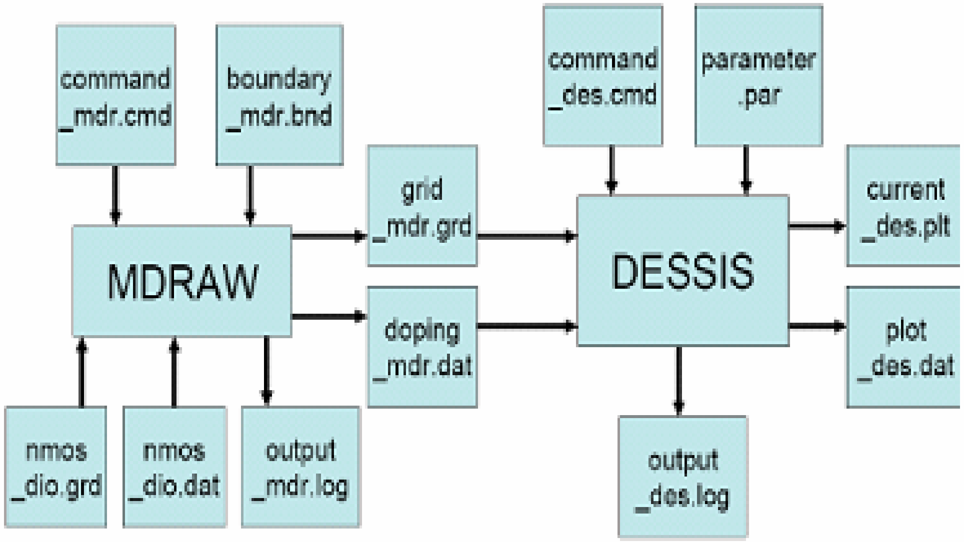
CPU time: 100 min
no. grid points: 60 000

- SRH (Shockley-Read-Hall) recombination
- Auger recombination
- impact ionization
- trap models
- doping dependent mobility and high field saturation model, band to band tunneling
- surface recombination model

Simulation procedure:

Procedure

1. Design structure in MDRAW
2. Feed results into DESSIS
3. Combine simulation of device (DESSIS) and circuit (SPICE)



Characterisation segmented sensor:

