Compensation of temperature effects in solid state dosimeters

Miguel A. Carvajal – University of Granada

2nd WORKSHOP ELICSIR PROJECT, 9-10.03.2021

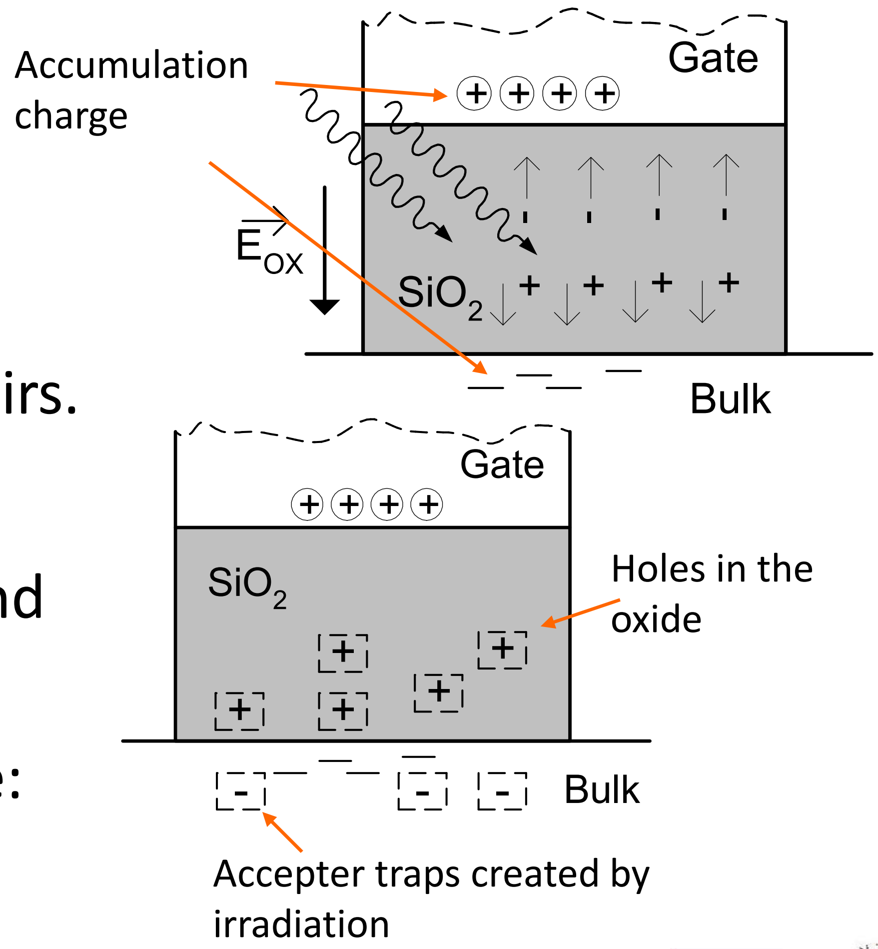
Outline

- Radiation effects in MOSFETs
- MOSFET dosimeter: Read out configuration
- Linear range improvement: two current method
  - Theoretical model
  - Experimental validation: Dose measurements
- Thermal compensation: 3 currents method
  - Theoretical model
  - Thermal compensation: 3 currents method
    - Experimental validation: Temperature and dose response
- Thermal compensation in DMOS Transistors
  - Thermal characterization
  - Thermal compensation using the parasitic diode: Algorithm and experimental validation
  - Dose measurements
- Conclusions

Radiation effects in MOSFETs

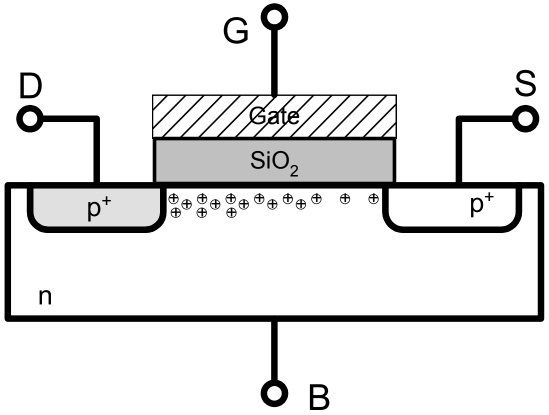
During irradiation:

- Ionizing radiation produces electron-hole pairs.
- Electric field in the oxide separates the pairs.
- Holes drift to Si-SiO2 interface
- Holes are trapped in states in the oxide and near interface
- Traps for electrons near the gate interface:
  Filled<=>Neutral



Radiation effects in MOSFETs

Radiation effects in I-V: $I_D = -\frac{\beta}{2}\left(|V_{GS}| - |V_t|\right)^2$



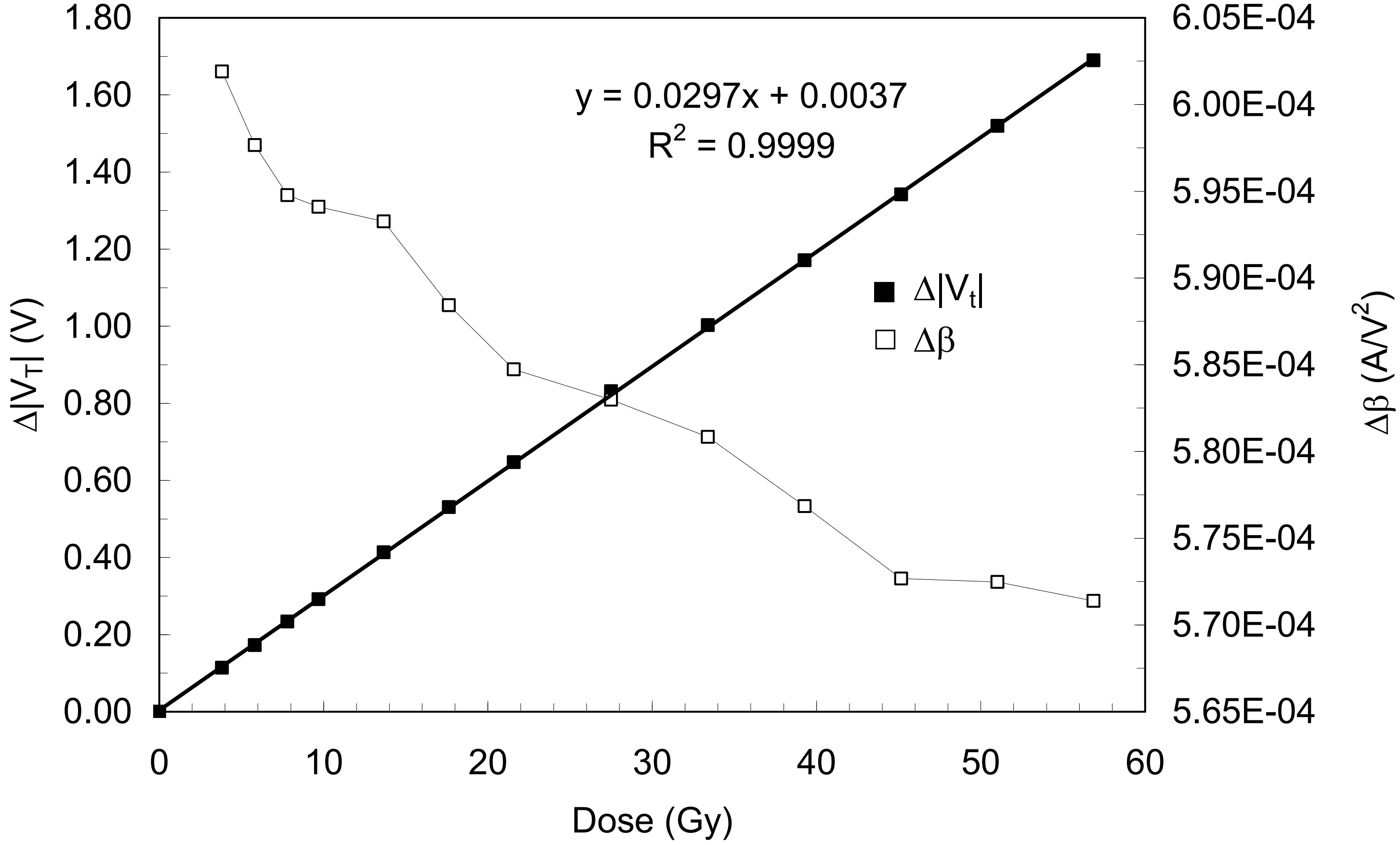
- Holes in the oxide shield the electric field
- If $|V_{GS}| > |V_t|$, interface traps are empty, then positive charge
- Channel carries' mobility is reduced due to charges at the interface traps

$$\boxed{\begin{array}{l}\Delta |V_t| > 0 \\ \Delta\beta < 0\end{array}}$$

Radiation effects in MOSFETs

The lateral pMOS 3N163 of Vishay-Siliconix (USA):

- Nickel encapsulation
- Semicondcutor analyzer, the HP-4145B
- Average sensitivity: ~30mV/Gy



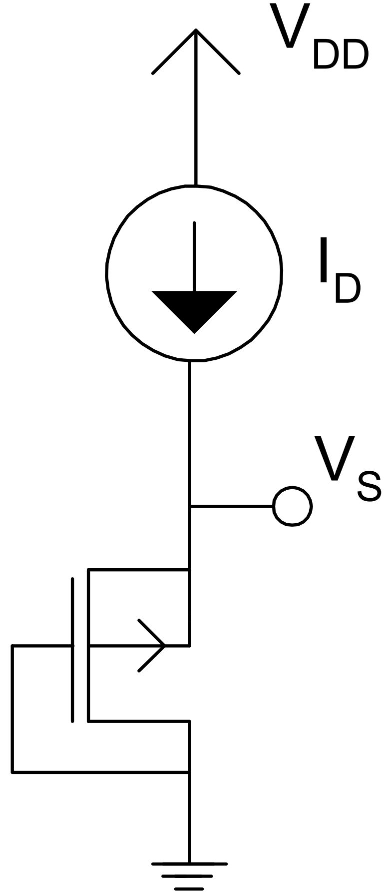
MOSFET dosimeter: Read out configuration

Constant drain current measurement of V_t

- V_{GD}=0 => saturation region:

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

$$\left.\begin{array}{r} If\ \beta \approx cte \quad \Rightarrow \Delta|V_{GS}| \approx \Delta|V_t| \\ V_G = 0 \end{array}\right\} \Rightarrow \boxed{\Delta V_S \approx \Delta|V_t|}$$

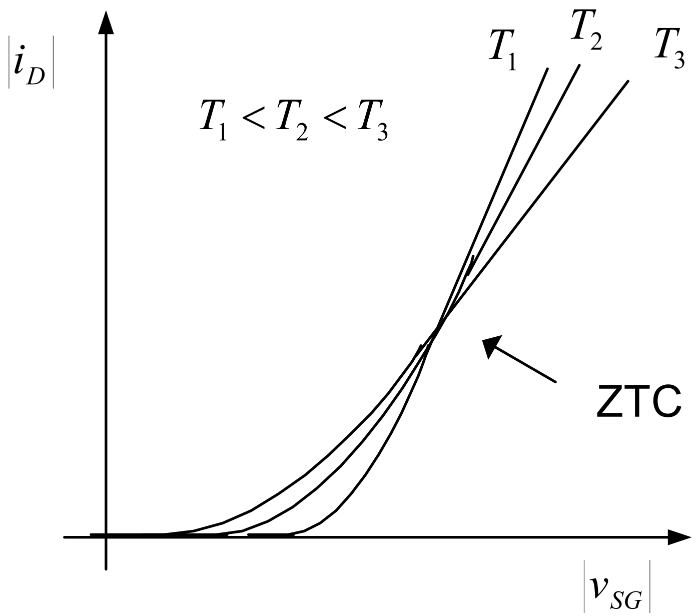


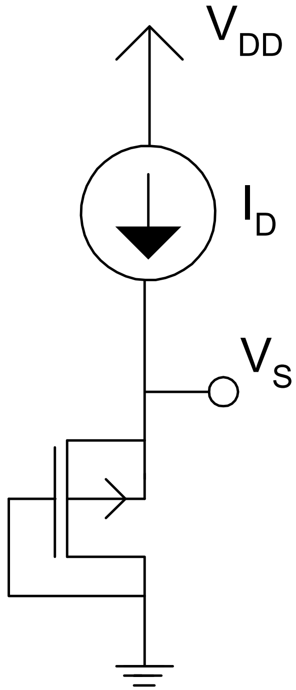
- β parameter reduction diminishes the linear range

MOSFET dosimeter: Read out configuration

The most common thermal compensation techniques (I):

- Using I_{ZTC} (Zero Temperature Coefficient)





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

$$\Downarrow \quad \beta \approx cte$$

$$\boxed{\Delta|V_t| \approx \Delta V_S}$$

Linear range improvement: two current method

- Theoretical model

Single MOSFET with V_{GD}=0

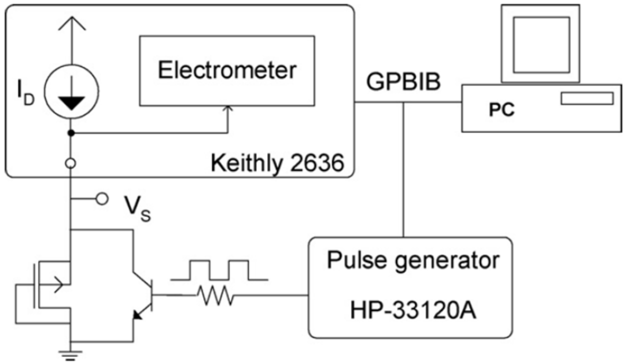
$$I = \frac{\beta}{2}\left(V_S - |V_t|\right)^2 \Rightarrow |V_t| = V_S - \sqrt{\frac{2I}{\beta}} \Rightarrow \left\{ \begin{array}{l} |V_t^{post}| = V_S^{post} - \sqrt{\dfrac{2I}{\beta^{post}}} \\ \\ |V_t^{pre}| = V_S^{pre} - \sqrt{\dfrac{2I}{\beta^{pre}}} \end{array} \right\} \Rightarrow \Delta|V_t|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

