Radiation Damage on MOS-Structure

Q. Wei, L. Andricek, H-G. Moser, R. H. Richter
Max-Planck-Institute for Physics Semiconductor Laboratory
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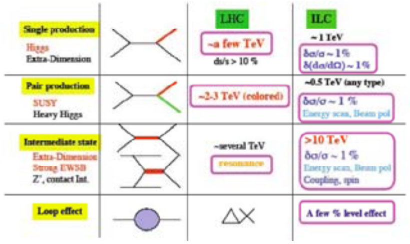
Outline

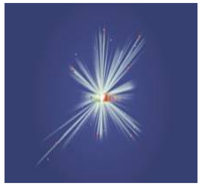
- Motivation
- Radiation damage & effects on MOS-structure
- Experimental Conditions and Results
- Conclusion

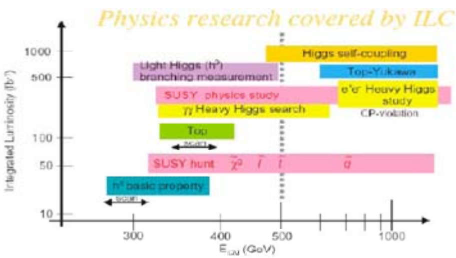
Motivation

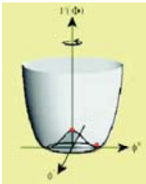
Physics topics

- Unexpected phenomena
- Mechanism of electroweak symmetry breaking
- New physics: SUSY; extra dimension; link to cosmology

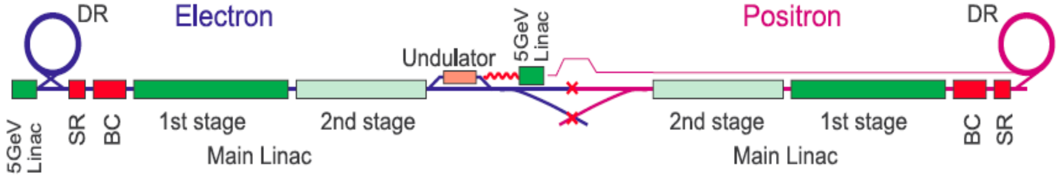






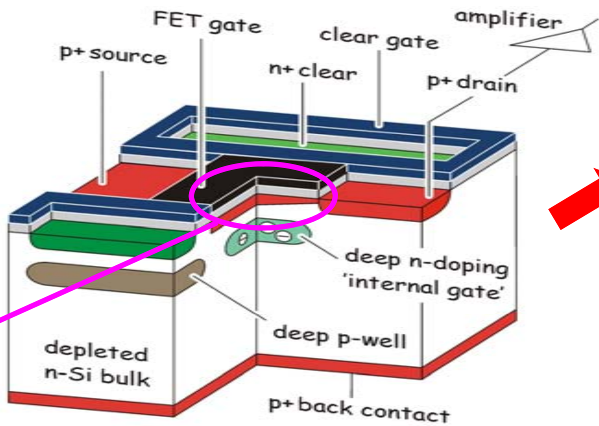


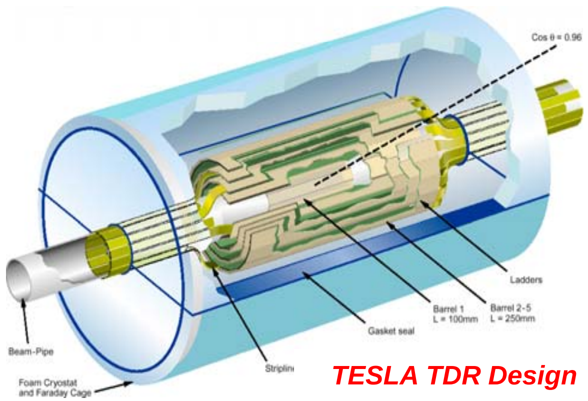
International Linear Collider



precise vertex detector (DEPFET)

Depleted P-channel FET





TESLA TDR Design

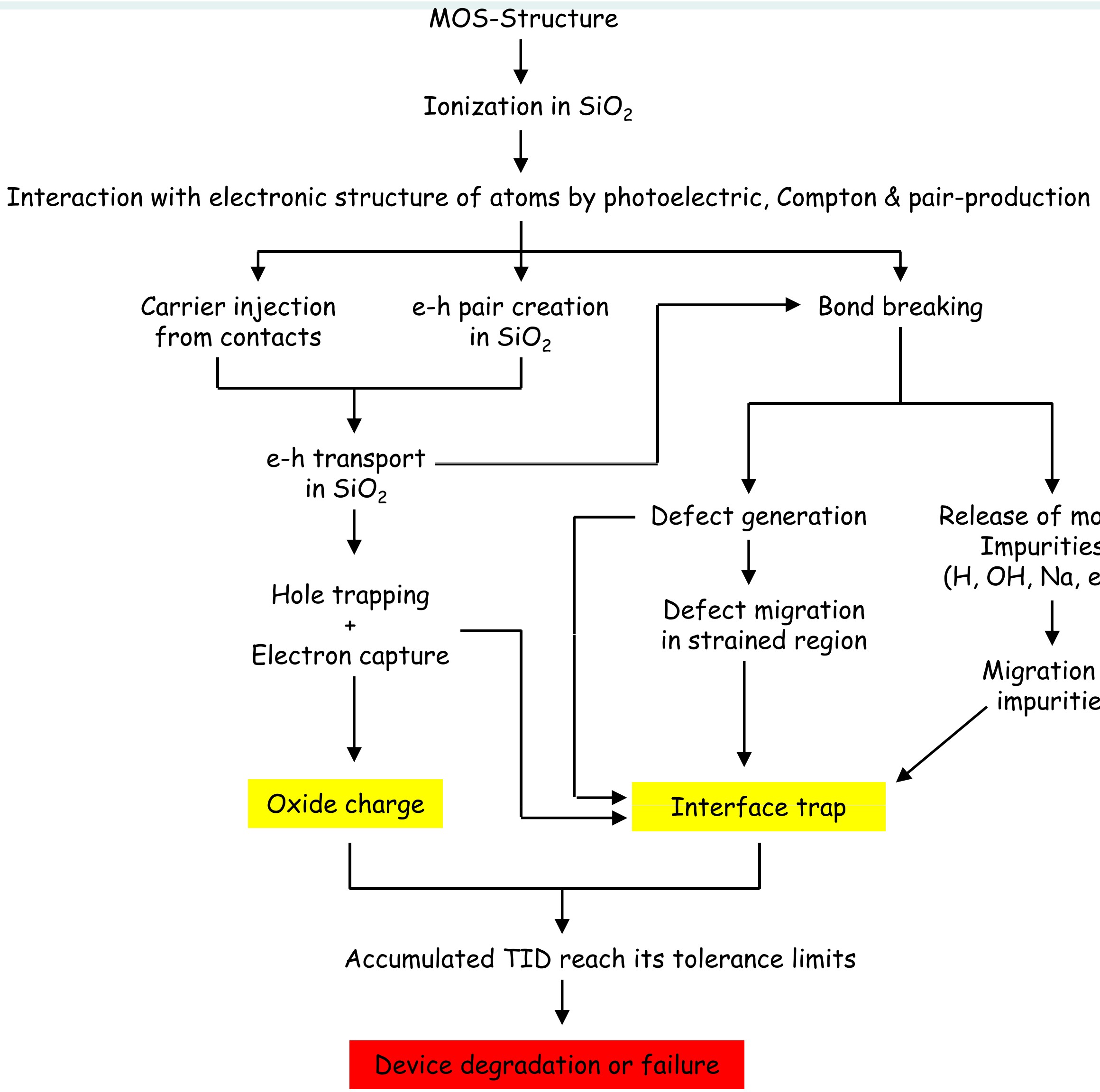
To do

Radiation on MOS-structure (MOS-Capacitance & -DEPFET)

Research of radiation effect (damage mechanism & model)

Radiation hardness structure

Radiation Damage I

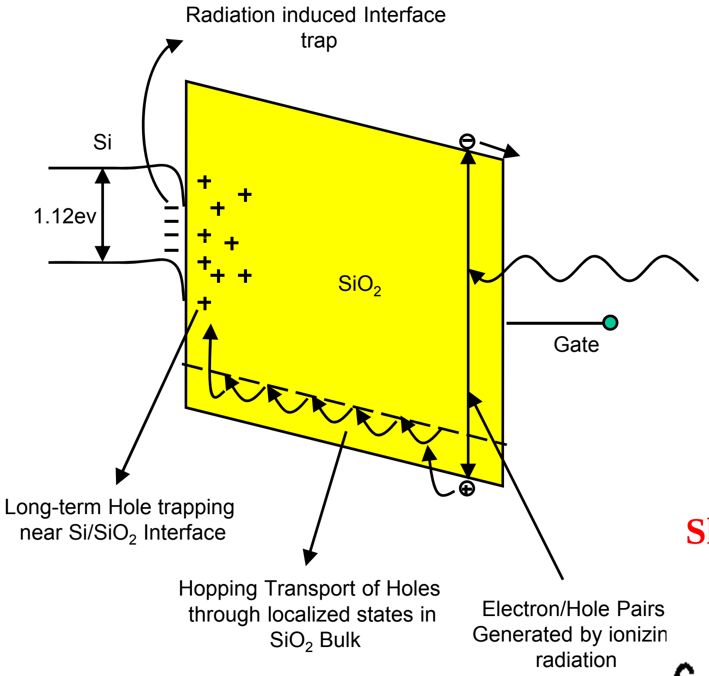


Radiation Damage II

- Radiation damage in MOS-Structure:
  - Surface damage due to Ionizing Energy Loss (IEL)
    - accumulation of charge in the oxide (SiO_2) and Si/SiO_2 interface
      - Oxide charge → shifts of flat band voltage, (depleted → enhancement)
        → annealing at RT
      - Interface traps → leakage current, degradation of transconduction,…
        → no annealing below 400 ^{0}C
- S/N Ratio deteriorated!

