Response to ionizing radiation of commercial and RADFET transistors

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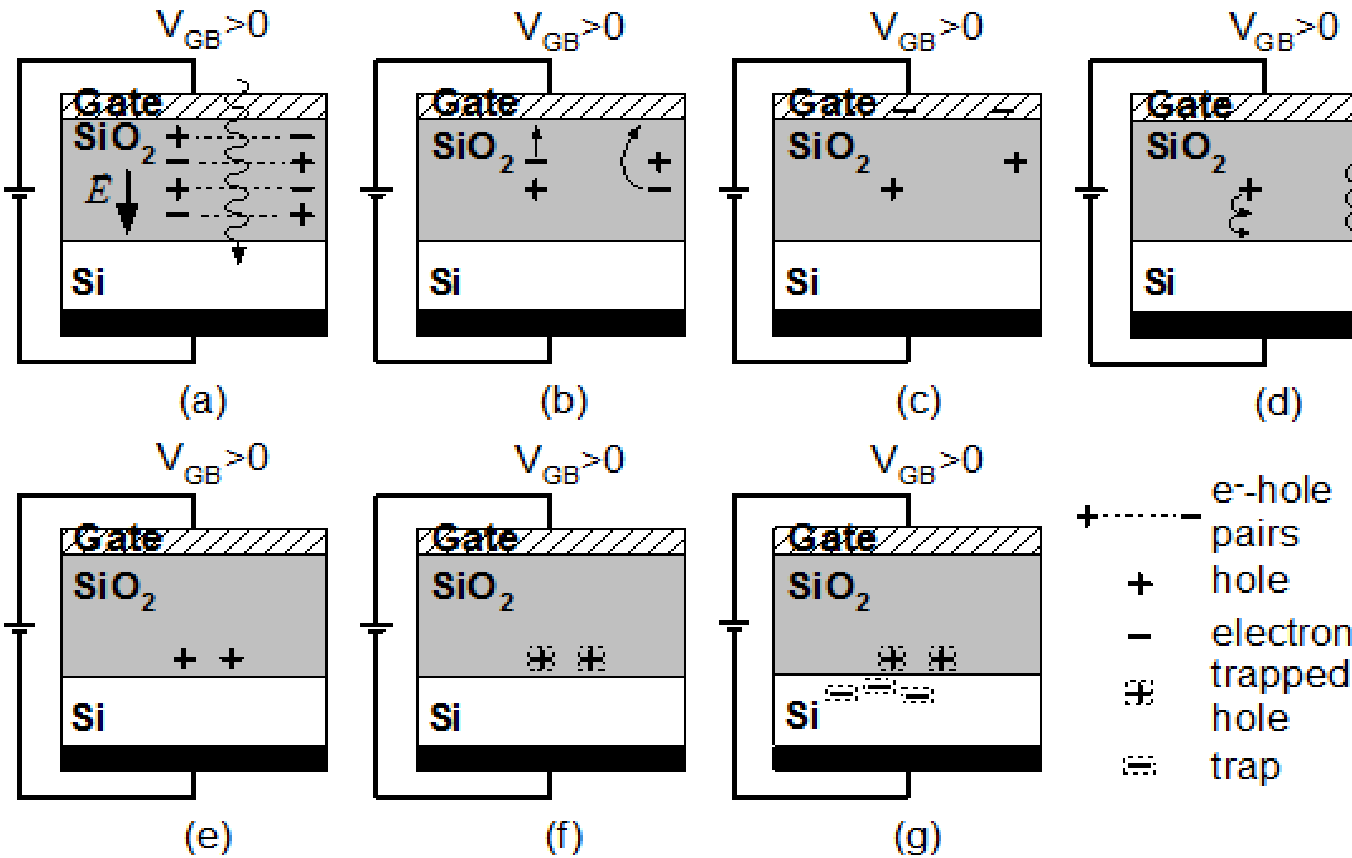
2nd ELICSIR ONLINE TRAINNING SCHOOL

Outline

- Introduction
  - Physical Aspects
  - Modelling
- Materials and Methods
  - Transistors
  - Radiation sources
  - Experimental setup
  - Sensor Modules
  - Reader Unit
  - Previous Algorithms
- Response to ionizing radiation
  - Thermal characterization
  - Commercial Transistors: response to photon beams
  - Commercial Transistors: response to electron beams
  - RADFET transistors
- Conclusions

Physical aspects: MOS structure response to ionizing radiation



Response → Radiation-induced trapped oxide charges

Bias voltage during irradiation → sensitivity increase

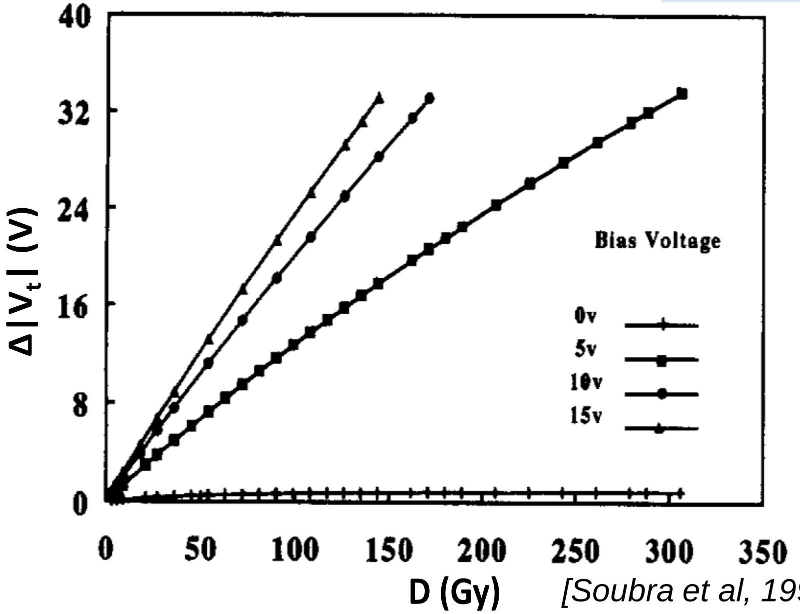
Modelling: Accumulated dose

$$\Delta|V_t| = \sum_i \Delta|V_{t,i}|$$

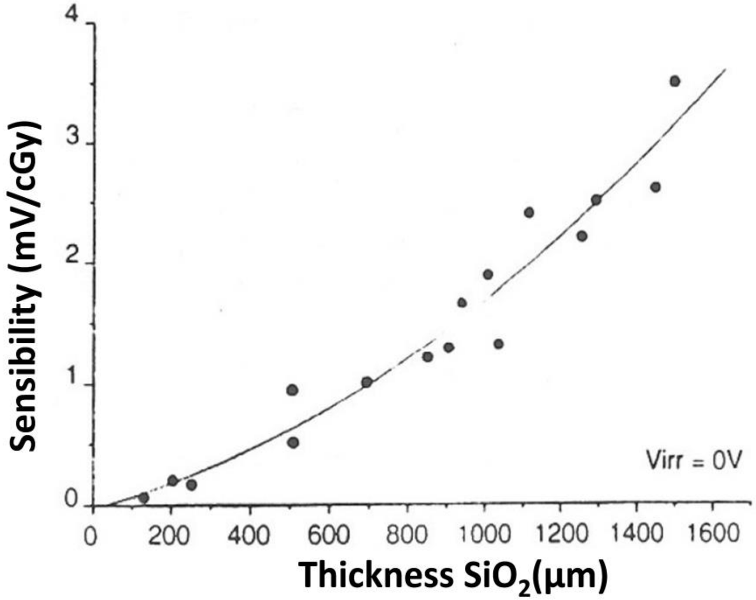
$$\Delta|V_t| = A \cdot D^n$$

$n = 1 \rightarrow A = S$

$$S = \frac{\Delta|V_t|}{D}$$



[Soubra et al, 1994]



[Sarrabayouse et al, 1998]

Influential factors on pMOS sensitivity:

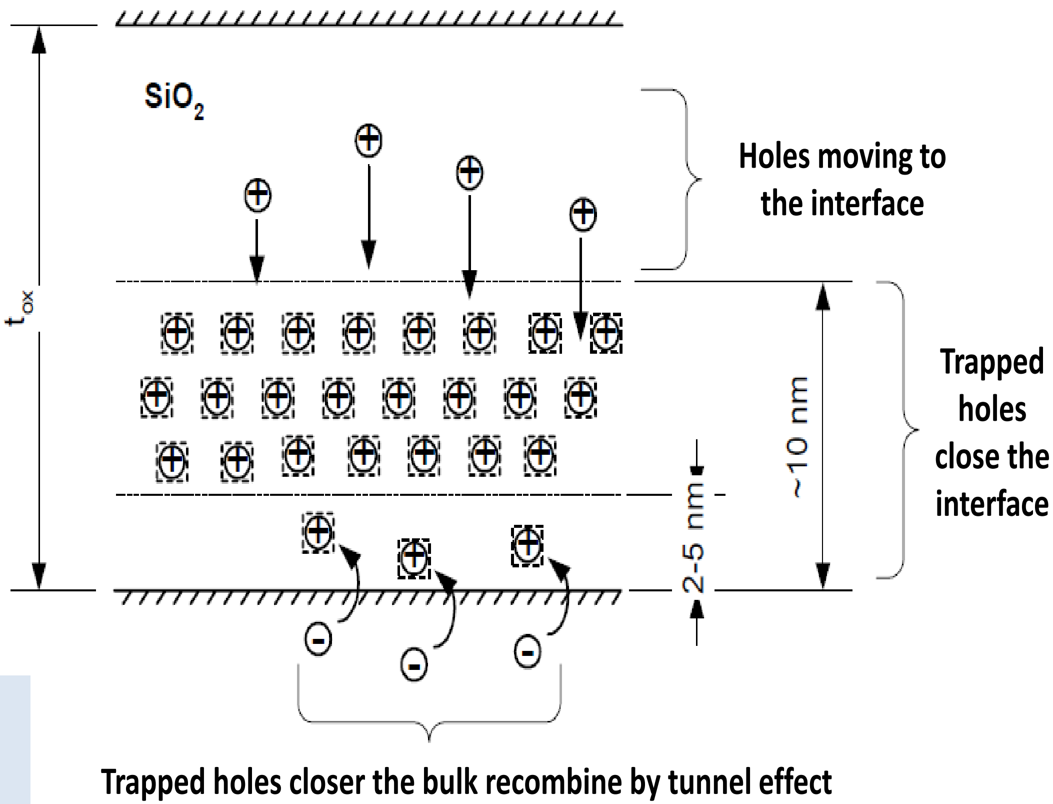
- Gate bias
- Oxide thicknesses
- Implanted and doped oxide traps
- Electric field shielding → trapped charge oxide → loss of Sensitivity

Modelling: Fading

Fading: partial V_t recovery after irradiation:

- Oxide trapped (h^+) recombines with substrate (e^-).
- Exponential recovery of V_t by tunnel effect recombination.

$$F = \frac{V_t(0) - V_t(t)}{V_t(0) - V_{t0}} = \frac{V_t(0) - V_t(t)}{\Delta V_t(0)}$$



[Carvajal 2008]

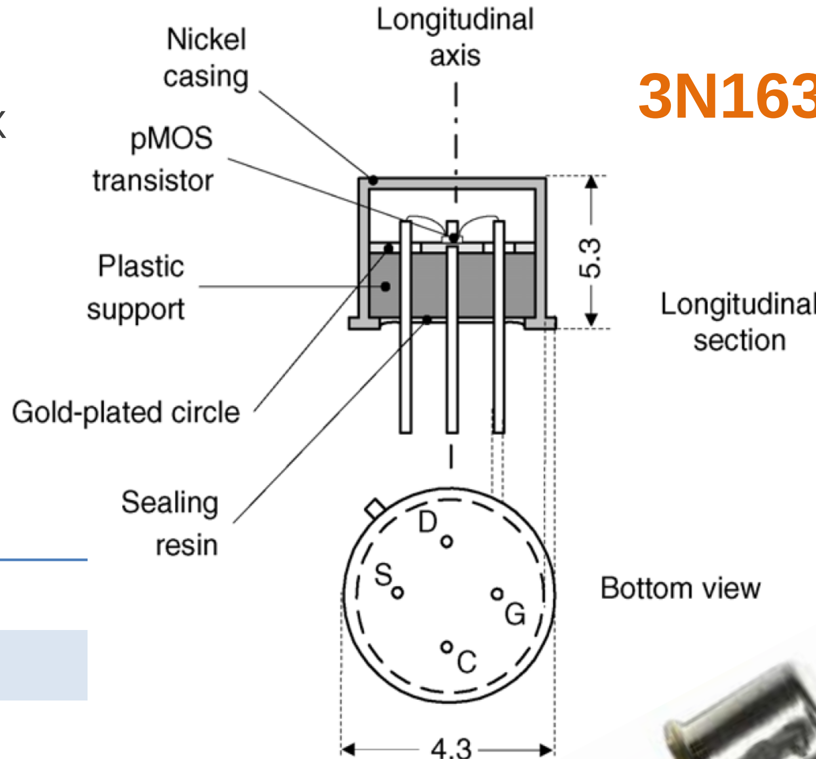
Outline

- Materials and Methods
  - Transistors
  - Radiation sources
  - Experimental setup
  - Sensor Modules
  - Reader Unit
  - Previous Algorithms

