Radiation Damage Studies of Si-Sensors for the XFEL

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1. Why ? XFEL Requirements
2. Irradiation Facility at DORIS
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4. Results
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1.X-FEL Requirements (for imaging Si-pixel detectors)

Integrated 12 keV photon flux up to 10^{16}cm^{-2} (1GGy)

→ no bulk damage expected (threshold 300 keV), but

- built-up of oxide charges
- built-up of Si-SiO_2 interface states

→ change of field distribution (device stability)
→ dark current → noise + impact on read-out electronics

aims: - determine relevant parameters for device simulations
- predict detector performance vs. dose

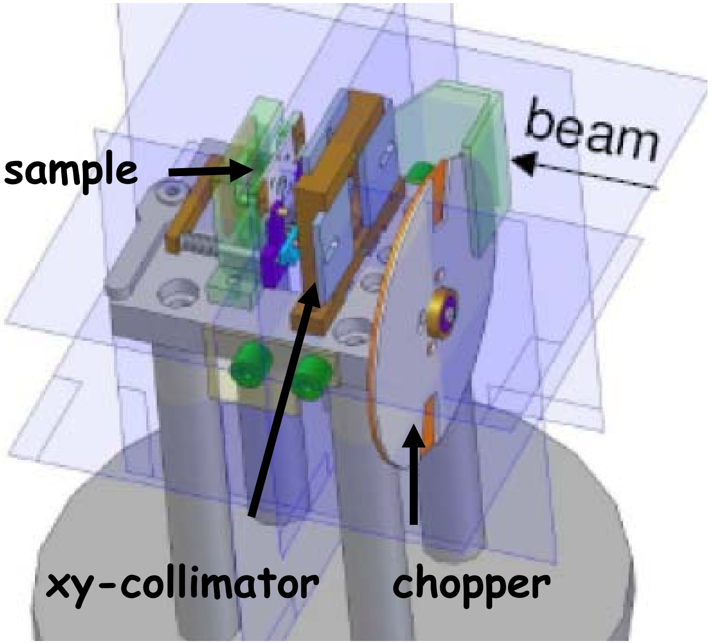
Instantaneous (tens of fs) 12 keV photon flux of 10^5/pixel

→ "plasma effect(s)" → talks by K.Gärtner and J.Becker

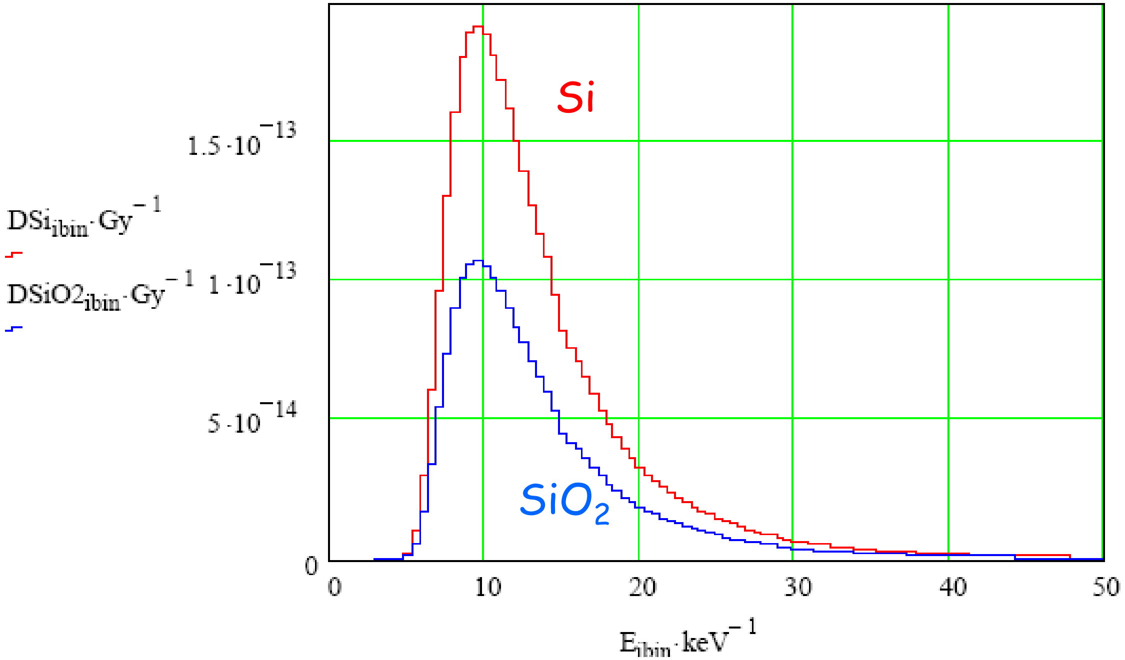
2. X-ray irradiation facility in F4 beam line at HASYLAB (DORIS)

- **energy**: 10 keV (±5 keV)
- **dose rate**: 0.5-150 kGy/s (SiO_2)
- **spot size**: (2mm x 5mm) + scanning
- sample can be biased
- **T-control**: (H_2O – room temp.)