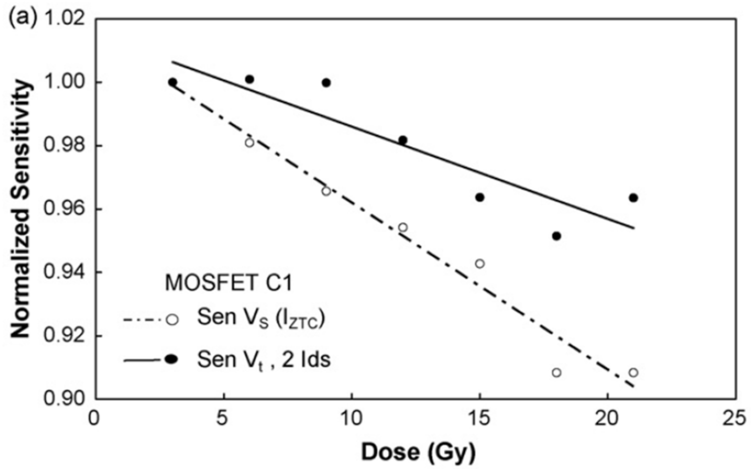
For two currents, we can write:

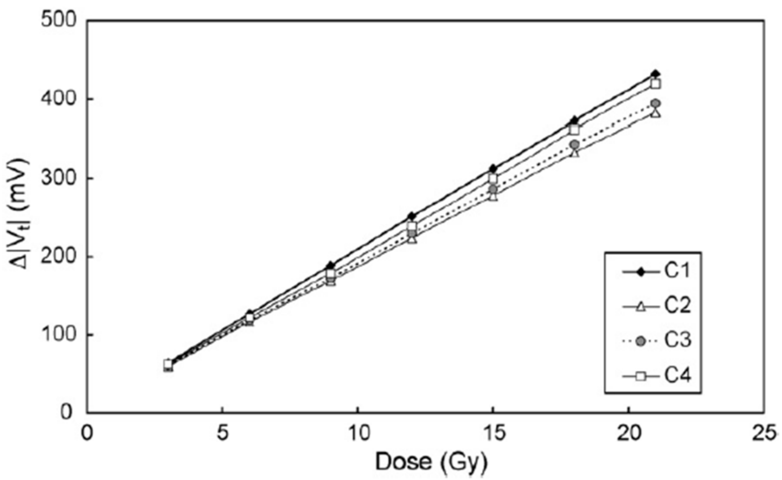
$$\left. \begin{array}{l} \Delta|V_t| = \Delta V_{S1} - \sqrt{2I_1}\left(\sqrt{\dfrac{1}{\beta^{post}}} - \sqrt{\dfrac{1}{\beta^{pre}}}\right) \\ \Delta|V_t| = \Delta V_{S2} - \sqrt{2I_2}\left(\sqrt{\dfrac{1}{\beta^{post}}} - \sqrt{\dfrac{1}{\beta^{pre}}}\right) \end{array} \right\} \Rightarrow \boxed{\Delta|V_t| = \Delta V_{S1} + \frac{\Delta V_{S2} - \Delta V_{S1}}{1 - \sqrt{\dfrac{I_2}{I_1}}}}$$

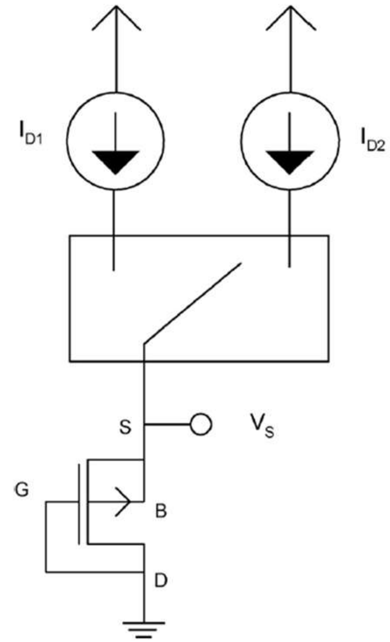
Linear range improvement: two current method

- Experimental validation: Dose measurements

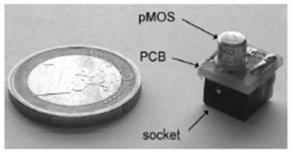








	DC modes	
	I_{ZTC}	Two I_D
m (mV/Gy²)	−0.153	−0.095
Mean sensitivity (mV/Gy)	20.6	19.7
Linear range (Gy)	6.8	10.3



Numerical thermal correction is needed

M.A. Carvajal et al. / Sensors and Actuators A 157 (2010) 178–184

Thermal compensation: 3 currents method

- Theoretical model

Linear thermal model:
$$\Delta V_{S1}(T) = \Delta V_{S1}^0 + \alpha_1 \Delta T$$
$$\Delta V_{S2}(T) = \Delta V_{S2}^0 + \alpha_2 \Delta T$$
$$\Delta|V_t|(T) = \Delta|V_t^0| + \alpha_{|Vt|}\Delta T$$

$$\Delta|V_t| = \Delta V_{S1} + \frac{\Delta V_{S2} - \Delta V_{S1}}{1-\sqrt{\frac{I_2}{I_1}}} \Rightarrow \Delta|V_t| = \Delta V_{S1}^0 + \alpha_1\Delta T + \frac{\Delta V_{S2}^0 + \alpha_2\Delta T - \Delta V_{S1}^0 - \alpha_1 \Delta T}{1-\sqrt{\frac{I_2}{I_1}}} \Rightarrow$$

$$\Rightarrow \Delta|V_t| = \Delta V_{S1}^0 + \frac{\Delta V_{S2}^0 - \Delta V_{S1}^0}{1-\sqrt{\frac{I_2}{I_1}}} + \underbrace{\left(\alpha_1 + \frac{\alpha_2 - \alpha_1}{1-\sqrt{\frac{I_2}{I_1}}}\right)}_{\alpha_{|Vt|}}\Delta T \Rightarrow \alpha_{|Vt|} = \alpha_1 + \frac{\alpha_2 - \alpha_1}{1-\sqrt{\frac{I_2}{I_1}}} \Rightarrow \boxed{\alpha = \alpha_{|Vt|}\left(1-\sqrt{\frac{I}{I_{ZTC}}}\right)}$$

$$I_1 = I_{ZTC} \Rightarrow \alpha_1 = 0$$
$$I_2 = I \Rightarrow \alpha_2 = \alpha$$

Thermal compensation: 3 currents method

- Theoretical model

ΔV_S Thermal compensated

$$\left.\begin{aligned}\Delta V_{S1} &= \Delta V_{S1}^0 + \alpha_1 \Delta T \\ \Delta V_{SC} &= \Delta V_{SC}^0 + \alpha_2 \Delta T\end{aligned}\right\} \Rightarrow \Delta V_{S1} - \Delta V_{SC} = \left(\Delta V_{S1}^0 - \Delta V_{SC}^0\right) + (\alpha_1 - \alpha_2)\Delta T$$

Without radiation: $\Delta V_{S1}^0 \approx \Delta V_{SC}^0$

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

$$\Delta V_{S1}^0 = \Delta V_{S1} - \alpha_1 \Delta T \quad \Rightarrow$$

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

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

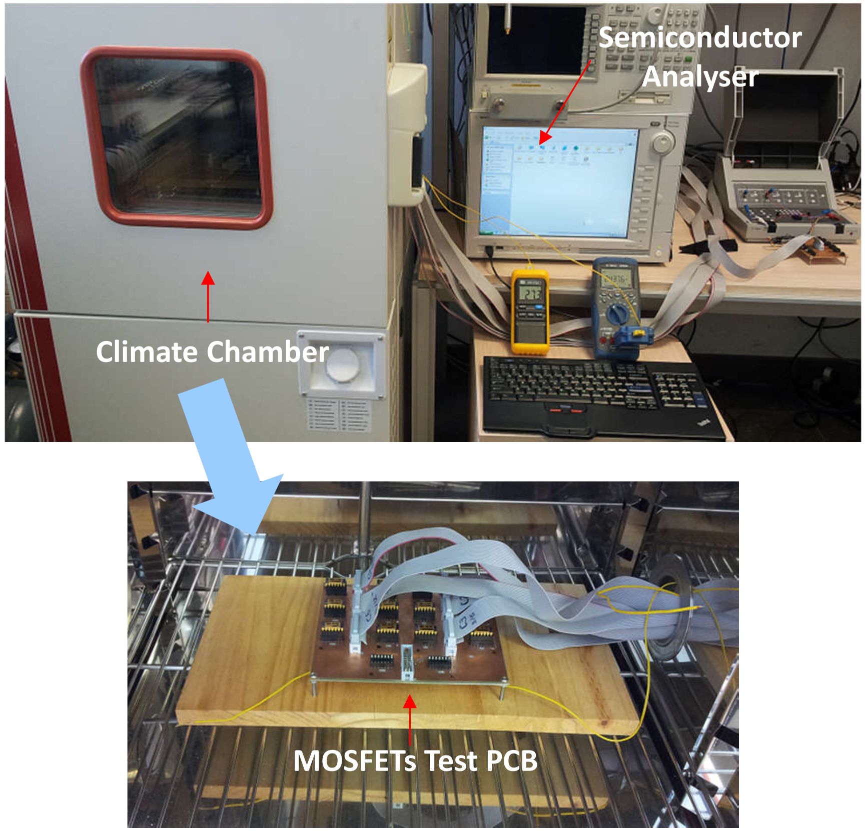
$$\boxed{\Delta V_{S1}^0 = \Delta V_{S1} + \left(\Delta V_{SC} - \Delta V_{S1}\right)\frac{\sqrt{I_1} - \sqrt{I_{ZTC}}}{\sqrt{I_1} - \sqrt{I_C}}}$$

Thermal compensation: 3 currents method

- Theoretical model
  - $\Delta|Vt|$ thermal compensated $\Delta\left|V_t\right| = \Delta V_{S1}^0 + \dfrac{\Delta V_{S2}^0 - \Delta V_{S1}^0}{1 - \sqrt{\dfrac{I_2}{I_1}}}$
  - Simplification $I_{D1} = I_{ZTC}$: $\Delta V_{S1}^0 = \Delta V_{S,ZTC}$
  - Additional current, I_C, to calculate $\boxed{\Delta V_{S2}^0 = \Delta V_{S2} + \left(\Delta V_{SC} - \Delta V_{S2}\right)\dfrac{\sqrt{I_2} - \sqrt{I_{ZTC}}}{\sqrt{I_2} - \sqrt{I_C}}}$
  - Therefore: $\boxed{\Delta\left|V_t\right| = \Delta V_{S,ZTC} + \dfrac{\Delta V_{S2}^0 - \Delta V_{S,ZTC}}{1 - \sqrt{\dfrac{I_2}{I_{ZTC}}}}}$

Thermal compensation: 3 currents method

- Experimental validation

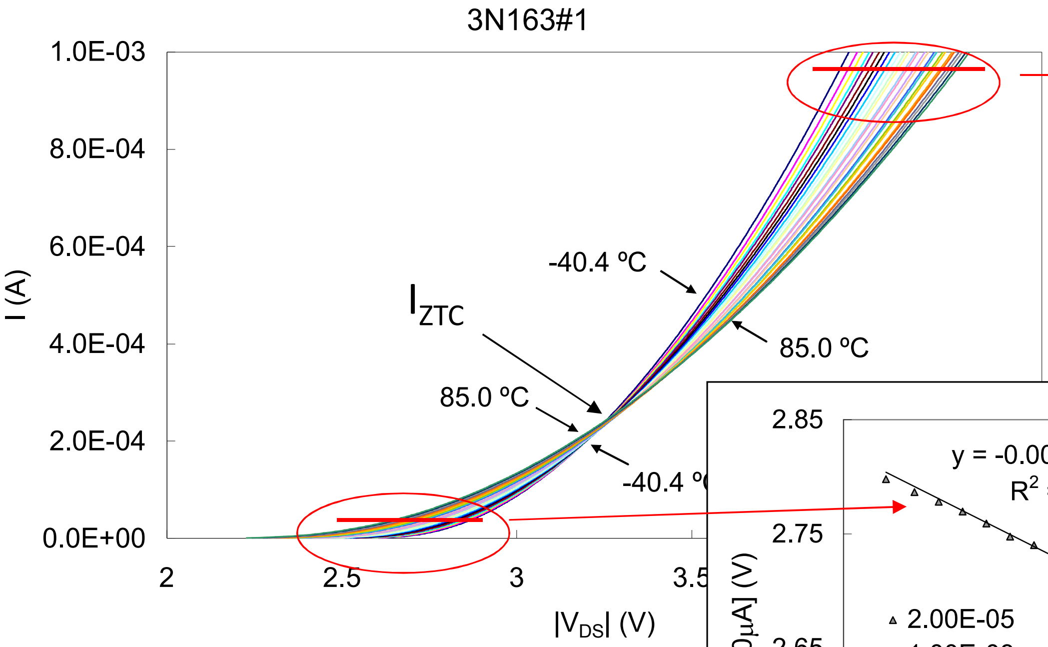


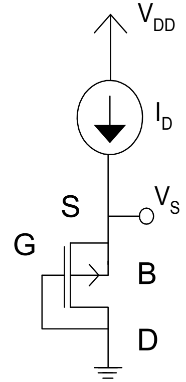
Electrical and thermal Characterization:

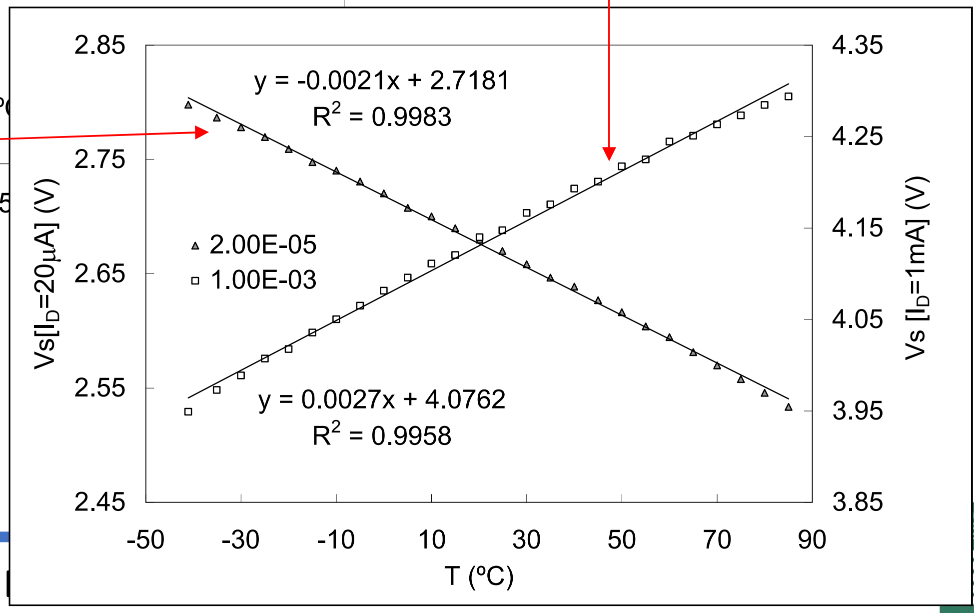
- I-V characteristics at different temperatures
- Extracted by a B1500 Semiconductor Analyser.
- Temperature controlled in a climate chamber (VCL4006 Vötsch)
- Lateral transistors:
  - 3N163: Vishay Siliconix.
  - 3N170: Linear Systems.
  - RADFETs from Tyndall.

