MOSFETS dosimetry

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- Thermal dependence:
  - Thermal model for lateral transistors
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- Readout process: deferred mode
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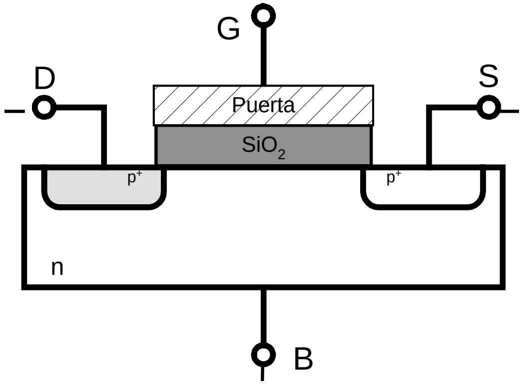
Introduction

- **Why MOSFET dosimeters for in-vivo dosimetry?**
  - Small size and low cost
  - Immediately readout
  - Linearity
  - Easy calibration
  - Reproducibility



Radiation effects

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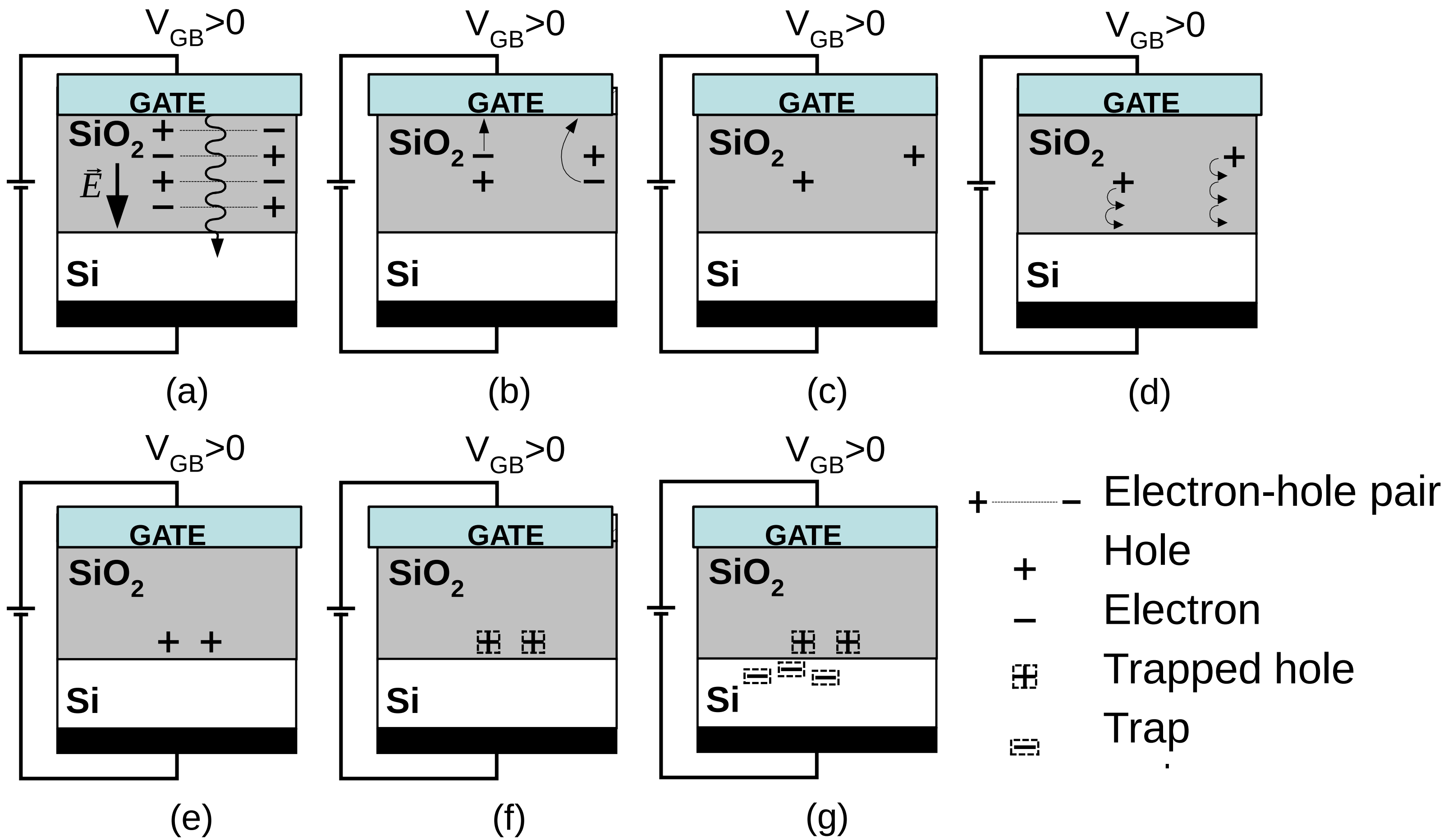
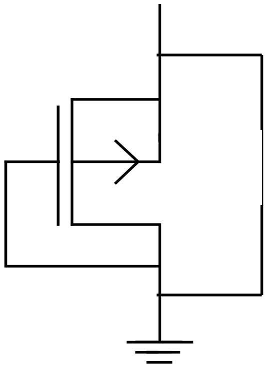
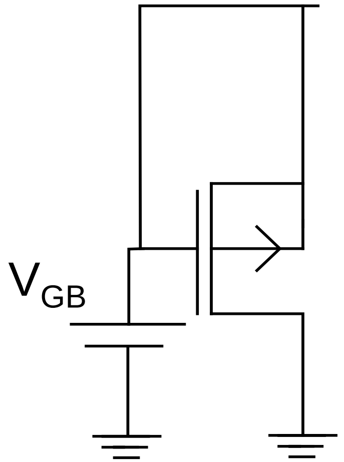


Radiation effects

- Unbiased mode:
  - No external voltage.
  - Low sensitivity



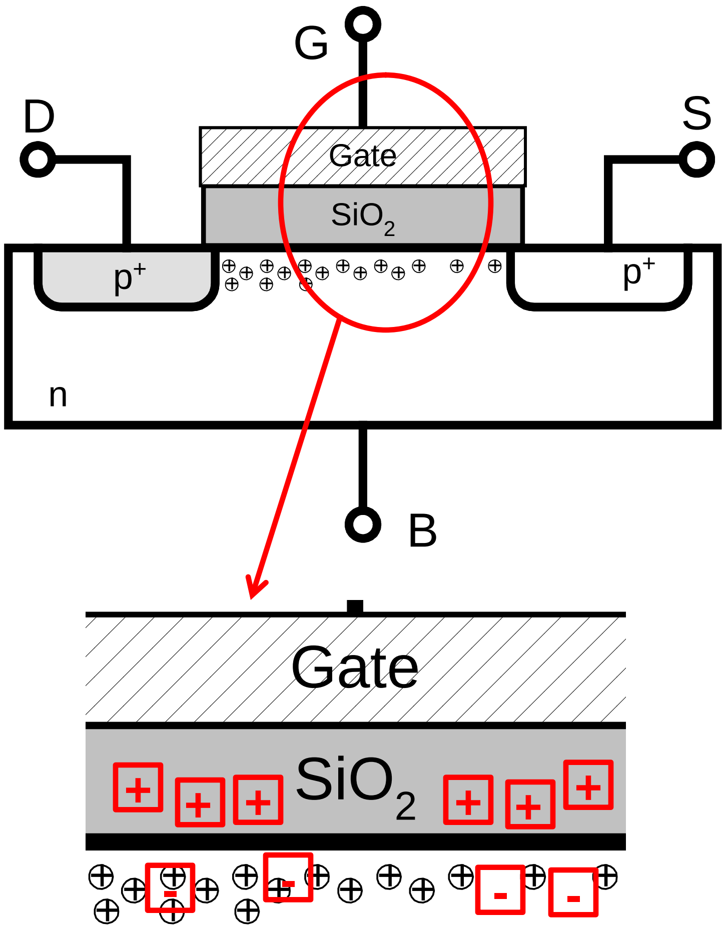
- Biased mode:
  - External V_{GB} during irradiation
  - Higher sensitivity and linearity.



