MOS Dosimetry

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Dosimetry Principles

Dose, or deposited dose, is a measure of the ammount of energy imparted by a radiation field to the unit mass of a medium through ionizing events.

$D = Q.W / q.m$

Q : ionized charge
W : Energy per ionized electron
q : electron charge
m : sample mass

[D] = erg/g =: *rad* , or joule/kg =: *Gray*

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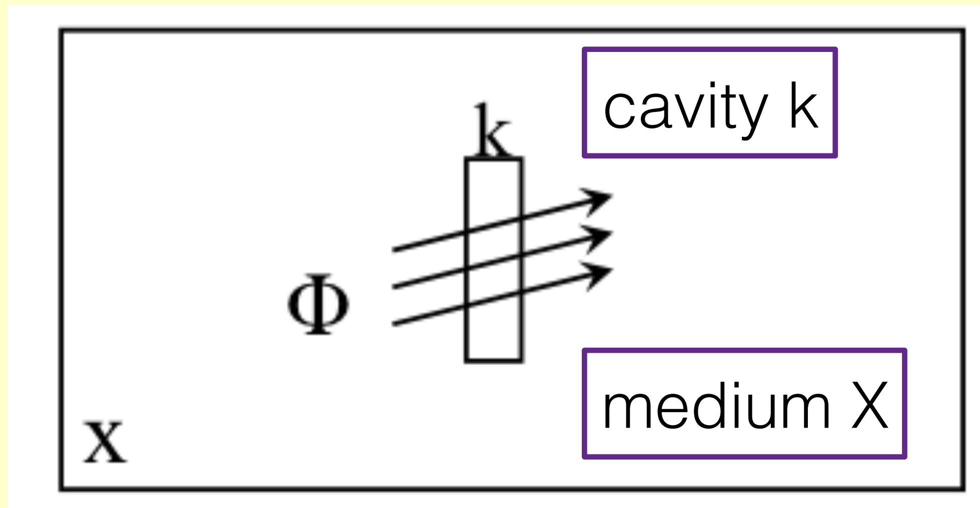
Cavity Bragg-Gray theory



$$D_x = \Phi_x \left(\frac{dT}{\rho dx}\right)_{col}$$

$$D_k = \Phi_k \left(\frac{dT}{\rho dx}\right)_{col}$$

$$\frac{D_x}{D_k} = \frac{\Phi_x \left(\frac{dT}{\rho dx}\right)_{col}}{\Phi_k \left(\frac{dT}{\rho dx}\right)_{col}} = {}^{x}_{k}\left(\frac{dT}{\rho dx}\right)_{col}$$

under B-G conditions

→ *Bragg-Gray relation*

Bragg-Gray theory Conditions

$$\frac{D_x}{D_k} = {}^{x}_{k}\left(\frac{dT}{\rho dx}\right)_{col}$$

The B-G relation give that the dose relation between the cavity and the medium is given by the mass stopping power ratio

B-G conditions:

Deposited dose are only due to charged particles

The particle fluence does not change over the cavity

→ *VERY SMALL CAVITY*

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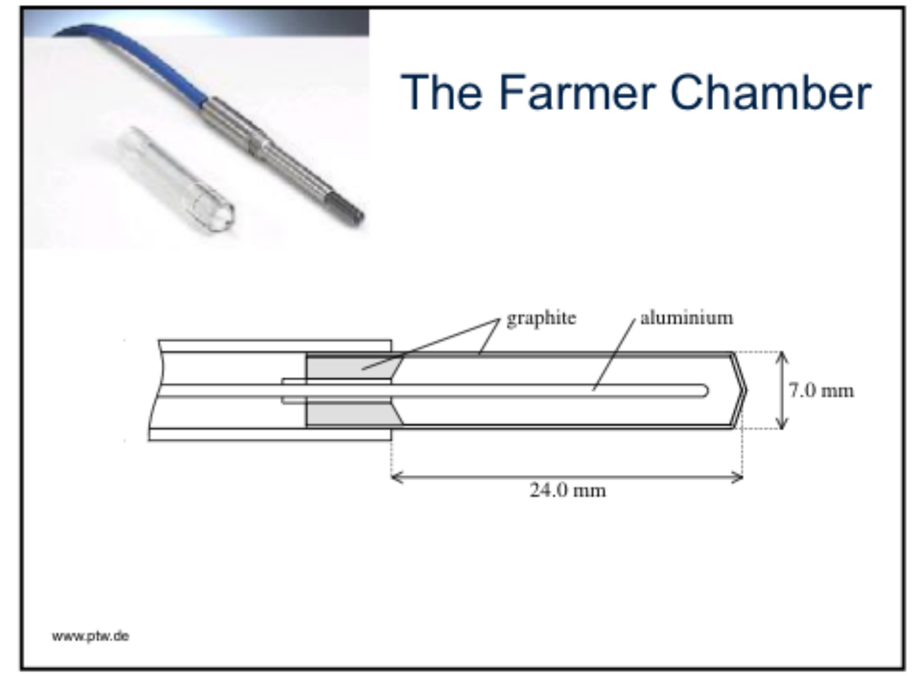
Ionization chamber

...but not so small in order to have sufficient ionization volume for the output current to be measurable.



Advantages:

- Portable and relatively easy to use.
- Good absolute accuracy (calibrated against secondary standard).
- Farmer chamber good for high-energy photon beams.
- Markus chamber good for electron beams.

Disadvantages:

- Require temperature and pressure corrections.
- Relatively large measurement volume.
- Some directional and energy dependence.
- Single point measurement only.

Common use:

- Routine QA of medical linacs and x-ray equipment.
- Continuous monitoring & feedback control of linac output.

$$I = dQ/dt = q.m/W \quad dD/dt$$

$$= q.ro.Vol/W \quad dD/dt$$

...smaller dosimeter need:
higher density
lower W

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Semiconductor dosimeters

$I = q.ro.Vol/W \;\; dD/dt$

$= Sensitivity.Vol \;\; dD/dt$

...smaller dosimeter need:

higher density

lower W

→ Higher Sensitivity

Semiconductor dosimeters have 18000 (Si) higher sensitivity than ionization chamber

A small dosimetric volume that satisfies the B-G conditions in most practical circumstances.

→ *Allows high spatial resolution*

Si to water mass power stoping ratio almost constant over energy range covered by RT leads to a response close to that of human tissues in this range.

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Commercially available diode dosimeters

Application-Specific In Vivo Semiconductor Diodes for VIVODOS® and MULTIDOS® Dosemeters

					
	T60010L (blue)	**T60010MP (yellow)**	**T60010HP (red)**	**T60010EP (green)**	**T60010RO (black)**
Application	entrance dose, exit dose, TBI	entrance dose, exit dose	entrance dose, exit dose	entrance dose, exit dose	risk organ monitoring
Energy range	Photons (1 ... 5) MV	Photons (5 ...13) MV	Photons (13...25) MV	Electrons (4 ...30) MeV	Photons/ Electrons
Build-up material	Titanium	Lead	Tungsten	Epoxy Resin/ PMMA	Epoxy Resin/ PMMA
Total build-up	1.0 g/cm²	2.0 g/cm²	3.0 g/cm²	0.17 g/cm²	0.55 ± 0.05 g/cm² [1]
Response, typ.	175 nC/Gy	10 nC/Gy	10 nC/Gy	10 nC/Gy	350 nC/Gy

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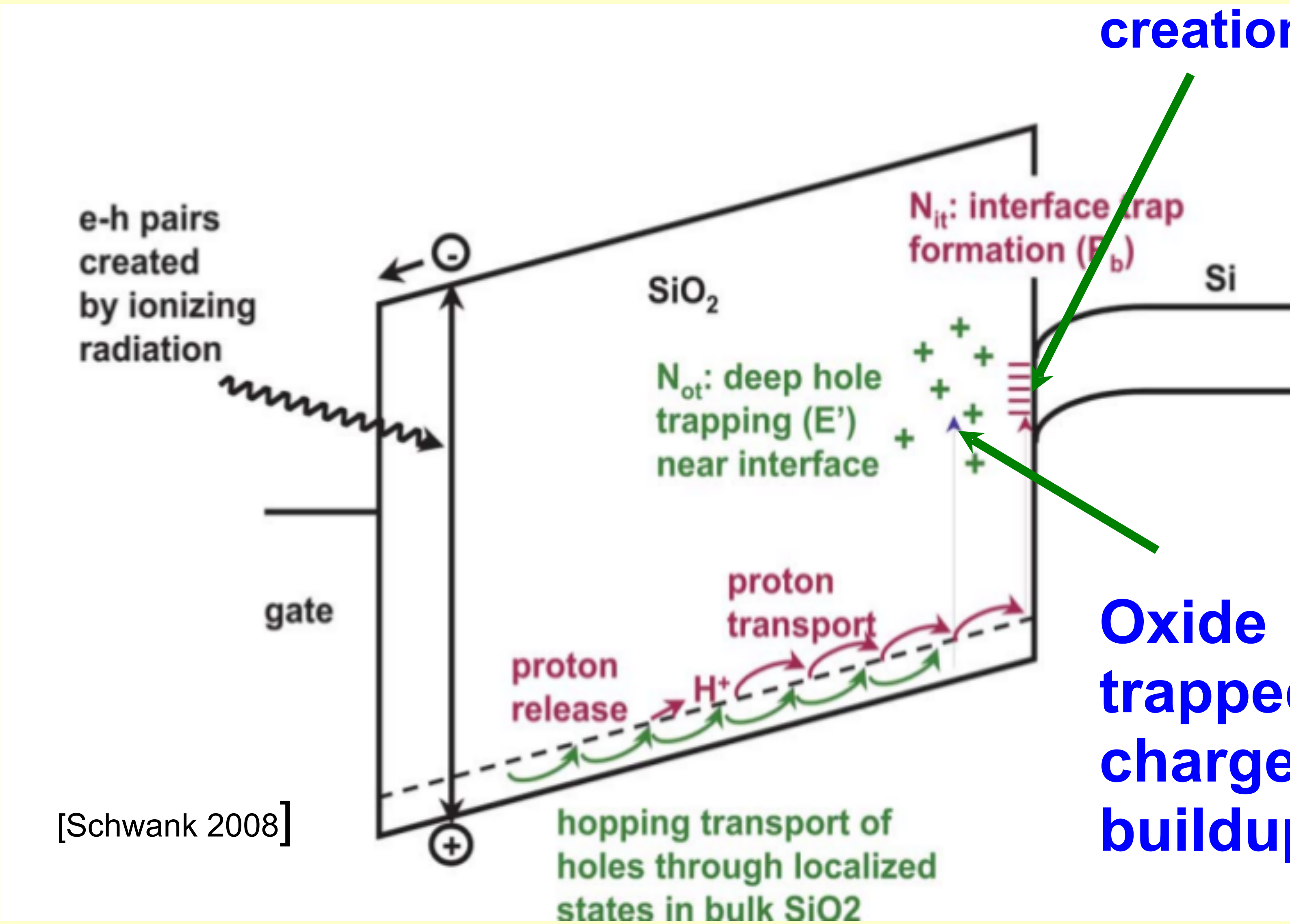
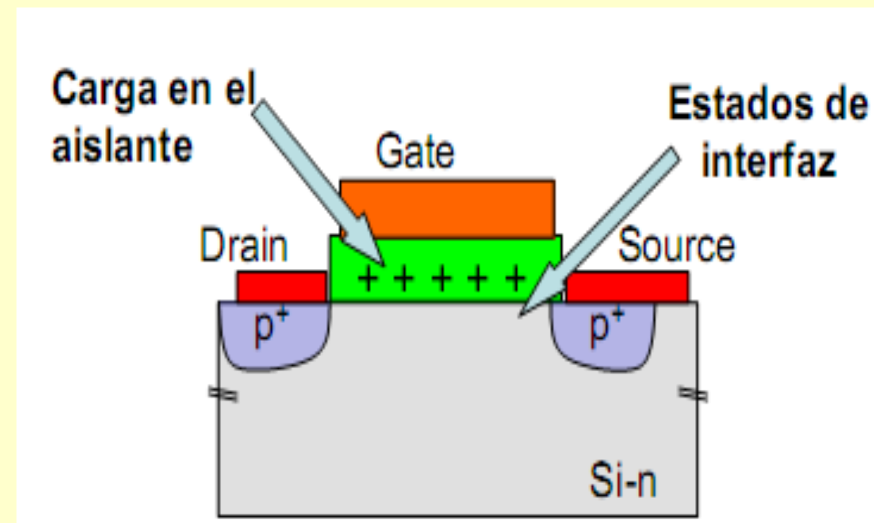
Physical mechanisms in MOS dosimetry

Interface traps creation.



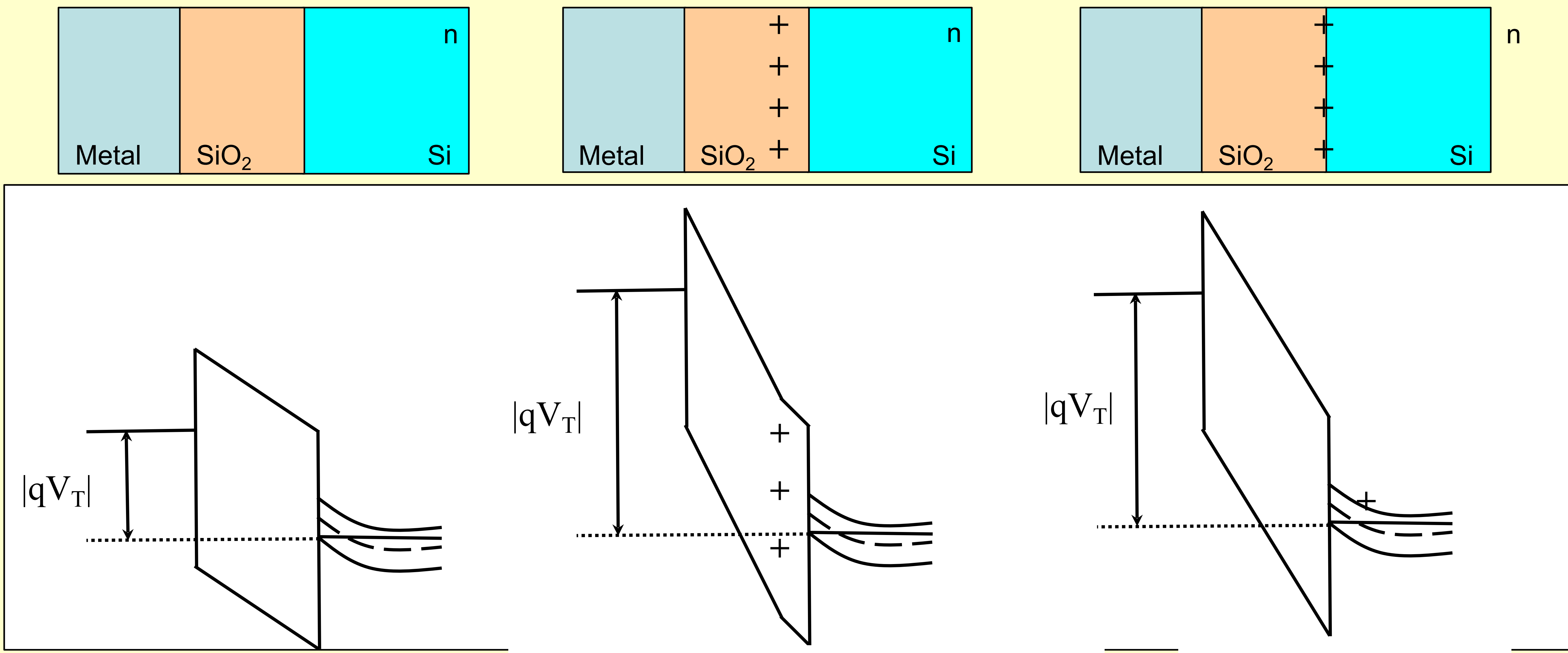
Oxide trapped charge buildup



Threshold Voltage Shift

Charge trapping and interface states. Threshold voltage shift.

Ideal MOS | **With oxide charge:** | **With interface states:**



$$\Delta V_T = \Delta V_{FB} = -\frac{1}{C_{ox}} \int_0^{t_{ox}} \frac{x}{t_{ox}} \rho(x) dx$$

$$\Delta V_T = -\frac{Q_{it}(2\phi_B)}{C_{ox}}$$

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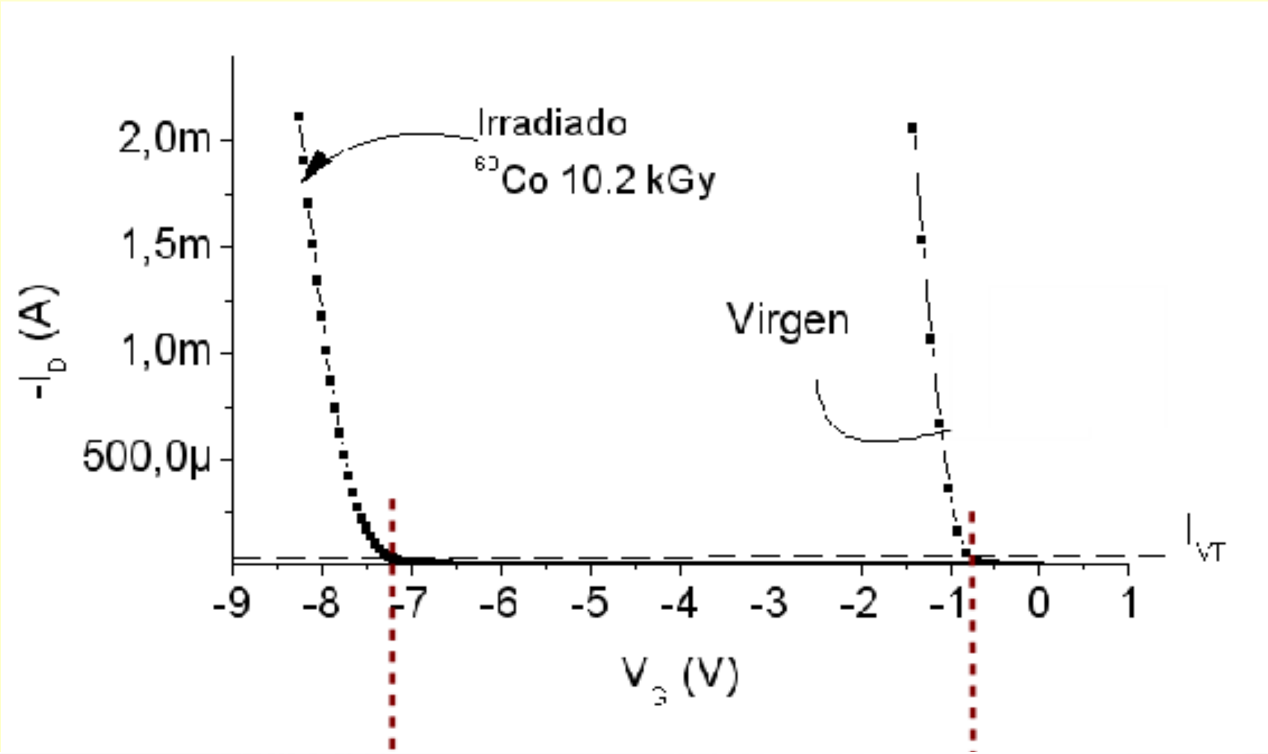
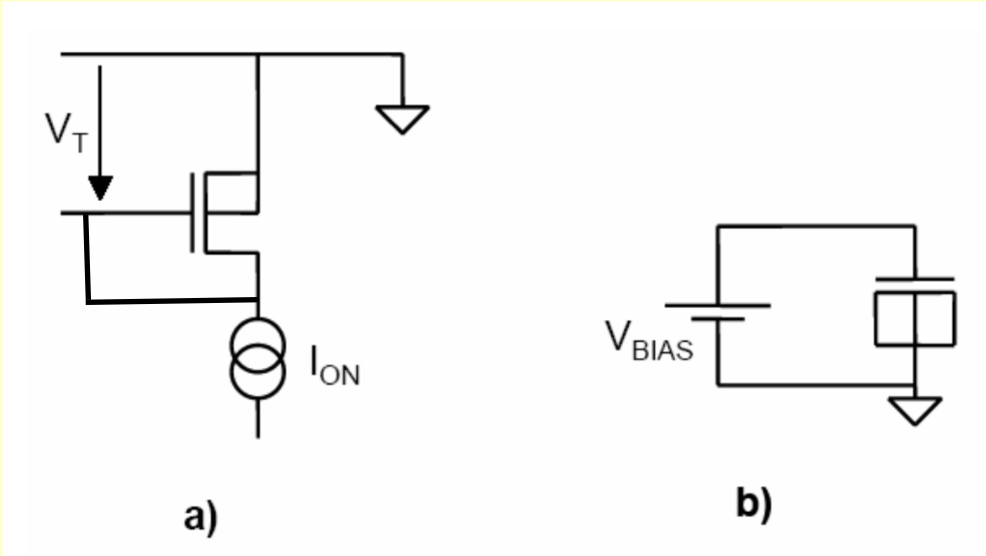
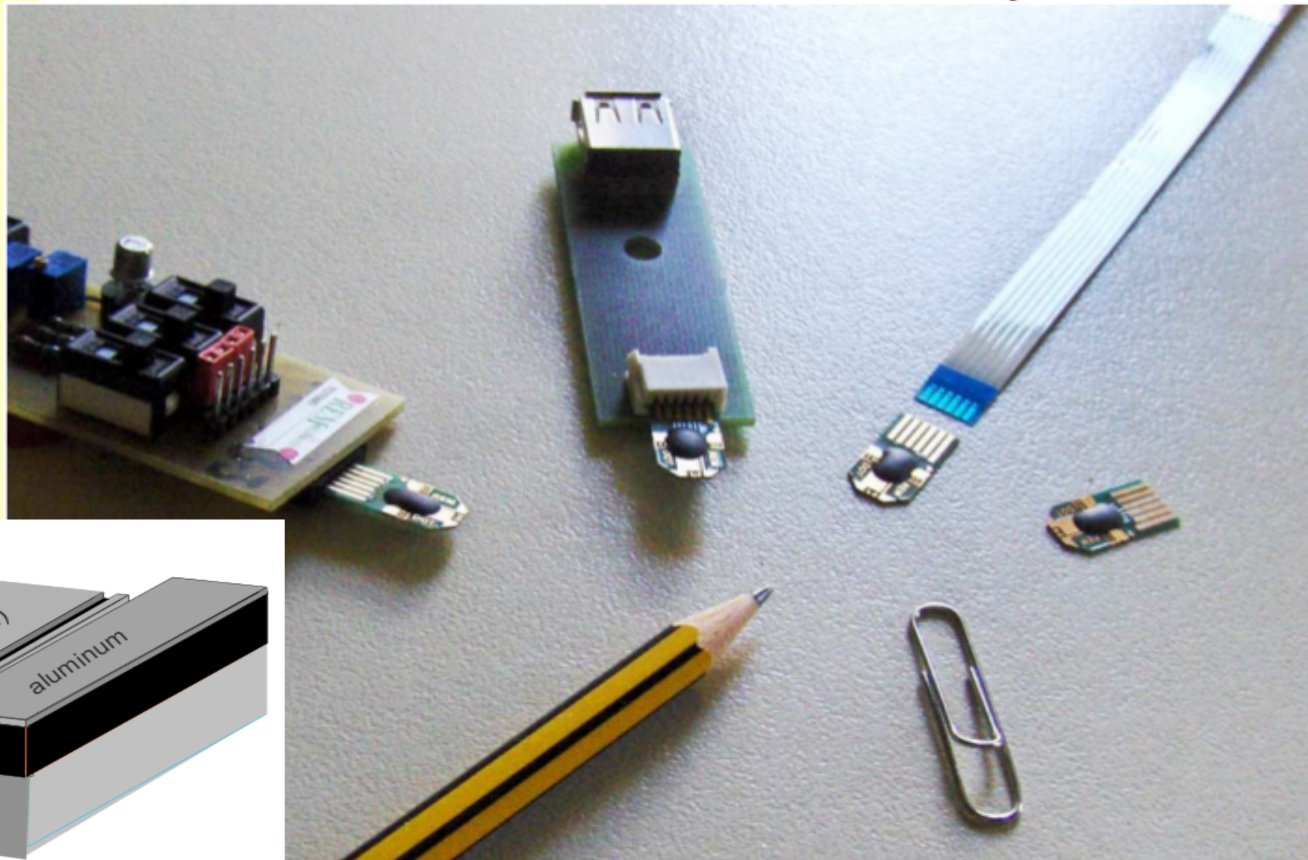
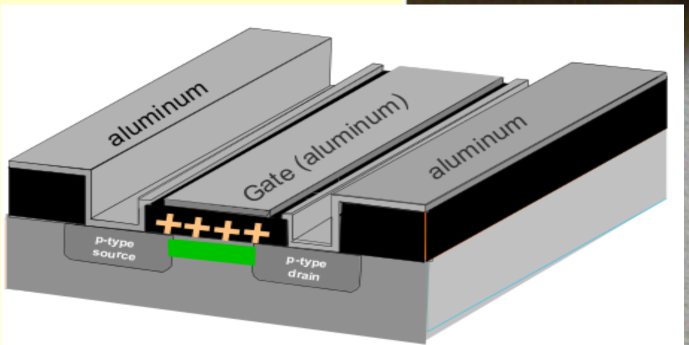
MOS Dosimeters

- The radiation-induced V_T shift is used to quantify the absorbed dose.
- Usually V_T is measured as the shift in a point of the I-V curve.
- Allows real-time, automatic measurement of the accumulated dose.









