Radiation Damage on MOS-Structure

Q. Wei, L. Andricek, H-G. Moser, R. H. Richter
Max-Planck-Institute for Physics Semiconductor Laboratory
HLL Project Review, Ringberg, 2007

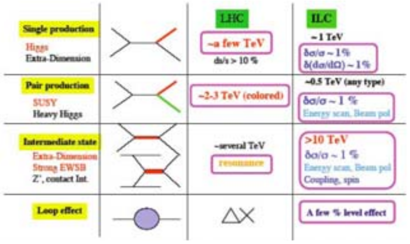
Outline

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

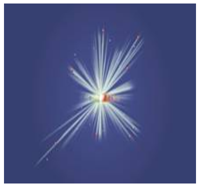
Motivation

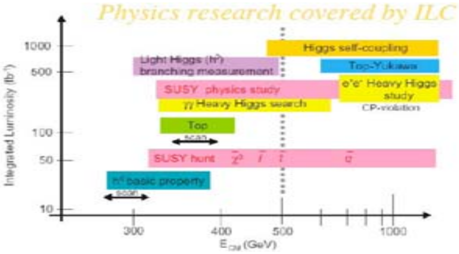
Physics topics

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

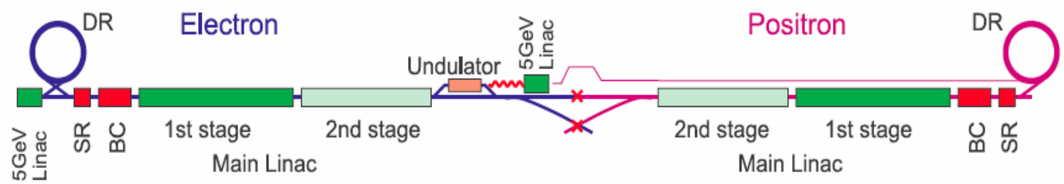


		LHC	ILC
Single production Higgs Extra-Dimension		~a few TeV ds/s > 10 %	~1 TeV δσ/σ ~ 1% δ(dσ/dΩ) ~ 1%
Pair production SUSY Heavy Higgs		~2-3 TeV (colored)	~0.5 TeV (any type) δσ/σ ~ 1 % Energy scan, Beam pol
Intermediate state Extra-Dimension Strong EWSB Z', contact Int.		~several TeV resonance	>10 TeV δσ/σ ~ 1 % Energy scan, Beam pol Coupling, spin
Loop effect		ΔX	A few % level effect

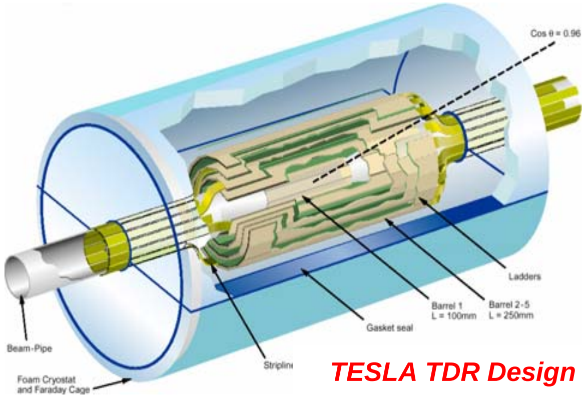




International Linear Collider

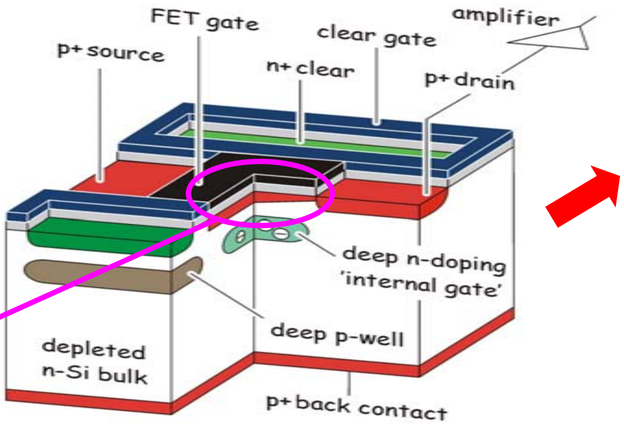


precise vertex detector (DEPFET)



TESLA TDR Design

Depleted P-channel FET



To do

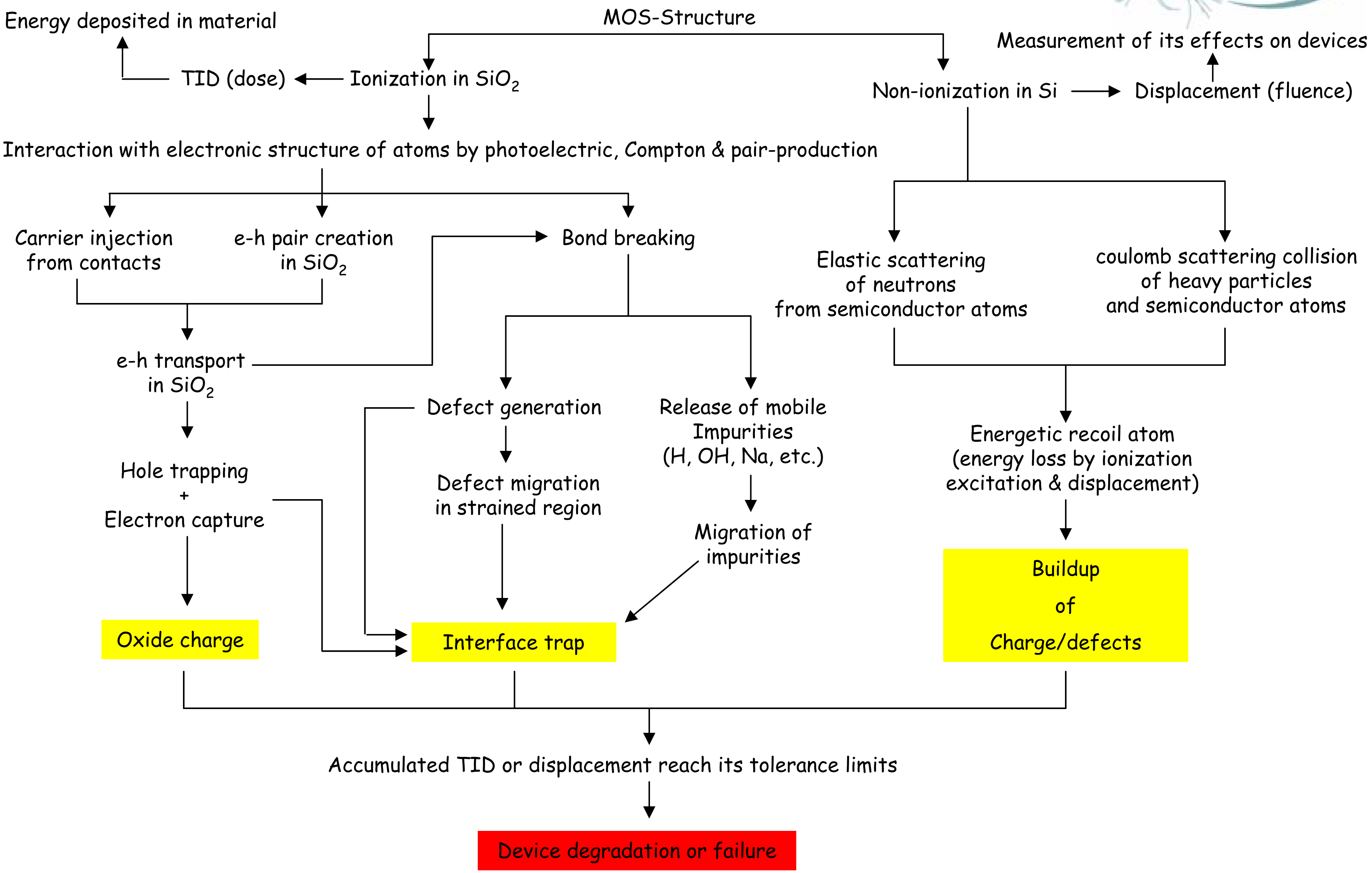
Radiation on MOS-structure (MOS-Capacitance & -DEPFET)