Thermal compensation: 3 currents method

- Experimental validation





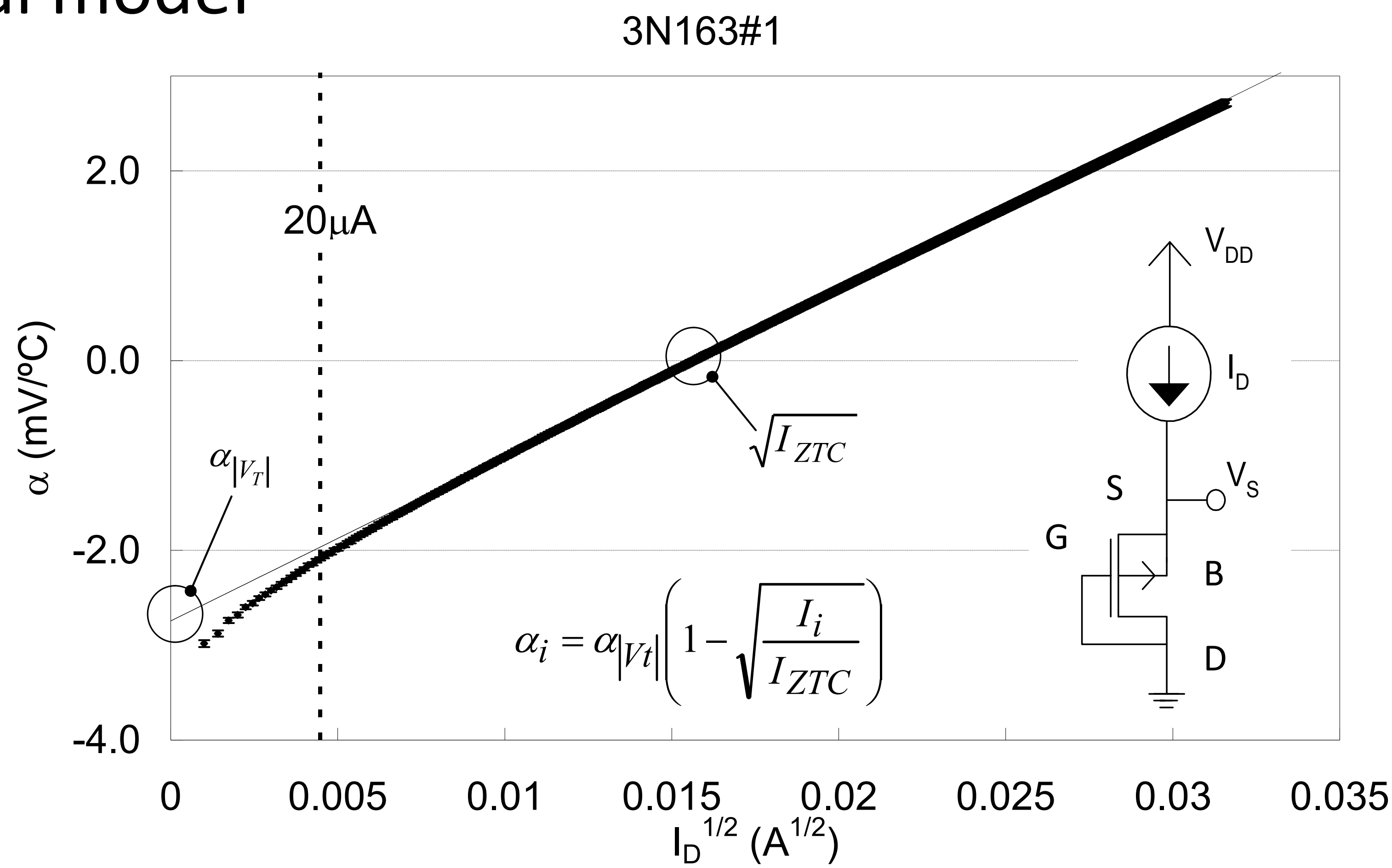


$$\alpha_i = \alpha_{|Vt|}\left(1-\sqrt{\frac{I_i}{I_{ZTC}}}\right)$$

3N163 from Vishay

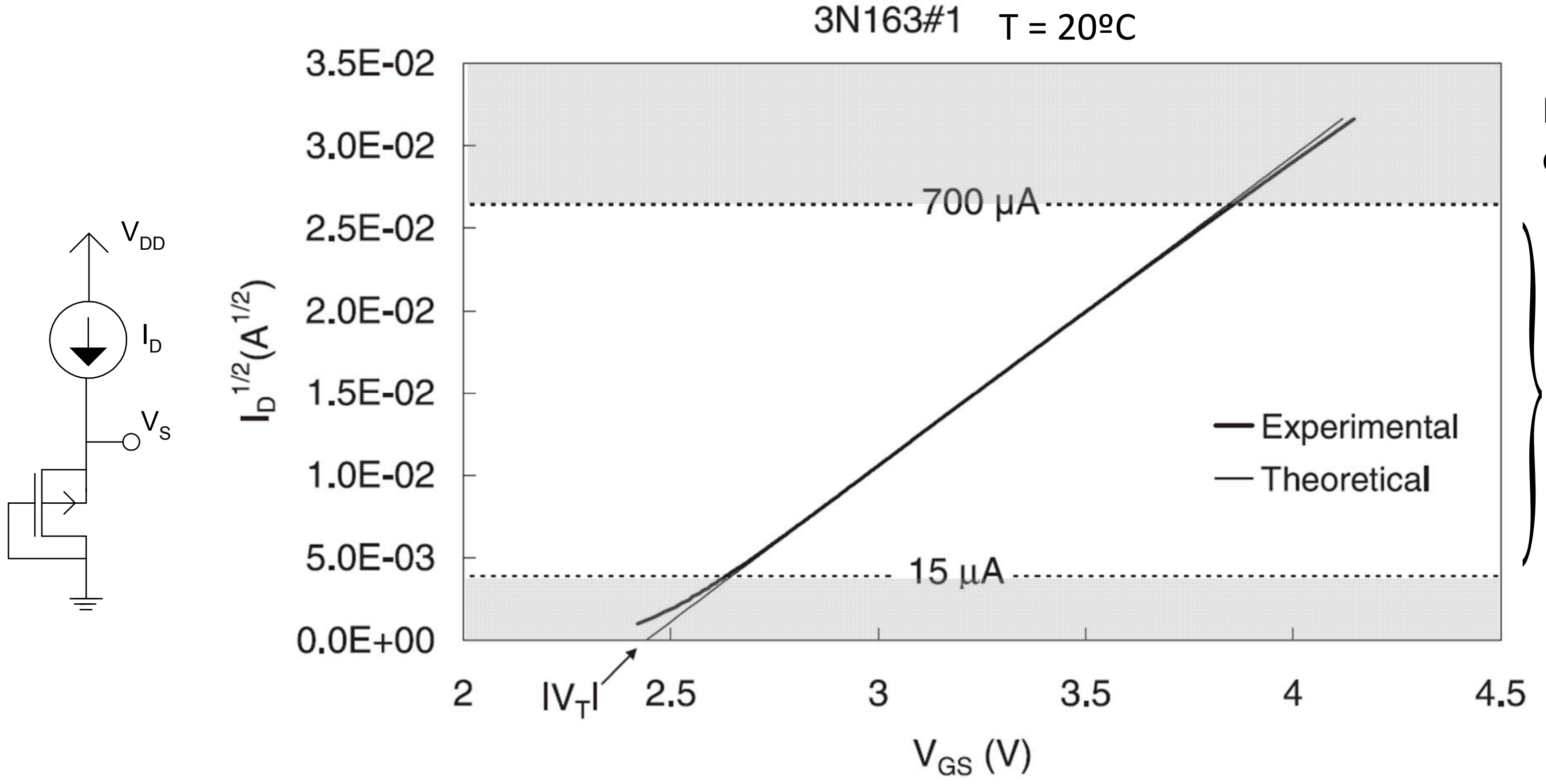
Thermal compensation: 3 currents method

- Thermal model



Thermal compensation: 3 currents method

- Saturation model, current limitations:



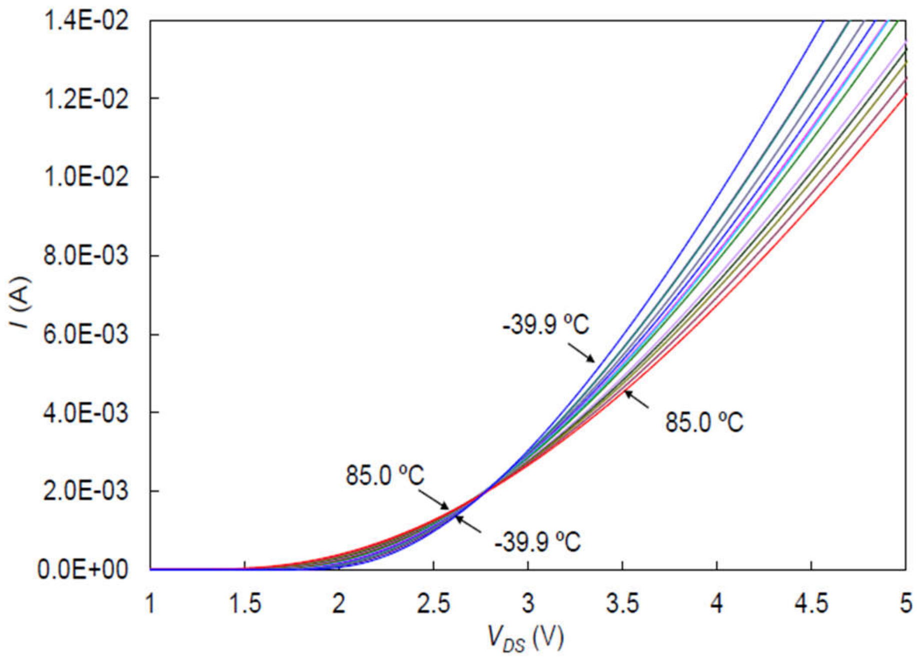
$$I_D = \frac{\beta}{2}\left(V_S - |V_t|\right)^2$$

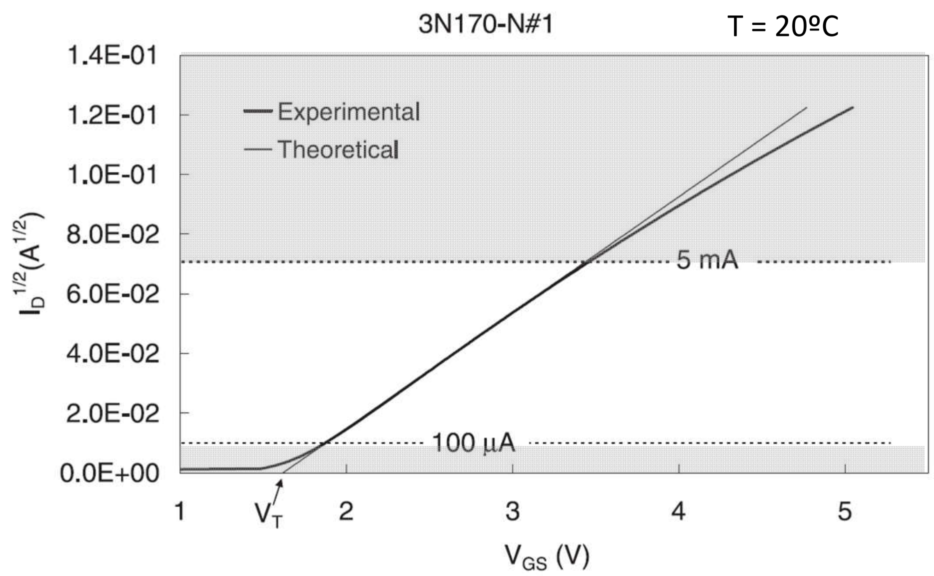
M A Carvajal *et al* Semicond. Sci. Technol. **29** (2014) 095017