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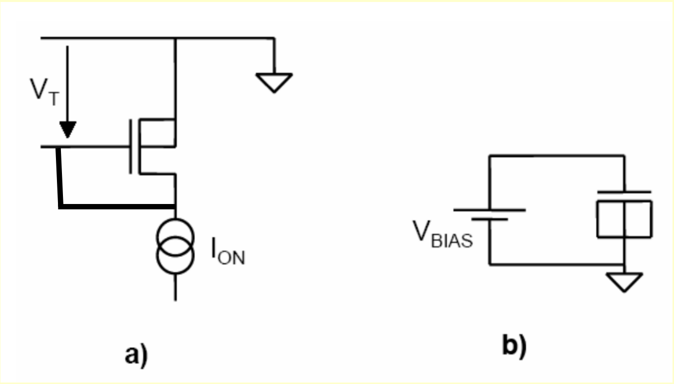
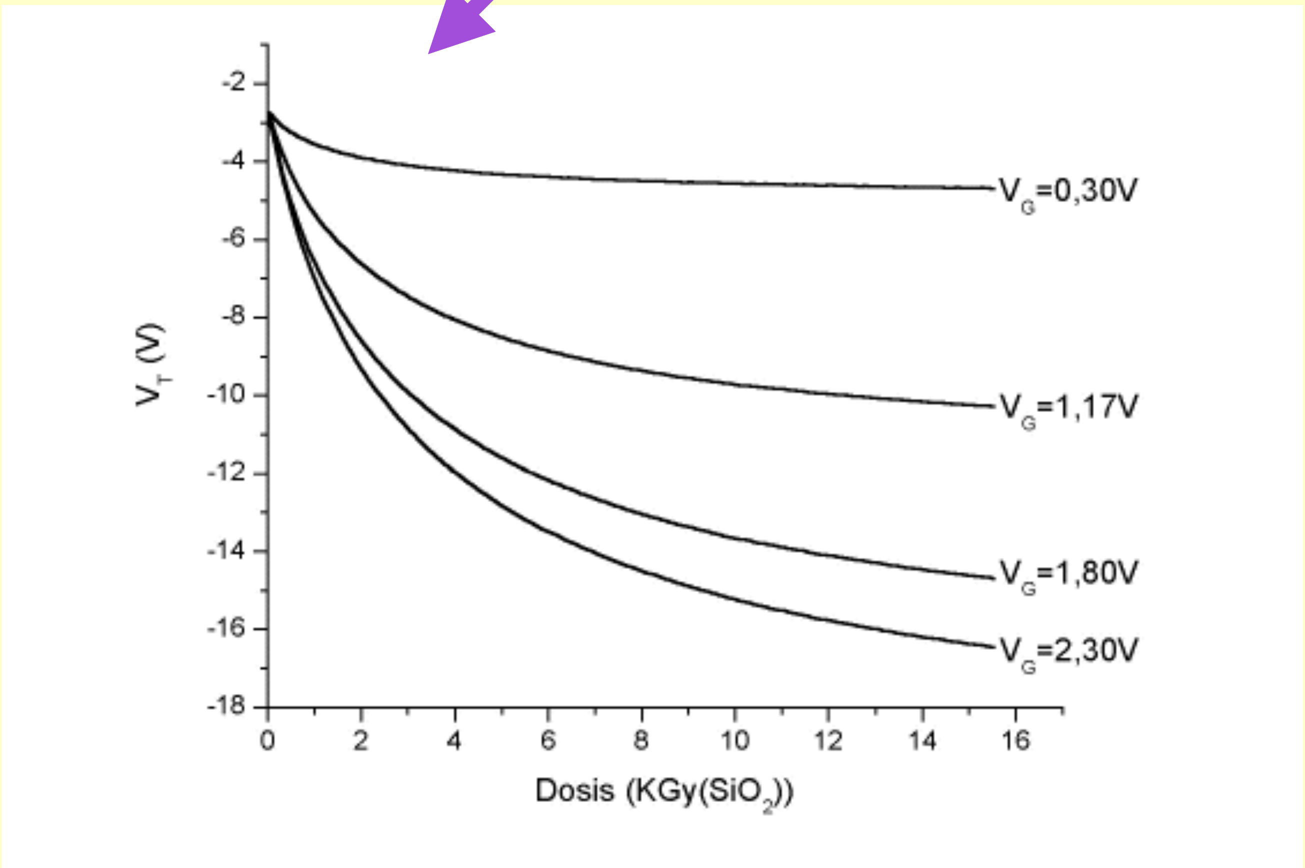
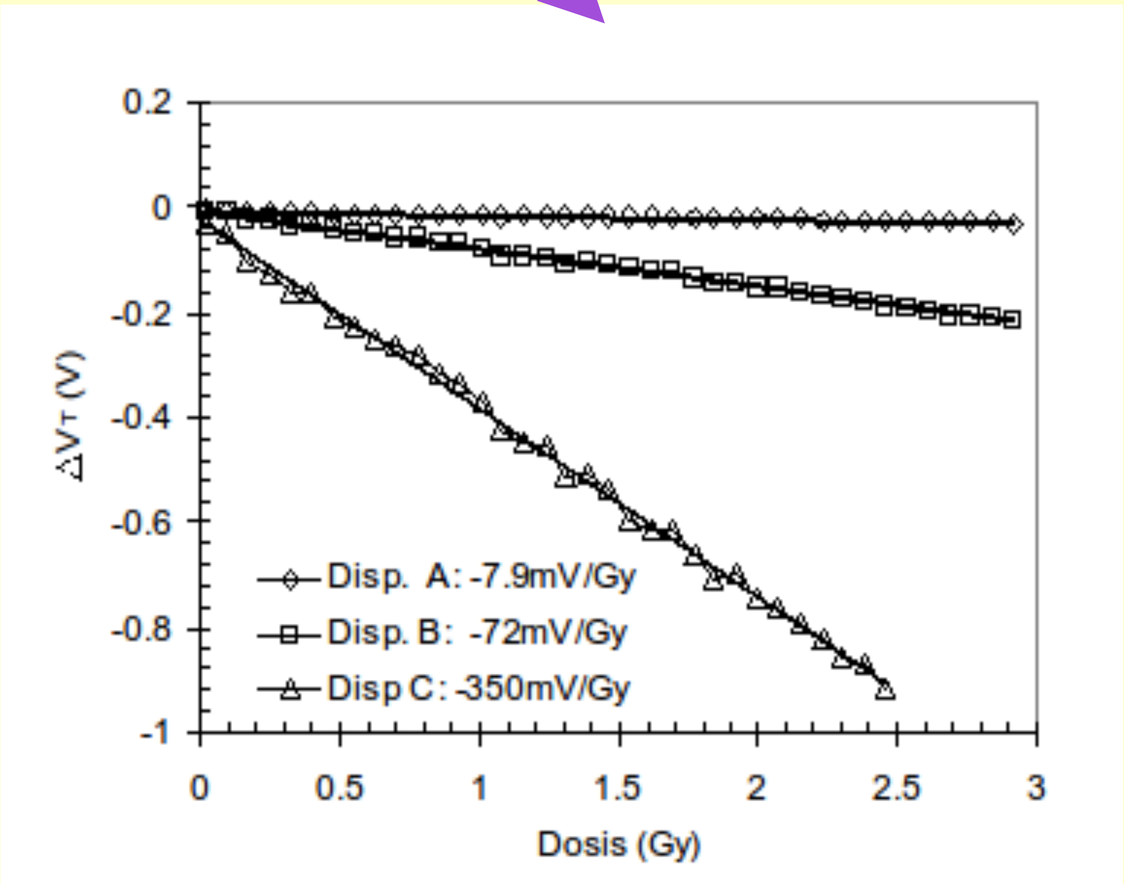
Response curves



- Sensitivity depends on
  - Oxide Thickness.
  - BIAS voltage.
- $\Delta V_T = \kappa\ Q_{OX} / C_{OX}$ (κ aprox 1)





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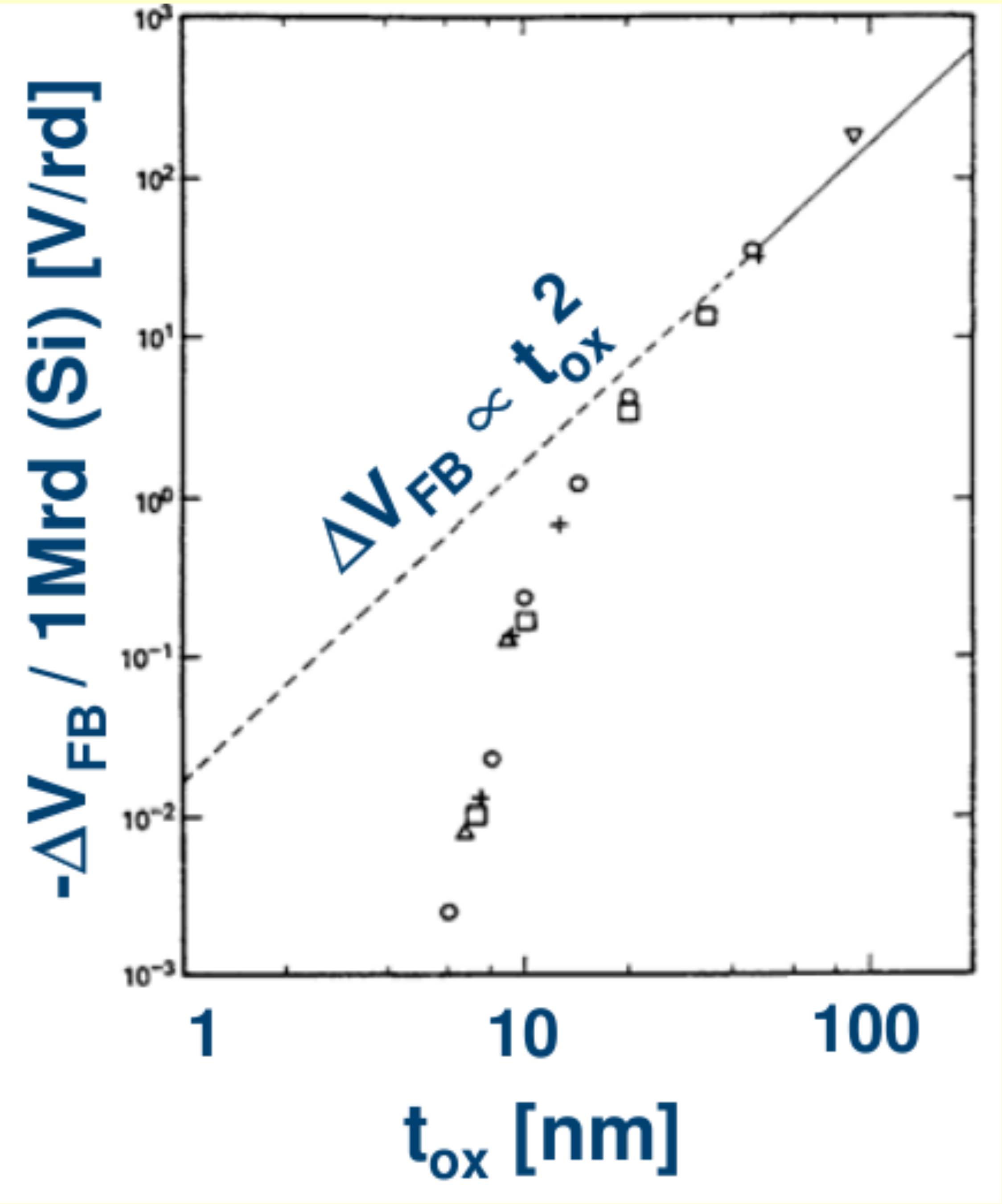
Dependence of sensitivity with oxide thickness (t_{ox})

Delta-Vt= Q/Cox . (Tox-x)/Tox
but
Q = const.Vol = const.A.Tox
and
Cox = const .A / Tox
then
Delta-Vt= const.Tox^2 . (Tox-x)/Tox

- For thick oxides, V_T shift is
- **proportional to t_{ox}^2**
- ...and **independent of the area**



Sensibility to radiation of oxides with different thicknesses
[Saks 1986]

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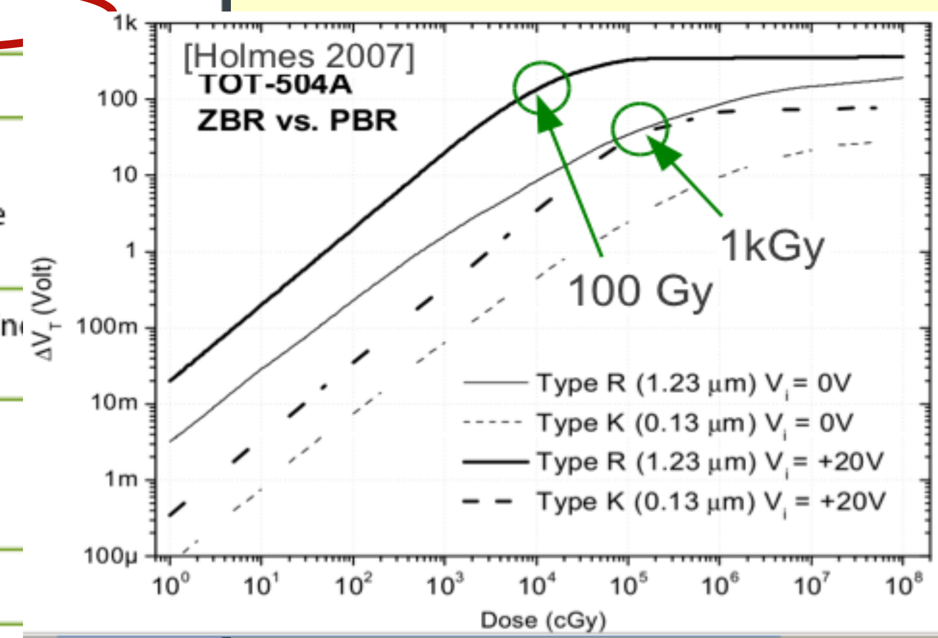
Comercially available MOS dosimeters

FEATURES & SPECIFICATIONS	ONE DOSE SICEL	RT Dose (MOSFET) Best Medical Canada
Surface/Skin Dose Measurements	YES	YES
Depth-Dose Measurements (Dmax) w/ Build-up for radiotherapy	NO. Limited	YES for all Photon and Electron Energies using Brass and Solid Water Caps
Reusable Dosimeter	NO. Single Use	YES. Multiple use
Number of Dose Fractions per Dosimeter	1 fraction	100 to 200 fractions
Cost per Dose Fraction	~15 $	< 1 $
Dosimeter Size	6 mm wide	1 mm & 2 mm options MicroMOSFET fits inside 5 or 6 Fr catheter
Dose Points in Real-Time	1 dose point off-line	Up to 40 dose points on-lin in real-time
Dose Readout Mode	Single read mode	Single or Continuous readout mode at variable time intervals
Energy Dependence	NO	NO
Isotropic for 360 °	NO 2% at 0°-45°*	YES ±2% for 360°
Accuracy	±5% typical	±2% on High Setting
Temperature Dependence	YES "Accuracy only within ±5 C variance"*	NONE 0.5% from 20 to 40 C



MOS dosimetry in LFDM

- **A bit of history**
- Reusability of MOS sensors
- Extension of the dosimeter range. New measurement techniques
- Design of structures and circuits
- Numerical simulation
- Developments and applications

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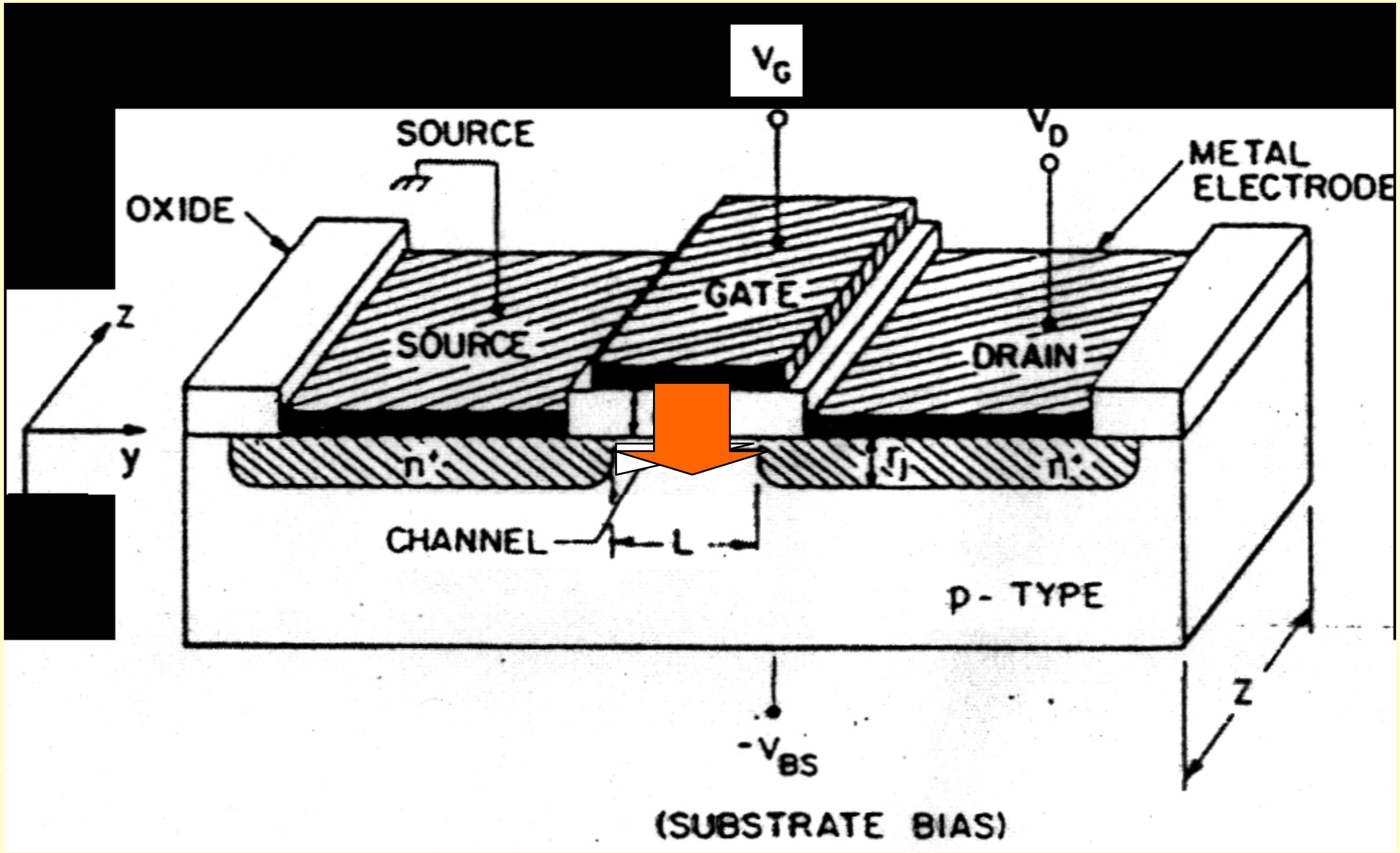
Tunel through the insulator



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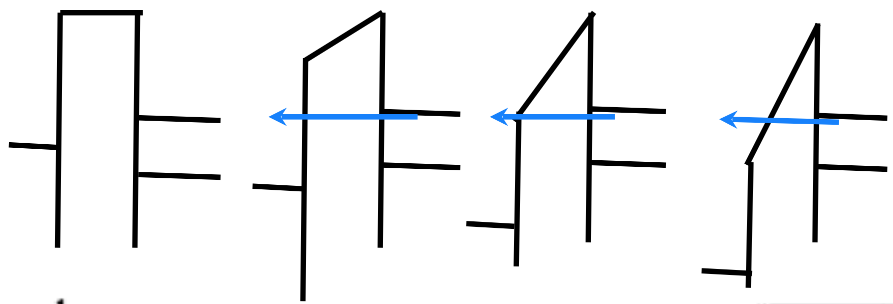
Tunel trough ultrathin oxides



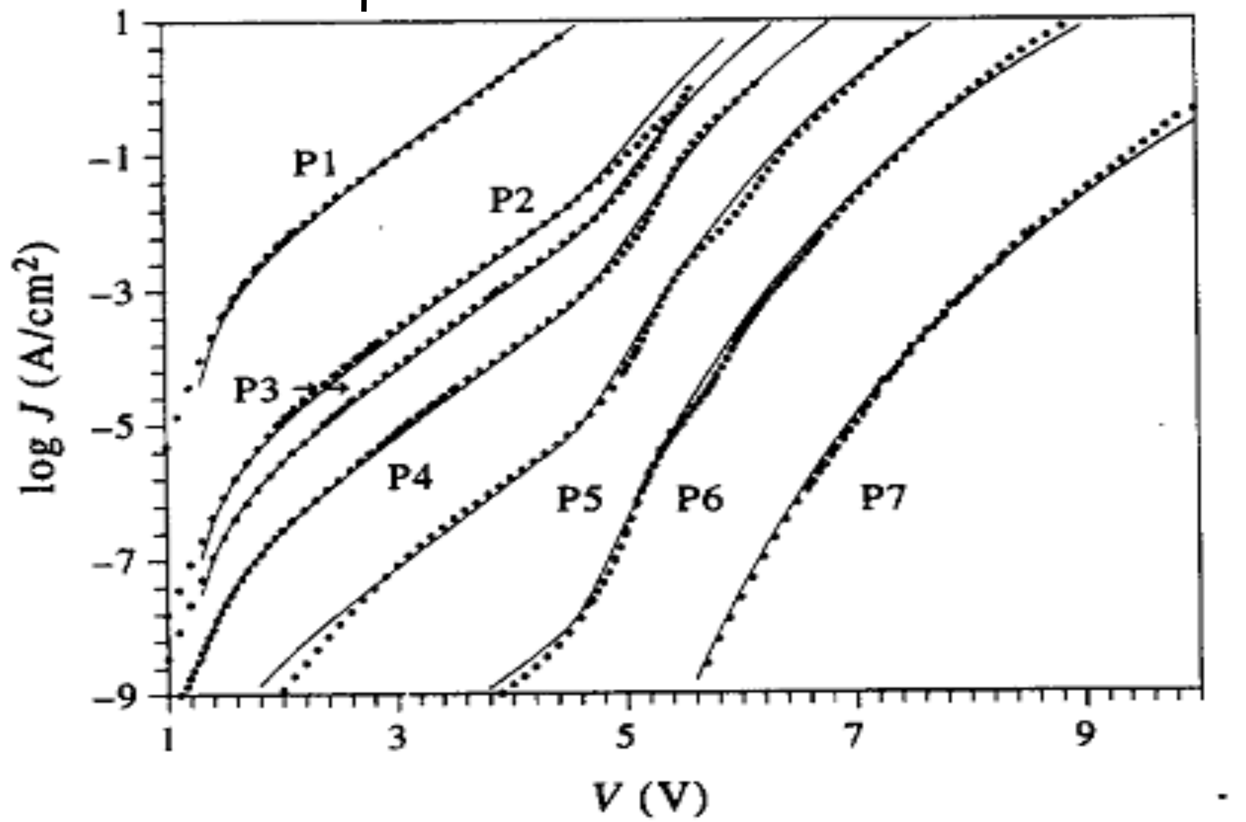


Fig. 1. Experimental and calculated—eqns (8) and (14)—log J–V curves for all samples. Fitting oxide thicknesses are: P1—22.2 Å, P2—30.5 Å, P3—32.2 Å, P4—35.3 Å, P5—41.3 Å, P6—50.0 Å and P7—67.5 Å.