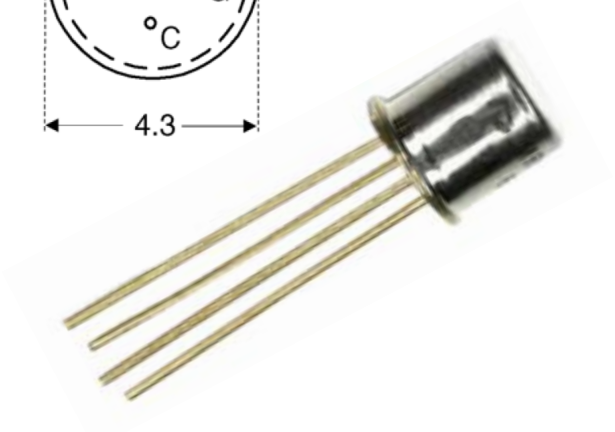
Commercial Transistors

1. Oxide thickness → $V_{GS\ MAX}$
2. Area underneath gate oxide
3. Geometry
4. Encapsulation
5. Nature of the used beam

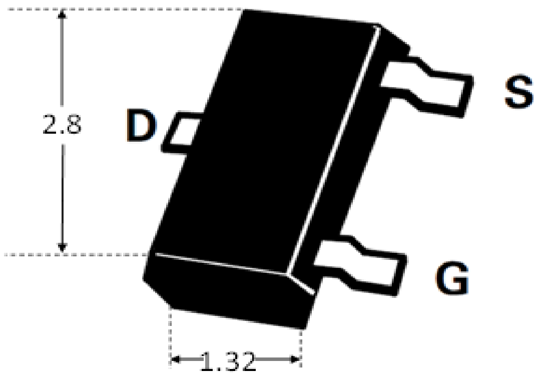
3N163

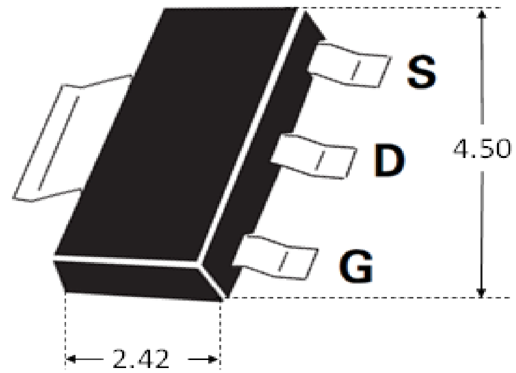


MANUFACTURER	Vishay Siliconix (USA)
PRICE	2.20 €
OXIDE THICKNESS	~200 nm
GEOMETRY	Lateral
ENCAPSULATION	Nickel (TO-72)
BEAM	Photon beams



Commercial Transistors





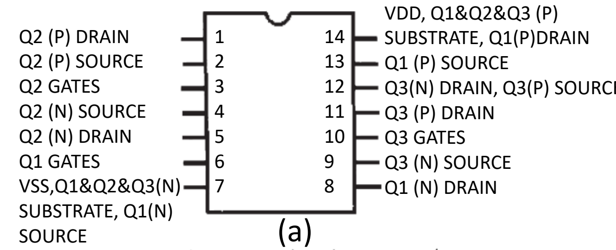
ZVP3306
ZVP4525
BS250F

NAME	ZVP3306	ZVP4526	BS250F
MANUFACTURER	Diodes Incorporated (USA)		
PRICE	0.49-0.57 €		
GEOMETRY	Vertical (DMOS)		
ENCAPSULATION	3-pin SOT-23	4-pin SOT-89	3-pin SOT-23
BEAM	Photon and Electron beams		

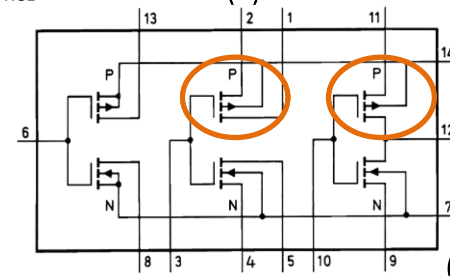
Commercial Transistors

CD4007

MANUFACTURER	Texas Instruments (USA) NXP Semiconductors (Netherlands)
PRICE	0.25-0.30 €
OXIDE THICKNESS	~100-120 nm
GEOMETRY	Lateral
ENCAPSULATION	Integrated circuit (SMD-DIP-14)
BEAM	Photon and electron beams



(a)



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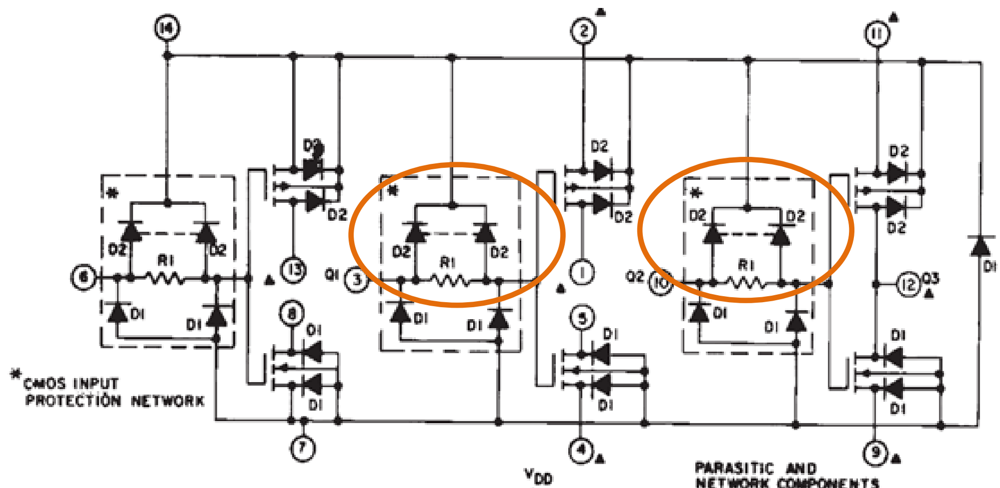
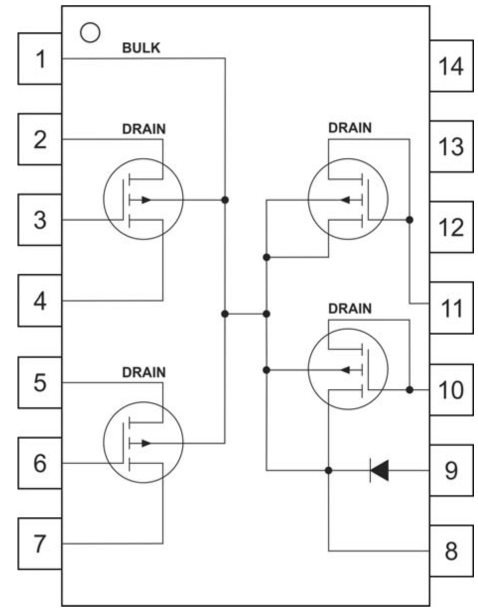


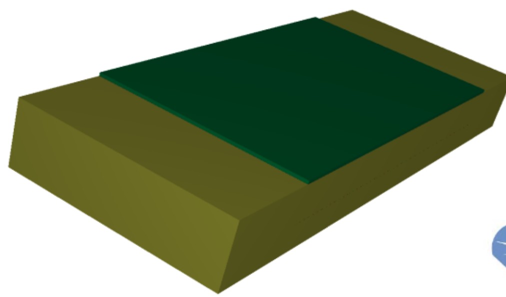
RADFETs

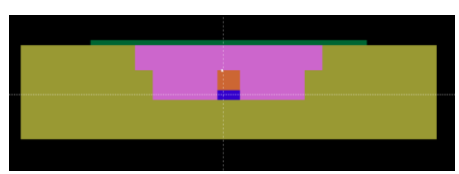
MANUFACTURER	Tyndall National Institute (Ireland)
OXIDE THICKNESS	100 and 400 nm and 1 μm
GEOMETRY	Lateral
ENCAPSULATION	Integrated circuit DIP-14
SIZE (W/L)(μm)	300/50; 690/15
BEAM	Photon and electron beams

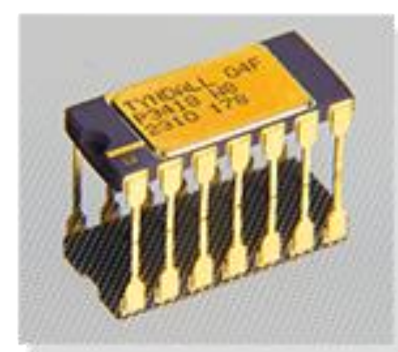


Referenced as:

- 100 nm
- 400nm_W5
- 400nm_W7
- 400nm_W8







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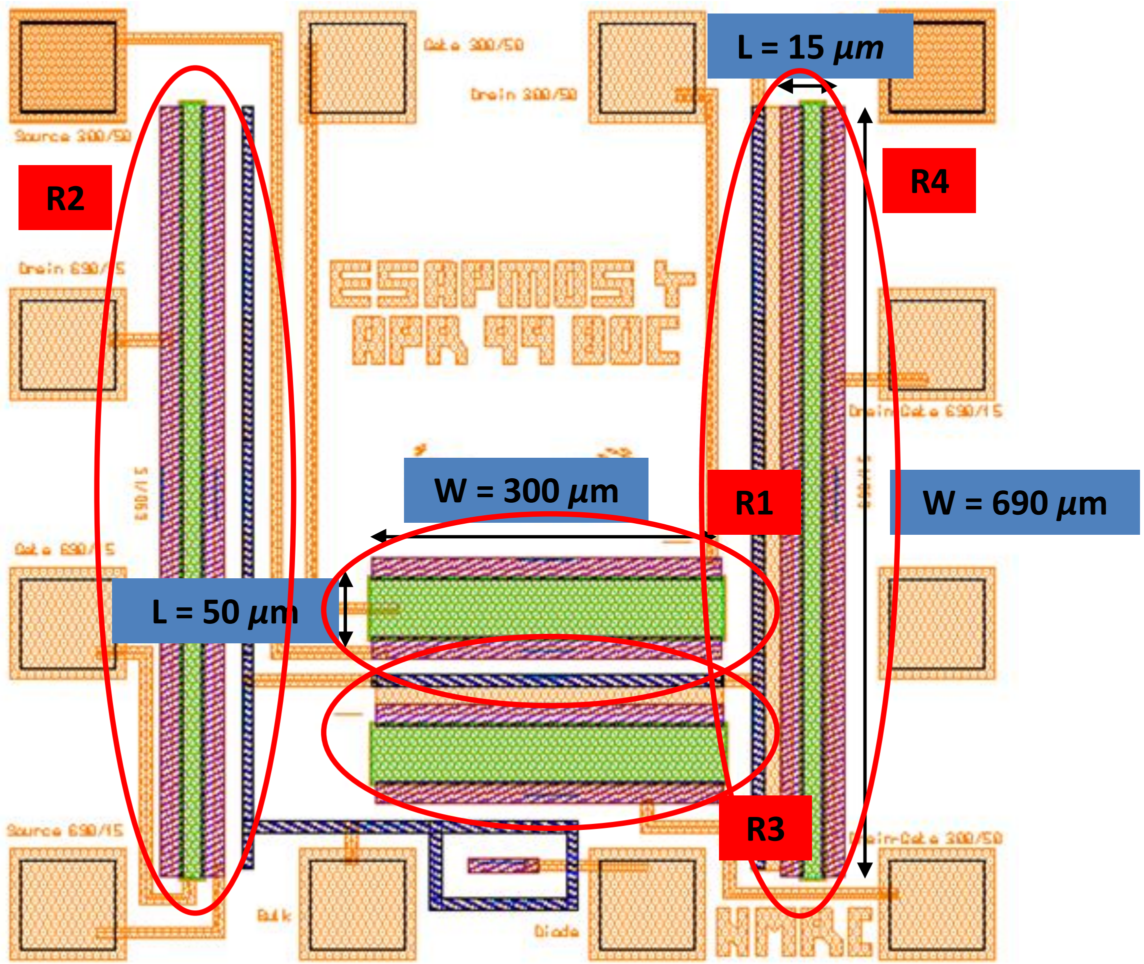
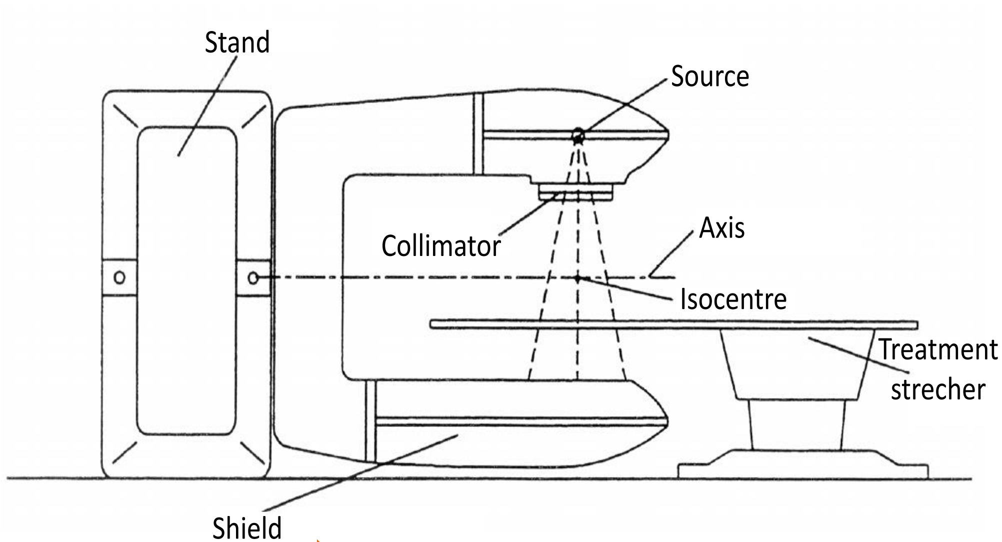
RADFETs

- Layout RADFETs



Radiation sources

- Cobalt therapy unit (^{60}Co): **AECL Theratron-780** (University Hospital San Cecilio Granada).



- ^{60}Co → ^{60}Ni
  - Two emitted photons:
    - 1.17 MV and 1.33 MV.
  - Average energy: 1.25 MV.