Thermal compensation: 3 currents method

- Experimental validation

3N170 #1





Modulation channel effects

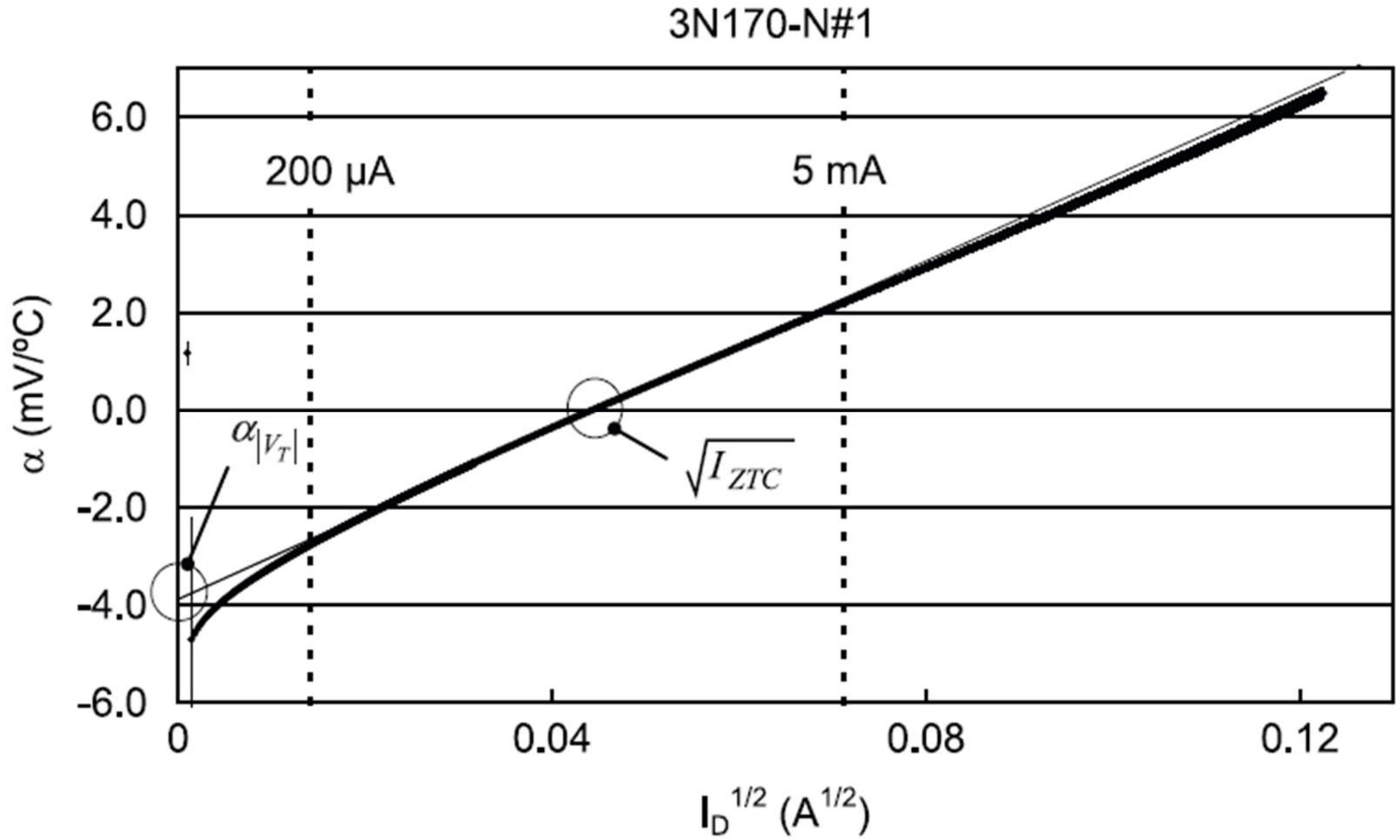
$$I_D = \frac{\beta}{2}\left(V_S - |V_t|\right)^2$$

Weak inversion

3N170 from Linear Systems

Thermal compensation: 3 currents method

- Thermal model



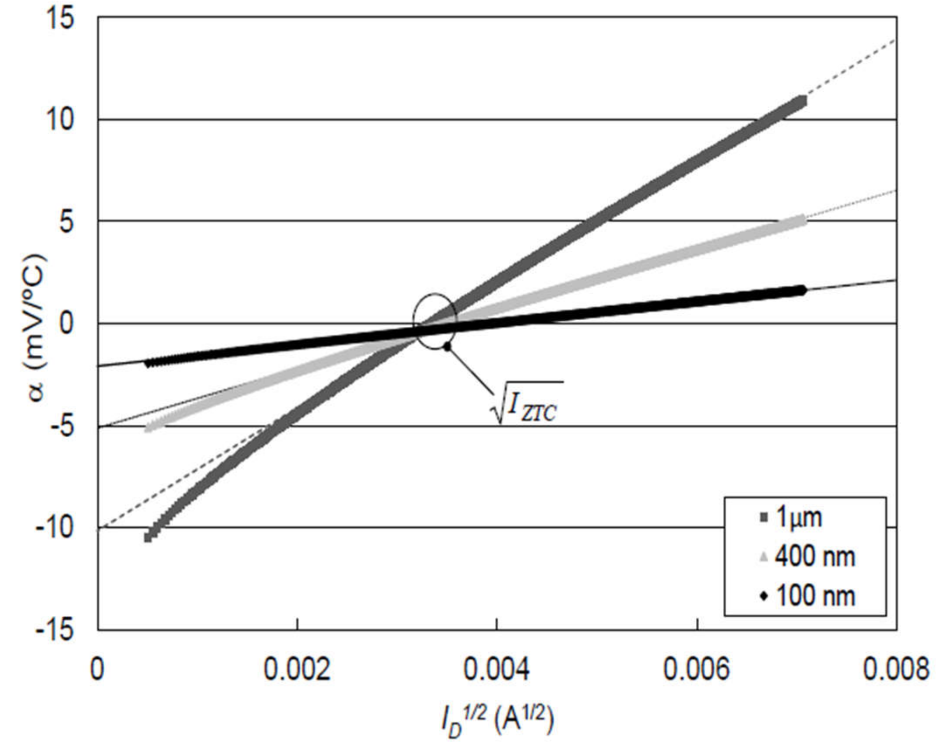
Thermal compensation: 3 currents method

- Thermal model limitations
  - Low currents → Weak inversion.
  - High currents → Modulation channel effects, self-heating.
  - Ranges:
    - 3N163: From 20 μA to 1000 μA
    - 3N170: From 200 μA to 5 mA
  - **This model can be applied to any lateral MOSFET transistor**

Transistor	Parameter	Average
3N163	$\alpha_{\lvert Vt \rvert}$ (mV/K)	-2.74 ±0.07
	I_{ZTC} (μA)	243±7
3N170	$\alpha_{\lvert Vt \rvert}$ (mV/K)	-3.92 ±0.12
	I_{ZTC} (mA)	2.03±0.06

Thermal compensation: 3 currents method

- Application in RADFETs

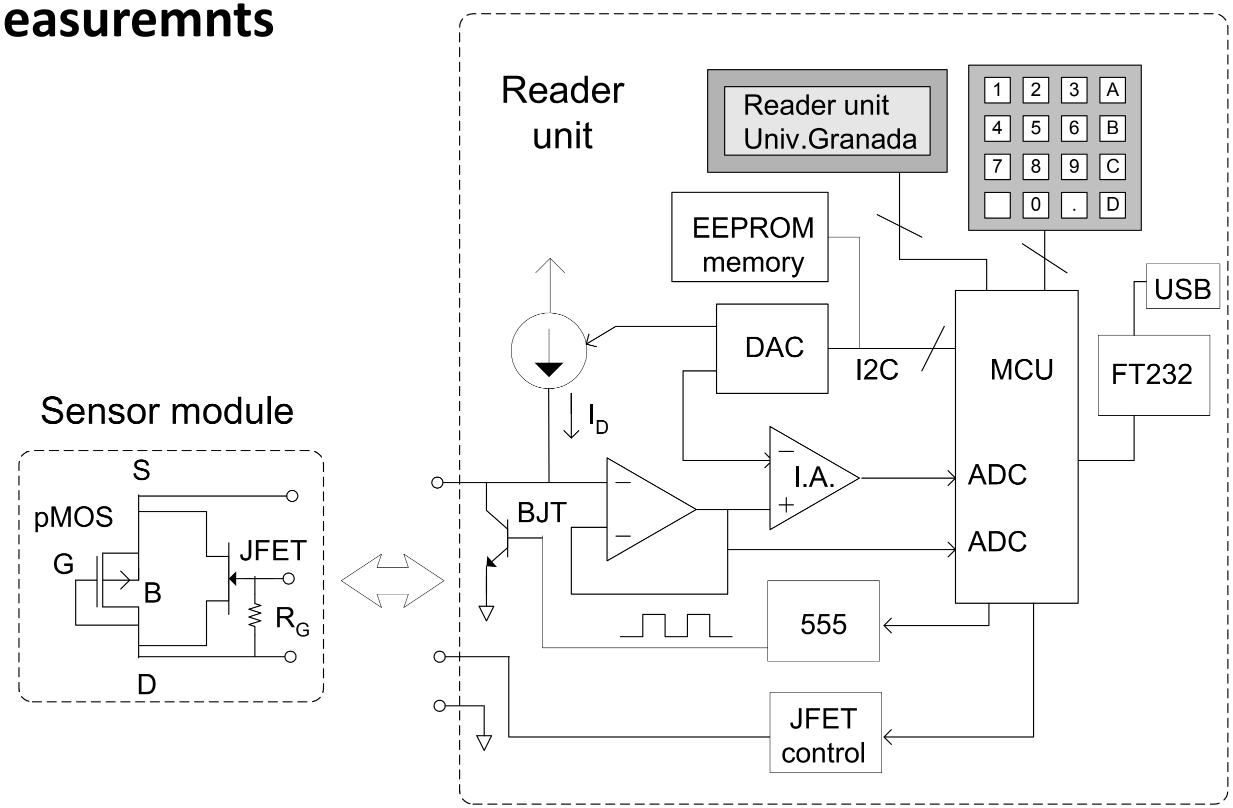


RADFETs from Tyndall Institute.

W/L = 300/50

Thermal compensation: 3 currents method

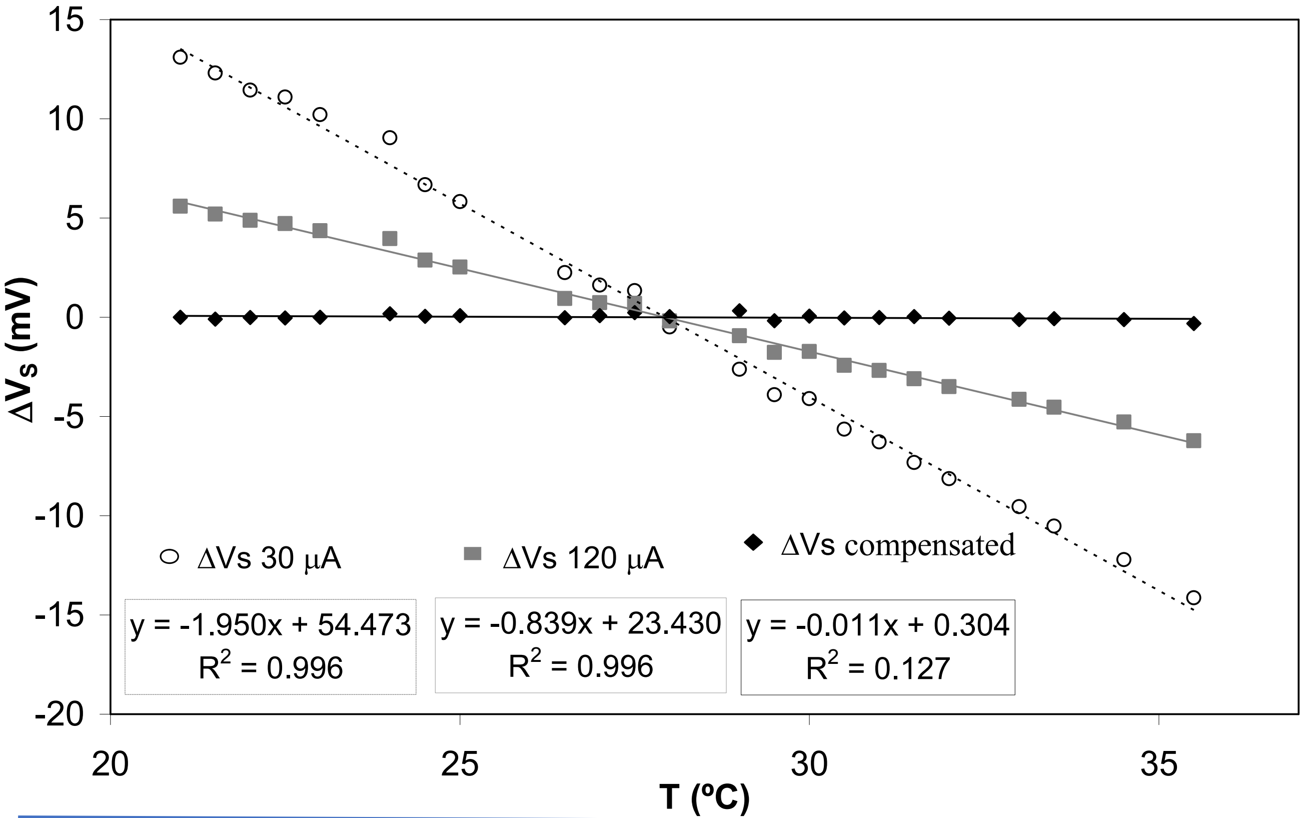
- **Experimental validation: Dose measuremnts**



