Status Report on the Analysis of Radiation Damage for X-Rays in Silicon

E. Fretwurst[1], F. Januschek[1], R. Klanner[1],
H. Perrey[1], I. Pintilie[2], F. Renn[3], A. Srivastava[1]

[1] Institute for Experimental Physics, University of Hamburg
[2] National Institute of Materials Physics, Romania
[3] Summerstudent at DESY, University of Heidelberg

and lots of help from DESY:
H. Graafsma, A. Rothkirch, T. Wroblewski

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Overview

Overview

1. Introduction
2. Irradiation and Measurement Set-Up
3. Analysis of Radiation Damage in Gate-Controlled Diodes
4. Simulation of Gate-Controlled Diodes
5. Next Steps
6. Summary and Outlook

Specifications at the XFEL

- integrated photon fluxes up to $10^{12}\,\gamma/\,\mathrm{pixel} \mathrel{\hat{=}} 10^{9}\,\mathrm{Gy}\,[10^{9}\,\mathrm{J/kg}]$
- photon energies of $E_\gamma \approx 12\,\mathrm{keV}$

Possible effects on detectors and electronics

- no bulk damages: only to be expected at energies $E_\gamma \gtrsim 300\,\mathrm{keV}$
- charge build-up at the oxide and Si-SiO_2 interface:
  - $\Rightarrow$ shift of flatband voltage V_{fb}
  - $\Rightarrow$ high fields (danger of breakdown)
- damage at the interface causes dark current and leakage of storage capacitors

All detectors and electronics
will have to be tested for radiation hardness

Overview

1. Introduction

2. Irradiation and Measurement Set-Up
    - Irradiation Setup at DORIS
    - Measurement Setup in the Detector-Laboratory

3. Analysis of Radiation Damage in Gate-Controlled Diodes

4. Simulation of Gate-Controlled Diodes

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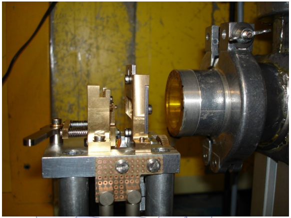
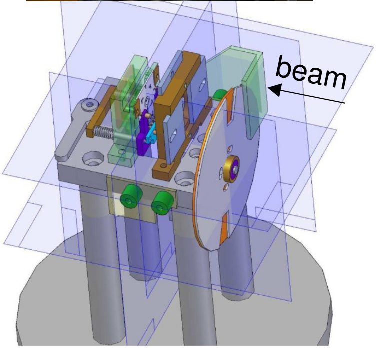
6. Summary and Outlook

Irradiation Setup in Beam F4 at DORIS





- Beam properties
  - typical energy: $10\,\mathrm{keV}$
  - spot-size: $2\,\mathrm{mm} \times 5\,\mathrm{mm}$
  - dose rate $0.5 - 150\,\mathrm{kGy/s}$ (in SiO_2)
- Installation properties
  - samples easily exchangeable
  - motor allows larger structures to be scanned with beam
  - watercooled to $20^\circ\,\mathrm{C}$
  - set-up movable to other locations

Current status

- DORIS is operational again
- setup at beamline is being returned to previous state

Measurement Setup in the Detector-Laboratory

- Samples are connected either
    - via probe station, or
    - via mobile box
- Measuring C/V and I/V curves together with sample temperature
- Mobile box is temperature controlled
- Measurements and data taking are PC-controlled

Overview

1. Introduction

2. Irradiation and Measurement Set-Up

3. Analysis of Radiation Damage in Gate-Controlled Diodes
    - Test Structures: Gate-Controlled Diodes
    - C/V and I/V Measurements
    - Extracting Interface Properties

4. Simulation of Gate-Controlled Diodes

5. Next Steps

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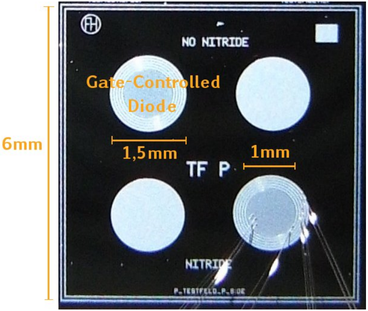
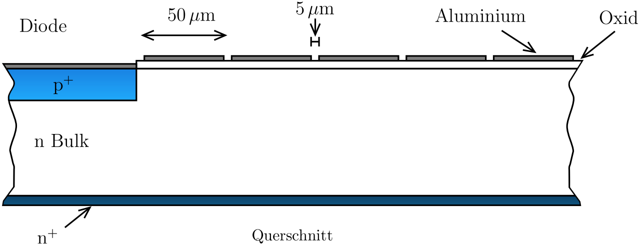
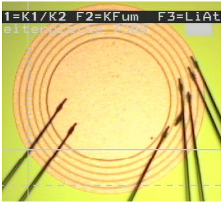
Test Structures: *Gate-Controlled Diodes*