irradiation set-up

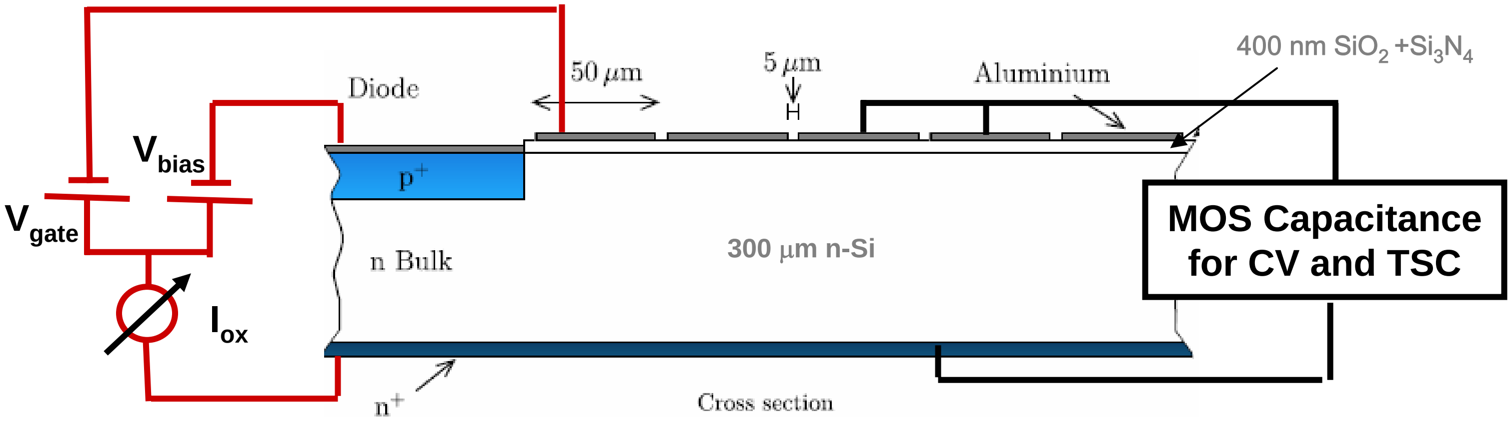


relative dose at surface vs x-ray energy



CV,IV measurements in hall; CV,IV,TSC,DLTS,etc in HH detector lab@500m

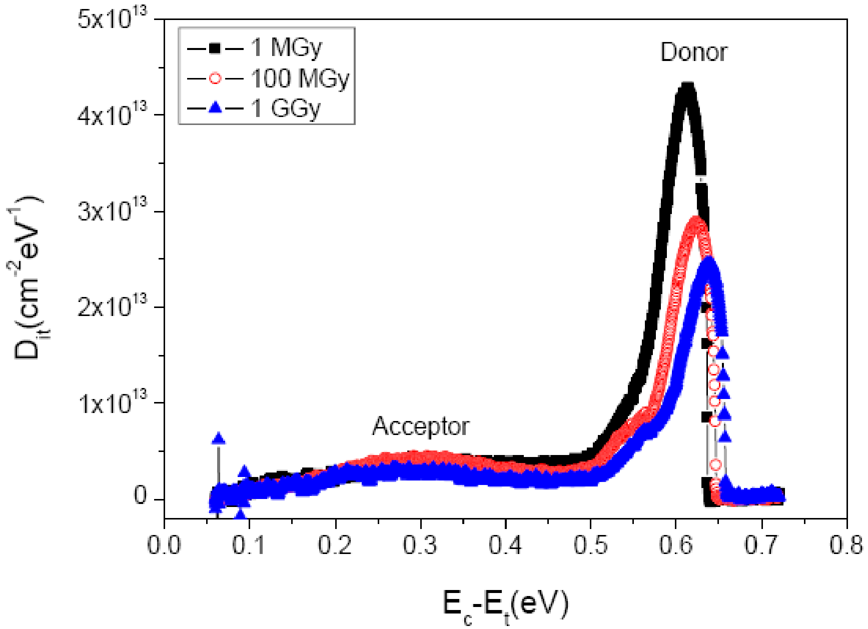
3. Test Structure (gated diode) and Measurement Techniques

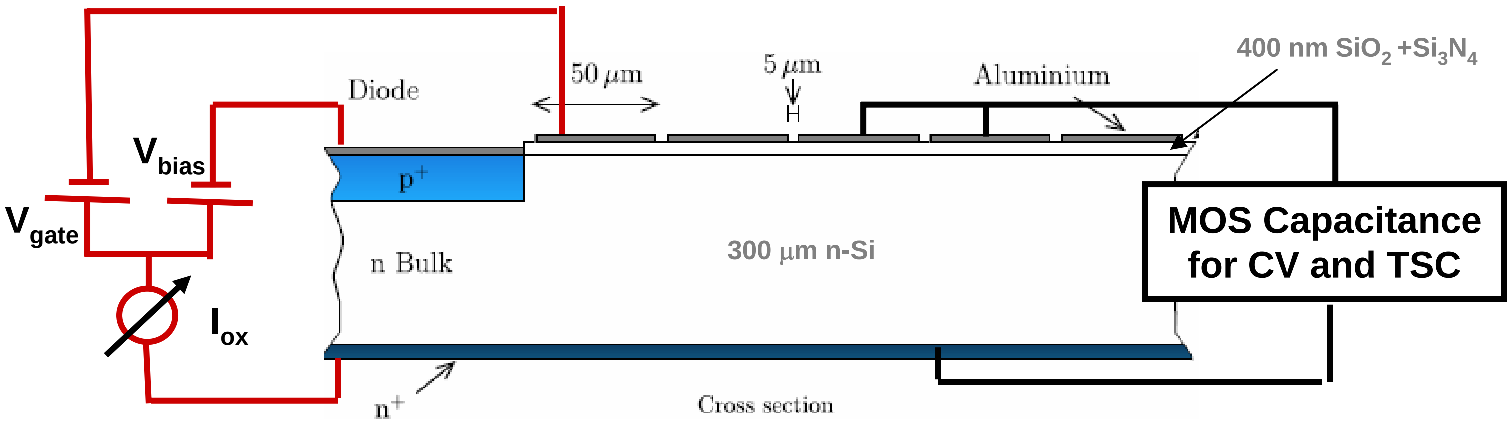


a) **TSC = Thermally Stimulated Current**

- cool down with carrier injection
- heat up sample with constant rate (0.18K/s) with reverse bias on
- measure current due to discharge of filled traps

→ D_{it} [$eV^{-1}cm^{-2}$] = density interface traps in band gap



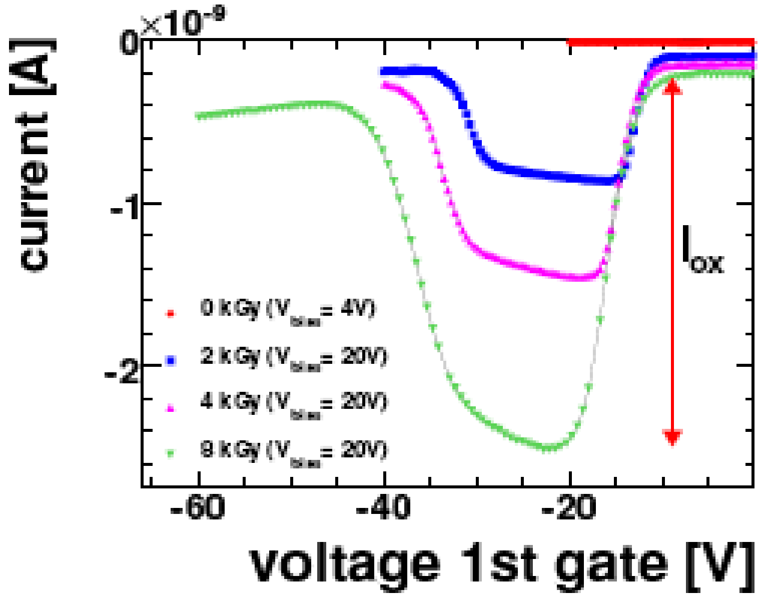


b) **IV$_{(gate)}$** (for fixed V_{bias})