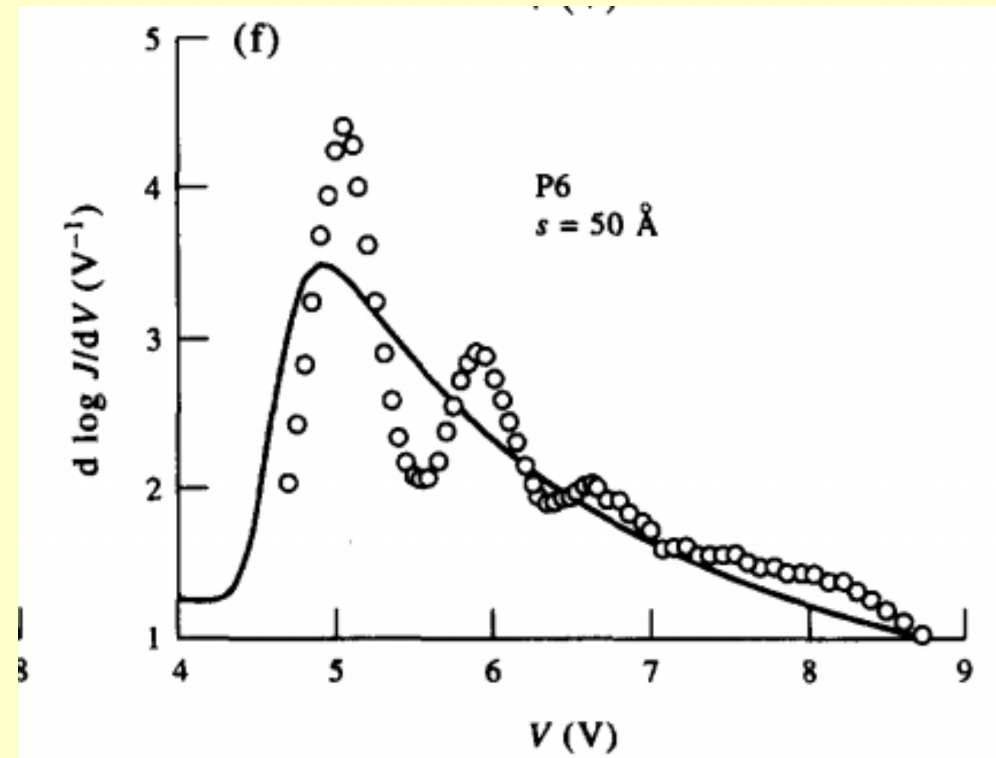


Fig. 5. The logarithmic derivative

A semi-empirical model for the tunnel current-voltage characteristics in Al-SiO_2-Si(p) structures

A. Faigón[a, †] and F. Campabadal[b]

Solid-State Electronics
Volume 39, Issue 2, February 1996, Pages 251-260

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Tunel trough thick oxides
Fowler-Nordheim tunel

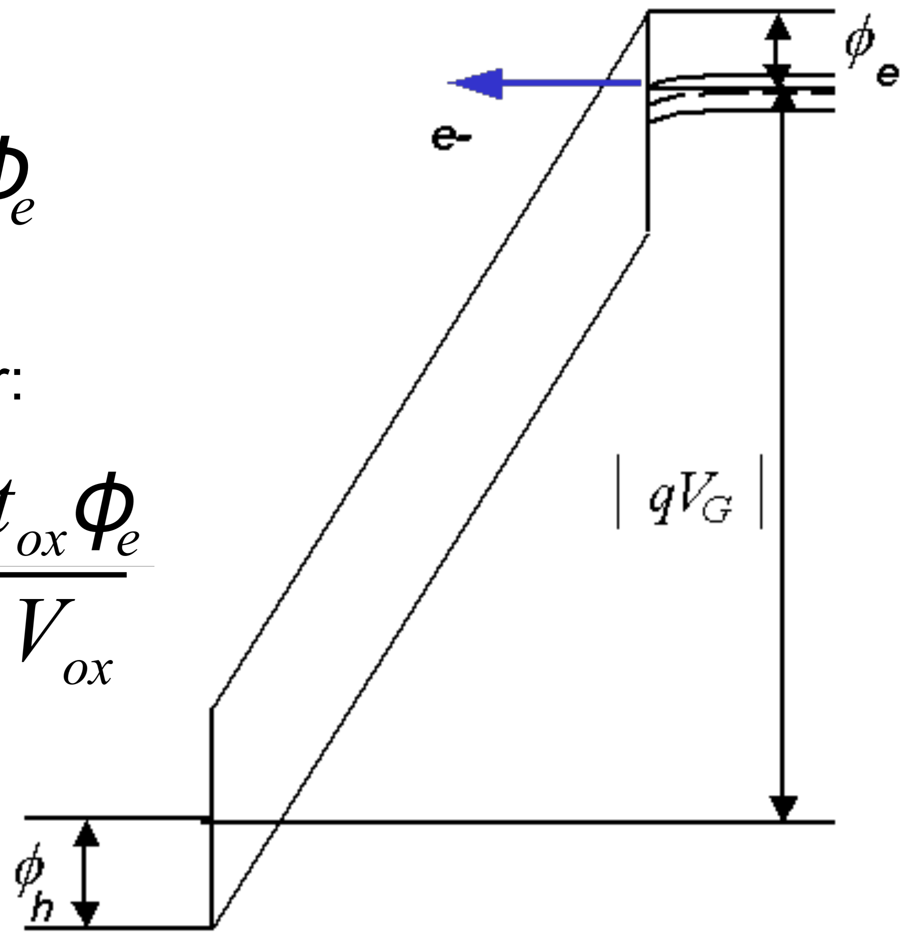
In thick oxides the tunneling occurs through the triangular barrier

Alto:

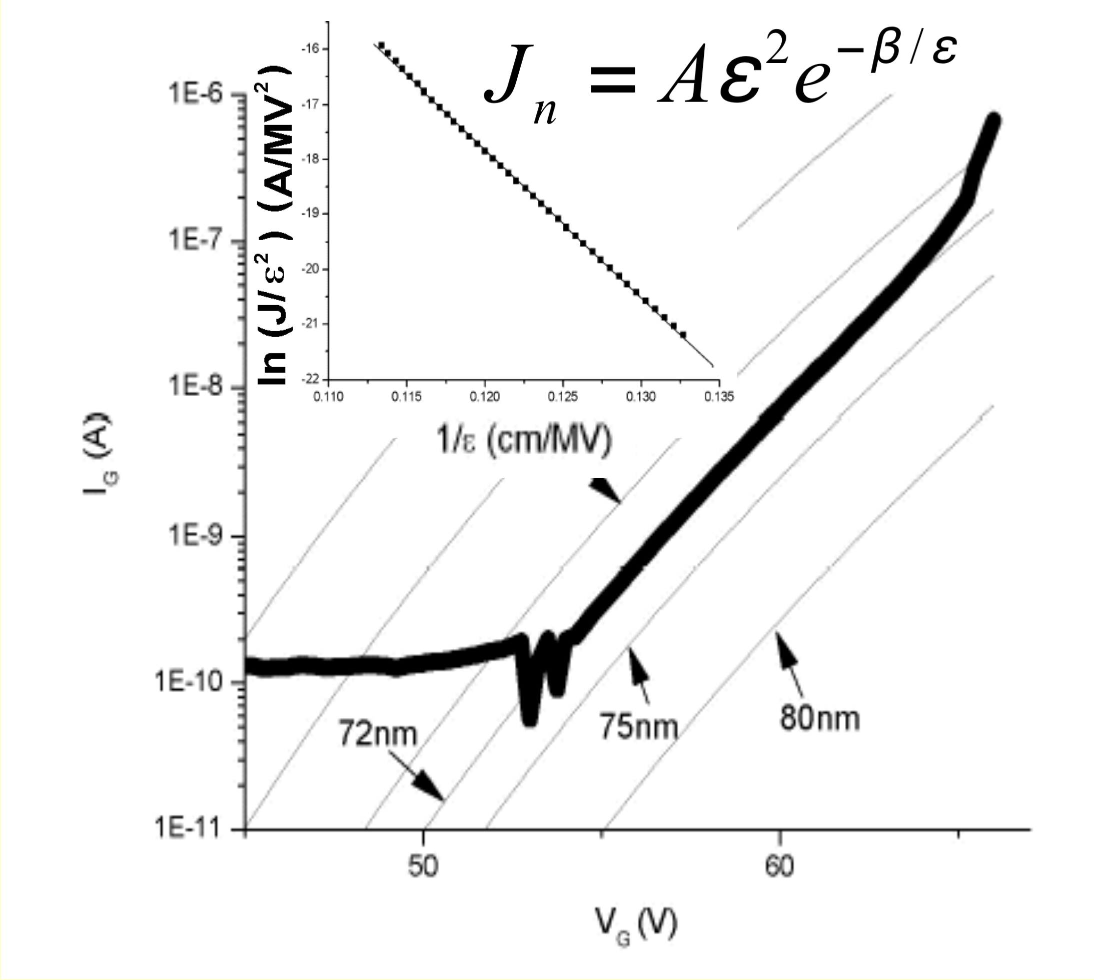
$$\phi_e$$

Espesor:

$$s = \frac{t_{ox}\phi_e}{V_{ox}}$$



The field dependence of the tunnel current in F-N regime



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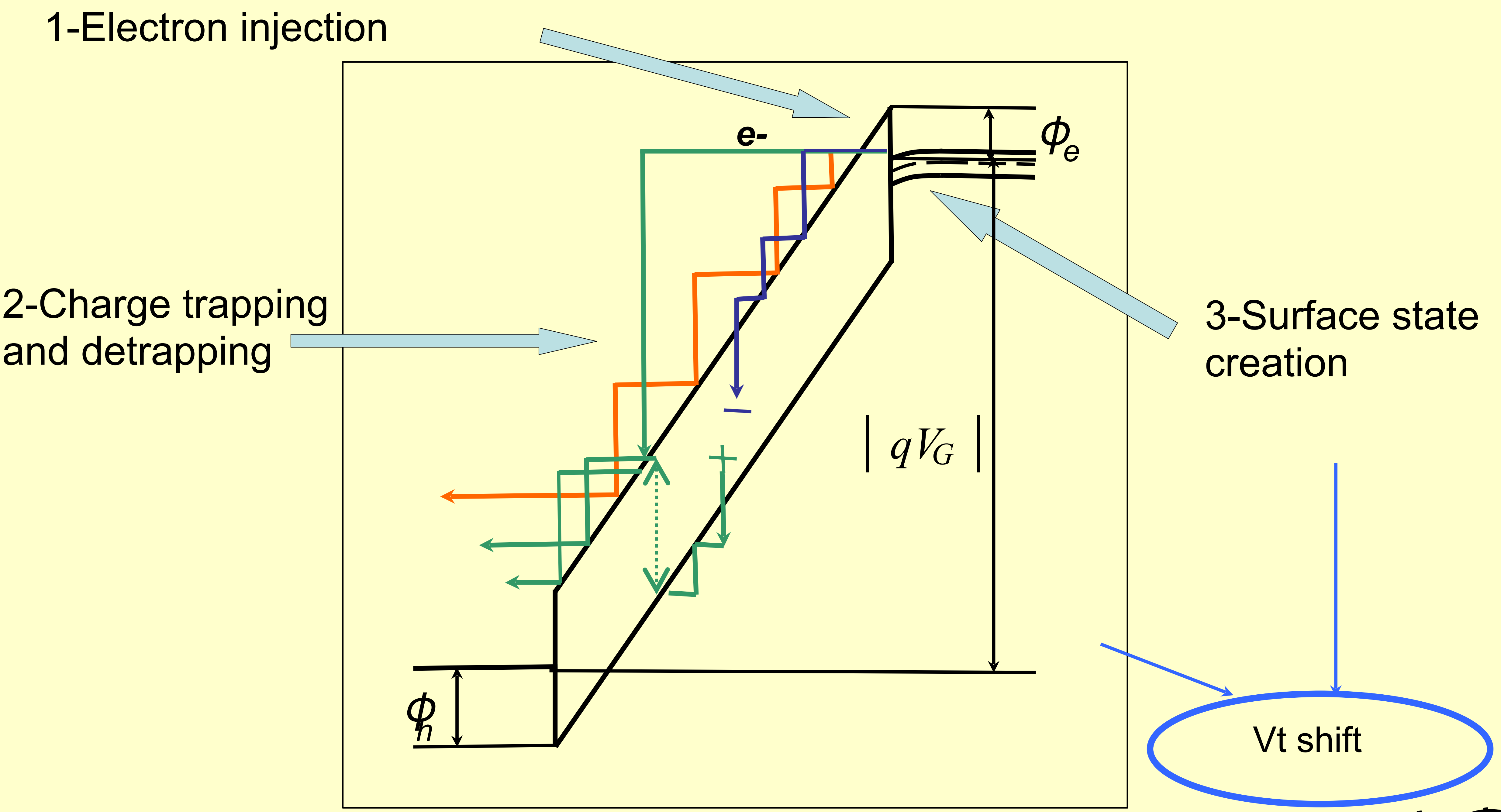
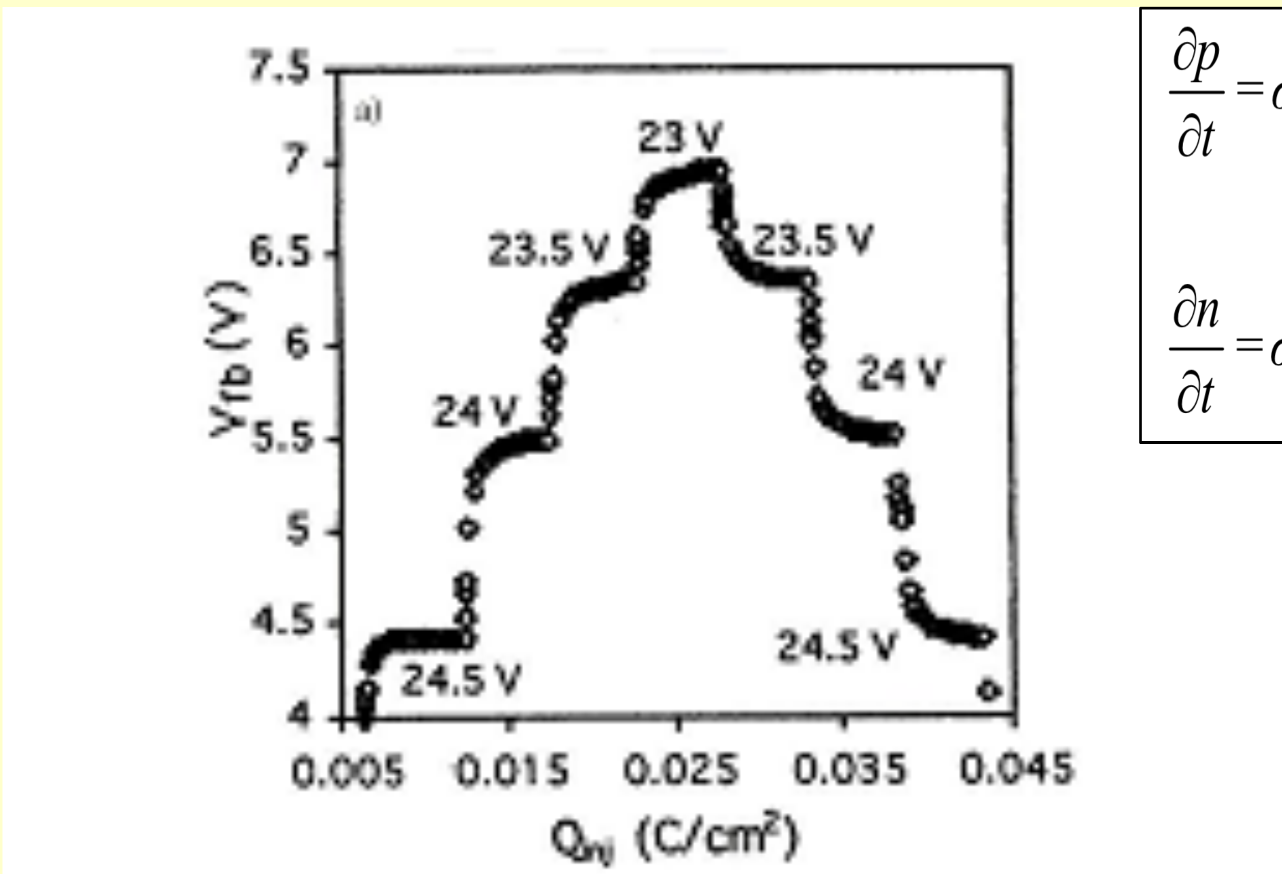
Tunelling associated phenomena



Oxide charge control by tunneling

The oxide charge reaches a steady level determined by the electric field during the injection



$$\frac{\partial p}{\partial t} = \sigma_p \cdot J_p \left(N_p - p\right) - \sigma_n \cdot J_n \cdot p$$

$$\frac{\partial n}{\partial t} = \sigma_n \cdot J_n \left(N_n - n\right) - \sigma_p \cdot J_p \cdot n$$

At these levels there is a dynamic balance between trapping and detrapping

Modeling of the I-V characteristics of high-field stressed MOS structures using a Fowler-Nordheim-type tunneling expression

Authors: Miranda E.[1]; Redin G.; Faigon A.
Source: Microelectronics Reliability, Volume 42, Number 6, June 2002 , pp. 935-941(7)
Publisher: Elsevier

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MOS dosimetry in LFDM

- **Reusability of MOS sensors**
- Extension of the dosimeter range. New measurement techniques
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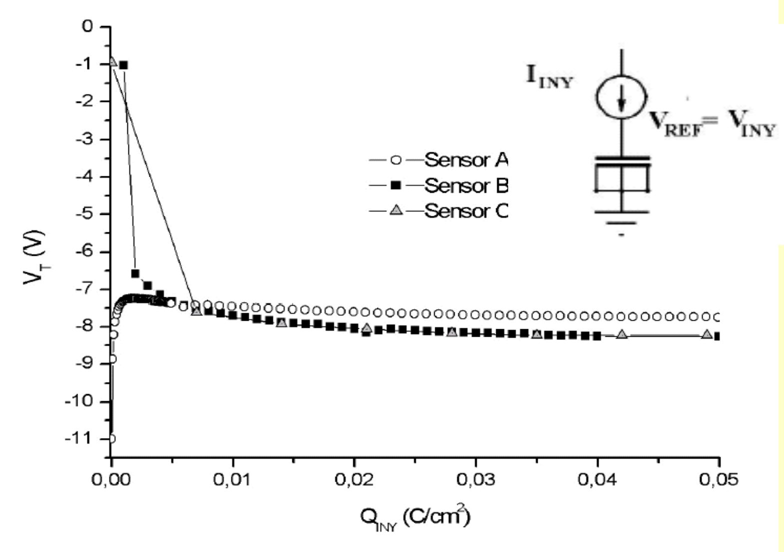
Electrically erasable MOS dosimeter

Preinyección

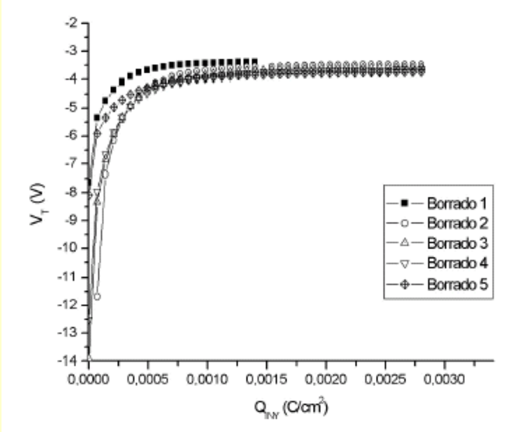


Satura estados de interfaz.

$J_n = 7.10^{-4}$ A/cm^2

$Q > 1,4.10^{-2}$C/cm^{-2}

Seteo y borrado. Inyección túnel

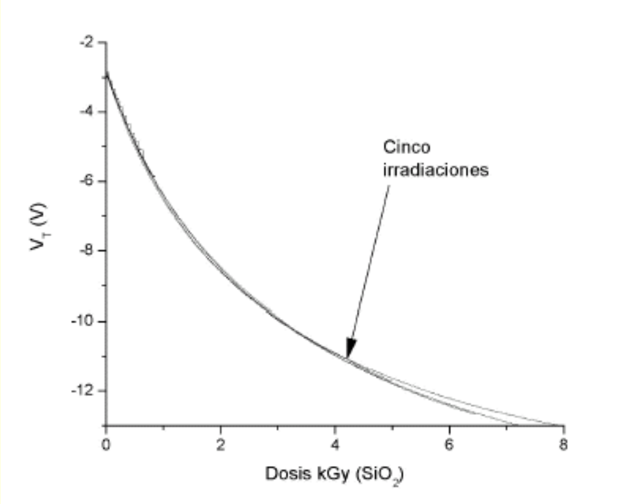


Fija la tensión de umbral inicial.

$J_n = 7.10^{-6}$ A/cm^2

$Q > 7.10^{-4}$C/cm^{-2}

Mediciones sucesivas en irradiación



Cambia la tensión de umbral con la radiación

V_B=1,80V

Redin-Faigon Patent 2001

Electrically Erasable Metal-Oxide-Semiconductor Dosimeters, Lipovetzky, J. Redin, E.G. Faigon, A.
Nuclear Science, IEEE Transactions on
On page(s): 1244 - 1250 , Volume: 54 Issue: 4, Aug. 2007

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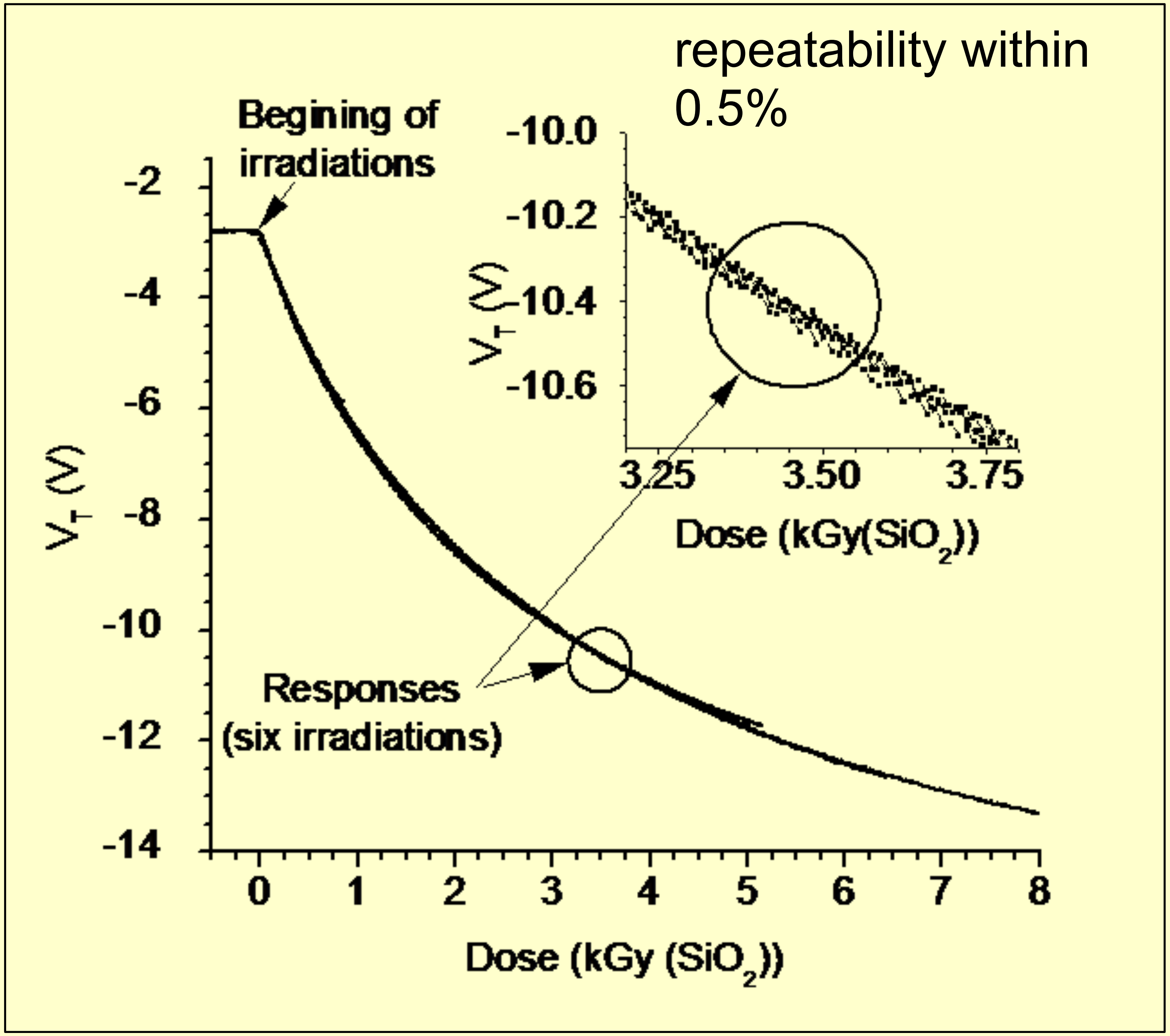
Reusability y Repeatability



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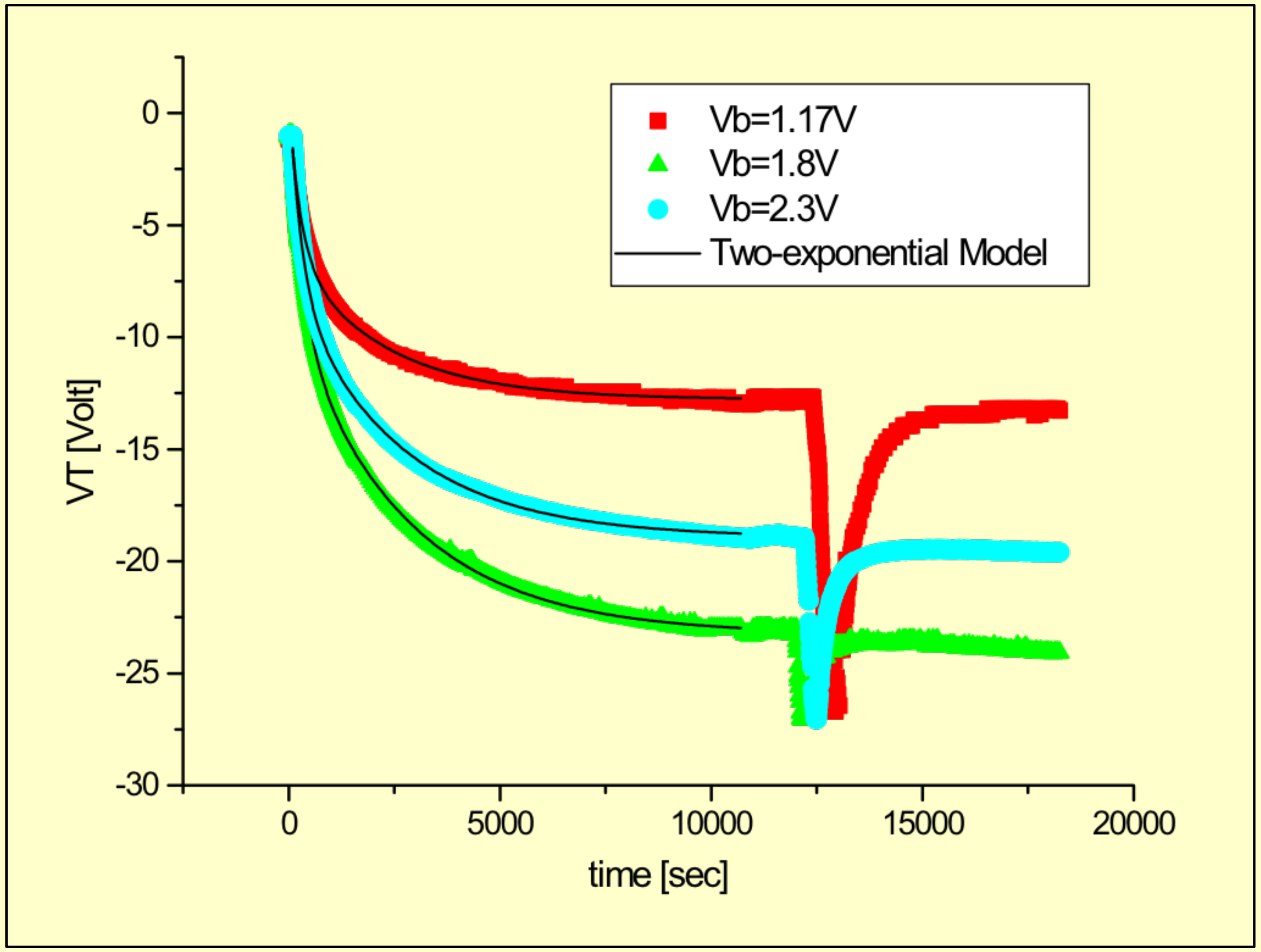
Bias dependence of the response to irradiation