Properties

- 5 aluminium gate rings
- 280 μm thick
- high resistivity ($\rho \approx 3.4\,\text{k}\Omega\text{cm}$)
- 380 nm isolation layer (consisting of SiO_2 + Si_3N_4) between gates and n-bulk





C/V and I/V Measurements

Parameter extraction

from C/V and G/V measurement
of MOS-capacitance (2nd & 3rd ring)

⇒ N_{ox} $[\mathrm{cm}^{-2}]$
oxide charge density

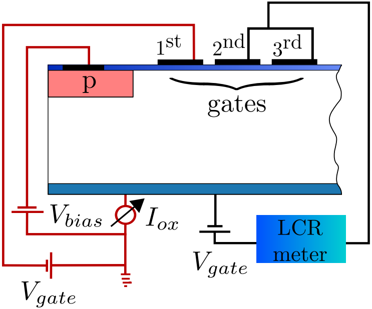
⇒ D_{it} $[\mathrm{cm}^{-2}\mathrm{eV}^{-1}]$
density of interface states in band gap

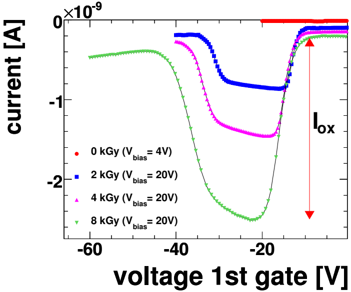
⇒ $V_{fb}(N_{ox}, D_{it})$ [V]
flat band voltage

from I/V measurement of gated diode
(diode & 1st ring)

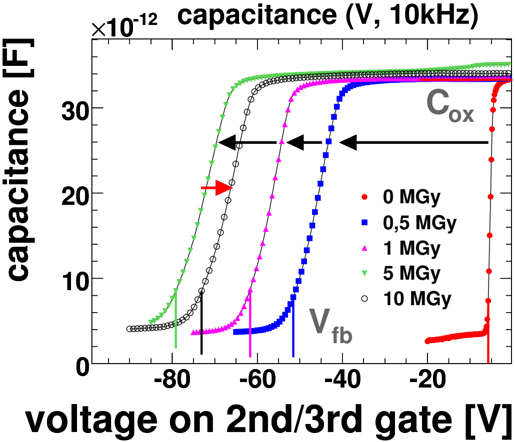
⇒ V_{fb} [V]
flat band voltage

⇒ I_{ox} [A]
surface current





Results: Dose Dependence of MOS-Capacitance

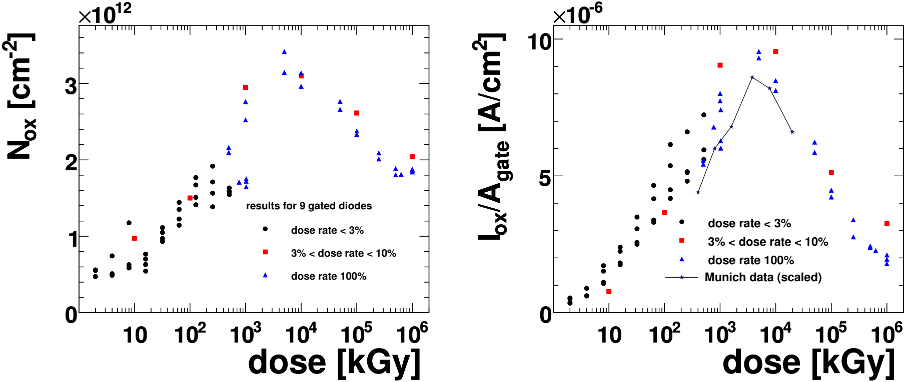


Capacitance as function of voltage on 2nd and 3rd gate ring

- C/V curve shown for four irradiation steps
- Lines mark C_{ox} (horizontal) and V_{fb} (vertical)