Research of radiation effect (damage mechanism & model)

Radiation hardness structure

Radiation Damage I

MPI Halbleiterlabor



MOS-Structure

Energy deposited in material

TID (dose)

Ionization in SiO_2

Interaction with electronic structure of atoms by photoelectric, Compton & pair-production

Carrier injection from contacts

e-h pair creation in SiO_2

Bond breaking

e-h transport in SiO_2

Hole trapping + Electron capture

Oxide charge

Defect generation

Defect migration in strained region

Release of mobile Impurities (H, OH, Na, etc.)

Migration of impurities

Interface trap

Measurement of its effects on devices

Non-ionization in Si

Displacement (fluence)

Elastic scattering of neutrons from semiconductor atoms

coulomb scattering collision of heavy particles and semiconductor atoms

Energetic recoil atom (energy loss by ionization excitation & displacement)

Buildup of Charge/defects

Accumulated TID or displacement reach its tolerance limits

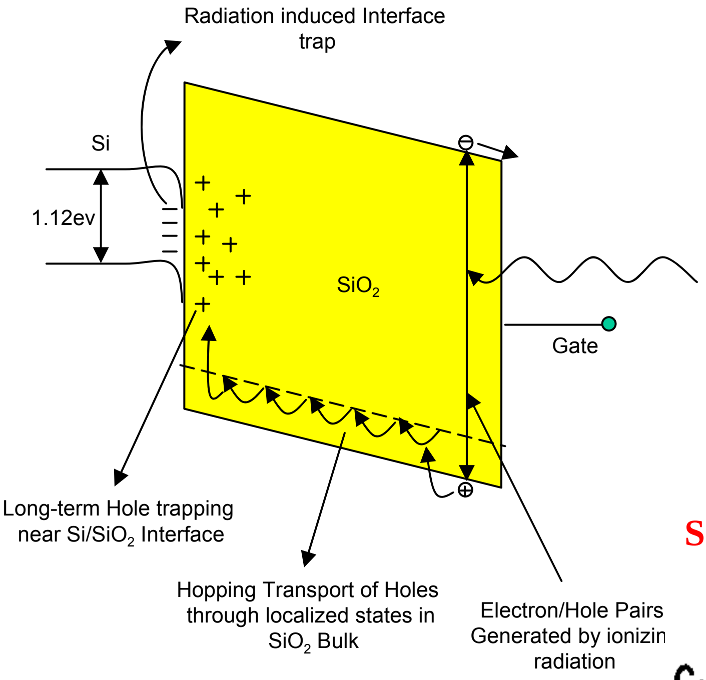
Device degradation or failure

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 ^0C
- S/N Ratio deteriorated!

Damage mechanism (MOS)

Ionizing radiation:



Damage mechanisms:

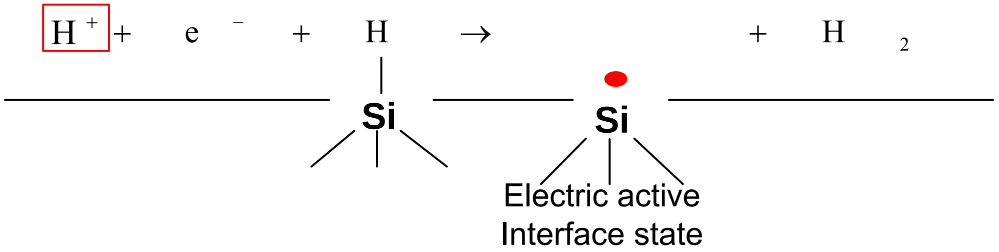
$$h\nu \rightarrow \left[\begin{array}{l} \text{free Holes } h^{+} \rightarrow \begin{array}{l}\text{Excitons} \\ \text{STH (self trapping holes)}\end{array} \\ \text{free Electrons (removed from the Oxide)} \end{array} \right.$$

$$\equiv \text{Si} - O\text{H} + \text{Exciton} \rightarrow \equiv \text{Si} - + \boxed{\text{H}}$$