Damage mechanism (MOS) I

Ionizing radiation (positive oxide charge)



N_{ox}: positive oxide charge and positively charged oxide traps have to be compensated by a more negative gate voltage → negative shift of the threshold voltage ($\sim t_{ox}^2$)

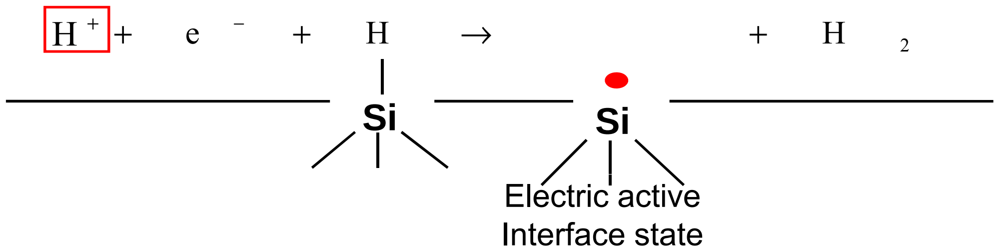
N_{it}: increased density of interface traps → higher 1/f noise and reduced mobility (g_m)

Damage mechanisms: interface state

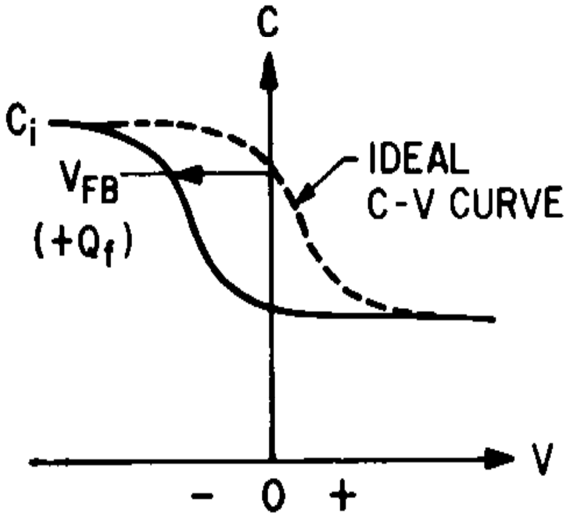
$h\nu \rightarrow$ [free Holes $h^+ \rightarrow$ Excitons / STH (self trapping holes) ; free Electrons (removed from the Oxide)]

$\equiv Si - OH + Exciton \rightarrow \equiv Si - + H$

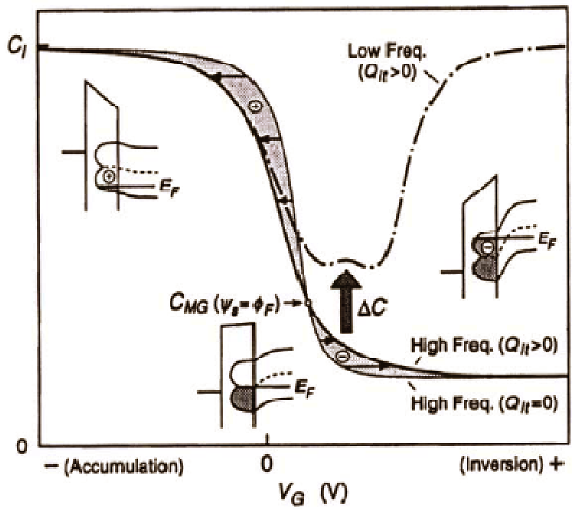
$H + STH \rightarrow H^+$



Shifts of flat band voltage: ~ N_{ox}

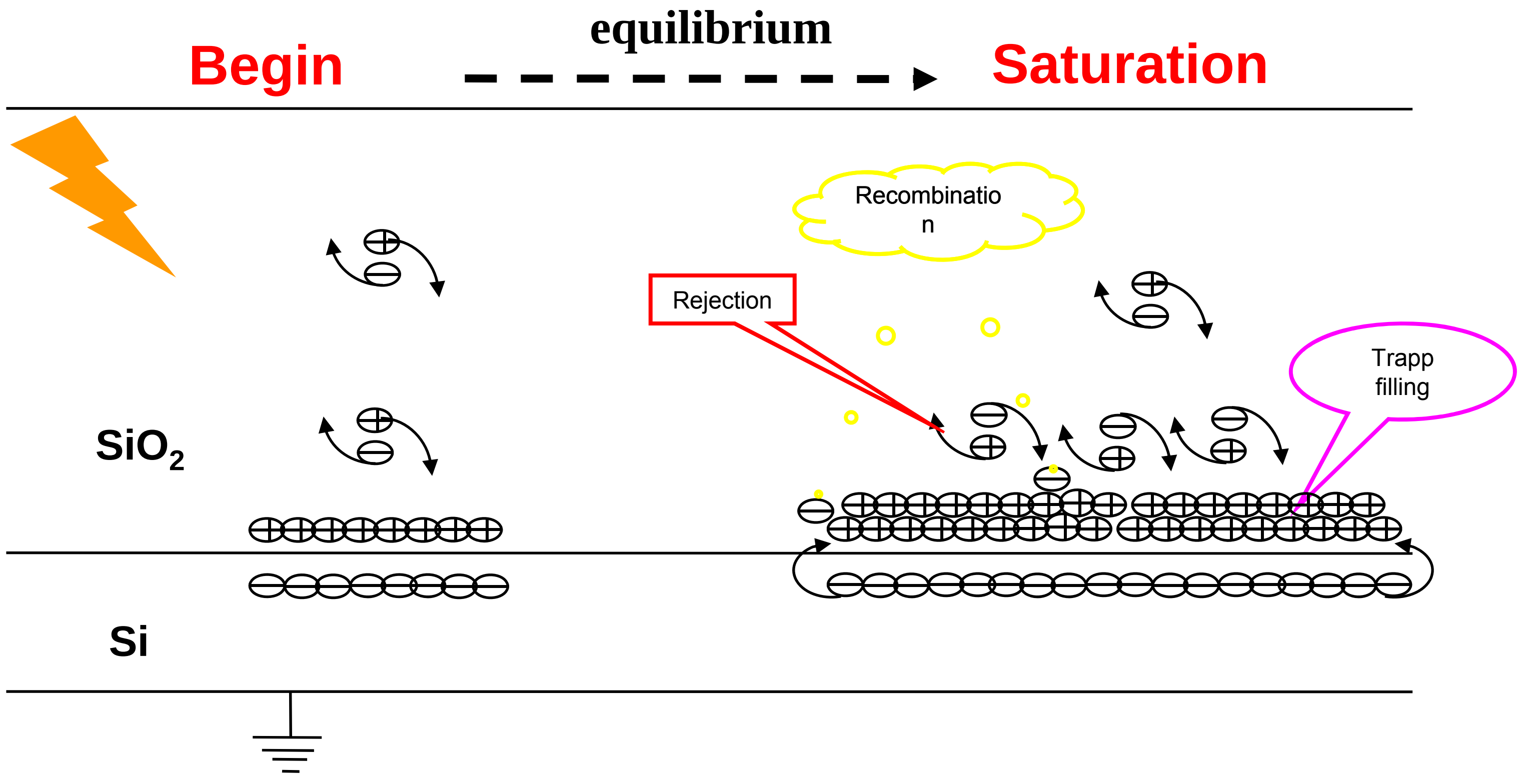


Stretch-out of CV curve: ~ N_{it}



Damage mechanism (MOS) II

Saturation mechanism



• **Reservoir: hole traps are not exhausted, unless a larger bias voltage is applied on the gate!**

• **Saturation: equilibrium between trapped filling and recombination**

-Generated holes are pushed away!

-Recombination of trapped holes with electrons

- Recombination of tunneled electrons from silicon into interface with trapped holes!

Experiment Conditions and Methods

- ***Irradiation (X-Ray)***:
  - Co^{60} (1.17 MeV and 1.33 MeV)
    - GSF – National Research Center for Environment and Health, Munich
  - CaliFa (17.44 KeV)
    - Max-Planck-Institute Semiconductor Labor, Munich
  - Roentgen facility (20 KeV)
    - Research center, Karlsruhe
- ***Dose***: irradiation up to 1 Mrad with different dose rate (1rad=0.01J/kg)
- ***Process***: No annealing during irradiation ~ irradiation duration from 1 day to 1 week
- ***Radiation levels at the ILC VTX***: $D_{ionization} \approx$ 100 .. 200 Krad