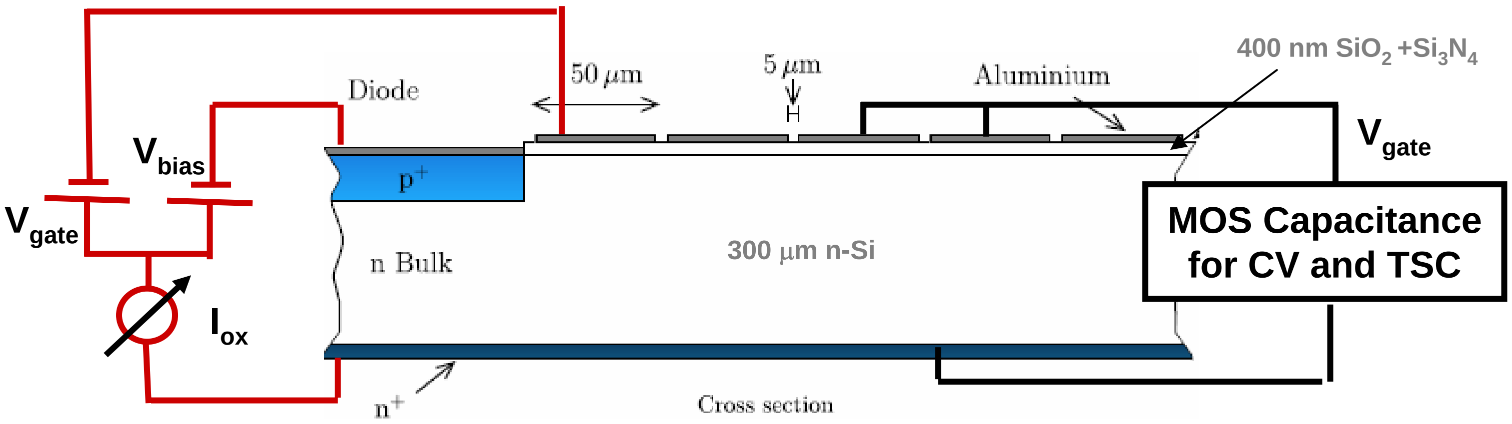
change V_{gate}

- accumulation → I_{diode}
- depletion → I_{oxide} + I_{diode}
- inversion → I_{diode}

→ J_{oxide} [$A \cdot cm^{-2}$] sensitive to D_{it} in middle of band



(in addition information on V_{fb} flat-bend voltage; I_{ox} not used in analysis, but checked that in qualitative agreement with other measurements)

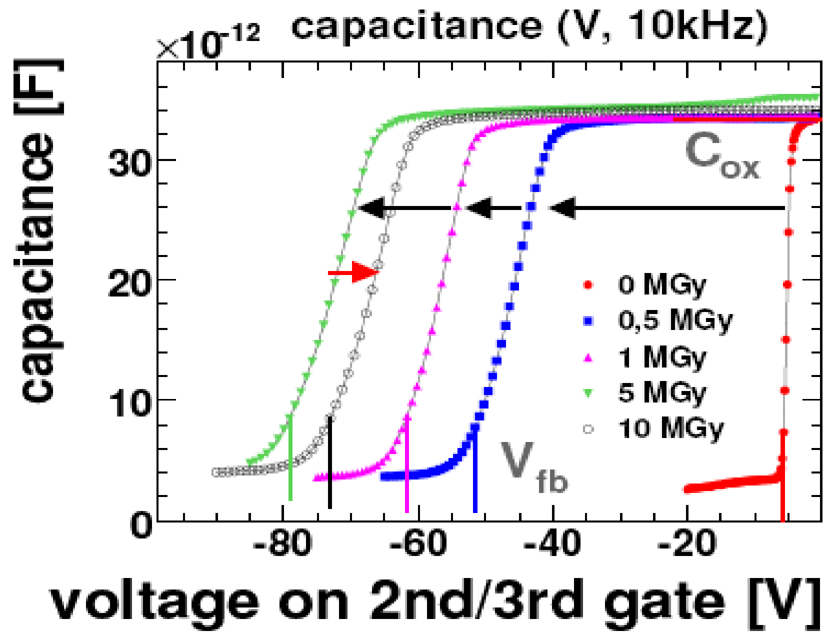


c) CV_{gate} vs frequency, V_{max}, ...

transition from accumulation to inversion

ΔV depends on oxide + interface charges

- shape CV-curve (slope) on D_{it}
- frequency dependence on D_{it}



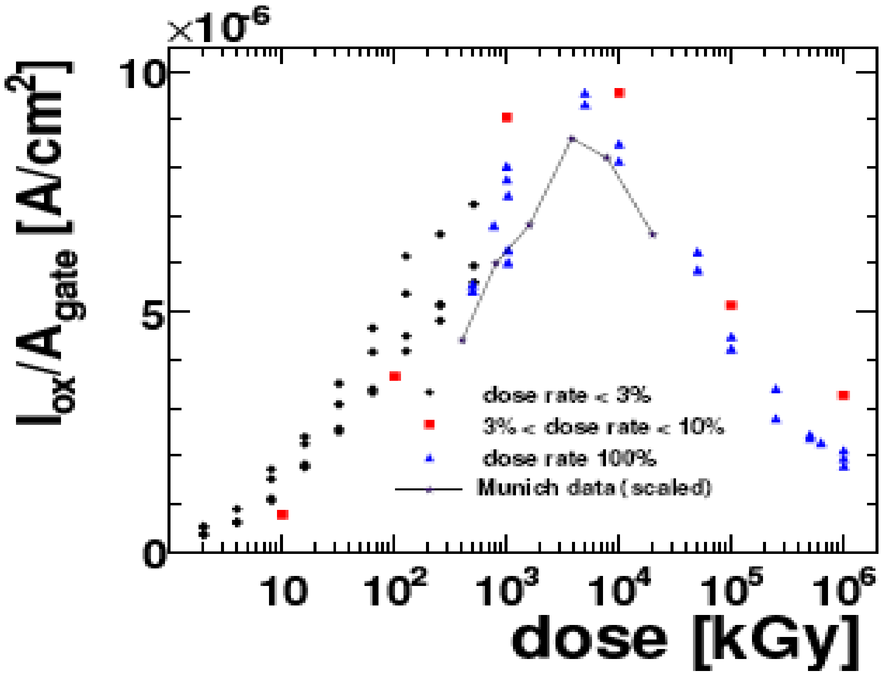
Analysis Method:

- obtain D_{it} from TSC measurement
- model calculation to predict shift ΔV_{it}, shape and frequency dependence of CV-curve
- obtain density of oxide charge (N_{ox}) from difference ΔV_{meas} – ΔV_{it}
- check that CV curves are described

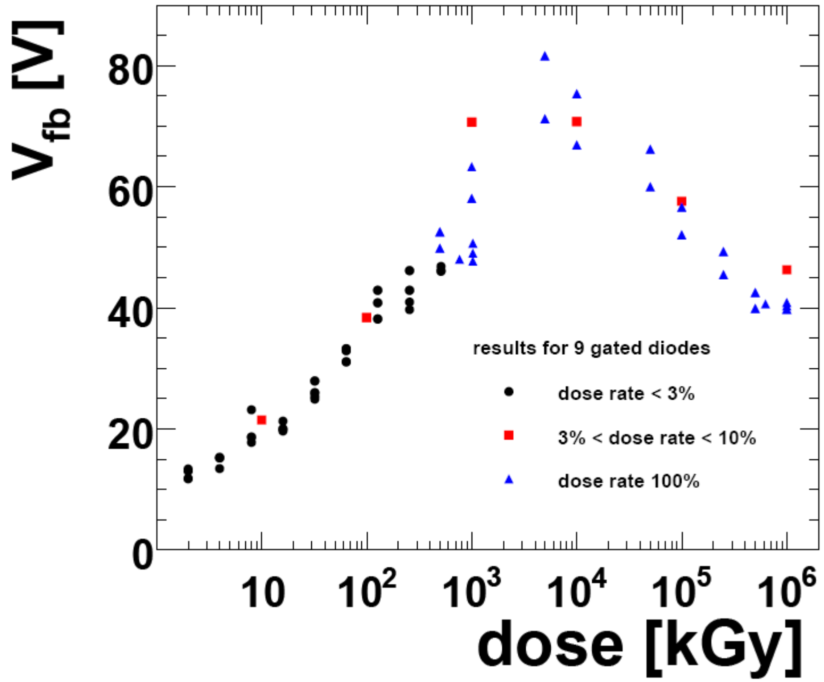
4. Results

a) 1st "on-line" analysis ~immediately after irradiation

I_{Ox} oxide current vs dose



V_{fb} flatband voltage vs dose



→V_{fb} [N_{Ox}+N_{it}] and I_{Ox} [N_{it}] reach maxima at few MGy – then decrease

Comment: It has been checked, that decrease is not effect of annealing due to the heating of the sample during irradiation (100 kGy/s = 100 kW/kg → ~0.5 W)

b) "Reproducibility" of CV curves

Voltage shift (ΔV taken at $\frac{1}{2}$ C_{ox}) strongly depends on "history" + "measurement conditions"

- for 0.2 s waiting time Δt:

1. CV for V_{gate} 0 → -100 V
   CV for V_{gate} -100 V → 0
2. repeat 1.

- for 60 s waiting time Δt:

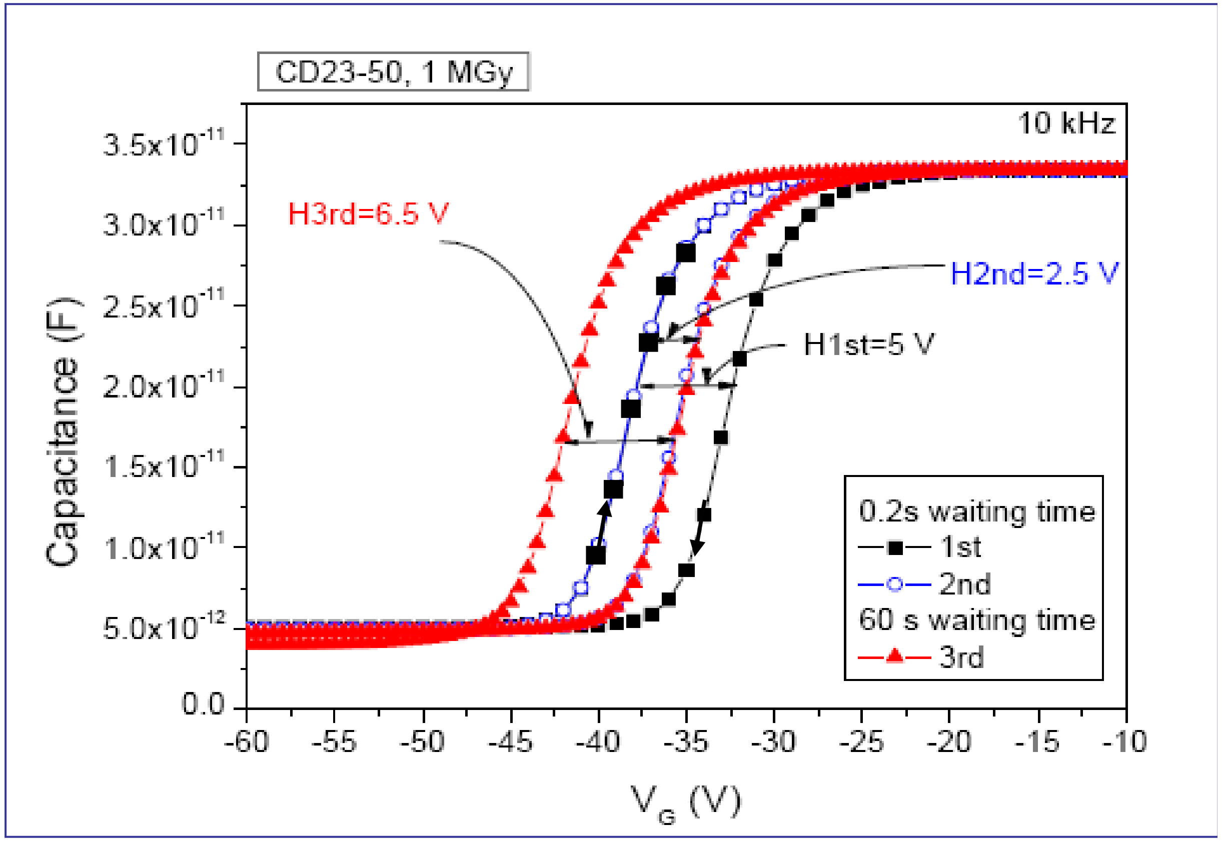
3. CV for V_{gate} 0 → -100 V
   CV for V_{gate} -100 V → 0