M.A. Carvajal et al. / Sensors and Actuators A 182 (2012) 146–152

Thermal compensation: 3 currents method

- Experimental validation



$$\boxed{\frac{\Delta V_{S1}^0}{\Delta T} < 70\ \mu V/^oC}$$

$$I_1 = 30\ \mu A$$

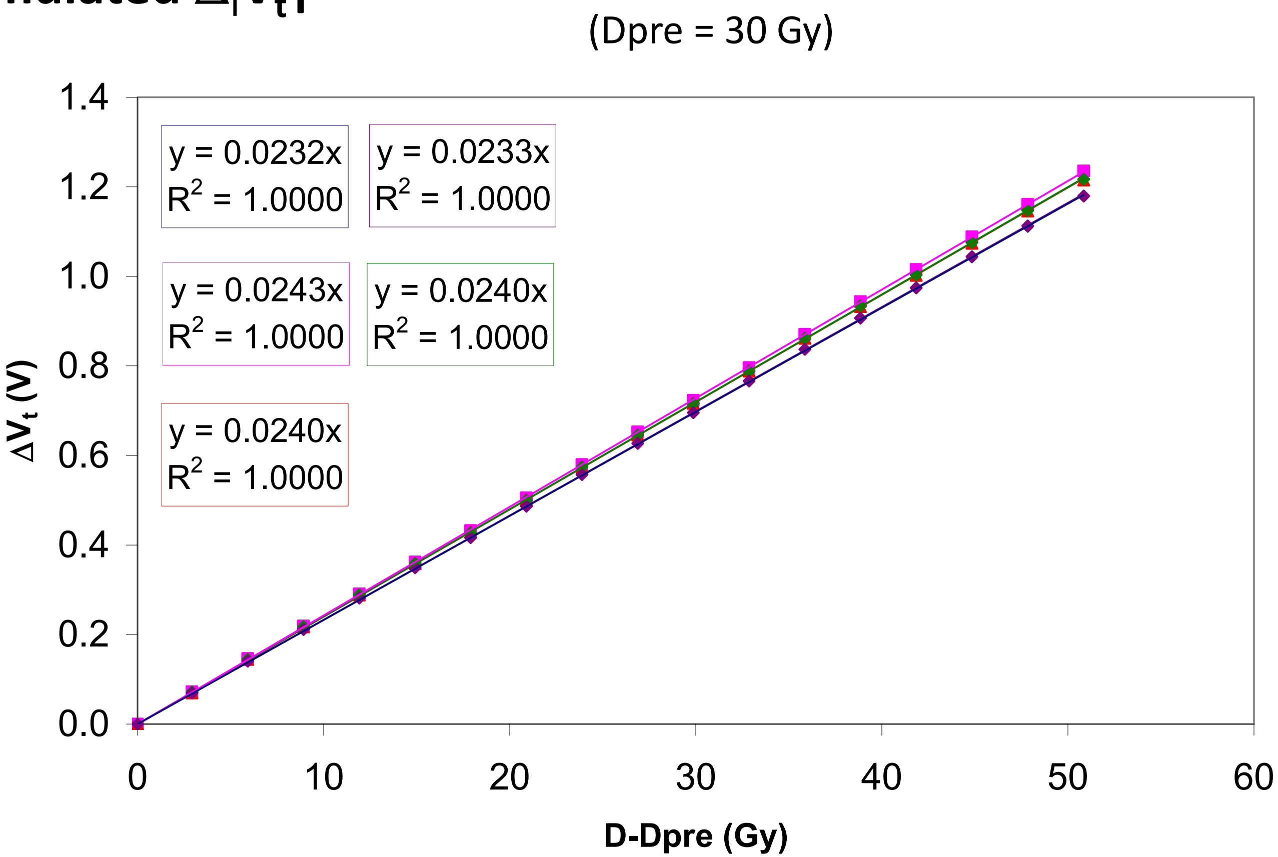
$$I_C = 120\ \mu A$$

$$I_{ZTC} = 225\ \mu A$$

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

Thermal compensation: 3 currents method

Accumulated $\Delta|V_t|$



3N163 from Vishay

Thermal compensation: 3 currents method

- **One current:**
  - To thermal compensation $I_D=I_{ZTC}$. (traditional mode) or using the thermal coefficient to carry out numerical compensation
- **Two currents:**
  - To increase the linear range use

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

  - To thermal compensation (without using I_{ZTC})

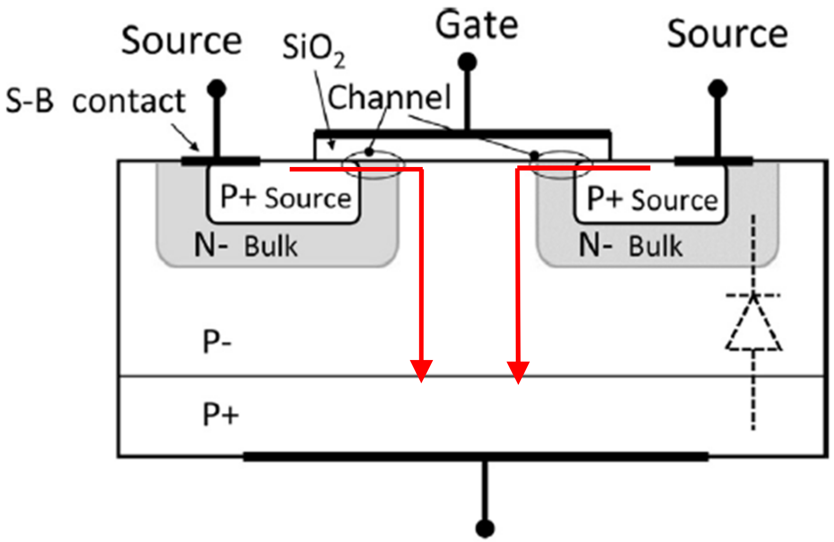
$$\Delta V_{S1}^0 = \Delta V_{S1} + (\Delta V_{SC} - \Delta V_{S1})\frac{\sqrt{I_1} - \sqrt{I_{ZTC}}}{\sqrt{I_1} - \sqrt{I_C}}$$

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

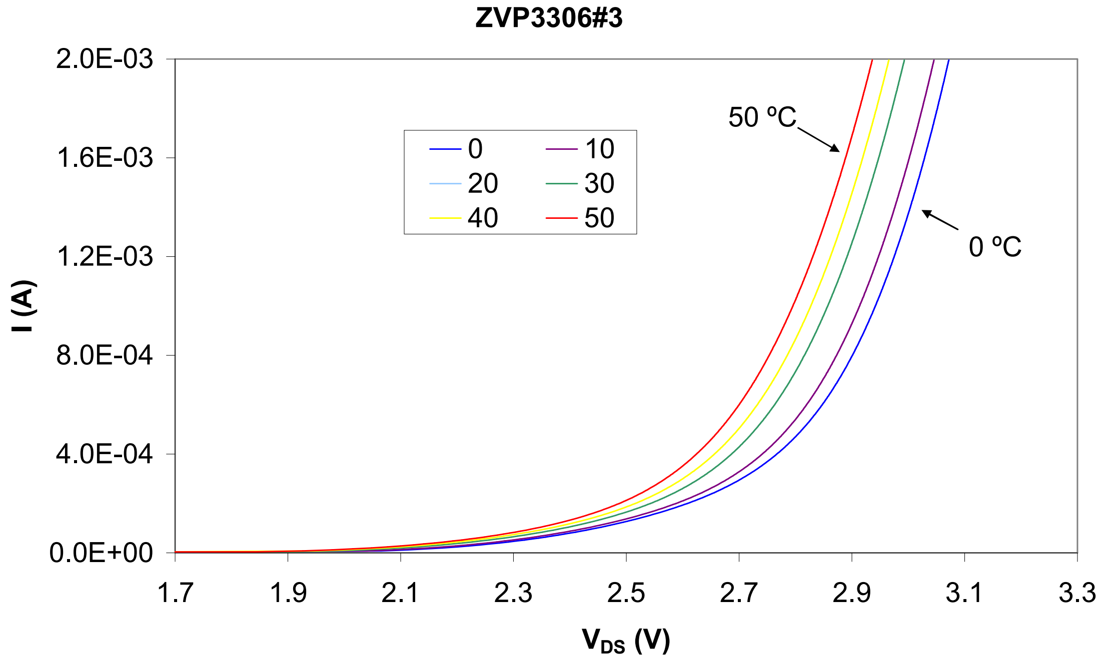
$$\Delta V_{S2}^0 = \Delta V_{S2} + (\Delta V_{SC} - \Delta V_{S2})\frac{\sqrt{I_2} - \sqrt{I_{ZTC}}}{\sqrt{I_2} - \sqrt{I_C}} \qquad \Delta|V_t| = \Delta V_{S,ZTC} + \frac{\Delta V_{S2}^0 - \Delta V_{S,ZTC}}{1 - \sqrt{\frac{I_2}{I_{ZTC}}}}$$

Thermal compensation in DMOS Transistors

- Thermal characterization
  - ZVP3306 manufactured by Vishay-Siliconix

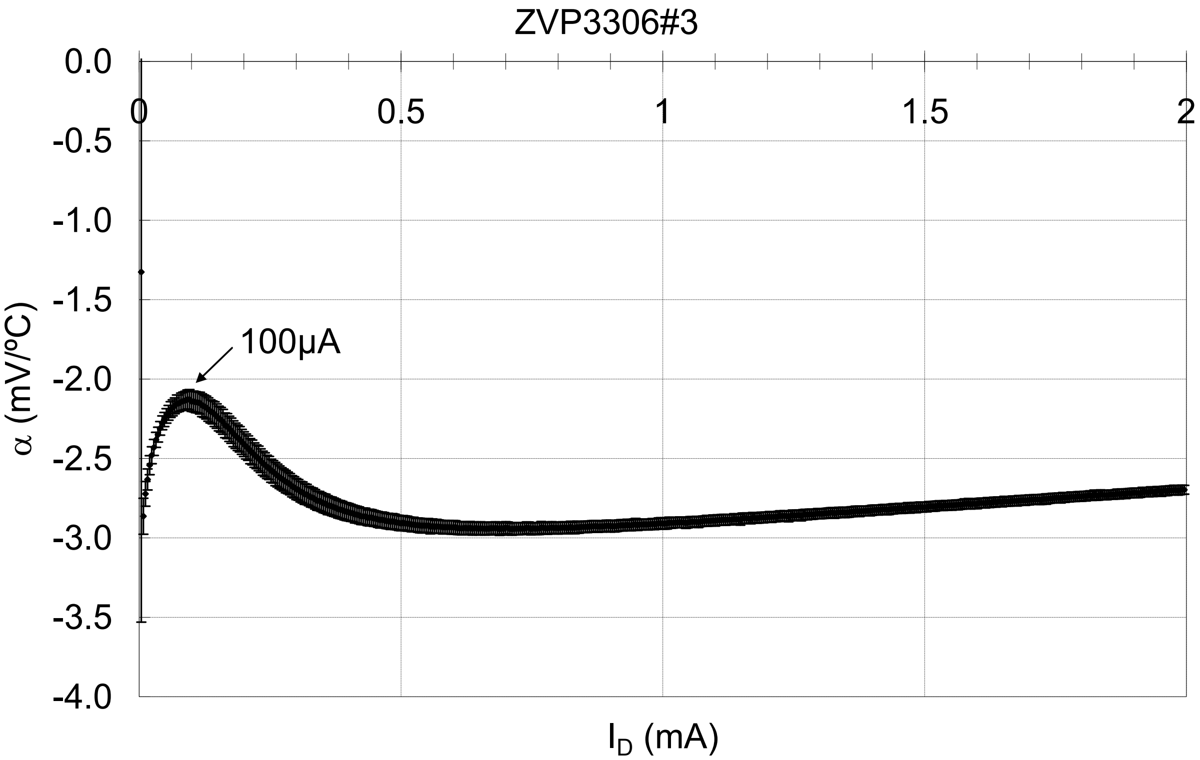


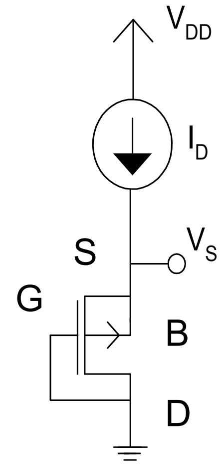
  - I_{ZTC} was not found in the studied current range.