  $\Phi \approx 10^{10} .. 10^{11}$ neq(1MeV)/cm^2

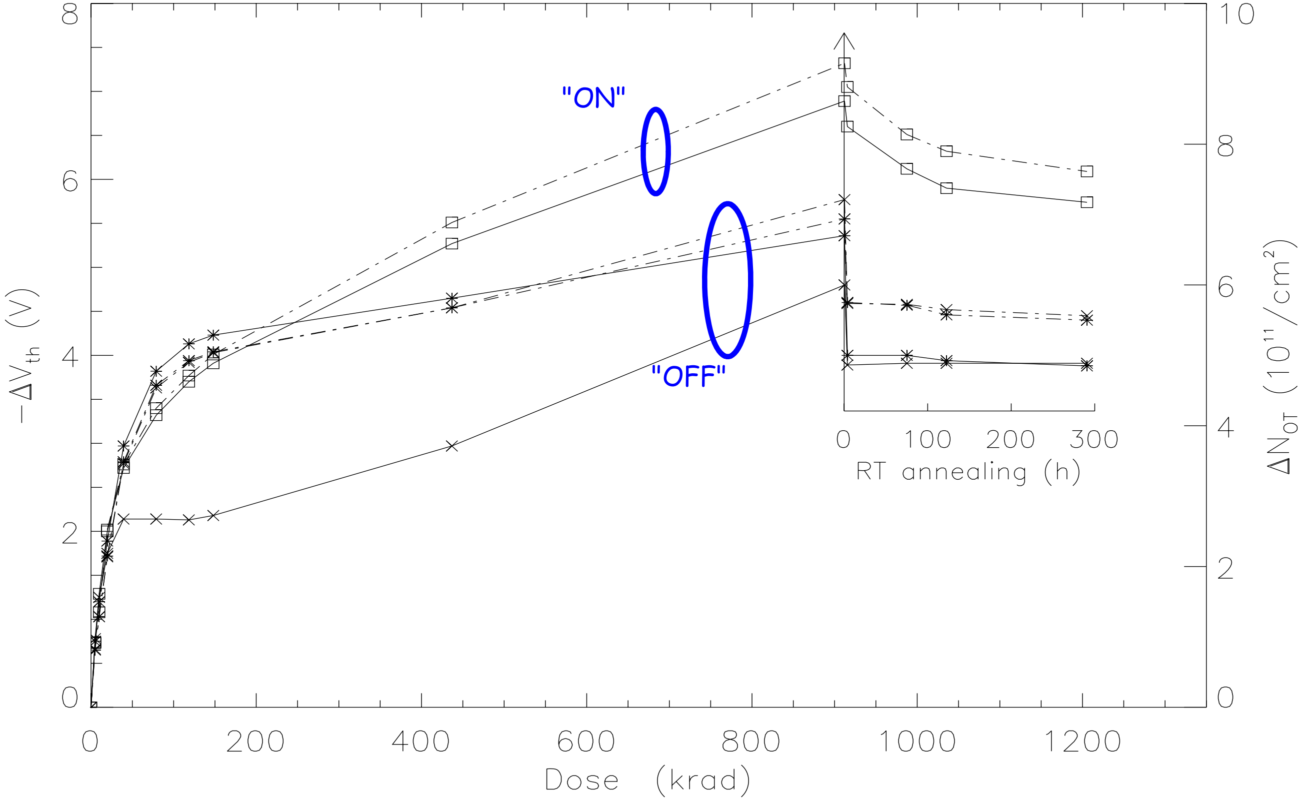
- *Comparison of different semiconductor devices*

	DEPFET	MOS-C
N_{ox} (method)	ΔV_t (IV-Measurement)	ΔV_{FB} (CV-Measurement)
N_{it} (method)	Subthreshold slope (Subthreshold technique)	Stretch-out (High-low frequency based on the CV)
Other parameters	g_m (IV-Measurement)	

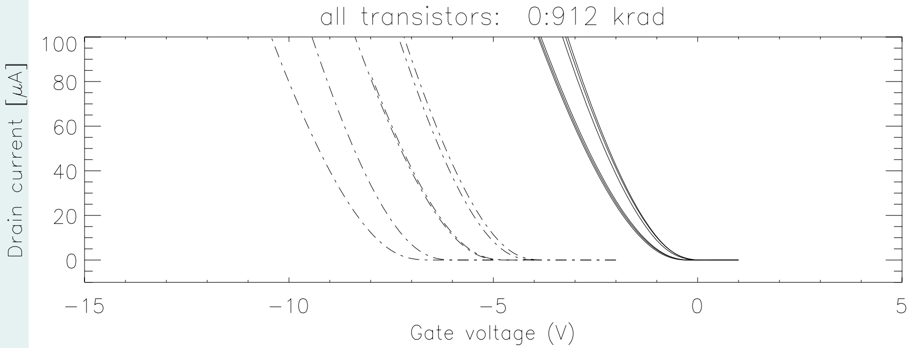
Results for MOSDEPFET

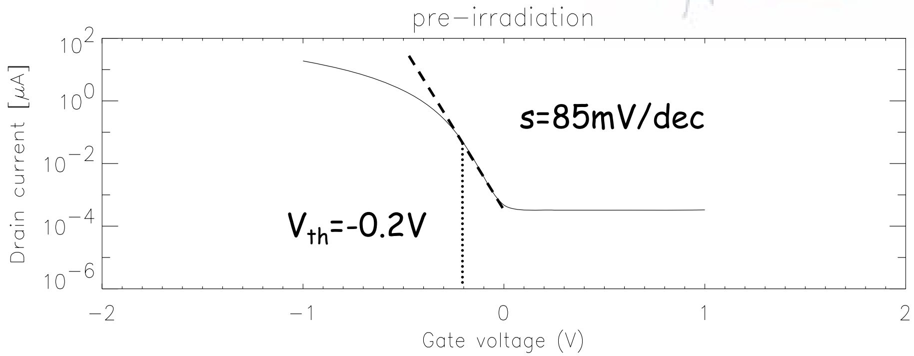
Bias during irradiaton:

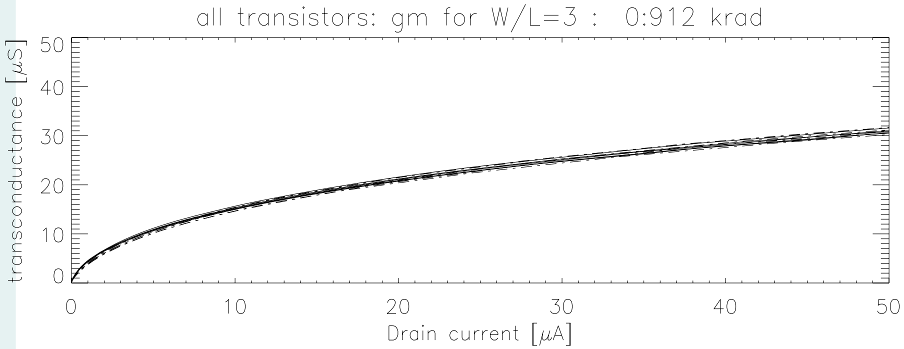
1: empty int. gate, in „off“ state, V_{GS}= 5V, V_{Drain}=-5V → $E_{ox} \approx 0$
2: empty int. gate, in „on“ state, V_{GS}=-5V, V_{Drain}=-5V → $E_{ox} \approx$ -250kV/cm

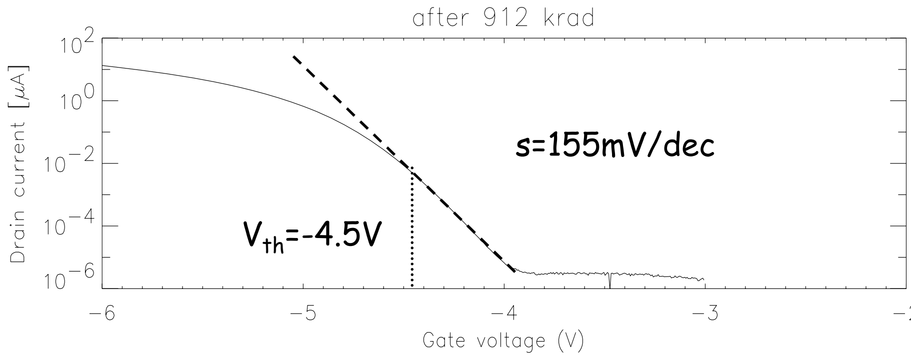


Transcondductance and Subtreshold slope









No change in the transconductance g_m

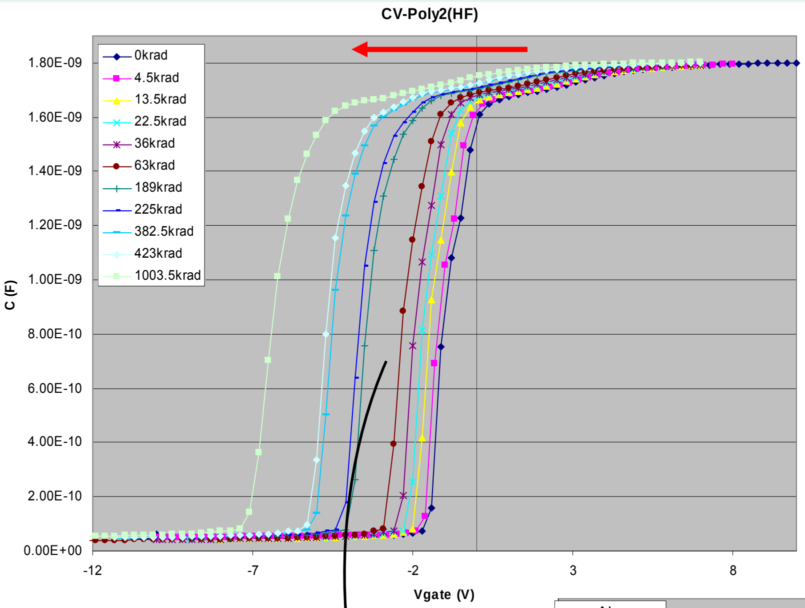
$$N_{it} = \left[\frac{C_{ox}}{kT} \ln(10) \right] (S_{D2} - S_{D1})$$

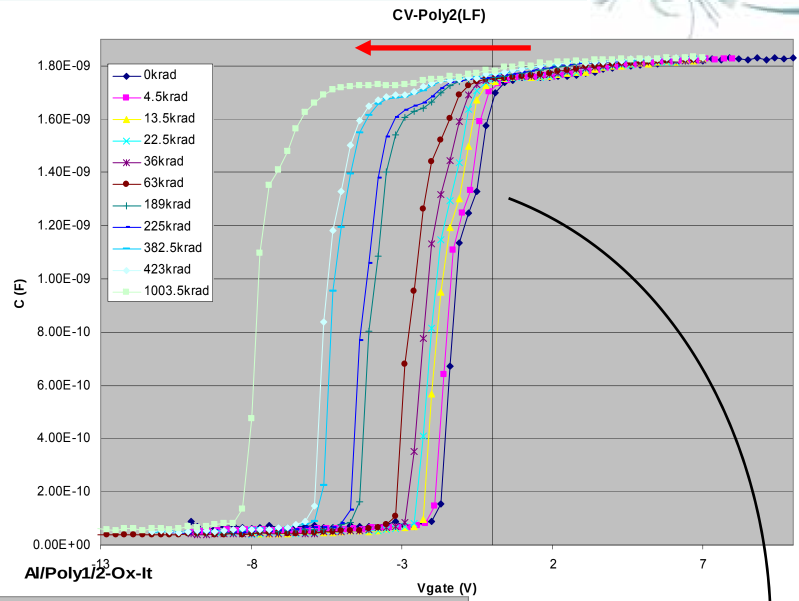
300 krad → $N_{it} \approx 2 \cdot 10^{11}$ cm^{-2}