- Flatband voltage V_{fb} is shifted with dose
- Calculate N_{ox} from V_{fb}

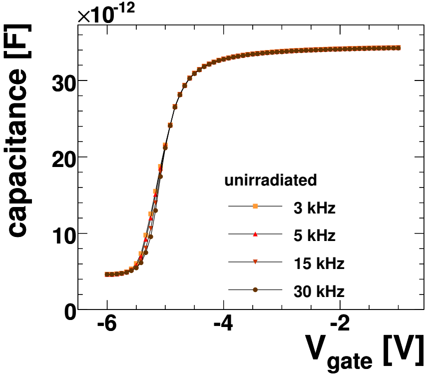
Results: Dose Dependence of N_{ox} and I_{ox}

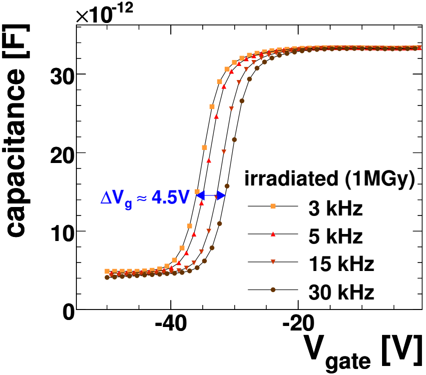


Oxide charge density N_{ox} and surface current per gate area I_{ox}/A_{Gate}

- shown are the results for nine diodes as function of dose
- both N_{ox} and I_{ox}/A_{Gate} reach a maximum at $\approx 5\,\mathrm{MGy}$
- maximum is seen regardless of dose rate ($100\% \mathrel{\widehat{=}} 150\,\mathrm{kGy/s}$)
- decrease not caused by temperature induced annealing

Capacitance Measurements and Interface Traps

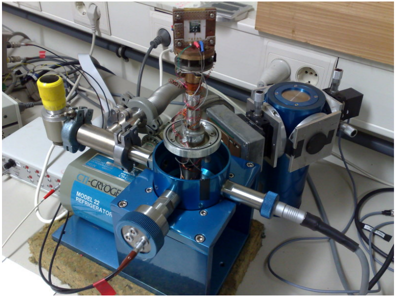


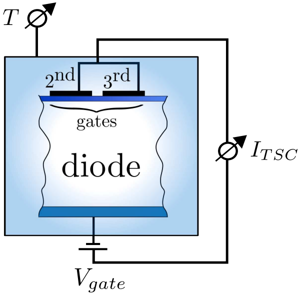


- Irradiated diodes show strong frequency dependence
  - caused by presence of interface states N_{it}
- Shift of curves to higher gate voltages is caused by both
  - charges in the oxide (N_{ox}) and
  - charges at the interface (N_{it})

⇒ N_{it} strongly effects V_{fb}!

Measuring Position of Interface Traps in Band Gap



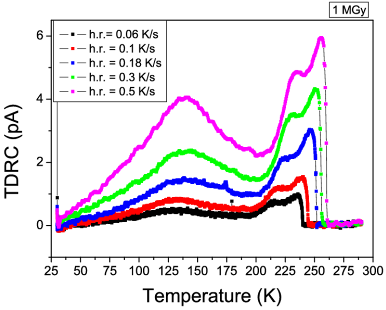


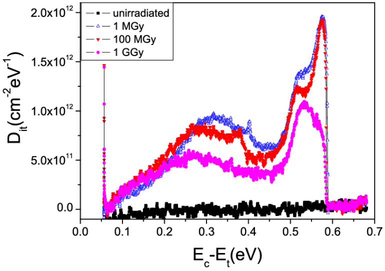
Receipe for measuring the Thermally Stimulated Current (TSC)

1. Cool down with MOS biased in accumulation
2. At 30° K switch bias to depletion
    - stored charge is frozen
3. Heat sample up with constant heating rate in depletion
    - Fermi level scans band gap
    - charges are emitted
    - measure current and temperature

Extract density of interface states D_{it} (from current) and capture cross section σ (from dependence on heating rate)

First Results From TSC Measurements





Measured TSC signal (*top*)

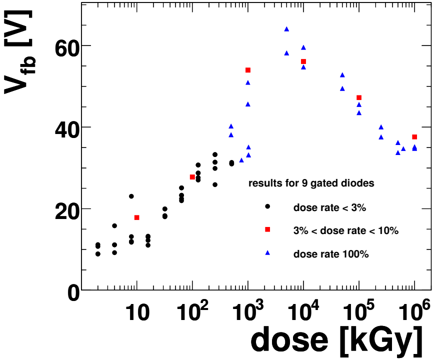
- Shown is current versus temperature
- for an irradiated 1 MGy diode
- and for different heating rates

