CHARACTERIZATION AND X-RAY IRRADIATION OF DEPLETED P-CHANNEL FET (DEPFET) TEST STRUCTURES

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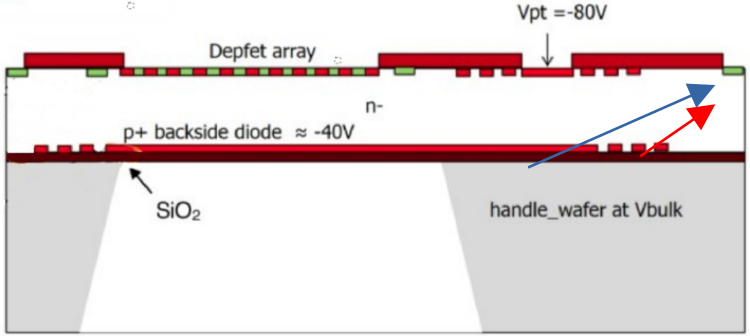
MOTIVATION

- DEPFET-wafers are made of handle wafer + sensor wafer
  - Wafers are bonded by two companies: IceMOS technology and Shin-Etsu Co.
- With high TID increased current at the backside of the DEPFET-modules
  - Currents are outside the sensitive area
- 2 possible reasons for the backside currents:
  - Radiation hardness of the burried SiO_2
  - State of the guard-rings



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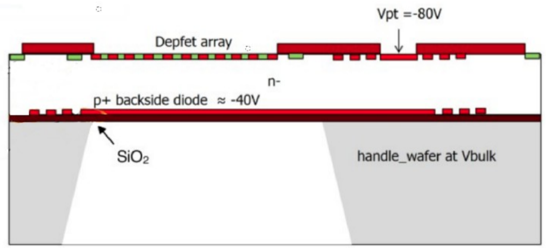
MOTIVATION

- Higher Backside currents in IceMOS- compared to Shin-Etsu-modules in PXD
- Why do we need MOSFET-structures?
  - Changing the voltage at the handle wafer
  - Simplification of the structure
- IV-Gate measurements → testing radiation hardness of the buried oxide and at the interface
- Gated diode IV → testing state of the guard-rings



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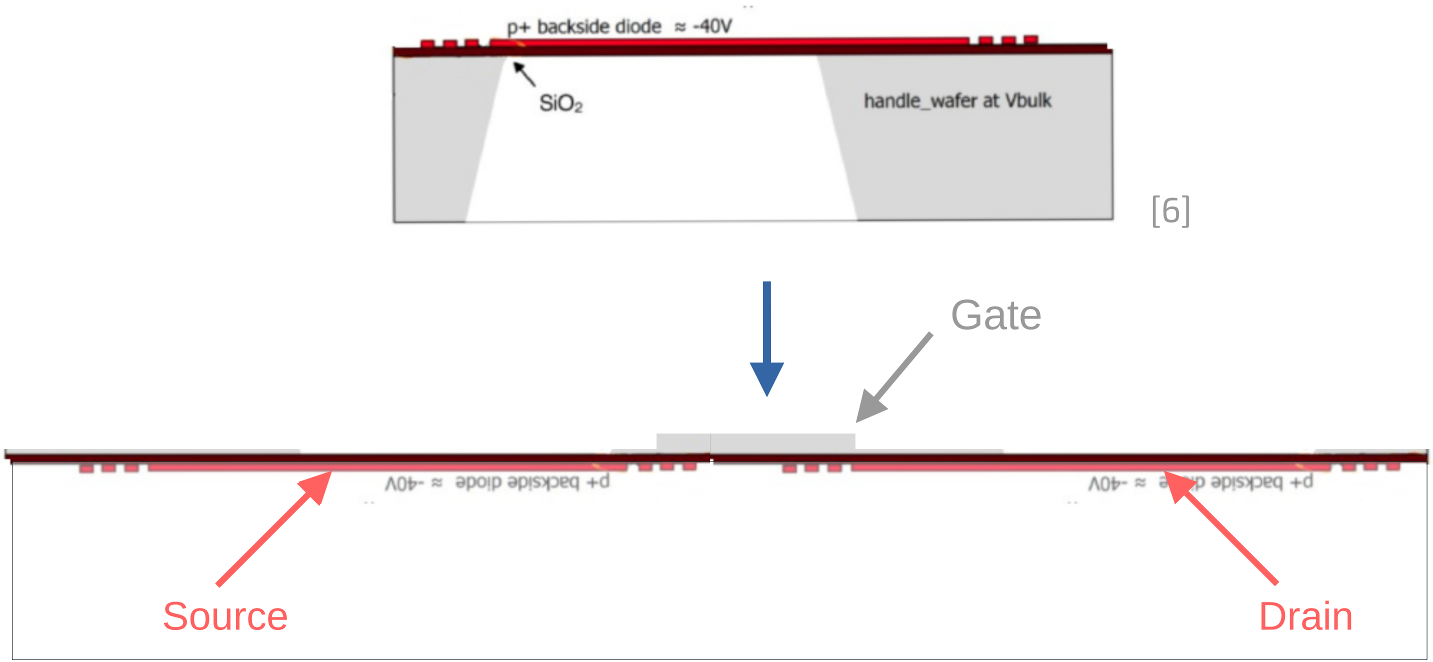
MOSFET STRUCTURE



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MOSFET-DUT

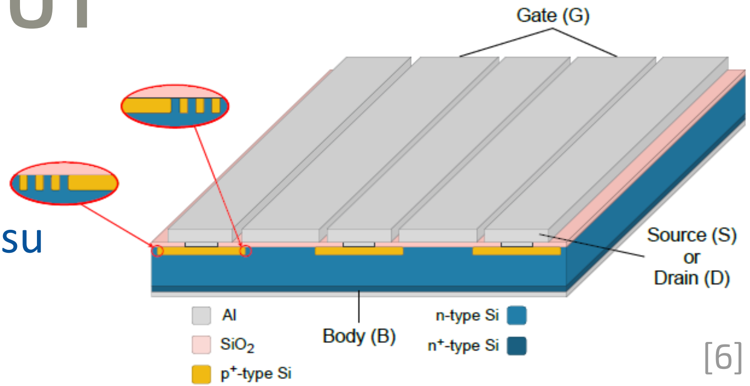
- Oxide layer on the sensor wafer is grown by HLL
- Handle wafer is bonded to sensor wafer by ShinEtsu Chemical Co. and IceMOS Technology
- Oxide thickness:

$$d_{\mathrm{Sh,Ox}} = (350.0 \pm 17.5)\,\mathrm{nm}$$

$$d_{\mathrm{Ice,Ox}} = (560 \pm 28)\,\mathrm{nm}$$

- Channel length:

$$Z = (2.0770 \pm 0.0012)\,\mathrm{mm}$$



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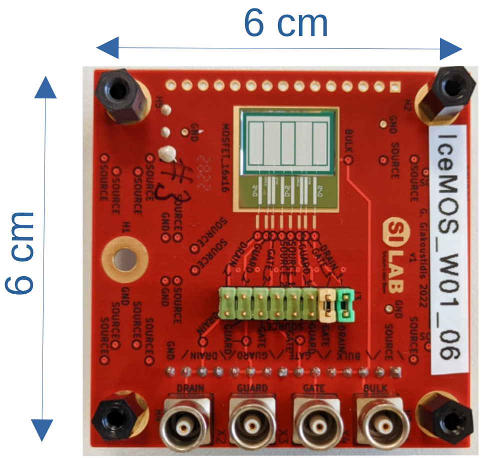
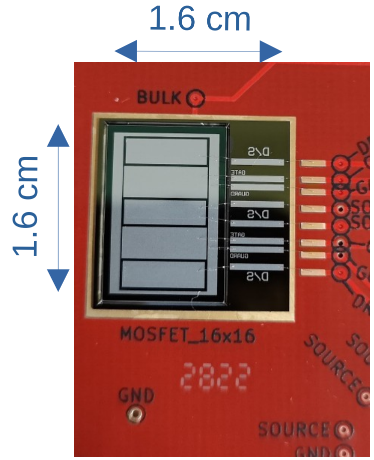
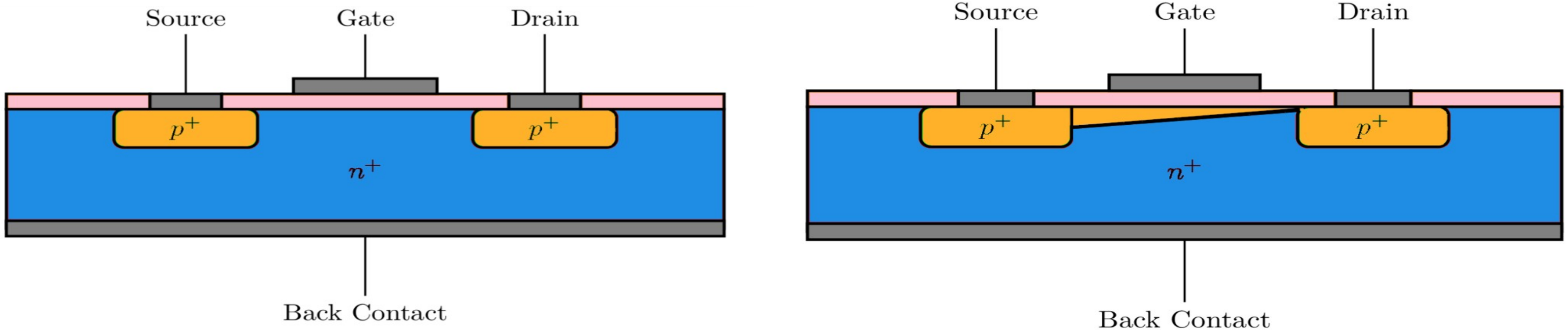




Theory and Context

MOSFET



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- The enhancement mode p-channel MOSFET is operated by applying a negative Gate voltage and a Voltage between Source and Drain
- Electrons are pushed away from the interface, while holes can accumulate

  → conductive channel
- By applying a higher drain voltage the channel is getting deformed up to a pinch-off point, where the drain current saturates

MOSFET

- Regions are seperated via the Pinch-off point at $V_{DS}=V_G-V_{th}$
- Saturation region at $V_D<V_G-V_{th}$ and Linear/Ohmic region at $V_D>>V_G-V_D$

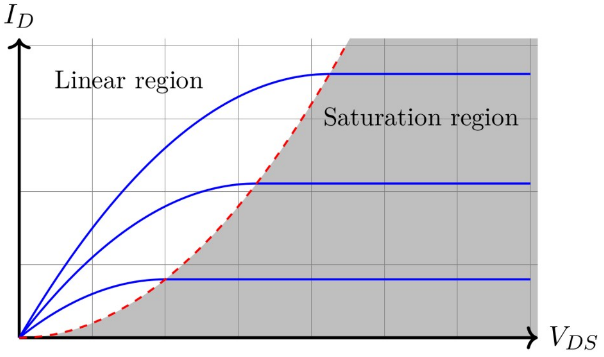
$$I_D = \frac{Z}{L}\mu_p C_{ox}\left(V_G - V_{th} - \frac{V_D}{2}\right)V_D$$ [3]

$$\mu_{eff} \simeq g_D L / Z C_{Ox}(V_G - V_T)$$ [4]

- In IV-Gate measurement the field mobility is calculated using the the transconductance

$$g_m = \frac{\partial I_D}{\partial V_g}, \qquad \mu_{FE} = g_m \frac{L}{Z C_{Ox} V_D}$$ [4]

- Threshold and mobility are effected by radiation damage



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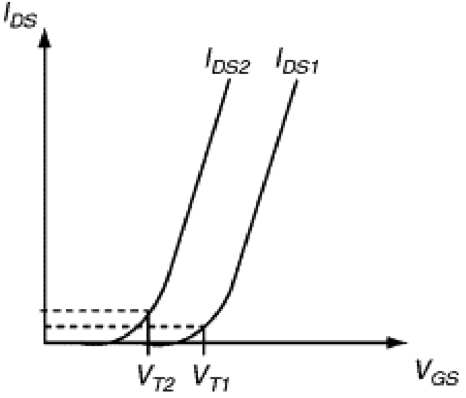

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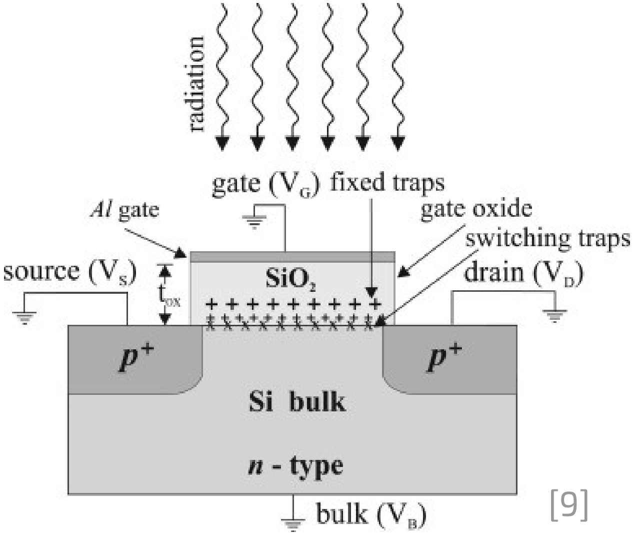
RADIATION DAMAGE

- Damage is categorized into NIEL(Non-Ionizing Energy Loss) damage and ionization damage
- NIEL damage negligible in Belle II PXD → focus on ionization damage (from X-rays)
- Ionization damage in MOSFETs → oxide and interface traps
    - Threshold shift $\Delta V_{\mathrm{th}}(\mathrm{D}) = V_{\mathrm{th}}(\mathrm{D}) - V_{\mathrm{th}}(\mathrm{D} = 0\,\mathrm{Gy}) = \Delta V_{\mathrm{it}} + \Delta V_{\mathrm{ot}}$
    - Mobility degradation