Radiation effects

- Ionizing radiation creates charge in the oxide and traps in the Si-SiO_2 interface.
- Charge in oxide and positive traps produce an increment in the threshold voltage, $|V_t|$.
- Interface traps degrade the carriers mobility and then, the β parameter is reduced.

$$I_D = -\frac{\beta}{2}\left(|V_{GS}| - |V_t|\right)^2$$



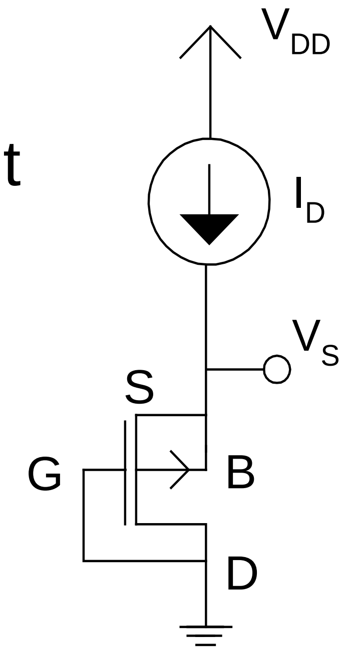
Constant current measurements

- Ionizing radiation creates charge in the oxide: Threshold voltage, V_t ,is the dosimetric parameter

$$I_D = -\frac{\beta}{2}\left(|V_{GS}| - |V_t|\right)^2 \qquad \Delta|V_t| > 0 \qquad \Delta\beta < 0$$

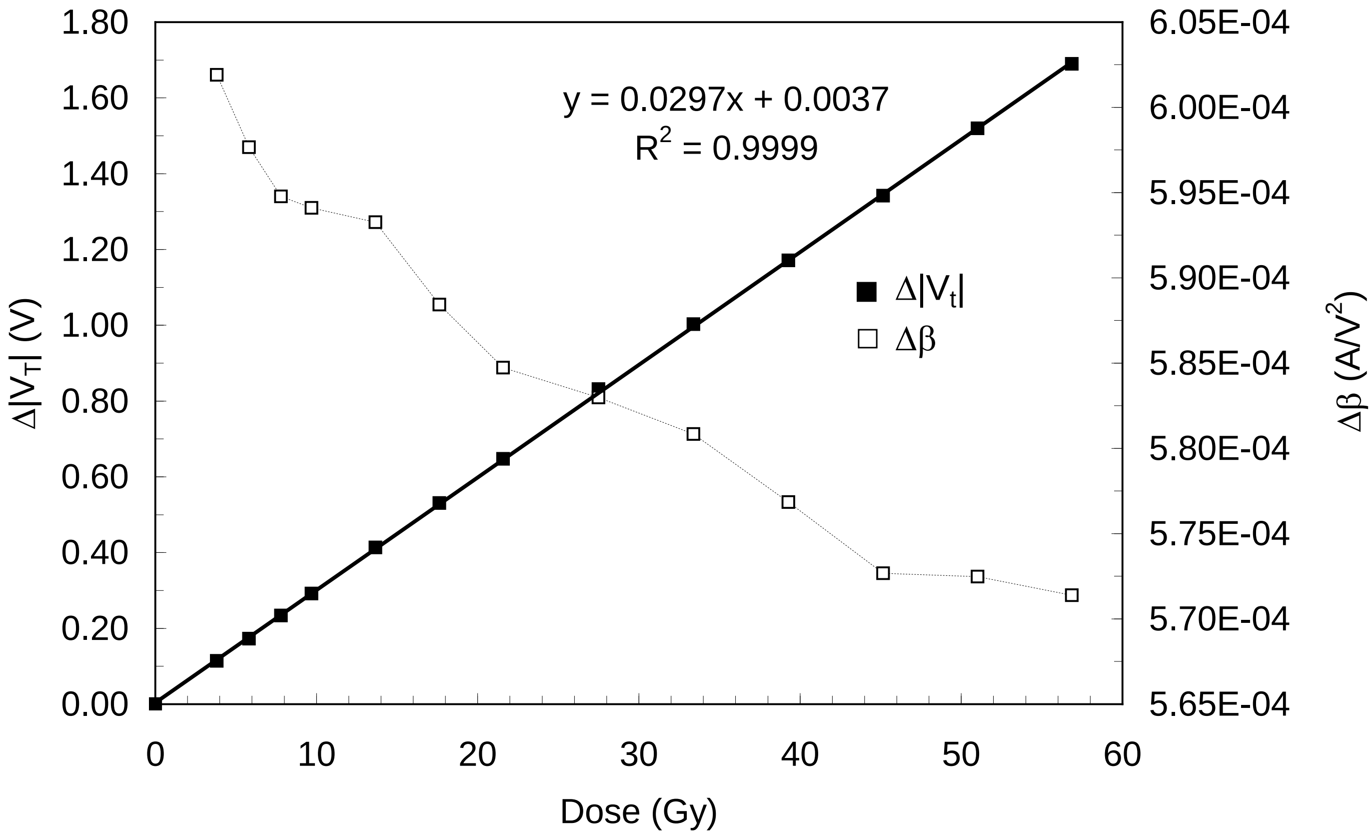
- Simplified measurement of V_t : V_S at constant drain current (V_{GD} = 0).

$$|V_t| = V_S - \sqrt{\frac{2I}{\beta}} \qquad \beta \approx \text{constant} \Rightarrow \quad \Delta|V_t| \approx \Delta|V_S|$$



Radiation effects in electrical parameters

- |Vt| increases and β reduces with absorbed dose



3N163, Vishay-Siliconix (USA)

- ^{60}Co Source
- Semicondcutor analyser HP-4145B
- Unbiased mode

Linear range improvement: Two currents method (2CM)

- Accounting for Δβ effect in ΔV_t

$$I = \frac{\beta}{2}\left(V_S - |V_t|\right)^2$$

- Pre- and post-irradiation parameters at constant current *I*:

$$|V_t| = V_S - \sqrt{\frac{2I}{\beta}} \Rightarrow \left\{ \begin{array}{l} |V_t^{post}| = V_S^{post} - \sqrt{\dfrac{2I}{\beta^{post}}} \\ |V_t^{pre}| = V_S^{pre} - \sqrt{\dfrac{2I}{\beta^{pre}}} \end{array} \right\} \quad \Delta|V_t| = \Delta V_S - \sqrt{2I}\left(\sqrt{\frac{1}{\beta^{post}}} - \sqrt{\frac{1}{\beta^{pre}}}\right)$$

Linear range improvement: Two currents method (2CM)

- Using two drain currents during read-out phase:

$$\Delta|V_t| = \Delta V_{S1} - \sqrt{2I_1}\left(\sqrt{\frac{1}{\beta^{post}}} - \sqrt{\frac{1}{\beta^{pre}}}\right) \qquad \Delta|V_t| = \Delta V_{S2} - \sqrt{2I_2}\left(\sqrt{\frac{1}{\beta^{post}}} - \sqrt{\frac{1}{\beta^{pre}}}\right)$$

- Threshold voltage shift without neglecting β degradation

$$\Delta|V_t| = \Delta V_{S1} + \frac{\Delta V_{S2} - \Delta V_{S1}}{1 - \sqrt{\frac{I_2}{I_1}}}$$

- **Problem:** Thermal compensated source voltage at two different currents are needed, thus the thermal compensation must be made using the thermal coefficient of V_t.

Thermal dependence

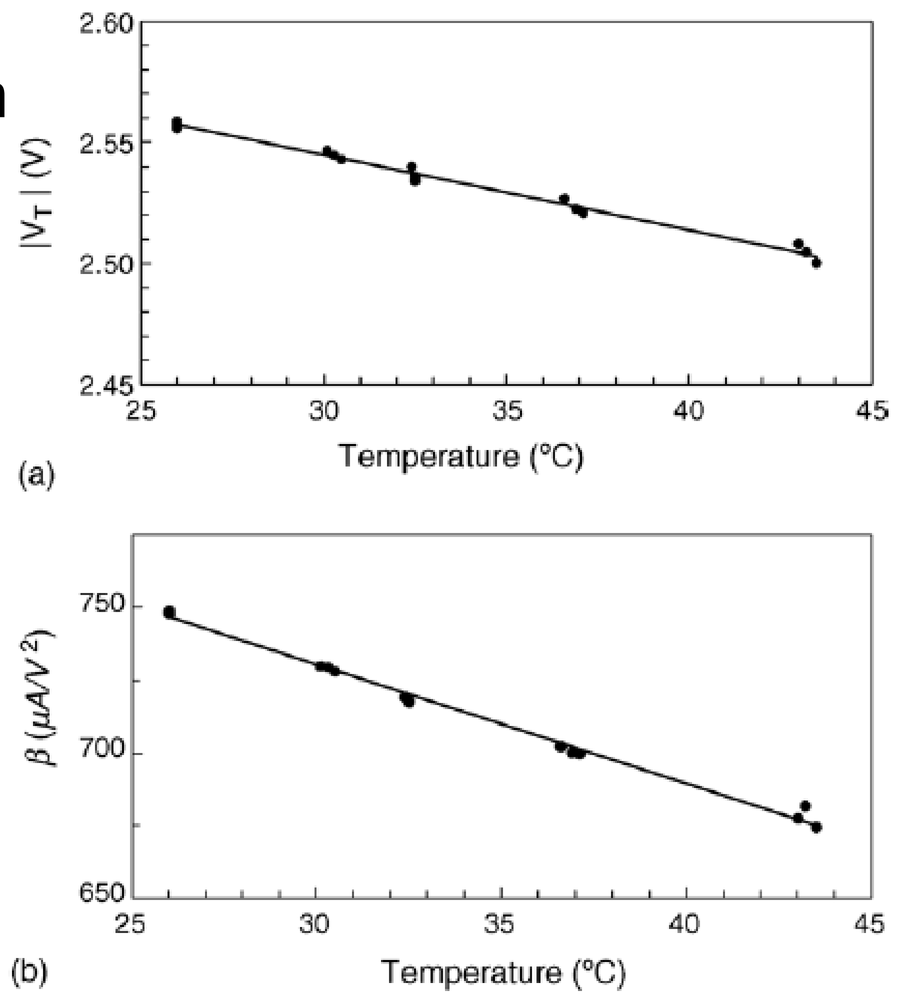
- Both $|V_t|$ and β decrease with temperature.

$$I_D = -\frac{\beta}{2}\left(|V_{GS}| - |V_t|\right)^2$$

$$\Downarrow$$

$$V_S = \sqrt{\frac{2|I_D|}{\beta}} + |V_t|$$

- Therefore, at constant current:
  - If T ↑ → $|V_t|$ ↓ → V_S ↓
  - If T ↑ → β ↓ → V_S ↑



