Properties of the X-ray Induced Radiation Damage at the SiO_2 - Si Interface

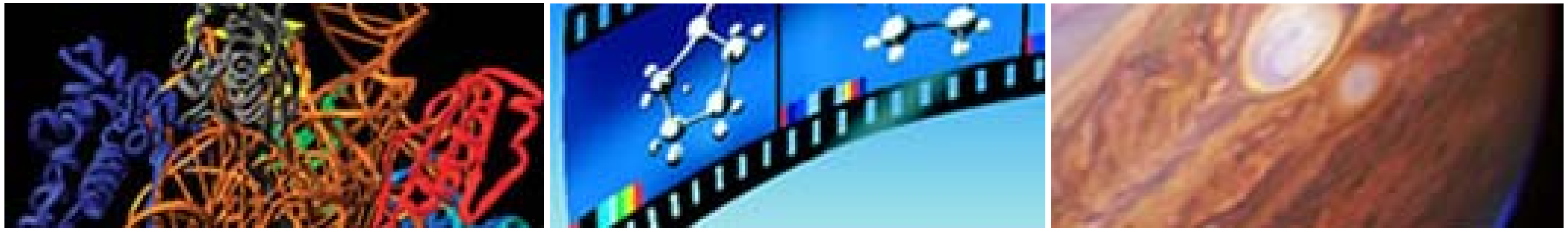
J. Zhang[1,2], R. Klanner[1], E. Fretwurst[1], I. Pintilie[3], J. Schwandt[1]

[1]Institute for Experimental Physics, Hamburg University
[2]Marie Curie initial training network – PArticle Detector (MC-PAD)
[3]National Institute of Materials Physics, Romania

Introduction

Next generation light source European X-ray Free Electron Laser (XFEL):

- **Opportunities:** single molecule imaging, movies of chemical reactions, exploration of material science, etc.



http://www.xfel.eu

- **Challenges for detector development:**

integrated dose ~ 10^9 Gy for E_{photon} ~ 12 keV.

The strategy of study:

- Perform microscopic and macroscopic studies on irradiated MOS capacitors, and understand properties of the X-ray induced radiation damage
- Extract damage-related parameters for TCAD simulation
- Optimize pixel sensor design for XFEL (J. Schwandt's talk on Mar 30)

Main effects on silicon devices at XFEL

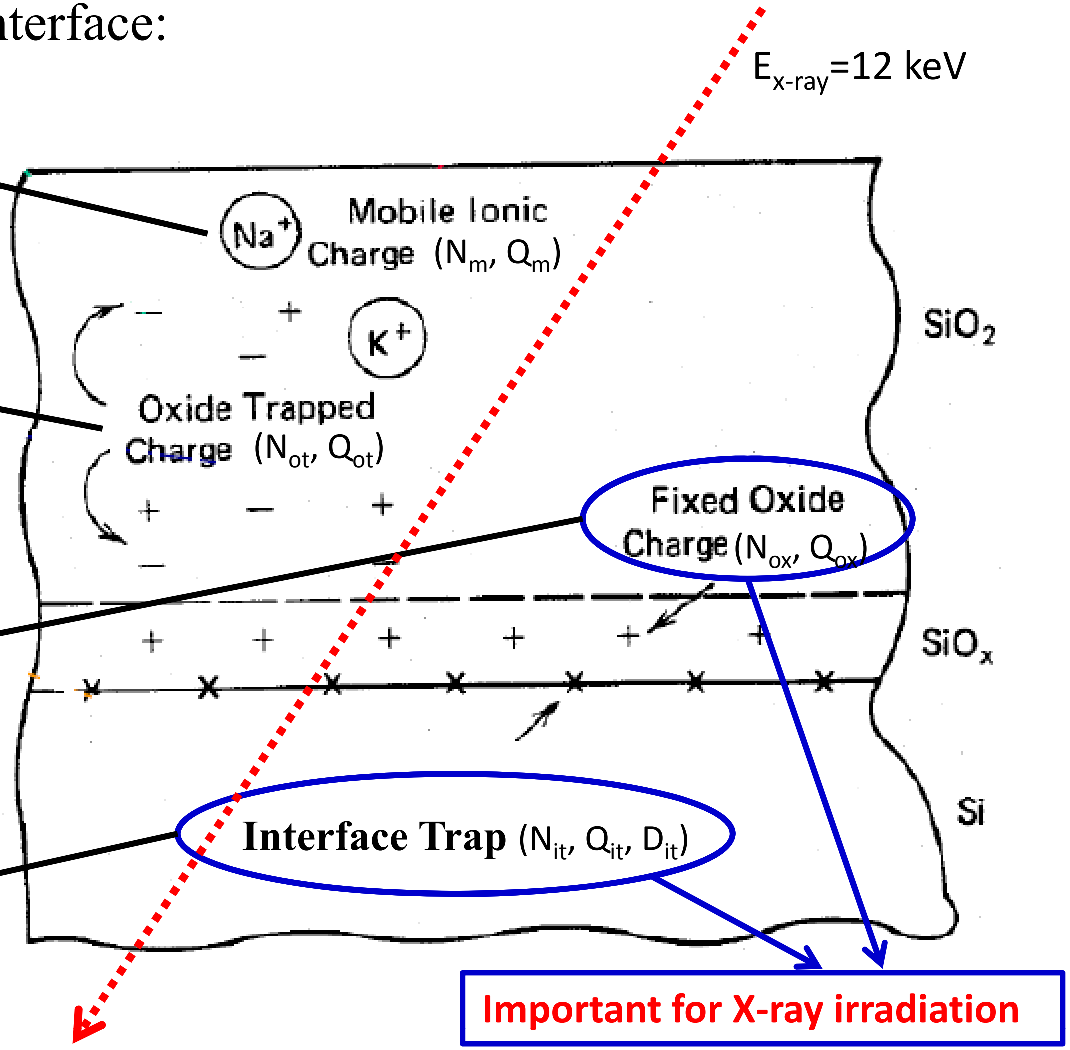
Charges in the SiO_2 and Si-SiO_2 interface:

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

Oxide Trapped Charge,
defects in the SiO_2 network, but difficult to communicate with free carriers.

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

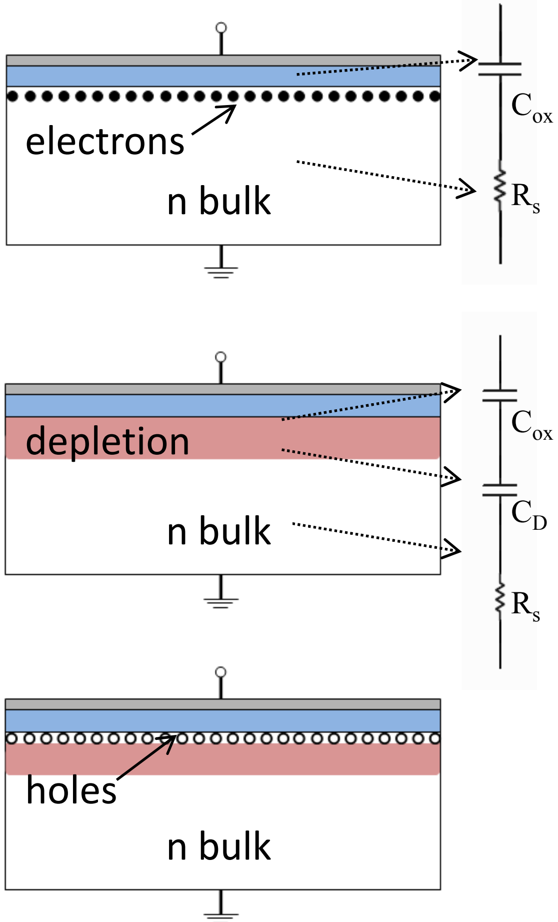
Interface trap,
due to dangling chemical bonds with new energy states in the forbidden band.



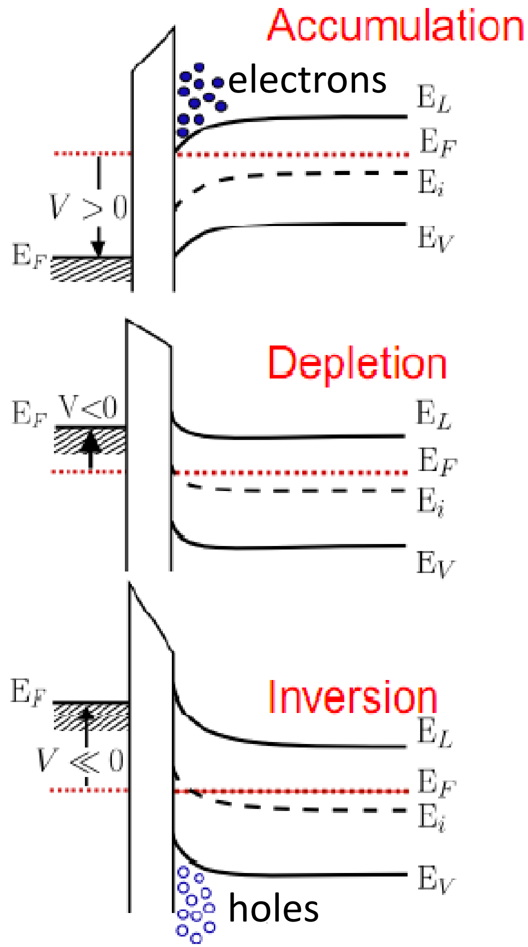
S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley, 1985