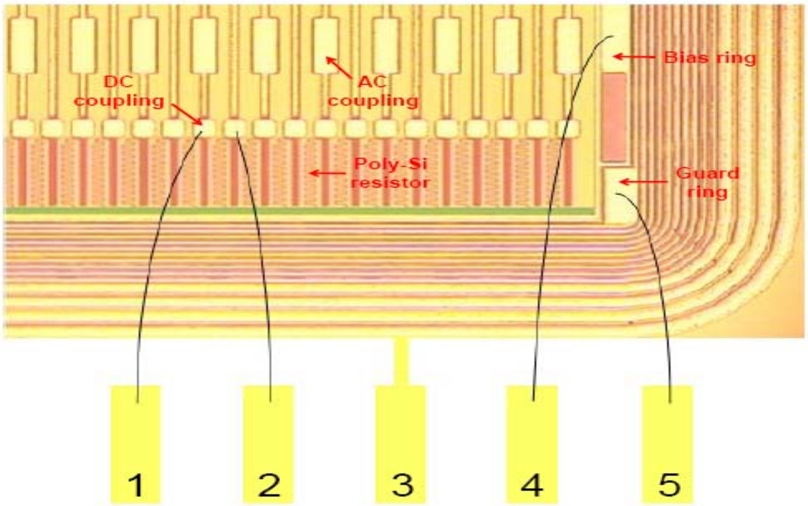
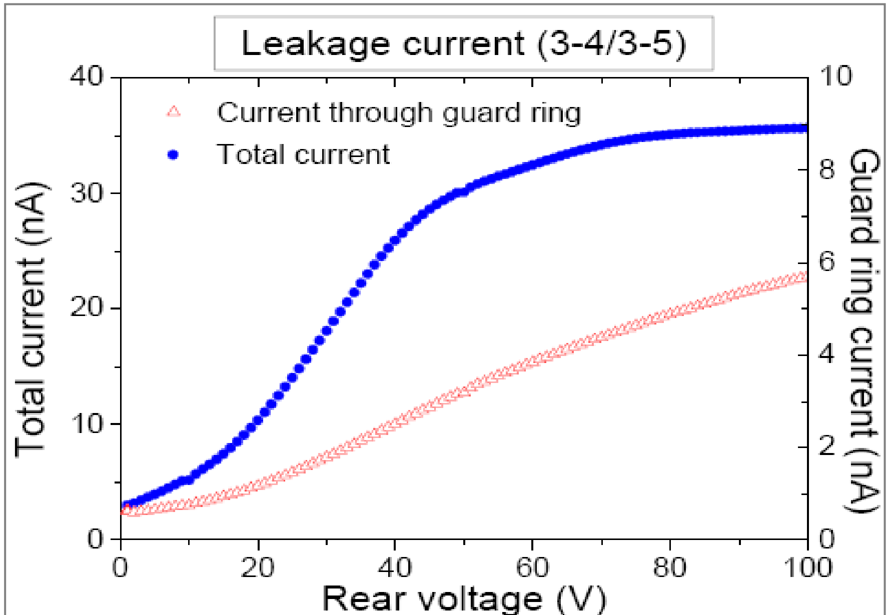
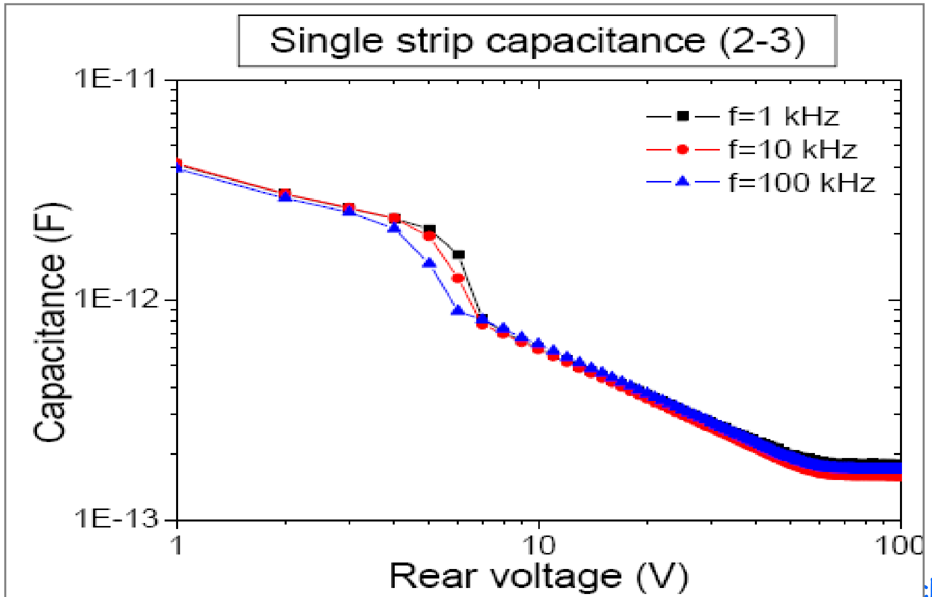
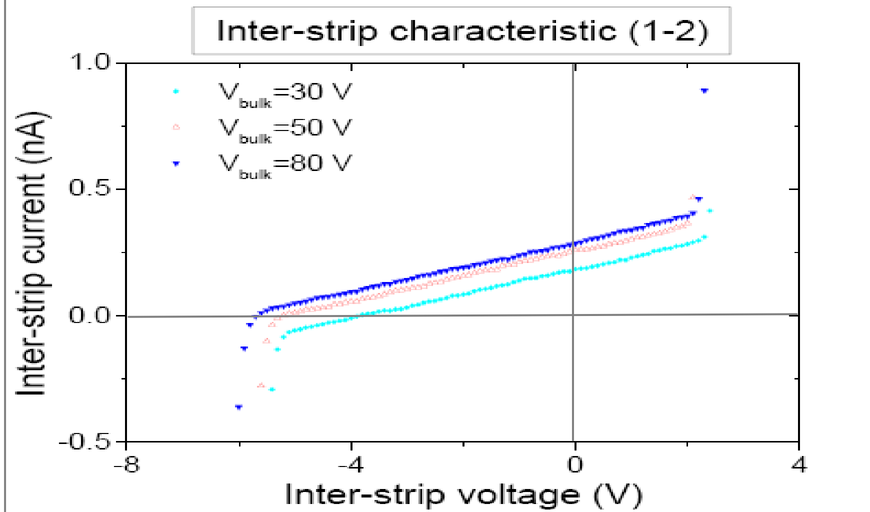