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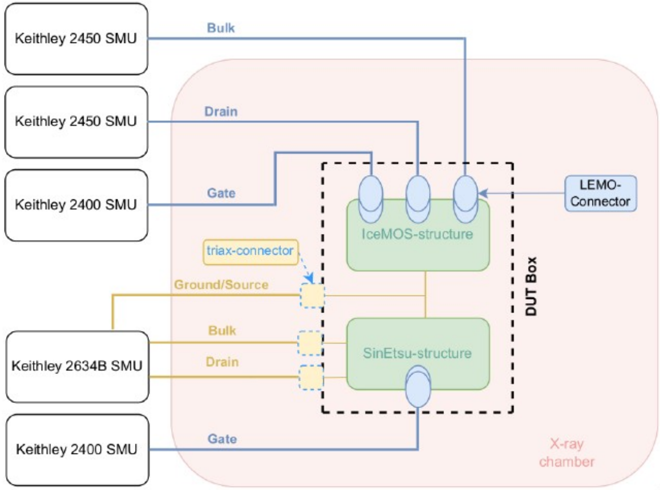
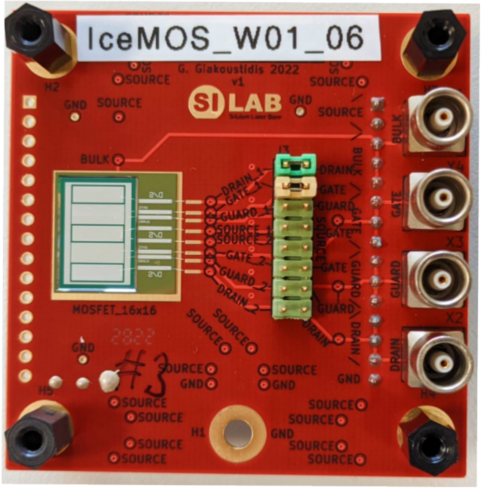
$$D = \frac{E}{m}\,; \qquad 1\,\mathrm{Gy} = 1\,\frac{\mathrm{J}}{\mathrm{kg}}$$

Measurement Setup

SETUP


Keithley 2450 SMU
Keithley 2450 SMU
Keithley 2400 SMU
Keithley 2634B SMU
Keithley 2400 SMU
Bulk
Drain
Gate
triax-connector
Ground/Source
Bulk
Drain
Gate
IceMOS-structure
SinEtsu-structure
DUT Box
LEMO-Connector
X-ray chamber


KEITHLEY 2634B SYSTEM SourceMeter
-000.34uA +000.71uA
SrcA:+000.000mV
CHANNEL A
CHANNEL B
SRC
MEAS
LIMIT
MODE
POWER
RANGE
OUTPUT
ON/OFF
CHAN A
CHAN B

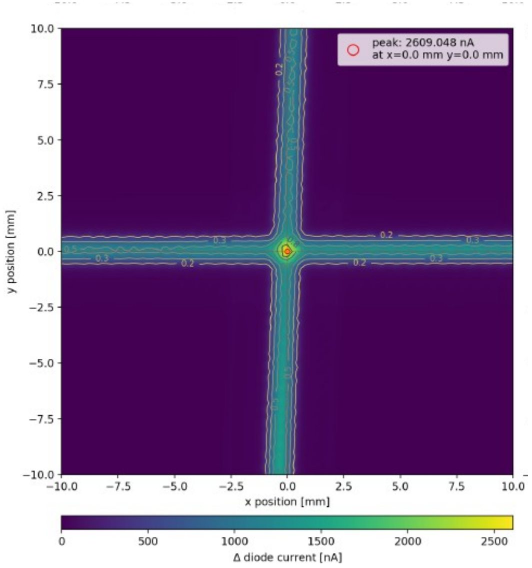

IceMOS_W01_06
G. Giakoustidis 2022
SI LAB
MOSFET_16x16
BULK
GATE
GUARD
DRAIN
SOURCE
GND
#3

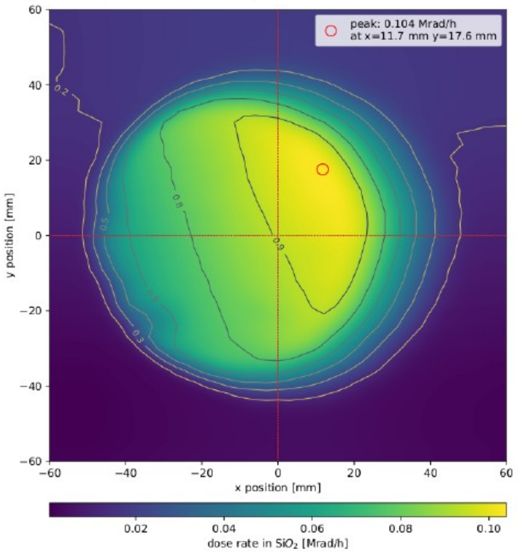
Measurement Procedure

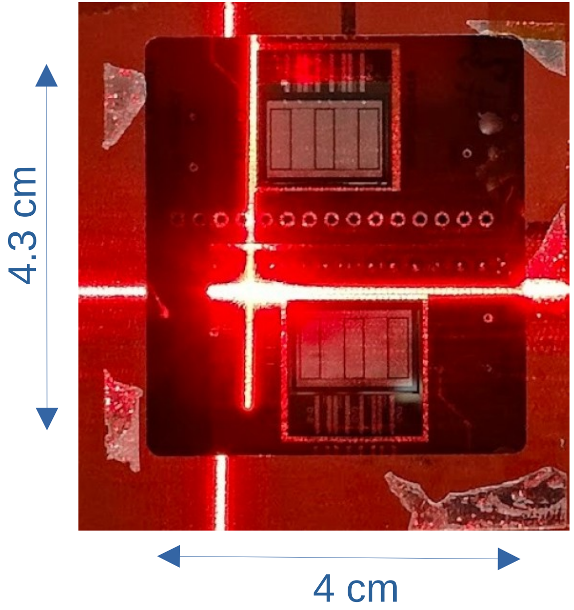
X-RAY TUBE CALIBRATION

- Two step calibration for the X-ray chamber with a diode mounted to the motor stage
  - 1. Step: Measure the alignment laser accuracy in order to account for possible shifts in the alignment
  - 2.Step: Measure the beam profile to determine the TID and the positioning in the 90% intensity area

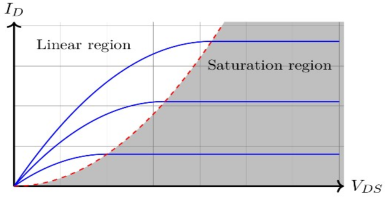
X-RAY TUBE CALIBRATION

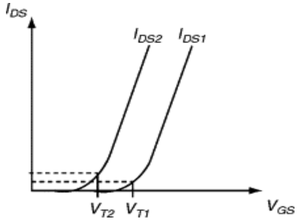






MEASUREMENT





- For each of the 18 irradiation steps 5 measurements were conducted
- Irradiation was done with a biasing of $V_G = 40V$
- The TID reached was approximatley 106 kGy
- Main measurements:
    - 1. Gated diode measurement

      -Study the state of the guard-rings
    - 2. IV-Gate measurement

      - Determining the threshold voltage V_{th} and enabling mobility analysis via the field effect mobility μ_{FE}
    - 3.IV-Drain measurement:

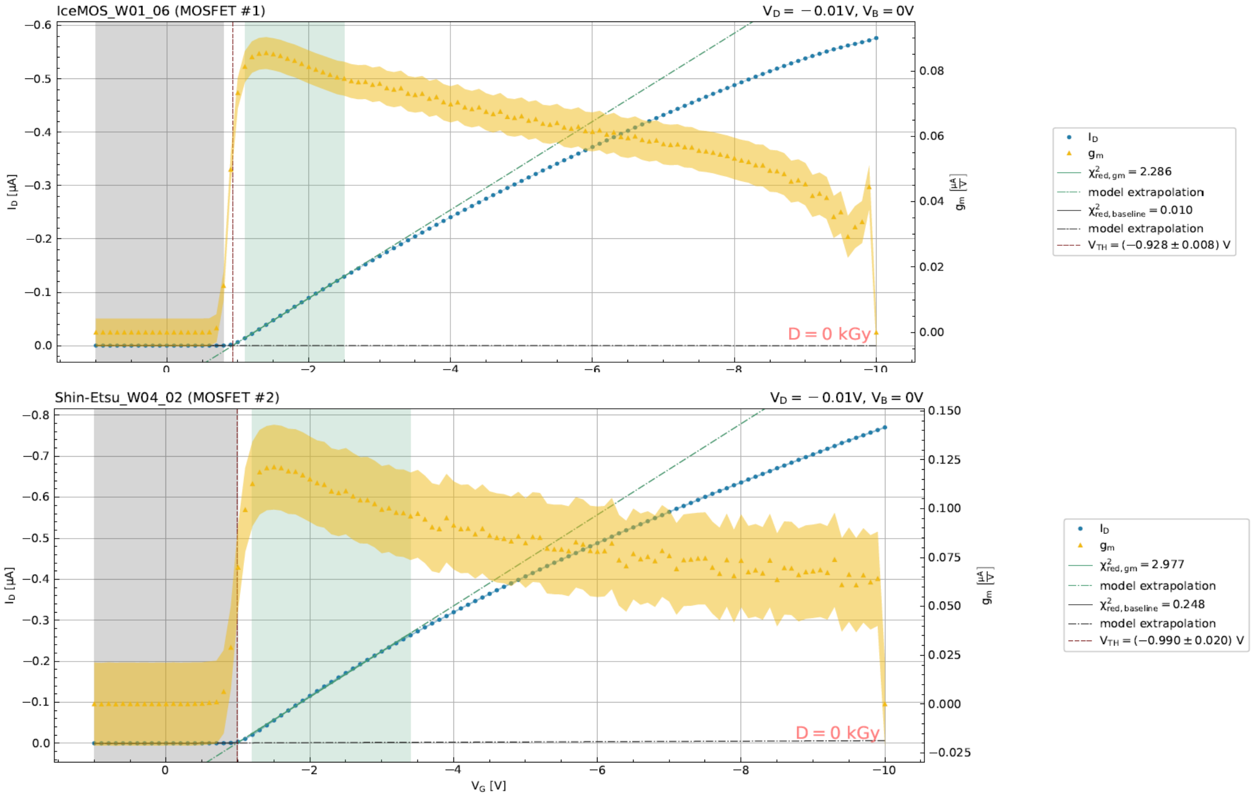
      - Allowing for further effective mobility μ_{eff} analysis

      - Measurement was conducted with a gate overdrive of 4 V and 7 V via the threshold estimation of the IV-Gate measurement $V_G = V_{th} - 4\,V; V_G = V_{th} - 7\,V$

MOSFET Test-Structure Characterization

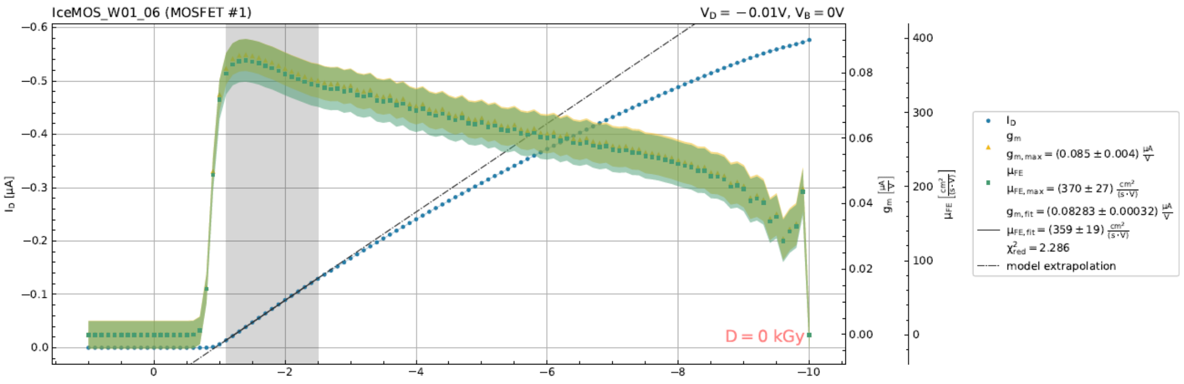
IV-Gate Measurement

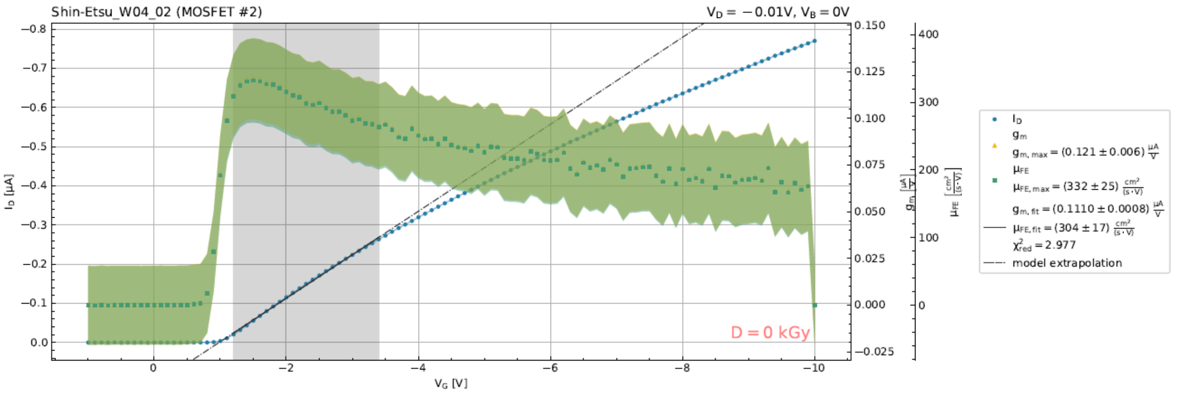
THRESHOLD ANALYSIS



- Threshold voltage extracted out of the intersection between a baseline and a linear fit
- The linear fit is determined for a χ^2- limit

MOBILITY ANALYSIS





- Observing the excpected mobility degradation due to a higher transverse electric field
- Reference measurement showing mobilities of:

$$\mu_{\mathrm{FE,Fit,IceMOS}} = (359 \pm 19)\,\frac{\mathrm{cm}^2}{(\mathrm{s}\cdot\mathrm{V})};$$

$$\mu_{\mathrm{FE,Fit,ShinEtsu}} = (304 \pm 17)\,\frac{\mathrm{cm}^2}{(\mathrm{s}\cdot\mathrm{V})}$$