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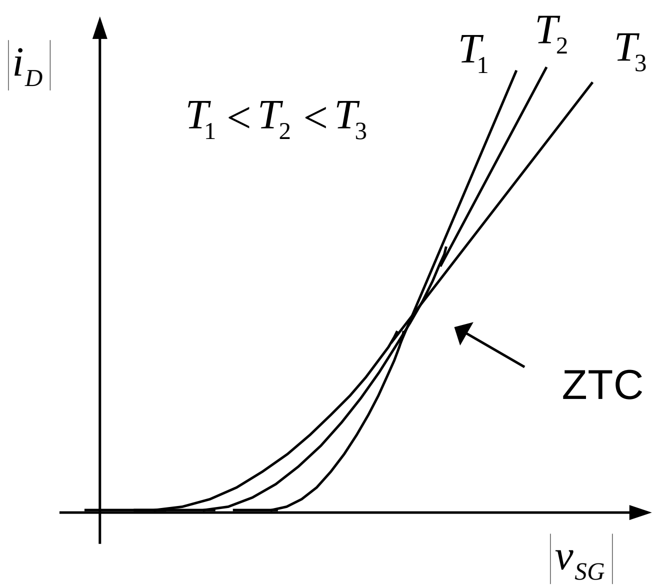
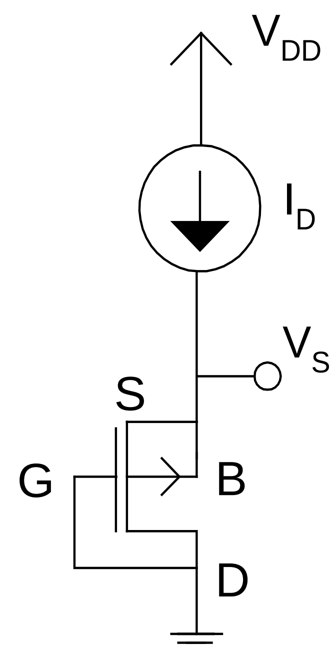
Thermal dependence

- Both effects are compensated at I_{ZTC} current (Zero Temperature Coefficient)
- The thermal dependence of V_S is minimized at I_{ZTC} current





Thermal model for lateral transistors

- **Thermal compensation: Model**
  - Starting hypothesis: linear thermal trend of voltages

$$\left.\begin{aligned}
\Delta|V_t| &= \Delta V_{S1} + \frac{\Delta V_{S2} - \Delta V_{S1}}{1 - \sqrt{\dfrac{I_2}{I_1}}} \\
\Delta V_{S1} &= \Delta V_{S1}^0 + \alpha_1 \Delta T \\
\Delta V_{S2} &= \Delta V_{S2}^0 + \alpha_2 \Delta T \\
\Delta|V_t| &= \Delta|V_t^0| + \alpha_{|Vt|} \Delta T
\end{aligned}\right\} \Rightarrow \boxed{\alpha_i = \alpha_{|Vt|}\left(1 - \sqrt{\frac{I_i}{I_{ZTC}}}\right)}$$

Thermal compensation: Three currents method (3CM)

- **ΔV_S Thermal compensation: Adding a new current**

$$If\ \ no\ radiation:\ \ \Delta V_{S1}^{0} \approx \Delta V_{SC}^{0}$$

$$\Delta V_{S1}(T) = \Delta V_{S1}^{0} + \alpha_1 \Delta T$$

$$\Delta V_{SC}(T) = \Delta V_{SC}^{0} + \alpha_C \Delta T$$

$$\Delta T \approx \frac{\Delta V_{S1} - \Delta V_{SC}}{\alpha_1 - \alpha_C}$$

$$\alpha = \alpha_{|Vt|}\left(1 - \sqrt{\frac{I}{I_{ZTC}}}\right)$$

$$\Delta V_{S1}^{0} = \Delta V_{S1} + \frac{\Delta V_{SC} - \Delta V_{S1}}{1 - \frac{\alpha_C}{\alpha_1}}$$

$$\Delta V_{S1}^{0} = \Delta V_{S1} + \left(\Delta V_{SC} - \Delta V_{S1}\right)\frac{\sqrt{I_1} - \sqrt{I_{ZTC}}}{\sqrt{I_1} - \sqrt{I_C}}$$

PROCEDURES OF MEASUREMENT
Three currents method (3CM)

- **Thermal compensation**
  - $\Delta|V_t|$ thermal compensated

$$\Delta|V_t| = \Delta V_{S1}^{0} + \frac{\Delta V_{S2}^{0} - \Delta V_{S1}^{0}}{1 - \sqrt{\dfrac{I_2}{I_1}}}$$

  - Simplification $I_1 = I_{ZTC}$

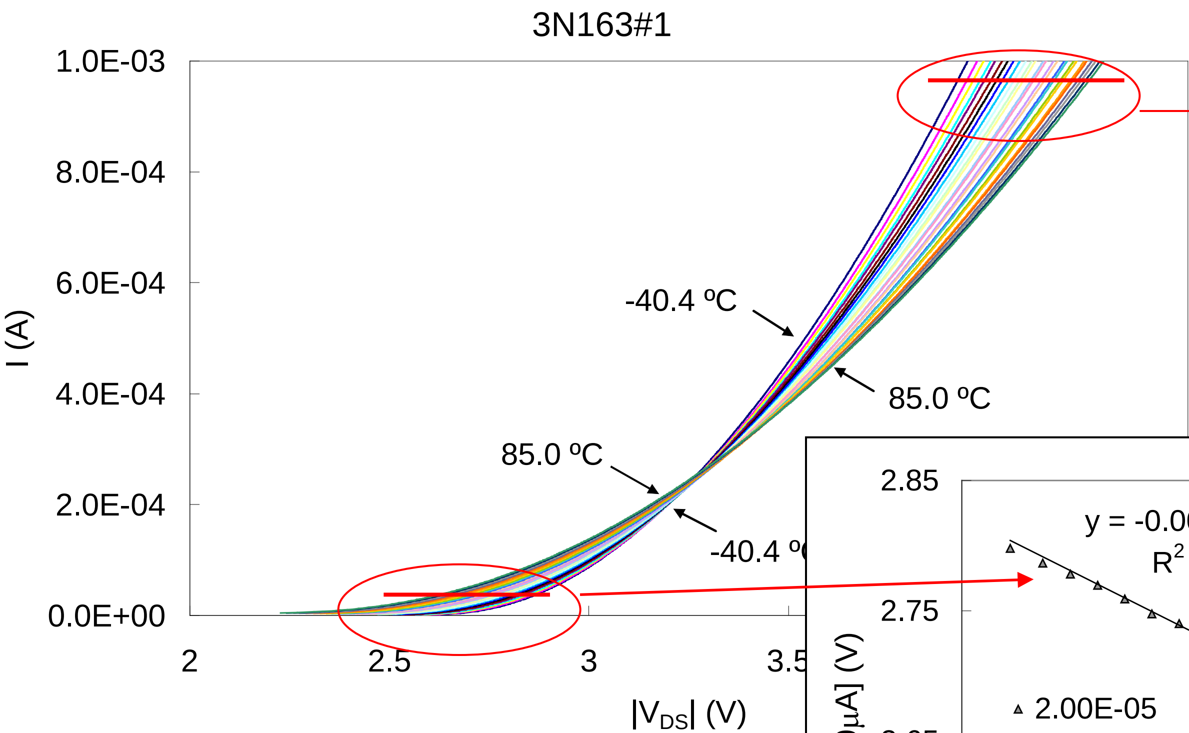
$$\Delta|V_t| = \Delta V_{S,ZTC} + \frac{\Delta V_{S2}^{0} - \Delta V_{S,ZTC}}{1 - \sqrt{\dfrac{I_2}{I_{ZTC}}}}$$

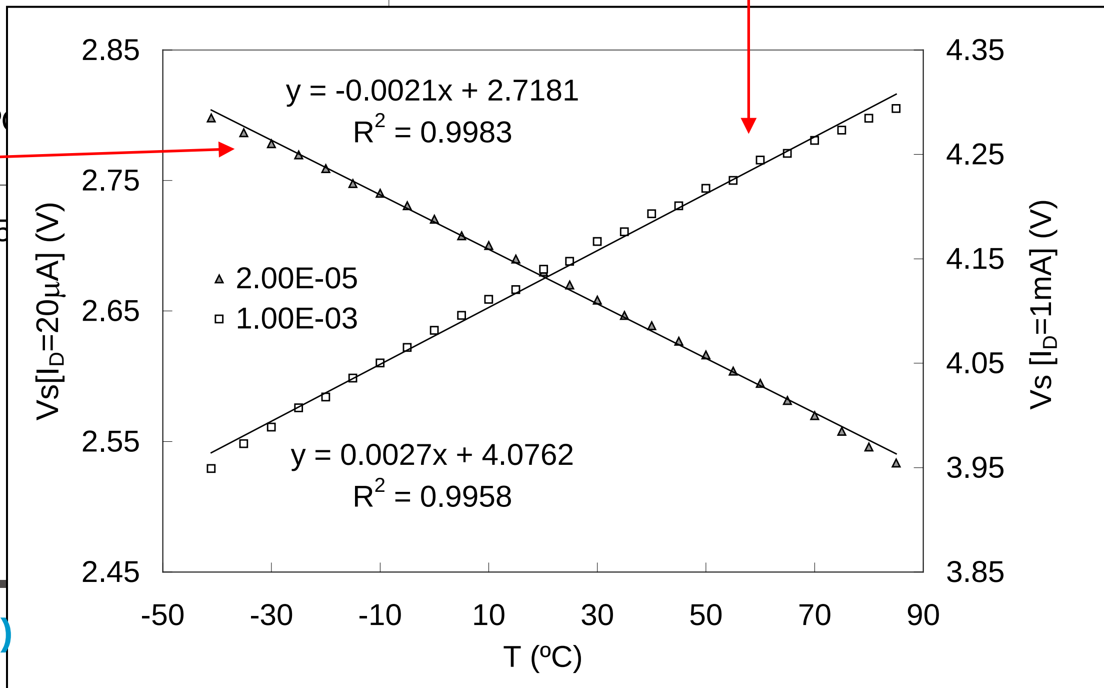
  - Additional current: I_C

$$\Delta V_{S2}^{0} = \Delta V_{S2} + \left(\Delta V_{SC} - \Delta V_{S2}\right)\frac{\sqrt{I_2} - \sqrt{I_{ZTC}}}{\sqrt{I_2} - \sqrt{I_C}}$$