Radiation sources

- **LINAC : Mevatron KDS** (University Hospital San Cecilio Granada).

Type of Beam	Field	Dose Rate (m.u./min)
Photons	6 MV	200/300
	18 MV	
Electrons	6 MeV	300 or 900 (High dose rate)
	8 MeV	
	10 MeV	
	12 MeV	
	15 MeV	
	18 MeV	

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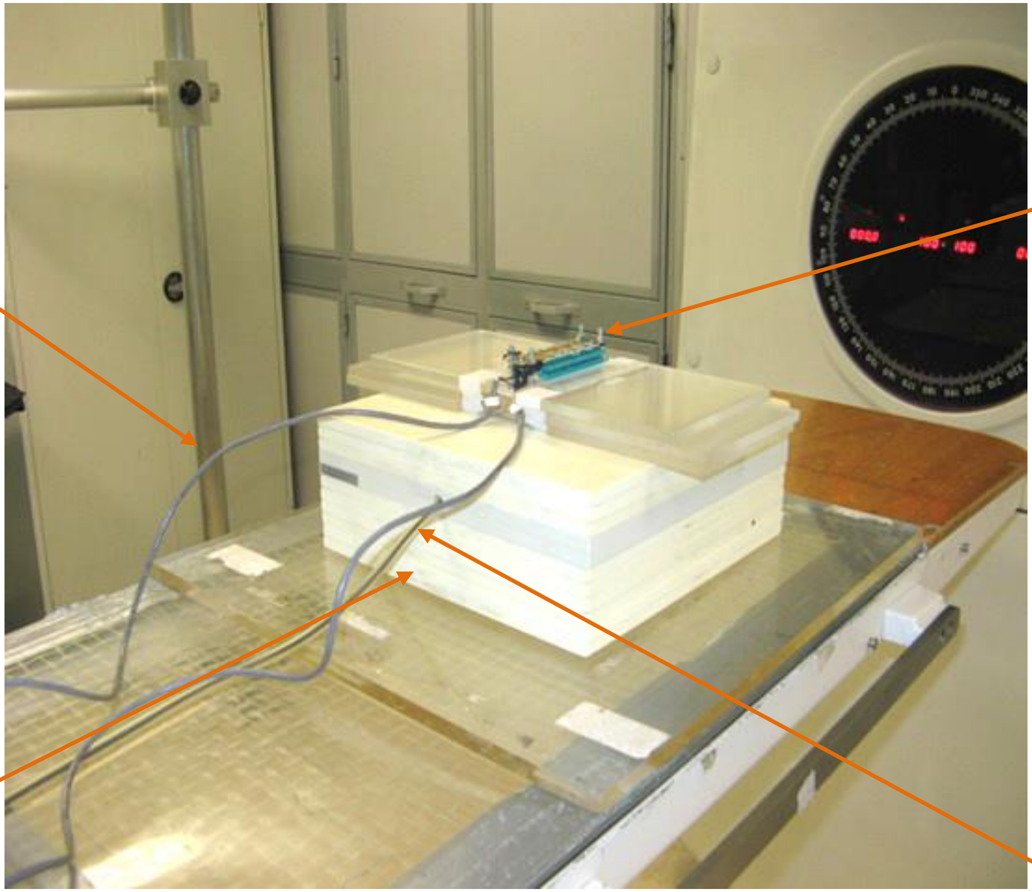
Experimental setup for irradiation

Bias System



Dosimeter modules

(At the isocentre)

Water Equivalent Phantom ($30x30x8\ cm^3$)

Ionization chamber PTW23332

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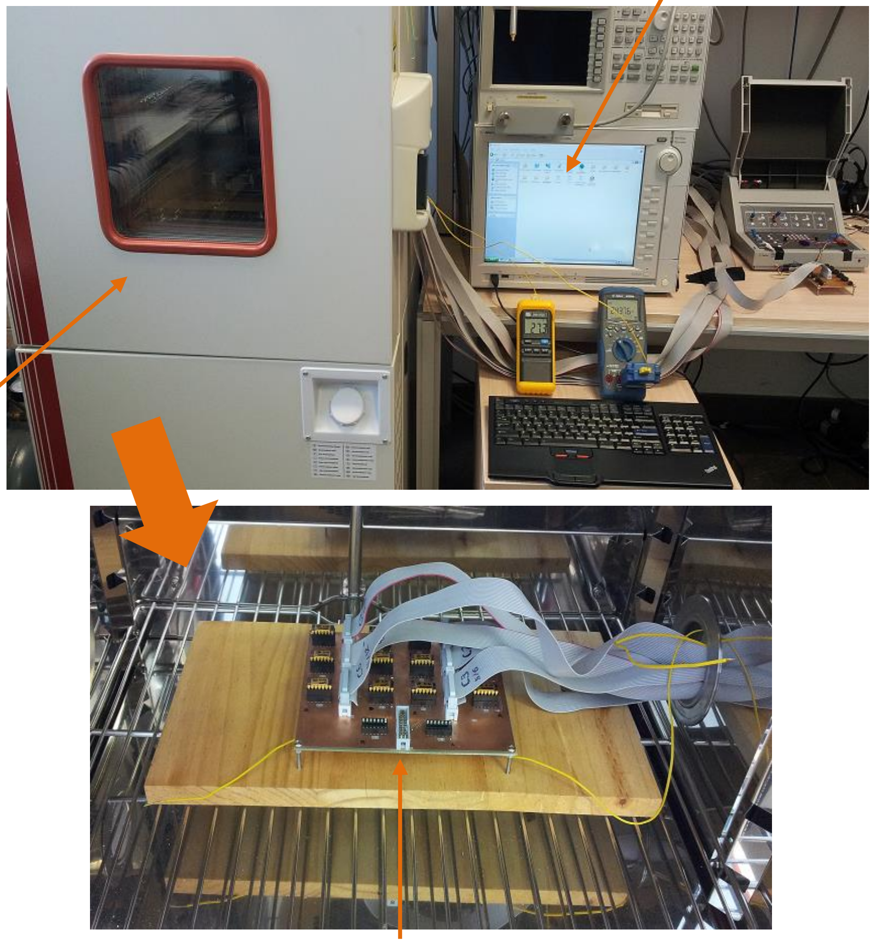
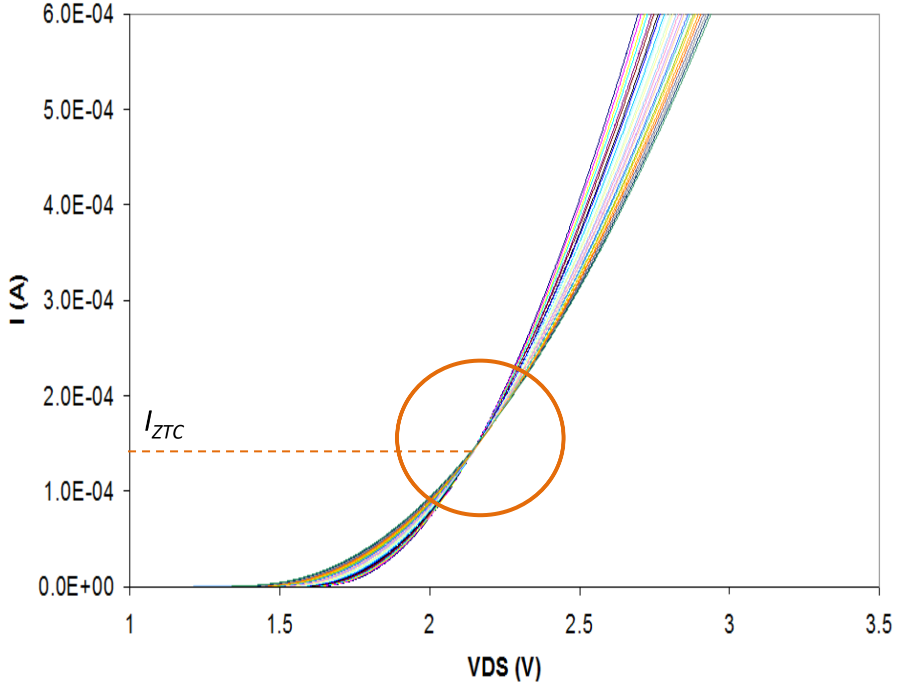
Experimental setup for thermal characterization

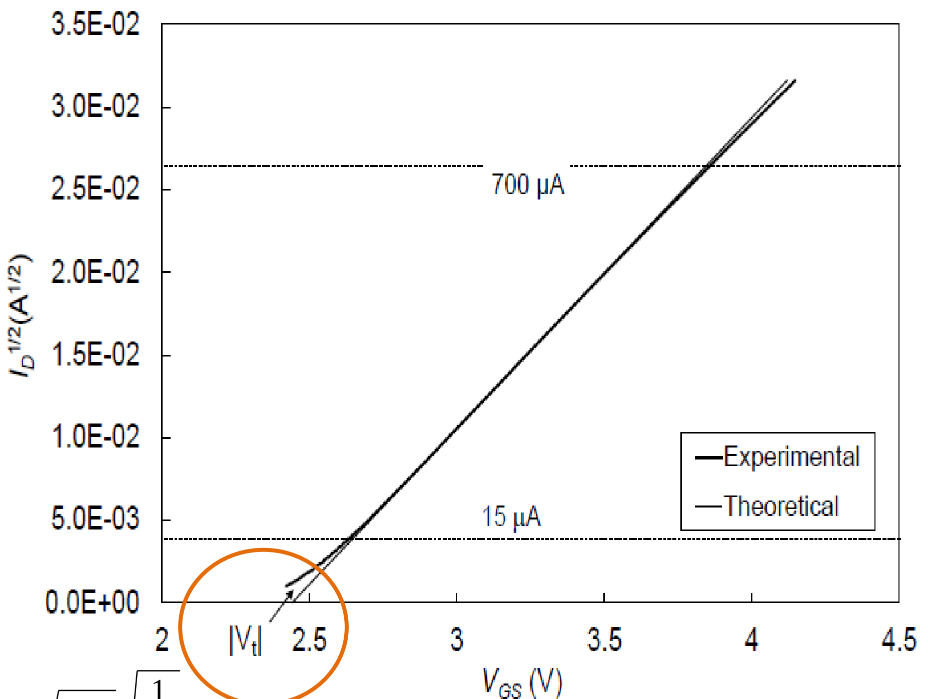
- VCL4006 Climate Chamber.
- Biasing currents and $I_{ZTC.}$
- Digital thermometers RS206-3722.
- Groups of 4 or 5 transistors per type.



Setting: Parameter calculation

- I_{ZTC} ➡ Cross point in the I-V curves.
- V_t ➡ Intersection with the abscissa axis of $\sqrt{I_D}$ (saturation regime).





$$|V_t| = V_S - \sqrt{2I_{D1}}\sqrt{\frac{1}{\beta}}$$

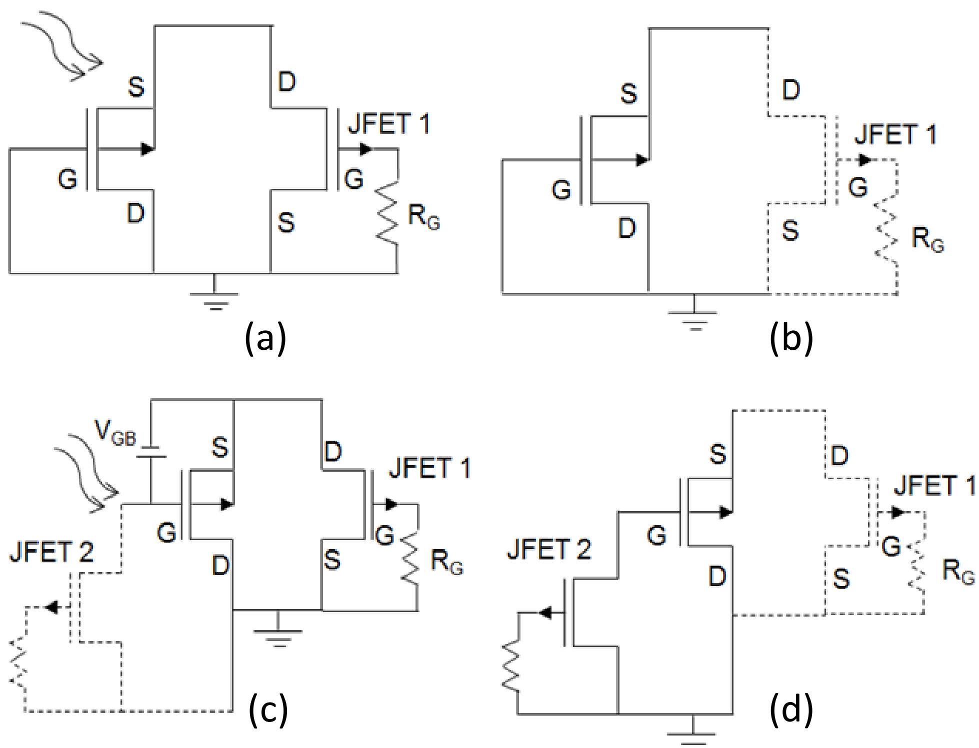
Sensor modules

- Single pMOS configuration:

IRRADIATION PERIOD READ-OUT PERIOD

UNBIASED CONFIGURATION

BIASED CONFIGURATION



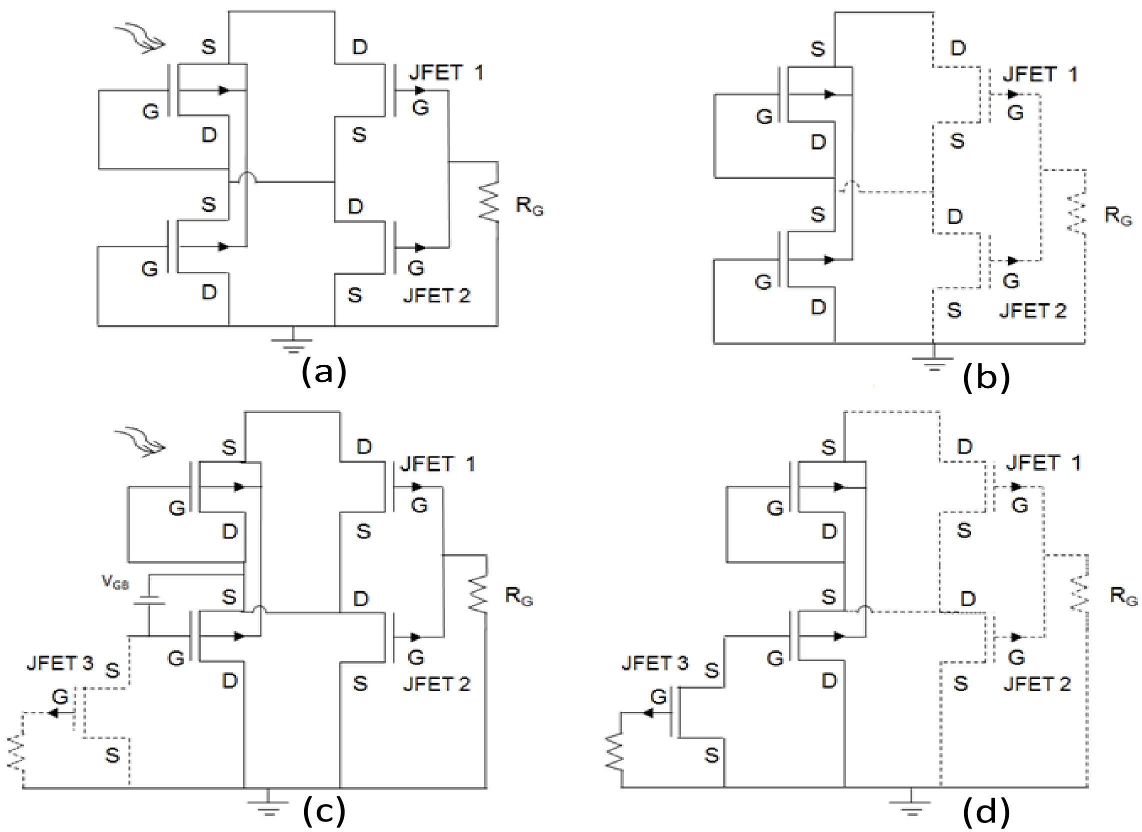
Sensor modules

- Two stacked pMOS configuration:

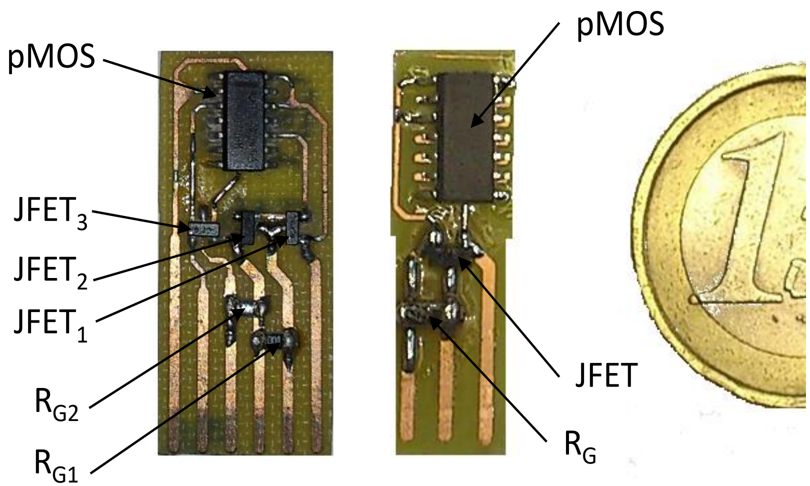
IRRADIATION PERIOD | READ-OUT PERIOD

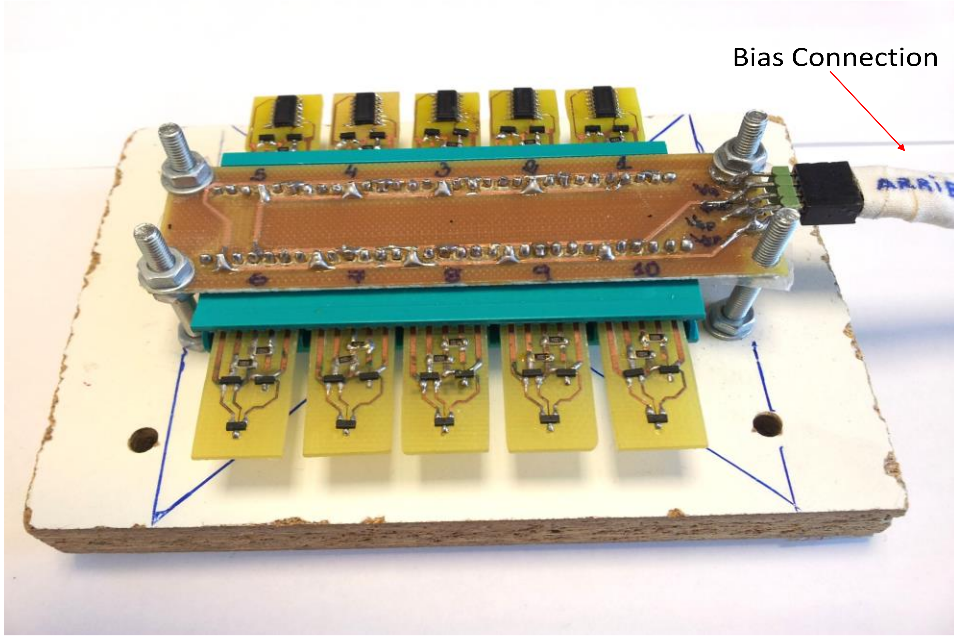
UNBIASED CONFIGURATION

BIASED CONFIGURATION



Sensor modules





Components of sensor module

PCB to bias

Reader unit

- **Reader Unit:**
  - 1 μA resolution drain current source.
  - Up to x100 of voltage amplification.

[Carvajal et al, 2012]

Previous algorithms

- **One** drain current: $I_D = I_{ZTC}$ for thermal compensation:

$$I_D = I_{ZTC} = -\frac{\beta}{2}\left(\left|V_{GS}\right| - \left|V_t\right|\right)^2 \qquad \beta \approx cte \quad \Rightarrow \quad \Delta\left|V_t\right| \approx \Delta\left|V_S\right|$$

- **Two** drain currents (2CM):
  - Accounting for $\Delta\beta$: linearity improv.

$$\Delta\left|V_t\right| = \Delta V_{S1} + \frac{\Delta V_{S2} - \Delta V_{S1}}{1 - \sqrt{\frac{I_{D2}}{I_{D1}}}} \qquad (1)$$

  - Accounting for thermal drift:

[Carvajal et al, 2011]

$$\Delta V_T^0 \approx \Delta V_{S1}^0 = \Delta V_{S1} + \left(\Delta V_{S2} - \Delta V_{S1}\right)\frac{\sqrt{I_{D1}} - \sqrt{I_{ZTC}}}{\sqrt{I_{D1}} - \sqrt{I_{D2}}} \qquad (2)$$

- **Three** drain currents (3CM):
  - Both corrections are included: (1)+(2) with:

[Carvajal et al, 2010]

$$\left.\begin{array}{l} I_{D1} = I_{ZTC} \\ \Delta V_{S2}^0 \ from\ Eq\ (2) \end{array}\right\}$$

$$\Delta\left|V_t\right| = \Delta V_{S,ZTC} + \frac{\Delta V_{S2}^0 - \Delta V_{S,ZTC}}{1 - \sqrt{\frac{I_{D2}}{I_{ZTC}}}}$$

Summary: Photon beams

Type	Field (cm²)	Source	Build-up	Configuration	Bias (V)
3N163	35x35	^{60}Co	No	Single	0
3N163	10x10	LINAC	1 cm	Single	0
3N163	10x10	LINAC	1 cm	Single	5
3N163	10x10	LINAC	1 cm	Single	10
3N163	10x10	LINAC	1 cm	Two stacked	0
3N163	10x10	LINAC	1 cm	Two stacked	10
ZVP3306	10x10	LINAC	1 cm	Single	5
ZVP3306	10x10	LINAC	1 cm	Single	10
CD4007 (SMD)	10x10	LINAC	1.5 cm	Single	0
Tyndall RADFETs (5 Types)	25x25	LINAC	1.5 cm	Single	0

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Summary: Electron beams

Type	Field (cm^2)	Source	Build-up	Configuration	Bias (V)
CD4007 (SMD)	25x25	LINAC	-	Single	0
CD4007	25x25	LINAC	-	Single	0.6
CD4007	25x25	LINAC	-	Two stacked	0
CD4007	25x25	LINAC	-	Two stacked	0.6
CD4007 (Texas Instruments)	25x25	LINAC	-	Two stacked	0
CD4007 (Texas Instruments)	25x25	LINAC	-	Two stacked	0.6
CD4007 (NXP Semiconductor)	25x25	LINAC	-	Two stacked	0.6
BS250F	25x25	LINAC	-	Single	0
ZVP4525	25x25	LINAC	-	Single	0
ZVP3306	25x25	LINAC	-	Single	0
ZVP3306	25x25	LINAC	-	Single	5
ZVP3306	25x25	LINAC	-	Single	10
ZVP3306	25x25	LINAC	-	Two stacked	0
Tyndall RADFETs (5 Types)	15x15	LINAC	1.3 cm	Single	0

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Outline

- Response to ionizing radiation
  - Thermal characterization
  - Commercial Transistors: response to photon beams
  - Commercial Transistors: response to electron beams
  - Subthreshold swing
  - RADFET transistors

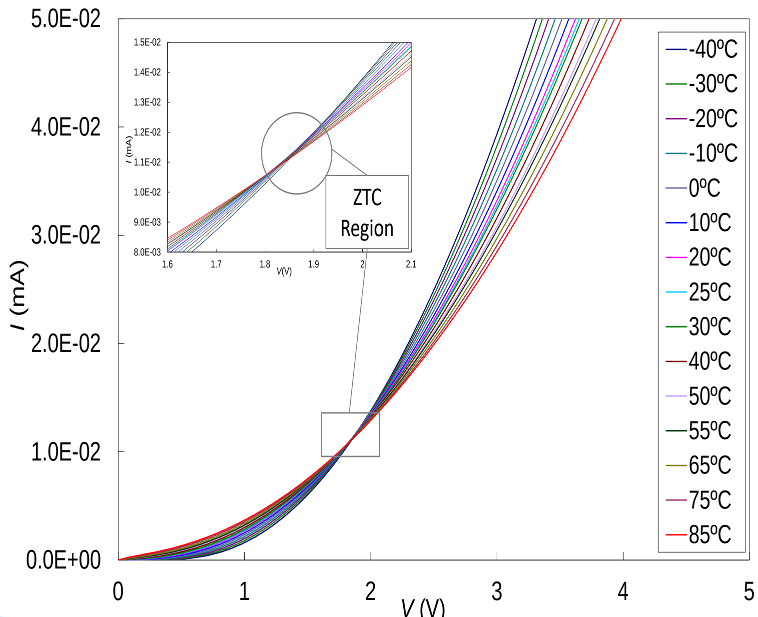
Thermal characterization

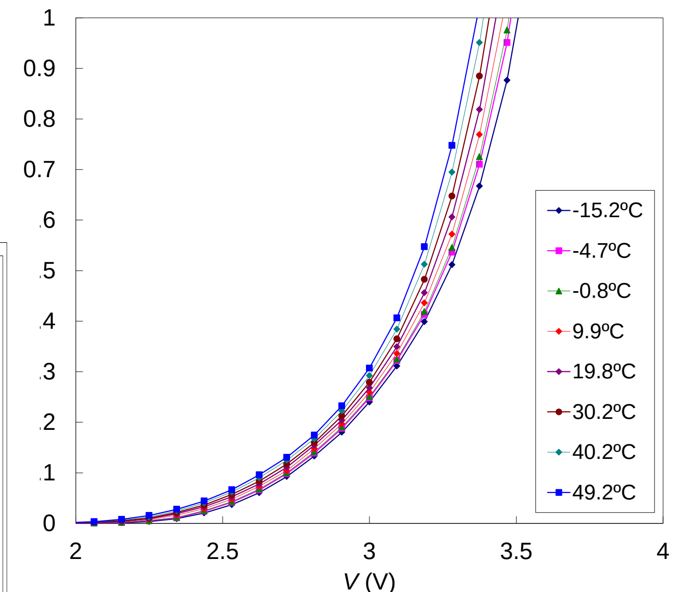
DMOS: ZVP3306, ZVP4525 and BS250F

- No crossing point was found ➡ Physical structure
- 2CM (pulse mode) and subtracting the thermal contribution