Thermal compensation in DMOS Transistors

- Thermal characterization



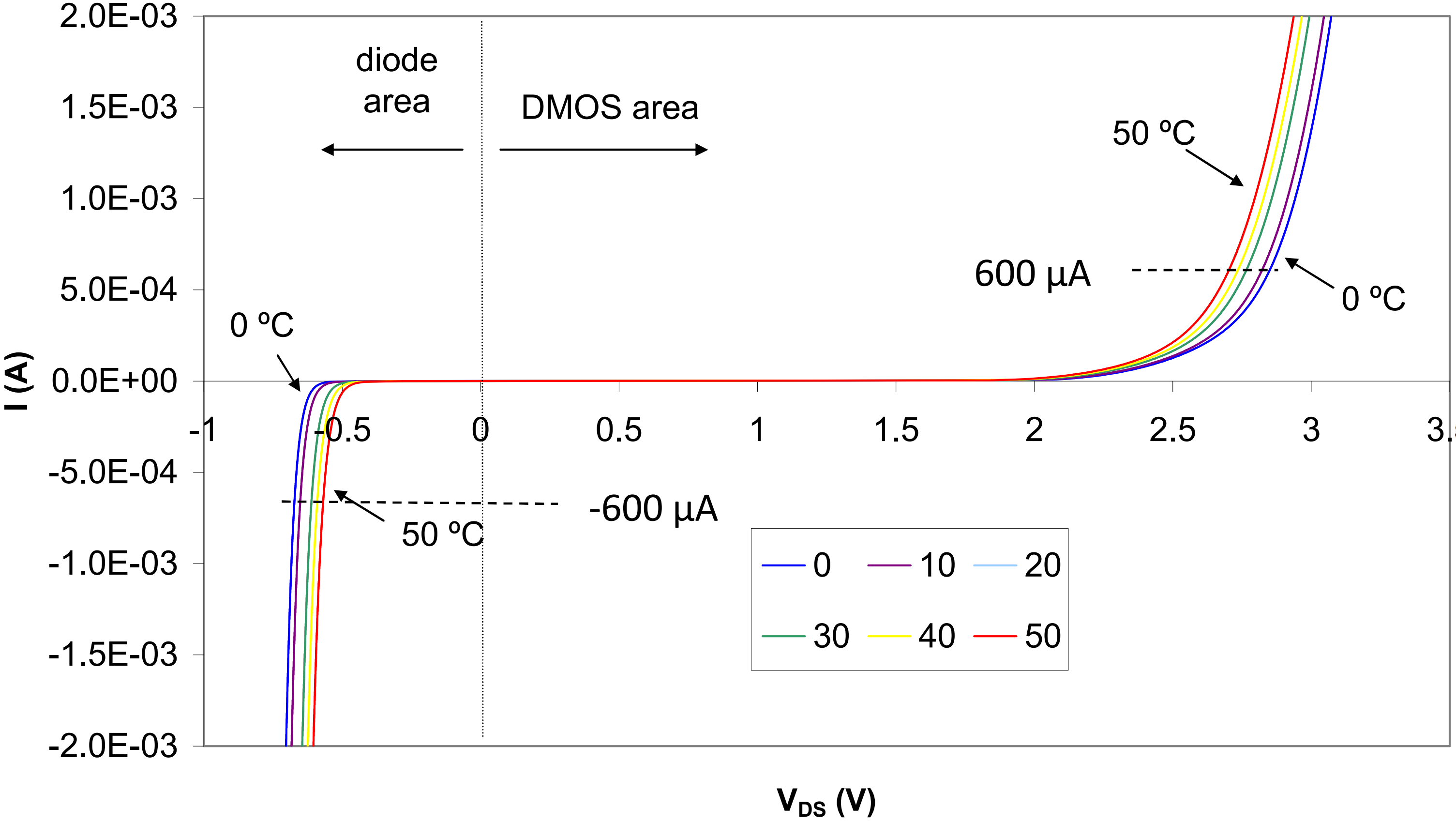


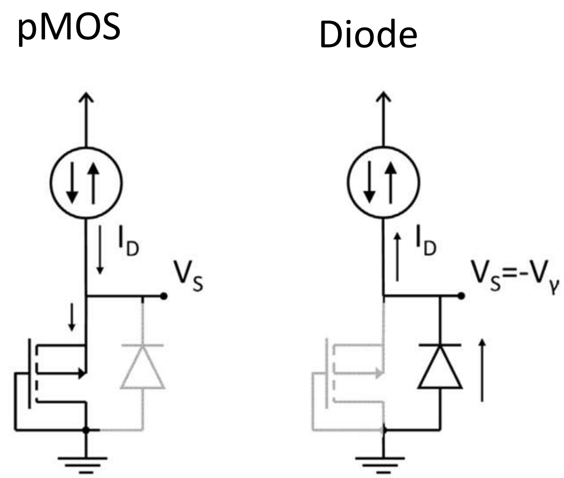
There is no current with α = 0

M.A. Carvajal et al. / Sensors and Actuators A 249 (2016) 249–255

Thermal compensation in DMOS Transistors

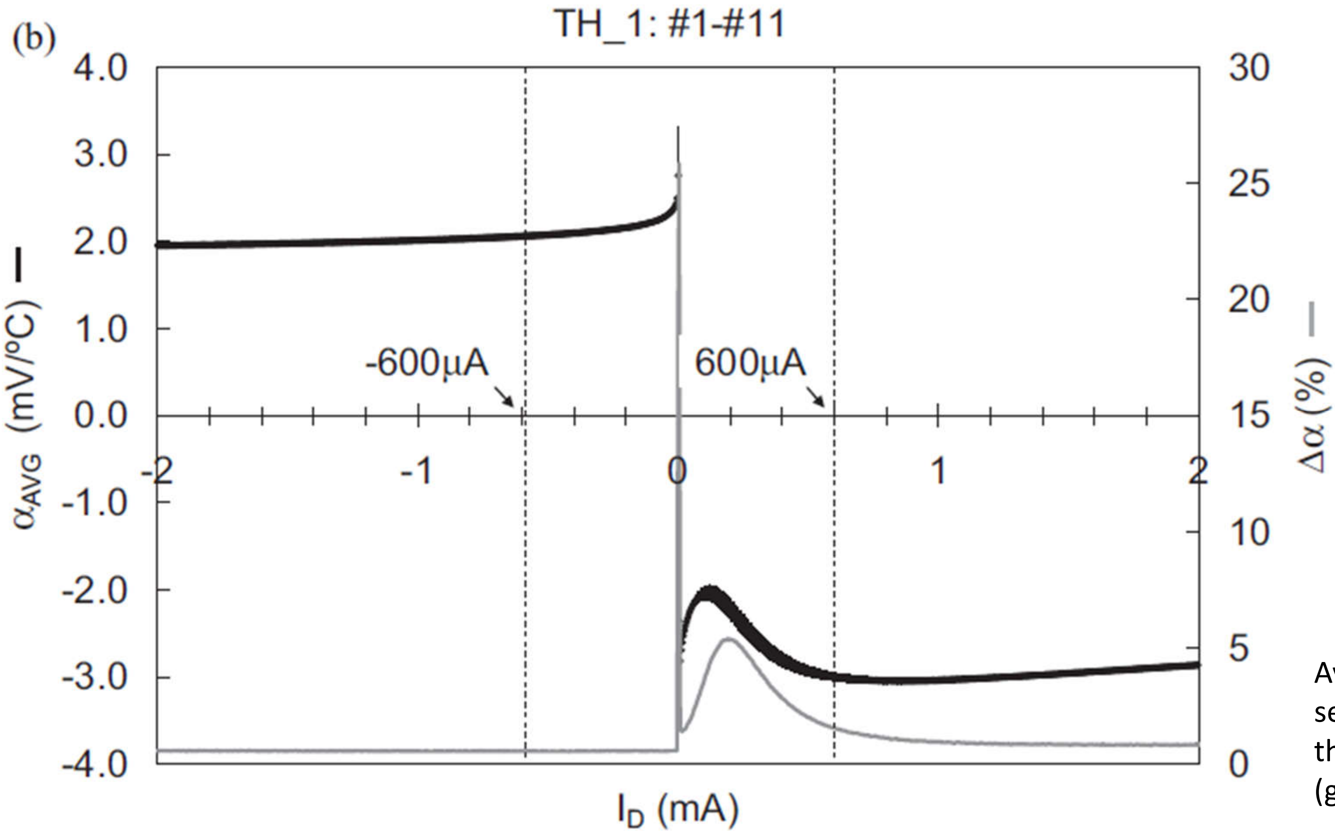
- Thermal compensation using the parasitic diode

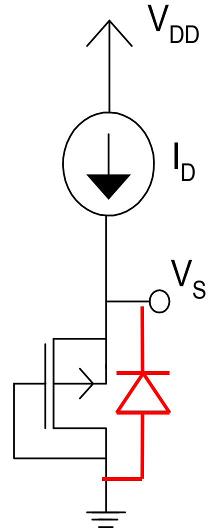




Thermal compensation in DMOS Transistors

- Thermal coefficient

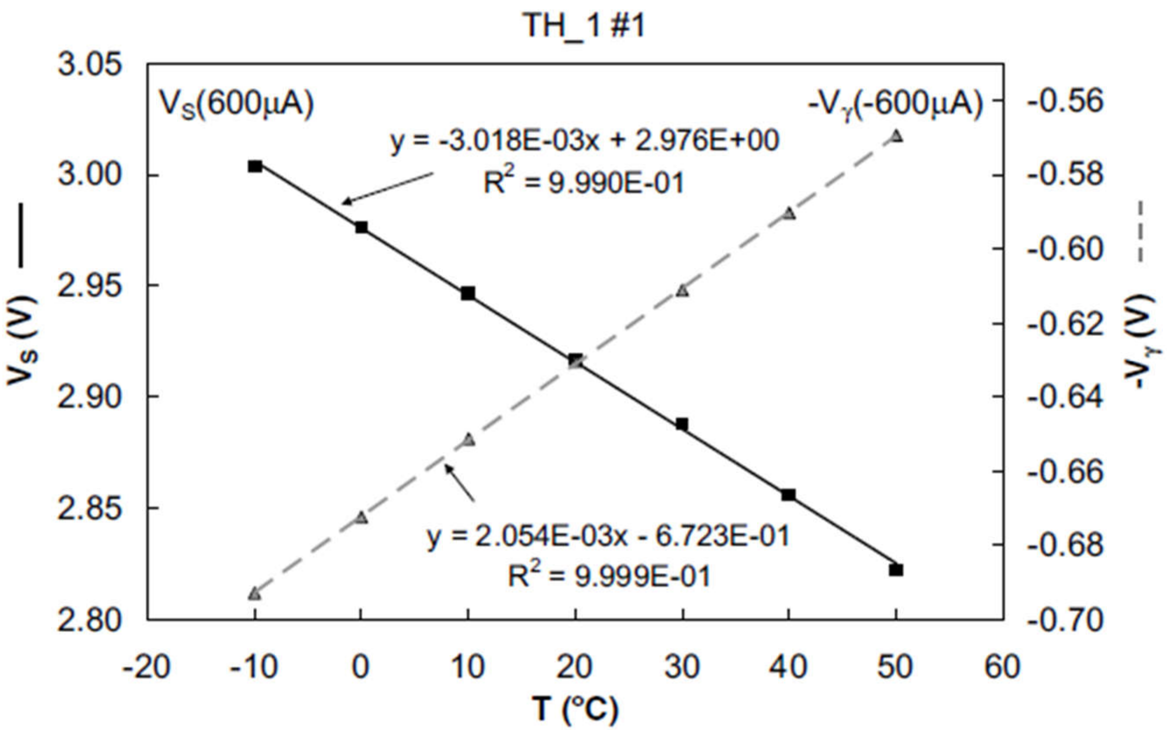


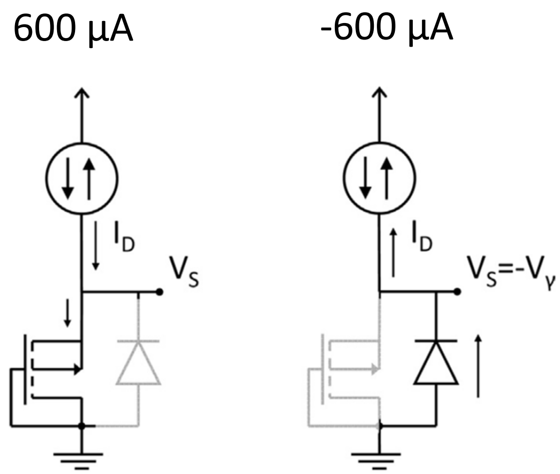


Average linear thermal coefficient of set TH 1 (black dots; error bars make the line thicker) and relative error (grey line).

Thermal compensation in DMOS Transistors

- Experimental validation: Thermal characterization

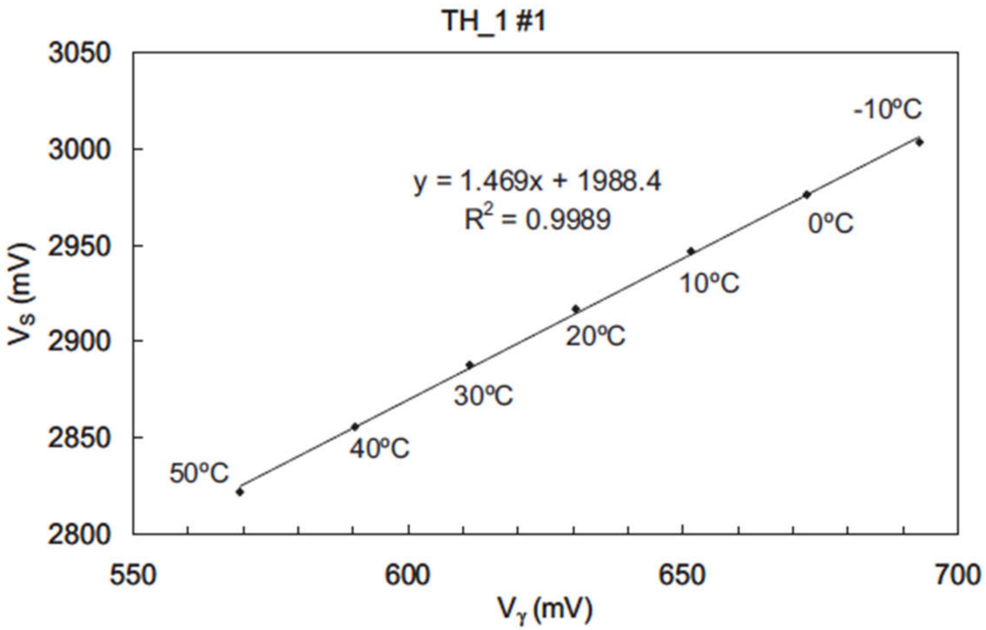




M.A. Carvajal et al. / Sensors and Actuators A 249 (2016) 249–255

Thermal compensation in DMOS Transistors

- Experimental validation: Thermal characterization



Individual and global linear fit coefficients of the correlation between V_S and V_γ for the set of transistors TH_1.