Thermal compensation: Three currents method (3CM)

- **Thermal model:** Experimental validation (I)

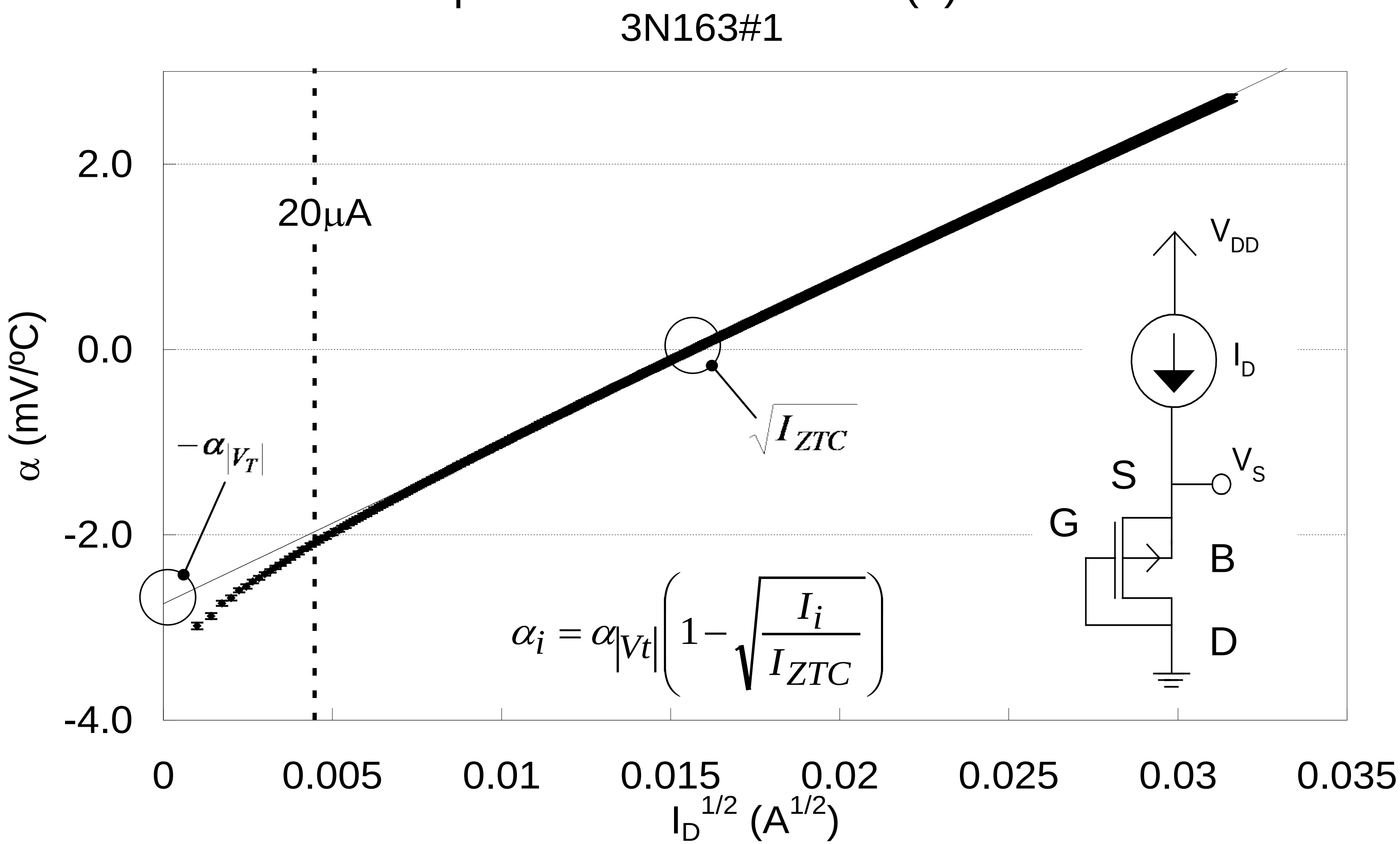




$$\alpha_i = \alpha_{|Vt|}\left(1-\sqrt{\frac{I_i}{I_{ZTC}}}\right)$$

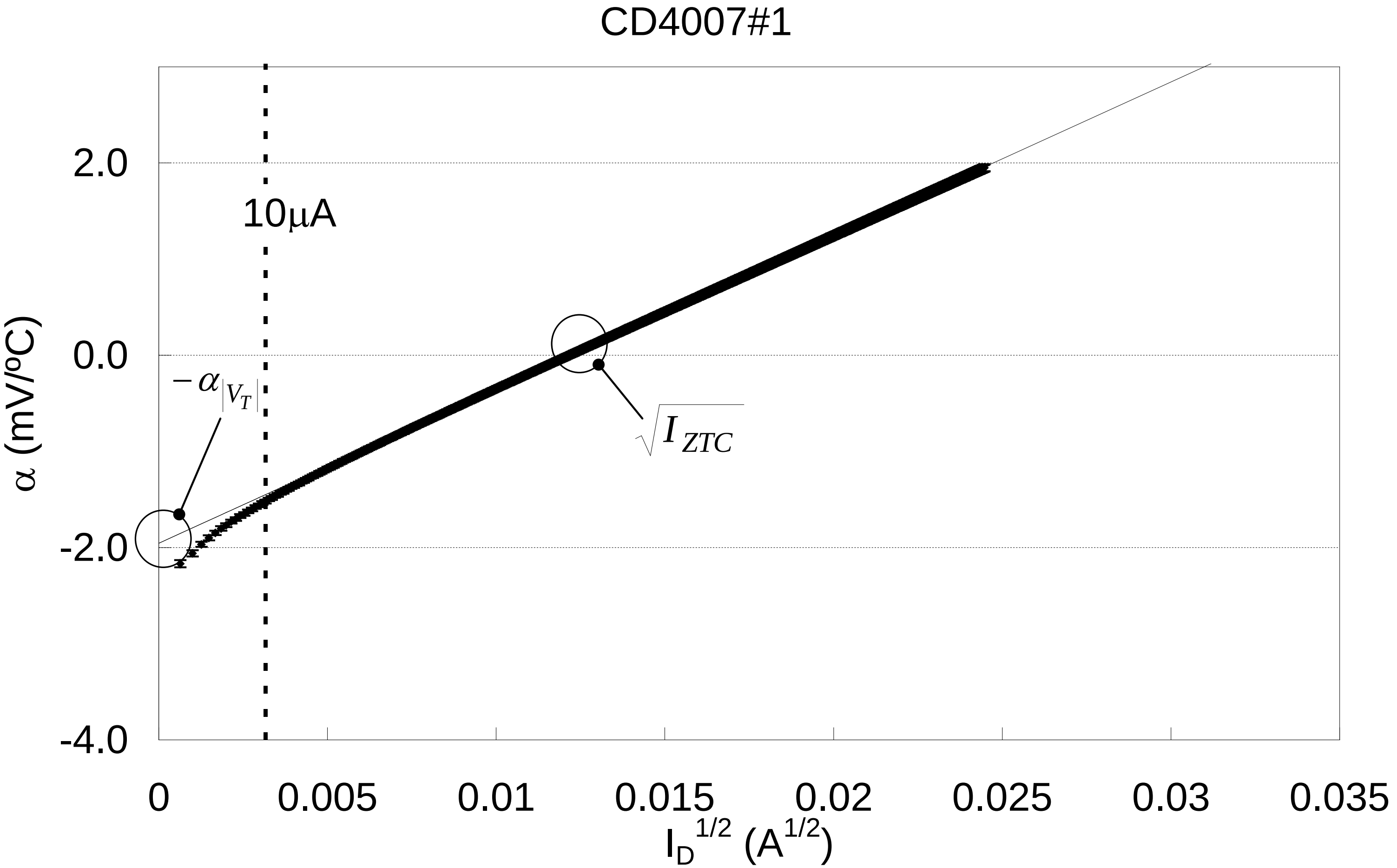
Thermal compensation: Three currents method (3CM)

- **Thermal model:** Experimental verification (II)