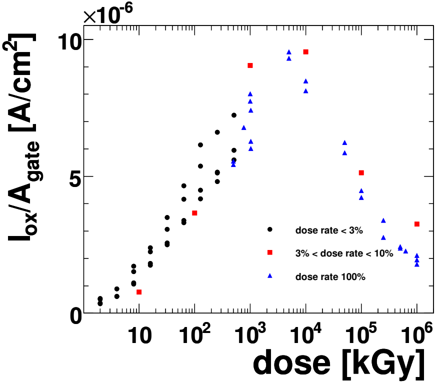
Extracted D_{it} (*bottom*)

D_{it} versus band gap energy
for different diodes at different doses

- very deep levels
- no signal for unirradiated diode
- highest D_{it} for 1 MGy, decrease of D_{it} with higher doses
- result of 2nd-order processes leading to electrically inactive defects?

Summary of Experimental Results





$N_{ox} \rightarrow V_{fb}$

$D_{it} \rightarrow V_{fb}, I_{ox}, I_{TCT}$

$\Rightarrow$ qualitative: decrease of V_{fb} due to D_{it}

Overview

Simulation (I)

Aim

Detailed simulation of sensor including radiation damage effects

Software

Device simulation through IC-TCAD DESSIS
(*2D Device Simulation for Smart Integrated Systems*)

Physics models used

- SRH recombination
- Auger recombination
- impact ionization
- surface recombination
- gate current (Lucky) model
- trap models
    - solving Poisson and electron/hole current-continuity equations
    - dependence of τ on N_{it} taken into account through τ_{eff}

Simulation (II)

Procedure

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

Input Parameters

MOS capacitor ($50 \times 300\,\mu$m)

$w_{gate} = 50\,\mu\mathrm{m}$, $t_{ox} = 0.405\,\mu\mathrm{m}$

Si n-type substrate

$N_{dop} = 1.28 \cdot 10^{12}\,\mathrm{cm}^{-3}$

$\phi_{ms} = -0.69\,\mathrm{V}$

$N_{ox} = 2.66 \cdot 10^{11}\,\mathrm{cm}^{-2}$

$N_{it,mg} = 2.1 \cdot 10^{10}\,\mathrm{cm}^{-2}$, $E_t = 0\,\mathrm{eV}$

$\tau_{eff} = 130\,\mu\mathrm{s}$

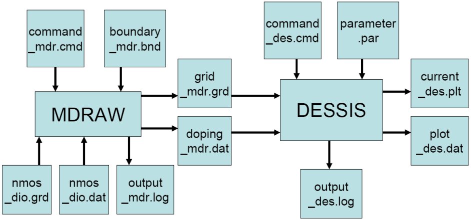
$\sigma_{eff} = 7 \cdot 10^{-17}\,\mathrm{cm}^{-2}$