$\mu_p(Si) = 500$ cm²/Vs

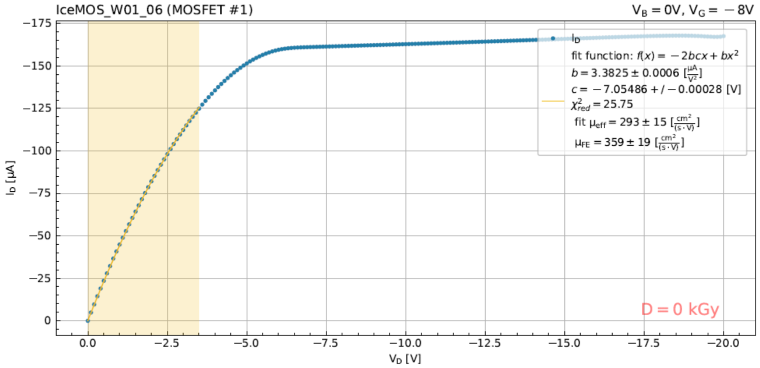
IV-DRAIN MEASUREMENT

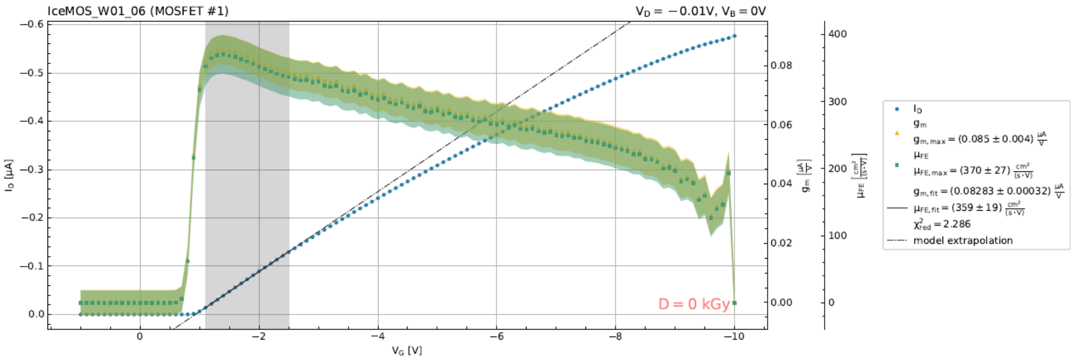
- Was conducted to confirm the mobility behavior from the IV-Gate measurement
- The fit was performed via the following fit function:

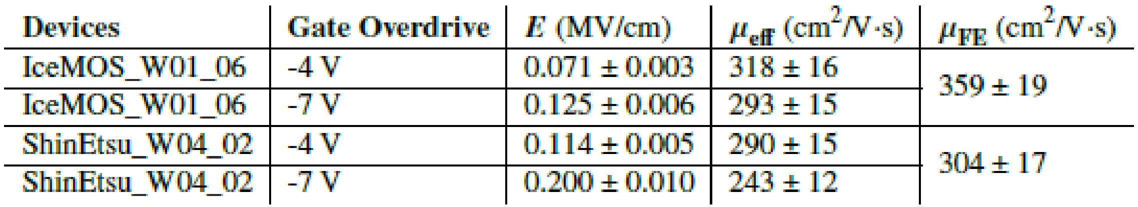
$$f(x) = -2bc \cdot x + b \cdot x^2 , \qquad c = V_\mathrm{G} - V_\mathrm{th} , \qquad b = \frac{Z}{2L} \mu_\mathrm{eff} C_\mathrm{Ox}$$

- Referring to: $I_\mathrm{D} = \frac{Z}{L} \mu_p C_{ox} \left(V_G - V_\mathrm{th} - \frac{V_D}{2} \right) V_D$

IV-DRAIN MEASUREMENT



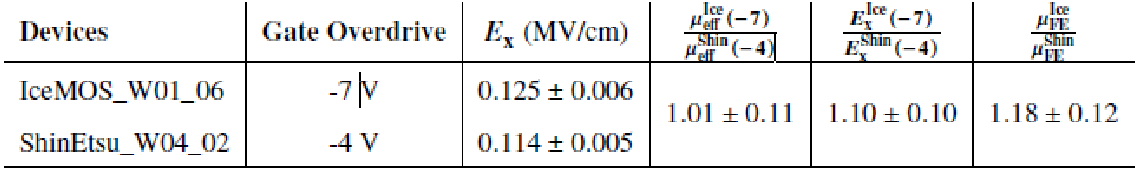




Devices	Gate Overdrive	E (MV/cm)	μ_{eff} (cm^2/V·s)	μ_{FE} (cm^2/V·s)
IceMOS_W01_06	-4 V	0.071 ± 0.003	318 ± 16	359 ± 19
IceMOS_W01_06	-7 V	0.125 ± 0.006	293 ± 15	
ShinEtsu_W04_02	-4 V	0.114 ± 0.005	290 ± 15	304 ± 17
ShinEtsu_W04_02	-7 V	0.200 ± 0.010	243 ± 12	

IV-DRAIN MEASUREMENT

- The following behavior can be observed:
  - Mobility decreases with higher gate voltages and is generally lower for the ShinEtsu-DUT
  - Reasons could be a difference in the transverse electric field
  - Check if the mobility is comparable for similar electric field



Devices	**Gate Overdrive**	E_x (MV/cm)	$\frac{\mu_{\mathrm{eff}}^{\mathrm{Ice}}(-7)}{\mu_{\mathrm{eff}}^{\mathrm{Shin}}(-4)}$	$\frac{E_x^{\mathrm{Ice}}(-7)}{E_x^{\mathrm{Shin}}(-4)}$	$\frac{\mu_{\mathrm{FE}}^{\mathrm{Ice}}}{\mu_{\mathrm{FE}}^{\mathrm{Shin}}}$
IceMOS_W01_06	-7 V	0.125 ± 0.006	1.01 ± 0.11	1.10 ± 0.10	1.18 ± 0.12
ShinEtsu_W04_02	-4 V	0.114 ± 0.005			

→ change is primary caused by the difference in the transverse electric field

TID Effects

TID THRESHOLD EFFECTS

- The expectation was a threshold shift under TID that was caused by oxide and interface traps