→ no change of shape CV

→ 1st 2nd meas. different

→ ΔV hysteresis effect

→ ΔV shift depends on Δt



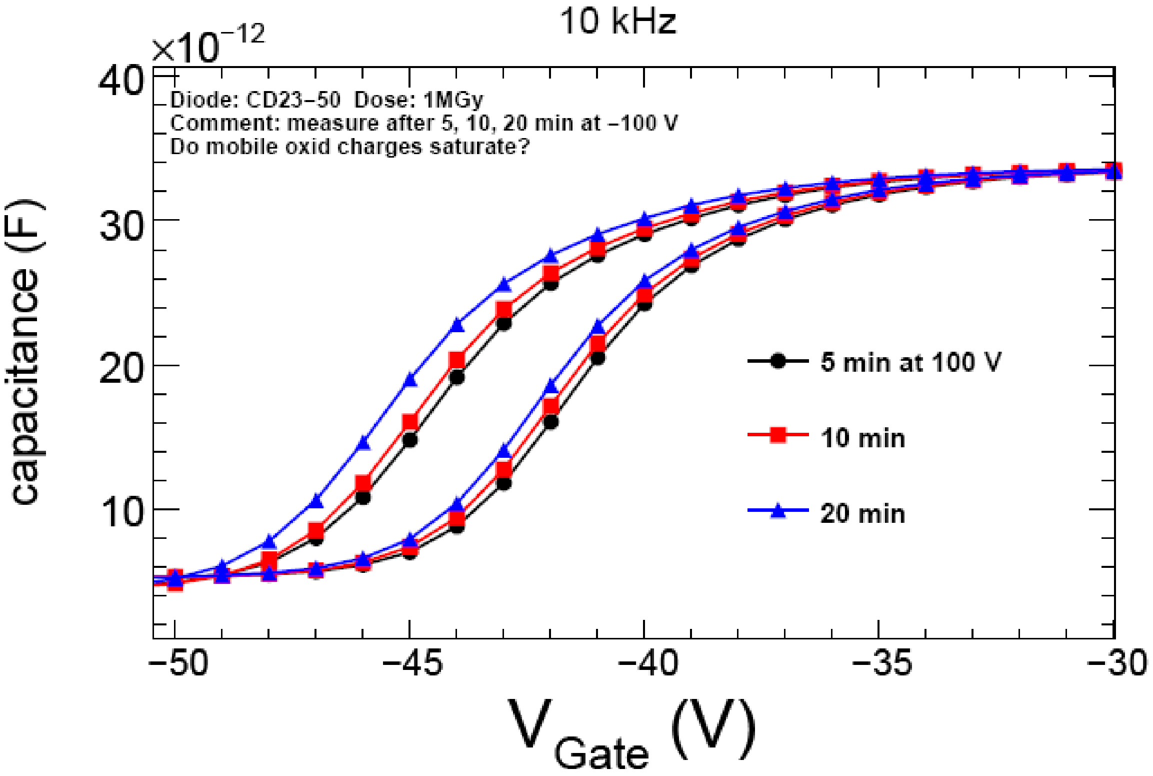
→ CV "history" + "hysteresis effects" + dependence on measurement speed

Results- Reproducibility

Voltage shift (ΔV taken at $\frac{1}{2}$ C_{ox}) strongly depends on "history" + "measurement conditions"

1. CV for V_{gate} 0 → -100 V
2. stay time T @ -100V
3. CV for V_{gate} -100 V → 0

→ no change shape CV
→ ΔV hysteresis effect
→ ΔV shift function of T



→ CV hysteresis effects + dependence on time biased at inversion

Results - Reproducibility

Voltage shift (ΔV taken at $\frac{1}{2}\, C_{ox}$) strongly depends on "history" + "measurement conditions"

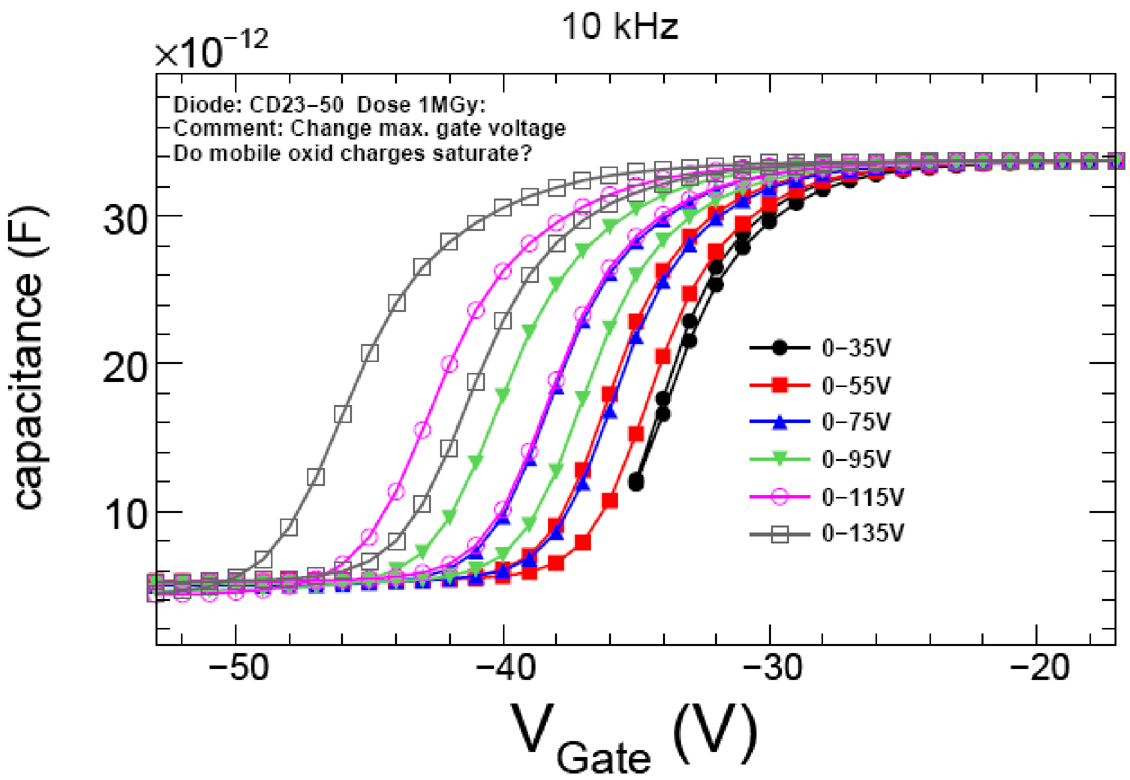
1. CV for V_{gate} 0 → -35 V
2. CV for V_{gate} -35 V → 0
3. CV for V_{gate} 0 → -55 V

i. ....

n. CV for V_{gate} -135 V → 0

→ no change of shape CV (once inversion reached)