$v_{(n/p)} = 2 \cdot 10^{7}\,\mathrm{cm/s}$

$S_0 = 2.4\,\mathrm{cm/s}$

$T_{lattice} = 300\,\mathrm{K}$

$f = 10\,\mathrm{khz}$, $V_{AC} = 0.1\,\mathrm{V}$



command _mdr.cmd

boundary _mdr.bnd

MDRAW

nmos _dio.grd

nmos _dio.dat

output _mdr.log

grid _mdr.grd

doping _mdr.dat

command _des.cmd

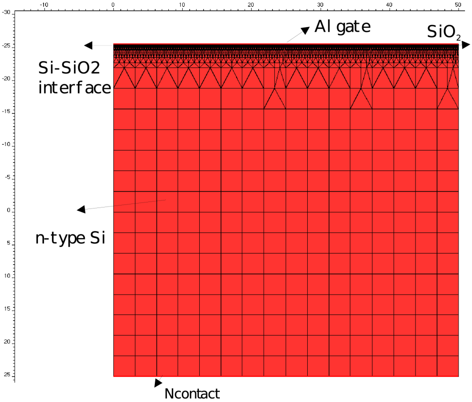
parameter .par

DESSIS

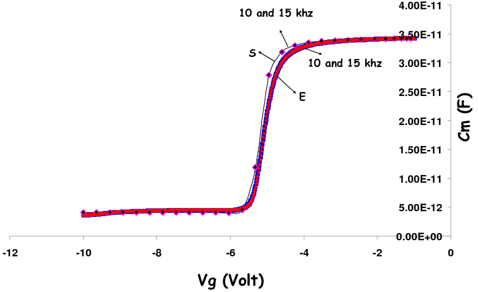
current _des.plt

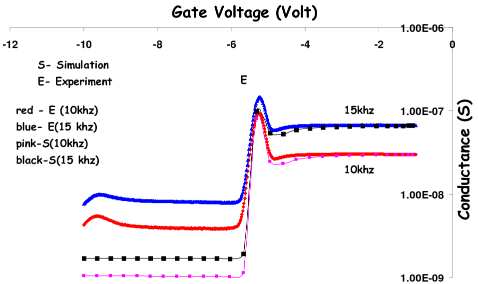
plot _des.dat

output _des.log



Simulation (III): First Results for G/V-Measurements





Comparison of data and simulation

for an unirradiated diode: frequency dependence of C/V (*top*) and G/V (*bottom*) measurements for two frequencies (10 kHz and 15 kHz) after optimization of parameters (D_{it}, E_t, N_{ox}, type of traps,..)

simulation of irradiated diodes

- implemented
- under studies

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Next Steps (I)

Irradiation/Measurement Setup

- DORIS beam is back so we need to
  - return setup to state before DORIS shutdown
  - reestablish beam properties
  - perform dose calibration
- new substrate with 16 pins
- connections for in-situ biasing and measurement
- optical table for easier changes of irradiation setup
- setup measurement stand at beamline
- improve temperature stabilization

Next Steps (II)

Analysis of present diodes

- for TSC measurements
  - extract D_{it} from more (irradiated) diodes
- for CMOS measurements
  - improve understanding and modeling of curves to verify results
  - study annealing effects

  ⇒ phenomenological model to describe
  D_{it} and V_{fb} dependency on dose and annealing
- for I_{ox} measurements
  - understand if structures are suitable
- compare data with measurements of other groups

New data and measurements

- analyze new structures (CMS TS – rectangular comb structures)
- irradiate new diodes and detectors at DORIS
- irradiation for other users

Next Steps (III)

Simulation

1. further adjust parameters to experimental C/V and G/V measurements
2. proceed with simulation of irradiated diodes
3. simulate pixel detector with/without radiation damage and compare to I/V and C/V measurements

Overview

Summary and Outlook

Summary

- D_{it} has been extracted from unirradiated and irradiated diodes
- After steep rise D_{it} drops with dose
- D_{it} effects measured V_{fb}

Outlook

- Analysis
  - compare with theoretical prediction and simulation
  - verify observed behaviour of D_{it} in other diodes
  - subtract effects of D_{it} on V_{fb} to extract N_{ox}
- Measurements
  - new irradiations possible soon
  - study annealing effects

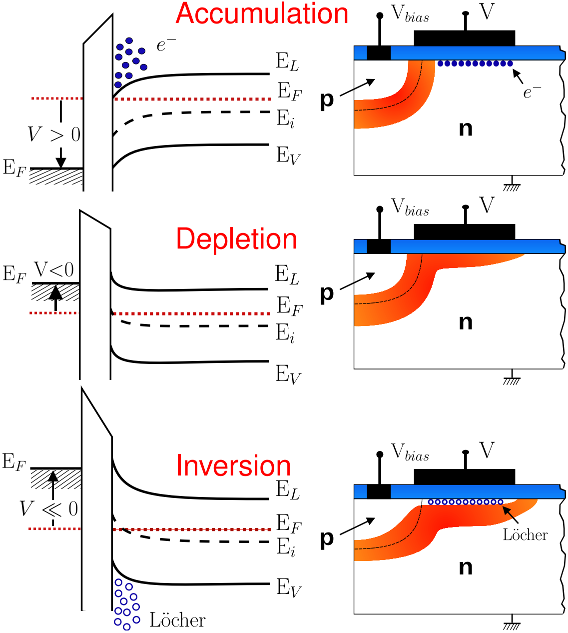
  ⇒ phenomenological model to describe
  D_{it} and V_{fb} dependency on dose and annealing

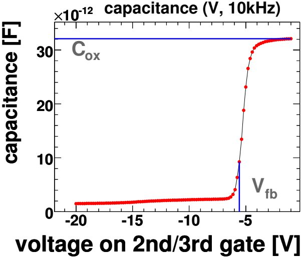
Overview

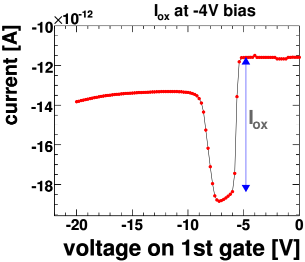
7 Backup

- Current- and Capacitance-Characteristics of MOS-Diodes
- Dose Dependence of Surface Current
- Conductance Method and First Results
- Conductance Method: Parallel Conductance G_p
- Conductance vs. Dose
- Capacitance and Conductance Corrected for R_{bulk}
- Temperature During Irradiation
- Detailed Simulation Parameters
- (Very) First Results From Model