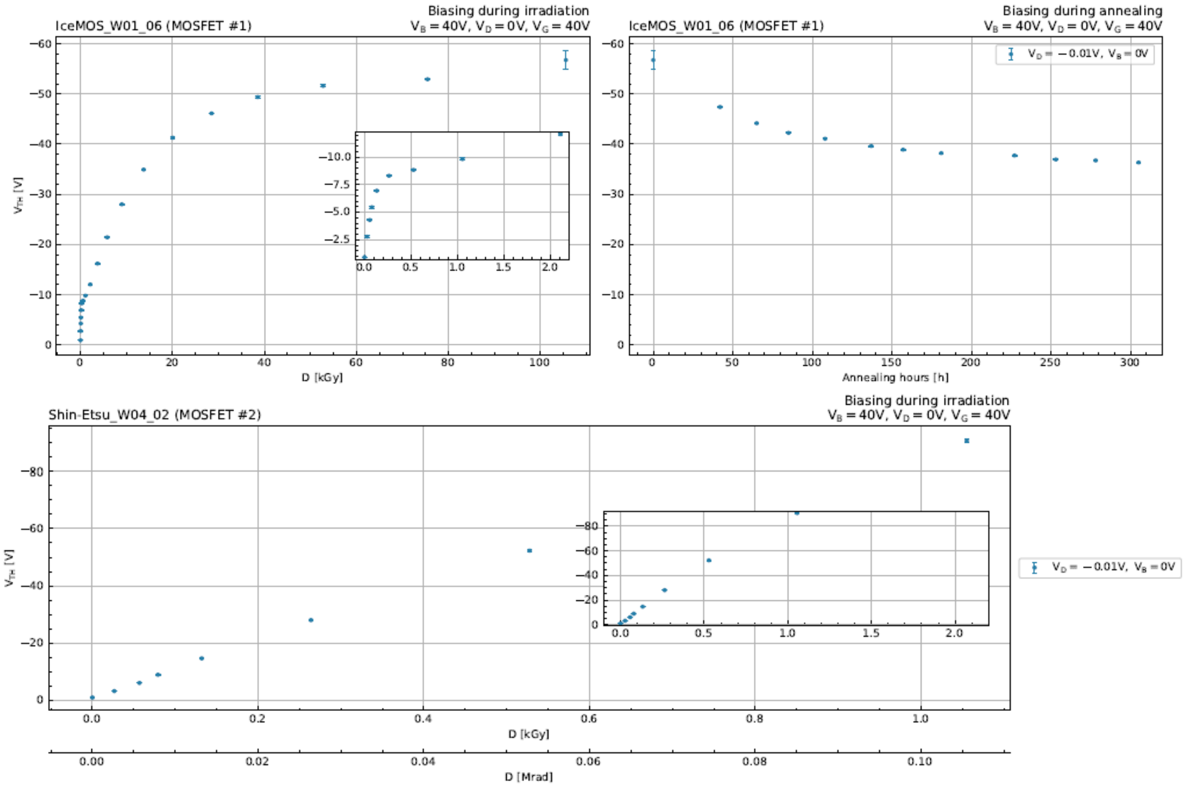
- Below a TID of 1kGy the main contributing factor for the threshold shift should oxide traps
  - Less time for interface traps to built up

→IceMOS-DUT is singnificantly more radiation hard

$$\frac{F_{\mathrm{t}}^{\mathrm{Shin}}}{F_{\mathrm{t}}^{\mathrm{Ice}}} = \frac{V_{OT}^{Shin}}{V_{OT}^{Ice}} \cdot \frac{d_{\mathrm{Ice}}^{2}}{d_{\mathrm{Shin}}^{2}} \approx 25.86 \pm 3.66$$

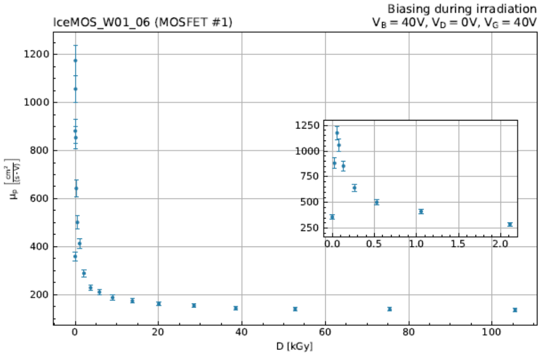
$$\Delta V_{OT} = -3.8 \times 10^{-8} d_{ox}^{2} D F(E) F_{t}$$ [8]

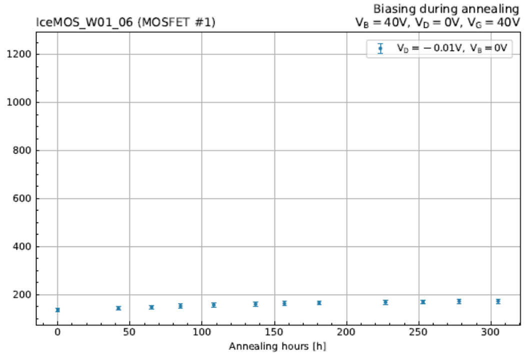
TID THRESHOLD EFFECTS

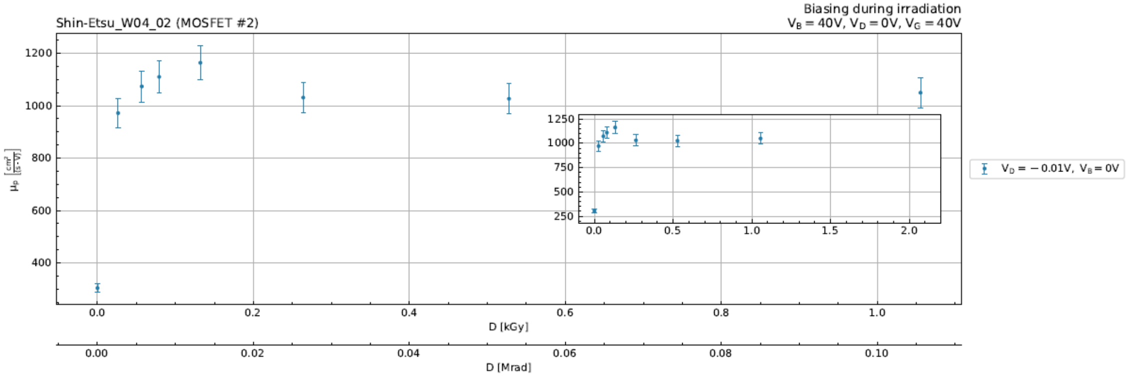


- Overall saturation trend due to limited oxide trap density
- ShinEtsu-DUT is more radiation hard due to a thinner oxide is not confirmed→ Bonding proccess is more relevant

TID MOBILITY EFFECTS







- Expectation:
    - Mobility decreases with higher TID because the amount of interface traps increases

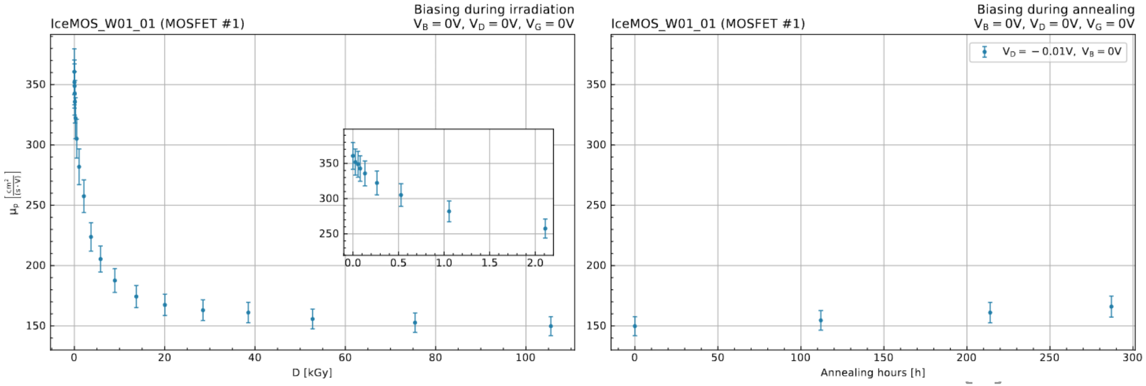
      → more scattering centers for the charge carriers
- What we saw:
    - Rapid increase for mobility in both devices for D<0.1kGy
    - Fast decrease in the case of the IceMOS-DUT
    - Slow decrease for the ShinEtsu-DUT