→ both up- and down-branch continued ΔV shift with V_{max} (no sign of saturation)



→ ΔV dependence on max voltage (at inversion) of CV measurement

Comment: It has been verified that measurements after same history agree

c) Analysis and tentative Interpretation of the Measurements

assume 3 components to describe $Si\text{-}SiO_2$ irradiation effects:

1. $N_{ox}(fix)$ fixed oxide charges → they just shift ideal CMOS CV-curve → (no bending, no frequency dependence, no dark current)
2. $N_{ox}(mob)$ mobile oxide charges (close to interface) → shift ideal CMOS CV-curve + responsible for hysteresis effects and other shifts
3. D_{it} interface traps (integral is N_{it}) → shift and bend CV-curve, frequency dependence of CV-curve; responsible for I_{ox}

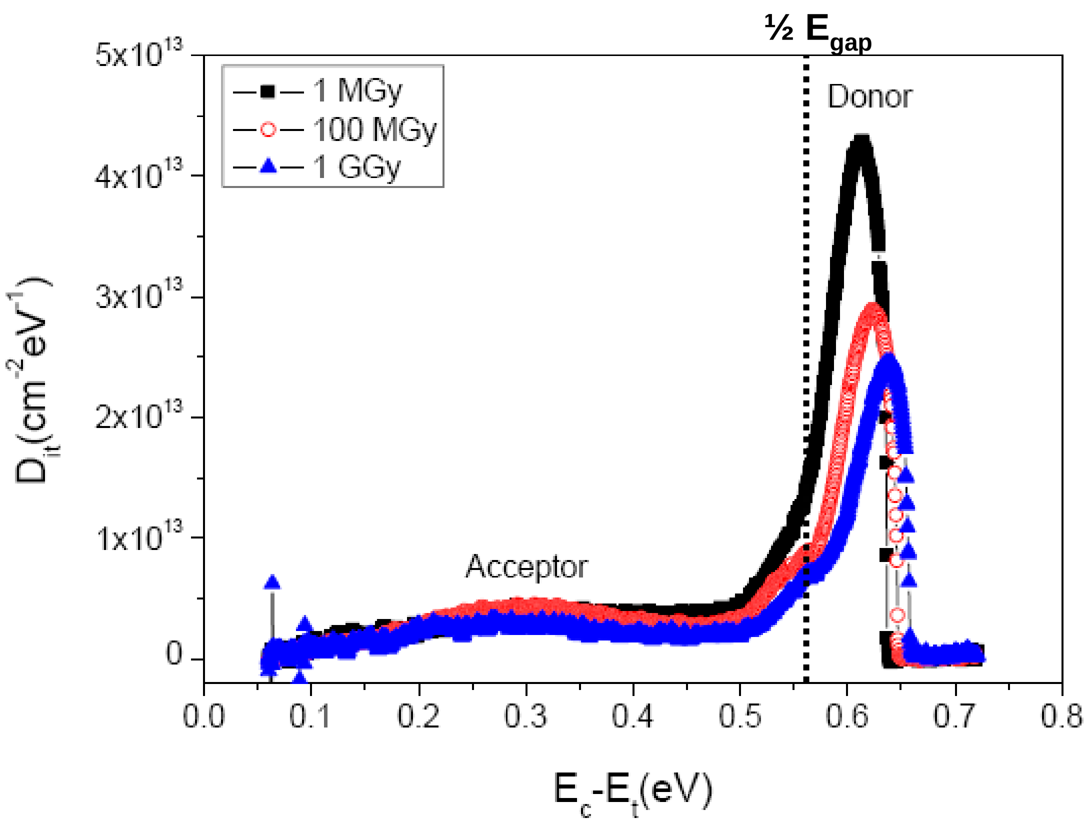
attempt to separate the 3 components:

1. N_{it} and D_{it} from TSC-data
2. Bring mobile oxide charges in well defined state (30'@80°C) – [hope was to remove them – does not seem to work] – determine from 1st CV curve $N_{ox}(fix) + N_{it}$
3. Simulate shape of CV-curve vs. frequency and compare to measurements
4. Obtain $N_{ox}(mob)$ from CV-curve (with 0.2s waiting time; V_{gate}= 0→-80V→0) → NB "arbitrary but reproducible definition" of $N_{ox}(mob)$!
5. Verify how well simulation describes measurements
6. Check that the results are consistent wit I_{ox} measurements

procedure well defined, but arbitrary – may cahnge with more experience

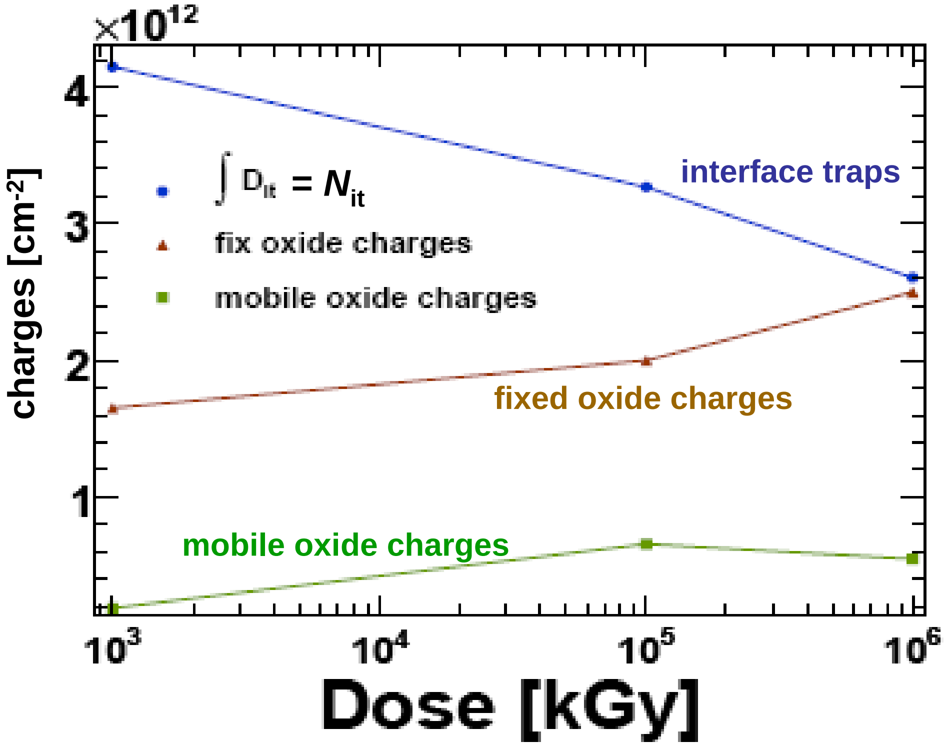
D_{it} [cm^{-2}eV^{-1}] Interface density vs Irradiation dose