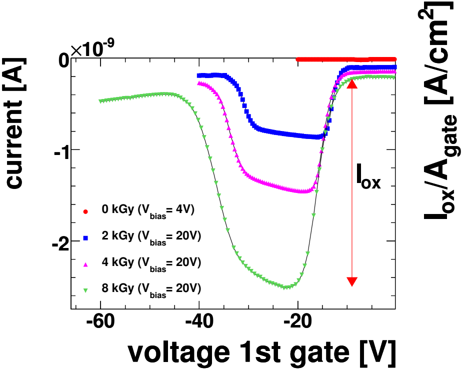
Current- and Capacitance-Characteristics







Results: Dose Dependence of Surface Current I_{ox}



Surface current density as function of dose

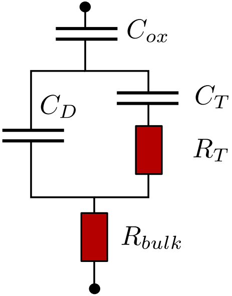
- shown are the results for nine diodes
- increase of I_{ox}/A_{Gate} by more than two orders of magnitude
- maximum of 10 $\mu\mathrm{A}/\mathrm{cm}^2$ (at $\approx 5\,\mathrm{MGy}$)
- maximum seen regardless of dose rate ($100\% \mathrel{\widehat{=}} 150\,\mathrm{kGy}/\mathrm{s}$)
- decrease probably not caused by temperature induced annealing

Conductance Method

Model through equivalent circuit

in depletion → minority carriers can be neglected

C_D	semiconductor depletion-layer capacitance
C_{ox}	oxide capacitance
R_{bulk}	resitance of *n*-bulk
R_T	energy loss through capture and emission from interface traps
C_T	charge storage in interface traps
τ	interface trap lifetime ($\tau = R_T \cdot C_T$)



Recipe for extracting D_{it}

1. correct measured G for C_{ox} and R_{bulk} → parallel conductance G_p
2. plot G_p/ω as function of frequency for a specific bias
3. function's peak position, height, and width give τ and D_{it}

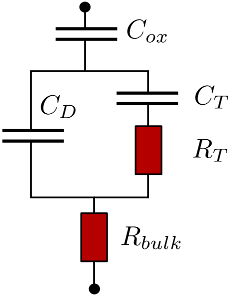
Conductance Method: Parallel Conductance G_p

Significance of G_p

From model follows:

$$\frac{G_p}{\omega} = \frac{C_T \omega \tau}{1 + \omega^2 \tau^2}, \qquad \text{with } \tau = R_T C_T$$

$\Rightarrow$ G_p is associated with response of traps to small ac voltage

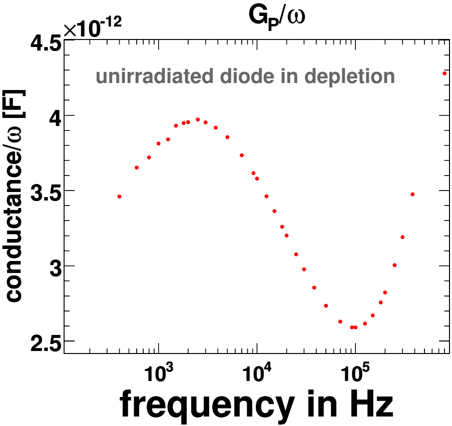


Band-bending fluctuations

Random distribution of charged traps (→ point charges) along the Si-SiO$_2$ interface

- gaussian distribution of surface potentials
- introduces dispersion term σ_s
- causes dispersion of τ (the trap time constant)

Conductance Method: First Results



G_p/ω for unirradiated diode in depletion

Now measure ..