$$\boxed{\text{H}} + \text{STH} \rightarrow \boxed{\text{H}^{+}}$$

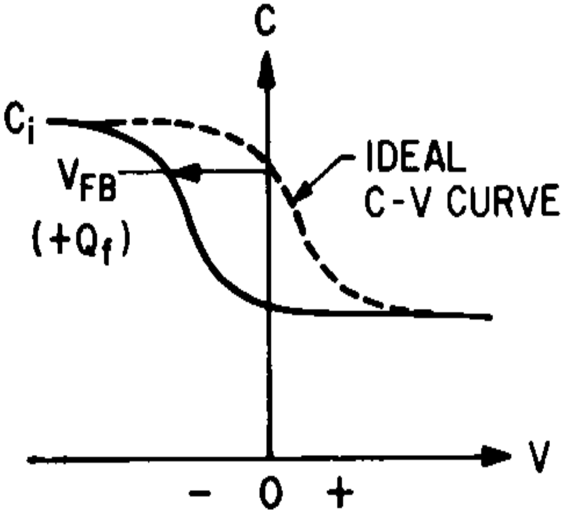
$$\downarrow$$

$$\boxed{\text{H}^{+}} + e^{-} + \text{H} \rightarrow \quad + \text{H}_2$$

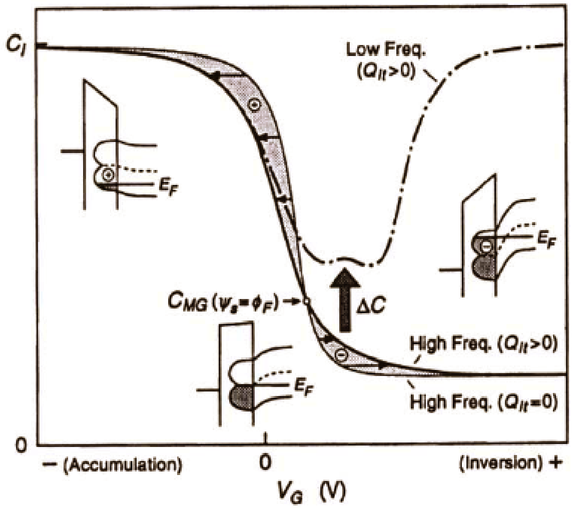


Electric active Interface state

Shifts of flat band voltage: ~ N_{ox}



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

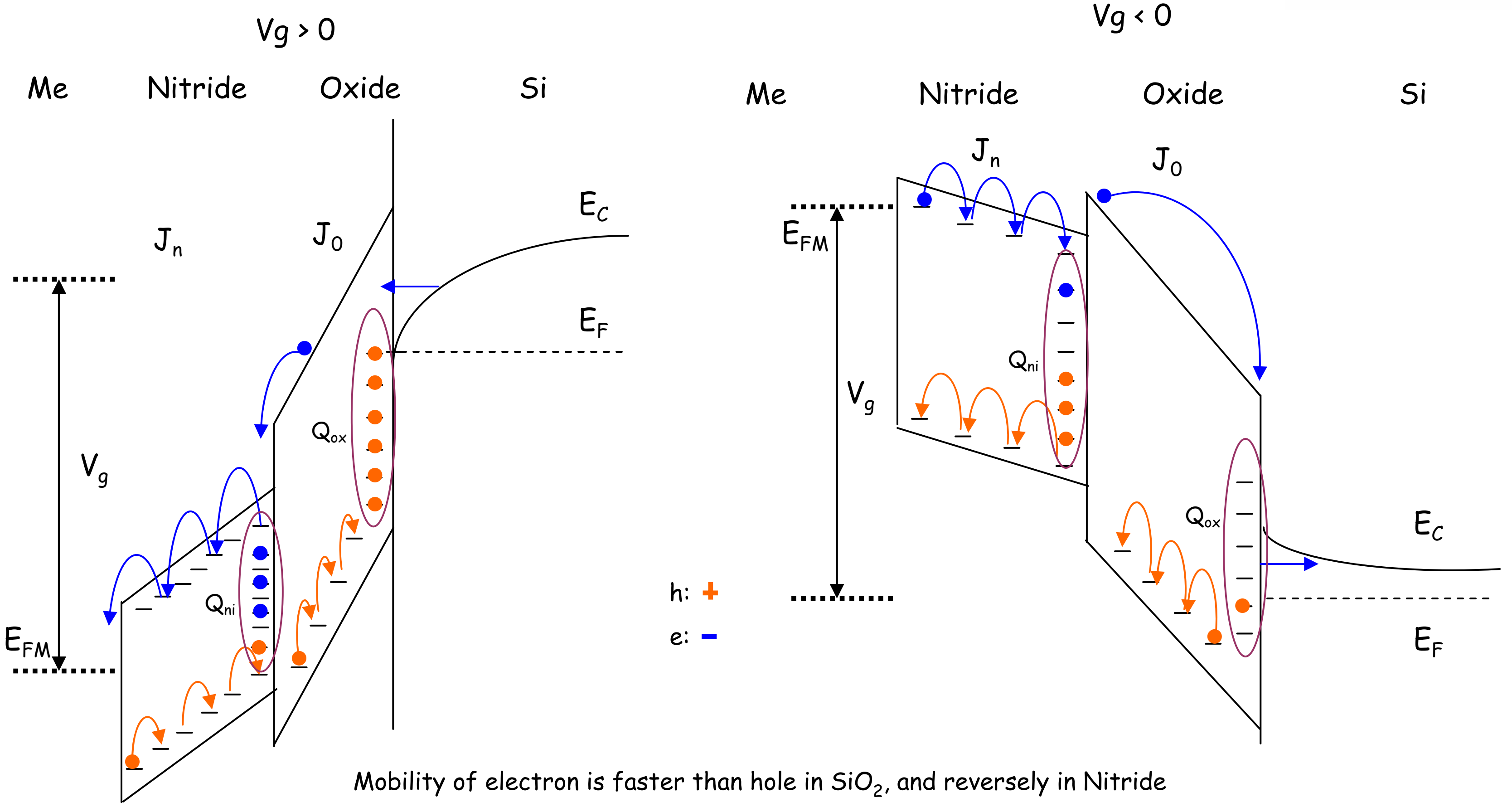


N_{ox}: positive oxide charge and positively charged oxide traps have to be compensated by a more negative gate voltage → negative shift of the threshold voltage (~t_{ox}^2)

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

Damage mechanism (MNOS) I

Energy band diagram of MNOS structure



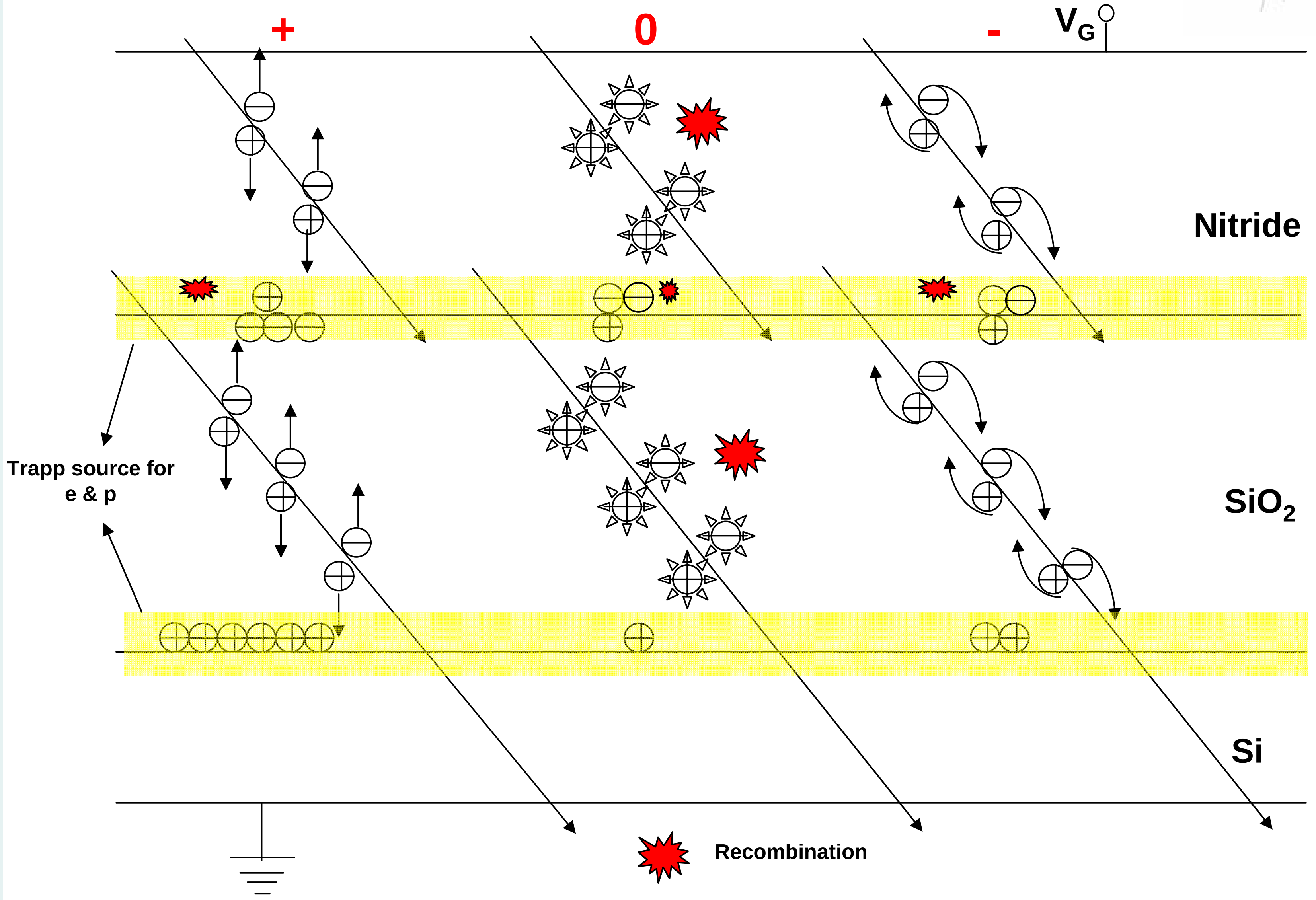
Mobility of electron is faster than hole in SiO_2, and reversely in Nitride

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!