CD4007, 3N163 and Tyndall RADFETS

- I_{ZTC}
- 3CM, pulse mode





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Thermal characterization

- Current selection for 2CM and 3CM readout

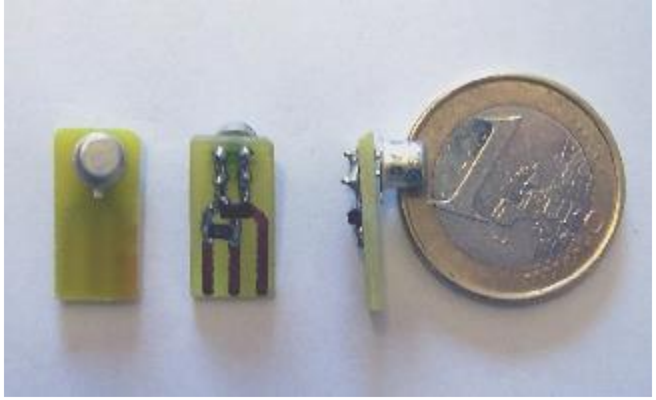
Type	W/L	I_C (μA)	I_{D2} (μA)	$I_{D1}=I_{ZTC}$ (μA)
3N163	-	30	120	230
BS250F	-	30	120	-
ZVP4525	-	30	120	-
ZVP3306	-	30	120	-
CD4007	-	40	80	145
100nm	300/50	8	32	16
	690/15	45	91	183
400nm_W5	300/50	6	24	12.2
	690/15	31	63	127
400nm_W7	300/50	6	22	10.8
	690/15	27	54	109
400nm_W8	300/50	6	24	11.2
	690/15	28	57	115
1μm	300/50	6	22	10.9
	690/15	30	60	120

Commercial Transistors: Response to photon beams

Experimental set-up

- 45 transistors
- 5 per group
- LINAC
- 10x10 cm^2
- **Photon beam of 6 MV**
- 100 cm to the source
- 30x30x10.5 cm^3
- 4 different configurations
- 6 minutes to measure
- PTW23332
- **3N163, ZVP3306 and CD4007**

Type	Gy per session	Dmax (Gy)	Build-up (cm)
3N163	1.92	25	1.0
ZVP3306	1.89	20	1.0
CD4007	3,4 and 5	25	1.5



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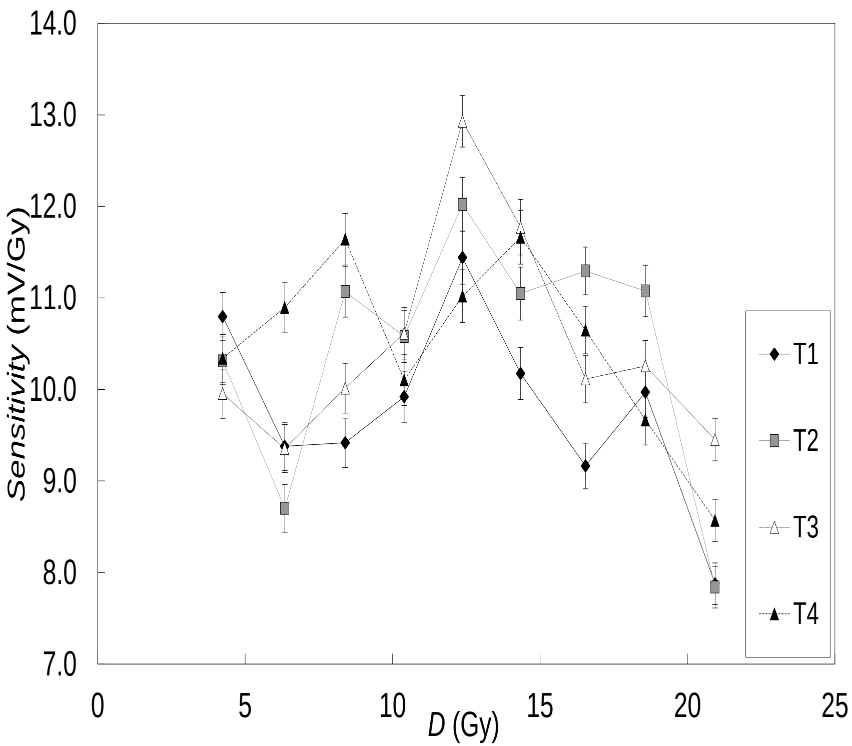
Commercial Transistors: Response to photon beams

Single pMOS



- 3N163 single biased
- ZVP3306 single unbiased

Type	Bias (V)	Sensitivity (mV/Gy)
3N163	0	21 ± 2
	5	47 ± 5
	10	55 ± 5
ZVP3306	0	4.1 ± 0.4
	5	7.5 ± 0.6
	10	10.5 ± 0.4
CD4007	0	5.27 ± 0.07

- Sensitivity of 3N163 improved by 5 and 4 for the ZVP3306 and CD4007.
- ZVP3306 and CD4007 discarded .

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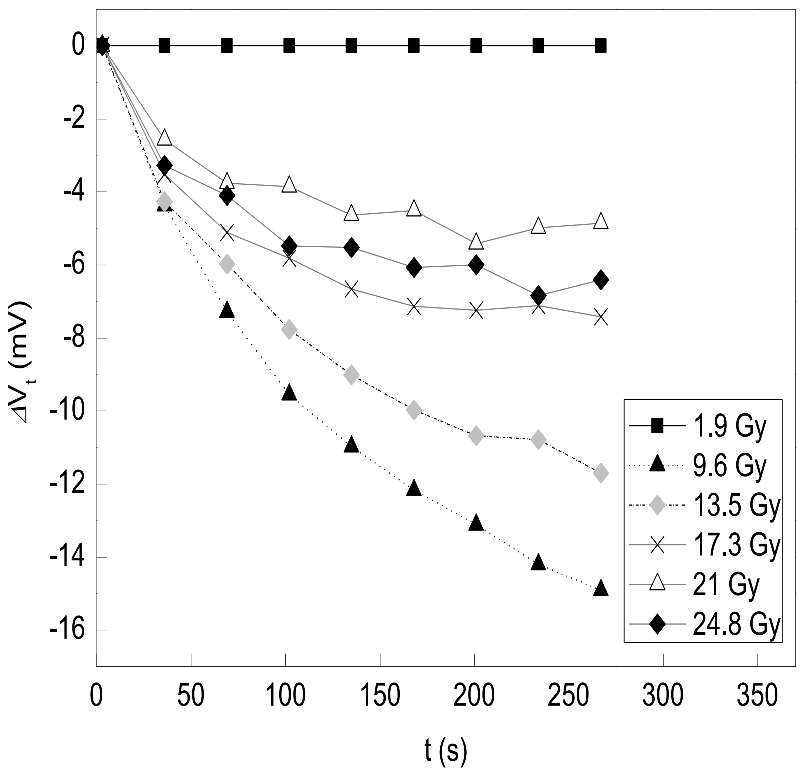
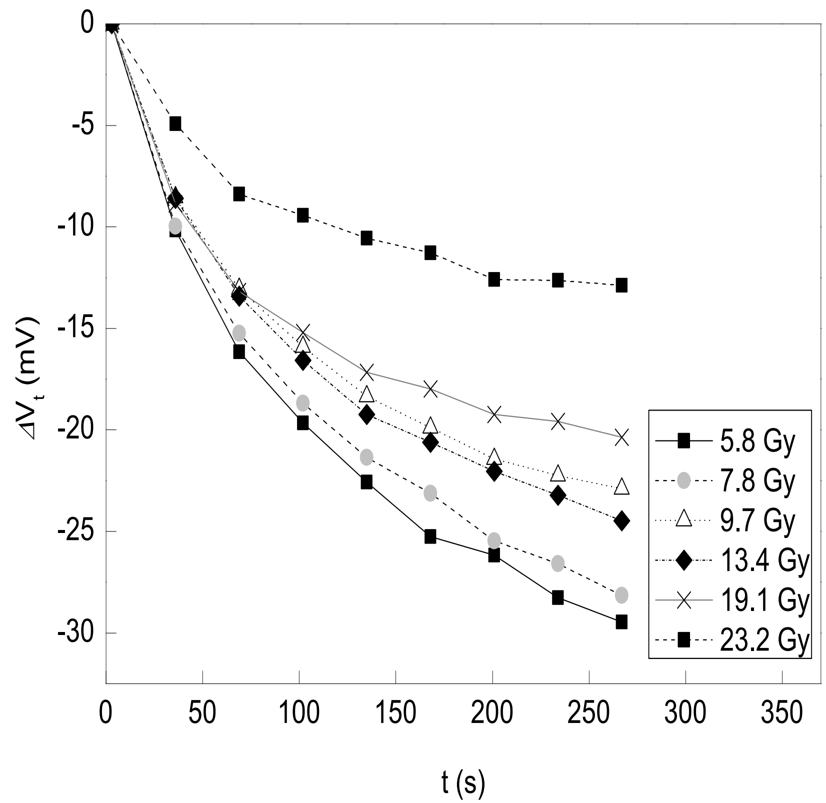
Commercial Transistors: Response to photon beams

Single pMOS : short-term fading with bias

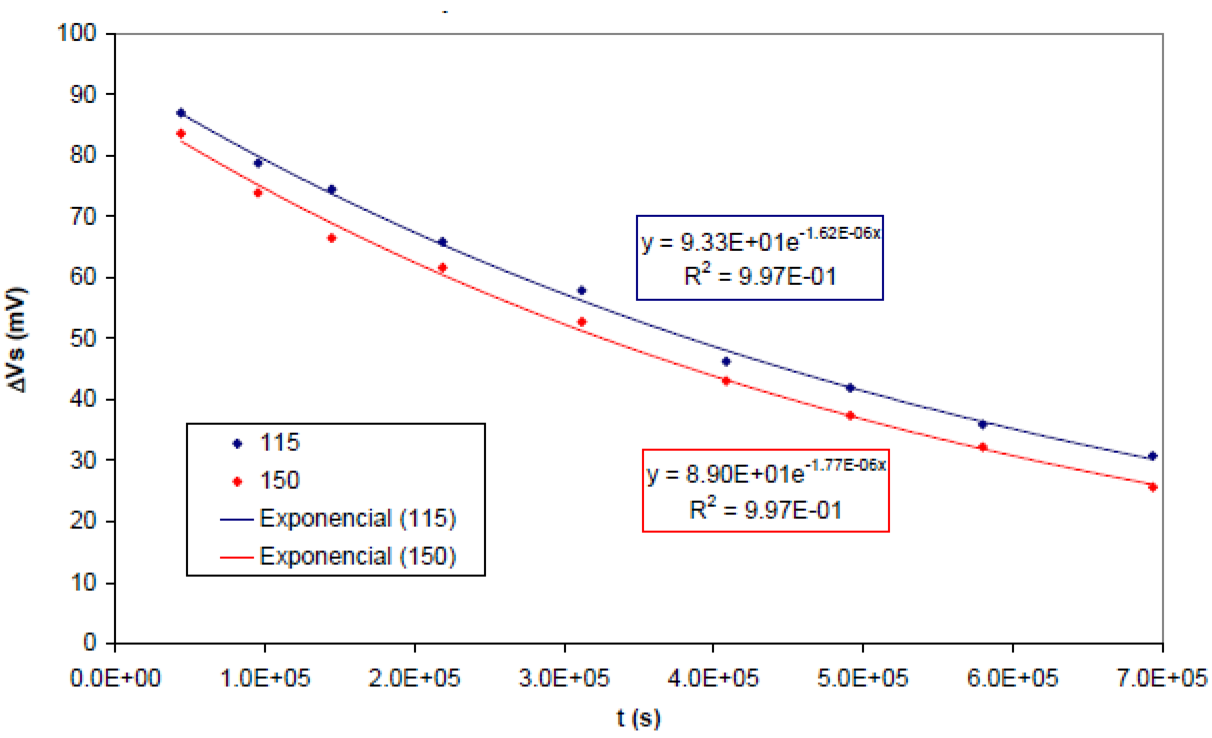




- 3N163 with bias 5 V (-16 mV).
- 3N163 with bias 10 V (-30 mV).

Commercial Transistors: Response to photon beams

Single pMOS : long-term fading



- 3N163 with bias 0 V.

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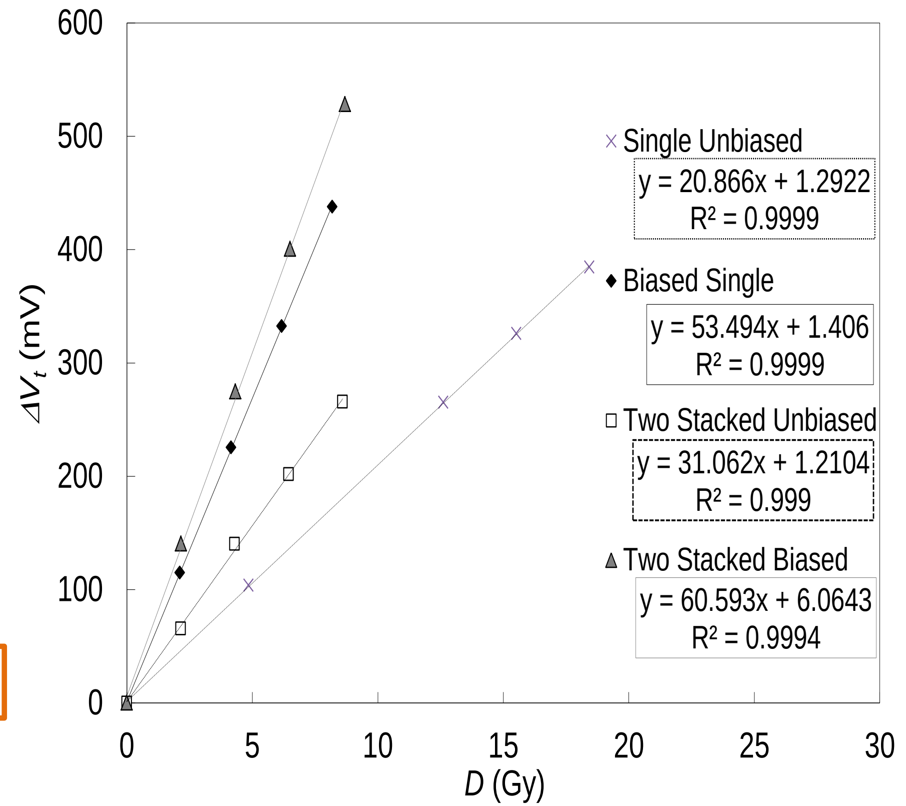
Commercial Transistors: Response to photon beams

Two stacked pMOS

Confi.	Type	Bias (V)	Sensitivity (mV/Gy)
Single	3N163	0	21 ± 2
		5	47 ± 5
		10	55 ± 5
	ZVP3306	0	4.1 ± 0.4
		5	7.5 ± 0.6
		10	10.5 ± 0.4
	CD4007	0	5.27 ± 0.07
Two stacked	3N163	0	33 ± 2
		10	62 ± 3



- Four configurations for 3N163.