D_{it} from peak conductance

τ from frequency of conductance peak

σ_s from spread in conductance curve

(repeat for different biases)

Results for this diode

$f_p \approx 3{\cdot}10^3\,\mathrm{Hz}$

$\sigma_s \approx 2.1\,\frac{\mathrm{k_B T}}{\mathrm{q}}$

$D_{it} \approx 2.94 \cdot 10^{10}\,\mathrm{eV^{-1}cm^{-2}}$

$\tau \approx 128\,\mu\mathrm{s}$

Difficulty:

- high bulk resistivity

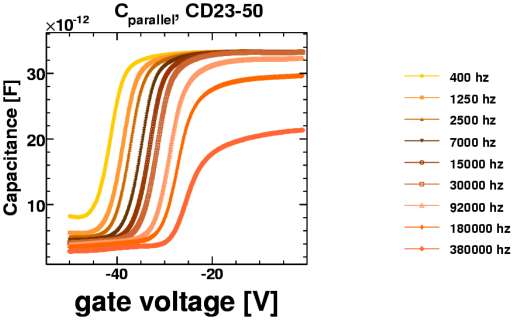
Extending Analysis to Irradiated Diodes (I)

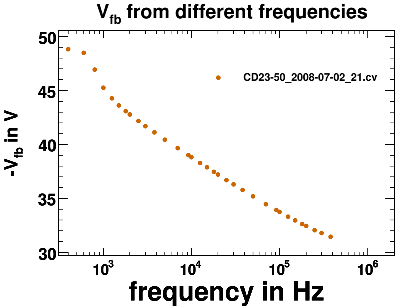
Irradiated diode (1 MGy)

Shown are capacitance curves for different frequencies *f* and the flat band voltage V_{fb} as determined from these measurements

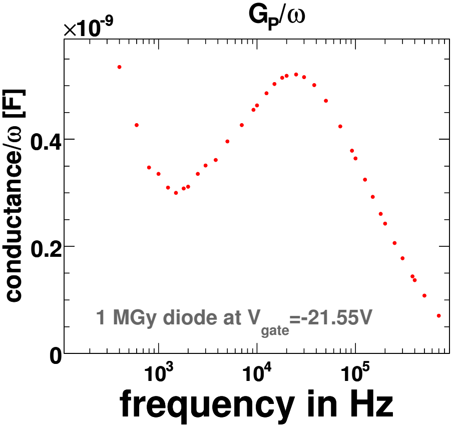
Curves shift with *f*

- freq. independed shift due to N_{ox}
- freq. dependend shift due to interface states
- interface charges modify surface potential





Extending Analysis to Irradiated Diodes (II)



G_p/ω for irradiated diode at 1 MGy, V_{gate} of $-21.55\,\mathrm{V}$

$D_{it} \approx 2.12\cdot10^{12}\,\mathrm{eV^{-1}cm^{-2}}$

$\tau \approx 4.2\,\mu\mathrm{s}$

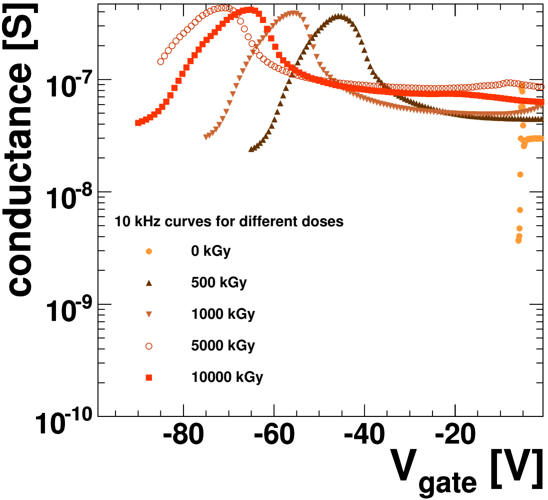
$\sigma_s \approx 0.65\,\frac{\mathrm{k_B T}}{\mathrm{q}}$

Increase of D_{it} by two orders of magnitude!

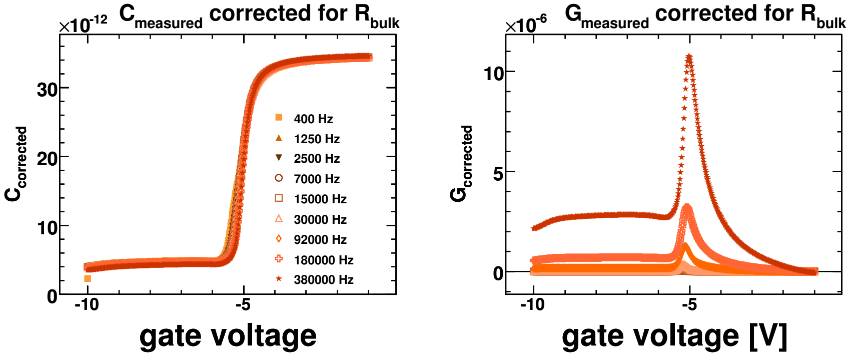
How to proceed

- Model shift in gate voltage due to interface charges
- Measure D_{it} for different gate voltages and extract position in band gap from model