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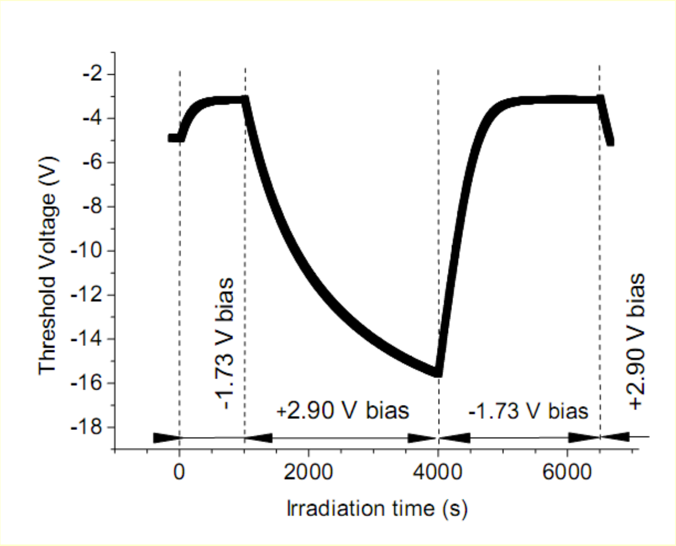
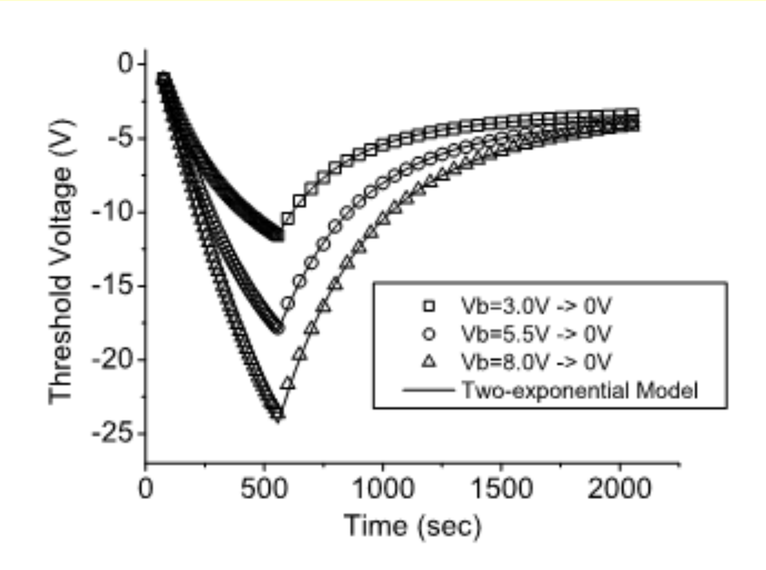
Dosimetry innovations: erasing stored charge techniques

Erasing by RICN



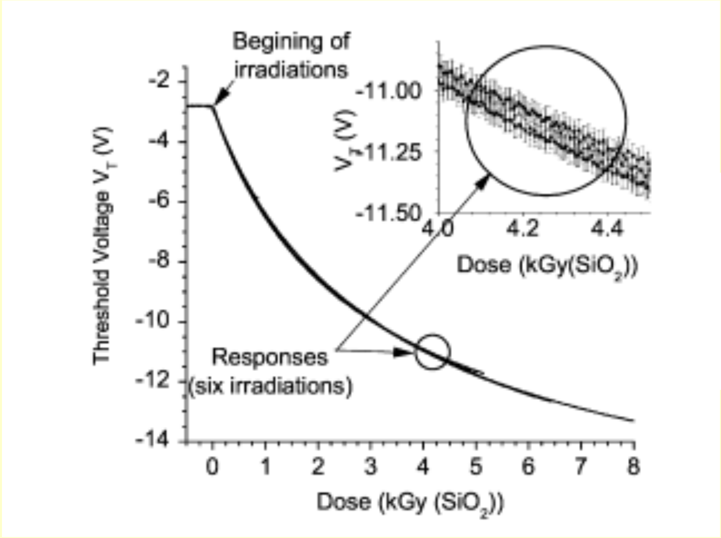
Faigón et. al., IEEE TNS 2008

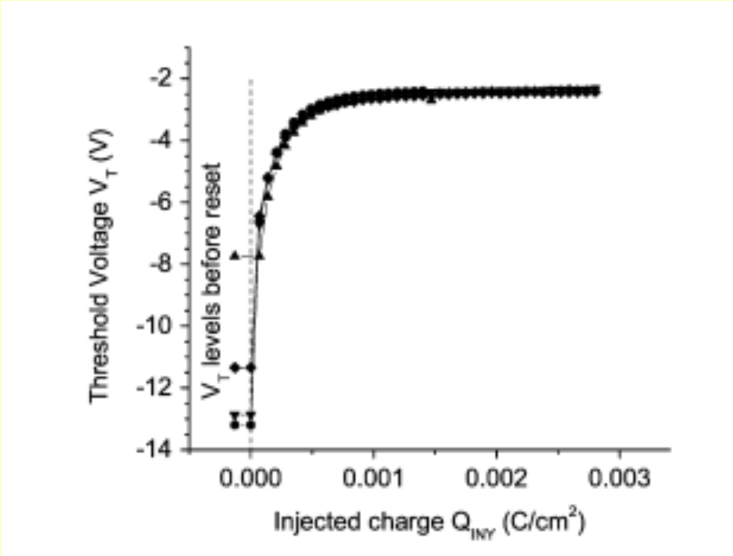
Patente 2008



Faigón et. al., sent RPC. 2008

Erasing through Fowler Nordheim tunnel





Redin-Faigon Patente 2001

Lipovetzky et. al., IEEE TNS 2007

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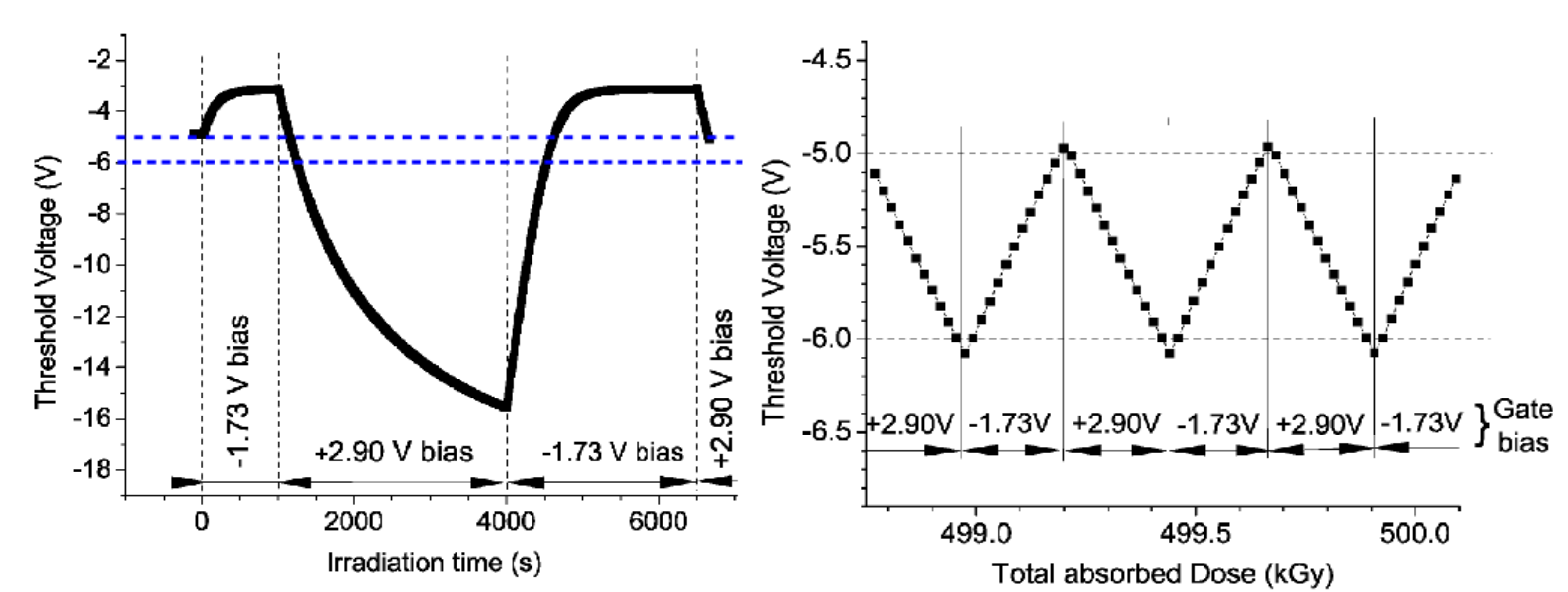
The BCCM Technique
Bias Controlled Cycled Measurement



p-MOS, t_{ox} = 70 nm ^{60}Co a 1.65 Gy/s

[Faigon IEEE Trans. Nucl. Sci. 2008 and patent]

The technique allows an extention of at least 1000 times in dose range.

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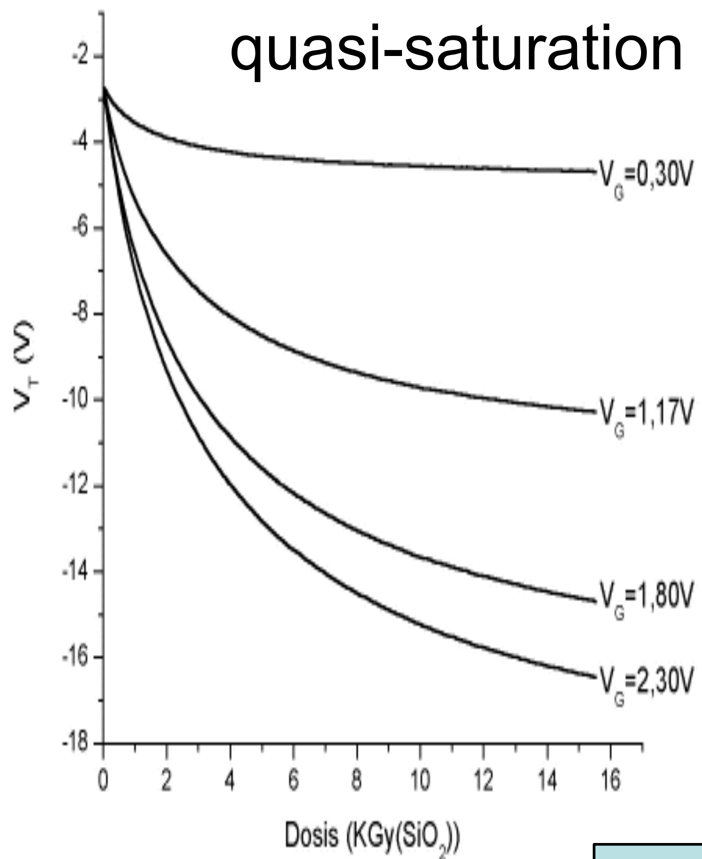
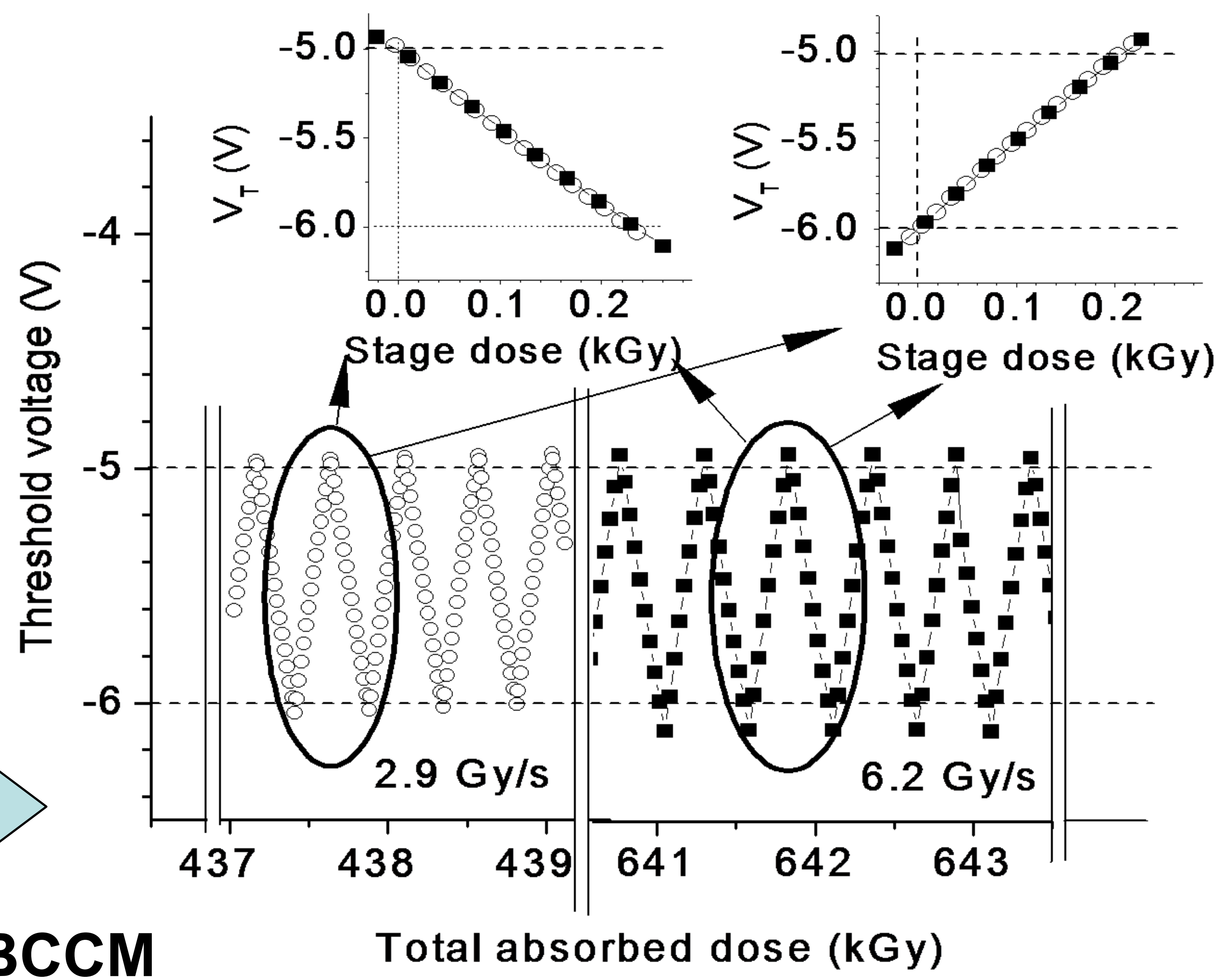
Sensitivity preservation



Standard use



BCCM

Extension of the Measurement Range of MOS Dosimeters Using Radiation Induced Charge Neutralization, Faigon, A. Lipovetzky, J. Redin, E. Krusczenski, G.
Nuclear Science, IEEE Transactions on
On page(s): 2141 - 2147 , Volume: 55 Issue: 4, Aug. 2008

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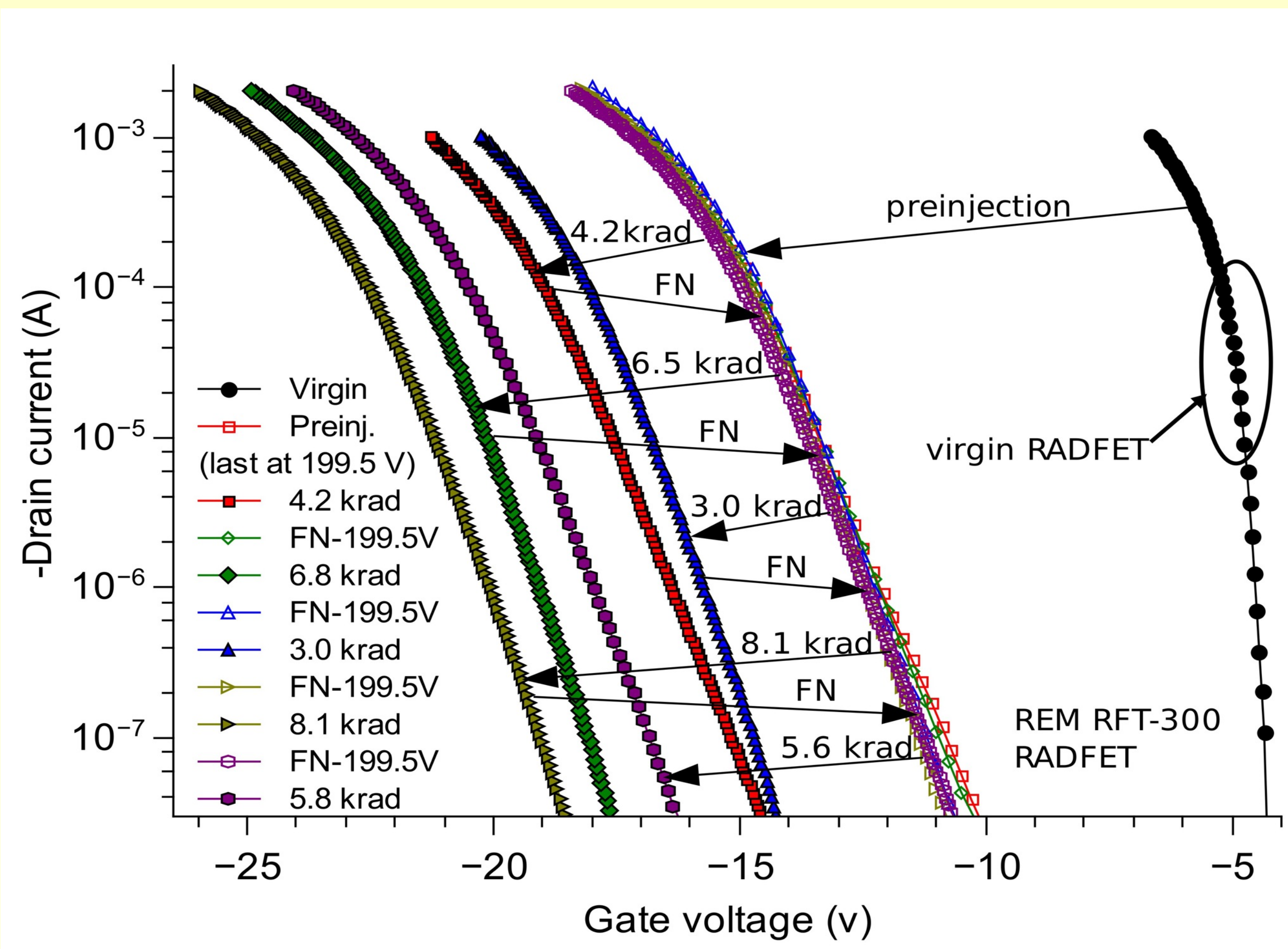
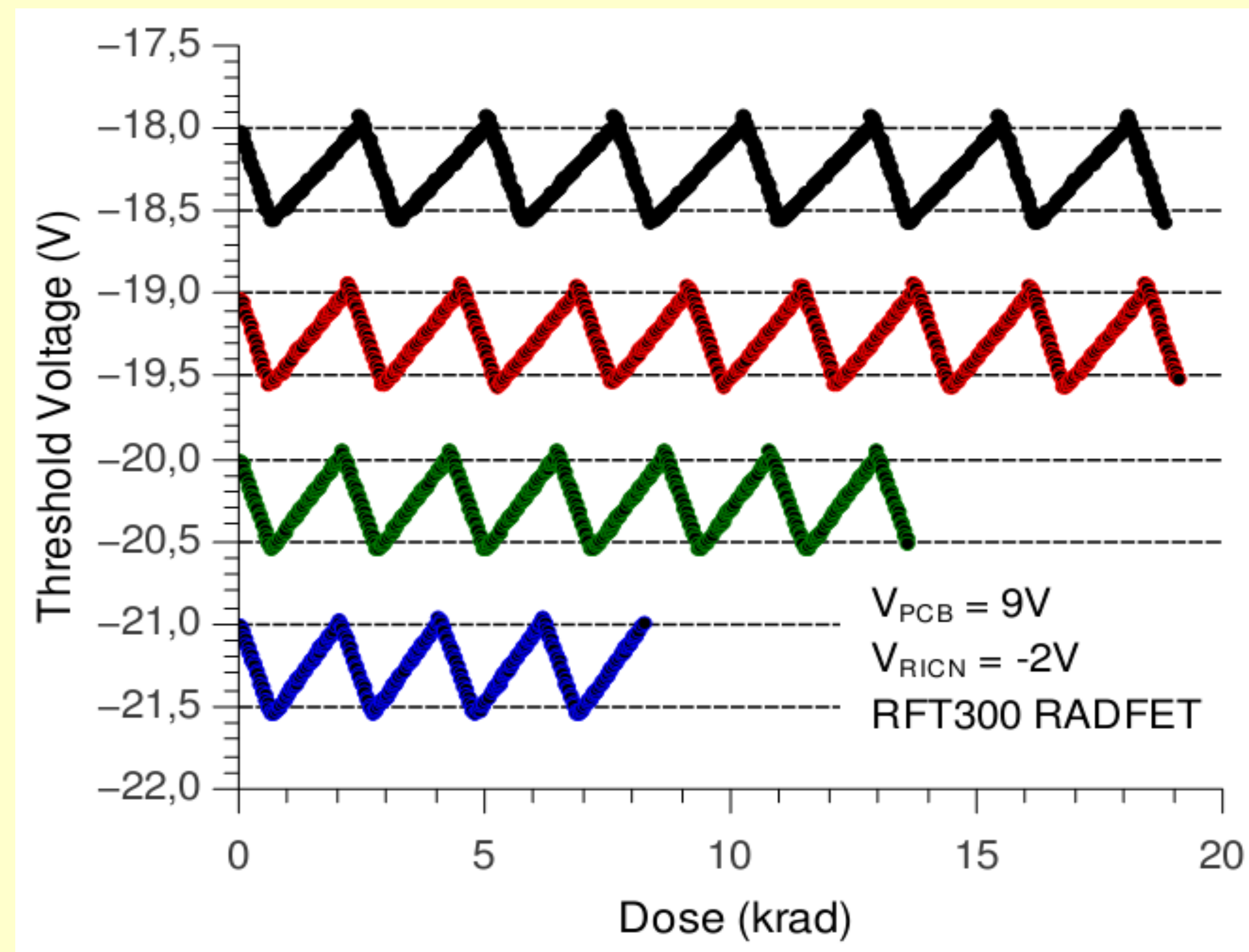
Reset methods and BCCM technique tested on commercial dosimeters

- 300nm commercial RADFETs in collaboration with REM Oxford LTD.