Fig. Photograph of microstrip sensor
Contacts:1&2 – adjacent strips; 3 – rear plane; 4 – bias ring; 5 – 1st guard ring.







- inter-strip resistance $R_{in} \approx 20\ G\Omega$
- Interstrip breakthrough voltage: -5~-6 V/ 2~3 V

Spice model: based on RC network [1)]

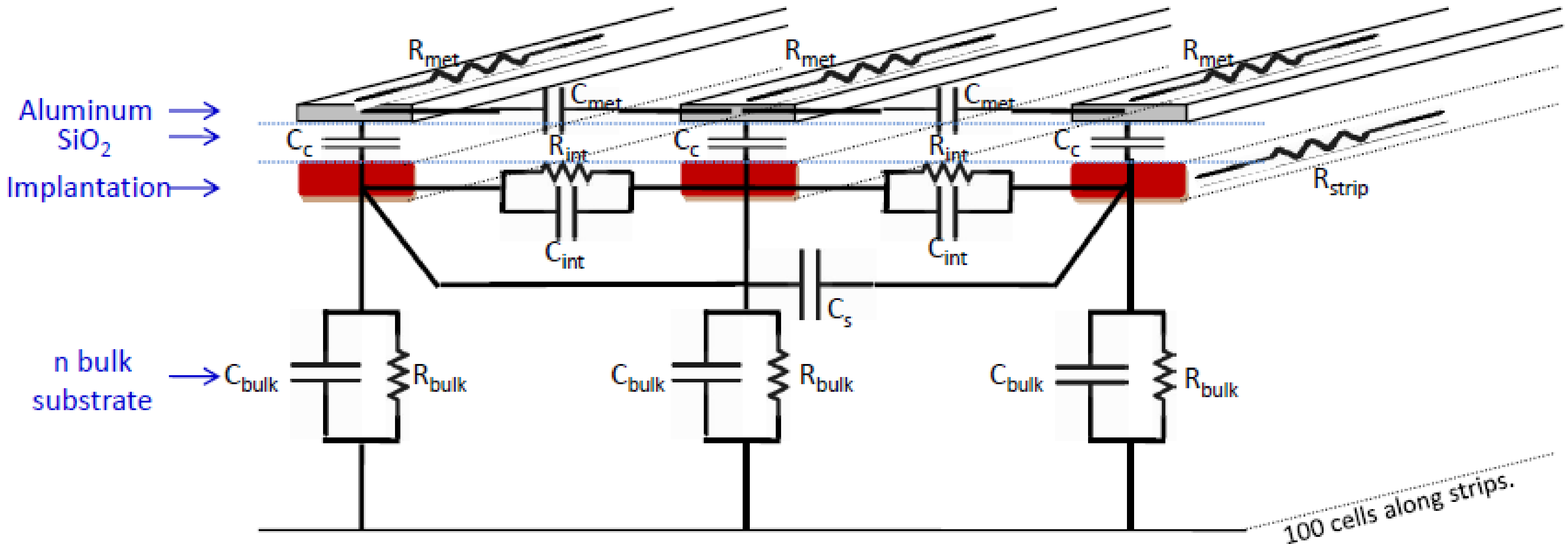


Fig 9. RC network of the strip sensor

- 10 parameters: C_{bulk}, R_{bulk}, C_{int}, R_{int}, C_c, R_{strip}, C_{met}, R_{met}, C_s, R_{bias}
- Able to simulate capacitance and resistance ***frequency response – C(f) & R(f)***
- In this simulation, 5 strips and 100 cells are used ~ 80 µm/cell

1) M.M. Angarano, et al. Nucl. Instru. & Methods, Vol. 428, No.2, 1999

bla-bla:

Total bulk, interstrip and coupling impedances *) :

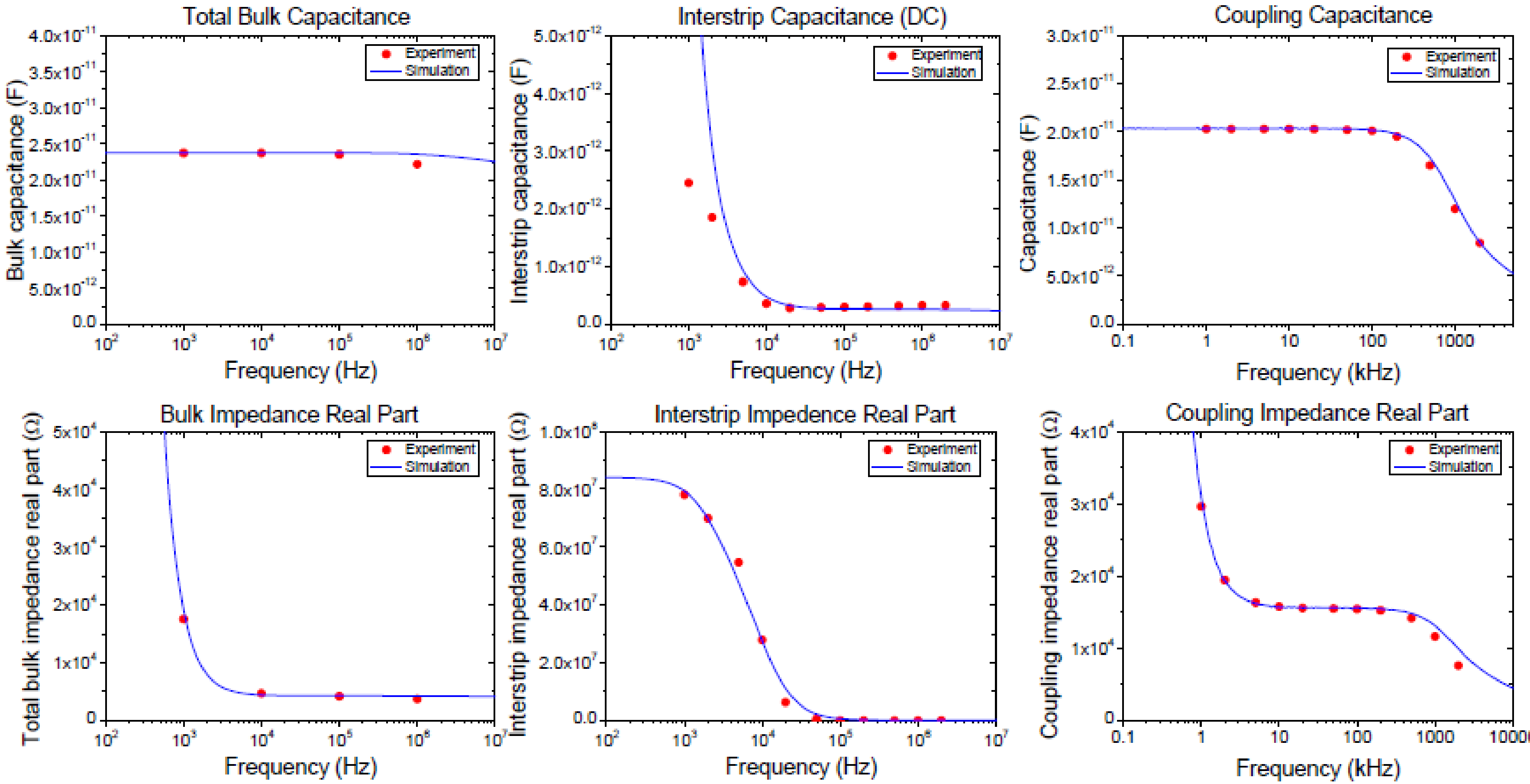


Fig 10. Comparison between spice simulation and experiment

Because of the presence of interface traps, this simple model won't work for irradiated sensor.

*) Series mode

J. Zhang, University of Hamburg 10 DPG Spring Meeting, Bonn 2010