Conductance vs. Dose



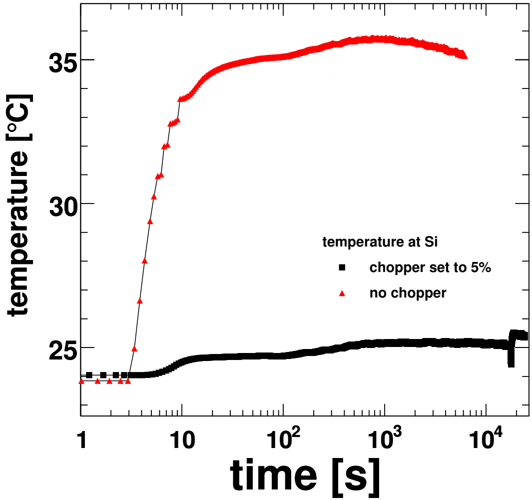
Capacitance and Conductance corrected for R_{bulk}



$$C_c = \frac{(G_m^2 + \omega^2 C_m) C_m}{a^2 + \omega^2 C_m^2} \qquad \text{and} \qquad G_c = \frac{(G_m^2 + \omega^2 C_m) a}{a^2 + \omega^2 C_m^2},$$

$$\text{with } a = G_m - (G_m^2 + \omega^2 C_m^2) R_{bulk}$$

Temperature During Irradiation

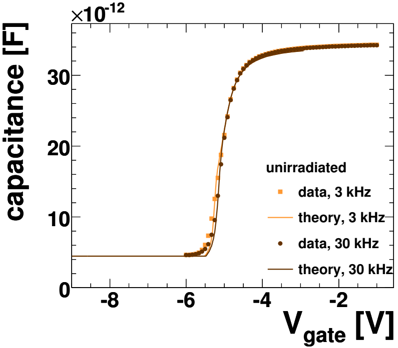


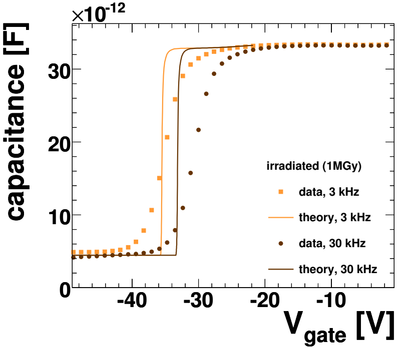
Simulation: Procedure and Parameters

Input Parameters (as of June 2008)

- MOS capacitor ($50 \times 50\,\mu\mathrm{m}$, gate width $= 50\,\mu\mathrm{m}$)
- n-type Si substrate ($Ndop = 1.28 \cdot 10^{12}\,\mathrm{cm}^{-3}$)
- $t_{ox} = 0.405\,\mu\mathrm{m}$
- $\phi_{ms} = -0.69\,\mathrm{V}$
- $N_{ox} = 2.66 \cdot 10^{11}\,\mathrm{cm}^{-2}$ – oxide charge density
- $N_{it,mg} = 10^{11}\,\mathrm{cm}^{-2}$ – interface state density (one donor level at mid-gap)
- $\tau_{eff} = 0.01\,\mathrm{ms}$
- $\sigma_{eff} = 2.5 \cdot 10^{-16}\,\mathrm{cm}^{-2}$ – eff. capture cross-section
- $v(n/p) = 2 \cdot 10^{7}\,\mathrm{cm/s}$
- $E_t = 0\,\mathrm{eV}$ – trap energy level
- $S_0 = 2.4\,\mathrm{cm/s}$ – surface recombination velocity
- $T_{lattice} = 300\,\mathrm{K}$
- $f = 10\,\mathrm{khz}$, $V_{AC} = 0.1\,\mathrm{V}$

(Very) First Results From Model





Comparison of data with model for homogeneous D_{it} distribution

unirradiated (left):

- $D_{it} = 2 \cdot 10^{10}\,\mathrm{cm}^{-2}\mathrm{eV}^{-1}$ (from conductance method)
- shift due to N_{ox}: $-4.9\,\mathrm{V}$
- good agreement with data

irradiated with $1\,\mathrm{MGy}$ (right):

- $D_{it} = 2 \cdot 10^{12}\,\mathrm{cm}^{-2}\mathrm{eV}^{-1}$
- shift due to N_{ox}: $-17\,\mathrm{V}$
  $\Rightarrow$ less than expected from V_{fb}!
- spread-out of data not described!
- improvement with distribution of D_{it}?