FN erase



BCCM



J. Lipovetzky, A. Holmes-Siedle, M. García Inza, S. Carbonetto, E. Redin, and A. Faigon
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 59, NO. 6, DECEMBER 2012

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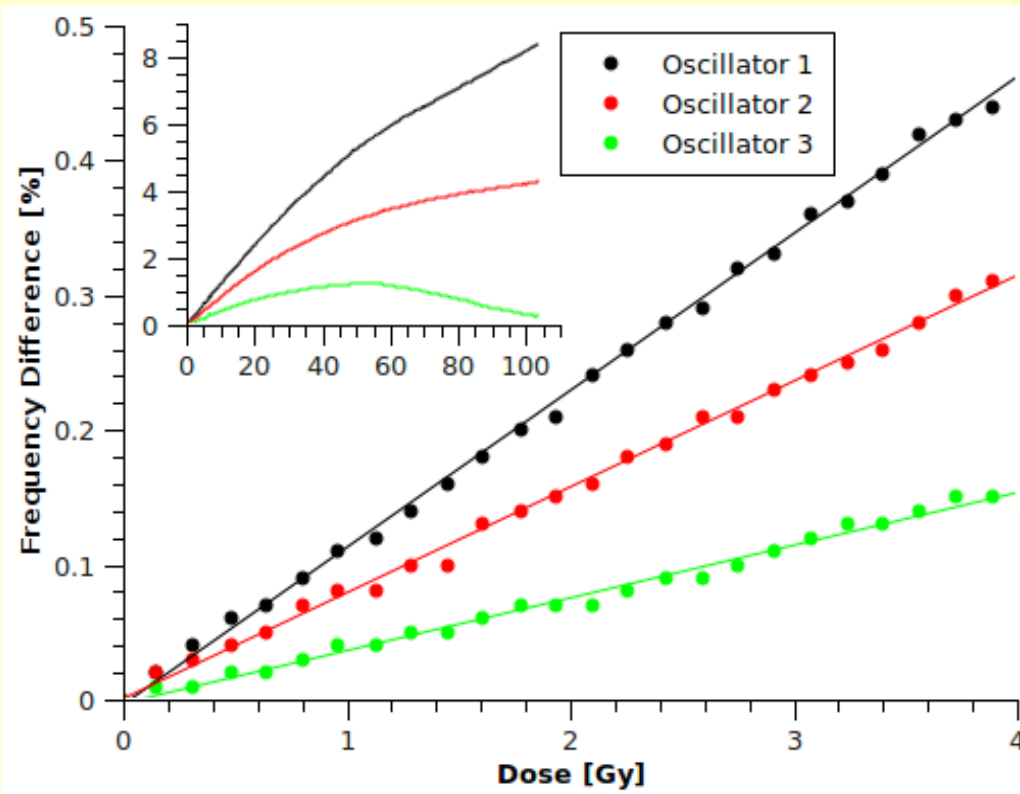
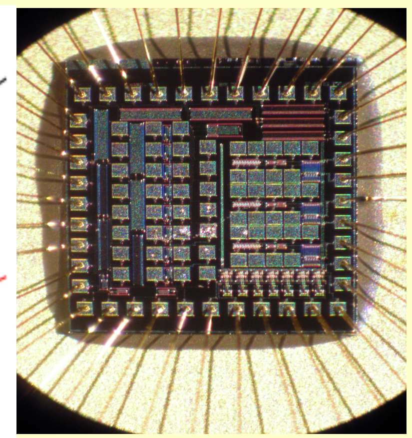
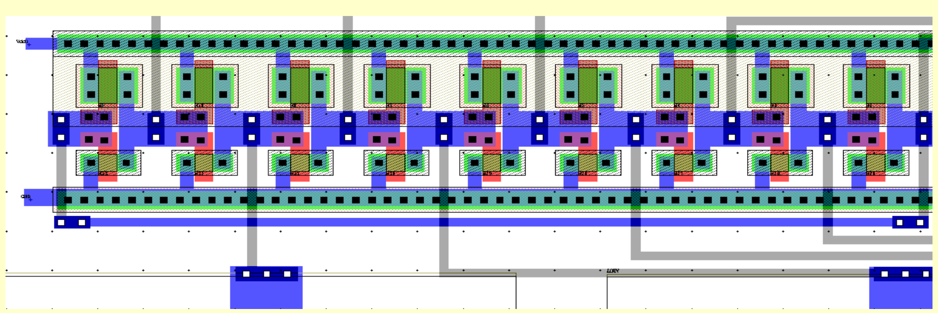
Experimental structures and circuits

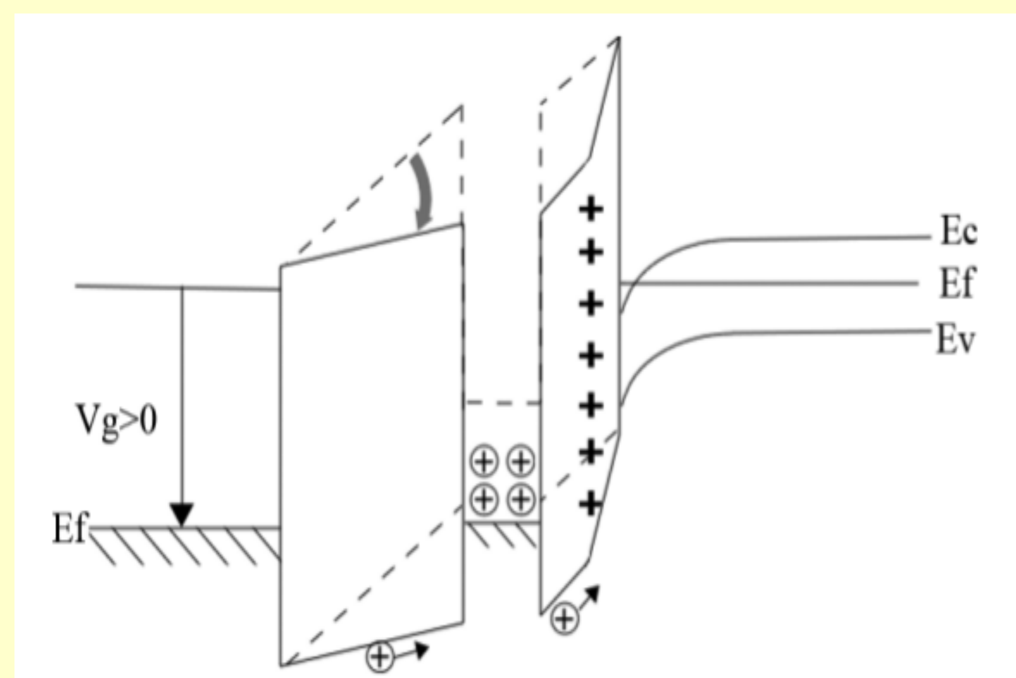
Ring Oscillator, using Δf as a measure of dose.
[Carbonetto 2009]

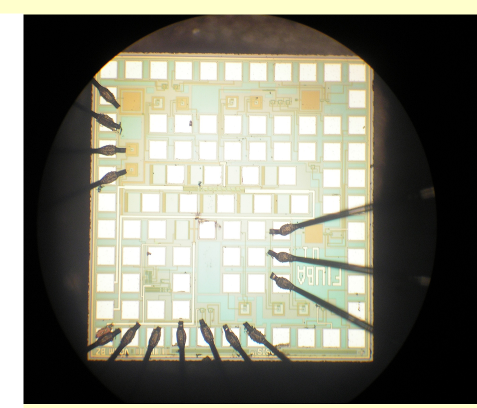






Floating gate transistors





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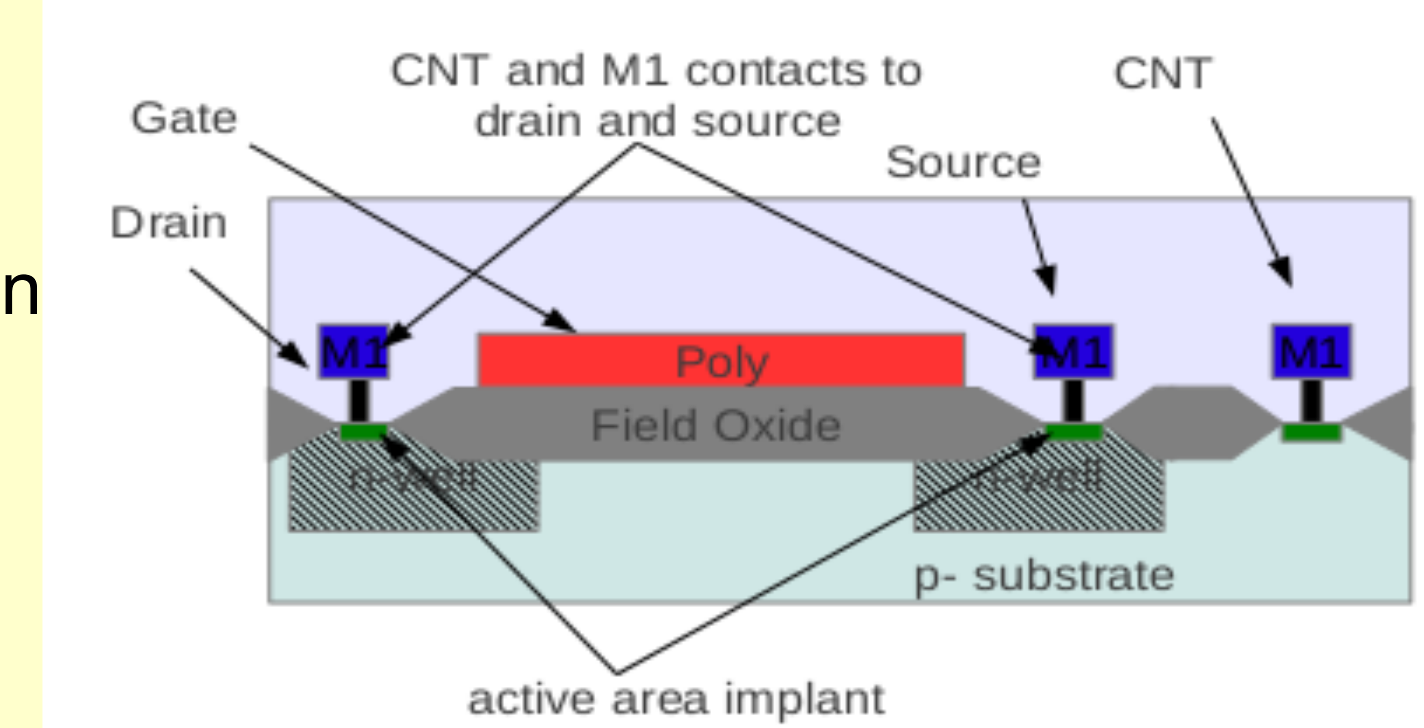
The FOXFET

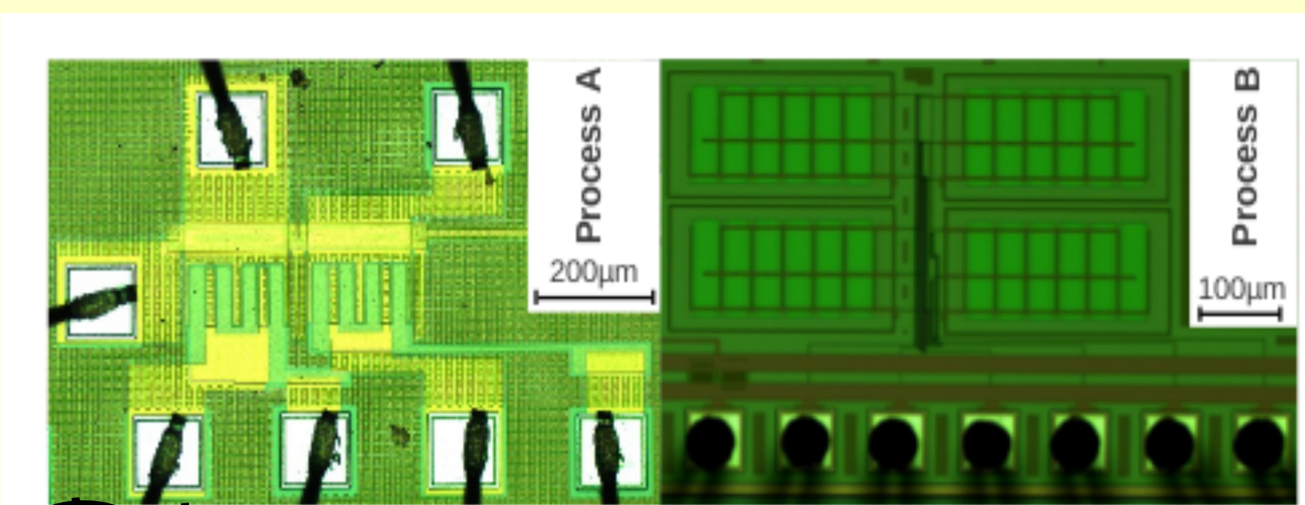
- To obtain high sensitivity, MOS dosimeters need thick gate oxides, fabricated in ad-hoc processes → $$$$
- We proposed to use MOSFETs fabricated in commercial CMOS processes to allow a reduction in cost.
- This would also allow the integration of reading electronics.
- Amplified dosimeters with temperature compensation using diferential pairs of FOXFETs.

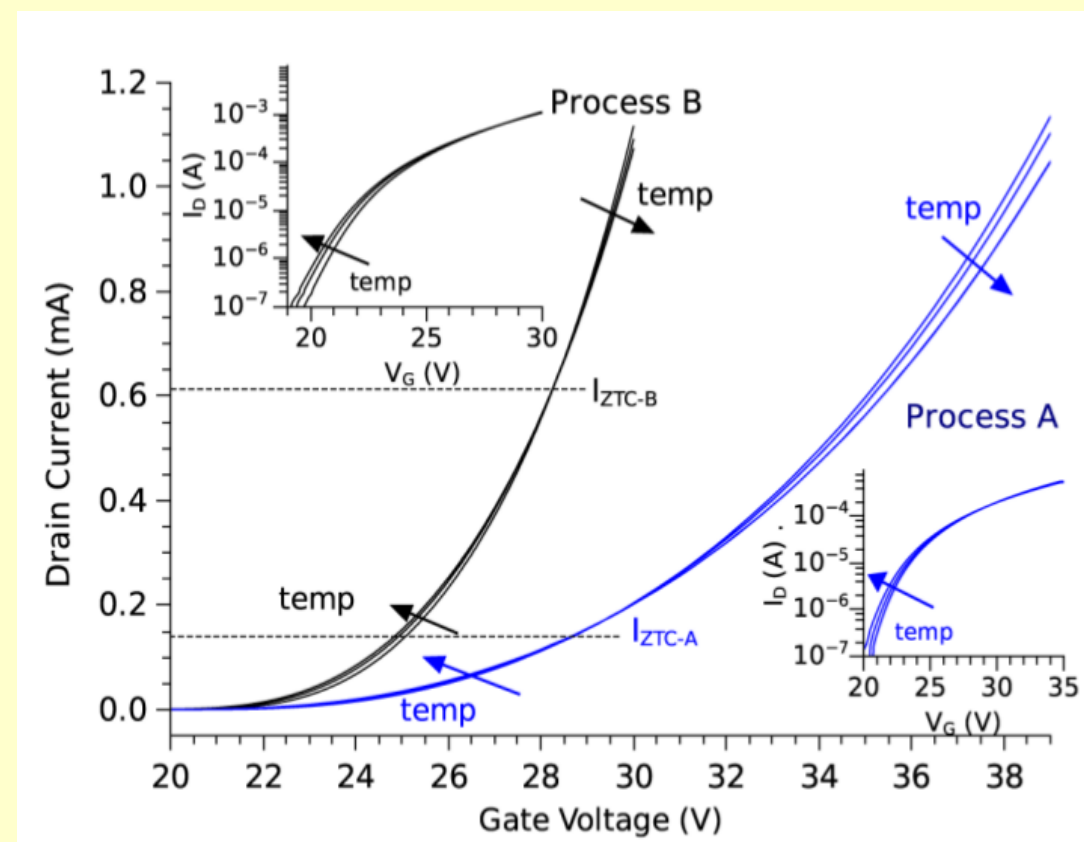
The FOXFET dosimeter.

- Use FOX as gate oxide: the FOXFET.
- Since V_T is high, preferred to use n channel devices.
- Built FOXFETs to evaluate the response to TID in two 0.5 µm CMOS processes.
- Layout must not violate DRC rules.
- Nice IV curves!



[Lipovetzky IEEE TNS 2013]





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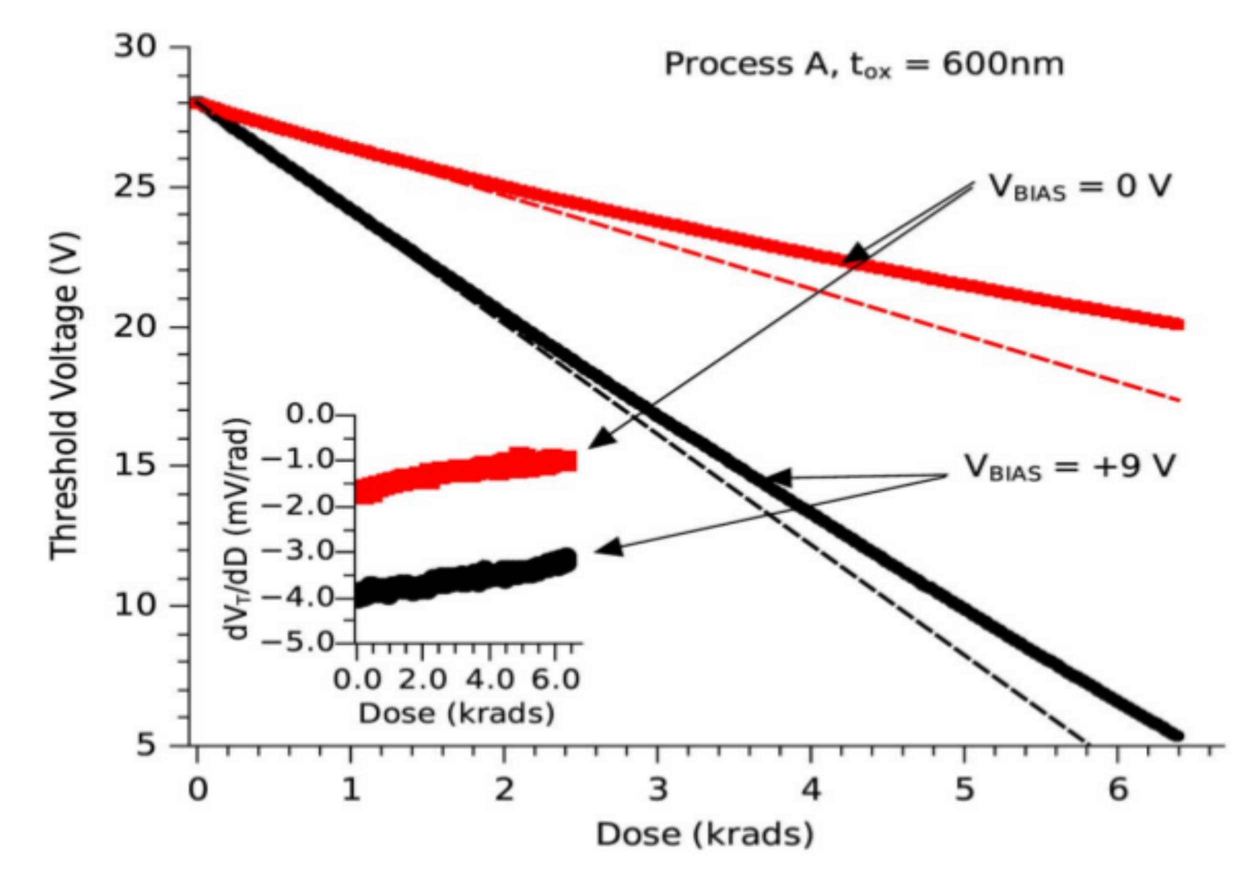
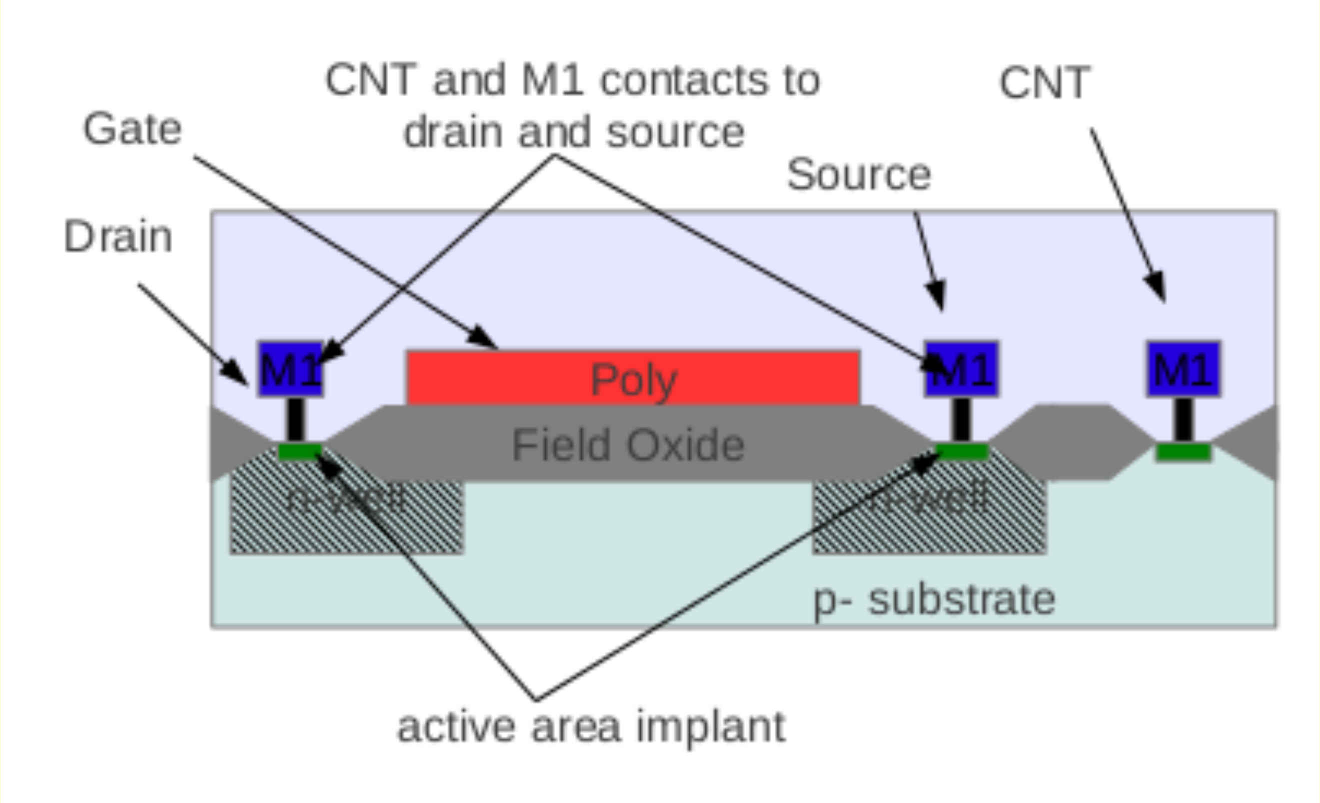
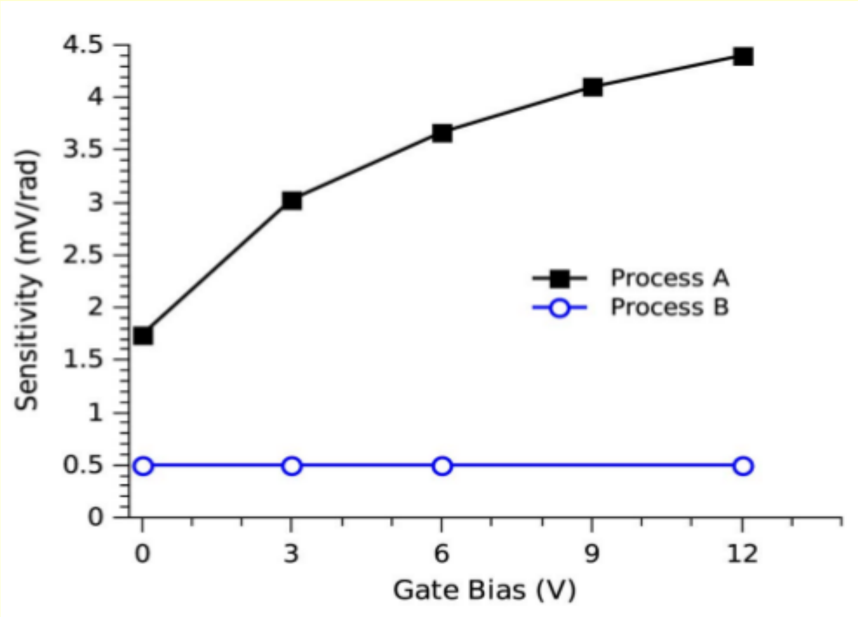
Response of FOXFETs

- Irradiated with ^{60}Co gamma rays







IEEE Transactions on Nuclear Science
Volume 60, Issue 6, December 2013, Article number 6678078, Pages 4683-4691
Field oxide n-channel MOS dosimeters fabricated in CMOS processes (Article)
Lipovetzky, J.ab , Garcia-Inza, M.A.a , Carbonetto, S.a , Carra, M.J.a , Redin, E.a , Sambuco Salomone, L.a , Faigon, A.ab

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Sensitivity comparison

The response depends on:

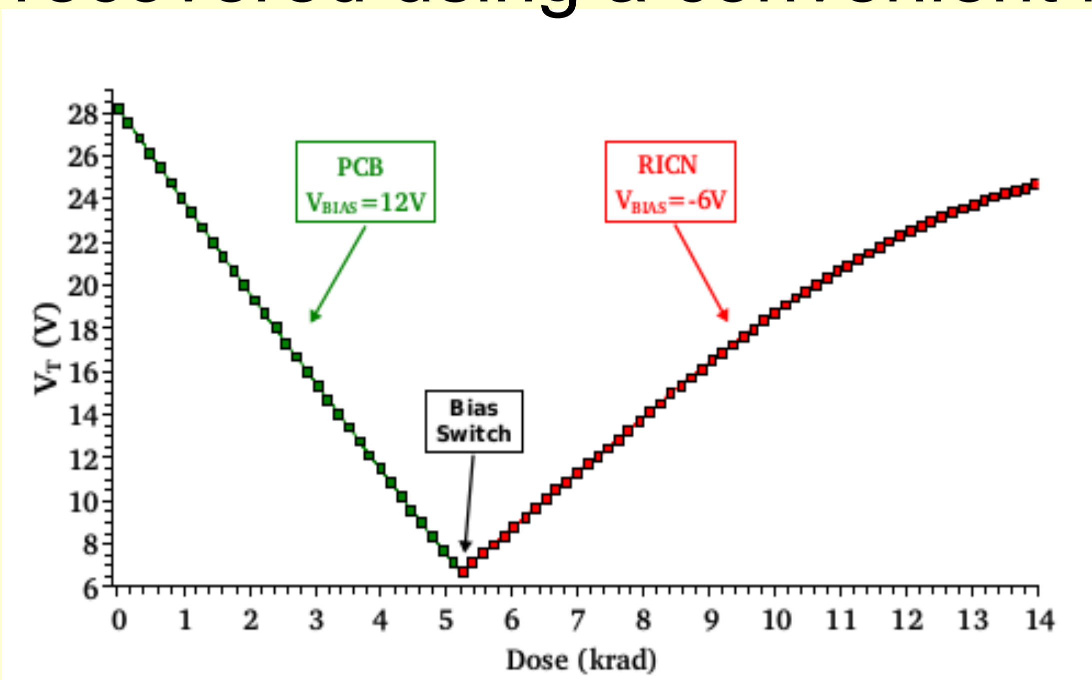
- the bias applied
- oxide thickness and quality

RESPONSIVITIES OF DIFFERENT THICK OXIDES

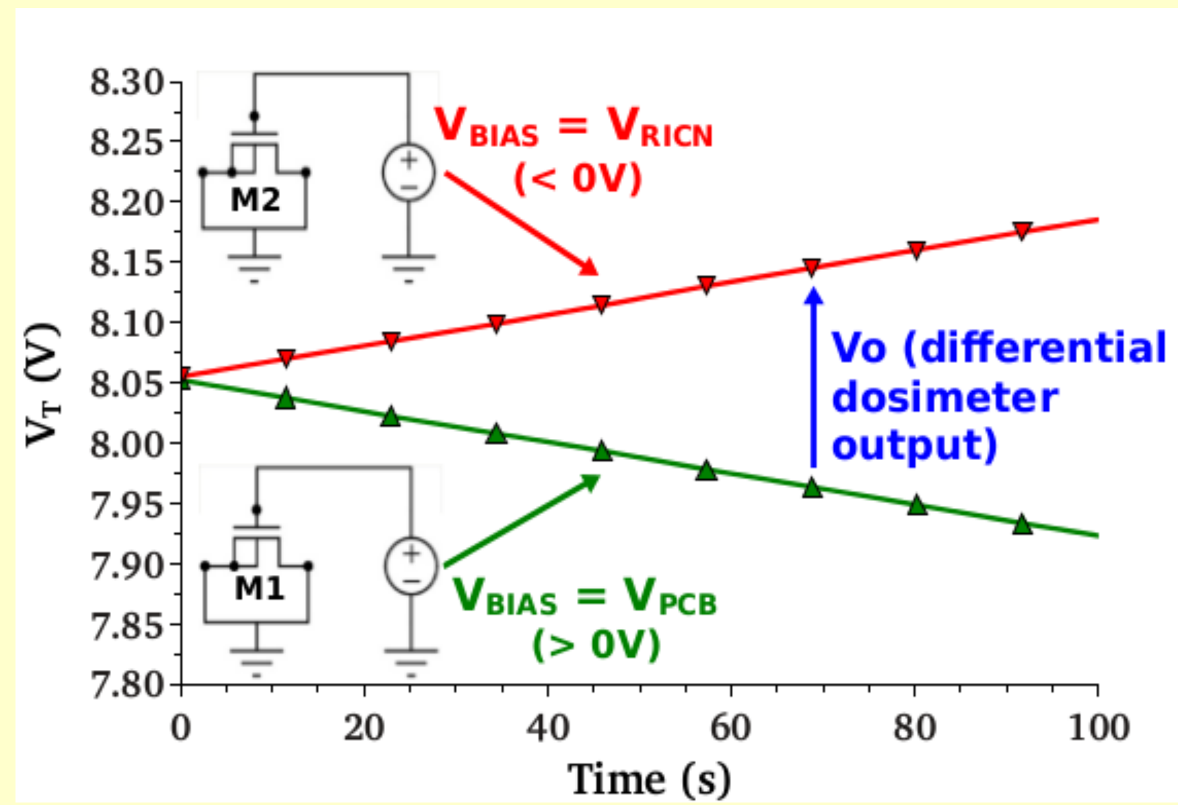
Device	t_{ox} (nm)	Bias (V)	External Field (MV/cm)	resp. (mV rad^{-1})
This paper:				
Process A nMOS	600	0 / +12	0 / 0.2	1.6 / 4.4
Process B nMOS	400	0 to +12	0 to 0.3	0.4
REM Oxford LTD				
RFT 300 pMOS [42]	300	0 / +9 / +18	0 / 0.3 / 0.6	0.20 / 1.25 / 1.75
TOT 501C "R" pMOS[7]	850	0V	0	0.91
TOT 504 "R" pMOS[7]	1230	0 / +20	0 / .16	2.3/20
Tyndall dosimeter pMOS[43]	400	+2.5 / +5V	0.0625 / 0.125	~0.8/~1.0
Best Medical 502RD pMOS[44] [45]	500	+5 / +15	0.1 / 0.3	1 / 3
LAAS PMOS dosimeter [46]	1600	0	0	4.2
3N163 MOSFET COTS pMOS [47]	~200	0	0	0.3
STI–FOX [48] [49] [50] [51]				
STI TSMC 180 pMOS @20krad	425	+1	0.02	1.38
ASU FOXCAP nMOS @20krad	320	+1.38	0.043	0.325
SOI Dosimeter SANDIA CMOS7 SOI [23]	200	0	0	0.125
Ukranian n-MOSFET n-channel dosimeter [27]	1000	0	0	1.80

Differential Dosimeter

The shift in V_T in an irradiated dosimeter can be recovered using a convenient bias.