912 krad → $N_{it} \approx 7 \cdot 10^{11}$ cm^{-2}

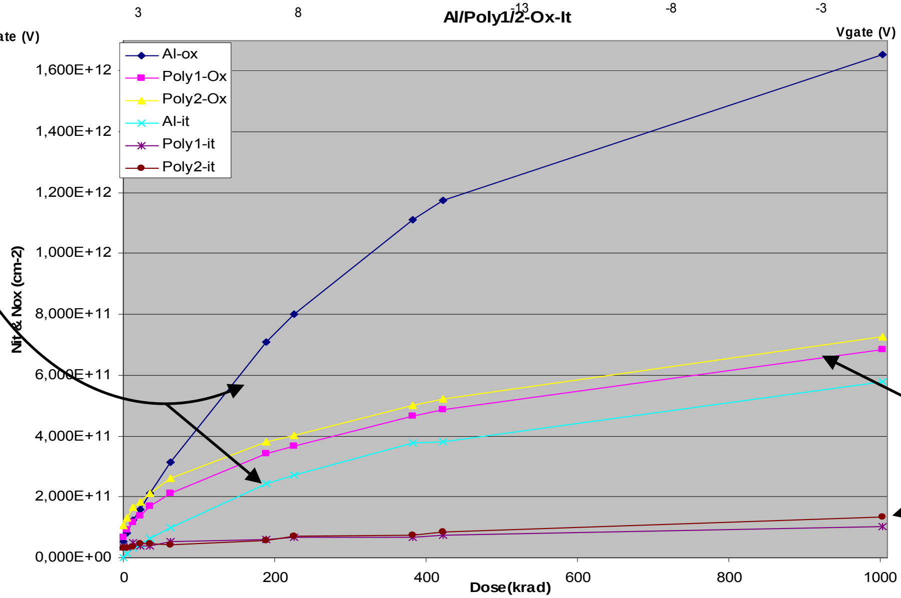
Literature:
After 1Mrad 200 nm (SiO_2):
$N_{it} \approx 10^{13}$ cm^{-2}