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Commercial Transistors: Response to photon beams

Summary:

1. All MOSFET types **linear performance**. Sensitivity range between 4.1 and 62 mV/Gy.
2. Sensitivity values 3N163 are **higher** than the ZVP3306 type.
3. ZVP3306 has **lowest dispersion** but needs post **thermal compensation**.
4. **3N163 Long-term fading:** 120s < t < 6.10^5s
5. **3N163 Short-term fading:** ΔV_t between -16 mV to -30 mV, with 5 V and 10 V.
6. Optimal configuration: **Two stacked biased mode for the 3N163 transistor** (62±3 mV/Gy).
7. CD4007 shows suitable reliability as dosimetry sensor.

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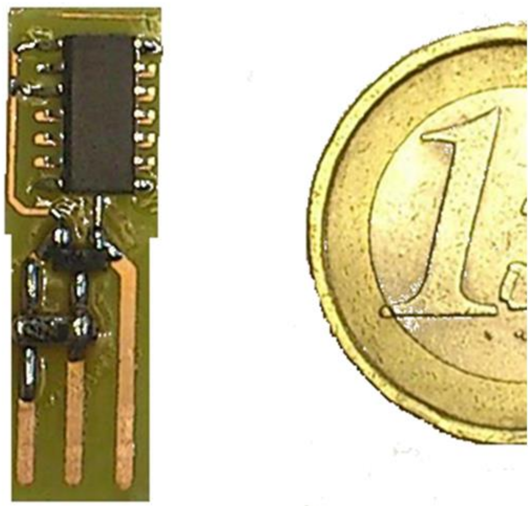
Commercial Transistors: Response to electron beams

Set-up

- 50 transistors
- 5 per group
- LINAC
- 25x25 cm^2
- **Electron beam of 6 MeV**
- 100 cm to the source
- 30x30x8 cm^3
- 4 different configurations
- PTW23332
- 1.8 and 5.6 Gy per session up to 59.4 Gy
- **No build up**
- 6 minutes to measure
- Types: **CD4007, ZVP3306, ZVP4525** and **BS250F**



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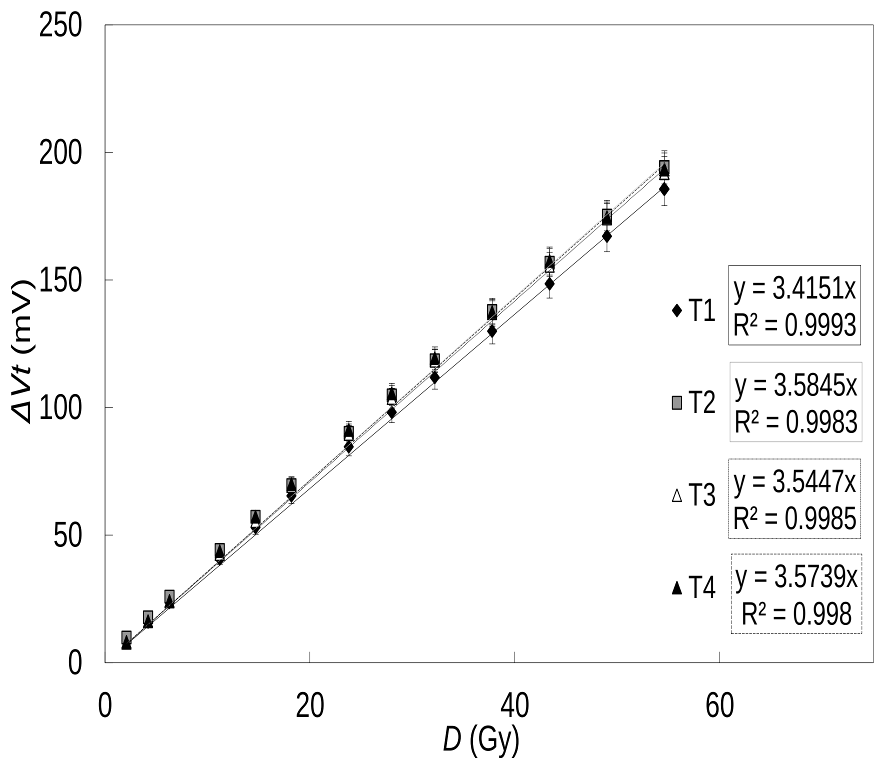
Commercial Transistors: Response to electron beams

Single pMOS

Type	Bias (V)	Sensitivity (mV/Gy)
BS250F	0	3.1 ± 0.4
ZVP4525	0	3.4 ± 0.4
ZVP3306	0	3.7 ± 0.3
	5	7.0 ± 0.3
	10	9.0 ± 0.9
CD4007	0	4.6 ± 0.1
	0.6	7.4 ± 0.1

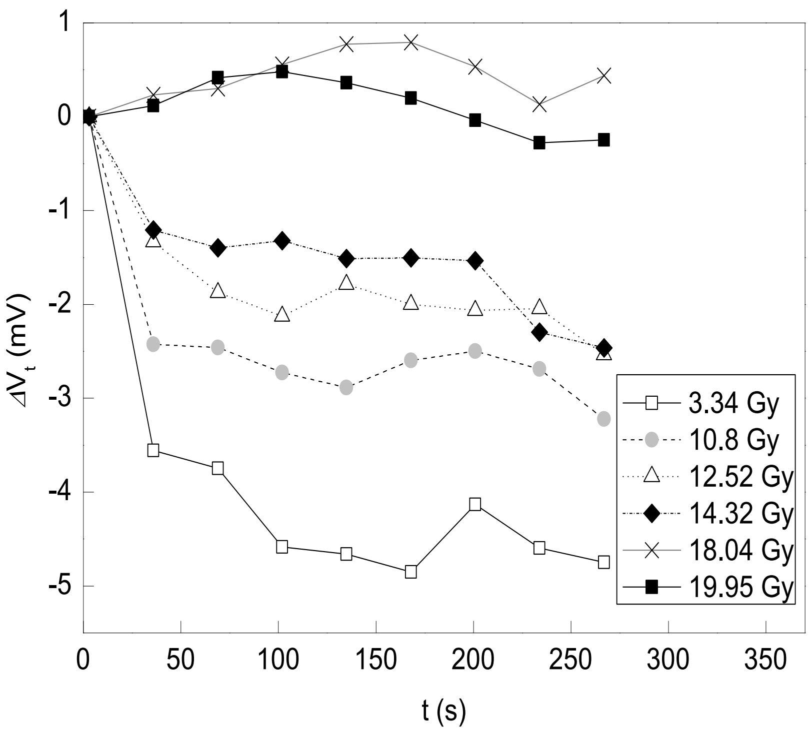


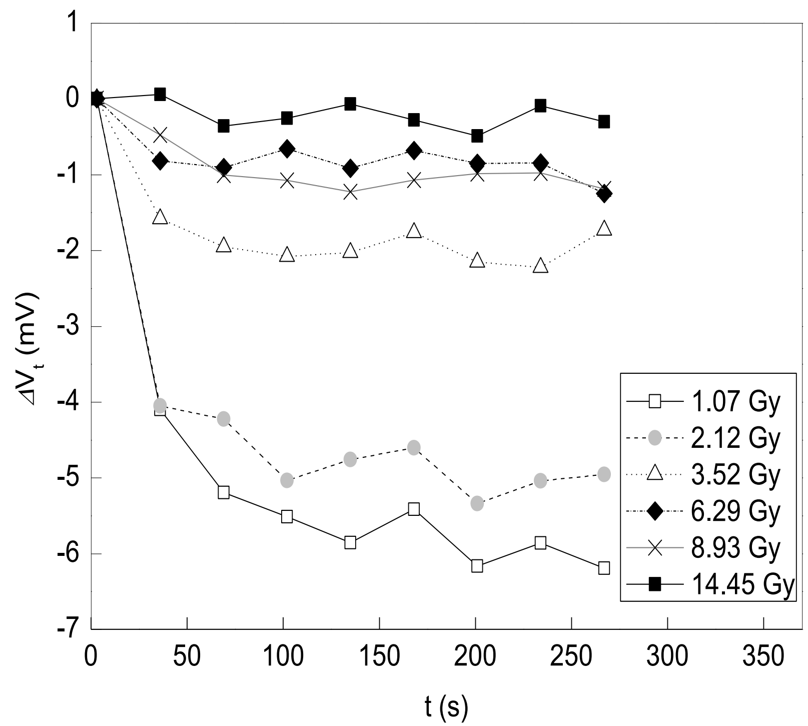
- ZVP3306 > 10% and 16% than ZVP4525 and BS250F (discarded).
- Biased mode *S* increased in 1.5 and 2.5 for ZVP3306 and CD4007.

- ZVP3306 single biased.

Commercial Transistors: Response to electron beams

Single pMOS: short term fading

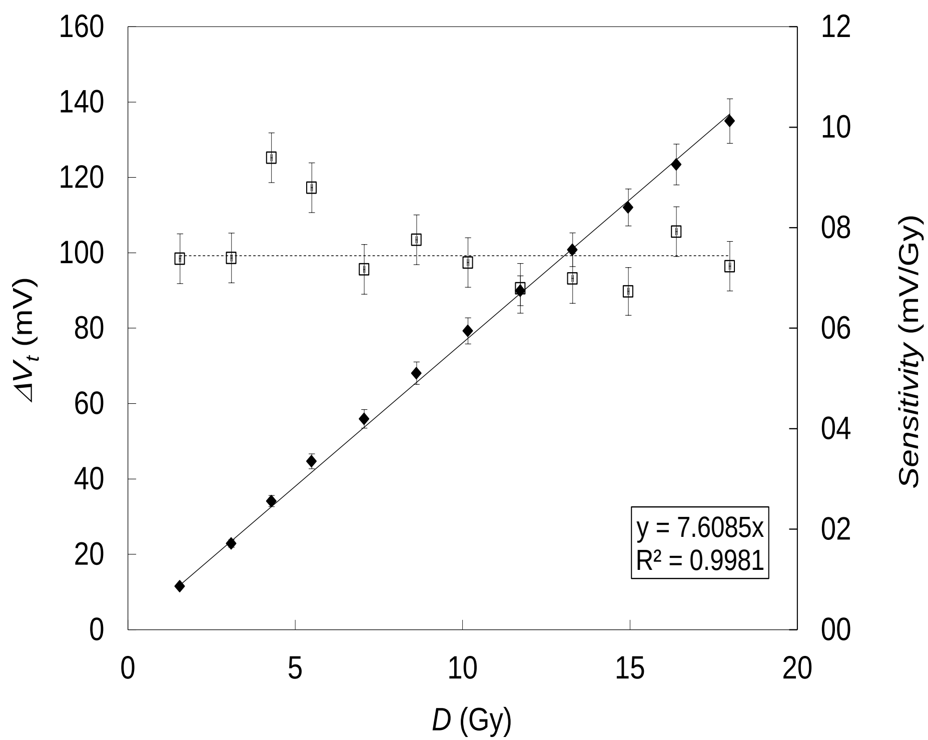


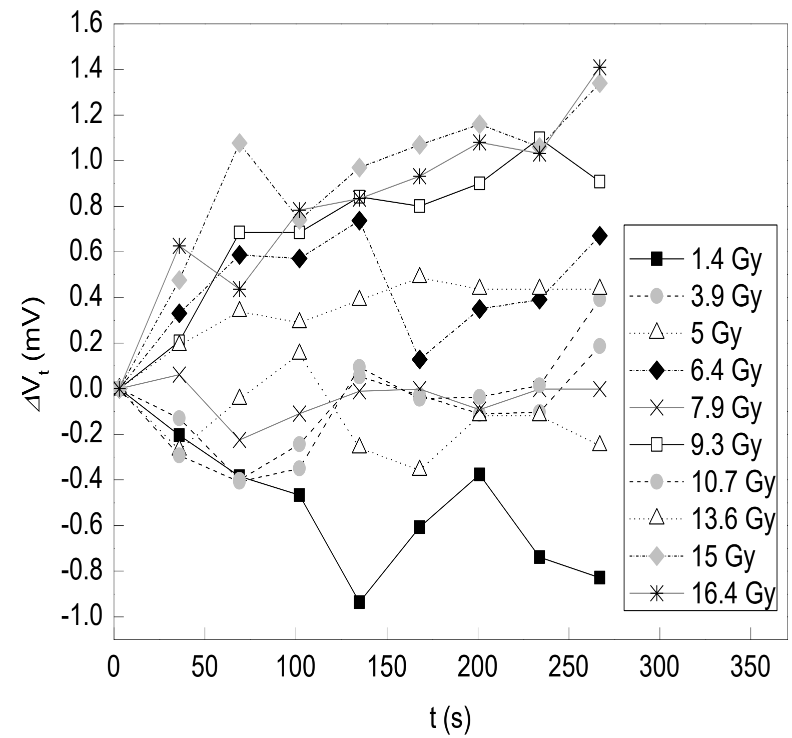


- ZVP3306 with bias 5 V (-5 mV).
- ZVP3306 with bias 10 V (-6 mV).