CMOS capacitor

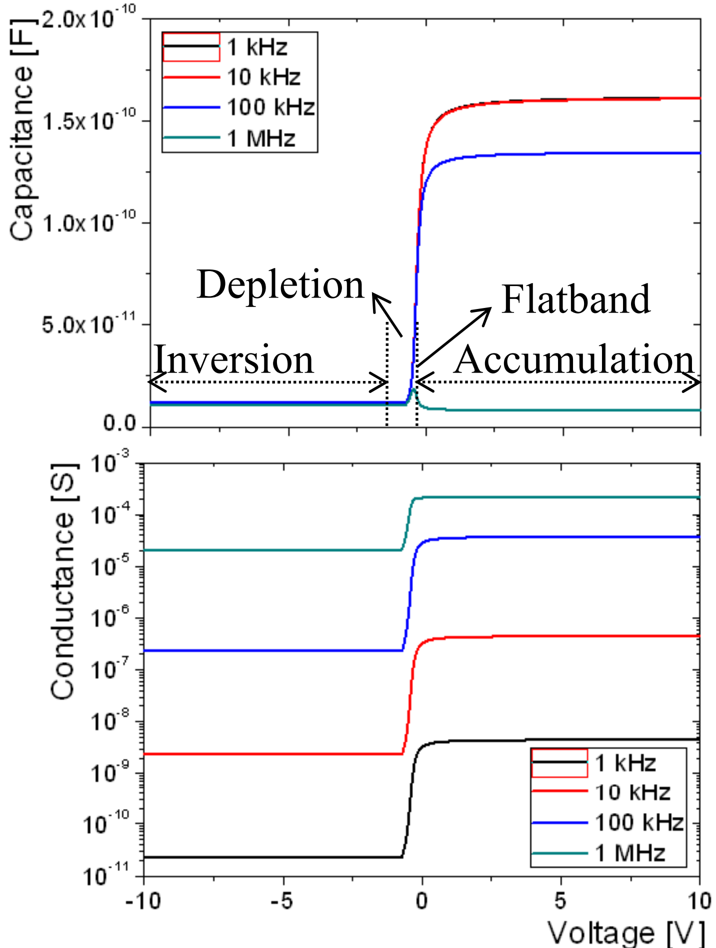
Ideal CV and GV curves (no bulk, interface traps or fixed oxide charges):



MOS capacitor



Energy band diagram



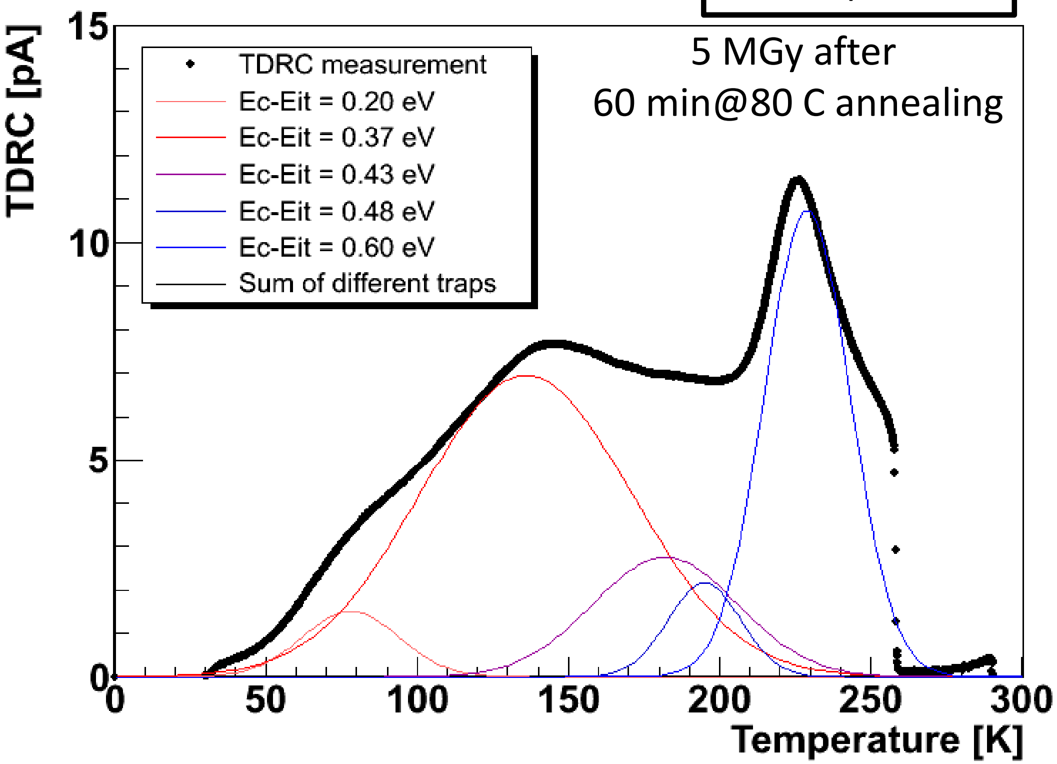
Ideal CV/GV curves

From microscopic defects to macroscopic properties

Microscopic measurement on interface states density D_{it} [$cm^{-2}eV^{-1}$]:

- **TDRC** (Thermally Dielectric Relaxation Current)

TDRC Spectrum



Principle of TDRC:

1. Fill interface traps with electrons at room temperature
2. Cool down the device to freeze the traps
3. Deplete Si-SiO_2 interface at low temperature (30 K)
4. Traps release charges, which induce current, during heating up the silicon device

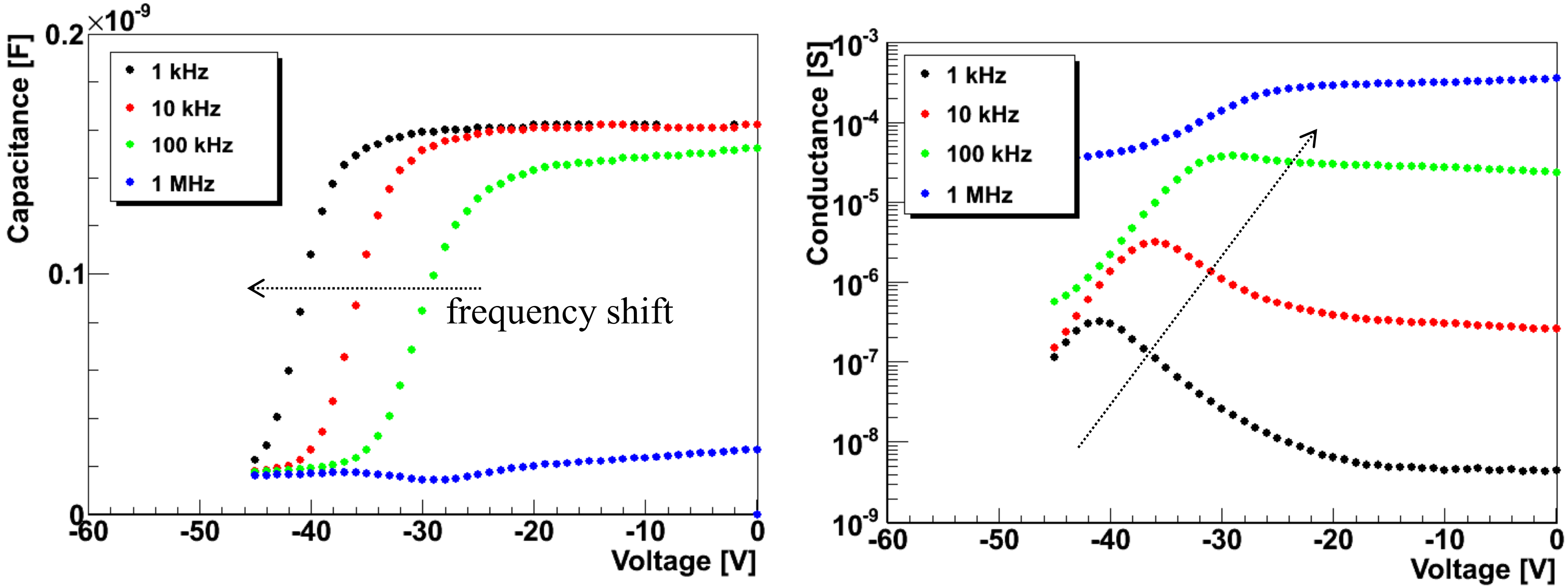
TDRC current [pA] → D_{it} [$cm^{-2}eV^{-1}$];
Temperature [K] → E_c-E_{it} [eV].

How microscopic defects affect macroscopic properties?

From microscopic defects to macroscopic properties

Macroscopic measurements of a MOS capacitor after 5 MGy X-ray irradiation:

- **CV & GV** (Capacitance - Voltage & Conductance - Voltage):



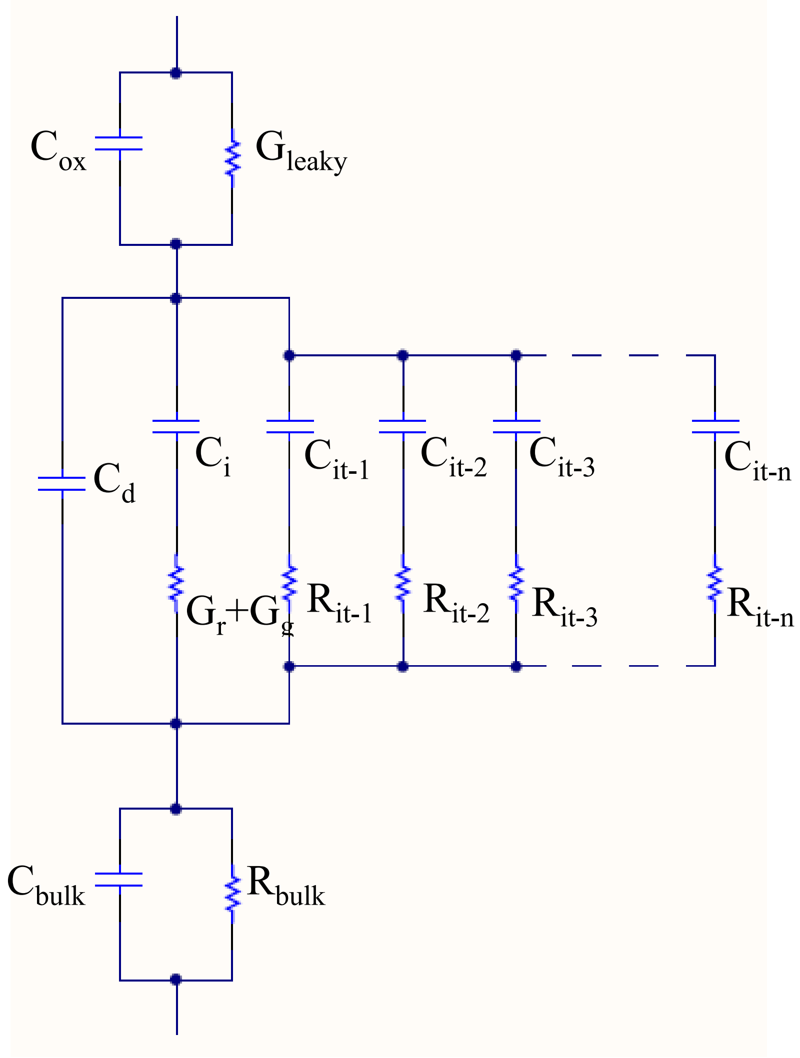
Compared with ideal CV/GV curves:

- Frequency shift for capacitance and conductance ← interface traps
- Add up conductance in depletion ← interface traps
- Shift of flatband voltage ← fixed oxide charges + interface traps

The model of MOS capacitor

Elements in the model:

- C_{ox} – oxide capacitance
- G_{leaky} – leaky conductance of the SiO_2 layer, isolation degradation due to irradiation
- C_d – capacitance of space charge region
- C_i – inversion capacitance, due to accumulated minority carriers at the interface
- G_r – recombination conductance, due to the diffusion of minority free carriers, $\rightarrow N_i^2/N_d$, τ_h, d_{si}, V_s
- G_g – generation conductance, from bulk traps, $\rightarrow \tau_e$, τ_h, d_{sc}, E_t, V_s



The model of MOS capacitor

Elements in the model:

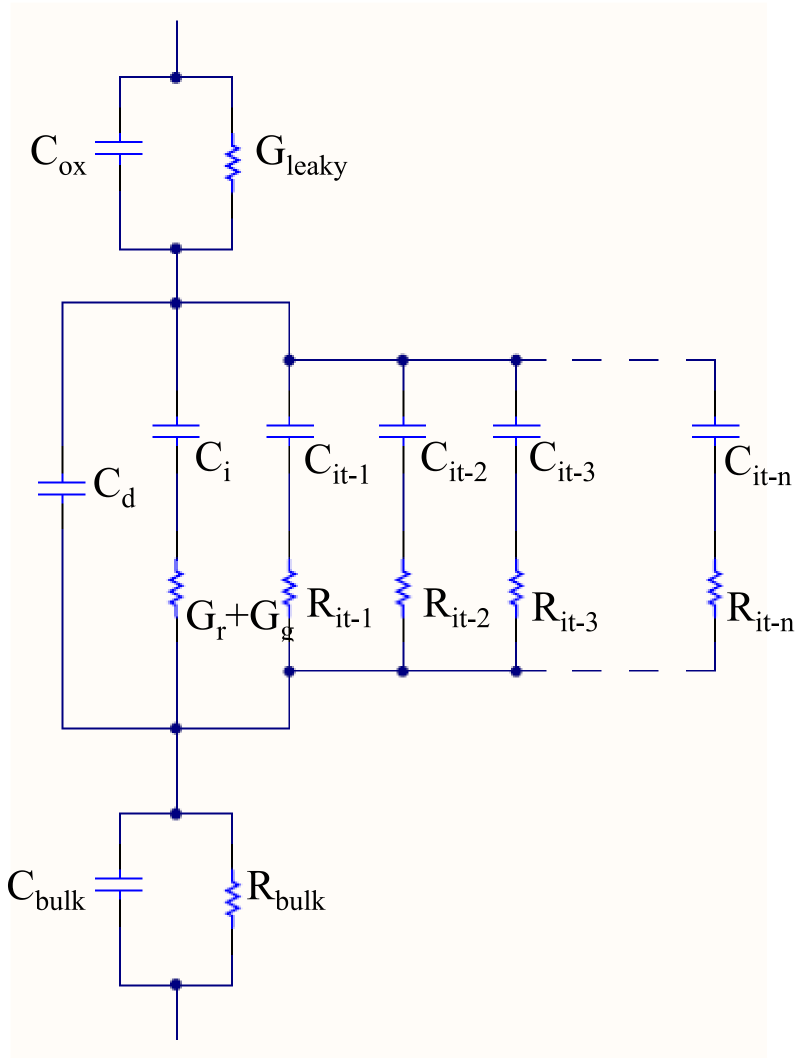
- **C_{it} – interface trap capacitance,**

  $\rightarrow N_d, D_{it}, E_{it}, \sigma_{eff}, V_s$
- **R_{it} – interface trap resistance**

  $\rightarrow N_d, D_{it}, E_{it}, \sigma_{eff}, V_s$
- C_{bulk} – capacitance from undepleted region
- R_{bulk} – resistance from undepleted region

Working range:

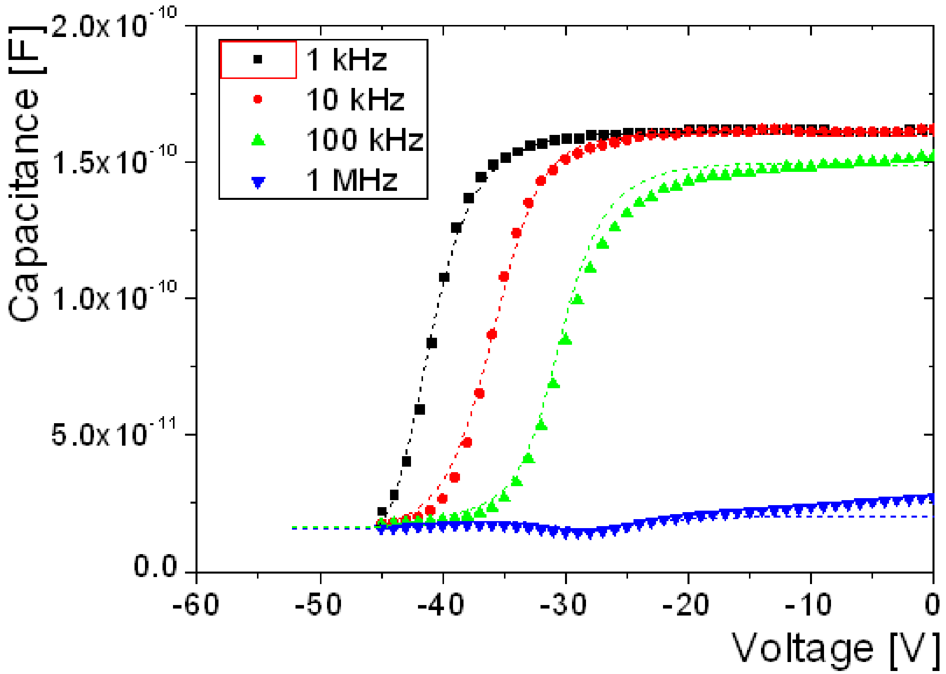
- Voltage: strong accumulation to inversion
- Frequency: (Hz?) kHz ~ MHz

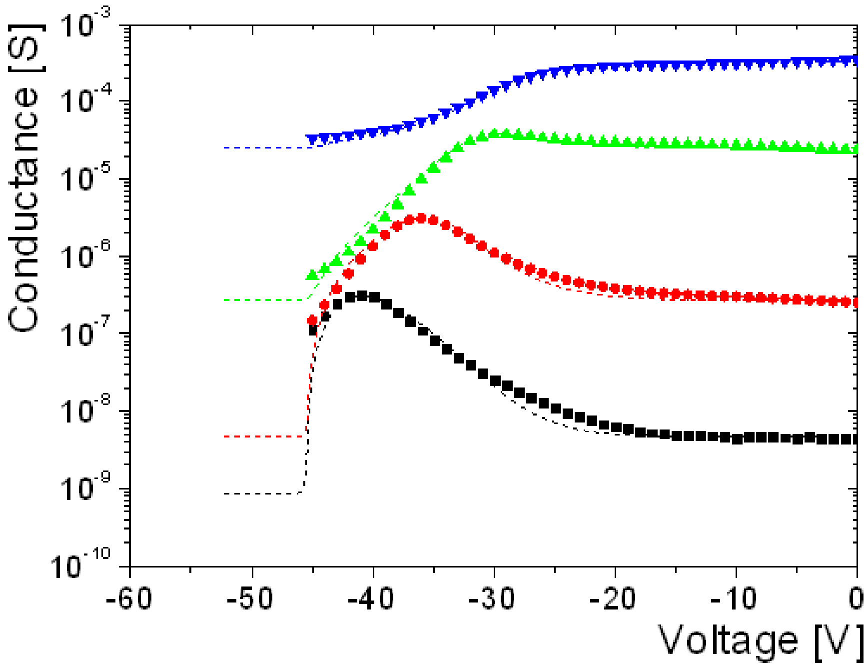


The model of MOS capacitor

Model calculation for a MOS capacitor after 5 MGy irradiation:

- TDRC spectrum as an input for D_{it} in the program
- CV & GV were calculated and compared with experimental results