Results for MOS-C





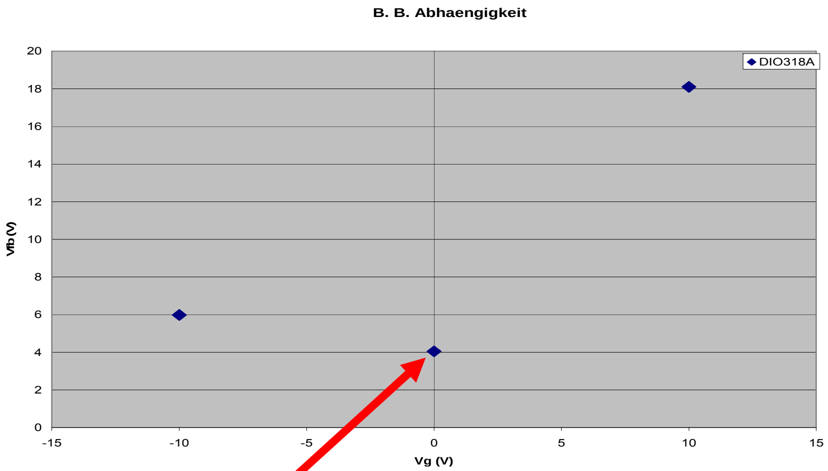
Flat band voltage Shift
→N_{ox}



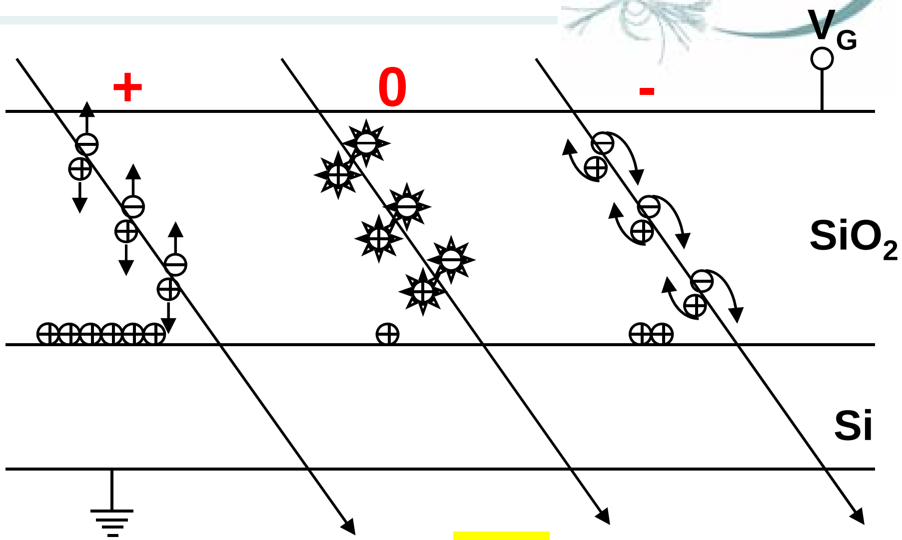
HF/LF CV
→ N_{it}

For MOS-C

Bias Effect



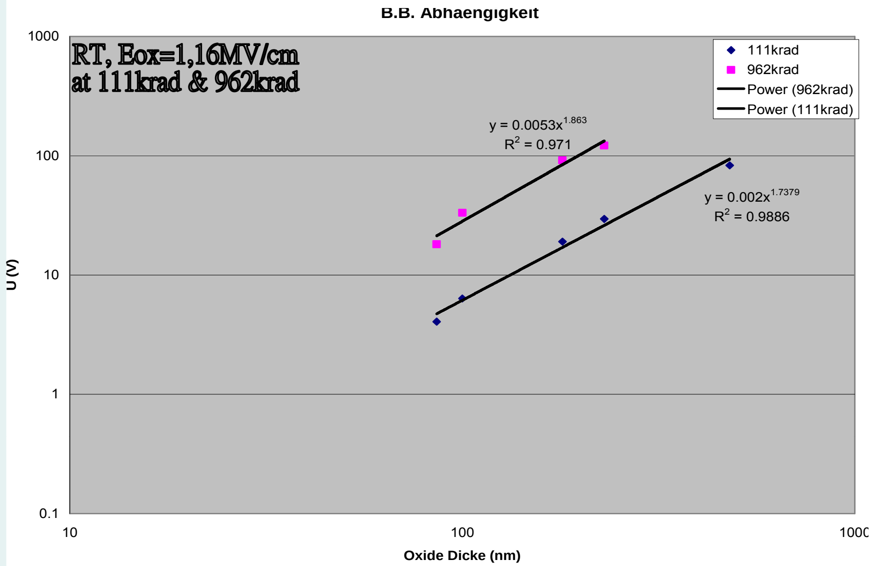
DEPFET

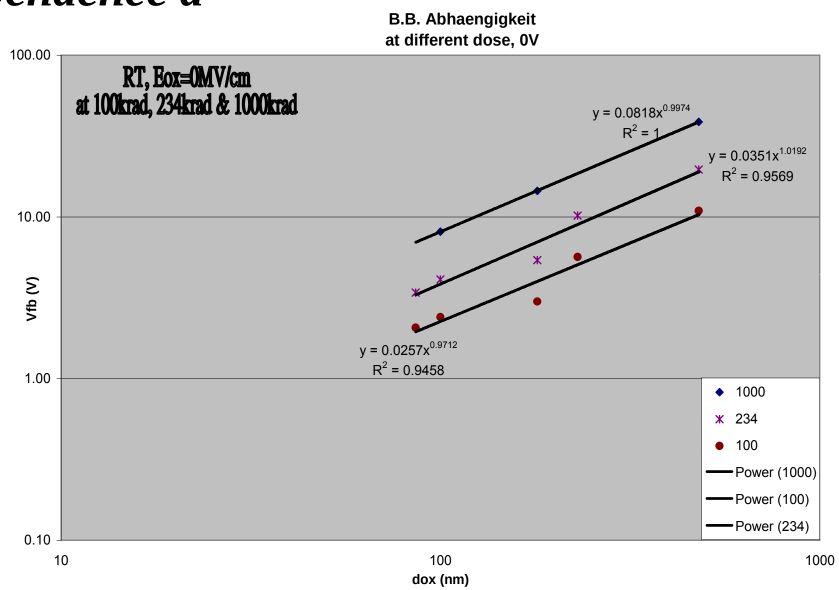


$n \approx 1.8 \pm 0.1$

thickness dependence d^n

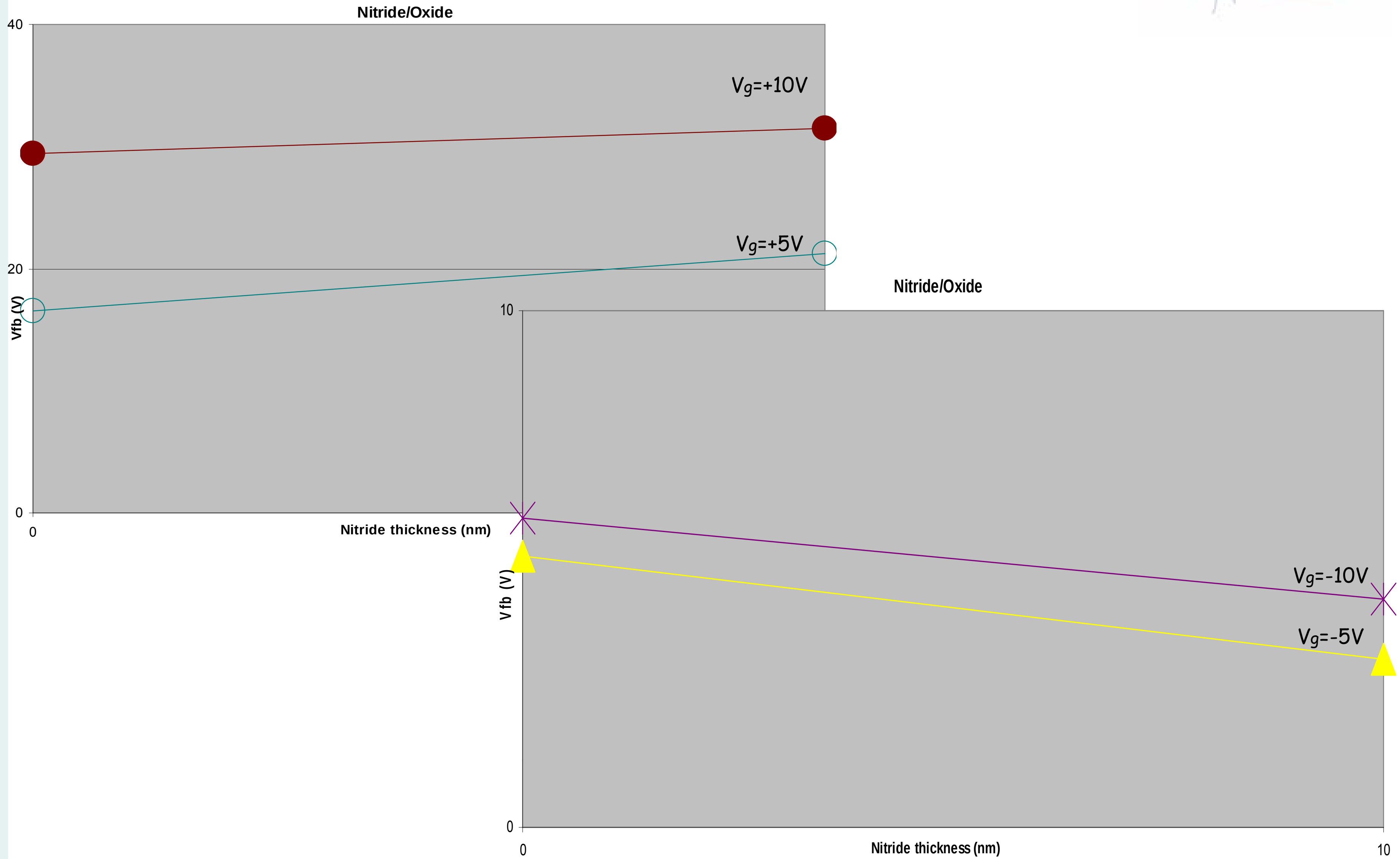
$n \approx 1$





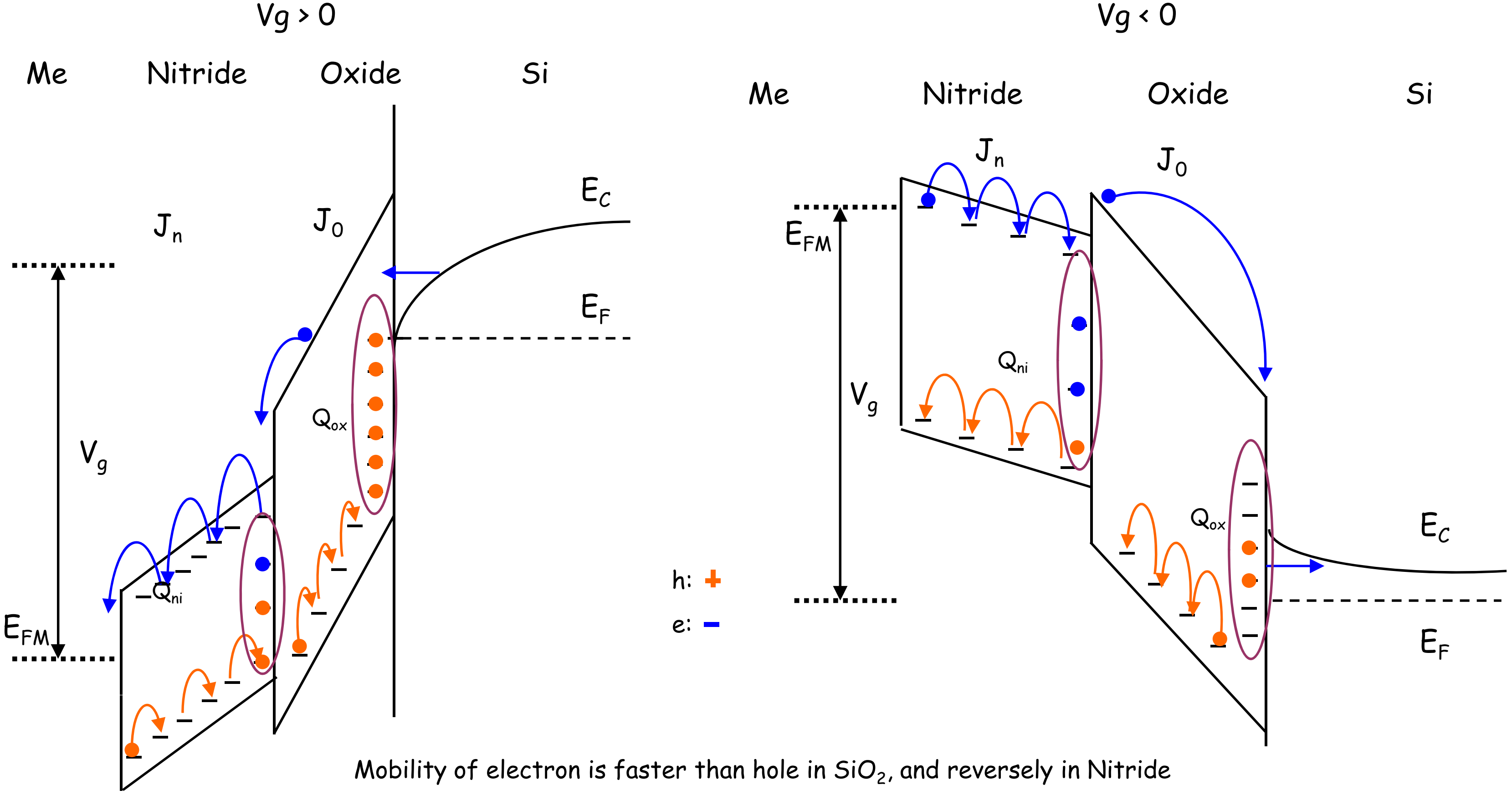
Radiation hardness by Nitride-layer (MNOS)

For MOS-C



Damage mechanism (MNOS) I

Energy band diagram of MNOS structure



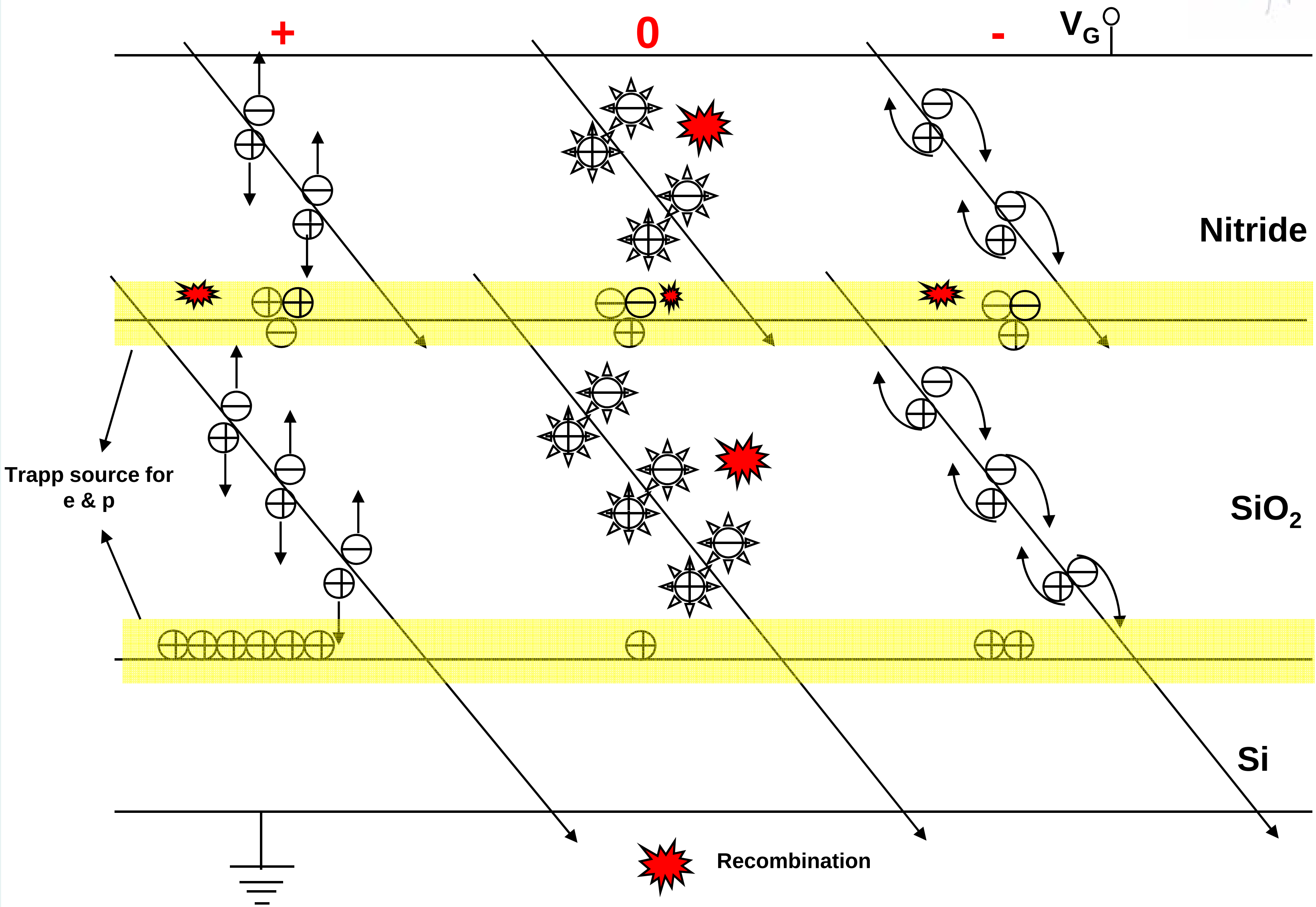
Mobility of electron is faster than hole in SiO_2, and reversely in Nitride

Discontinuity of current density J_n-J_O in short time lead to charge carriers accumulation & trapping in N/O strained interface

field dependence of current density & thickness of the dielectrics plays an important role!

charge in Si/SiO interface donot affect the field distribution in dielectrics!