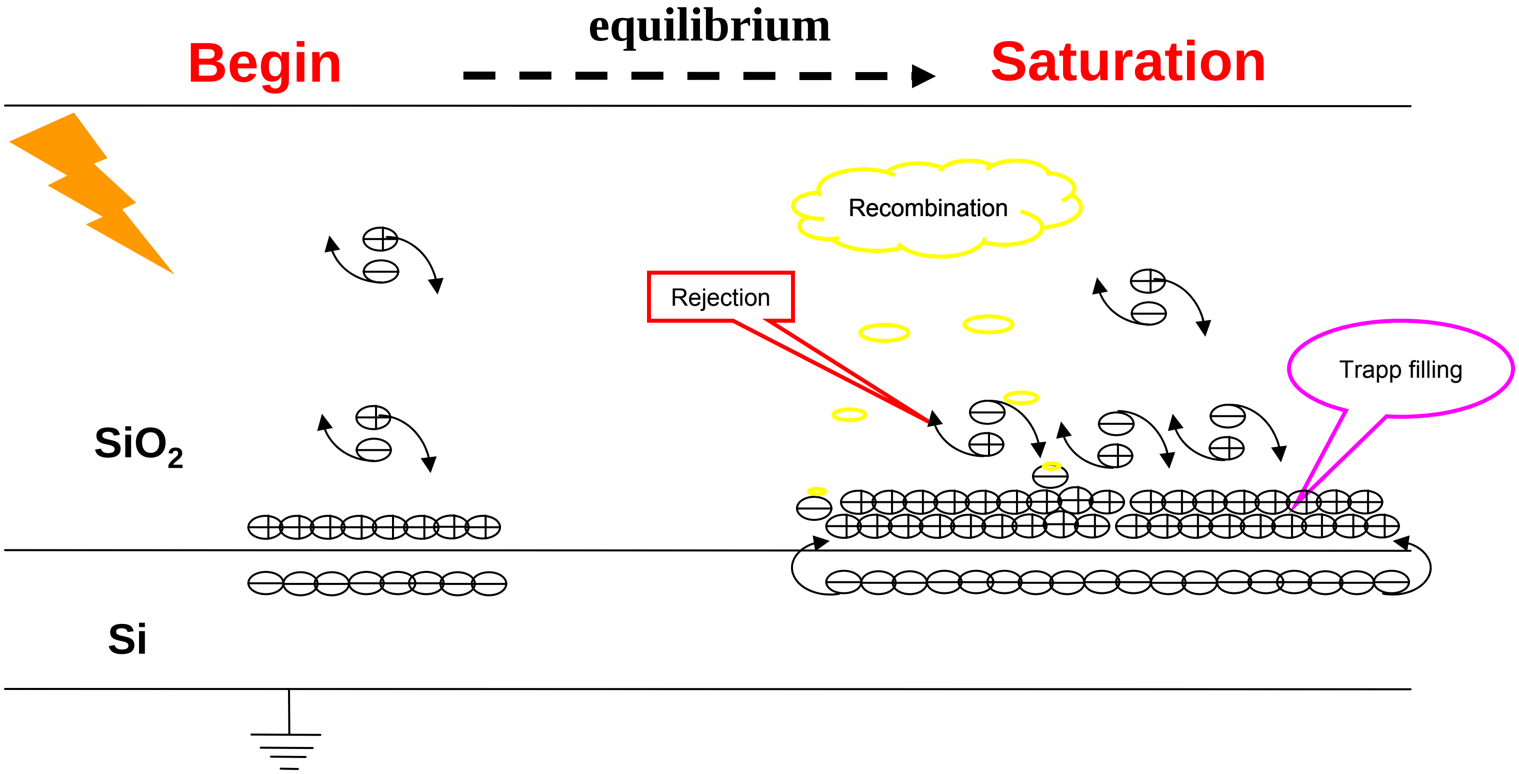
charge in Si/SiO interface donot affect the field distribution in dielectrics!

Damage mechanism II



Damage mechanism III

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***

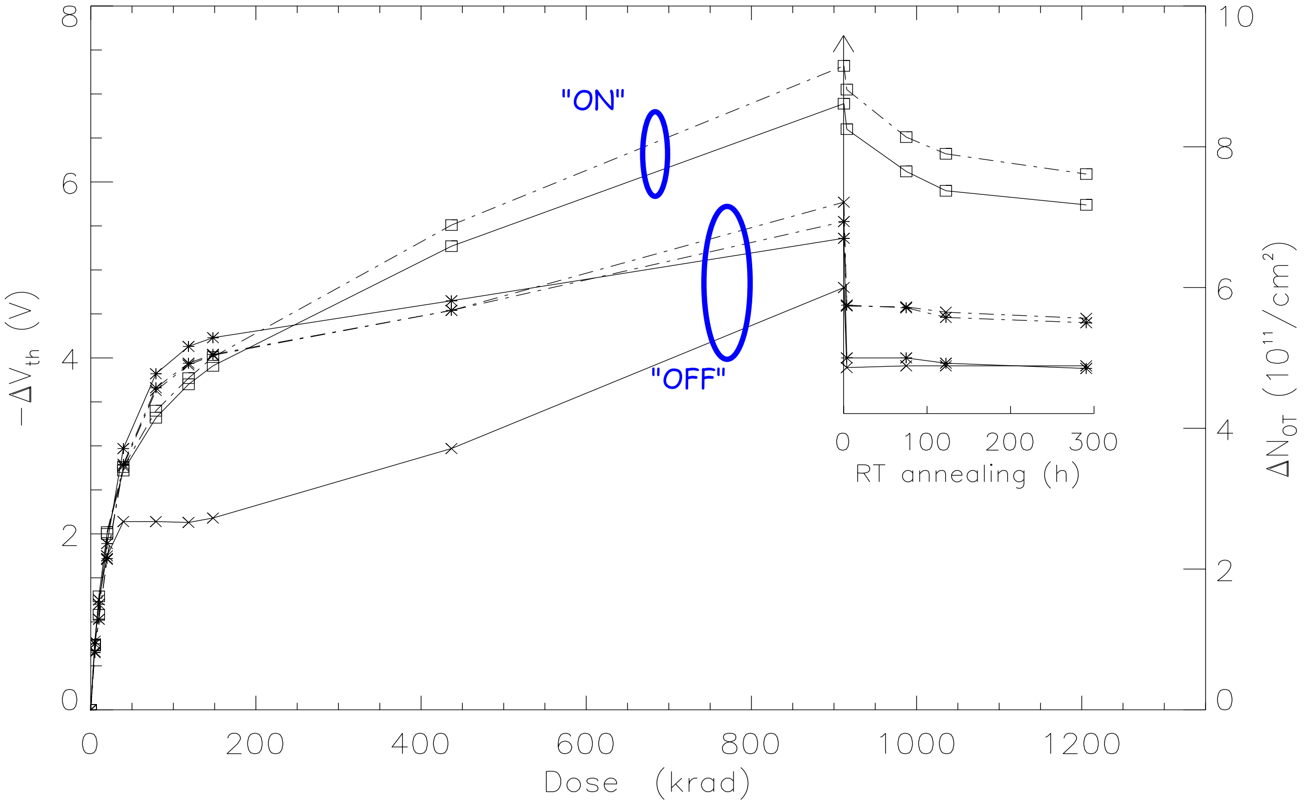
	DEPFET	**MOS-C**	**Gated diode**
N_{ox} (method)	ΔV_t (IV-Measurement)	ΔV_{FB} (CV-Measurement)	ΔV_{FB} & ΔV_g (CV-Measurement & gated diode technique)
N_{it} (method)	Subthreshold slope (Subthreshold technique)	Stretch-out (High-low frequency based on the CV)	Full width at 2/3 maximal of current (gated diode technique)
Other parameters	g_m (IV-Measurement)		S_0, τ (gated diode technique)