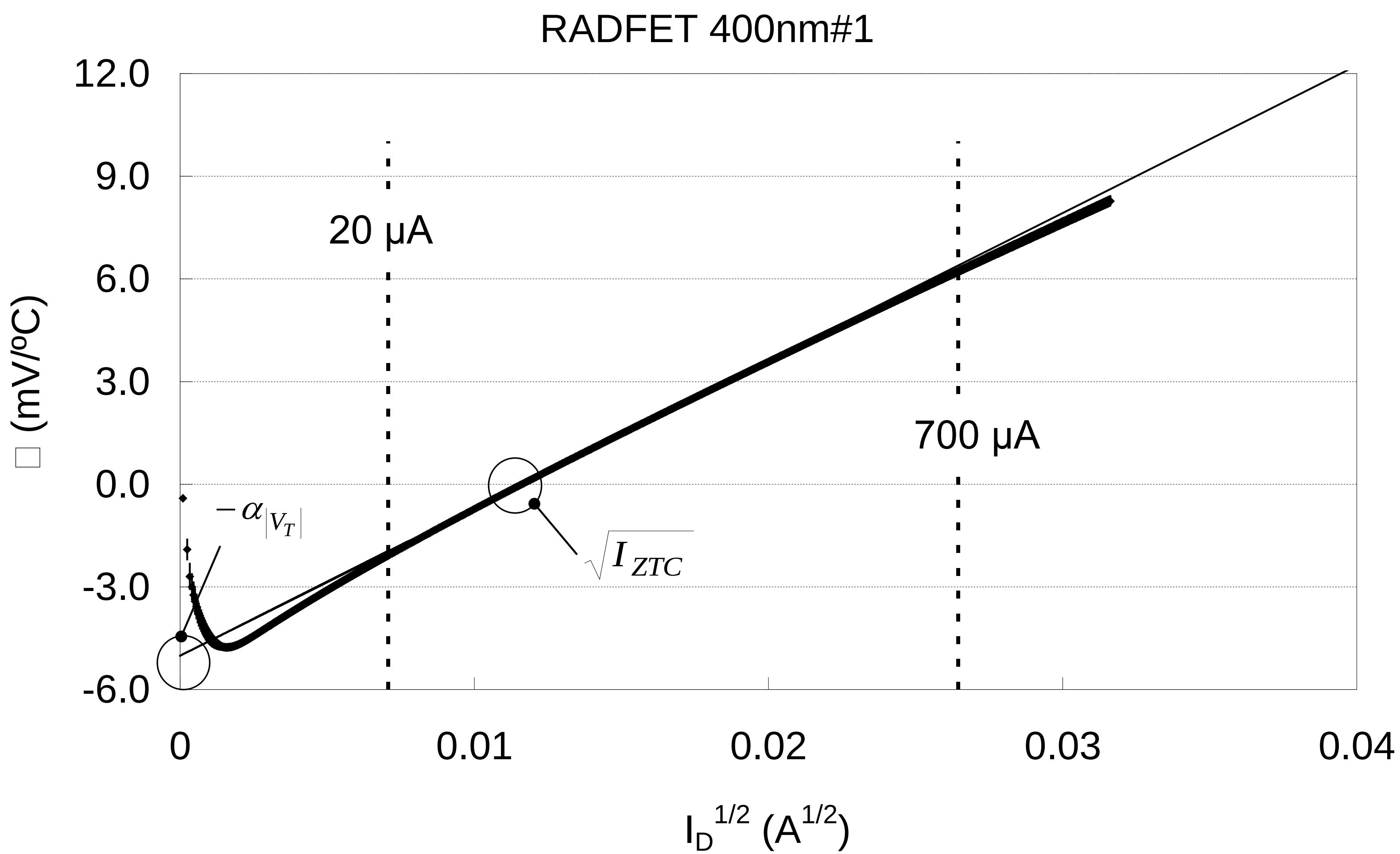
Thermal compensation: Three currents method (3CM)

- **Thermal model:** Experimental verification (III)



Thermal compensation: Three currents method (3CM)

- **Thermal model:** Experimental verification (IV)



Thermal compensation: Three currents method (3CM)

- **Thermal model:** I_{ZTC} summary

$I_{ZTC}(\mu A)$ for lateral MOSFETs

	Average	σ
3N163	247	5
CD4007	137	19
RADFET 400nm	136	6

Thermal compensation: Three currents method (3CM)

- **One current:**
  - To thermal compensation $I_D=I_{ZTC}$. (usual mode)
- **Two currents:**
  - To increase the linear range use $\Delta|V_t| = \Delta V_{S1} + \dfrac{\Delta V_{S2} - \Delta V_{S1}}{1-\sqrt{\dfrac{I_2}{I_1}}}$
  - To thermal compensation (without using I_{ZTC})

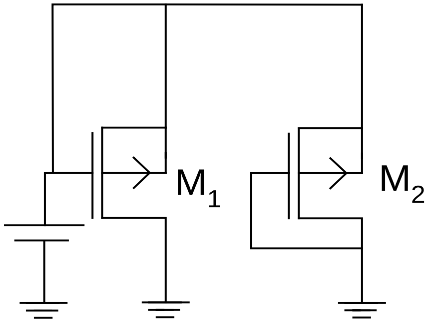
$$\Delta V_{S1}^0 = \Delta V_{S1} + (\Delta V_{SC} - \Delta V_{S1})\frac{\sqrt{I_1} - \sqrt{I_{ZTC}}}{\sqrt{I_1} - \sqrt{I_C}}$$

- **Three currents:**
  - Increasing the linear range and thermal compensation

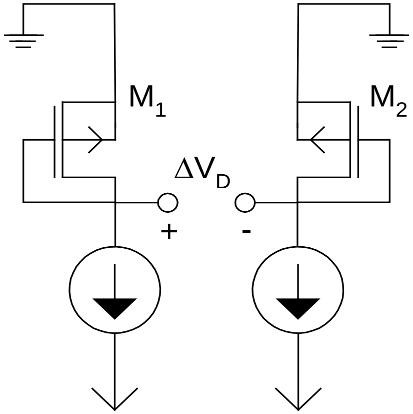
$$\Delta V_{S2}^0 = \Delta V_{S2} + (\Delta V_{SC} - \Delta V_{S2})\frac{\sqrt{I_2} - \sqrt{I_{ZTC}}}{\sqrt{I_2} - \sqrt{I_C}} \qquad \Delta|V_t| = \Delta V_{S,ZTC} + \frac{\Delta V_{S2}^0 - \Delta V_{S,ZTC}}{1-\sqrt{\dfrac{I_2}{I_{ZTC}}}}$$

Thermal compensation with two identical devices

- Sensing: Two identical pMOS with different sensibilities.
- Readout: Differential measurement.



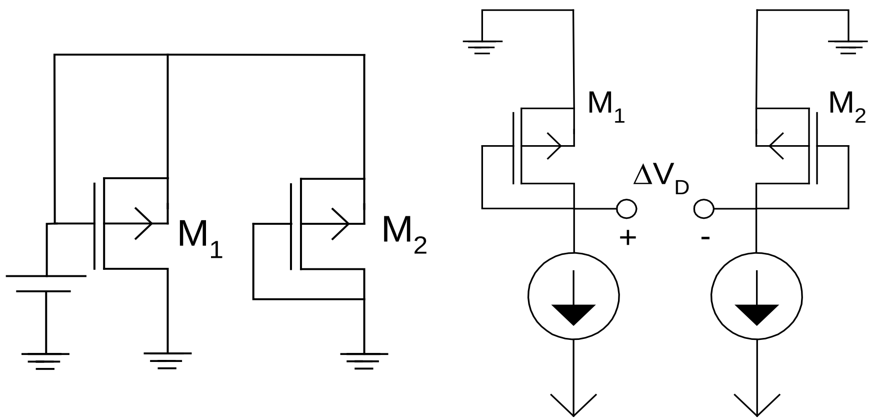
During irradiation



Read-out configuration

Thermal compesation using two identical devices

- During irradiation: Two different bias voltage, therefore different sensitivity to radiation
- The readout is carried out with the same conditions minimizing the interference of the temperature.



During irradiation

Read-out configuration

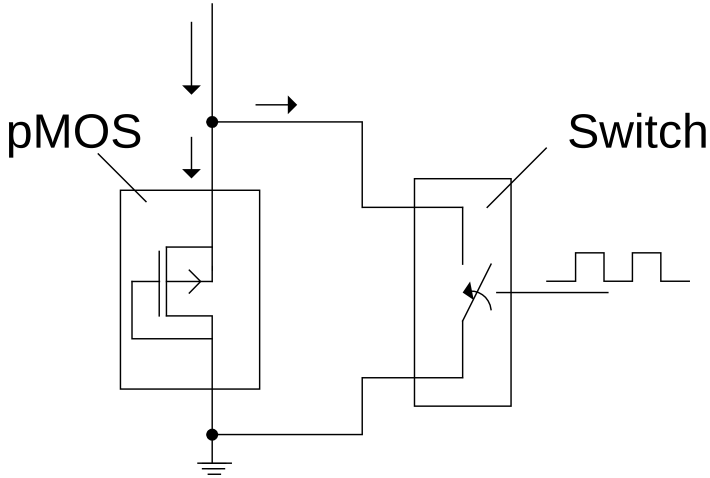
$$\left.\begin{aligned}\Delta V_{S1} &= S_1 D \\ \Delta V_{S2} &= S_2 D\end{aligned}\right\} \Rightarrow \Delta V_D = (S_1 - S_2) D$$

Thermal compensation techniques: Summary

- ONE TRANSISTOR (Lateral MOSFET):
  - One current: I_{ZTC}.
  - Two currents: Out of I_{ZTC} zone.
  - Three currents: I_{ZTC} and two currents for thermal compensation and linear range improvement.
- TWO TRANSISTORS:
  - Different bias voltages during irradiation and differential measurements.