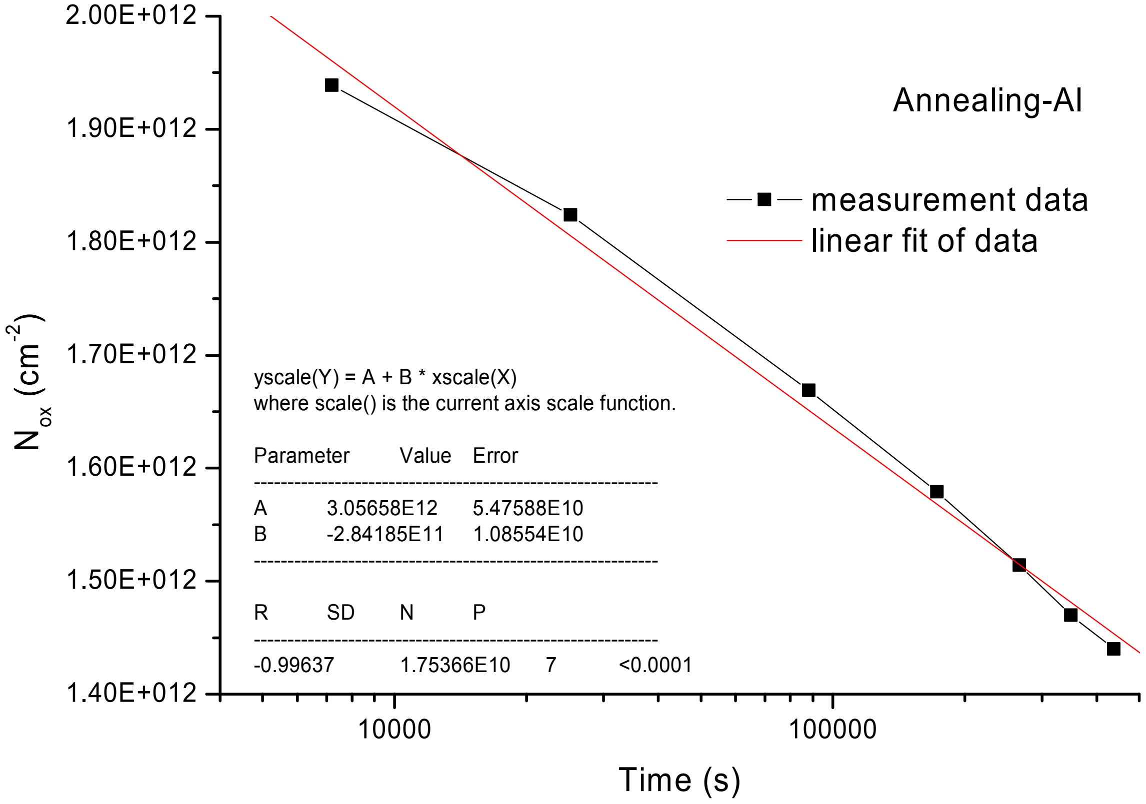
Damage mechanism II



Annealing for surface damage

Oxide charge decrease with time:

(Tunnel annealing @ RT)



Conclusion

- Radiation experiment
  - Study of saturation effect for surface damage (equilibrium between generation and recombination)
  - Study of bias dependence(“+“,“0“,“-“)
  - Study of different semiconductor devices, which are with different oxide thickness - to see the kind of relation between V_{fb} and oxide thickness (d_{ox}^{n})

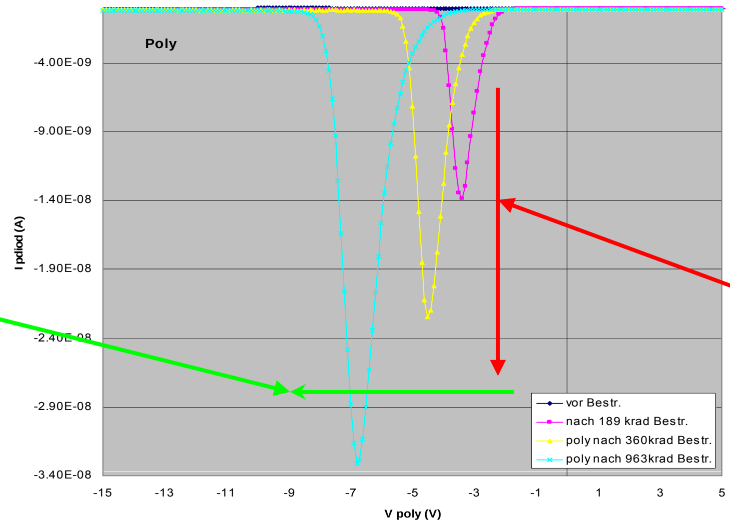
- Radiation hardness $\Gamma = N_{ox} / (\phi_h \times t) \leq 5\% \quad (\sim 1 Mrad)$
  - Reduced oxide thickness improves radiation hardness
  - Additional Nitride layer serve as a good protection against ionizing radiation *(electron trapping!)*
  - Surface damage can be reduced through annealing process with time

Backup slides

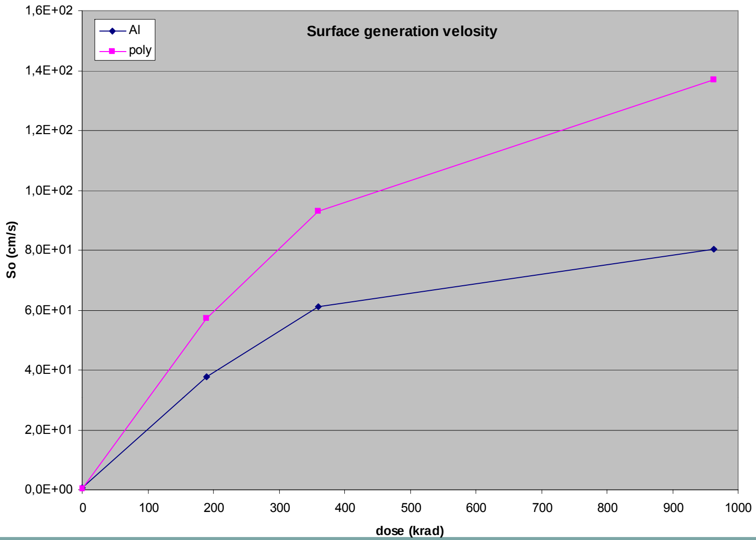
Results for gated diode

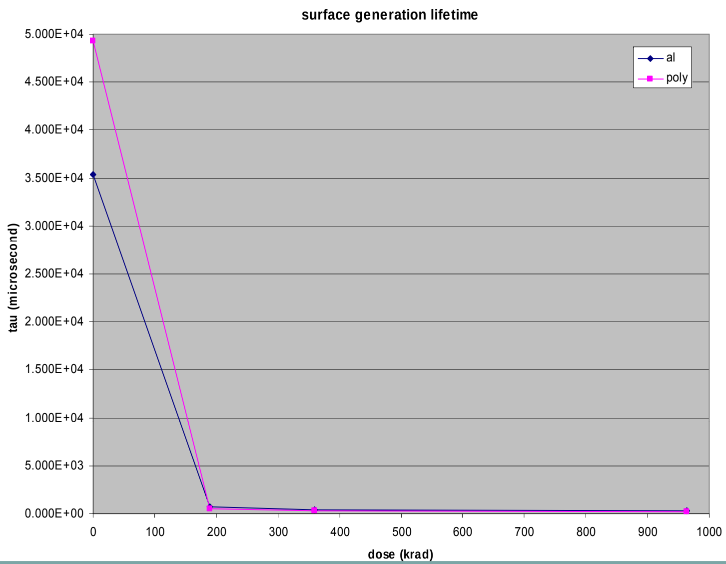
Shifts of generated current:

Increase of maximal current:



Increase of surface generation velocity & decrease of lifetime due to radiation:





Mathematics Expression I

Chip thickness (nm)		Electrically measured equivalent oxide thickness (CV)	Pre-Rad $V_{FB}(V)$	Post-Rad $V_{FB}(V)$ ~1Mrad Vg=-10V	Post-Rad $V_{FB}(V)$ ~1Mrad Vg=-5V	Post-Rad $V_{FB}(V)$ ~1Mrad Vg=0V	Post-Rad $V_{FB}(V)$ ~1Mrad Vg=+5V	Post-Rad $V_{FB}(V)$ ~1Mrad Vg=+10V
Equivalent Oxide thickness	Oxide/Nitride thickness							
86	86	76 ± 2	-0,6	6	5,3	4,1	18,6	19
91	86/10	85 ± 2	-1,4	4,4	3,3	2,3	16,4	22,7
100	100	95 ± 2	-0,7	7,1	6	5,5	16,6	29,4
105	100/10	103 ± 1.5	-1.4	5	3,4	2,6	21,3	31,5