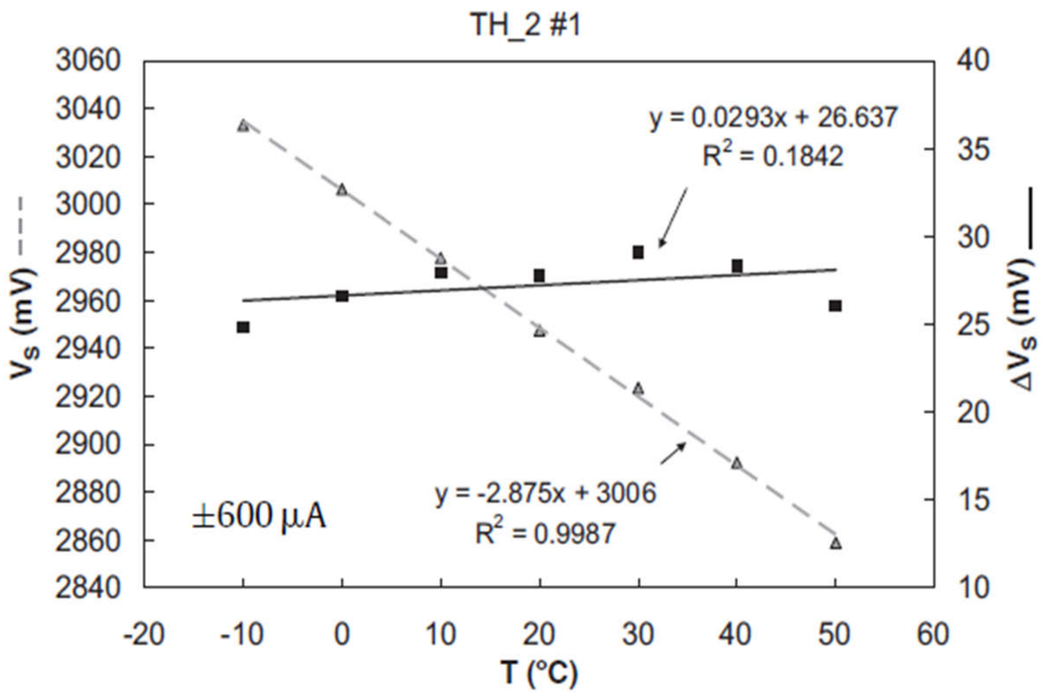
TH_1	M	b (mV)	R^2
#1	1.47 ± 0.02	1988 ± 14	0.9989
#2	1.44 ± 0.02	1970 ± 14	0.9988
#3	1.45 ± 0.02	1985 ± 14	0.9989
#4	1.45 ± 0.02	1998 ± 13	0.9990
#5	1.45 ± 0.02	1998 ± 14	0.9988
#6	1.46 ± 0.02	1996 ± 14	0.9989
#7	1.44 ± 0.02	2013 ± 15	0.9986
#8	1.45 ± 0.02	1964 ± 14	0.9988
#9	1.46 ± 0.02	1997 ± 14	0.9988
#10	1.47 ± 0.02	1985 ± 14	0.9989
#11	1.48 ± 0.02	1932 ± 13	0.9991
Avg	1.46 ± 0.03	1984 ± 14	–

- Correlation between $\Delta V_S(T)$ and $\Delta V_\gamma(T)$ was found

M.A. Carvajal et al. / Sensors and Actuators A 249 (2016) 249–255

Thermal compensation in DMOS Transistors

- Experimental validation: Thermal characterization

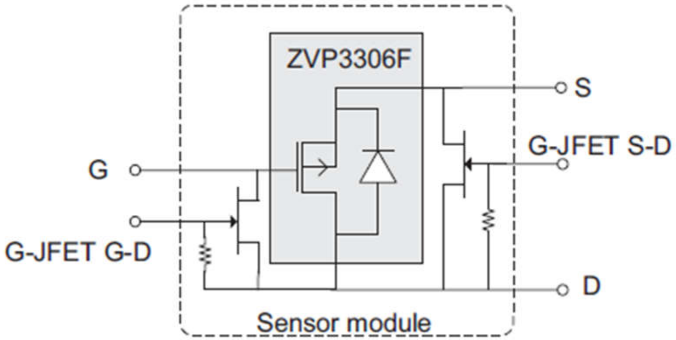


TH_2:	Thermal coefficient, m (mV/°C)		Reduction Factor
	Uncompensated	Compensated	
#1	−2.88 ± 0.05	0.03 ± 0.03	−98
#2	−2.71 ± 0.06	0.17 ± 0.04	−16
#3	−2.88 ± 0.05	0.05 ± 0.03	−62
#4	−2.87 ± 0.03	0.06 ± 0.02	−52
#5	−2.85 ± 0.04	0.04 ± 0.03	−79
Average	−2.84 ± 0.05	0.07 ± 0.03	−42

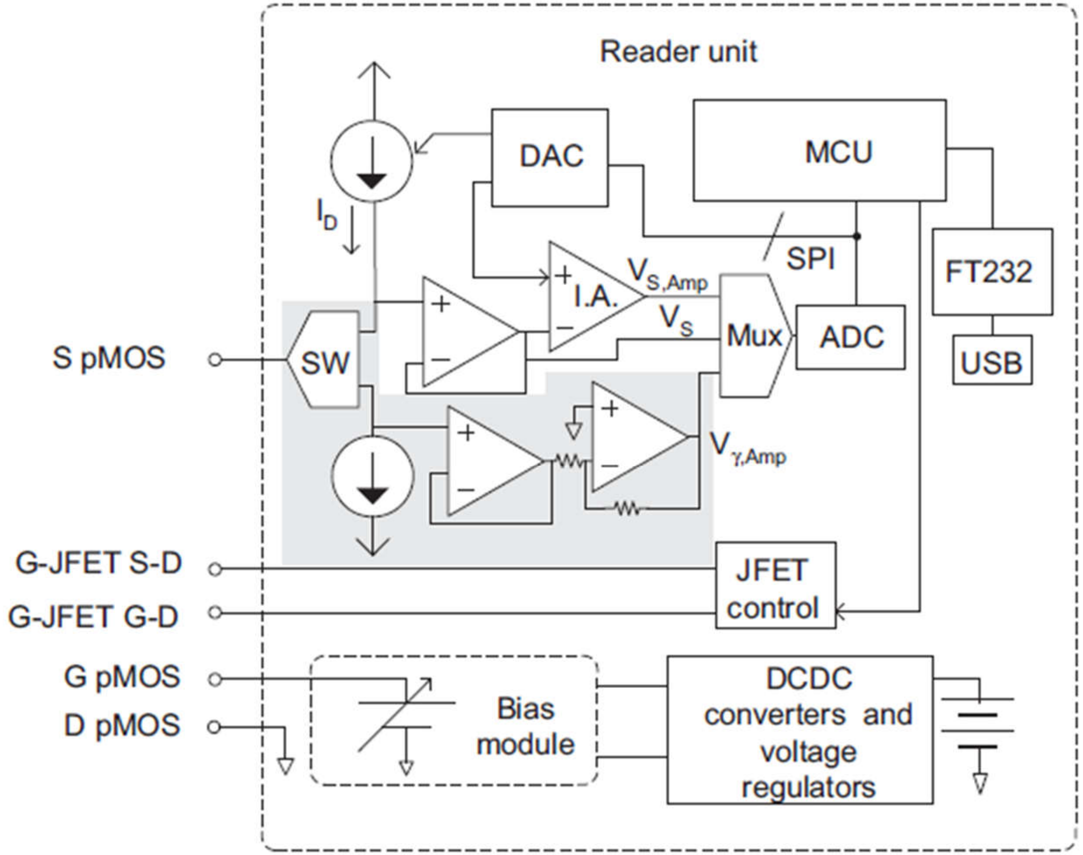
M.A. Carvajal et al. / Sensors and Actuators A 249 (2016) 249–255

Thermal compensation in DMOS Transistors

- Experimental validation: Dose measurements

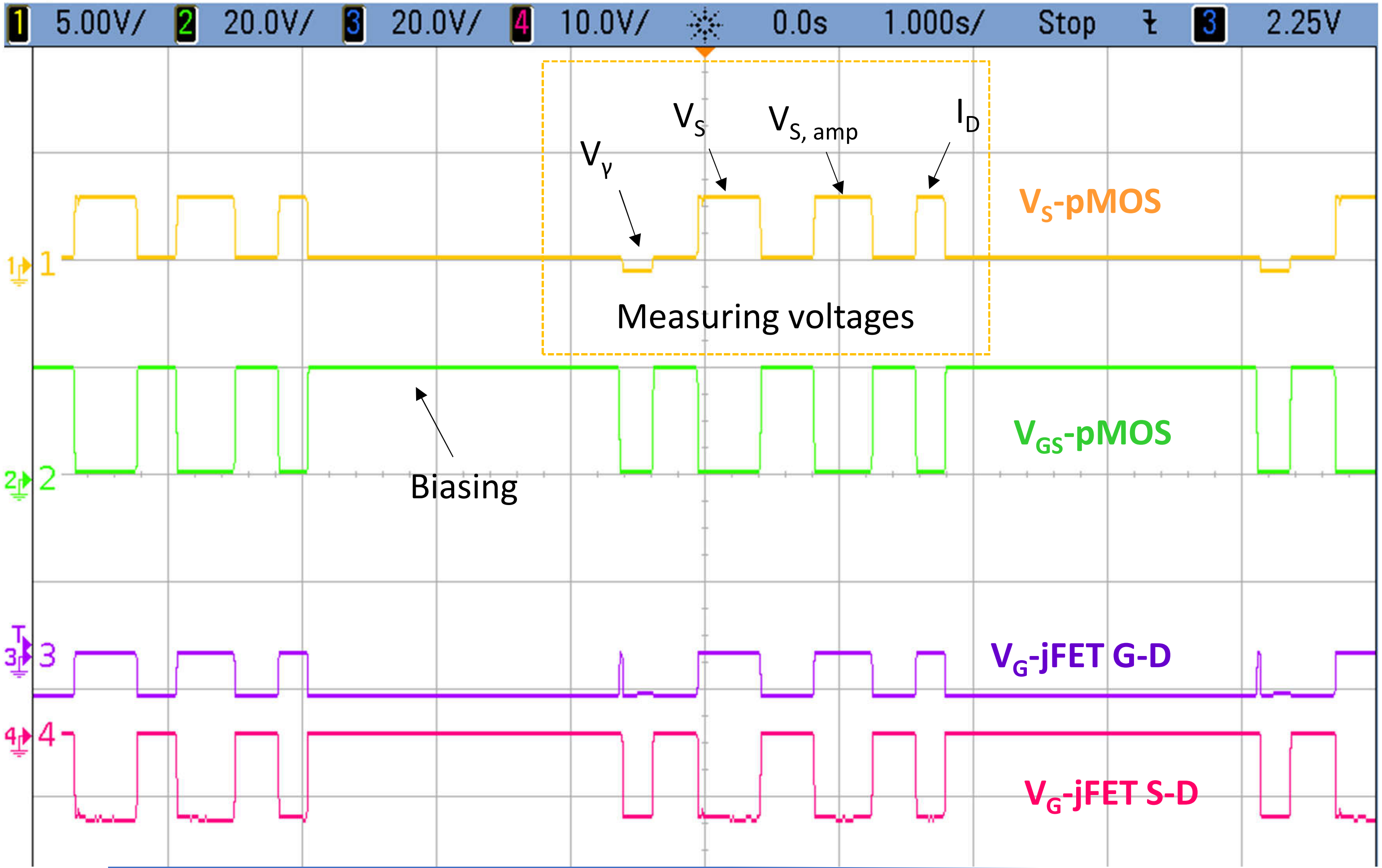


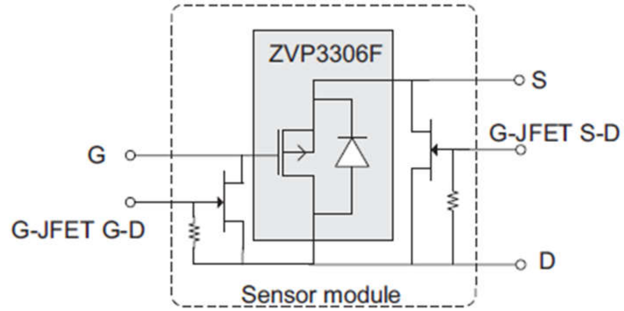
Sensor for bias mode operation



M.A. Carvajal et al. / Sensors and Actuators A 249 (2016) 249–255

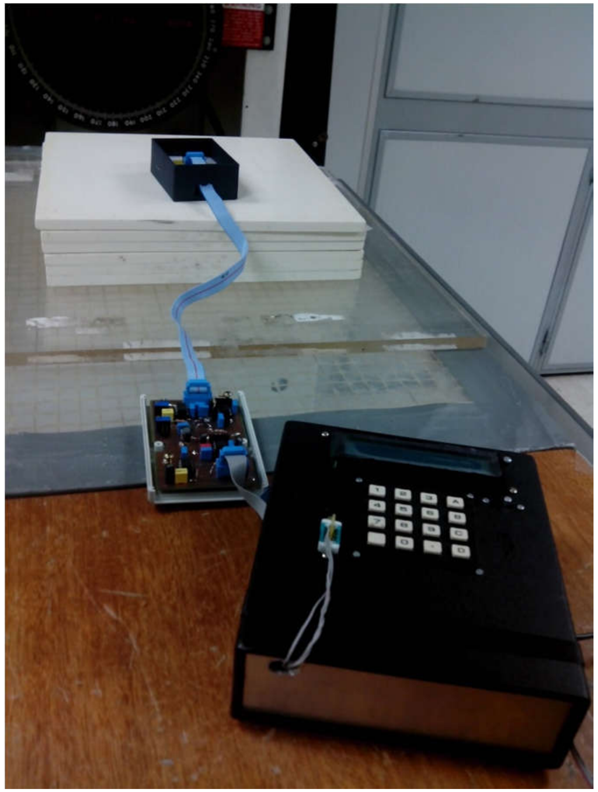
Thermal compensation in DMOS Transistors