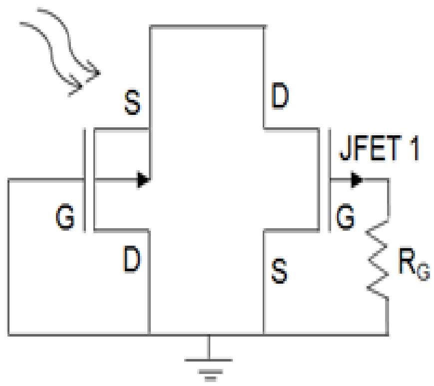
PROCEDURES OF MEASUREMENT
Pulsed biasing (PB)

- **SNR improvement**
  - Read-time instabilities caused by low frequency noise (LFN) (due to near-interface and interface traps)
  - How can LFN be reduced? Chopping the drain current as in other experimental techniques (i.e. spectroscopy) and averaging

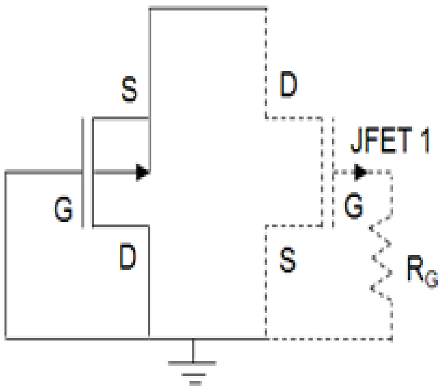


Sensor module

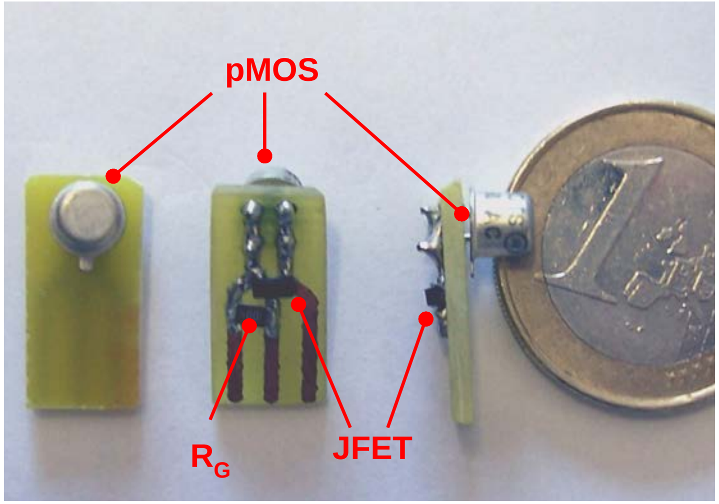
- **Unbiased mode**
  - JFET as a switch (shortcircuited during irradiation and storage and open during read-out)



Irradiation and storage

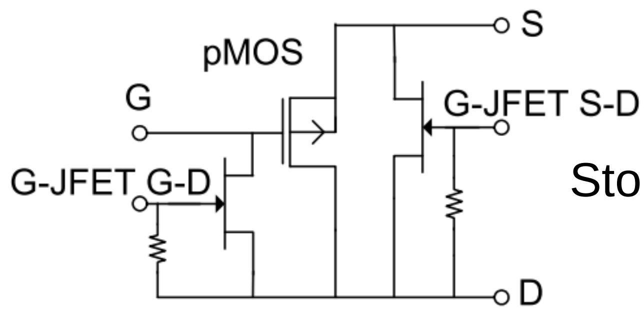


During readout



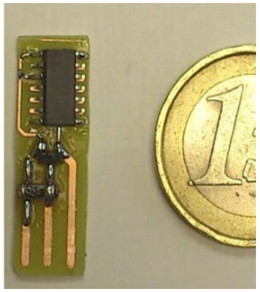
Sensor module

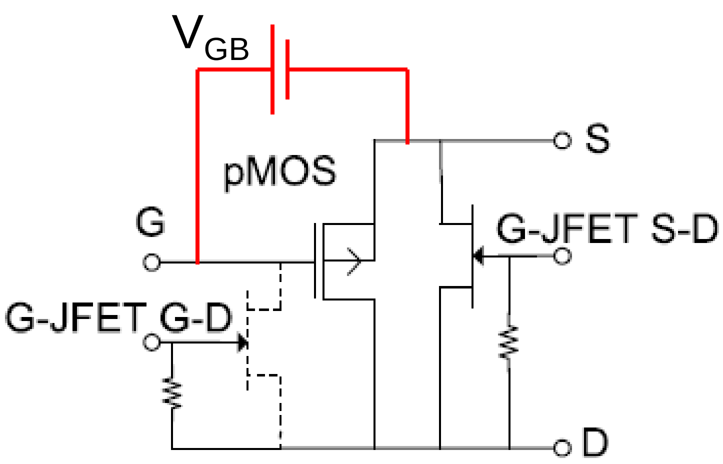
- **Biased mode:** Two JFET as switches



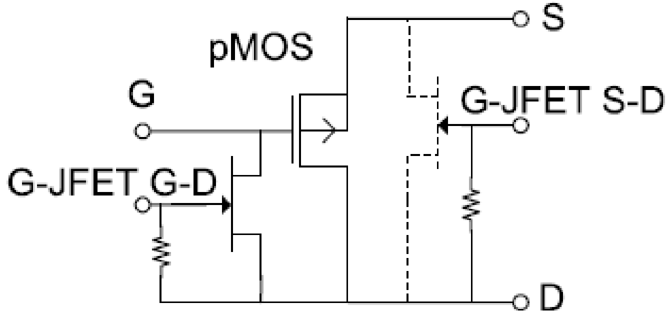
Storage

CD4007



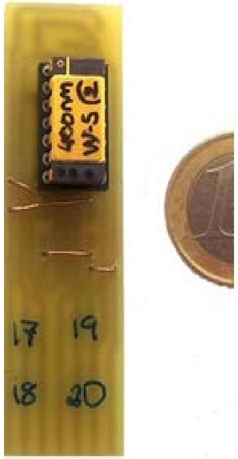


Irradiation



Readout

RADFET

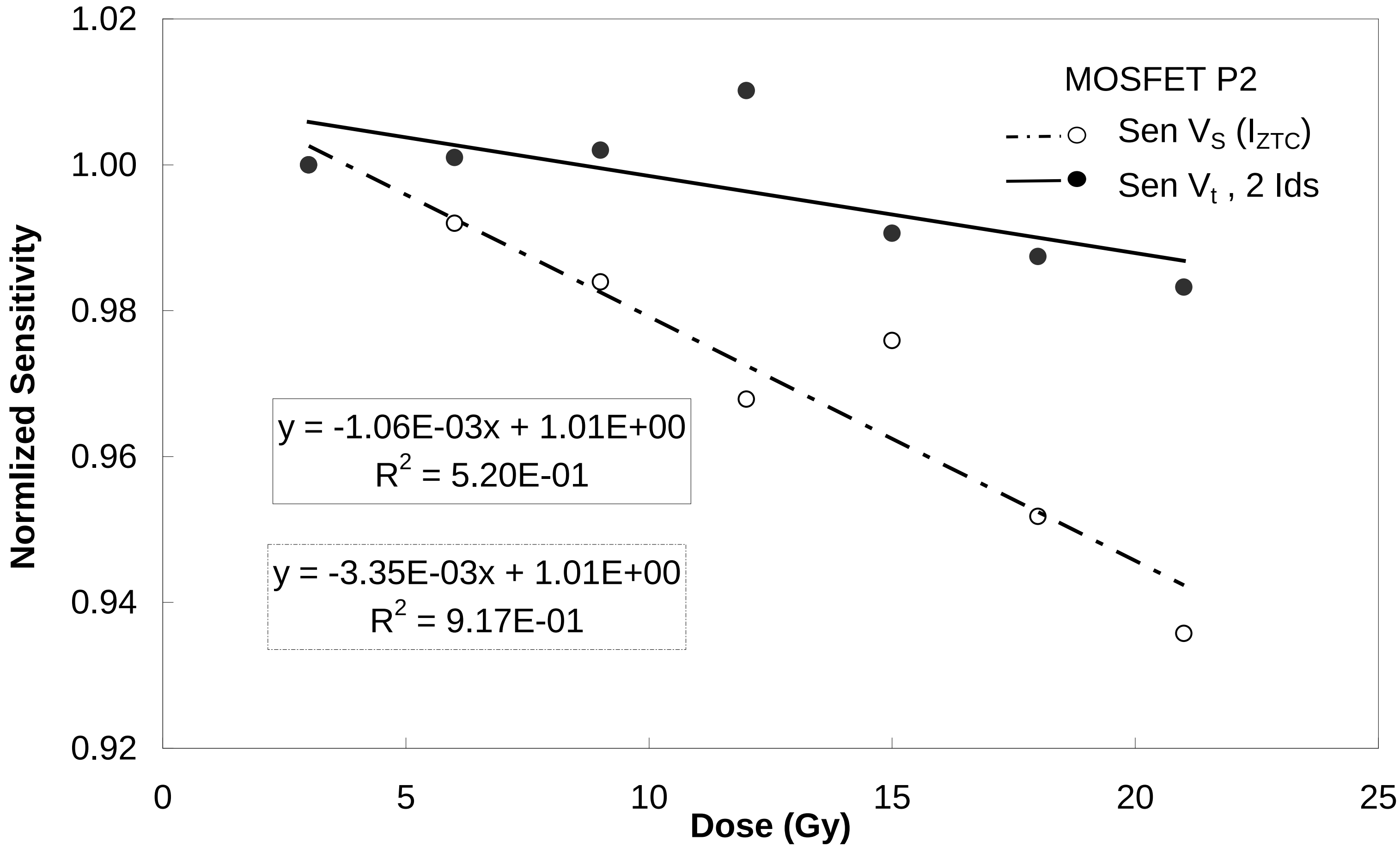


Readout process: deferred mode

- **Dose measurement process**
  - Zeroing:
    - Measurement and storage of pre-irradiation V_S at the two (three) drain currents
  - Irradiation
  - Timeout for short-term fading (2-3 minutes)
  - Dose measurement
    - Recovery of the pre-irradiation values from the memory.
    - Measurement and storage of the post-irradiation V_S at the two (three) currents
    - Dose calculation (calibration is required)

Results for 3N163 (unbiased and deferred mode): (PB+2CM)

- **Linearity improvement**
  - Irradiation source: Siemens KDS-6MV.