TID MOBILITY EFFECTS

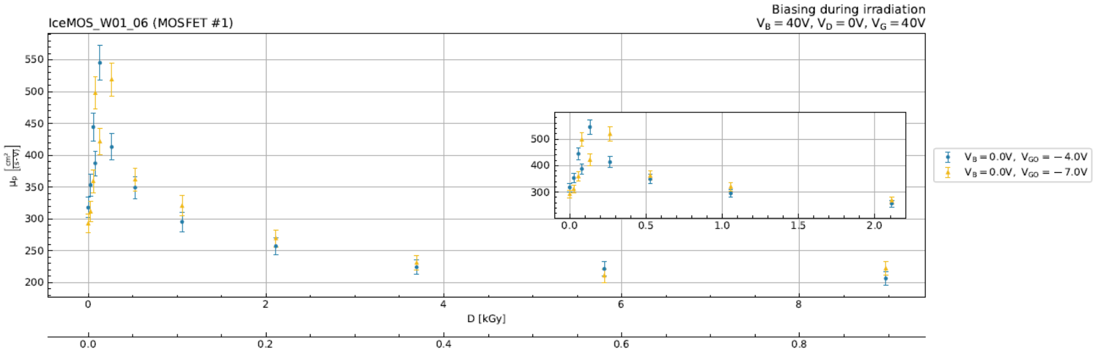
- Notable is the untypically high mobility compared to the intrinsic hole mobility of silicon

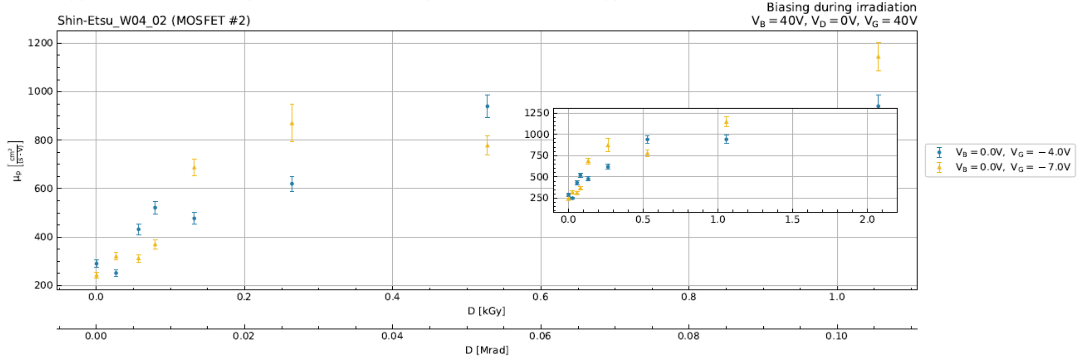
$\mu^{\text{Shin}}_{\text{FE,max}} = (1.16 \pm 0.06) \cdot 10^3 \, \frac{\text{cm}^2}{\text{s} \cdot \text{V}}$ and $\mu^{\text{Ice}}_{\text{FE,max}} = (1.18 \pm 0.06) \cdot 10^3 \, \frac{\text{cm}^2}{\text{s} \cdot \text{V}}$ $\mu_p(Si) = 500$ cm²/Vs

- This enhancement is only seen for irradiation with a biasing of $V_G = V_B = 40V$



TID MOBILITY EFFECTS





$$\mu^{\text{Shin}}_{\text{eff,max}} = (1\,140 \pm 60)\ \text{cm}^2/\text{Vs}, \qquad \mu^{\text{Ice}}_{\text{eff,max}} = (545 \pm 27)\ \text{cm}^2/\text{Vs}$$

TID MOBILITY EFFECTS

- Speculations for the occurrence of the enhanced mobility:
  - Passivate preexisting traps over the first irradiation period
  - Induced strain during the manufacturing process
  - Growth of additional oxide for the IceMOS-DUT, creating potentially two additional internal interfaces in the silicon dioxide affecting charge traps in the oxide

Conclusion and Outlook

CONCLUSION AND OUTLOOK

- IceMOS-DUT is more radiation hard than the ShinEtsu-DUT with a factor of approximately 25
- Radiation hardness is strongly dependent on the bonding process
- Unexpected mobility enhancement for both devices
- Possibilities for further investigations:
    - Observe if the mobility enhancement persists under operation and annealing at room temperature
    - Further analysis of the gated diode measurement
    - Conduct measurements for commonly used p-channel MOSFETs

THANK YOU FOR YOUR ATTENTION!

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THRESHOLD VOLTAGE

- The threshold voltage generally describes the voltage, which is needed to switch the MOSFET from an off-state to an on-state

- In the case of a MOSFET the threshold voltage can be explained via:

$$V_{\mathrm{th}} = V_{\mathrm{FB}} + 2\psi_{\mathrm{B}} + \frac{\sqrt{2\epsilon_{\mathrm{S}} q N_A (2\psi_{\mathrm{B}} - V_{\mathrm{B}})}}{C_{\mathrm{Ox}}} \quad [4]$$

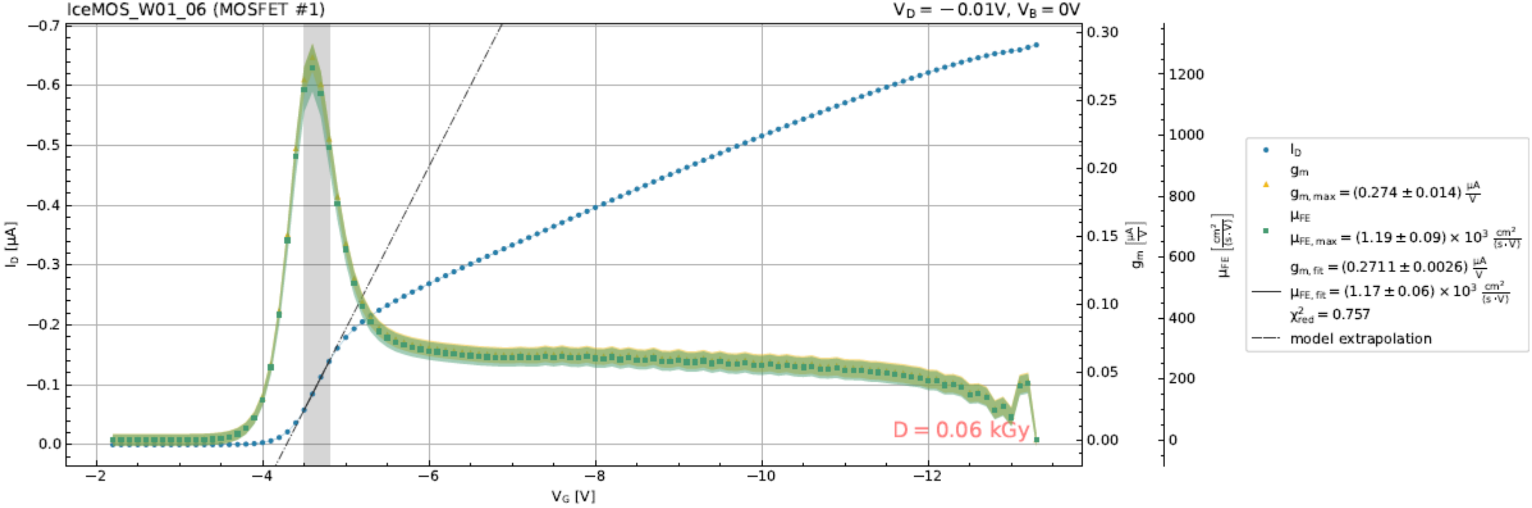
- Meaning a dependence on the voltage applied to the Bulk
  - Threshold voltge due to bulk voltage:

$$\Delta V_T(V_B) = V_T(V_B) - V_T(V_B = 0) = \frac{\sqrt{2\varepsilon_s q N_A}}{C_{ox}}(\sqrt{2\psi_B - V_B} - \sqrt{2\psi_B}) \quad [4]$$