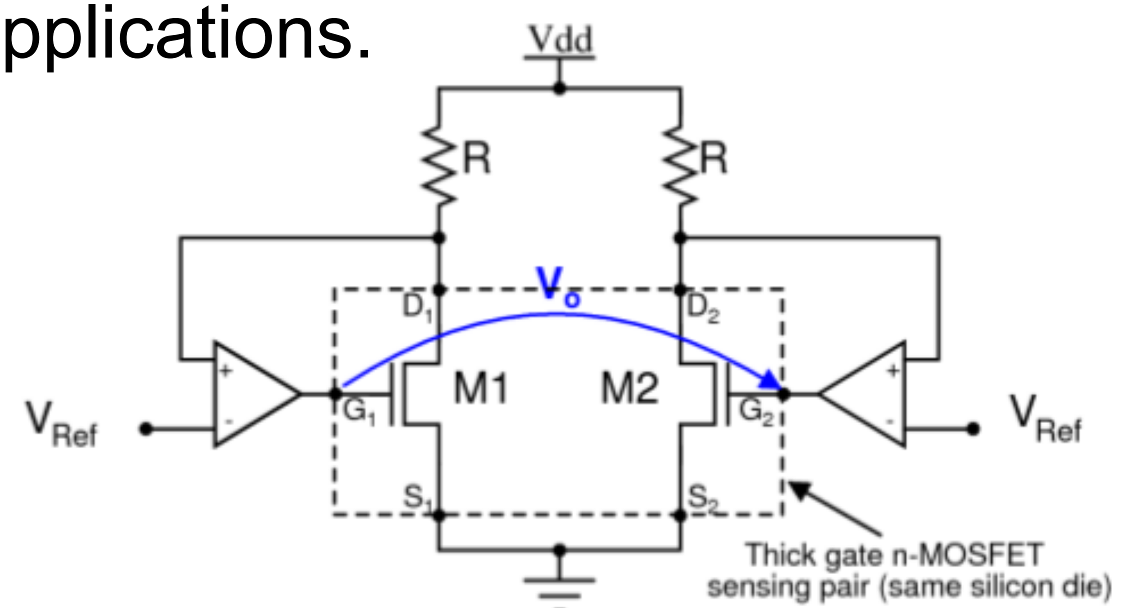


Differential BCCM dosimeter:



[García Inza TNS 2014]

Other differential circuit for radiotherapy applications.



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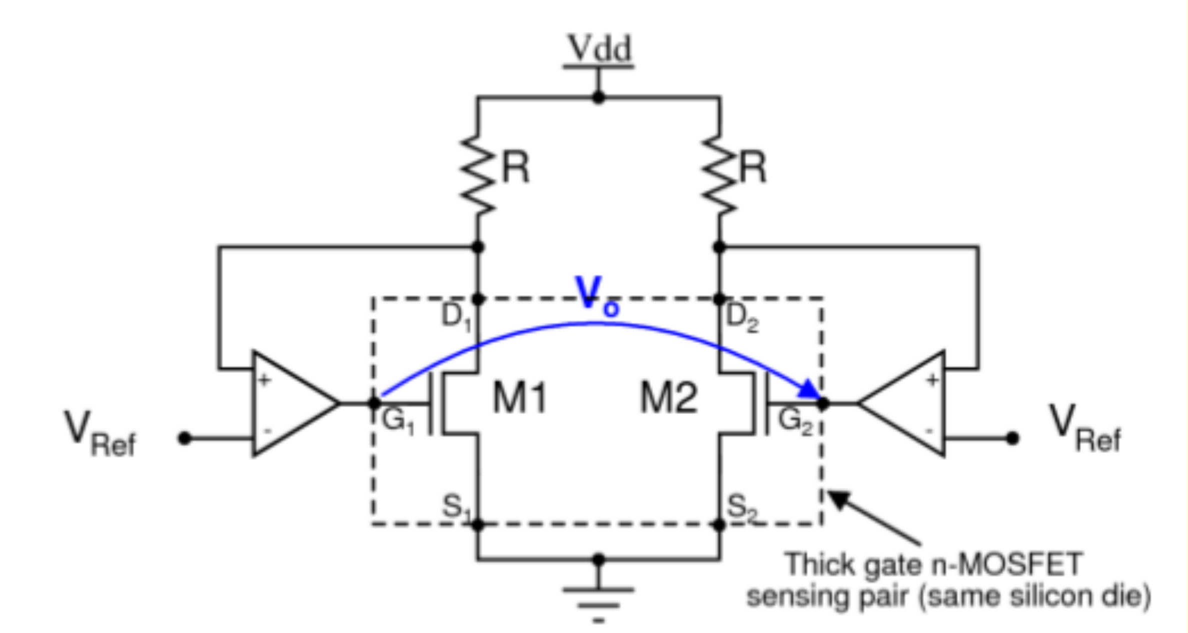
Temperature compensation using Differential Dosimeter and BCCM.

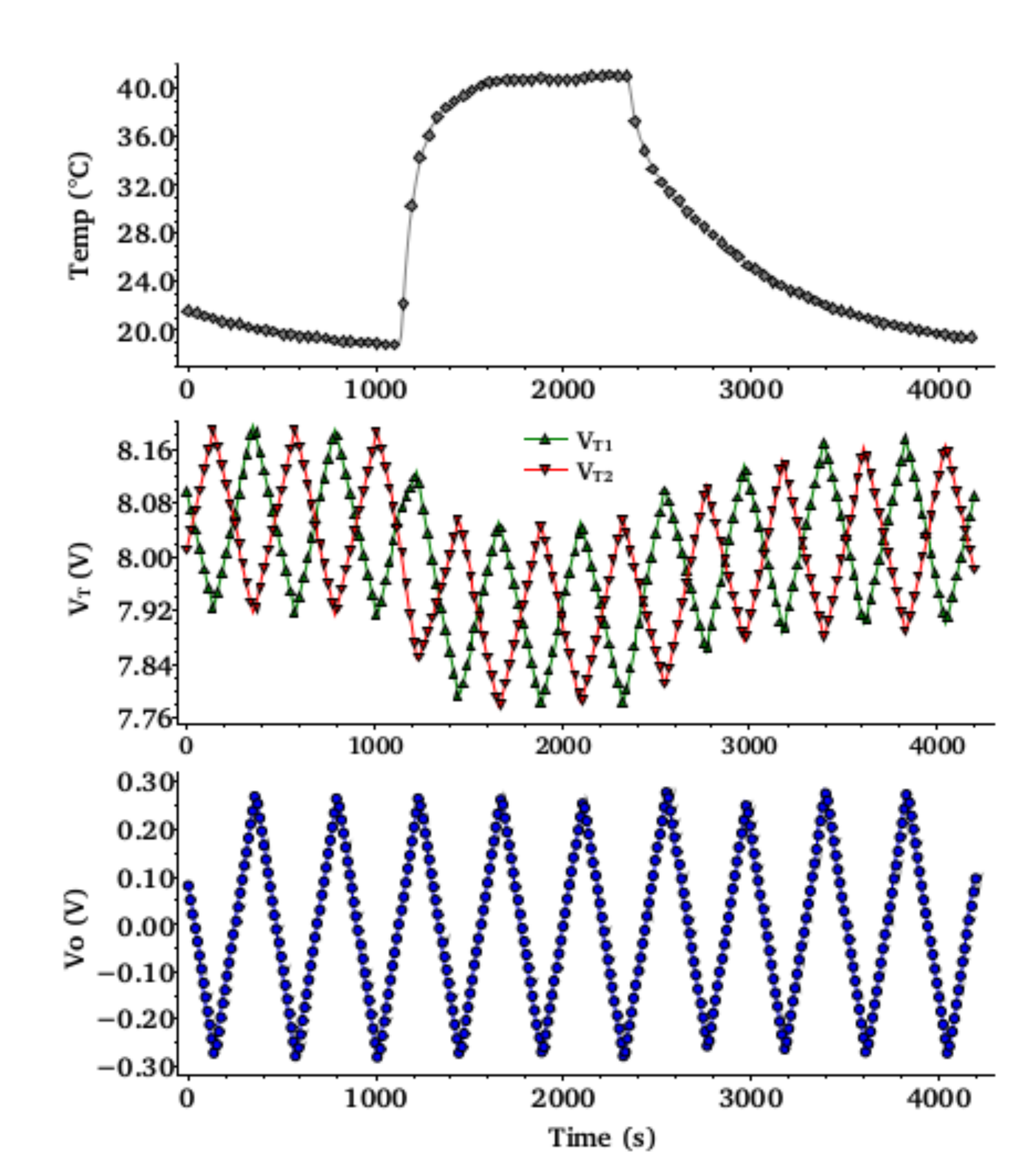
·The differential output mitigates temperature-induced V_T shifts.

·Extension of the dose measurement proved (as in previous works with thinner oxides).

·Relativelly more complex use.



Differential BCCM dosimeter:

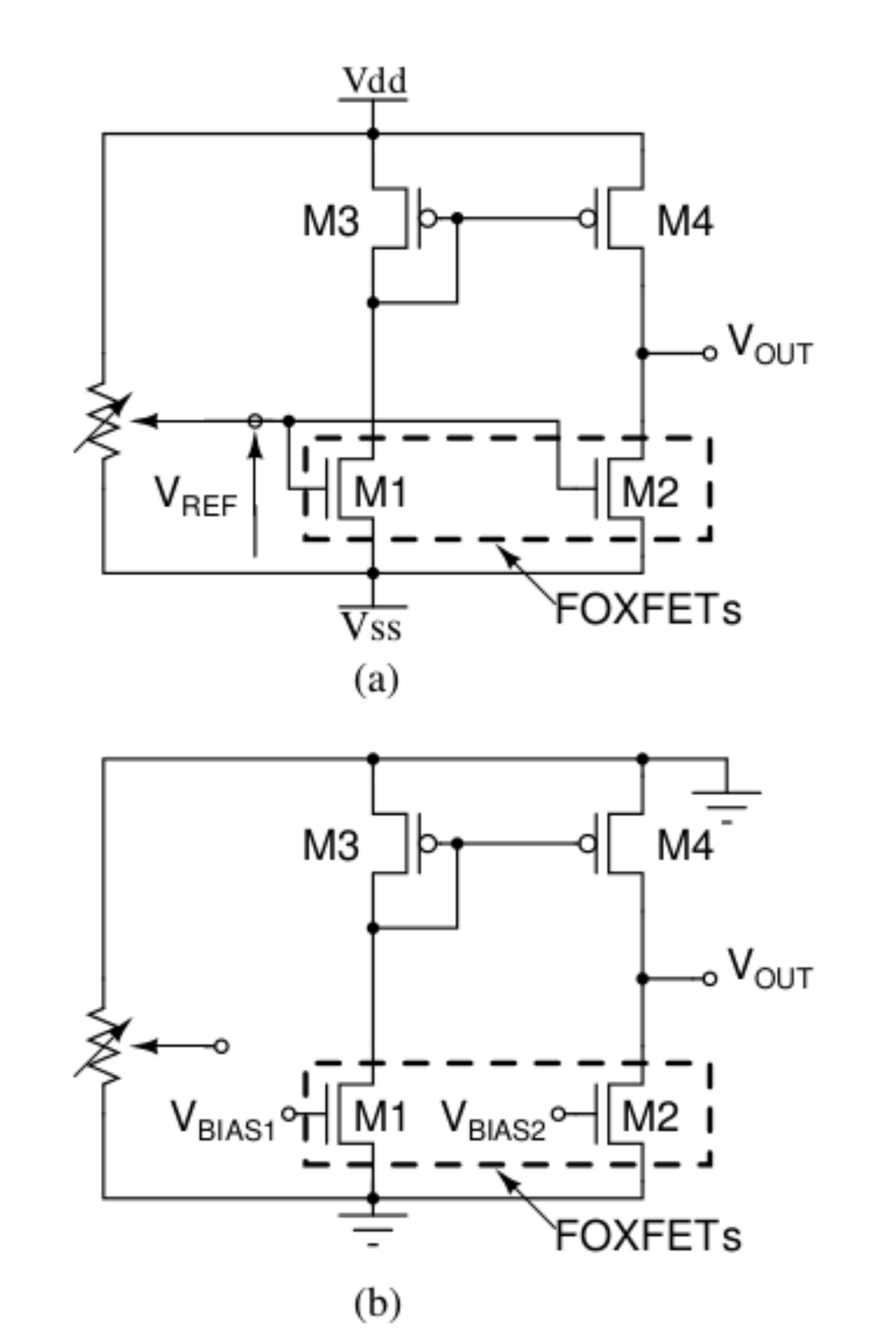


[García Inza TNS 2014]

LabFisDisp

The current mirror. A differential amplified sensor

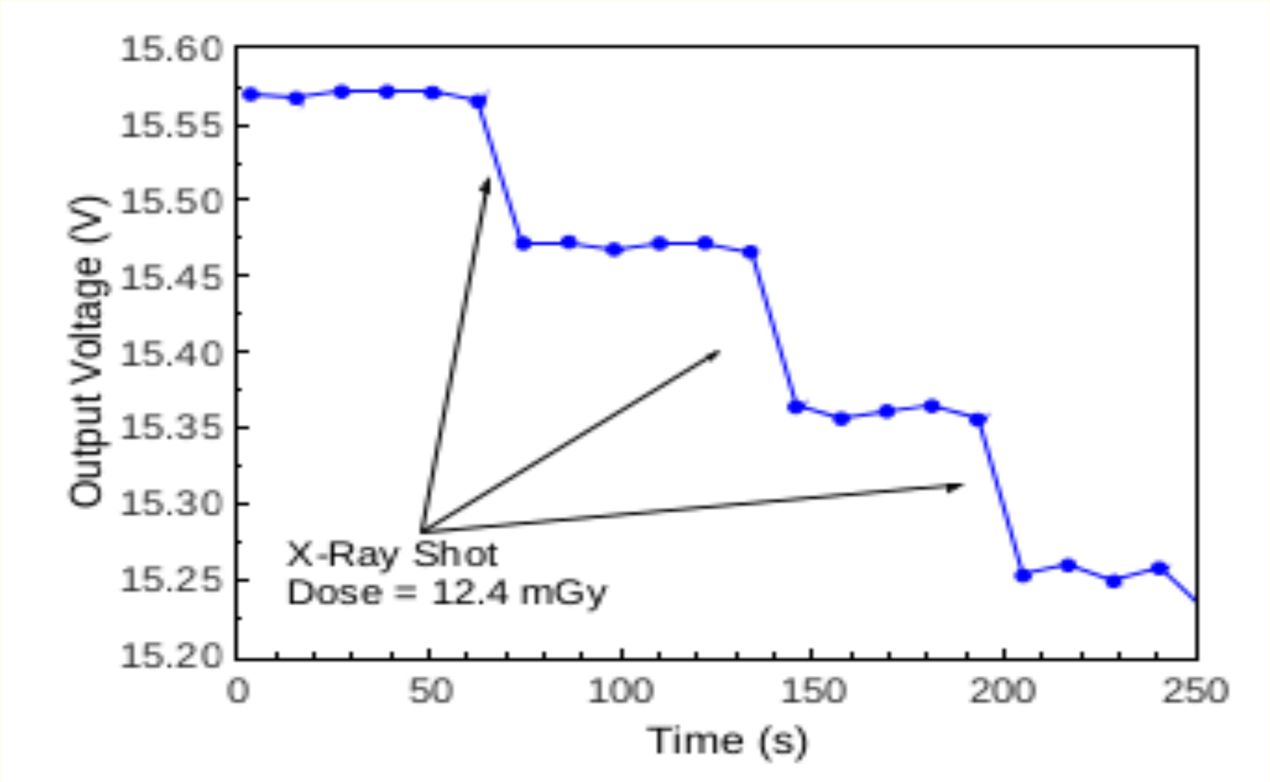
- Use of differential pairs differently biased (old idea)
- Temperature in common mode (first order approx)
- Amplification of response.

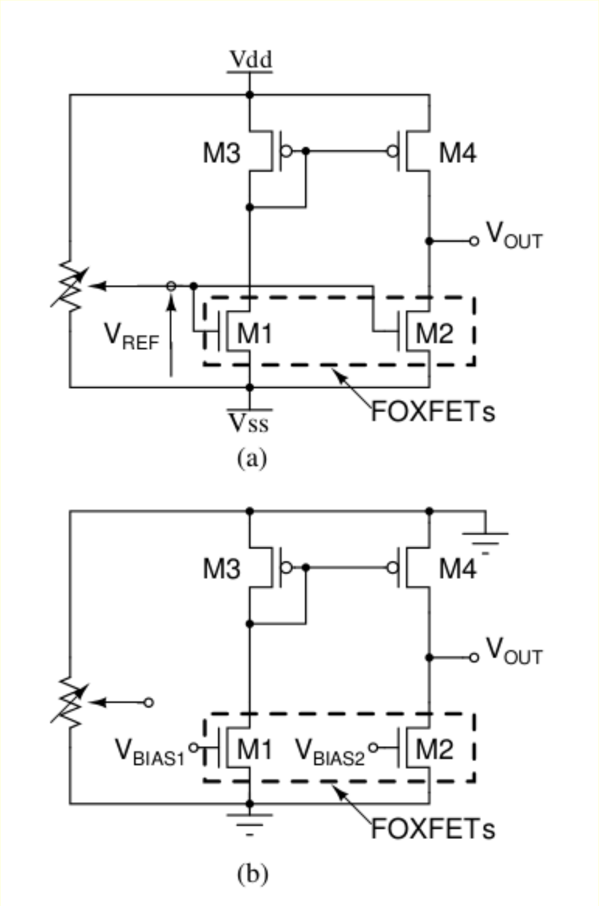


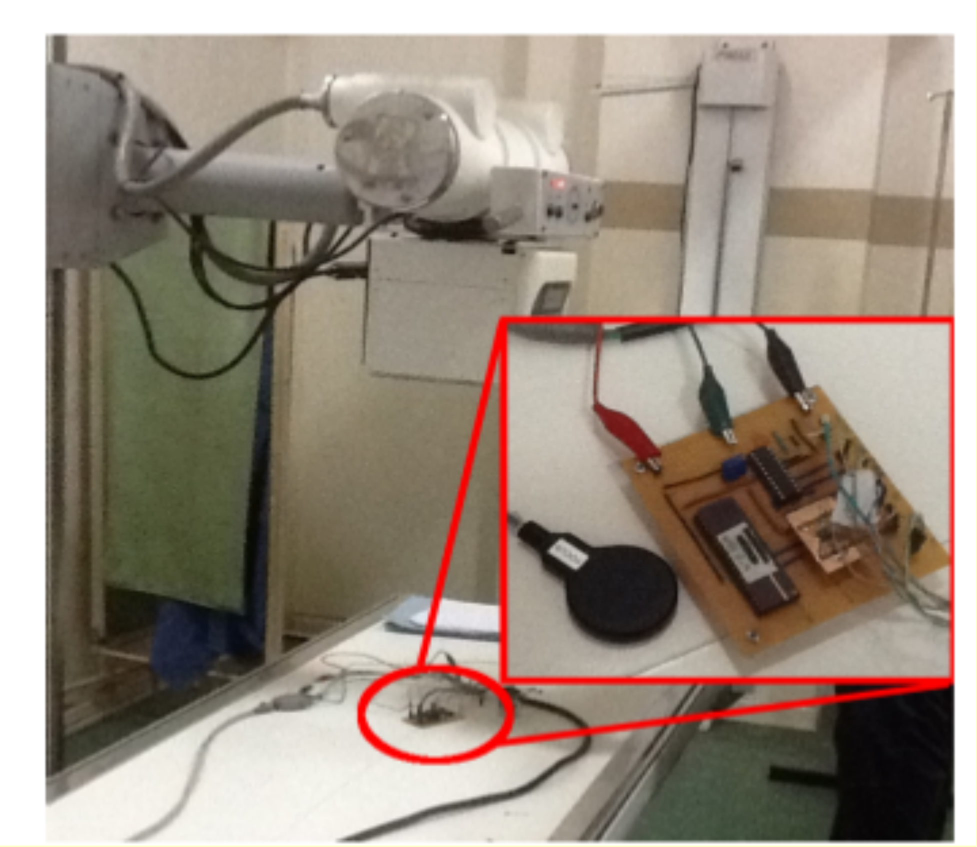
IEEE Transactions on Nuclear Science, 27 November 2014
CMOS Differential and Amplified Dosimeter with Field Oxide N-Channel MOSFETs
Carbonetto, S., GarcianInza, M., Lipovetzky, J., Carra, M. J., Redin, E., Salomone, L. S., Faigon, A.

Response to very low doses in x-ray imaging applications

- FOXFET + COTS implementation.
- Irradiated using an x-ray image system.
- Allowed a resolution of few mGys.
- Good thermal rejection.







LabFisDisp

[Carbonetto 2014 EAMTA]

Experimental structures and circuits: APS

- Active Pixel Sensor (APS).