Mathematics Expression II

$$\frac{dQ_{ox}}{dD} = \frac{dQ_{h,ox}}{dD} = F_h f_T = \{\gamma_{h,ox}(E_{ox})d_{ox}\}\{\sigma_{h,ox}(E_{ox})(\overline{Q_{h,ox}} - Q_{h,ox})\} = \beta_{h,ox}(\overline{Q_{h,ox}} - Q_{h,ox})$$

$$\frac{dQ_{ni}}{dD} = \frac{dQ_{h,ni}}{dD} - \frac{dQ_{e,ni}}{dD} = \beta_{h,ni}(\overline{Q_{h,ni}} - Q_{h,ni}) - \beta_{e,ox}(\overline{Q_{e.ni}} - Q_{e.ni})$$

$$Q_{ox} = \overline{Q_{h,ox}}(1 - \exp(-\beta_{h,ox}D)) \qquad Q_{ni} = \overline{Q_{h,ni}}(1 - \exp(-\beta_{h,ni}D)) - \overline{Q_{e,ni}}(1 - \exp(-\beta_{e,ox}D))$$

$$\Delta V_{FB} = -\left(\frac{Q_{ox}}{C_{eq,ox}} + \frac{Q_{ni}}{C_{ni}}\right) = -\frac{1}{C_{ni}}\left(\left[-\overline{Q_{e,ni}} + \overline{Q_{h,ni}} + \overline{Q_{h,ox}}\eta\right] + \left[\overline{Q_{h,ox}}e^{-\beta_{h,ox}D}\eta + \overline{Q_{h,ni}}e^{-\beta_{h,ni}D} - \overline{Q_{e,ni}}e^{-\beta_{e,ni}D}\right]\right)$$

$$\eta = 1 + \frac{\varepsilon_{ni}d_{ox}}{\varepsilon_{ox}d_{ni}} \qquad d_{eq,ox} = d_{ni}\frac{\varepsilon_{ox}}{\varepsilon_{ni}} + d_{ox} \qquad V_g = E_{ox}d_{eq,ox} \qquad C_{eq,ox} = \frac{\varepsilon_{ox}}{d_{eq,ox}}A \qquad \beta_{h,ox}(E_{ox}) = \gamma_{h,ox}(E_{ox})\sigma_{h,ox}(E_{ox})$$

Mathematics Expression III

D : dose

$d_{eq,ox}$: equivalent oxide thickness

d_{ox} : oxide thickness

d_{ni} : nitride thickness

V_g : gate voltage

$\varepsilon_{ni/ox}$: permittivity of nitride/oxide

A : gate area

$C_{eq,ox}$: equivalent oxide capacitance

$Q_{ni/ox}$: trapped charge in nitride/oxide

$E_{ox/ni}$: electric field in oxide/nitride

$F_{h/e}$: fluence per unit dose for radiation-generated hole or electron

f_T : fraction of trapped charge for radiation-generated hole or electron

ΔV_{FB} : flat band voltage shift

$\gamma_{h,ox/e,ox/h,ni}$: field-dependent charge generation coefficient for hole or electron in oxide/nitride

$\sigma_{h,ox/e,ni/h,ni}$: capture cross section of hole/electron in oxide/nitride

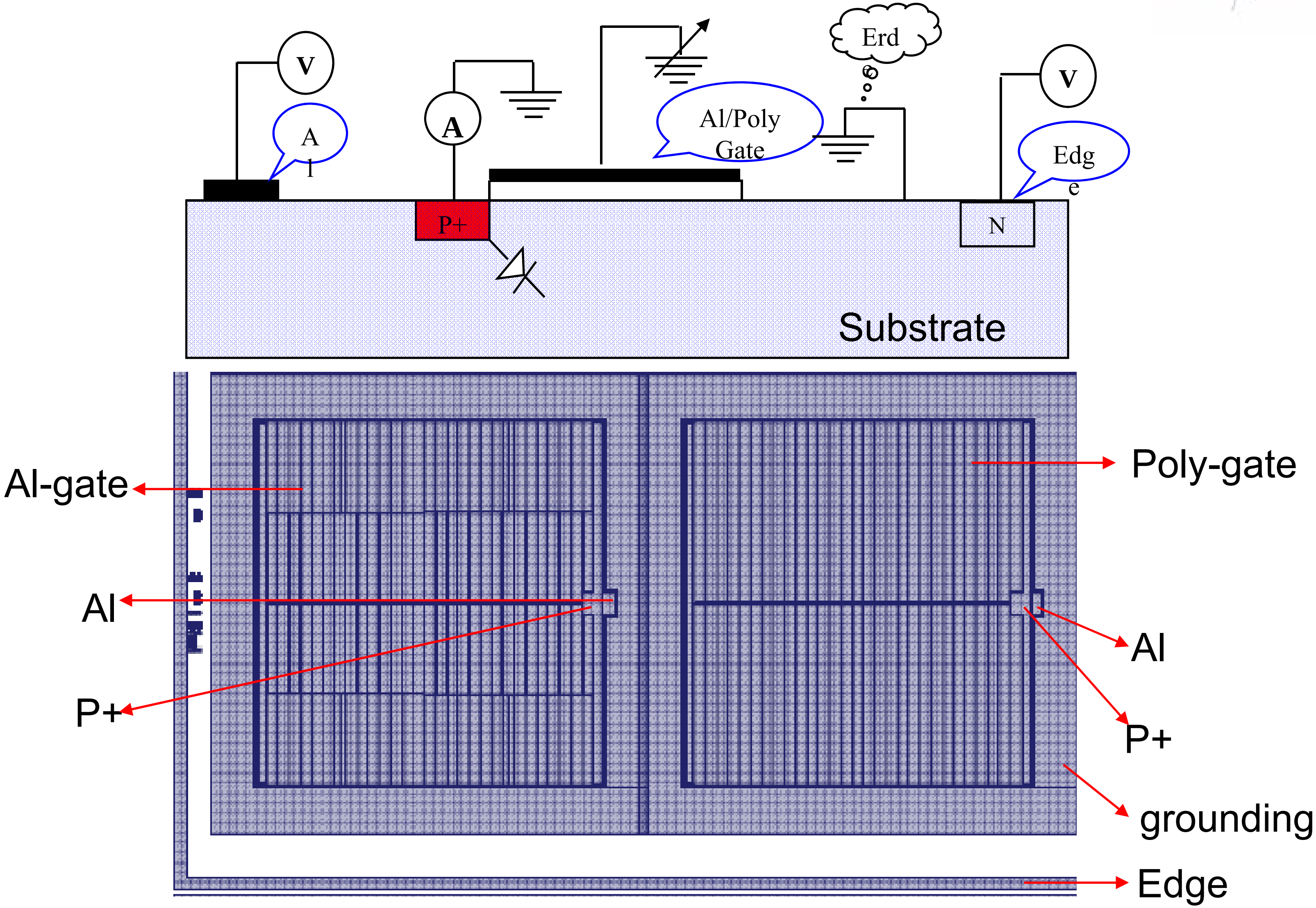
$\overline{N_{h,ox/e,ox/h,ni}}$: trapp density of hole/electron in oxide/nitride (approximately homogen distributed in interface Si/SiO or O/N)

$\beta_{h,ox/e,ox/h,ni}$: field-dependent factor

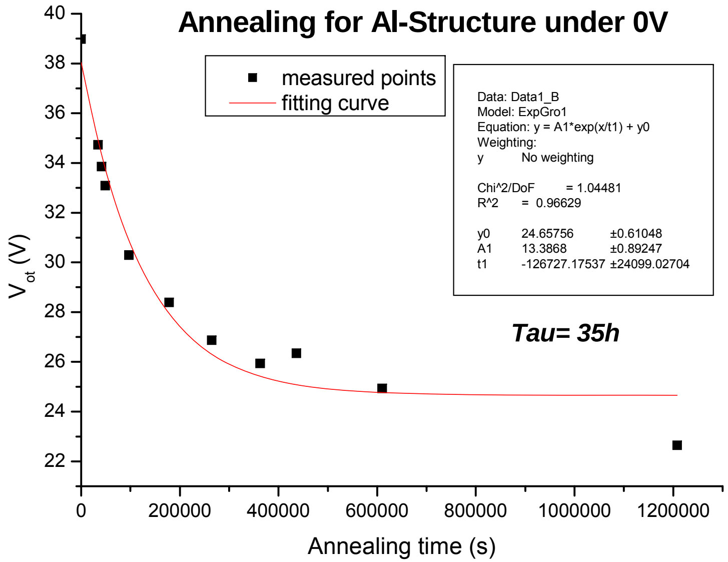
Assumption (positive gate bias)

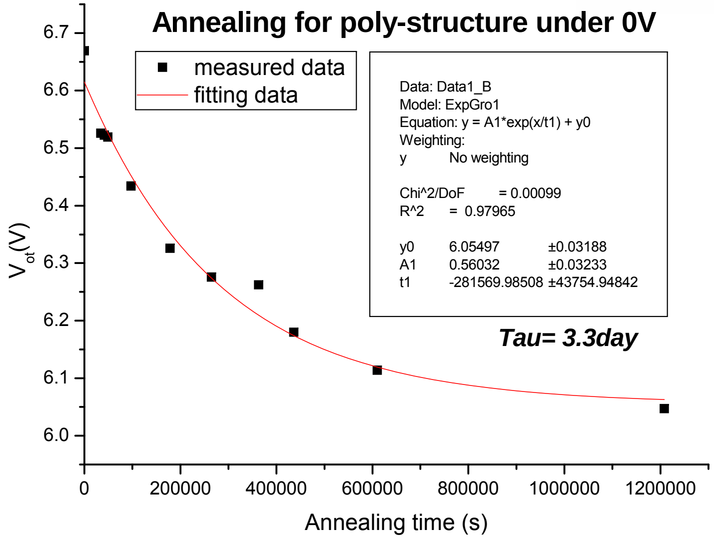
- Recombination at interface (Si/SiO or N/O) should be neglected
- Electron or hole trapps are distributed approximately homogen at interface
- There are no trapped charge at interface (pre-Rad)