Results for MOSDEPFET

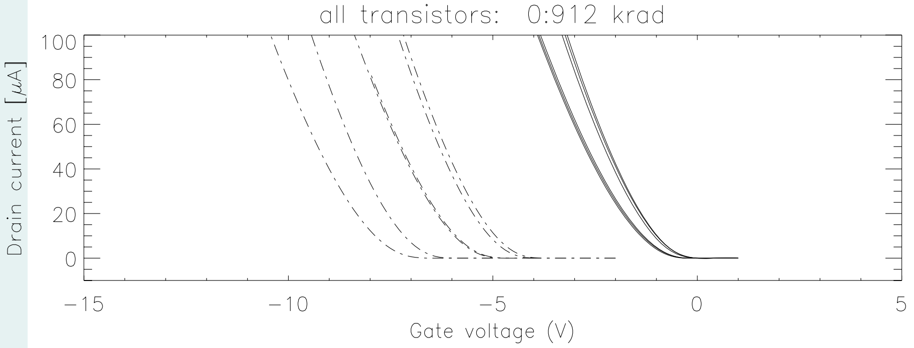
Bias during irradiaton:

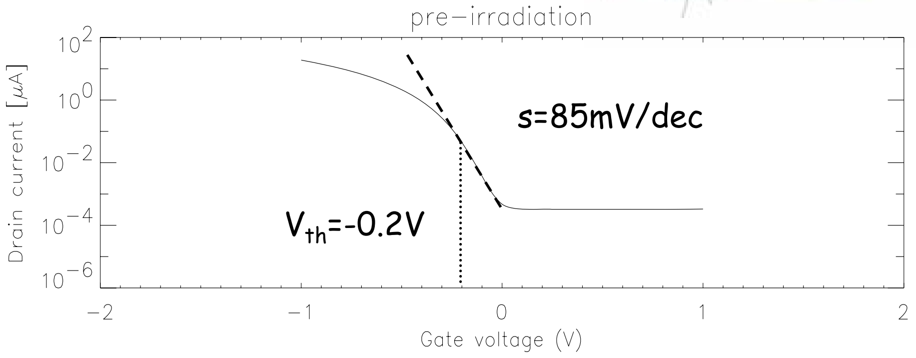
1: empty int. gate, in „off“ state, V_{GS}= 5V, V_{Drain}=-5V → $E_{ox} \approx 0$

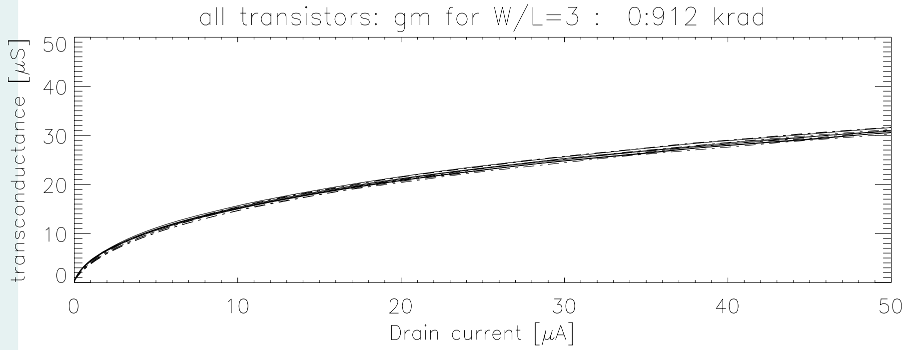
2: empty int. gate, in „on“ state, V_{GS}=-5V, V_{Drain}=-5V → $E_{ox} \approx$ -250kV/cm

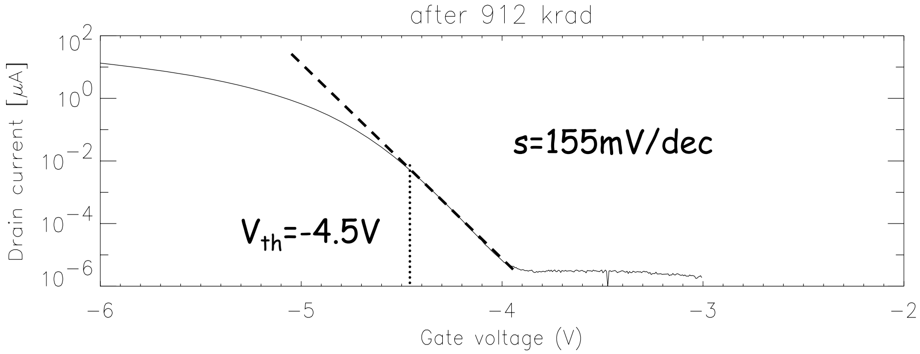


Transconductance and Subtreshold slope









No change in the transconductance g_m

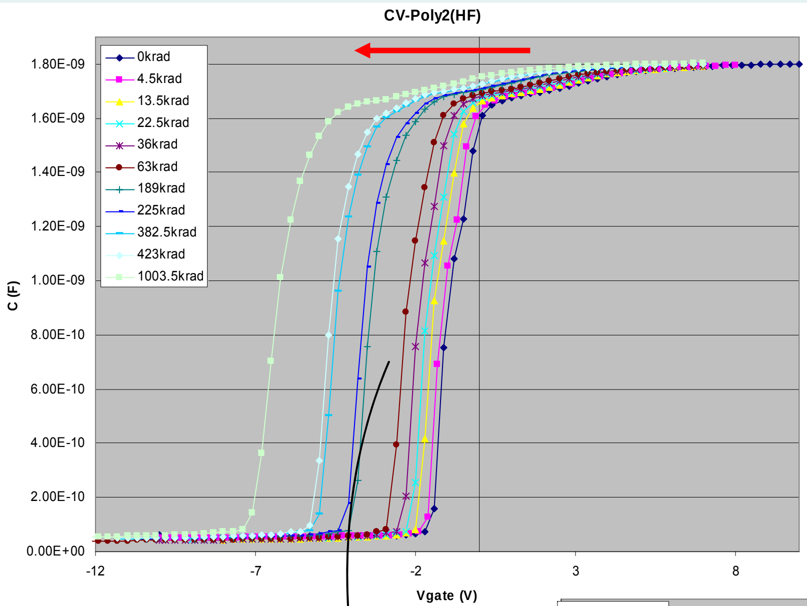
$$N_{it} = \left[{C_{ox}}/{kT} \ \ln(10) \right] (S_{D2} - S_{D1})$$