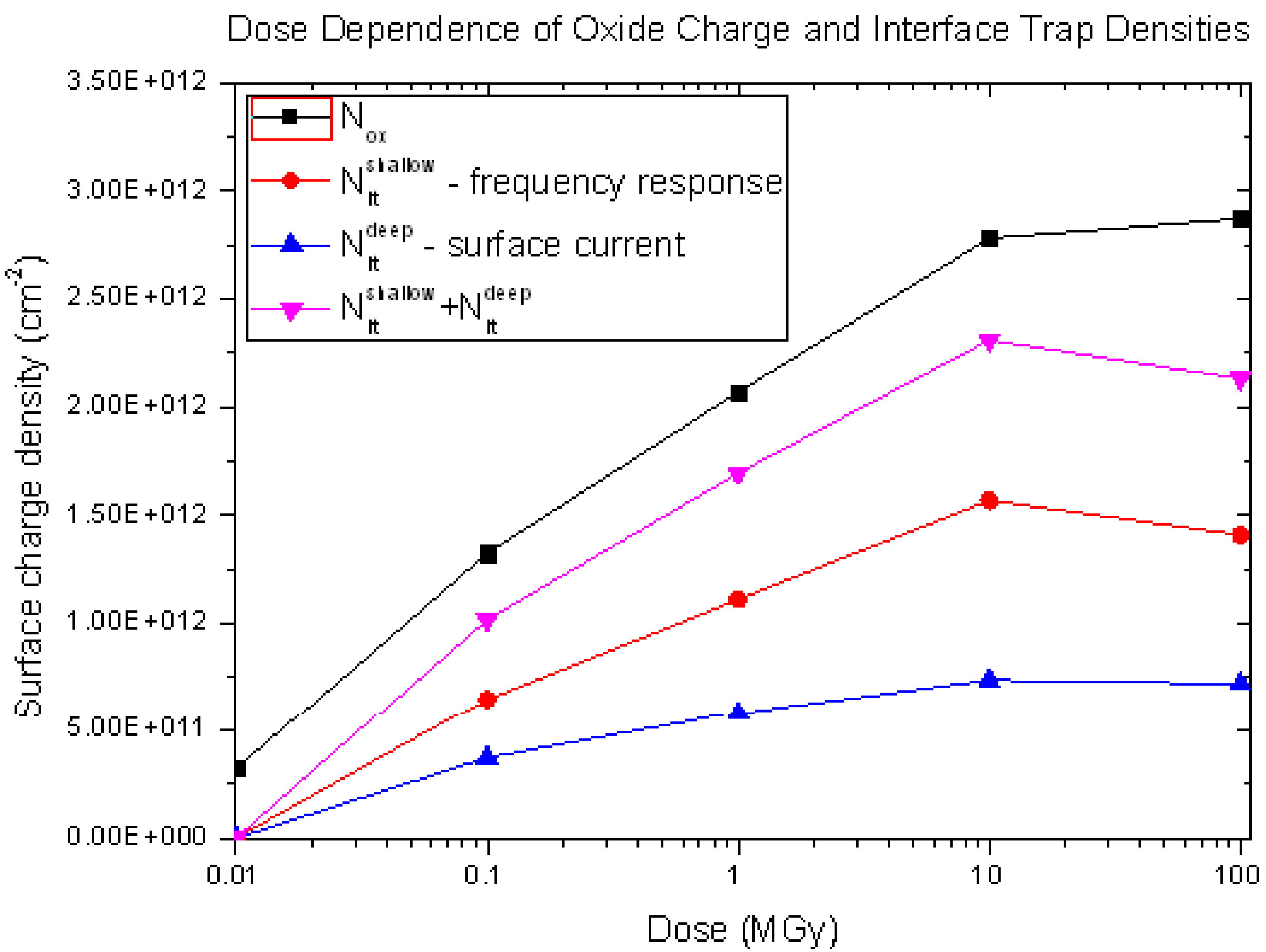




Model calculation was used to extract radiation introduced surface charges!

Extracted parameters based on model calculation

Results of fixed oxide charge density and interface trap density:



Summary

- Properties of X-ray induced surface charges were studied.
- Damage related parameters were extracted according to model calculation: it is shown that both fixed oxide charges and interface traps saturate at 10 MGy.
- Extracted parameters were put into Synopsys TCAD simulation to optimize sensor design for XFEL requirements.

Thank you!

Input parameters

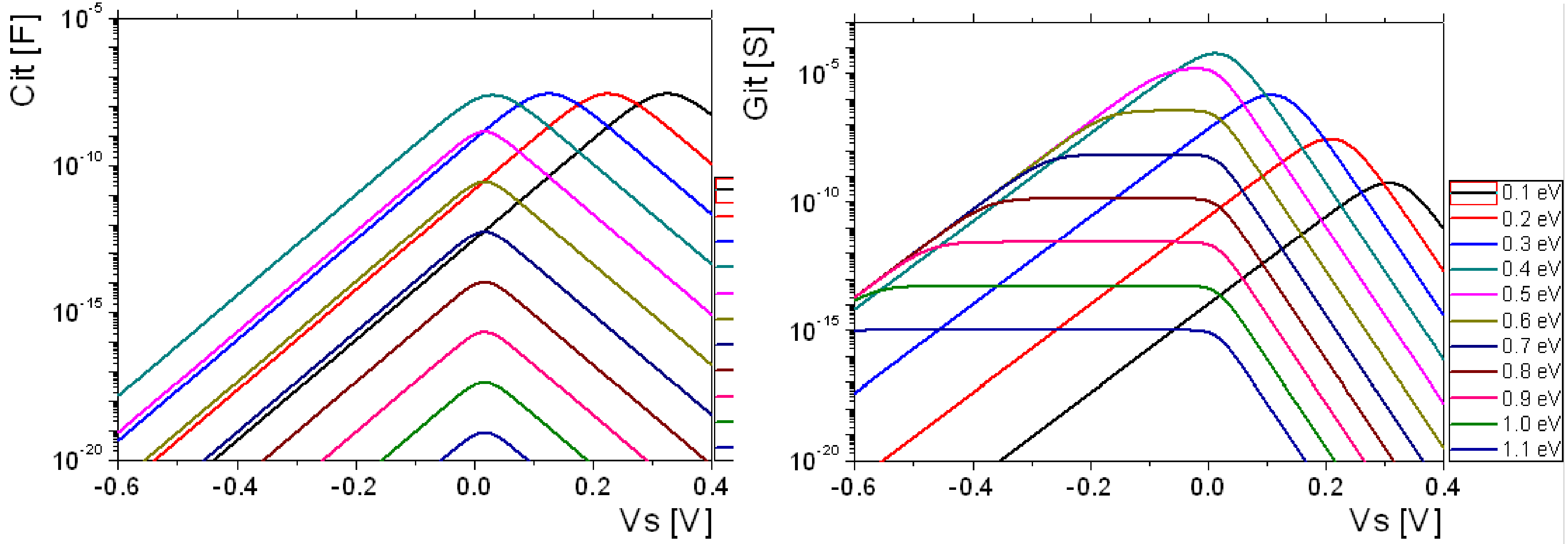
5 MGy MOS after 60min@80C annealing:

- N_d=2.55x10^{12}cm^{-3}
- N_{ds}=3.55x10^{12}cm^{-3}
- N_{ox}=2.55x10^{12}cm^{-2}
- dsi=285μm
- dox=377nm
- Gleaky=2x10^{-9}Ω^{-1}
- Sg=1.767x10^{-2}cm^2
- T=295K
- τe=170 μs, τh=170 μs
- Ec-Et=0.561eV
- σ_{eff}=2x10^{-15} cm^2 for Ec-Eit=0.2 & 0.37 eV
- σ_{eff}=1x10^{-16} cm^2 for Ec-Eit=0.43 & 0.48 eV
- σ_{eff}=8x10^{-16} cm^2 for Ec-Eit=0.60 eV
- Φms=0

Single energy level study:

- N_d=1.55x10^{12}cm^{-3}
- N_{ox}=5x10^{11}cm^{-2}
- dsi=285μm
- dox=377nm
- Gleaky=0Ω^{-1}
- Sg=1.767x10^{-2}cm^2
- T=295K
- τe=170 μs, τh=170 μs
- Ec-Et=0.561eV
- σ_{eff}=1x10^{-16} cm^2
- N_{it}=1x10^{12}cm^{-2}
- Φms=0

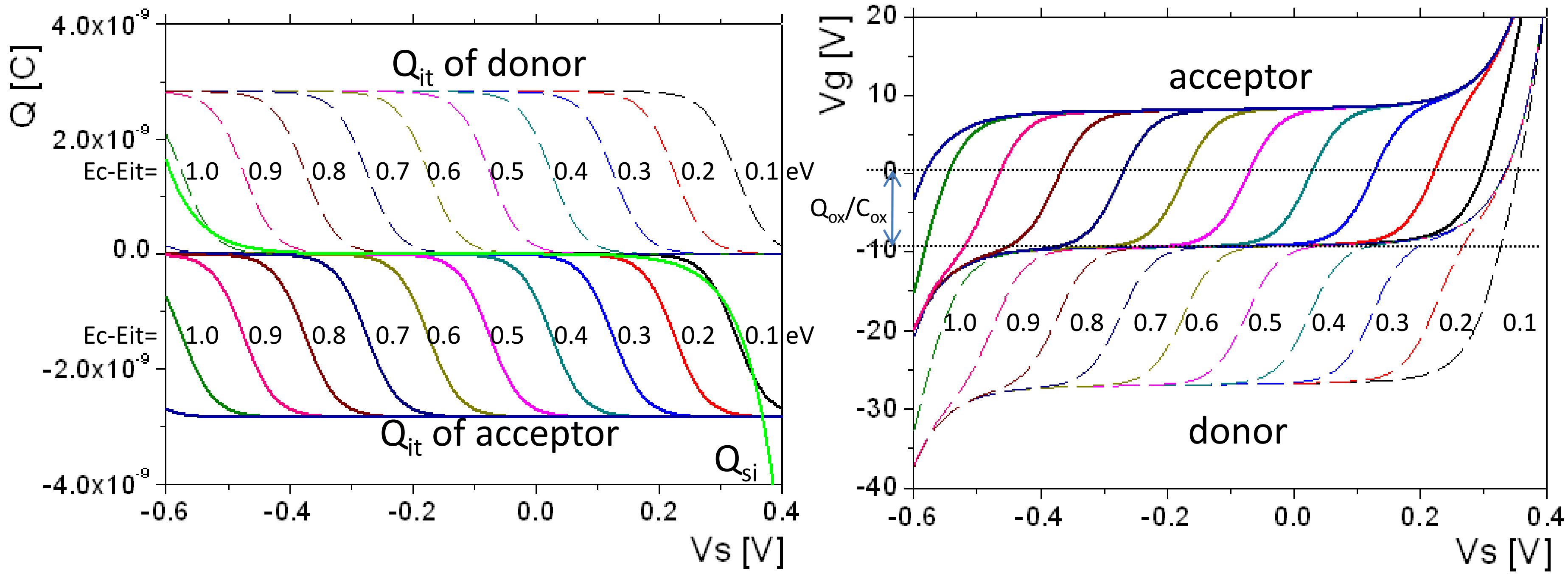
Cit and Git in parallel mode



How interface traps work

Properties of single energy level trap (E_c-E_{it} = 0.1 eV…1.0 eV, σ_{eff}=10^{-16}cm^2)

- Charges stored in the traps with a concentration 10^{12} cm^{-2} at T=295 K:



Acceptor-like trap: "-" when occupied by electrons; "0" when empty.