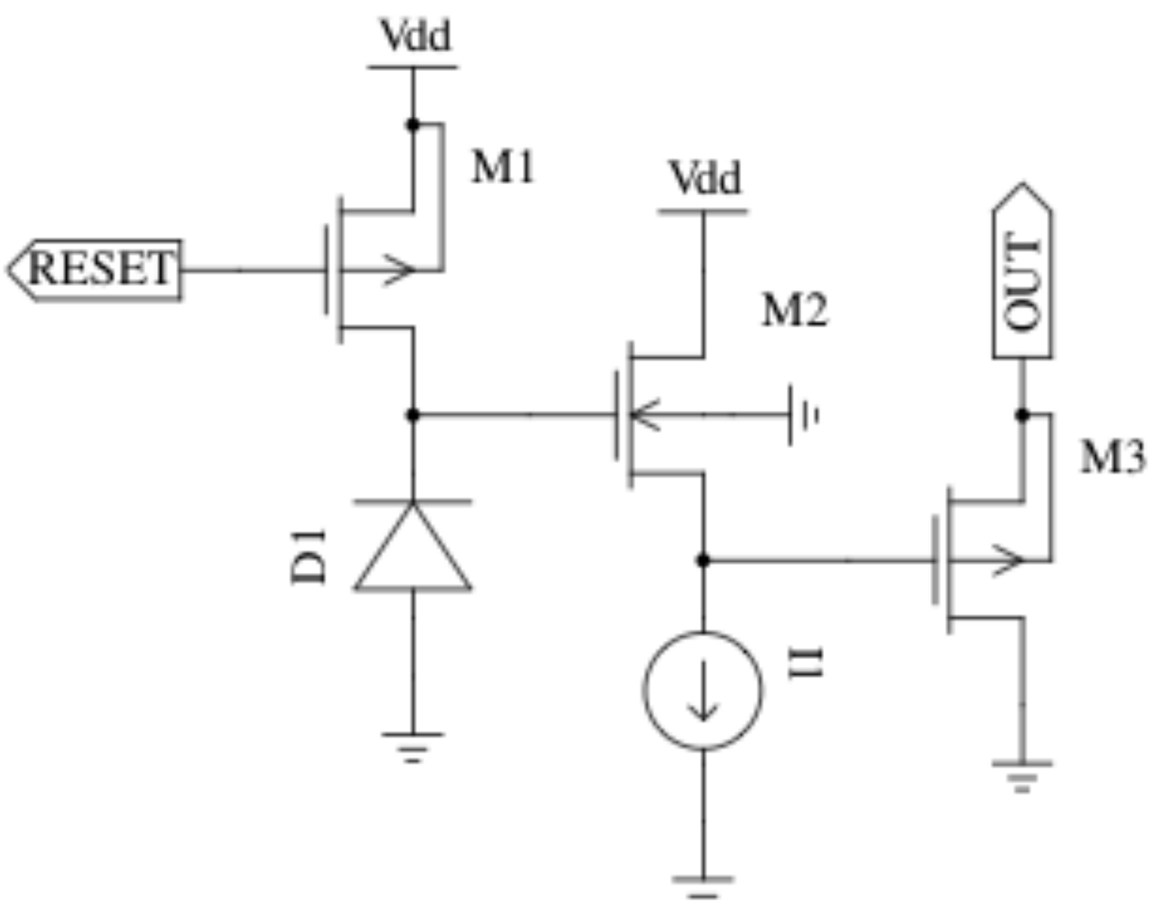


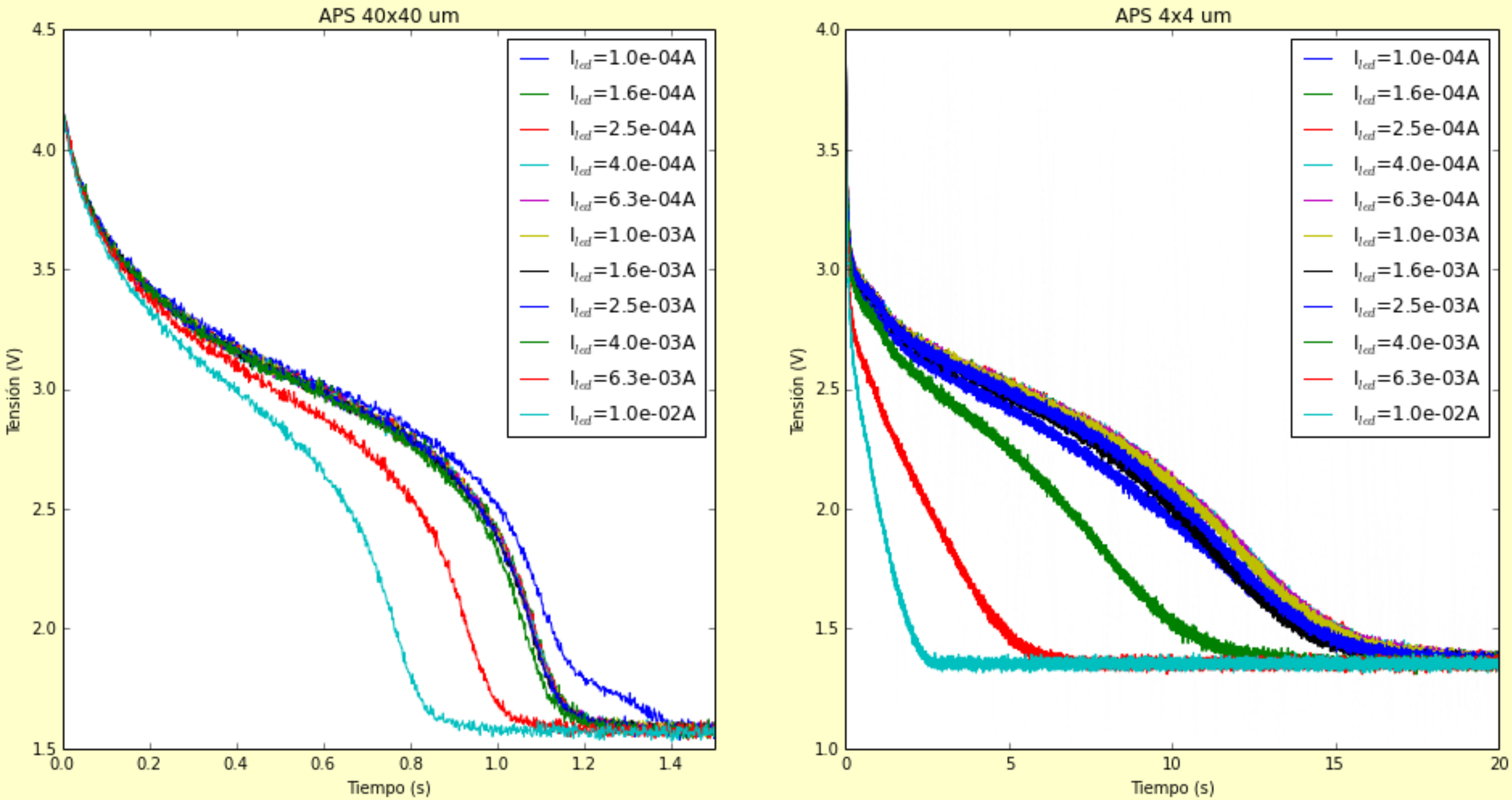
Fig. 1. APS circuit.

[I. Martinez Vasquez, A. Faigón 2015 EAMTA]

LabFisDisp

Experimental structures and circuits: APS

- Active Pixel Sensor (APS).

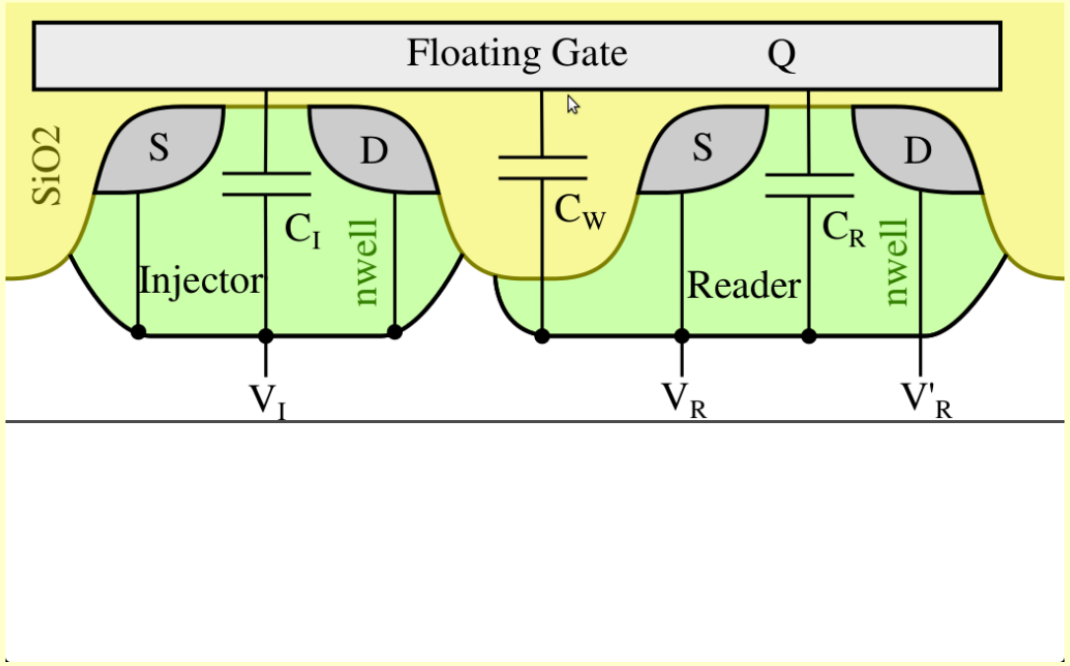


[I. Martinez Vasquez, A. Faigón 2015 EAMTA]

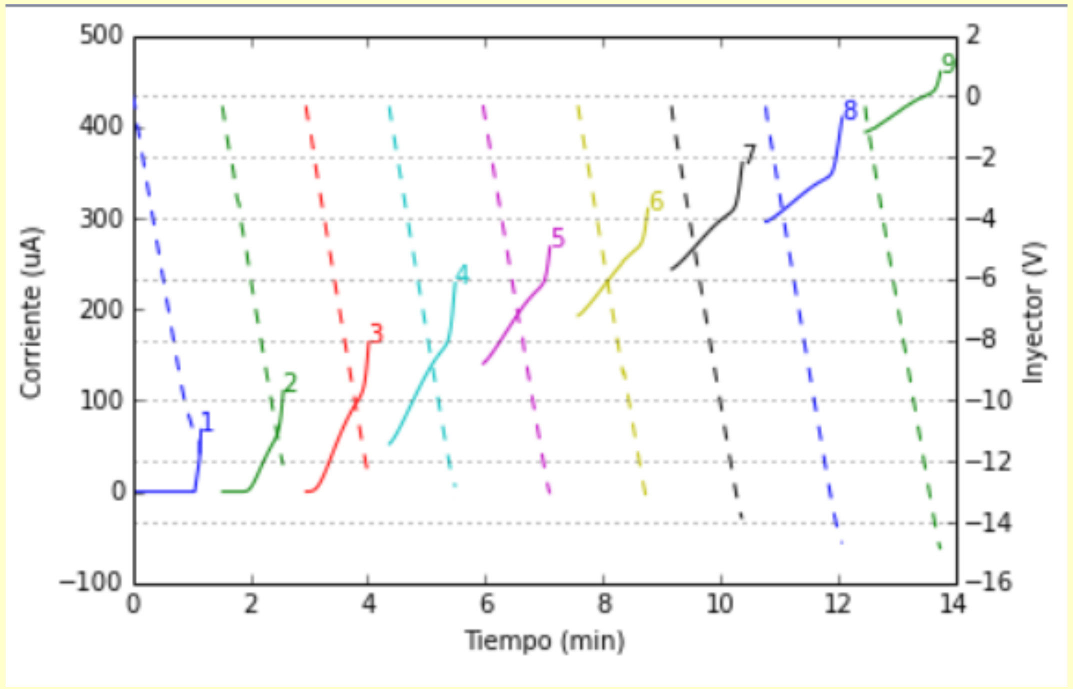
LabFisDisp

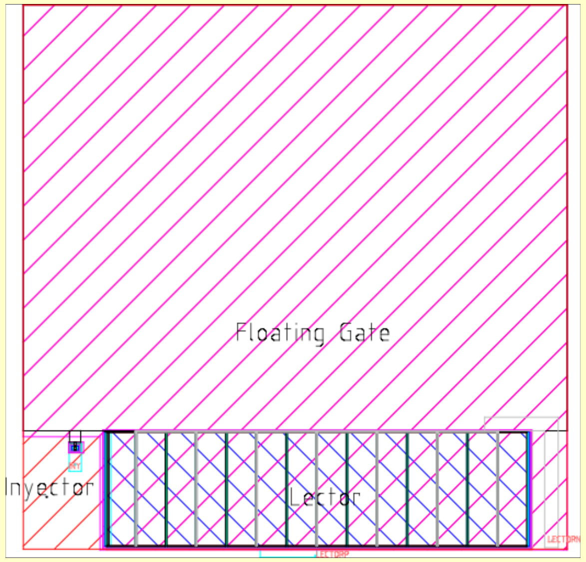
Experimental structures and circuits: FG

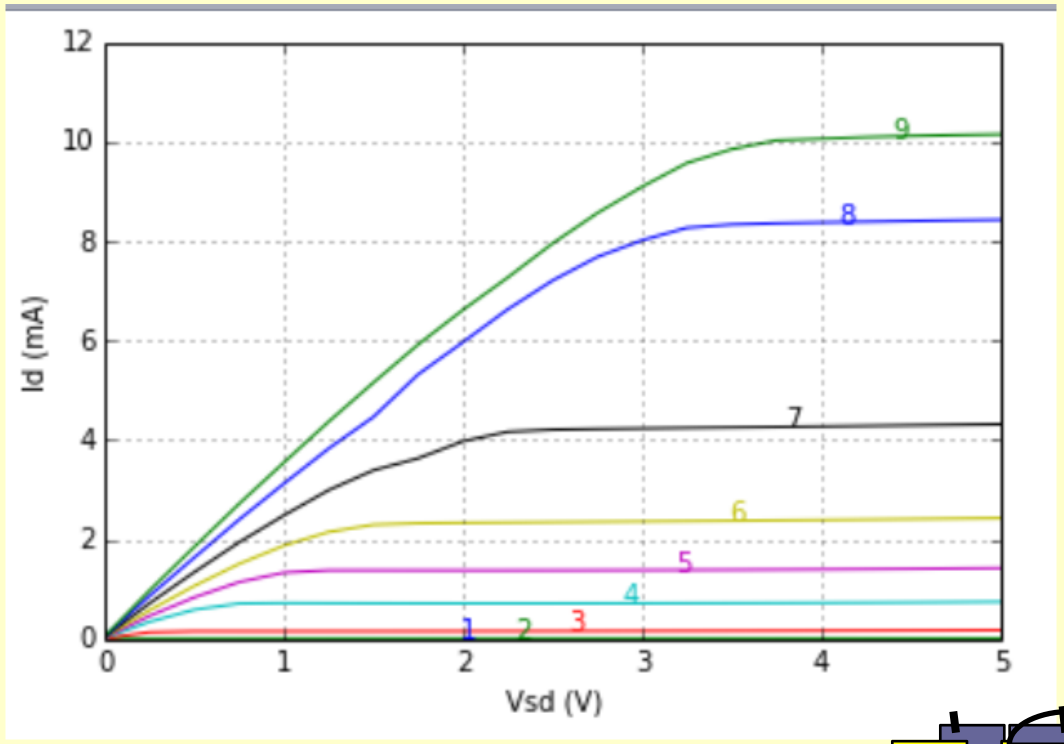
- Floating Gate Sensor (FG)



Charging curves

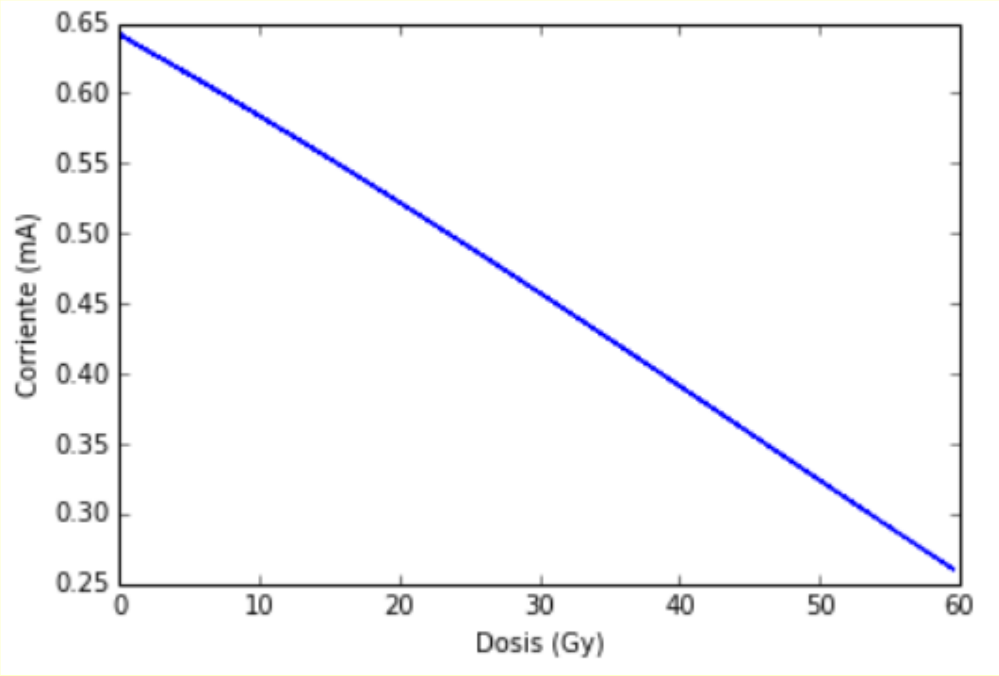


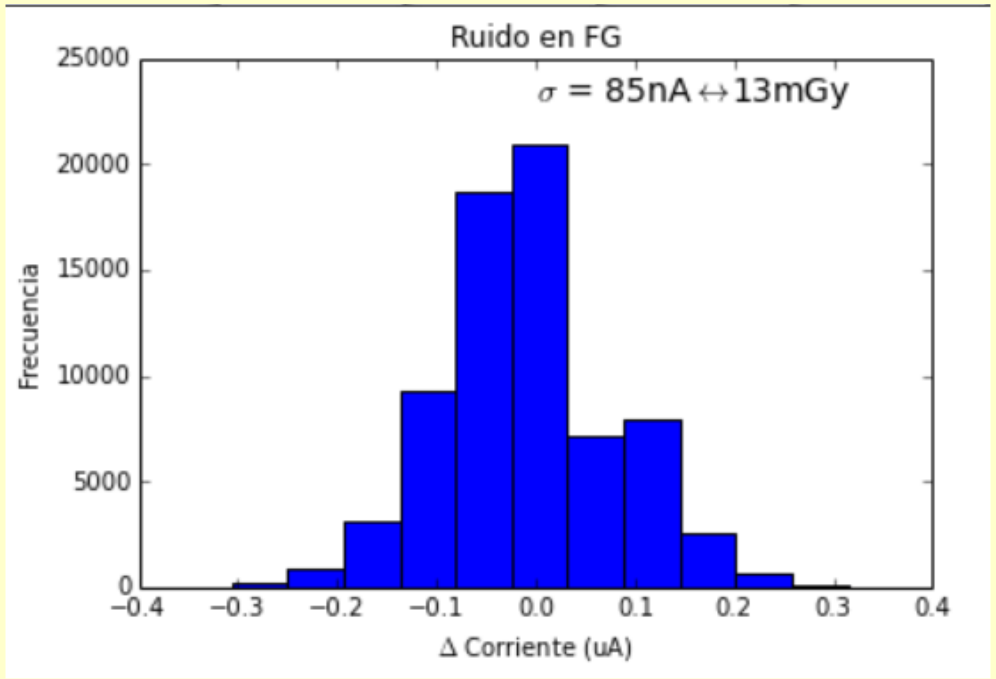


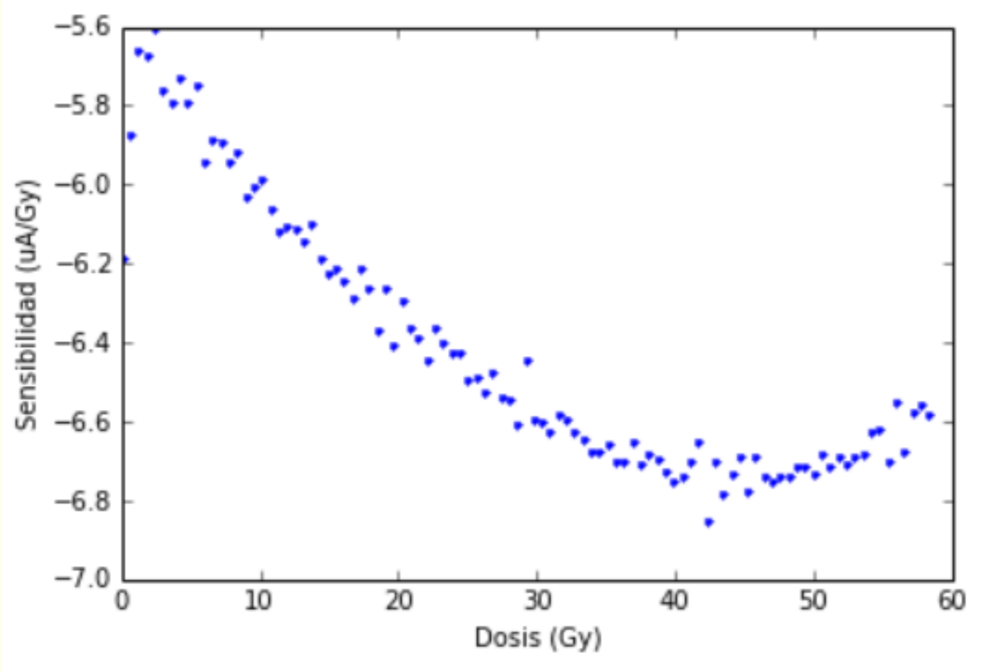


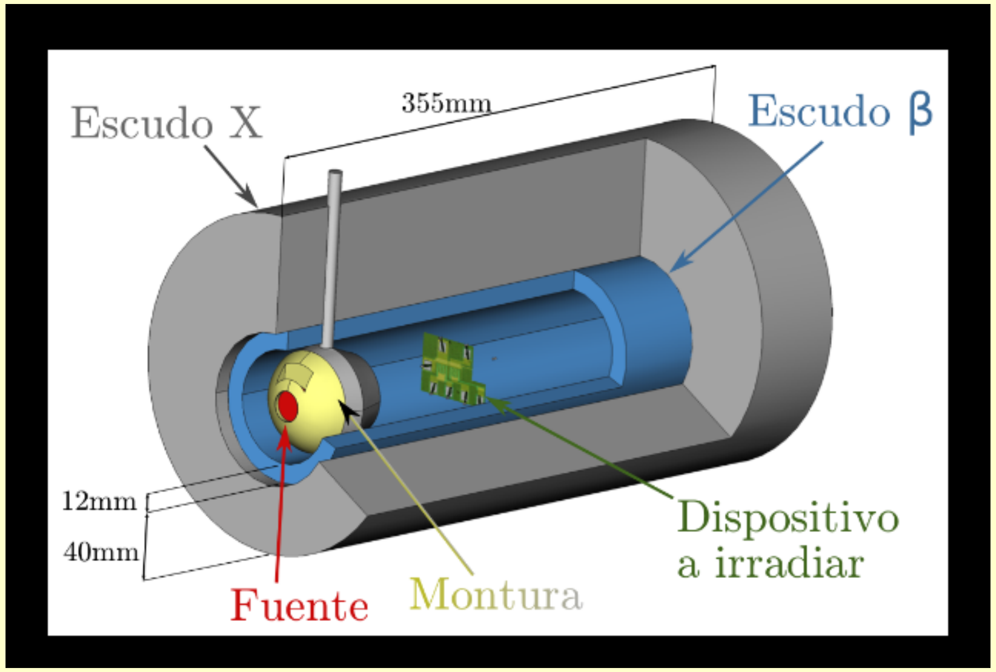
Experimental structures and circuits: FG

- Floating Gate Sensor (FG)









MOS dosimetry in LFDM

- Reusability of MOS sensors
- Extension of the dosimeter range. New measurement techniques
- Design of structures and circuits
- **Numerical simulation**
- Developments and applications