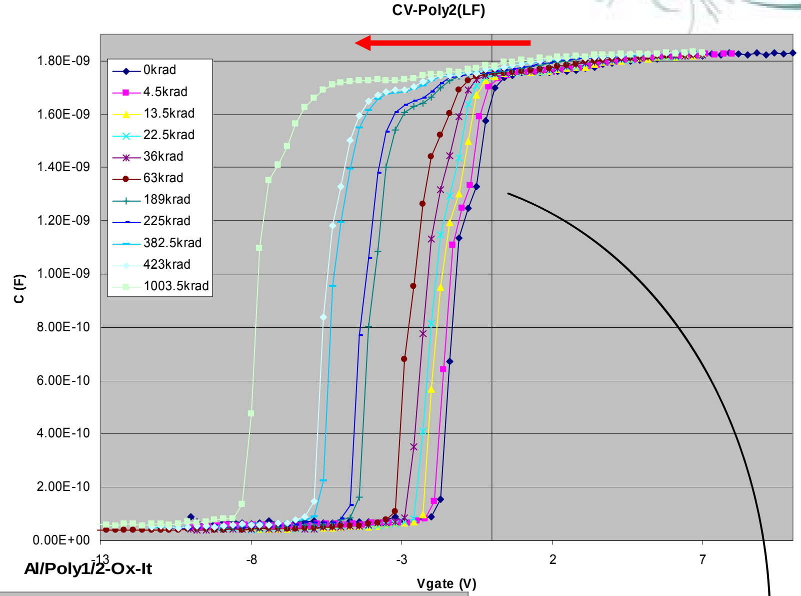
300 krad → $N_{it} \approx 2 \cdot 10^{11}$ cm^{-2}
912 krad → $N_{it} \approx 7 \cdot 10^{11}$ cm^{-2}