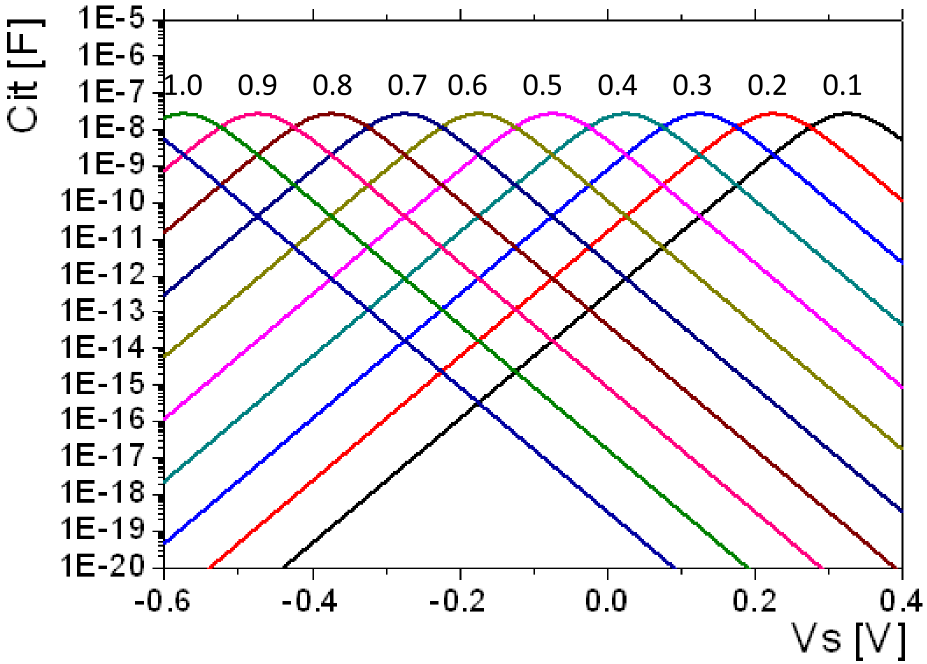
Donor-like trap: "0" when occupied by electrons; "+" when empty.

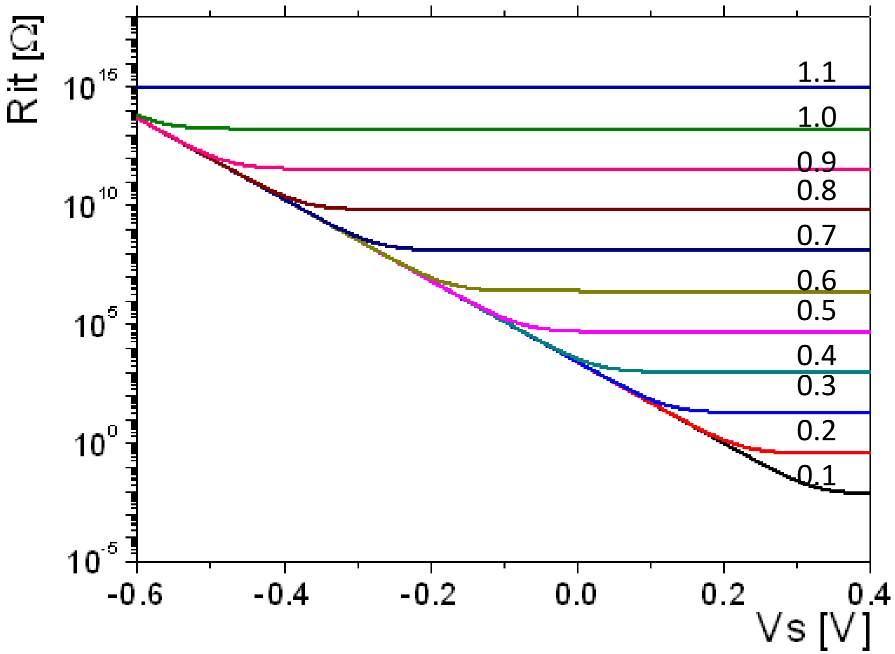
$$Vg = Vs + VF + \phi ms - \frac{Qsi}{Cox} - \frac{Qox}{Cox} - \frac{Qit}{Cox}$$

How interface traps work

Properties of single energy level trap (E_c-E_{it} = 0.1 eV…1.0 eV, σ_{eff}=10^{-16}cm^2)

- Interface trap capacitance and conductance (resistance):





C_{it} reaches maximum once Fermi energy level crosses the energy level of the trap

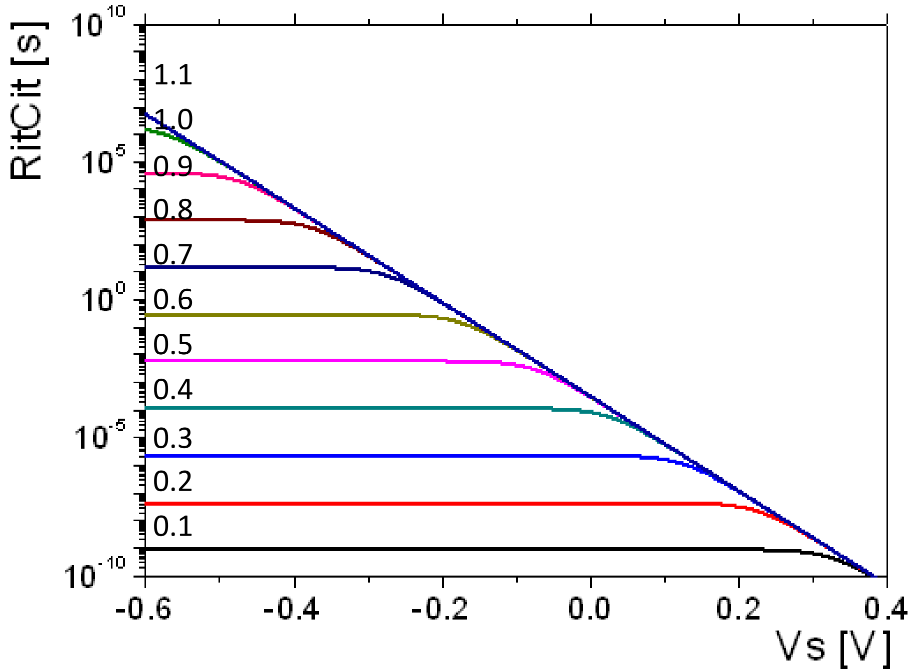
R_{it} stands for the “ability” of a trap to communicate with majority carriers.

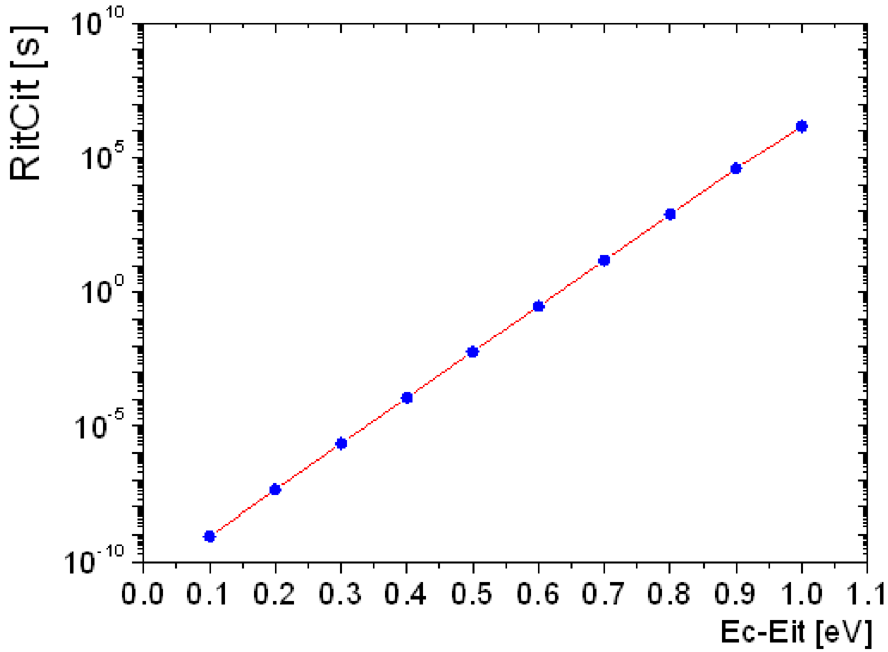
C_{it} and R_{it} do not show type of trap and frequency dependence! Frequency dependence of capacitance and conductance is due to the transformation from series mode to parallel mode.