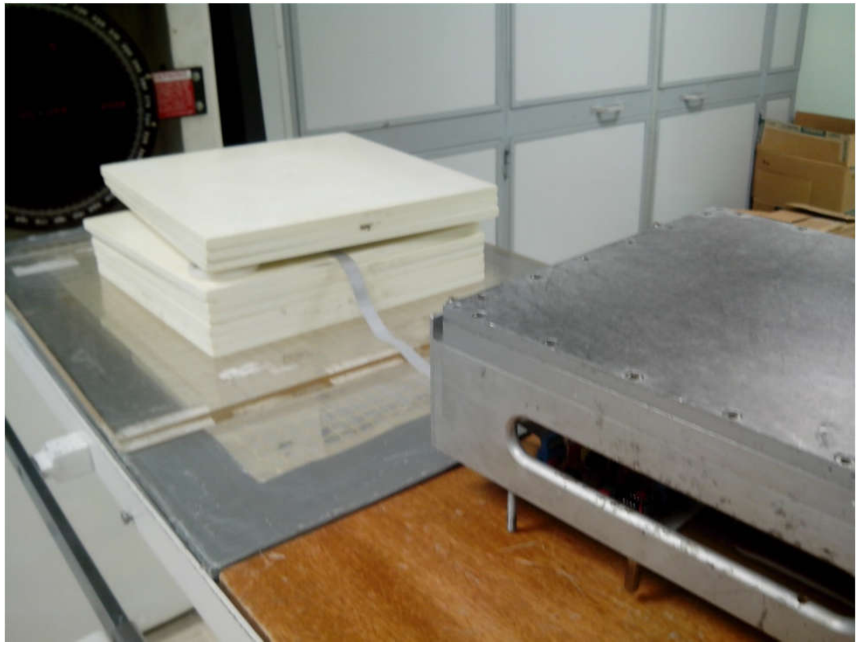




Thermal compensation in DMOS Transistors

- Dose measurements



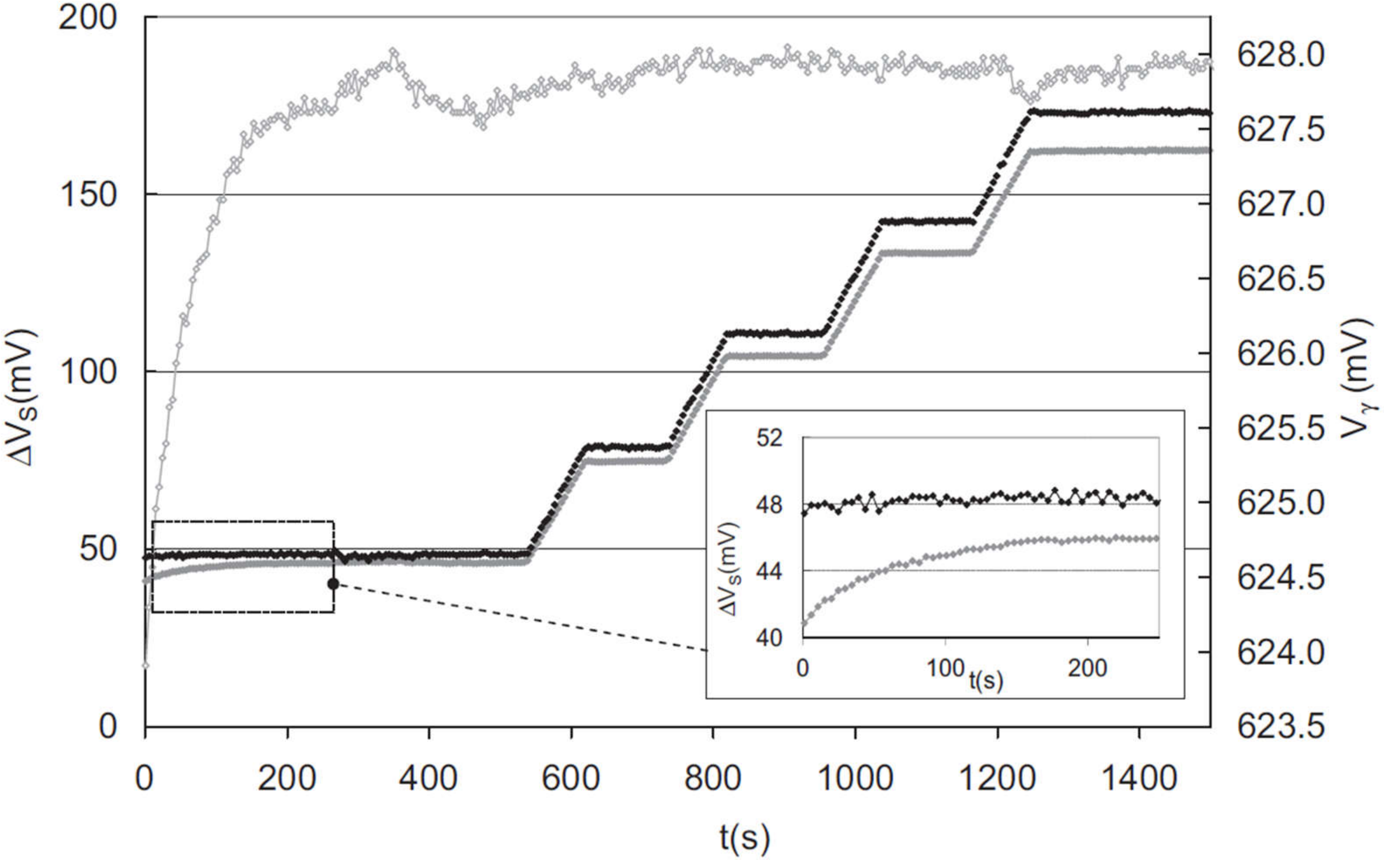


Thermal compensation in DMOS Transistors

- Dose measurements

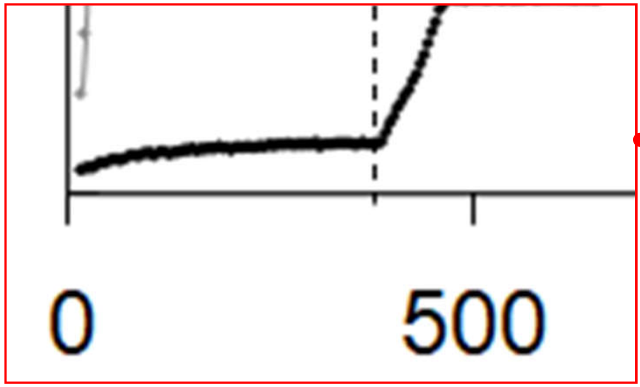
Sensitivity of MOS transistors of the DOSE_1 set.

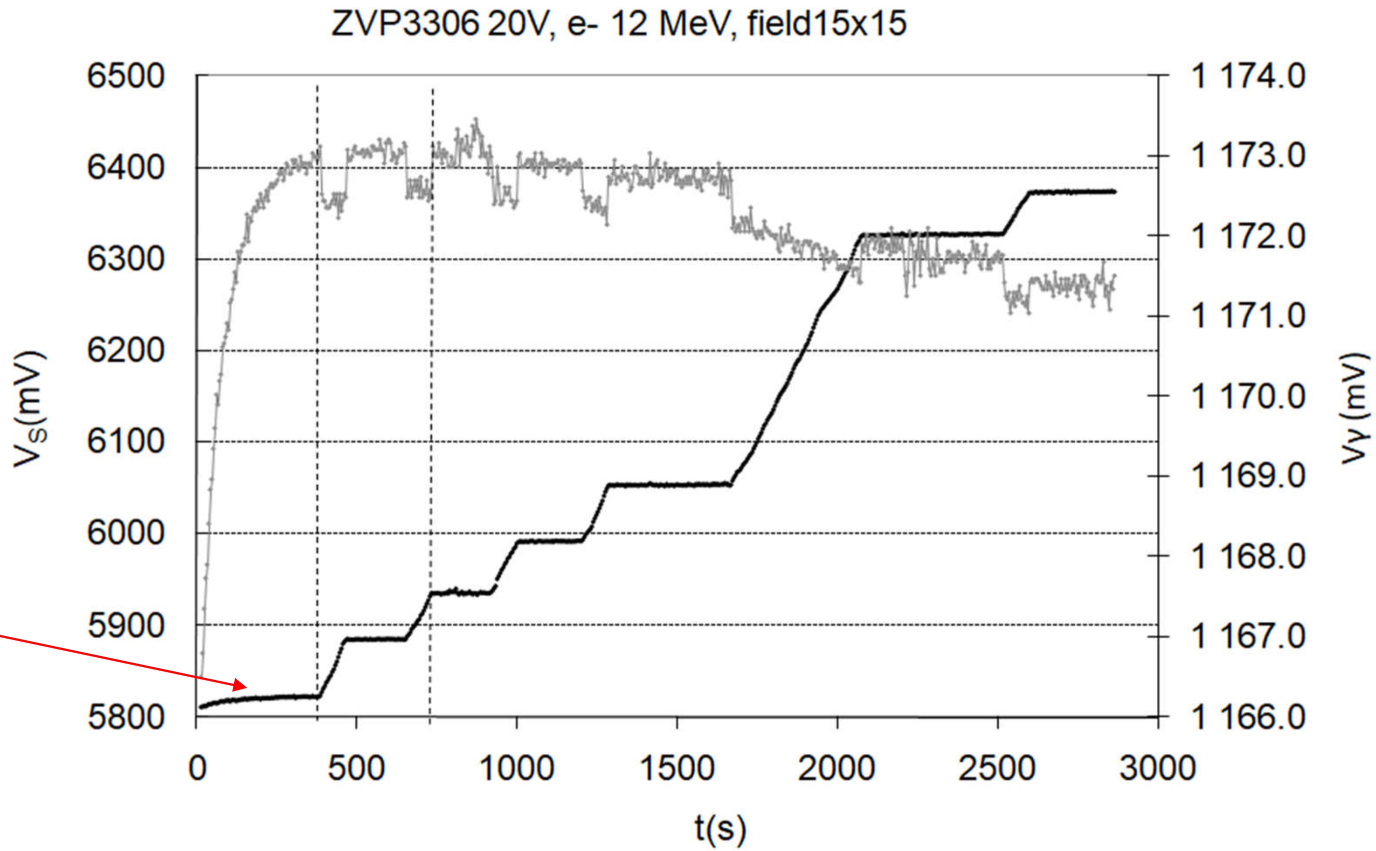
Dose (Gy)	S (mV/Gy)		
	#1	#2	#3
4	7.62 ± 0.12	7.88 ± 0.13	8.06 ± 0.20
4	8.00 ± 0.09	8.28 ± 0.12	7.80 ± 0.12
4	7.90 ± 0.08	7.80 ± 0.10	7.93 ± 0.12
4	7.70 ± 0.08	7.95 ± 0.10	8.11 ± 0.11
20	7.72 ± 0.03	7.85 ± 0.02	7.72 ± 0.03



Thermal compensation in DMOS Transistors

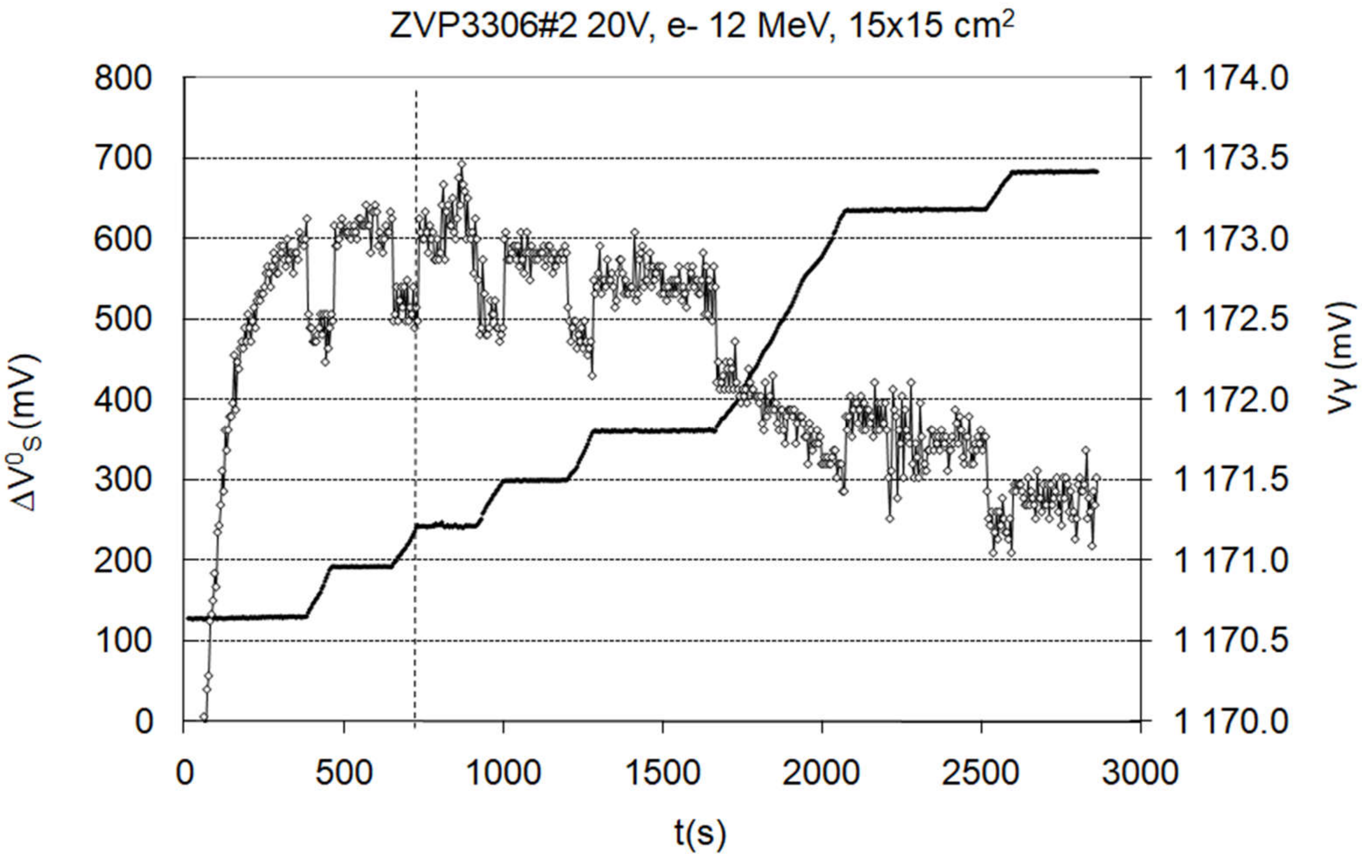
- Stacked DMOS





Thermal compensation in DMOS Transistors

- Stacked DMOS: Thermal compensated



Conclusions

- Thermal compensation for MOSFET
  - Lateral:
    - One current → I_{ZCT}.
    - Improved linear range (thermal compensated) → Three currents.
  - DMOS: Use the parasitic diode.

Compensation of temperature effects in solid state dosimeters

Miguel A. Carvajal – University of Granada

2nd WORKSHOP ELICSIR PROJECT, 9-10.03.2021

THANK YOU FOR YOUR ATTENTION- QUESTIONS?