Results for 3N163 (unbiased and deferred mode): (PB+2CM)

- **Linearity improvement**
  - Sensitivity decay coefficient, mean sensitivity and the linear limit (up to 5%).

	DC modes		PB	
	I_{ZTC}	2CM	I_{ZTC}	2CM
m (mV/Gy^2)	-0.153	-0.095	-0.113	-0.057
Mean Sensitivity (mV/Gy)	20.6	19.7	20.0	19.2
Linear Range (Gy)	6.8	10.3	8.8	16.8

20 % reduction of SD

$$\sigma_{Vs}^{DC} = 45.8\,\mu V$$

$$\sigma_{Vs}^{PB} = 36.4\,\mu V$$

Experimental results for 3N163 (3CM)

- **Thermal compensation:**
  - Reduction in a factor of 50 in the thermal drift

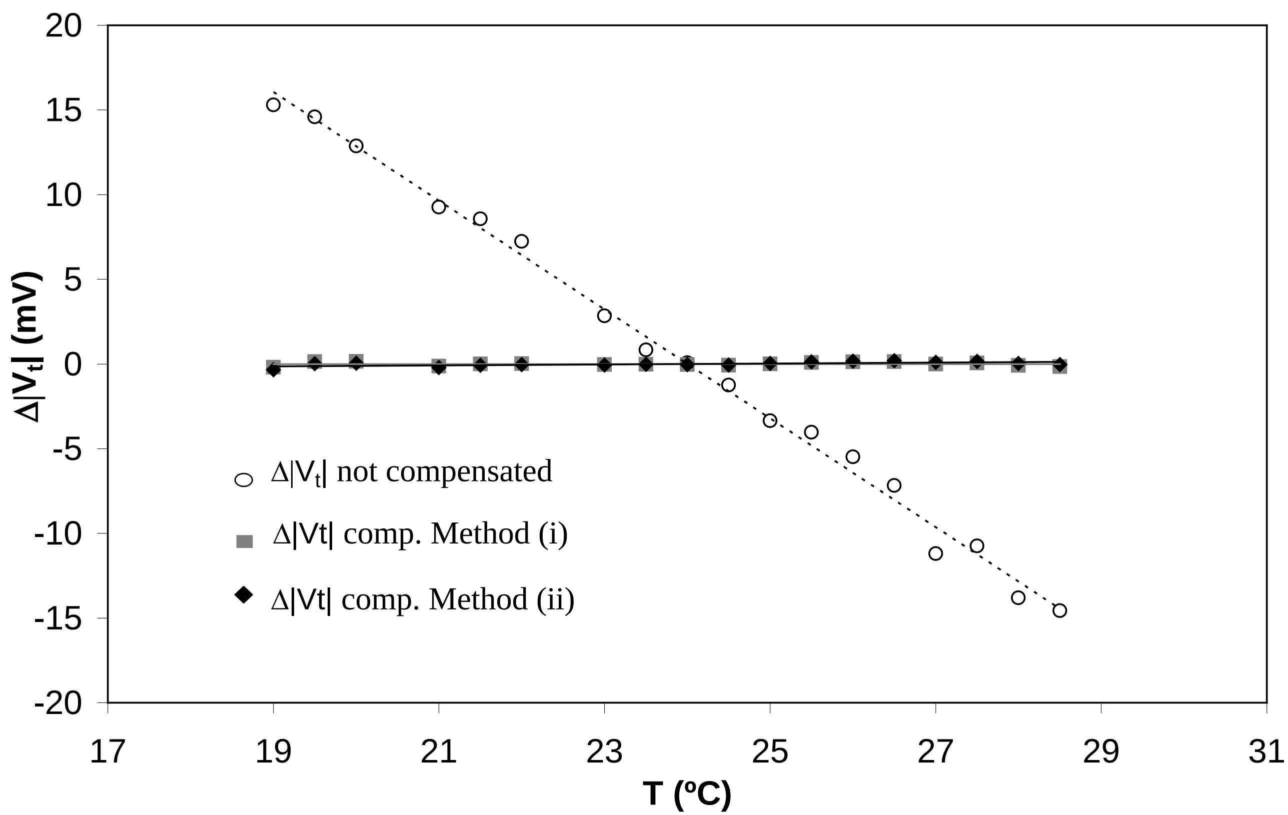
$$I_2 = 30\ \mu A$$

$$I_3 = 120\ \mu A$$

$$I_{ZTC} = 247\ \mu A$$

  - Compensated

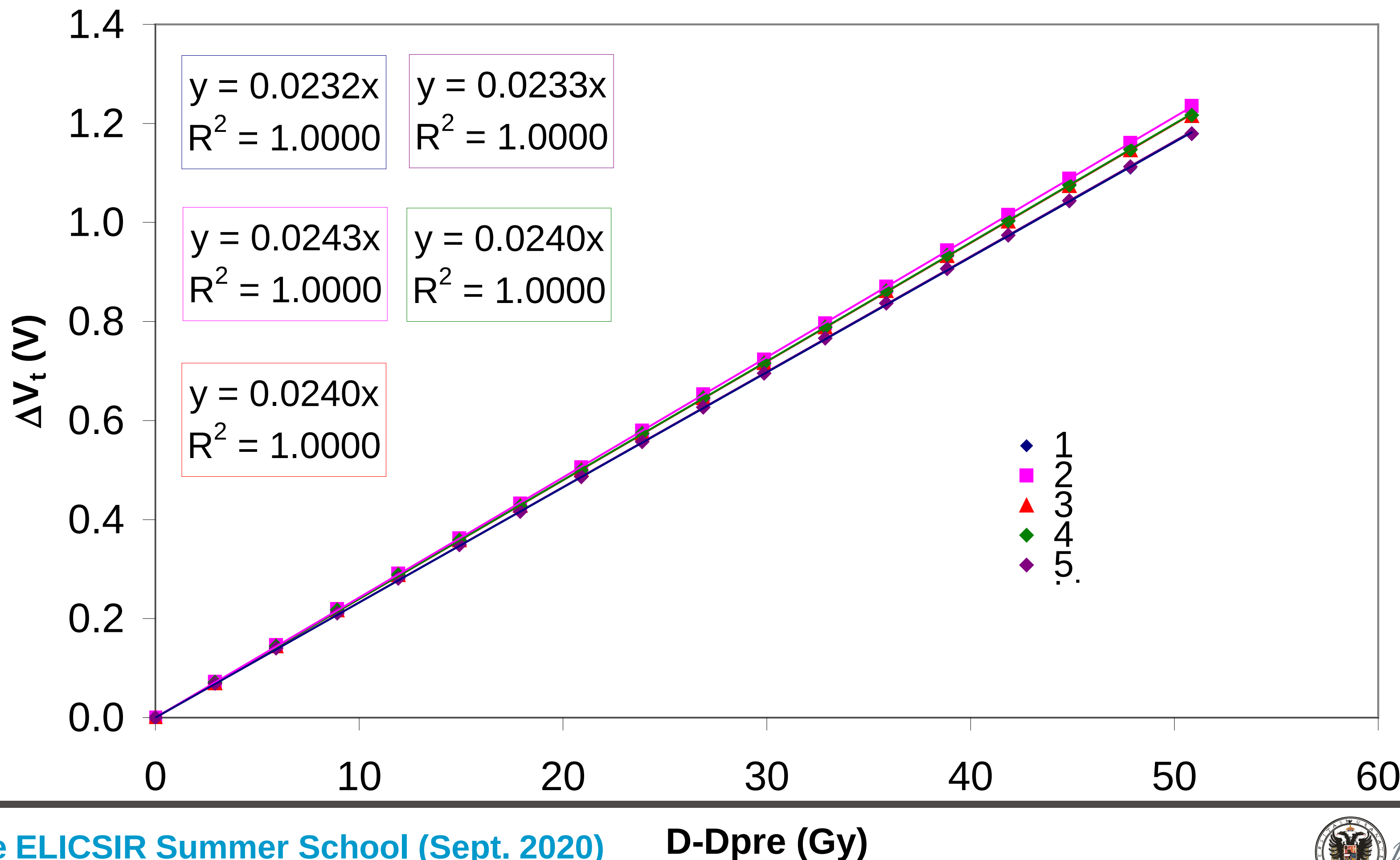
$$\frac{\Delta V_t}{\Delta T} < 70\ \mu V/^{o}C$$