- This also shows that for a thicker oxide we exspect a smaller threshold shift

$$C_{\mathrm{Ox}} = \frac{\epsilon_{\mathrm{Ox}}}{d_{\mathrm{Ox}}}$$

BACKUP: HIGH MOBILITY PLOT

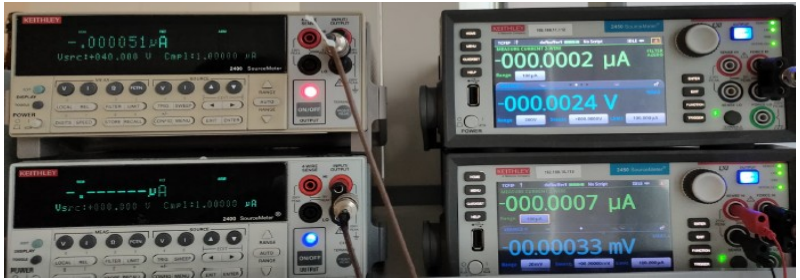


BACKUP: ALUMINUMFILTER

- Aluminumfilter is used to filter low energetic parts of the spectrum
- This area will not effect the burried oxide
    - Energy mostly absorbed in the upper layer of the MOSFET

SOURCE MEASURING UNIT

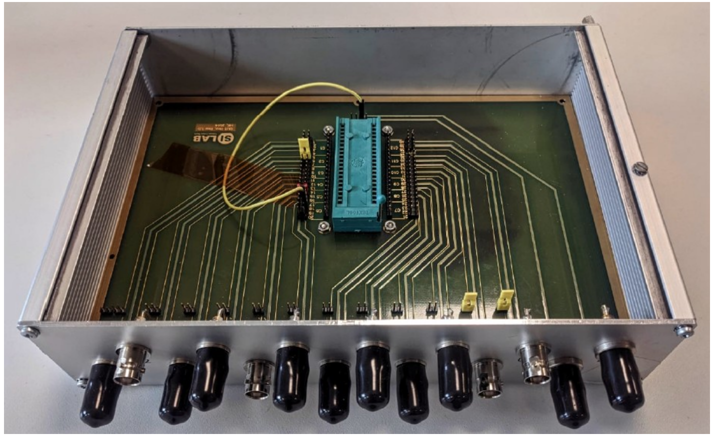
- The Source Measuring Unit is used to source either voltage or current while measuring the other quantity
- Measured with repeating instead of moving averaging filter with 10 averaging points
- Units need to heat up for round 1 hour



DUT-BOX

- To assemble the setup and connect the allow us to connect the SMUs via triax connectors the DUT-Box was used

- Dut-Box is a simple shielded Metal casing, which allows one device to be placed in the socket

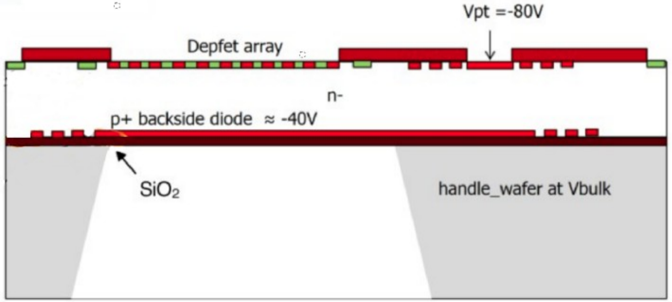


DEPFET BIASING

- In order to deplete the sensor a punch-through contact is used
  - The punch-through contact creates an conductive path to the backside

    →depleting the substrate
  - In addtion to the punchthrough contact bulk contacts are used in order to also deplete the sides od the sensor

$$V_\mathrm{B} - V_\mathrm{backside} \approx 40\,\mathrm{V}$$



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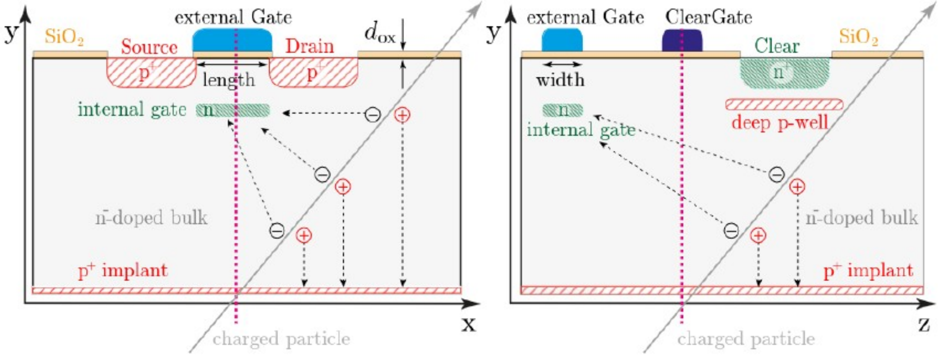
DEPFET

- The PxD in Belle 2 is based on a DEPFET-Design
  - In comparison to a MOSFET the DEPFET is designed with an additional internal gate allowing for internal amplification
  - Via the clear implant the internal gate can be cleared
  - Over the pixel matrix this process is done via a rolling shutter



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BACKUP: MAXIMUM TID

- Irradiation was done with a biasing of $V_G = 40V$
- The TID reached was approximatley 106 kGy
    - Comparable to earlier radiation campaigns
    - Expected TID over the lifetime of PXD ~200kGy at the DePFET pixels approximately 13-14kGy at the burried SiO_2
    - Radiation campaign is time consuming, low radiation dose rate

X-RAY CHAMBER

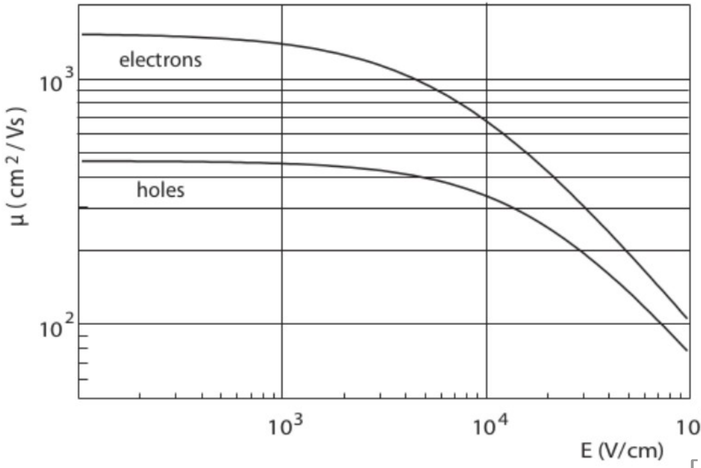
- The X-ray chamber is equipped with a tungsten target and an aluminum filter
- The point focus is just to achive a higher beam intensity
- The shutter is controlled electroncally and the radiation dose is determined via the calibration data

MOBILITY

- Mobility is temperature dependent
  - Constant temperature is assumed the low field mobility is given by:

$\rightarrow \mu_p(Si)=500$ cm²/Vs

$\mu_n(Si)=1450$ cm²/Vs [2]



[2]