Commercial Transistors: Response to electron beams

Single pMOS

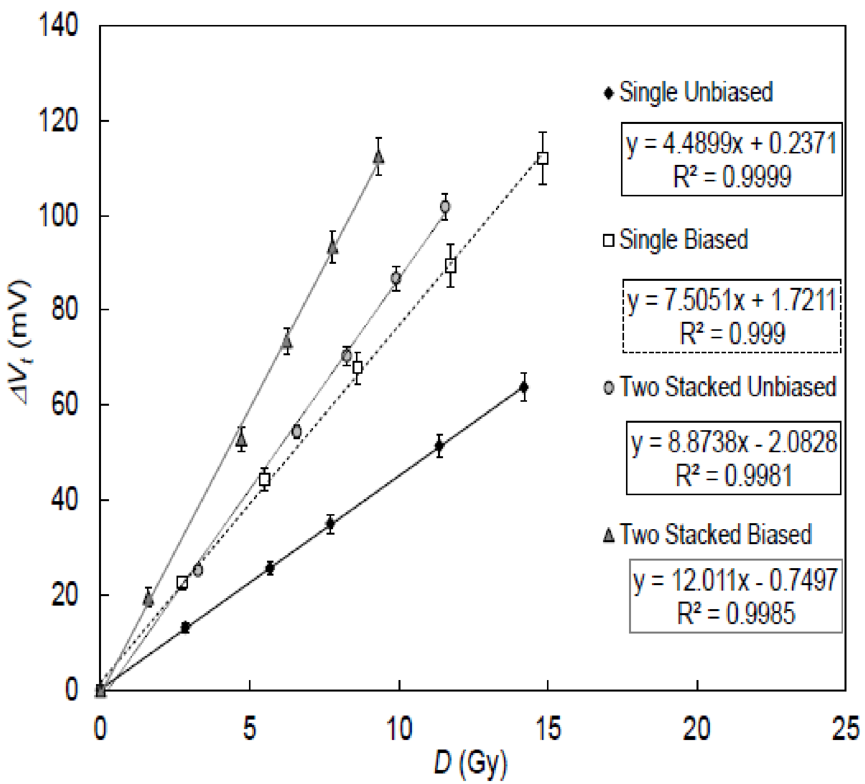


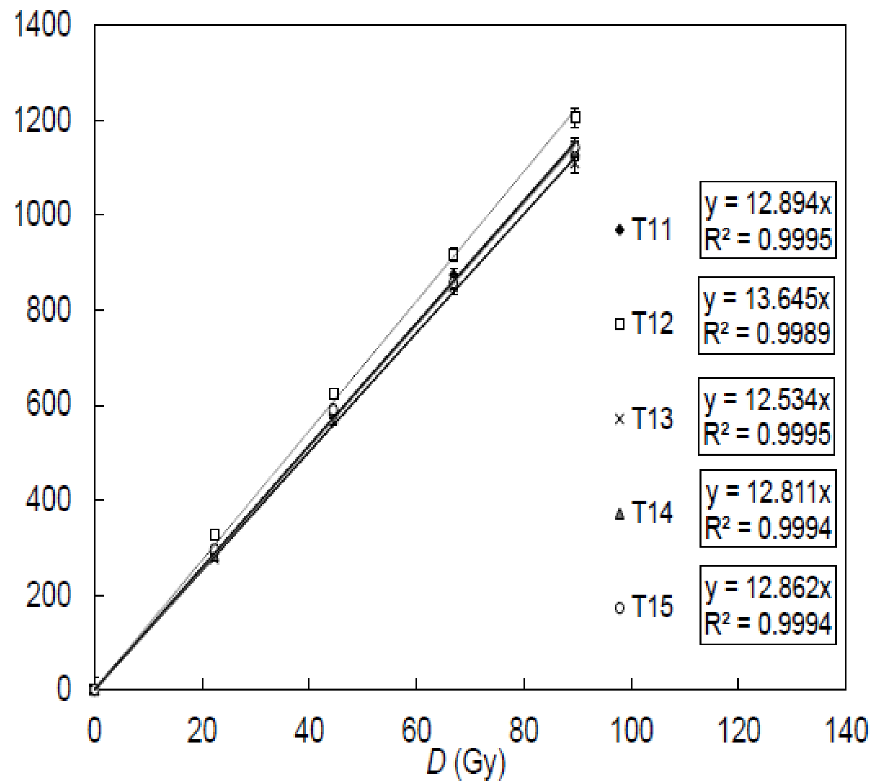


- CD4007 single biased.
- Short term fading: between [-1,1.6] mV.

Commercial Transistors: Response to electron beams

Two stacked pMOS (CD4007)





- Comparative configurations.
- IORT conditions (22 Gy per session): 12 .0 ± 0.3 mV/Gy.

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Commercial Transistors: Response to elecron beams

Two stacked pMOS

Confi.	Type	Bias (V)	Sensitivity (mV/Gy)
Single	BS250F	0	3.1 ± 0.4
	ZVP4525	0	3.4 ± 0.4
	ZVP3306	0	3.7 ± 0.3
		5	7.0 ± 0.3
		10	9.0 ± 0.9
	CD4007	0	4.6 ± 0.1
		0.6	7.4 ± 0.1
Two stacked	CD4007 (Texas Instruments)	0	9.5 ± 0.7
		0.6	13 ± 1
	CD4007 (NXP Semiconductors)	0.6	9.3 ± 0.9

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Commercial Transistors: Response to electron beams

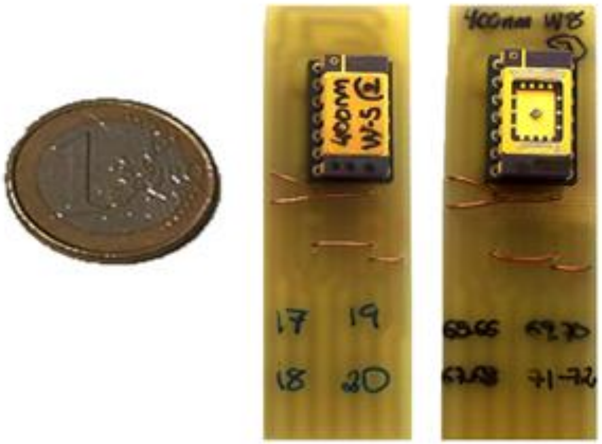
Summary:

1. **Linear response** and **low dispersion** in DMOS and CD4007. Sensitivities 3 -13 mV/Gy.
2. Sensitivity increased in stacked and biased mode.
3. Vertical pMOS did not show zero temperature regions.
4. **Fading:** ZVP33056 → ΔV_t of -6 mV (10 V). CD4007 [-1,1.6 mV].
5. **CD4007** shows a promising behaviour. Sensitivity 12.7 mV/Gy (Two stacked transistors and biased).

RADFETs

Set-up

- Comparative study of the response to photon (6 MV) and electron (6 MeV) beams.
- Biased with I_{ZTC} :
  - 3CM does not improve the linearity in RADFETs.
  - This is could be caused because $Q_{ot} >> Q_{it}$.
- 20 Chips → 80 RADFETs.
- LINAC.
- 100 cm to source.
- 10 minutes to read out.
- Portable reader unit from UGR.



RADFETs

Set-up

Beams	Type	Gy per session	Dmax (Gy)	Build-up (cm)	Field (cm^2)	Slab Phantom (cm^3)
Photon (6 MV)	400 nm and 1 μm	2.05 and 4.24	55	1.5	25x25	30x30x12
	100 nm	10.48 and 23.03	275			
Electron (6 MeV)	400 nm and 1 μm	2.06 and 4.66	50	1.3	15x15	30x30x8.2
	100 nm	10.79 and 22.73	208			

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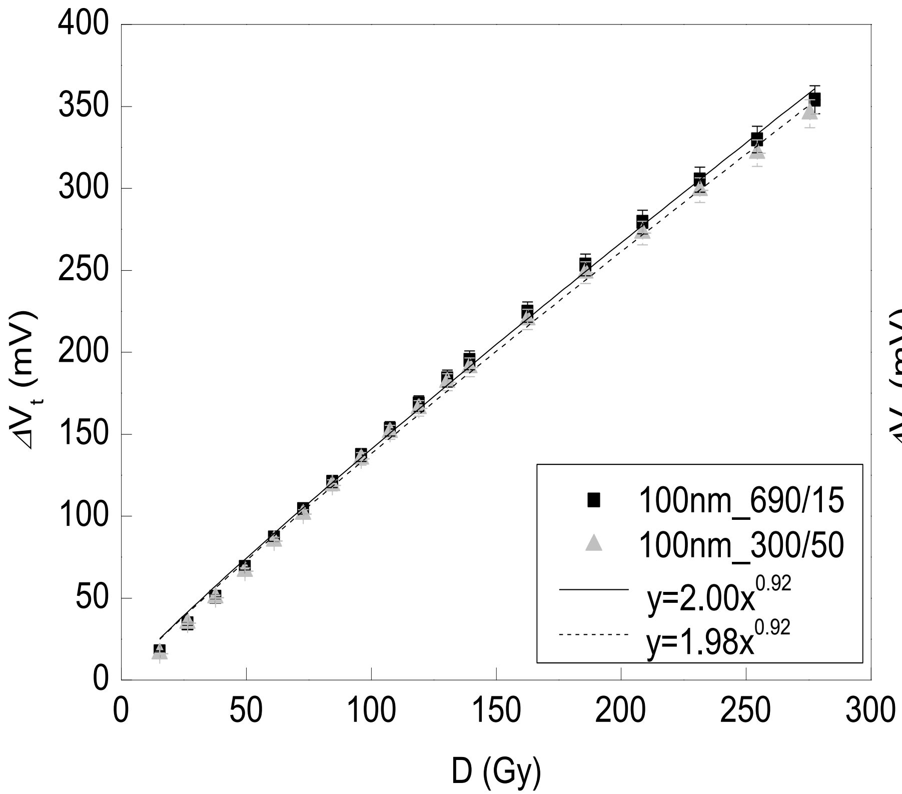
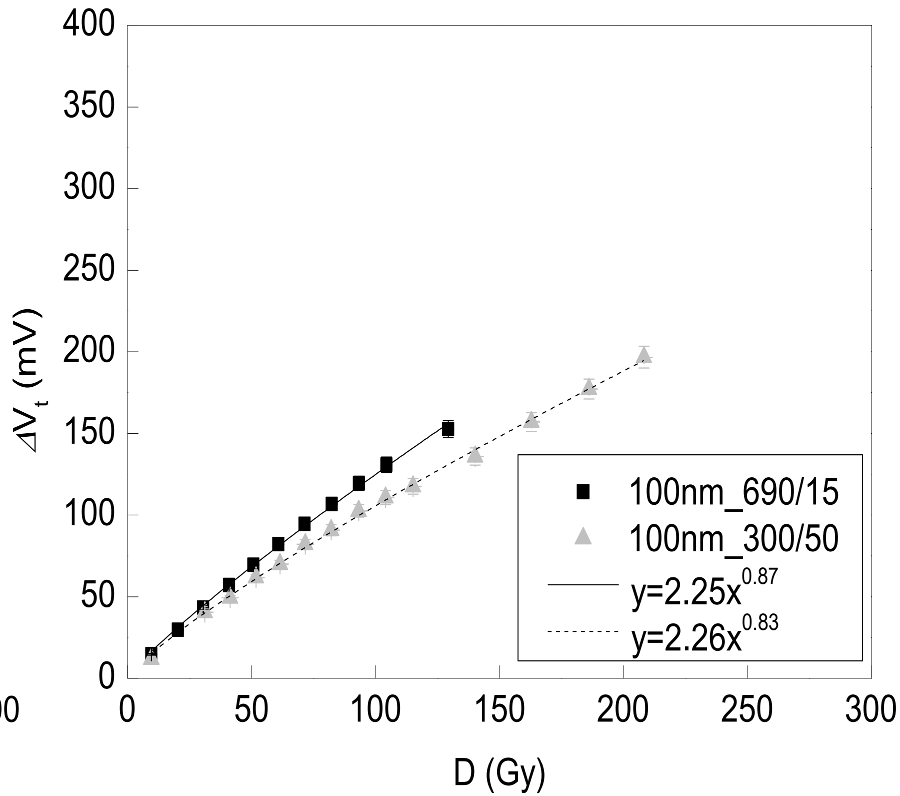
RADFETs

- *ΔVt* vs. Dose: 100 nm:



PHOTON BEAMS



ELECTRON BEAMS

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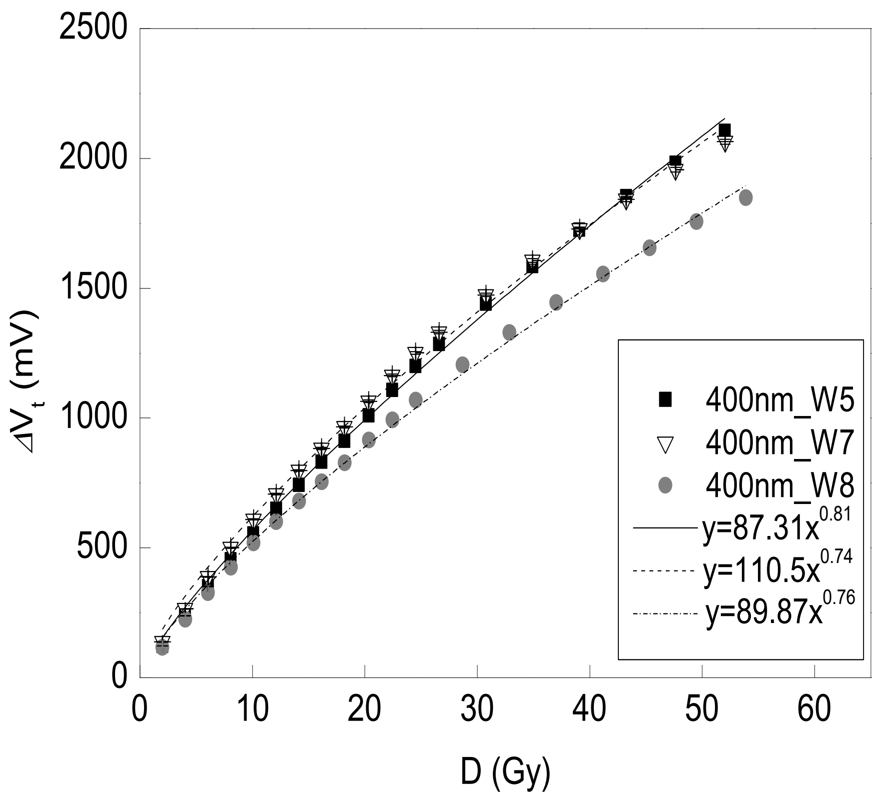
RADFETs