Unbiased and deferred mode (3CM+PB): 3N163

- **Radiation response of 3N163**

Dpre=30 Gy (^{60}Co)



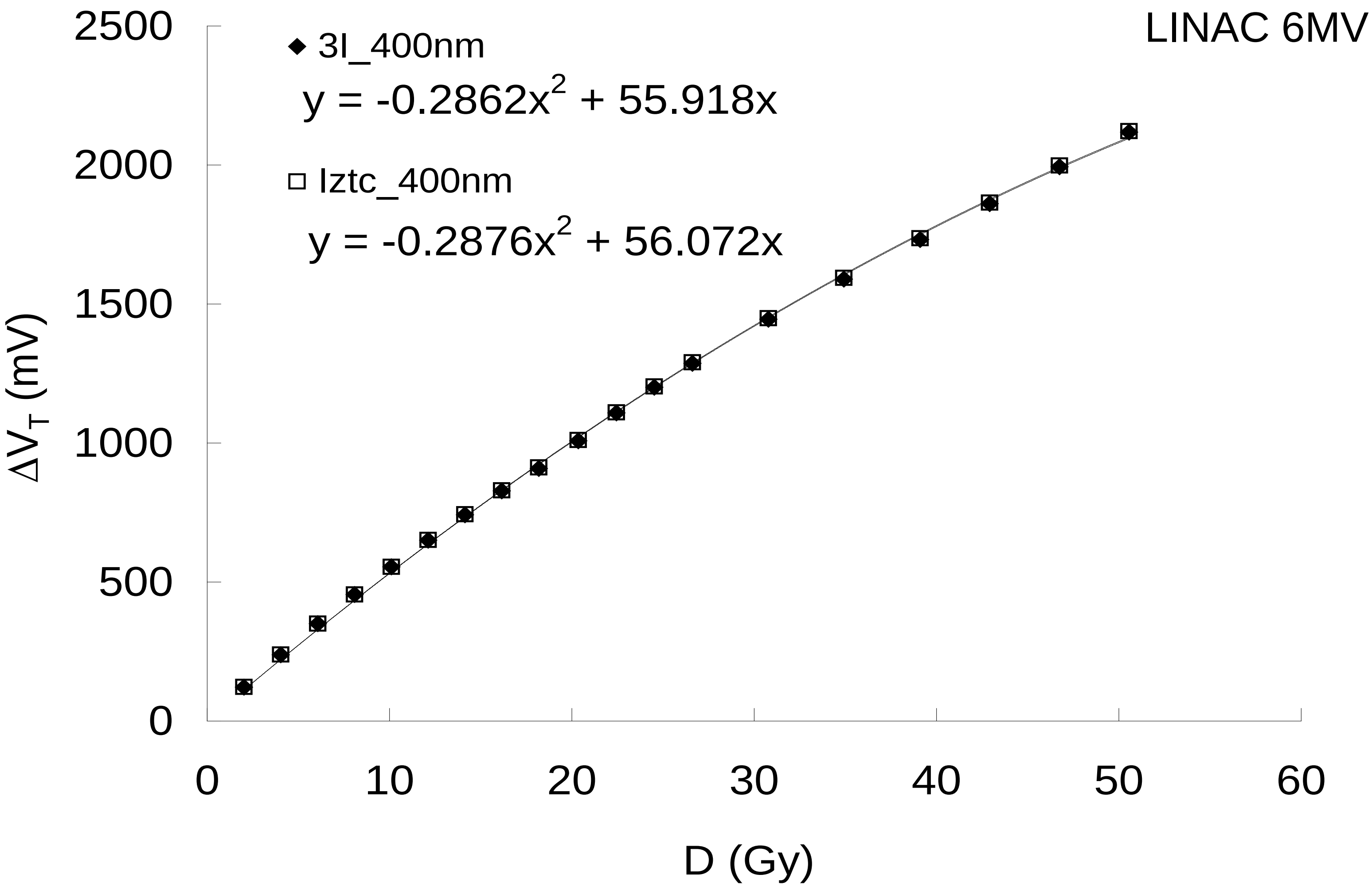
Unbiased and deferred mode (3CM+PB): 3N163

Temperature range	10 – 40 ºC
Resolution	1 cGy
Accuracy	± 3 %
Linear range	15 Gy > 80 Gy*
Thermal drift	< 3mGy/ºC
Delay after irradiation	2 – 3 minutes

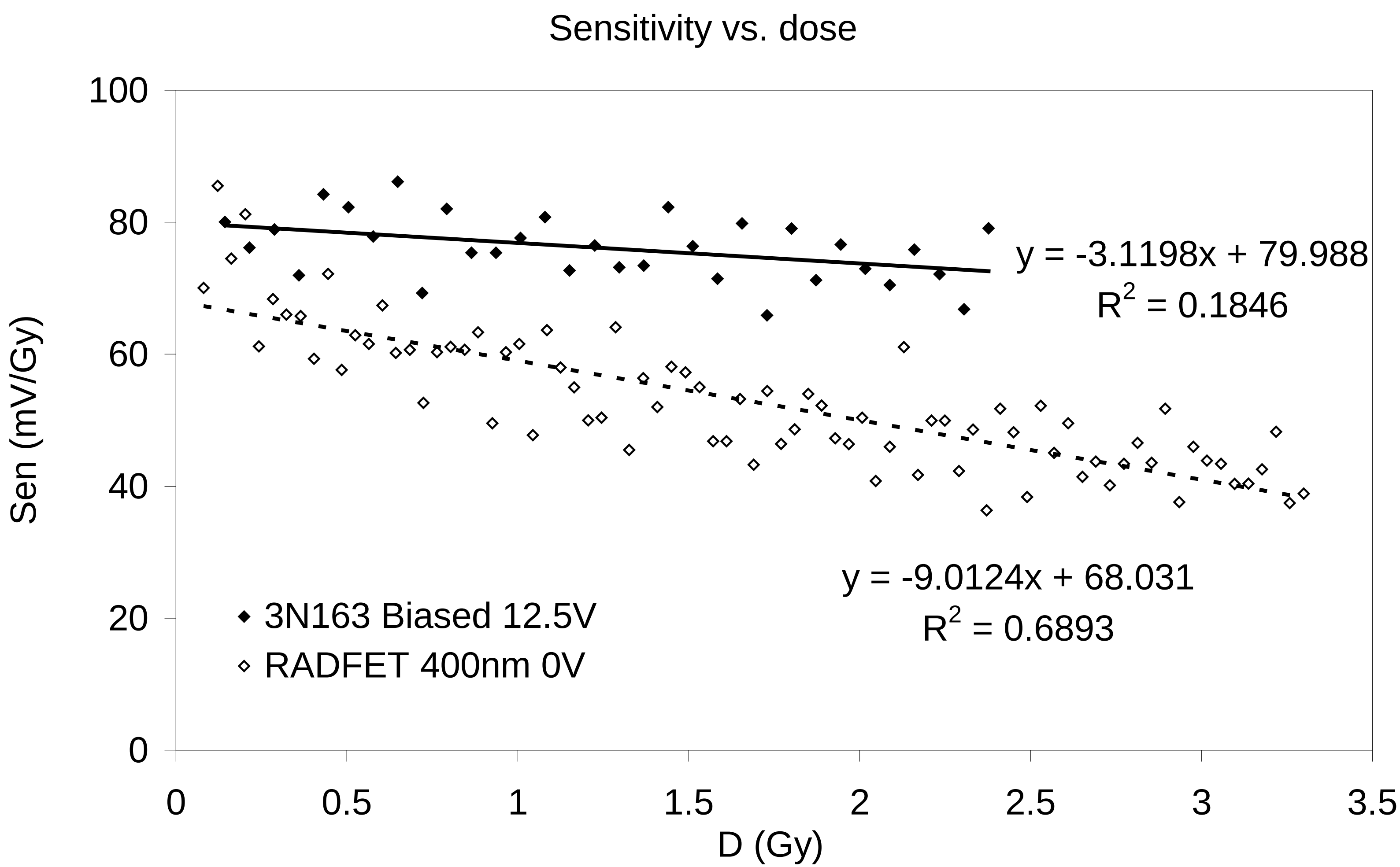
* with recalibrations every 15 Gy

Note: For 3N163 transistor

Dosimetry characterization, results RADFET 400nm



Deferred mode (3CM+PB): Summary



Deferred mode (3CM+PB): Summary

	Sensitivity (mV/Gy)	Bias (V)
CD4007	5.24 ± 0.17	0
3N163	21.5 ± 1.1	0
	48 ± 3	5
	55 ± 3	10
RADFET	55.4 ± 1.2	0

- Thermal model has been applied to RADFETs and lateral commercial transistors
- For RADFETs 3CM and I_{ZTC} method are equivalent
- 3N163 biased at 10 V presents a sensitivity similar to RADFETs of 400 nm in unbiased model, but showing much more fading.

Future talks

- Internal topology of the reader unit will be described
  - Programmable current source
  - Hardware for zeroing and resolution improvement
- Real-time measurements
- DMOS transistor:
  - Thermal compensation
  - Additional hardware required
  - Radiation response
- Etc.


see you in Granada
It´s here!
Thank you
for your attention
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