How interface traps work

Properties of single energy level trap (E_c-E_{it} = 0.1 eV…1.0 eV, σ_{eff}=10^{-16}cm^2)

- RC time constants of interface trap:





$R_{it}C_{it}$ time constants do not saturate until Fermi level below trap level

→ time needed to charge or discharge a trap depends on band bending

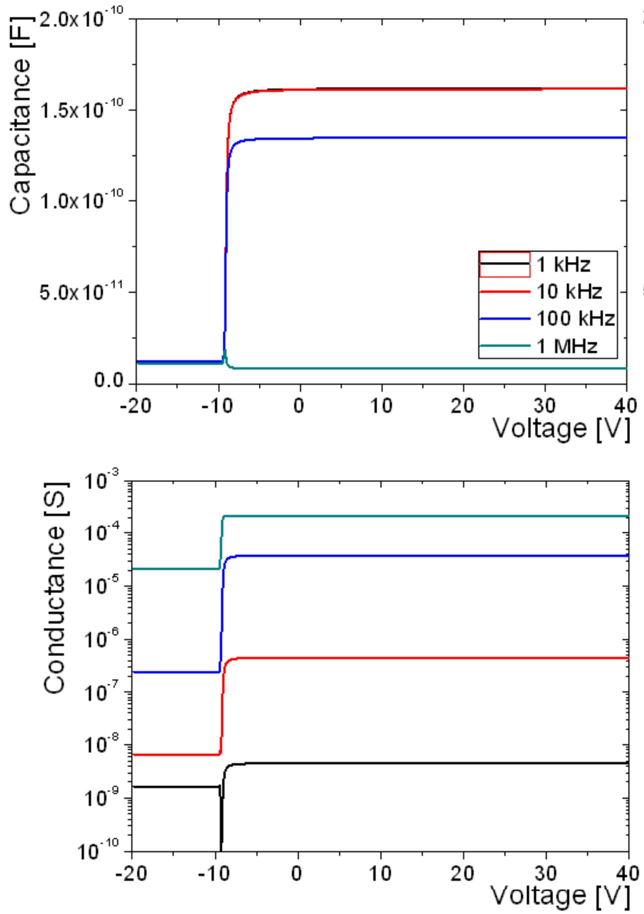
log ($R_{it}C_{it}$) linearly increases with the energy level of trap.

→ charging or discharging time depends on the energy level of the trap

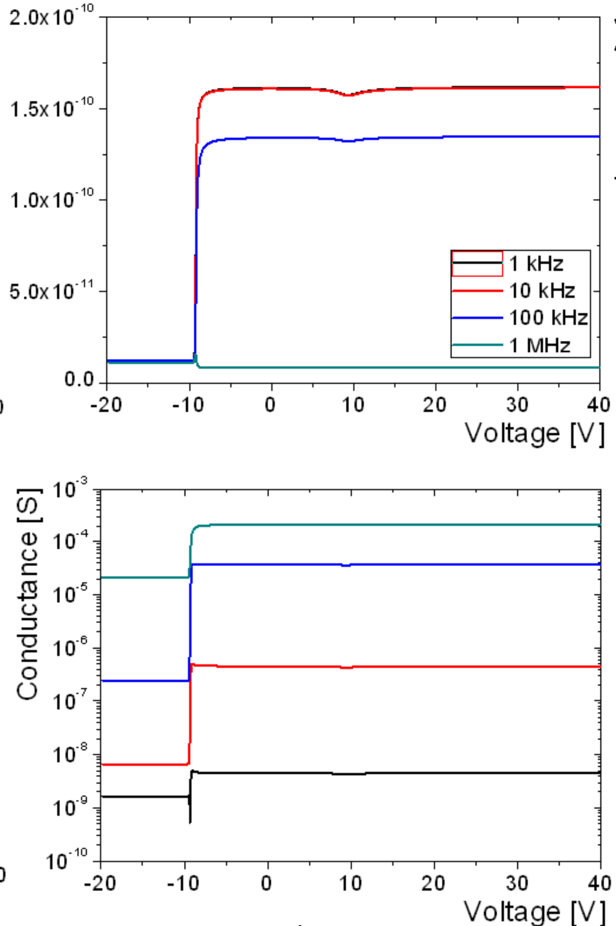
How interface traps work

Evolution of CV/GV due to single energy level trap:

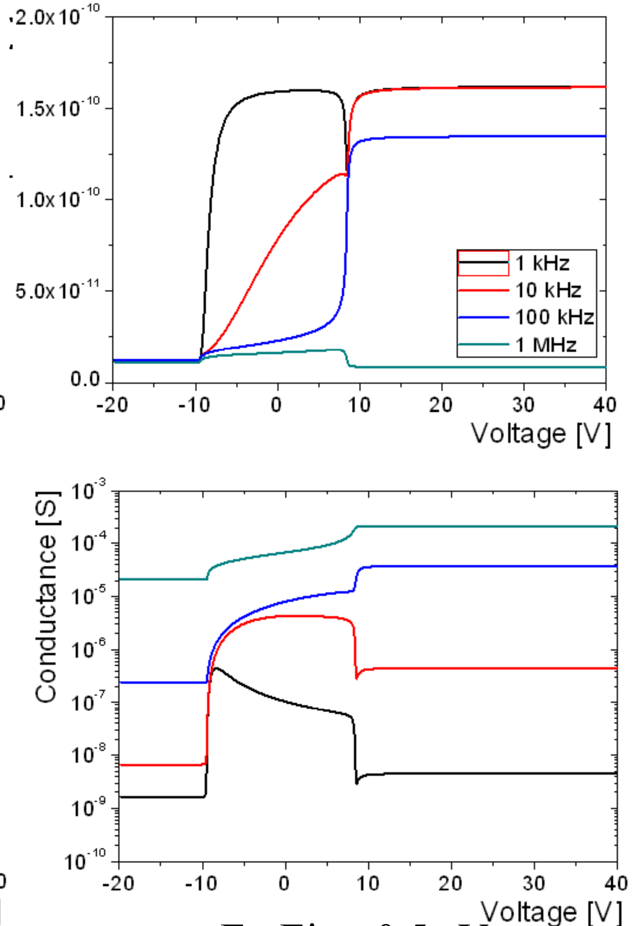
(E_c-E_{it} = 0.1 eV…0.9 eV, acceptor-like traps assumed, T=295 K, $\sigma_{eff}=10^{-16}cm^2$)



Ec-Eit = 0.1 eV



Ec-Eit = 0.3 eV

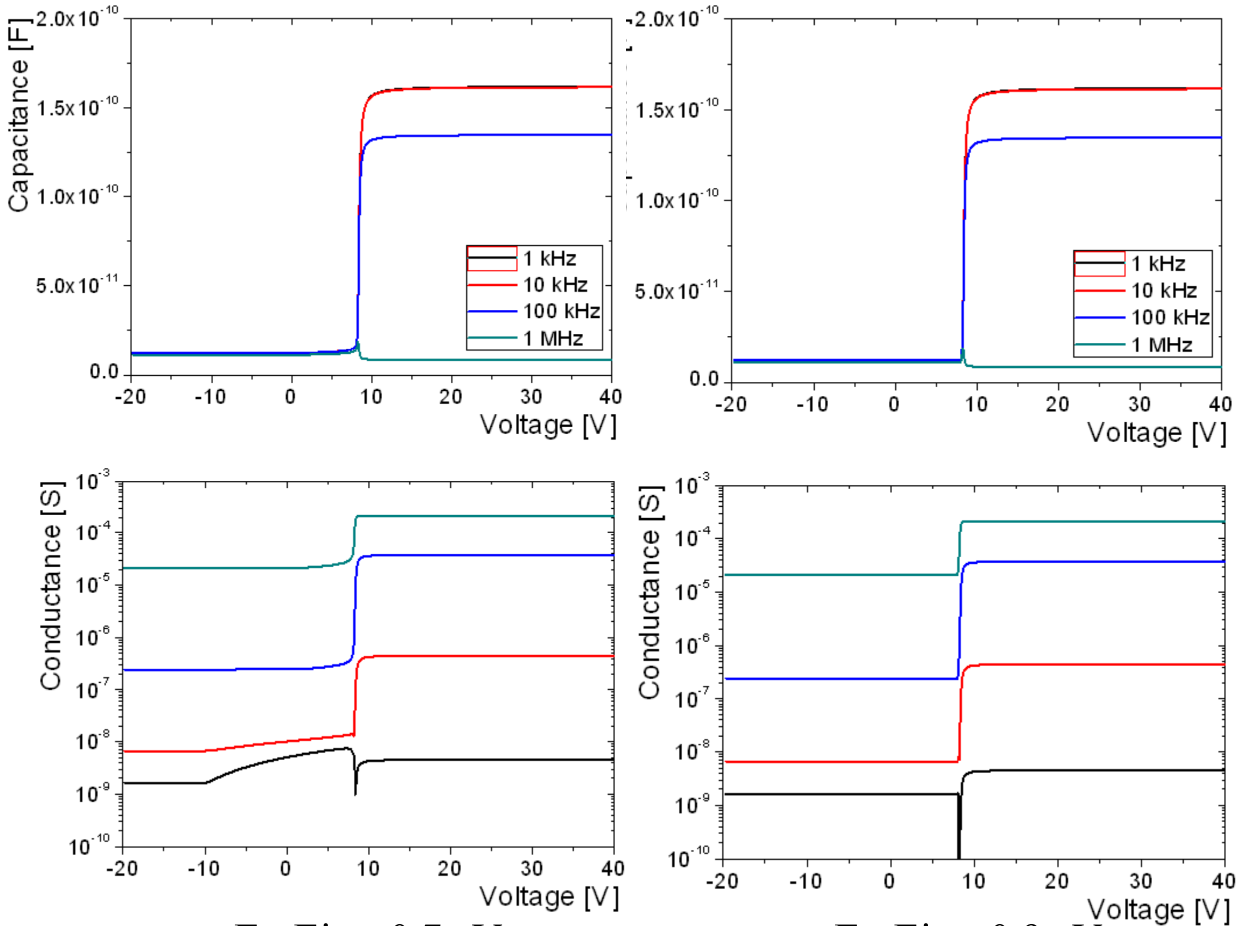


Ec-Eit = 0.5 eV

How interface traps work

Evolution of CV/GV due to single energy level trap:

(E_c-E_{it} = 0.1 eV…0.9 eV, acceptor-like traps assumed, T=295 K, $\sigma_{eff}=10^{-16} cm^2$)



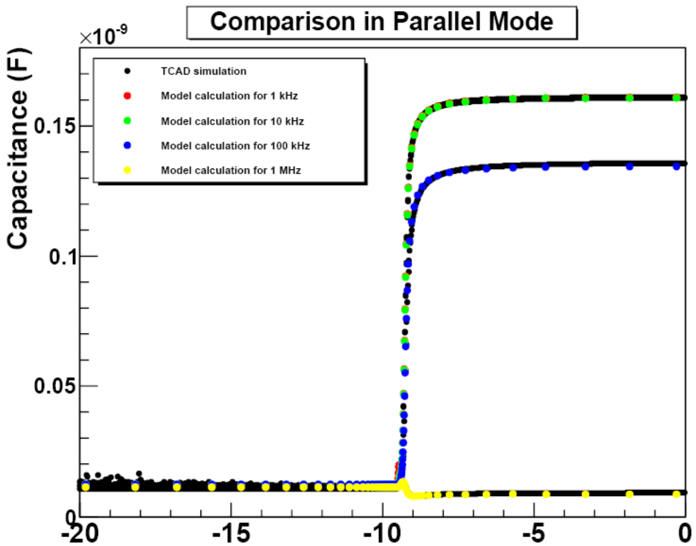
Ec-Eit = 0.7 eV

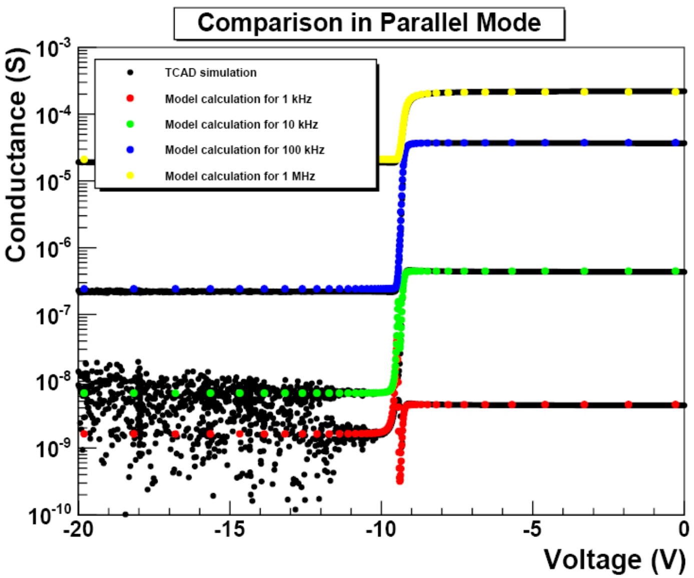
Ec-Eit = 0.9 eV

At room temperature, only the trap level (Ec-Eit) between 0.3 eV – 0.7 eV will disperse the CV (frequency dependence) and contribute to the total conductance!

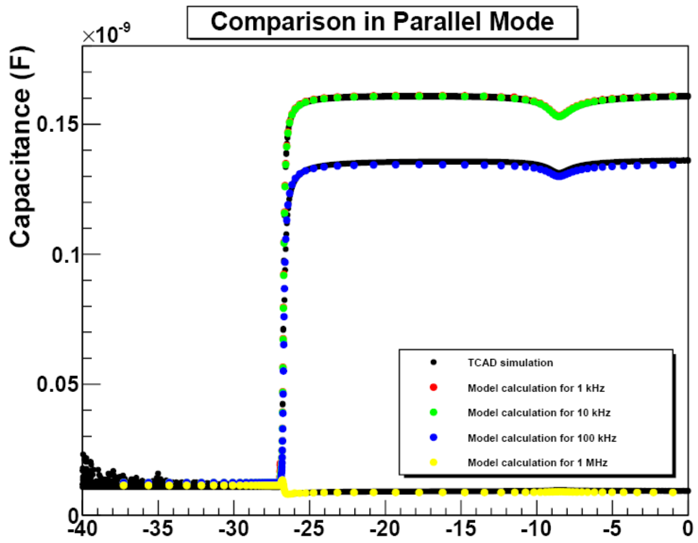
Comparison between model and TCAD simulation

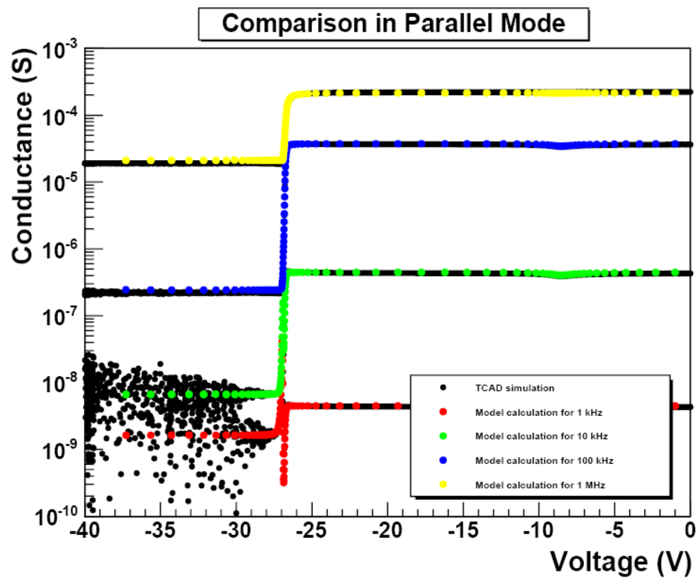
Ec-Eit= 0.35 eV, Nit=10^{12}cm^{-2}, acceptor-like trap





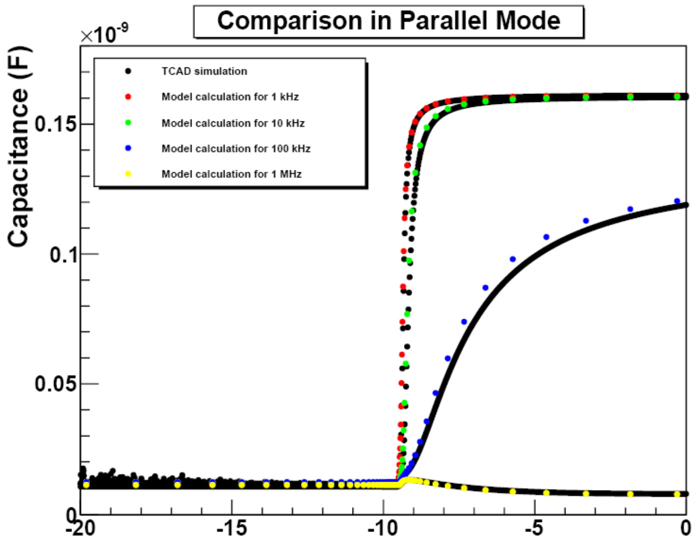
Ec-Eit= 0.35 eV, Nit=10^{12}cm^{-2}, donor-like trap

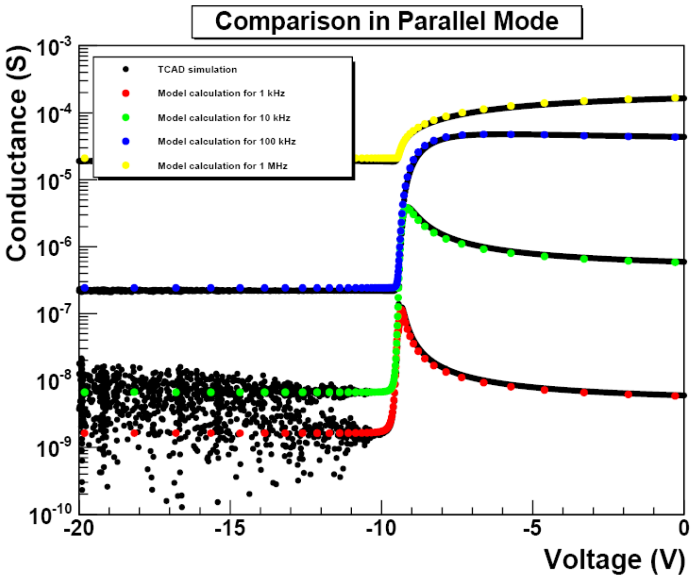




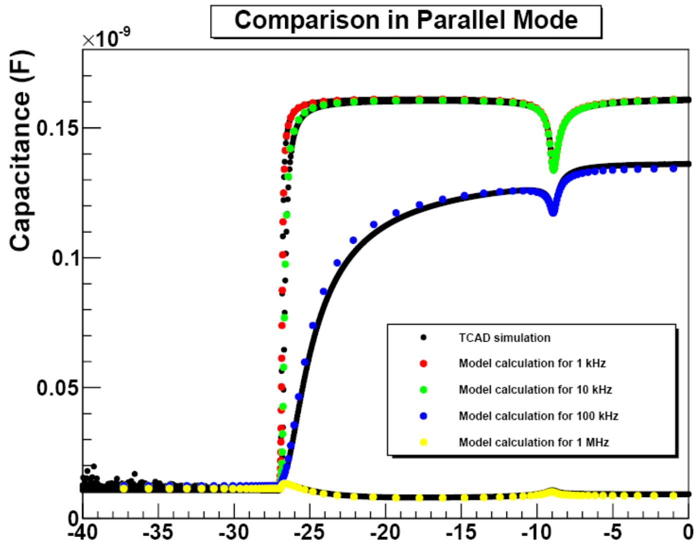
Comparison between model and TCAD simulation