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

Gate Bias conditions: 0V

Results for MOS-C

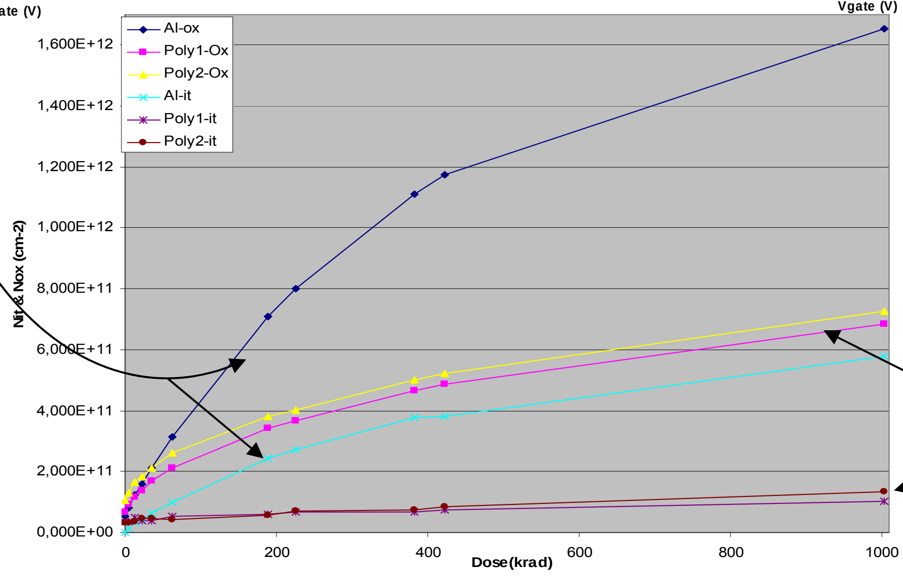




Flat band voltage Shift
→N_{ox}

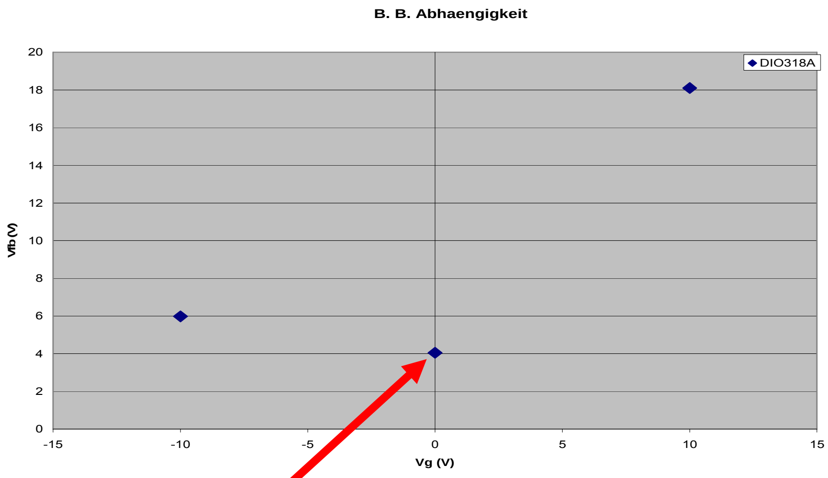
HF/LF CV
→ N_{it}

Al/Poly1/2-Ox-It

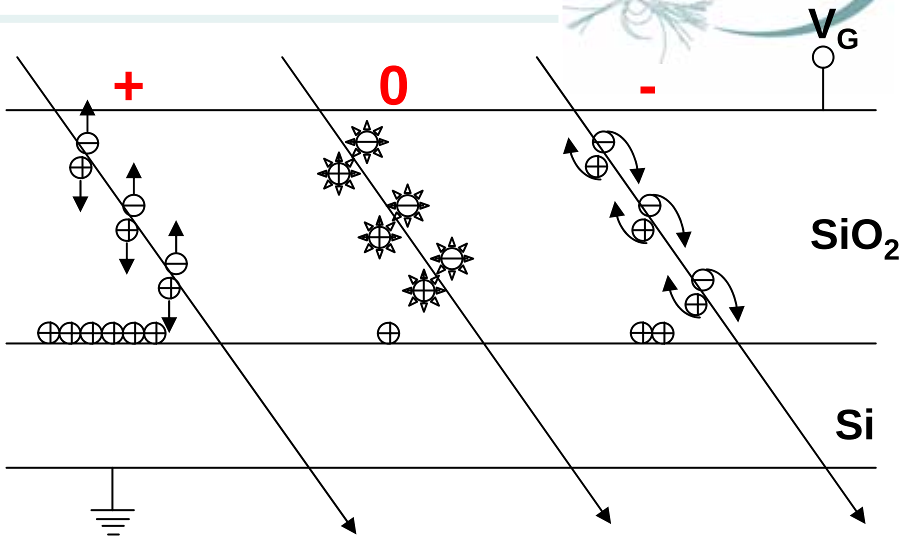


For MOS-C

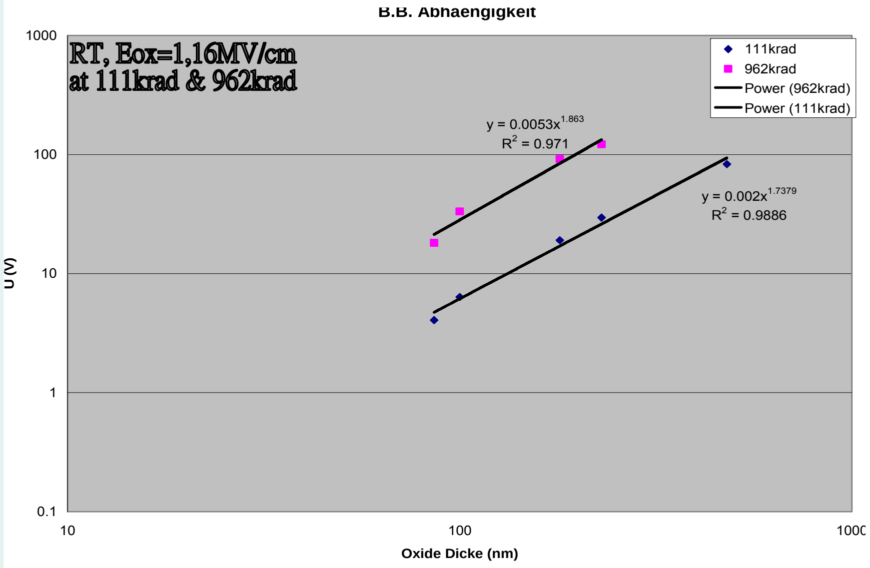
Bias Effect

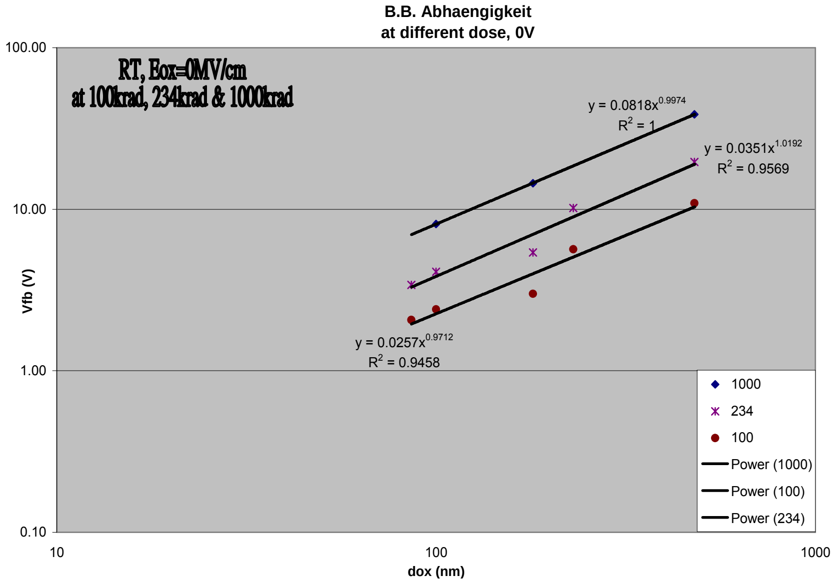


DEPFET



thickness dependence d^n

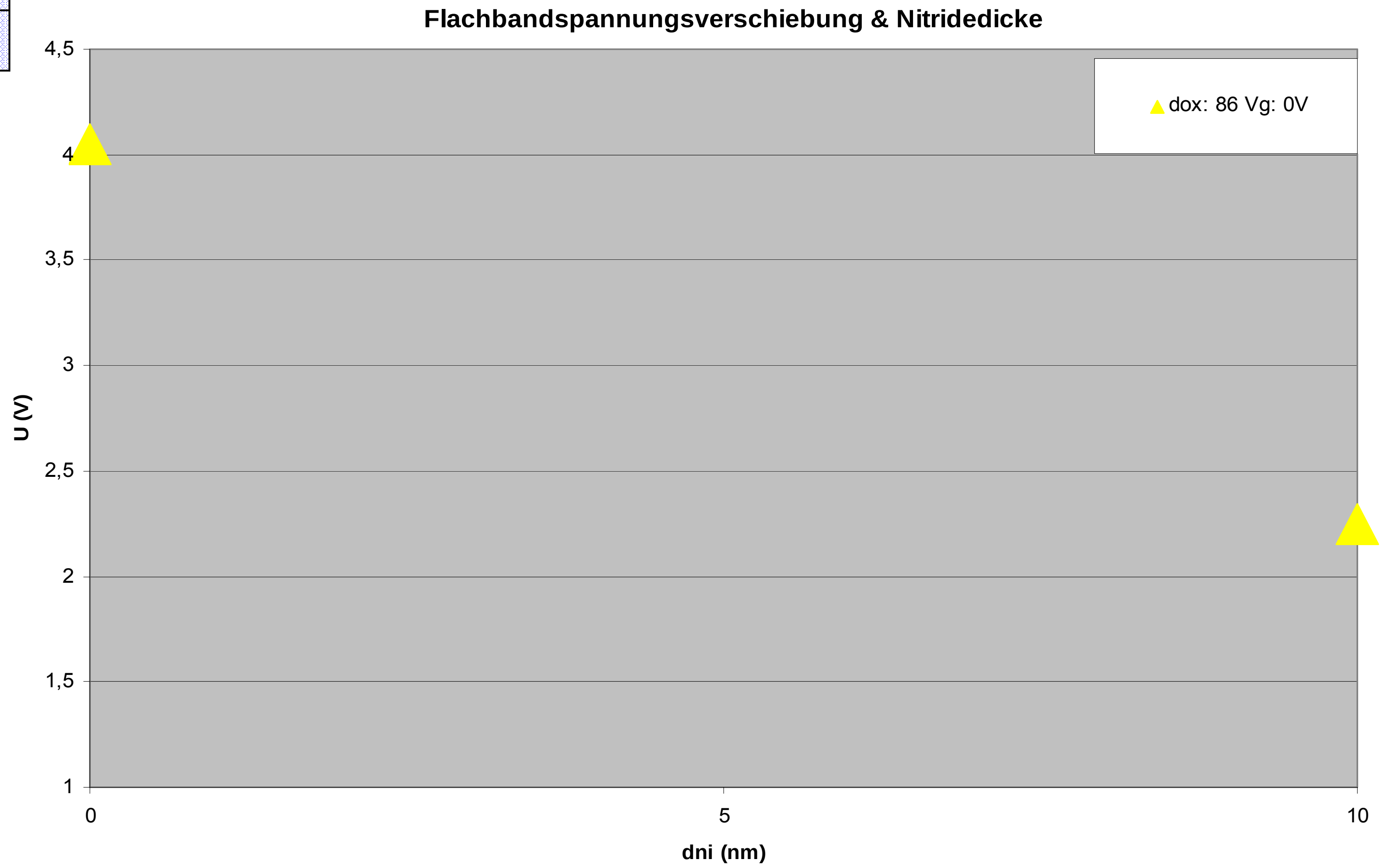




For MOS-C

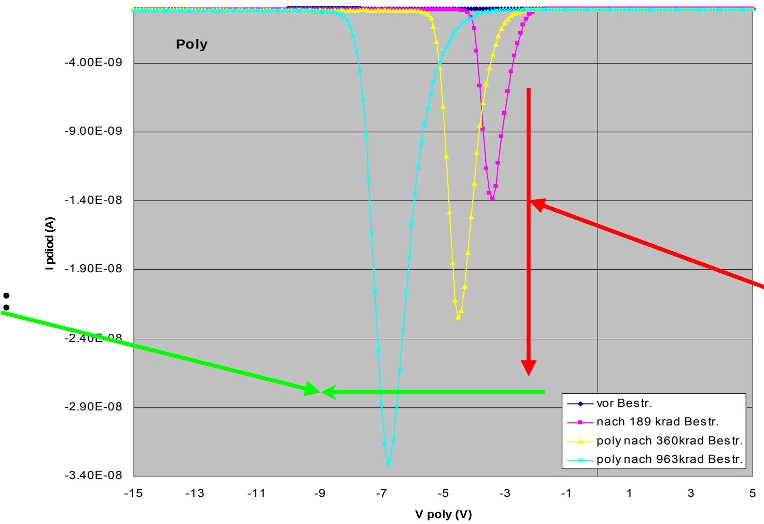
Radiation hardness by Nitride-layer

Al
LTO/Poly1/Poly2
Nitride
Oxide
Substrate n-Type



Flachbandspannungsverschiebung & Nitridedicke

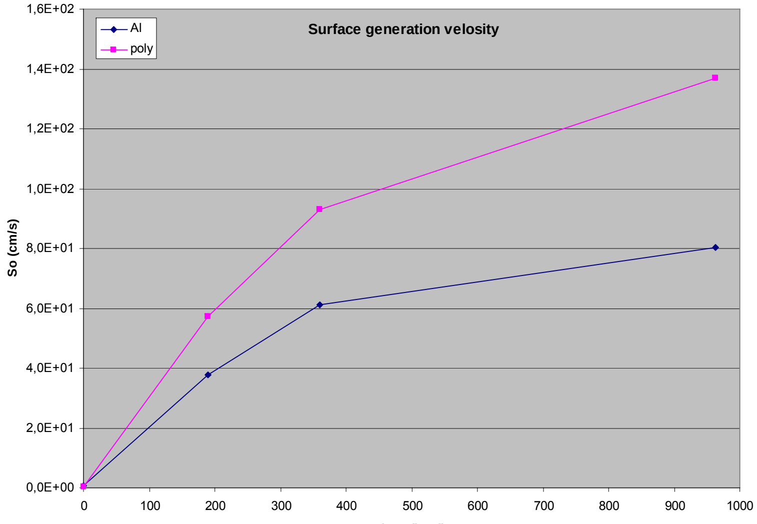
Results for gated diode

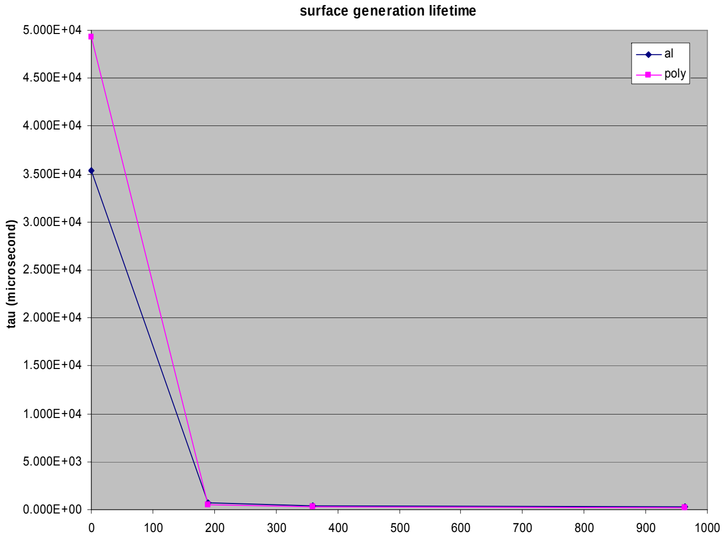


Shifts of generated current:

Increase of maximal current:

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

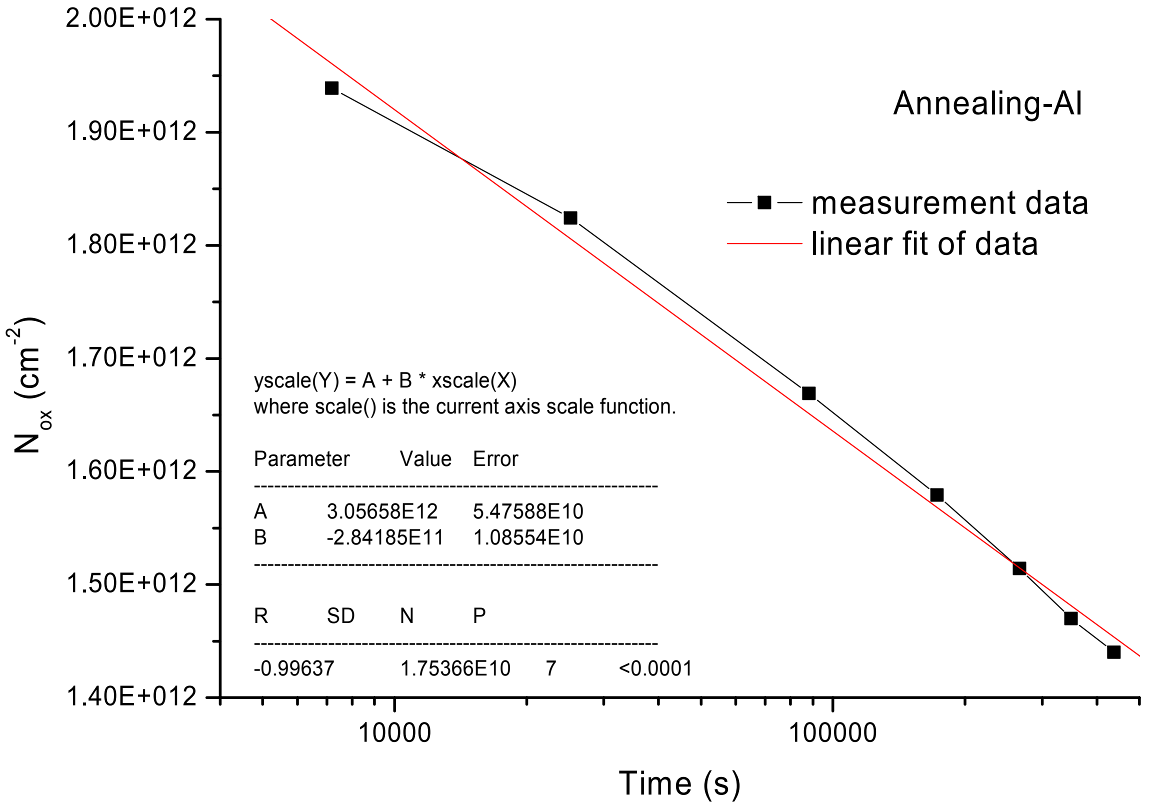




Annealing for surface damage

Oxide charge decrease with time:

(Tunnel annealing @ RT)



```
yscale(Y) = A + B * xscale(X)
where scale() is the current axis scale function.

Parameter        Value    Error
------------------------------------------------------------
A          3.05658E12     5.47588E10
B          -2.84185E11    1.08554E10
------------------------------------------------------------

R          SD         N          P
------------------------------------------------------------
-0.99637          1.75366E10     7          <0.0001
```

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 $\Gamma = N_{ox} / \left(\phi_h \times t\right) \leq 5\% \quad \left(\sim 1 Mrad\right)$
  - 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