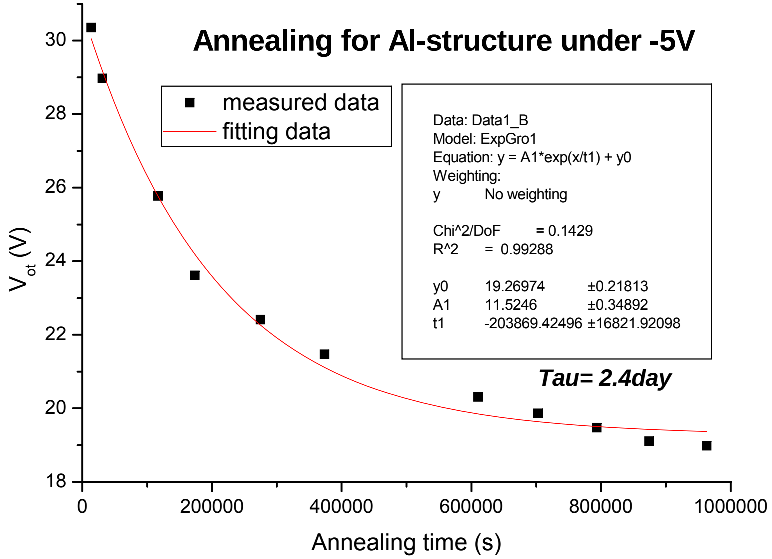
MOS-Gated Diode (device profile)

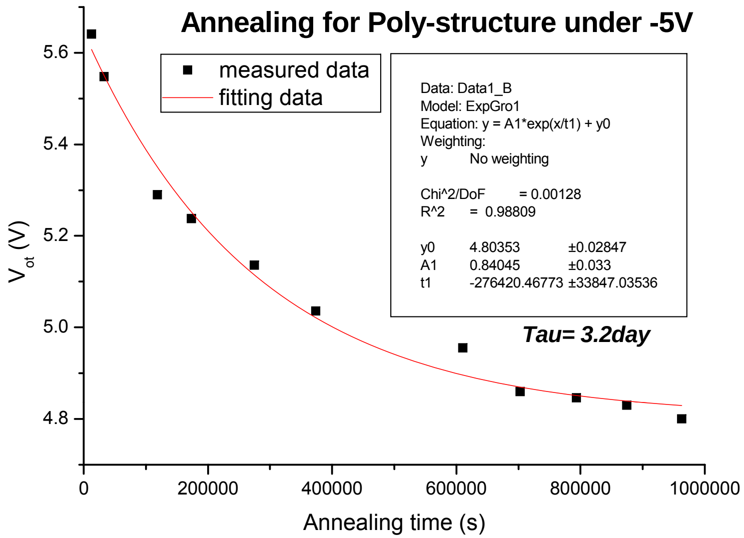


Annealing for MOS-C (PXD4)

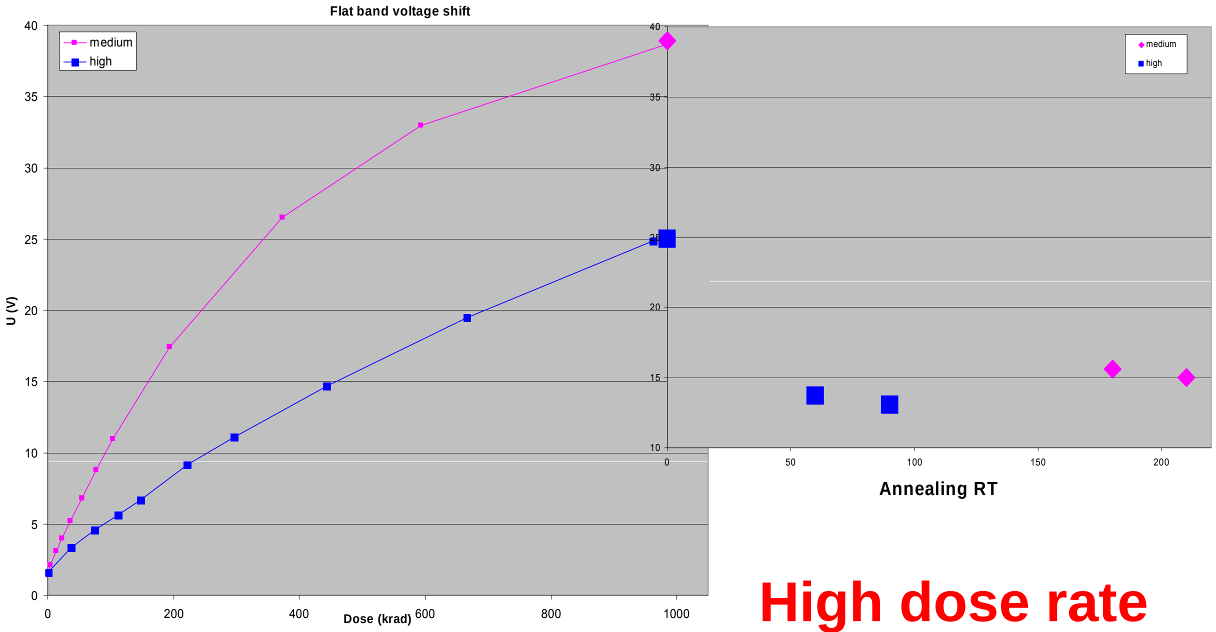


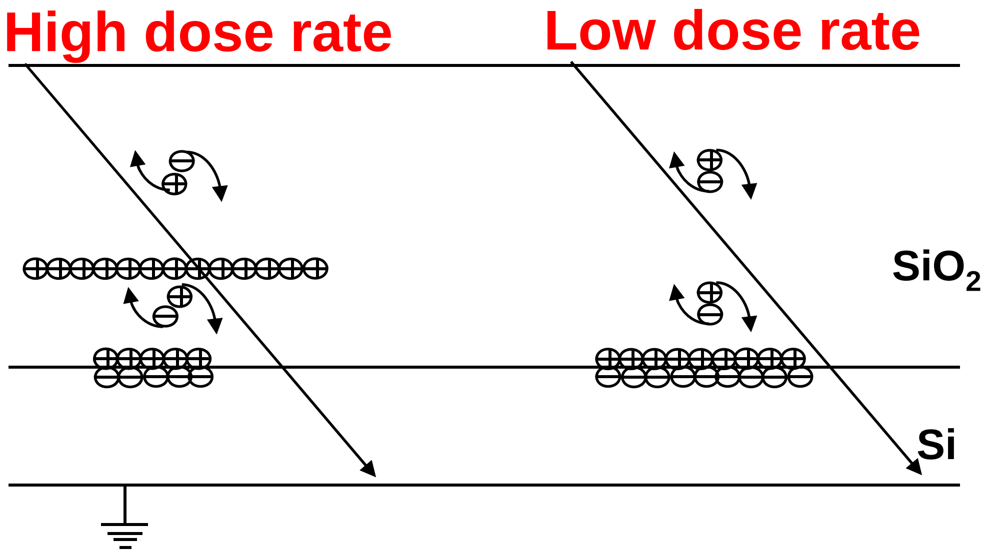






Dose rate effect





Radiation Damage

Two types of radiation damage in MOS-Structure:

- Surface damage due to Ionizing Energy Loss (IEL)
  - accumulation of charge in the oxide (SiO_2) and Si/SiO_2 interface
    - Oxide charge → shifts of flat band voltage, (depleted → enhancement)
    - Interface traps → leakage current, degradation of transconduction,...
- Bulk damage due to Non Ionizing Energy Loss (NIEL)
  - displacement damage, built up of crystal defects
    - Increase of leakage current → increase of shot noise,...
    - Change of effective doping concentration → higher depletion voltage,...
    - Increase of charge carrier trapping → signal loss!

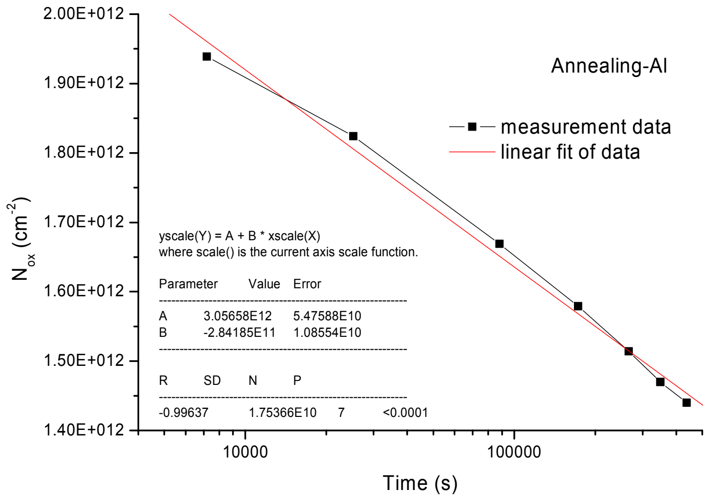
S/N Ratio deteriorated!

Annealing

For surface damage:

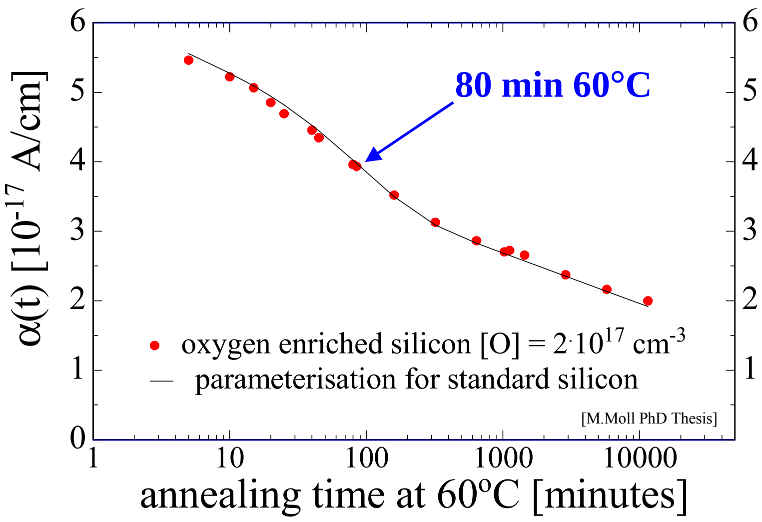
Oxide charge decrease with time:

(Tunnel annealing @ RT)



For bulk damage:

Leakage current decrease with time:



"Beneficial annealing" & "Reverse annealing"