- ΔV_t vs. Dose: 400 nm W/L= 300/50:

Tyndall National Institute



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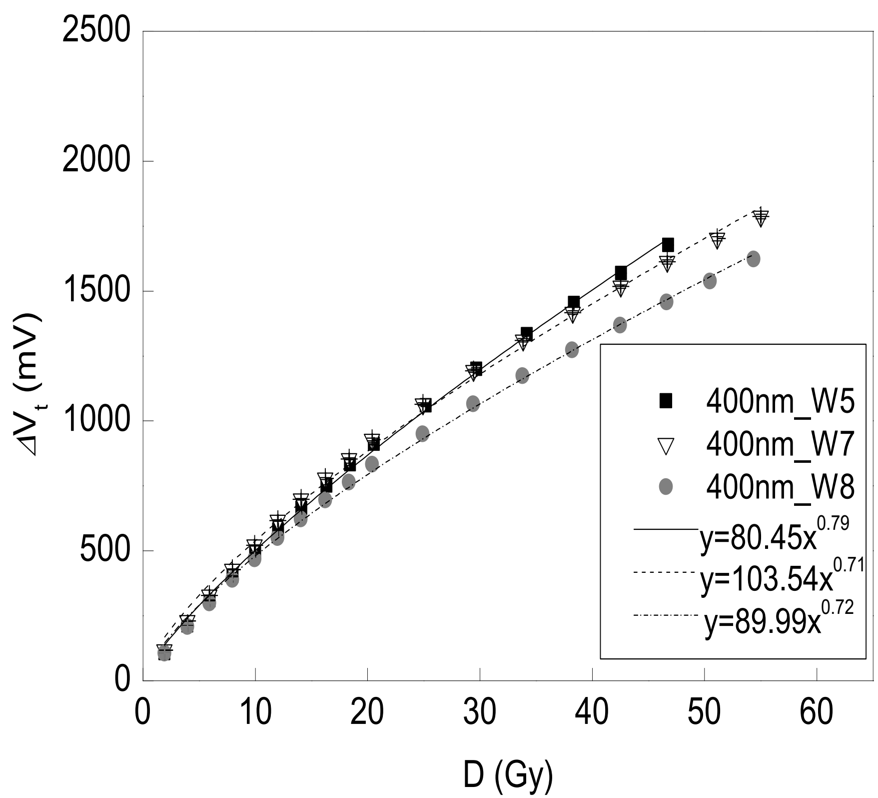

ELECTRON BEAMS

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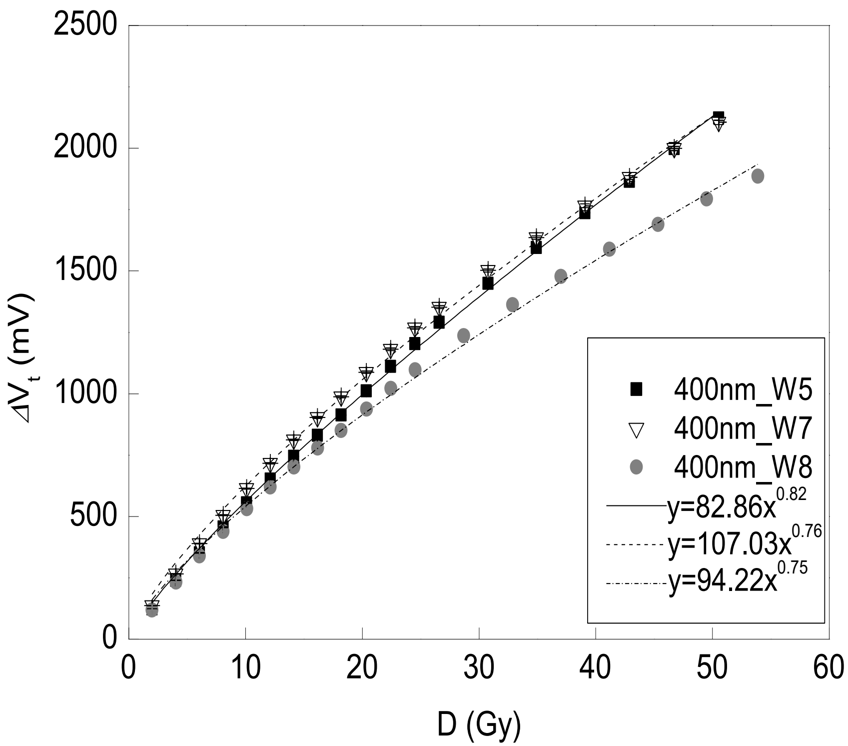
RADFETs

- ΔV_t vs. Dose: 400 nm W/L= 690/15:



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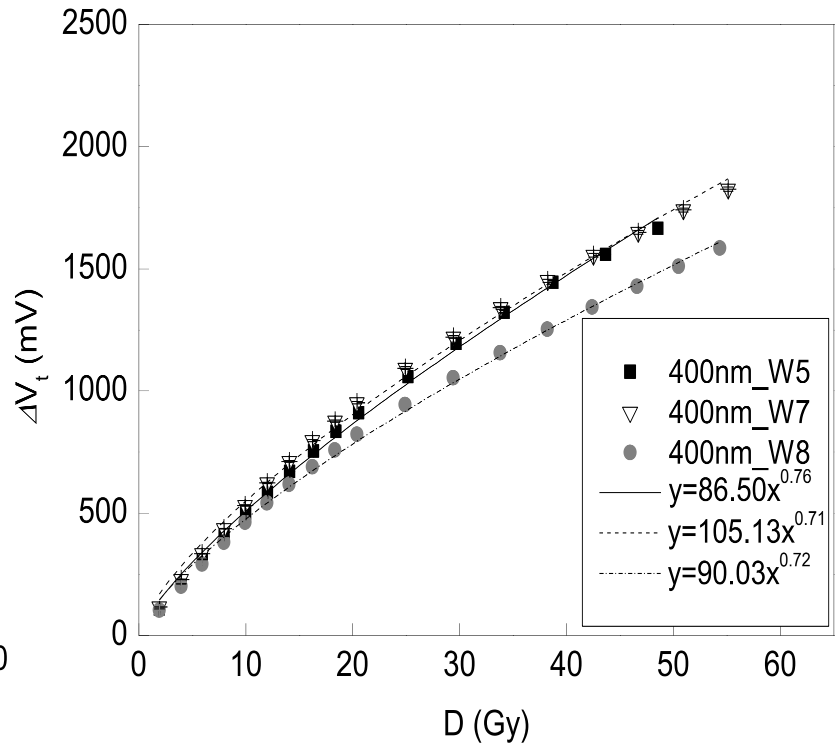
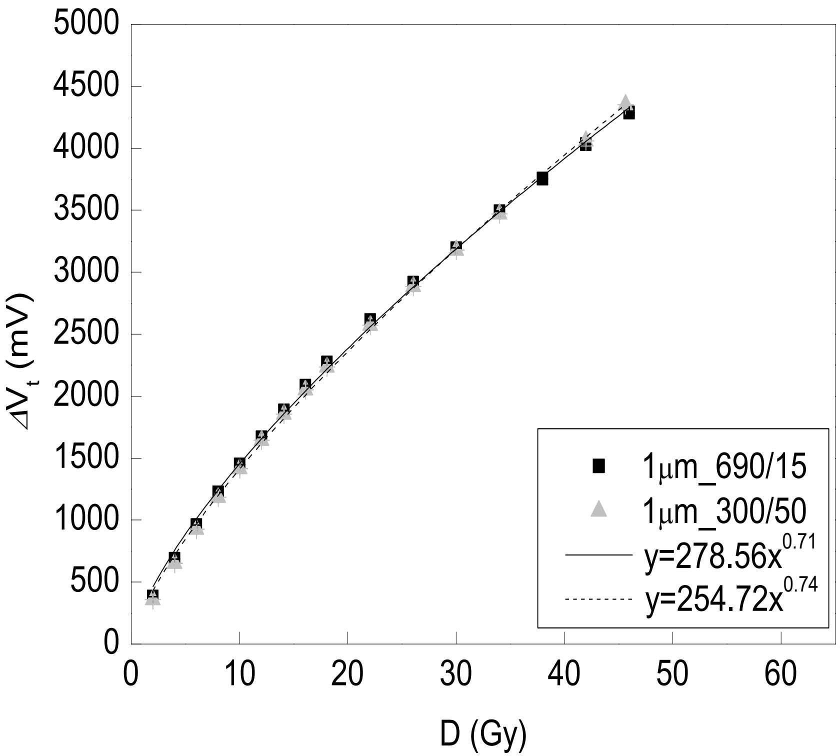


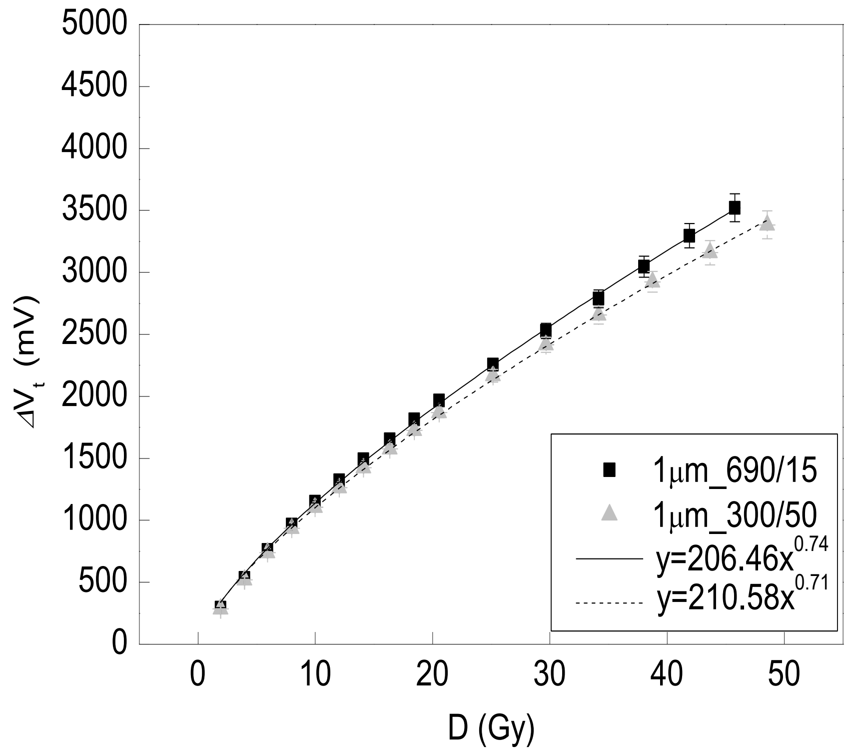
ELECTRON BEAMS

RADFETs

- ΔV_t vs. Dose: 1 μm:



PHOTON BEAMS



ELECTRON BEAMS

RADFETs

- Calibration parameters:

Tyndall National Institute

$$\Delta V_t = A \cdot D^n$$

Type	Size (W/L)	Photon Beam A	Photon Beam n	Electron Beam A	Electron Beam n
100 nm	300/50	2.0 ± 0.3	0.91 ± 0.03	2.2 ± 0.3	0.83 ± 0.03
	690/15	2.03 ± 0.19	0.92± 0.02	2.2 ± 0.3	0.87 ± 0.03
400 nm_W5	300/50	91 ± 5	0.80 ±0.01	79 ± 3	0.79 ± 0.01
	690/15	81 ± 4	0.83 ± 0.01	83 ± 6	0.78 ± 0.02
400 nm_W7	300/50	113 ± 8	0.74 ±0.02	104 ± 6	0.73 ± 0.01
	690/15	103 ± 5	0.77 ± 0.02	105 ± 6	0.72 ± 0.01
400 nm_W8	300/50	73 ± 11	0.81 ±0.05	79 ± 10	0.73 ± 0.01
	690/15	86 ± 10	0.77 ± 0.02	85 ± 7	0.73 ± 0.01
1 μm	300/50	239± 23	0.76 ± 0.02	213 ± 9	0.72 ± 0.01
	690/15	250 ± 50	0.74 ± 0.04	202 ± 9	0.74 ± 0.01

RADFETs

Summary:

1. Response to electron beams **similar** within experimental uncertainty to photon beams in reference conditions.
2. **Fading** t_{OX} =100 nm and 400 nm for <1% after 360 s. Non-negligible for t_{OX} =1 μm.
3. Previous conclusions in photon beams could be **valid** in electron beams, within the limits of our study.

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Conclusions:
Response to ionizing radiation

Commercial transistors:

1. All types showed a **linear performance** and **low dispersion**, with a sensitivity range between 4.1 and 62 mV/Gy for photon beams and 3 -13 mV/Gy for electron beam.
2. Optimal configuration: **Two stacked biased mode** both photon and electron beams.

Tyndall RADFETs

3. Higher sensitivity and low fading for 100 and 400 nm. Response of RADFETs to electron beams **similar** to photon beams in reference conditions within experimental uncertainty.

Thank you very much

Response to ionizing radiation of commercial and RADFET transistors

María Sofía Martínez García