(from TSC Thermally Stimulated Current- measurements):



→ significant decrease (1 MGy → 1 GGy) of D_{it}
in particular close to the middle of the band gap, where sensitivity to I_{Ox} highest

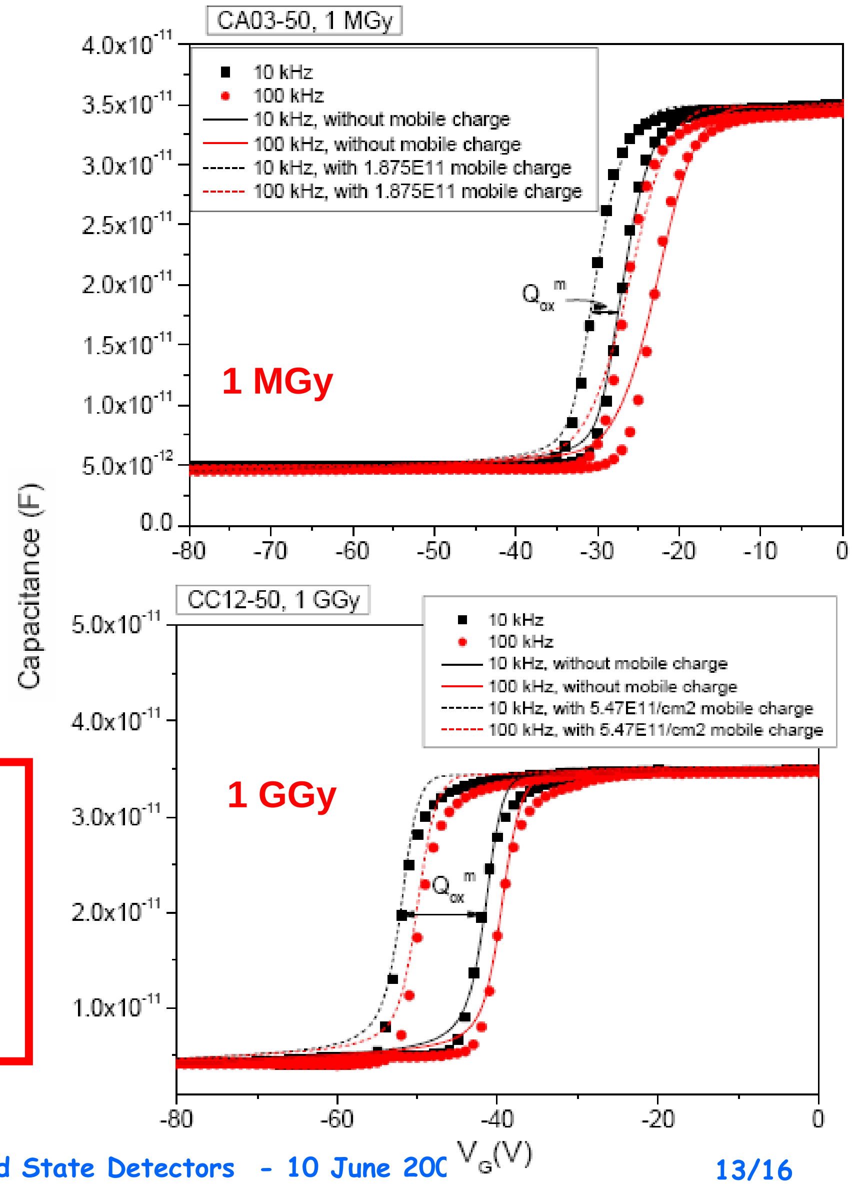
Results: (1, 100 and 1000 MGy)



→ results preliminary – have to be checked
- data can be described by microscopic model, which can be put into simulations
- reason for decrease of N_{it} not understood

"understanding" more complex than expected

Comparison to measurements:

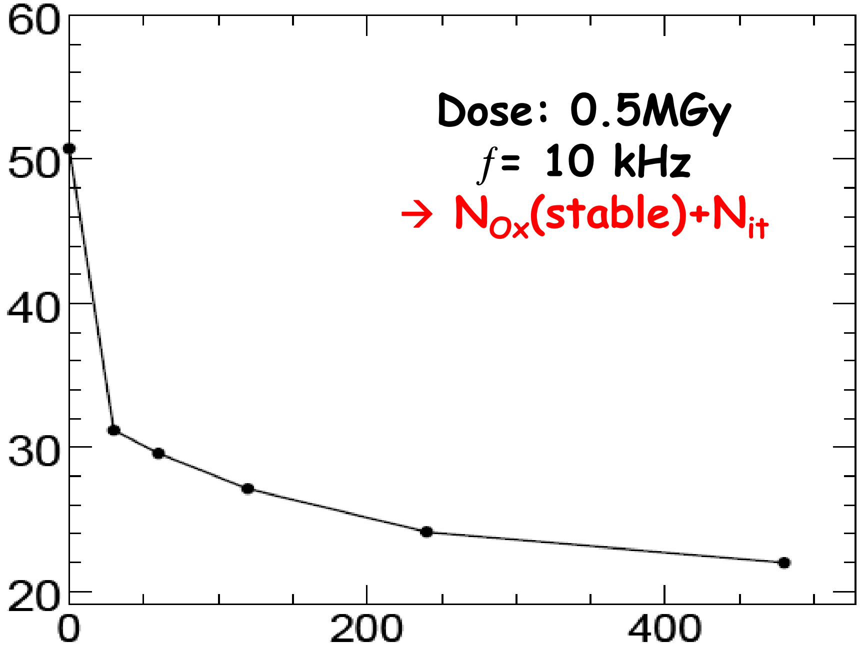


d) First results from Annealing Studies:

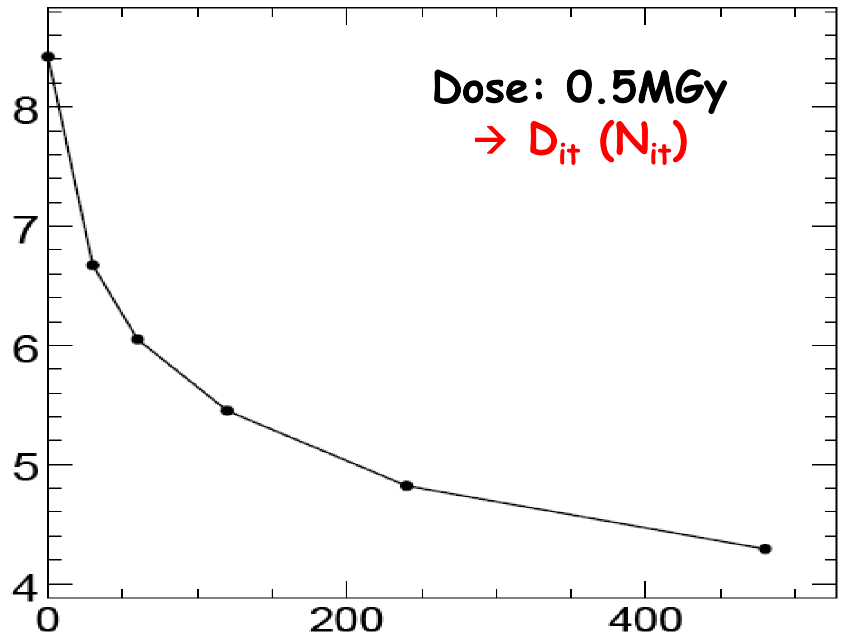
So far we: CV, IV and TSC-spectra vs annealing time at 80°C:

→ first preliminary results

Voltage($C=\frac{1}{2}C_{ox.}$)[V] vs annealing time



Δ Voltage(100kHz-10kHz) [V] vs $t_{annealing}$

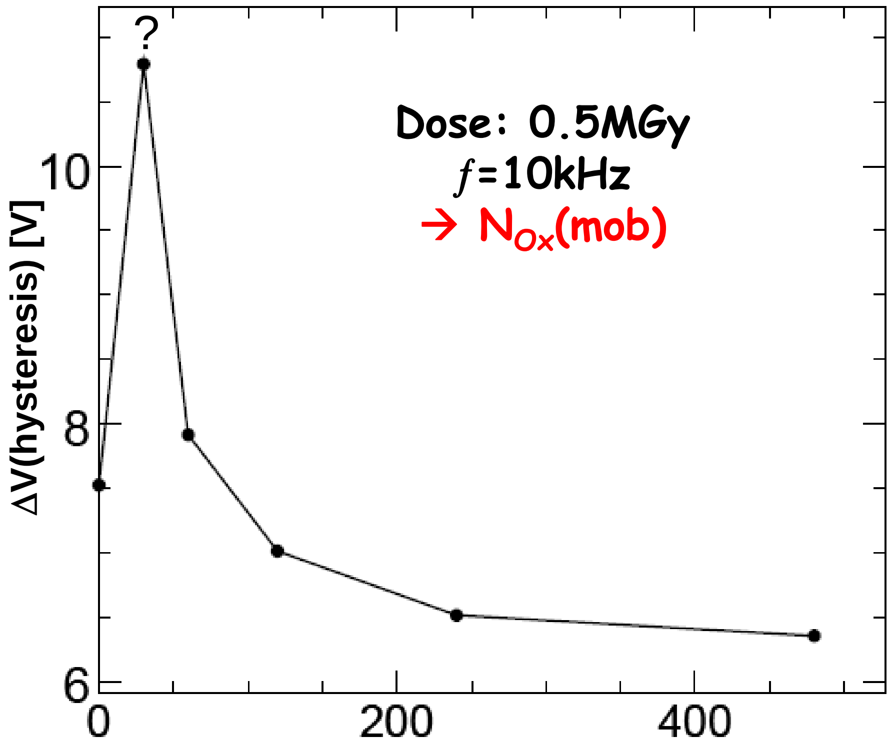


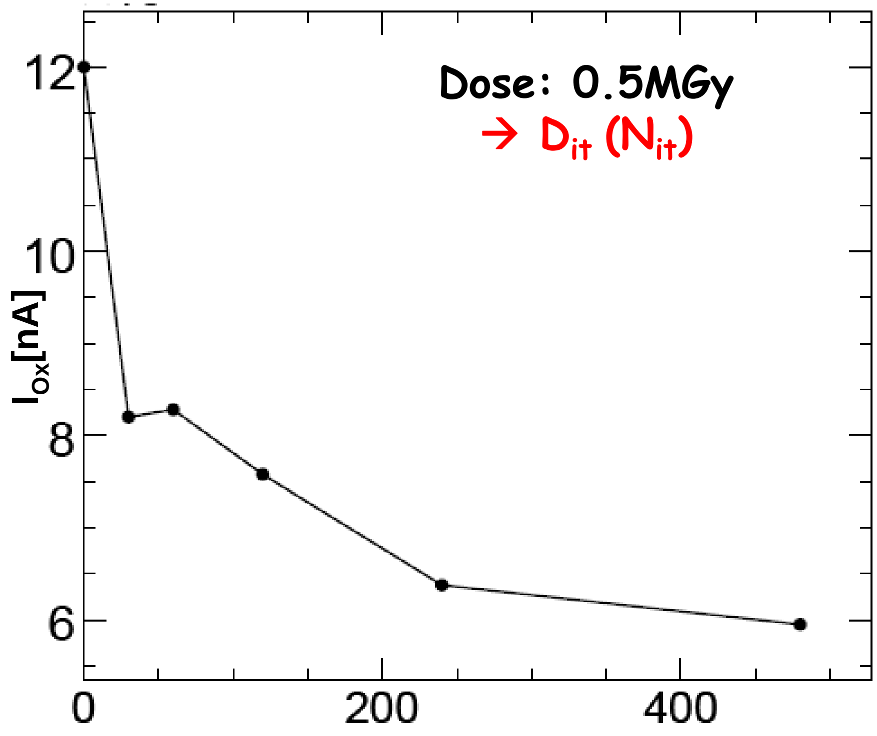
annealing time @ 80°C [minutes]

First annealing studies

ΔV(hysteresis)[V]@10 kHz vs $t_{annealing}$

I_{Ox} (nA) vs $t_{annealing}$





annealing time at 80°C [minutes]

→ strong annealing effects observed

→ still a lot to be understood

5. Summary and Outlook

- (as expected) X-ray radiation damage is complex and its study a time-consuming effort
- from measurements on gated diodes for doses up to 1 GGy:
  - interface traps: saturate (and even decrease) for doses above 1 MGy
  - fixed oxide charges: saturate (possibly small increase above 1 MGy doses)
  - mobile oxide charges: complex – still lots to be understood
- so far measurements only on unbiased structures
  → study effect of bias
- results put into sensor simulation ISE-TCAD – still to be verified that they agree with data and model simulation
- annealing studies have started
- next: irradiate pixel sensors and see if results can be understood on the basis of the data from the test structures put into simulations