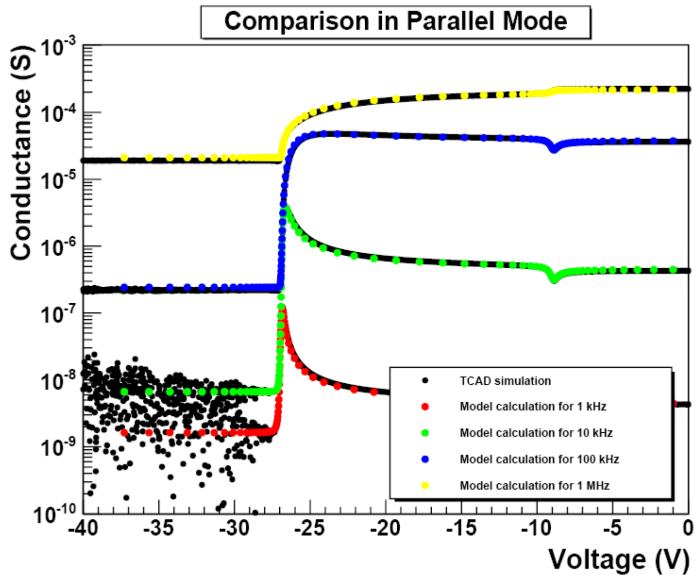
Ec-Eit= 0.45 eV, Nit=10^{12}cm^{-2}, acceptor-like trap





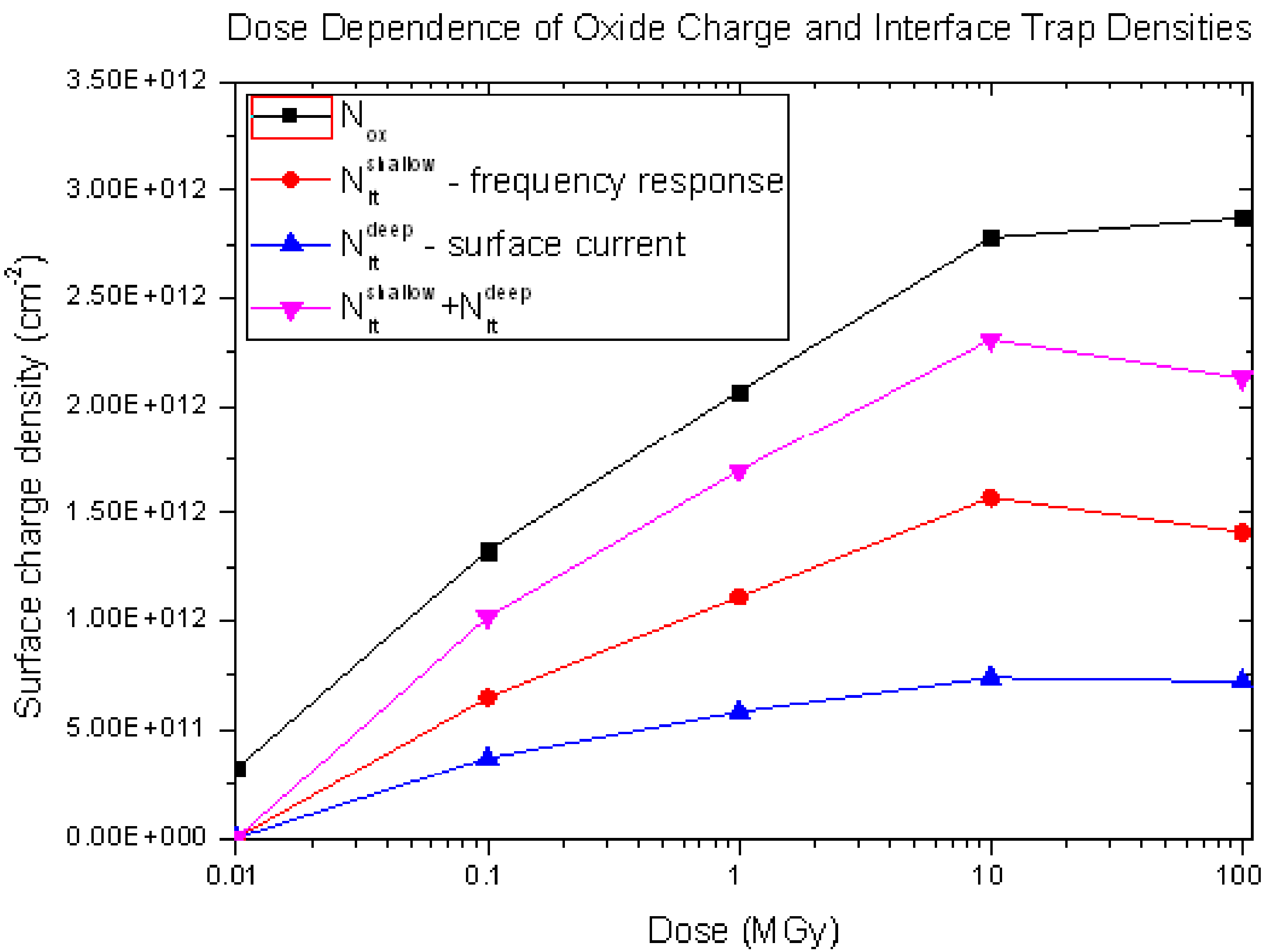
Ec-Eit= 0.45 eV, Nit=10^{12}cm^{-2}, donor-like trap





How to determine surface charges from experiments

Results of microscopic parameters:



Some typical values:

Oxide charge density:
$N_{ox}(sat) \sim 10^{12}\ cm^{-2}$

Interface trap density:
$N_{it}(sat) \sim 10^{12}\ cm^{-2}$

Surface current:
$I_{surface}(sat) \sim 10\ \mu A/cm^2$

Recombination velocity:
$S_o(sat) = I_{surface}/(q_0 * n_i)$
$\sim 7x10^3\ cm/s$

Surface charge densities saturate at 1 ~ 10 MGy

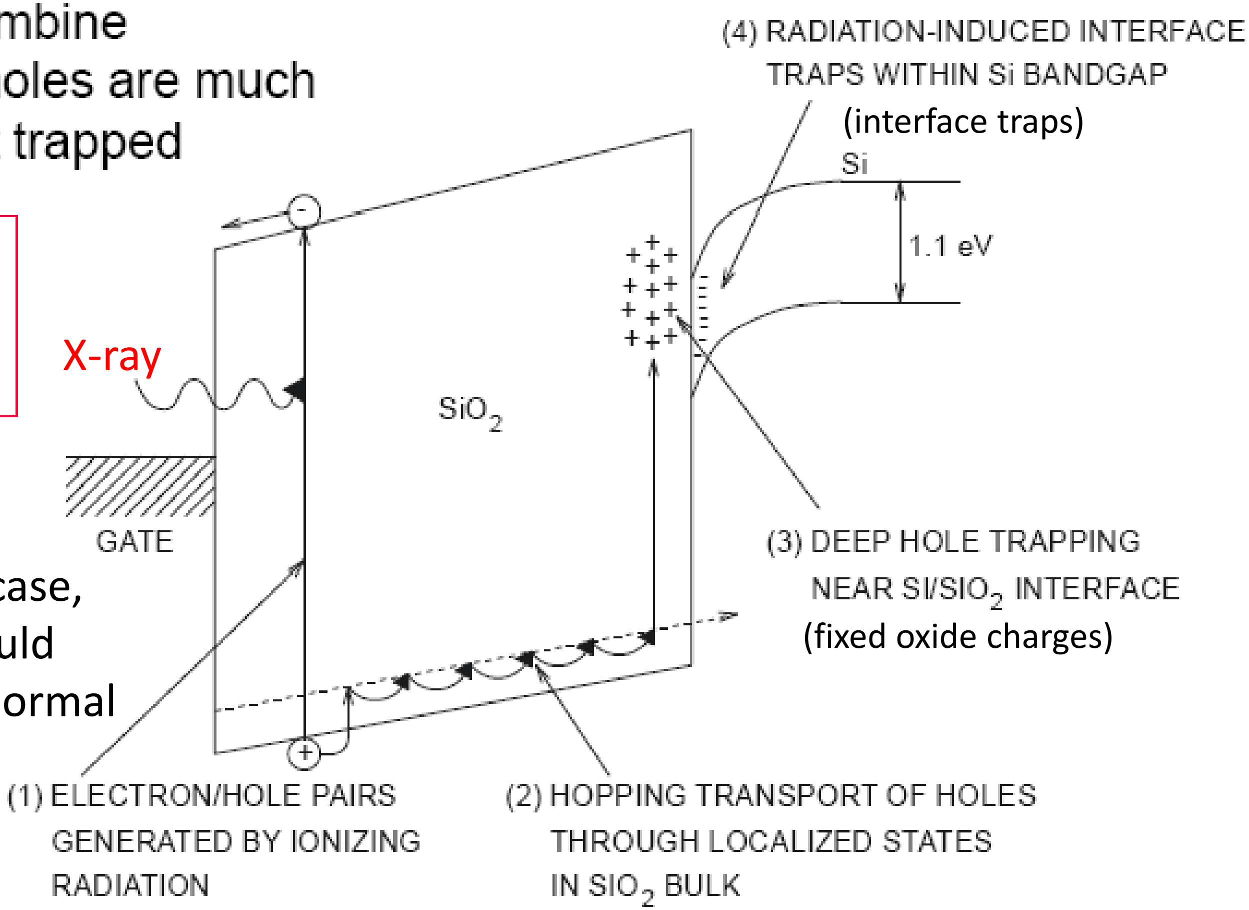
Charges built up

Basic mechanisms to form surface charges in an X-ray environment:

- Most e-h pairs recombine
- Electrons escape, holes are much slower and finally get trapped

SiO_2:
μ_n~20cm^2/(Vs),
μ_p~2x10^{-5} cm^2/(Vs)

- For high electric field case, oxide charge density could be 3 times larger than normal case.



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