Numerical simulations

$$\Delta V_t = -\frac{q}{\varepsilon_{ox}} \int_0^{t_{ox}} p_t \left(t_{ox} - x\right) dx$$

$$\frac{dF}{dx} = -\frac{q}{\varepsilon_{ox}}\left(p_t + p_f - n_f\right)$$

$$\frac{dn_f}{dt} = -\frac{dj_n}{dx} + R_g - R_n n_f p_t$$

$$\frac{dp_f}{dt} = -\frac{dj_p}{dx} + R_g - R_c p_f \left(P_t - p_t\right)$$

$$\frac{dp_t}{dt} = R_c p_f \left(P_t - p_t\right) - R_n n_f p_t$$

The equations

$$j_n = -\mu_n n_f F - \frac{kT}{q}\mu_n \frac{dn_f}{dx}$$

$$j_p = \mu_p p_f F - \frac{kT}{q}\mu_p \frac{dp_f}{dx}$$

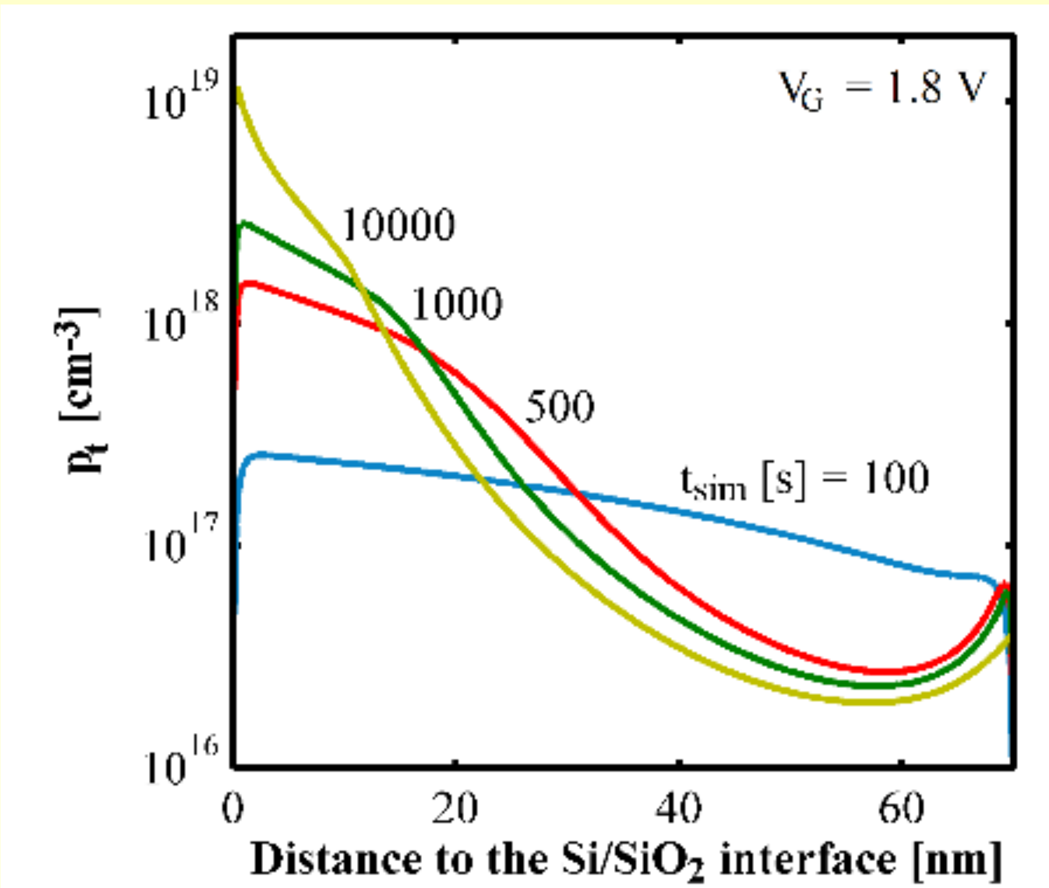
Parameters dependence

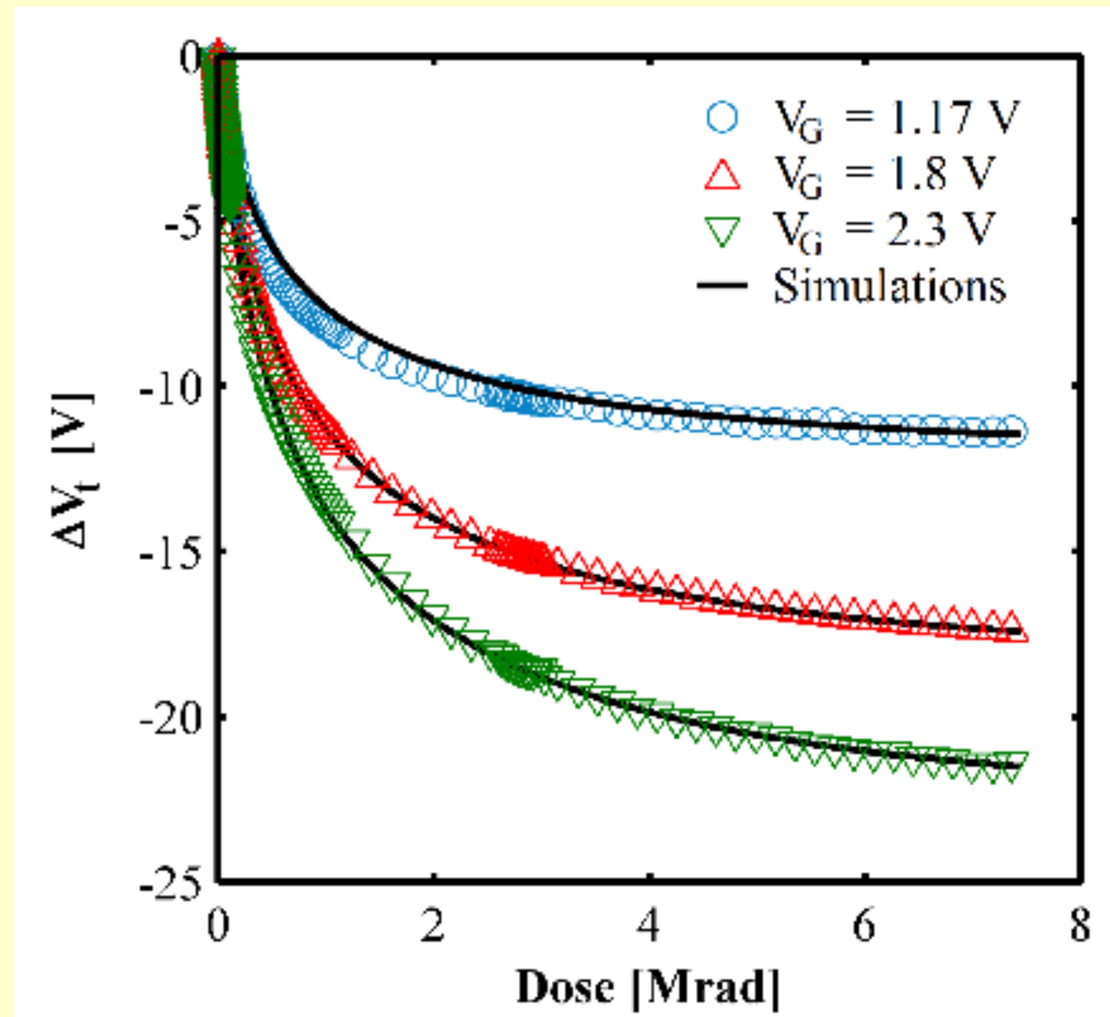
Rg=Rg(F,Dose): Effective pair generation
Rn=Rn(F): Neutralization probability
Rp=Rp(F): Hole trapping probability
Pt: Hole traps density

LabFisDisp

Numerical simulations

- Bss92



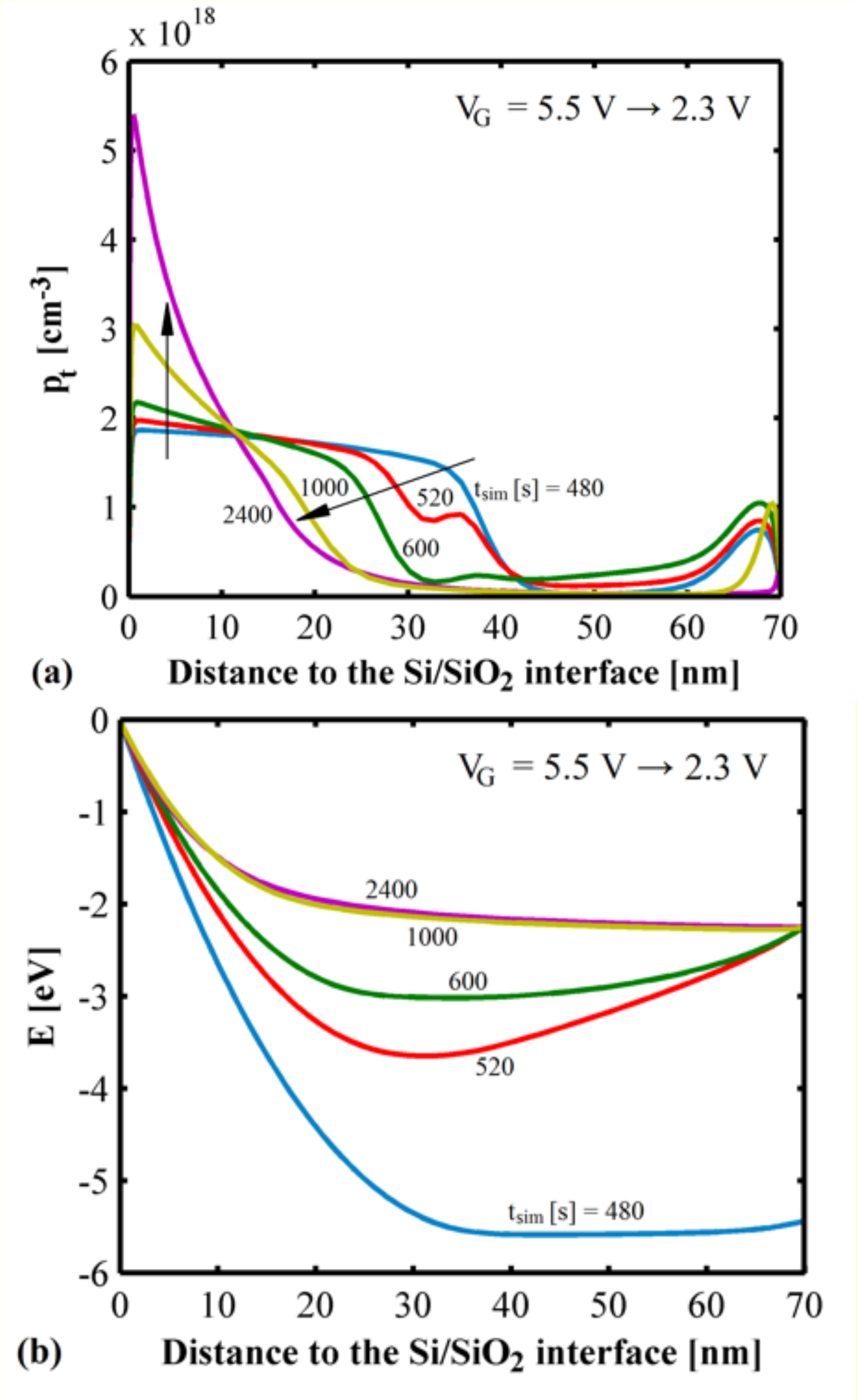


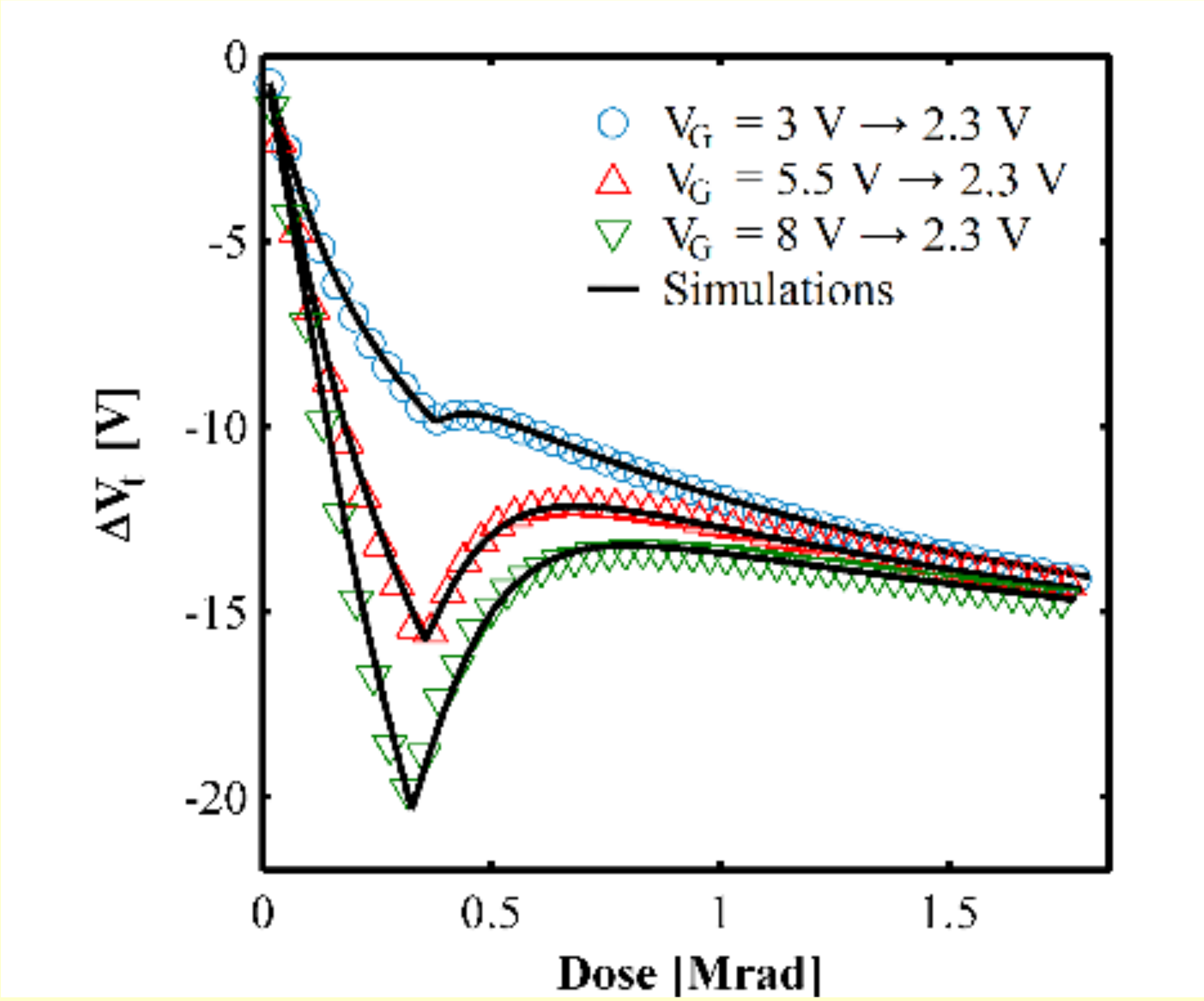
Numerical modeling of MOS dosimeters under switched bias irradiations

L. Sambuco Salomone, A. Faigón, and E. G. Redin

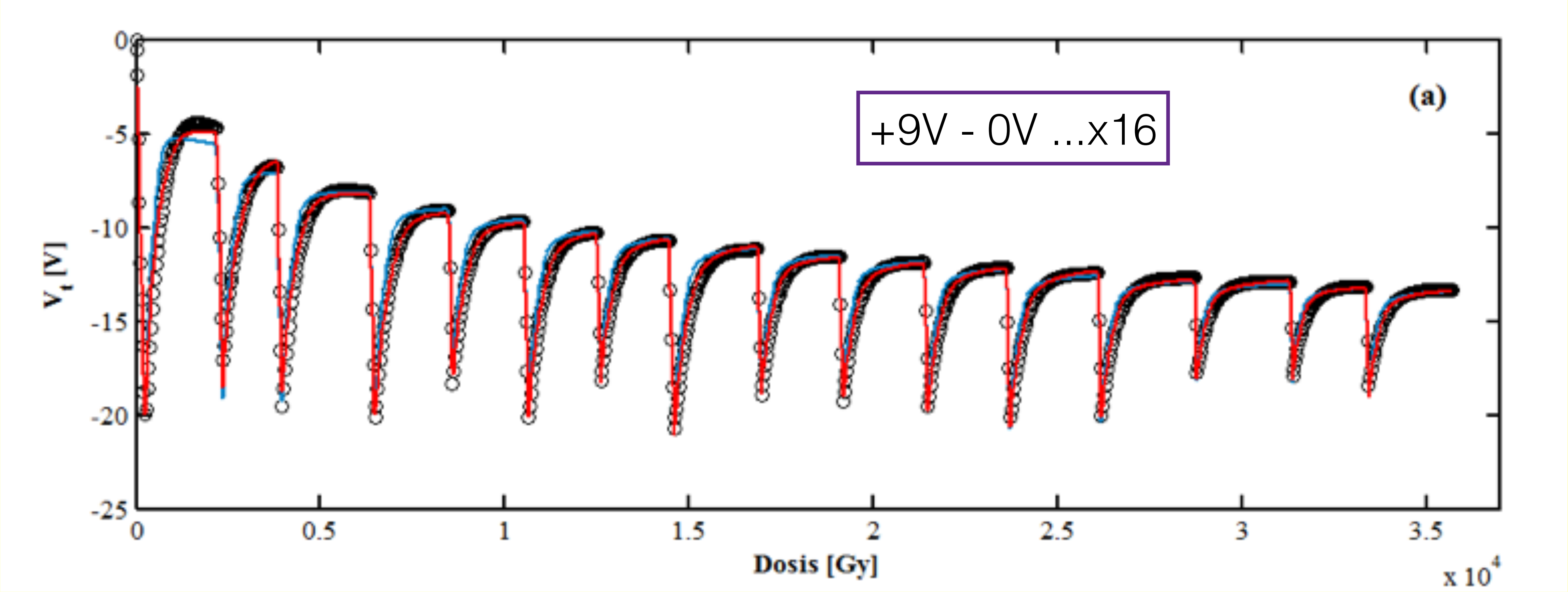
IEEE TRANSACTIONS ON NUCLEAR SCIENCE 62(4):1-1 · JULY 2015

Numerical simulations: Turn-around





Numerical simulations: bias switch sequence



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MOS dosimetry in LFDM

- Reusability of MOS sensors
- Extension of the dosimeter range. New measurement techniques
- Design of structures and circuits
- Numerical simulation
- **Developments and applications**

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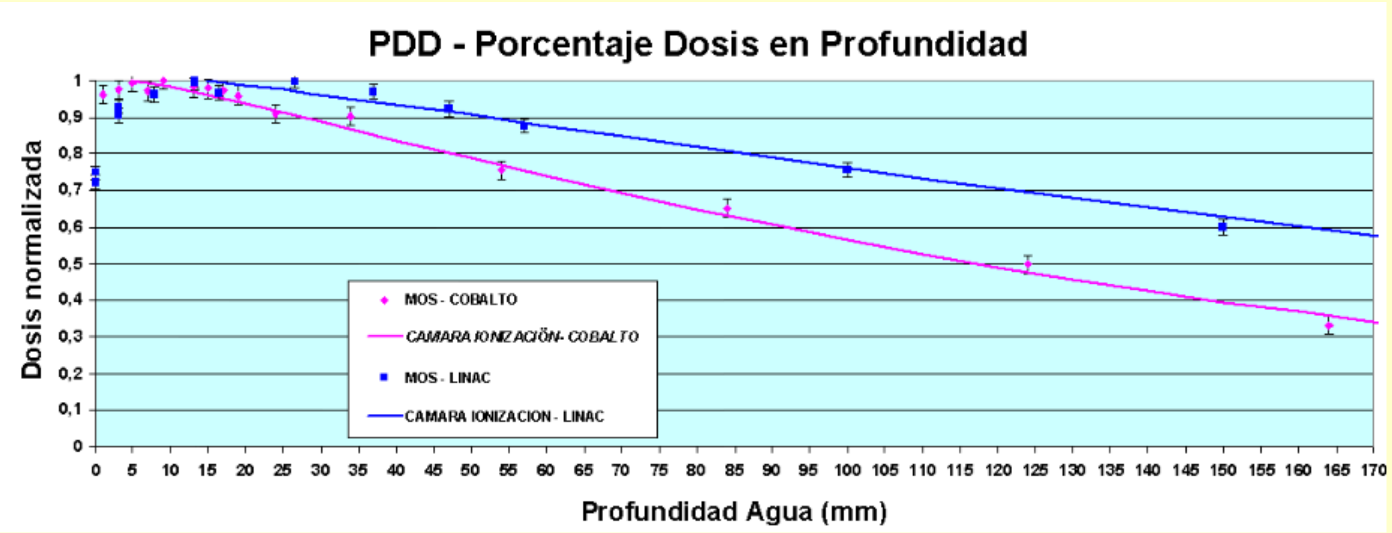
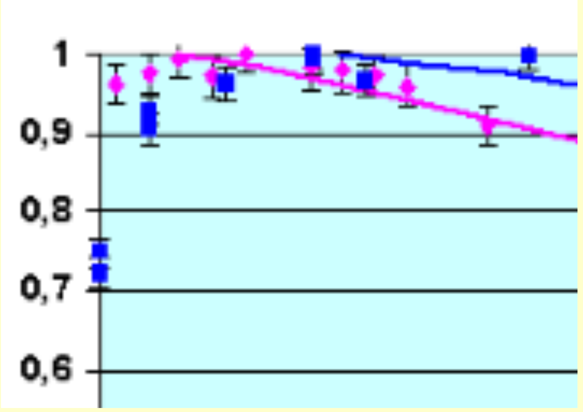
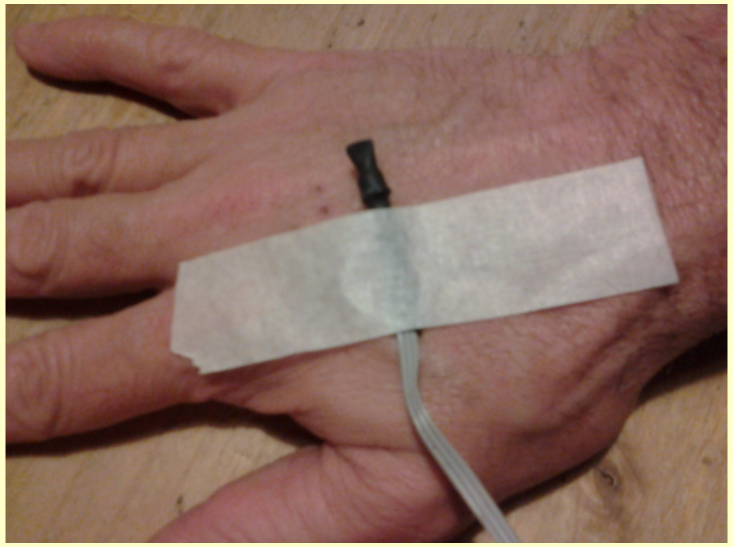
Characterization for clinical applications and first results







Resultados de mediciones "in vivo" en tiempo real en pacientes

MEDICION 1			
Tumor en Mama en Isocentro DFI=100cm			
DOSIS Planificada 100cgy + 100cgy = 200cgy			
	Campo 1	**Campo 2**	**Total**
Distancia Fuente Piel (cm)	93,5	94,5	
Profundidad tumor (cm)	6,5	5,5	
Dosis medida MOS (+/- 2,5cGy)	103	99	202
Diferencia con Planificador			1%
MEDICION 2			
Tumor en Región Pelvica - Cadera Lateral DFS= 80cm			
DOSIS Planificada 30cgy + 30cgy = 60cgy			
	Campo 1	**Campo 2**	**Total**
Distancia Fuente Piel (cm)	80	80	
Profundidad tumor (cm)	16,5	16,5	
Dosis medida MOS (+/- 2,5cGy)	32	30	62
Diferencia con Planificador			3%

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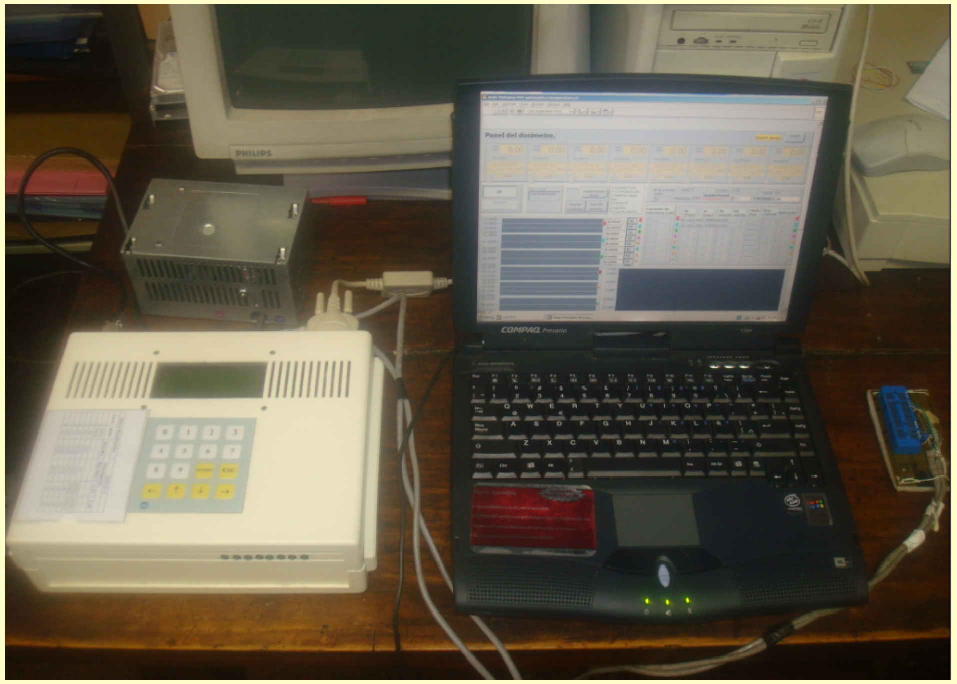
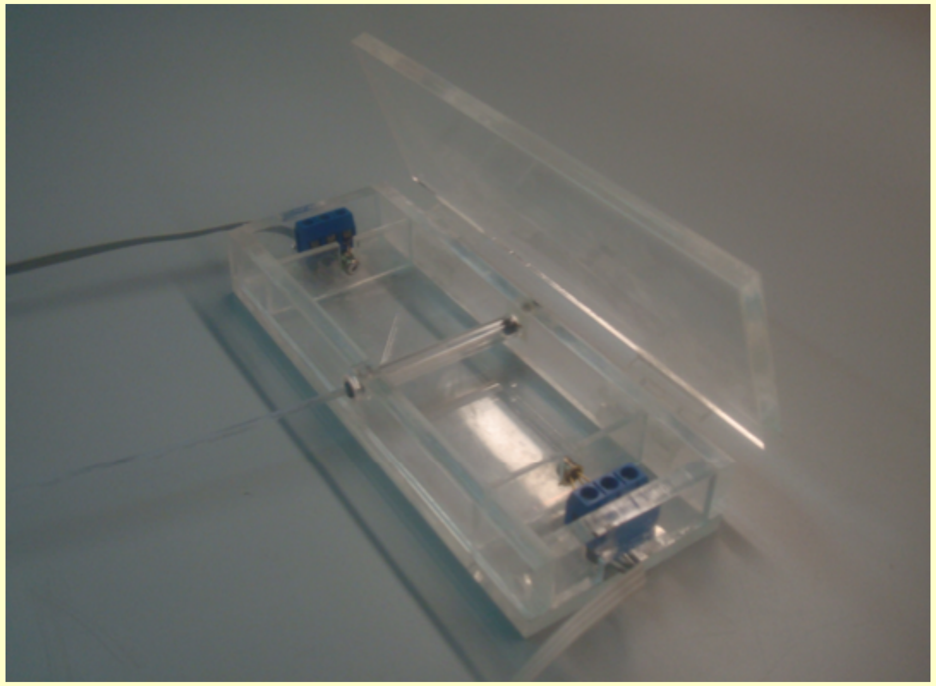
Aplicaciones desarrolladas

Dosímetros de altas dosis --decenas de kgy's– y de bajas dosis –resolución de 1 cgy--



Dosímetro de alta dosis para PISI



Cámara de calibración para braquiterapia

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Comparison with commercial sensors

Standard Sensitivity Dosimeter models TN-502RD, TN-502RDM, & TN-252LA5

Dosimeter	Bias Supply Setting	Nominal Sensitivity	Energy Source
Standard	Standard	1 mV/ cGy	^{60}Co with buildup
Standard	High	3 mV/ cGy	^{60}Co with buildup
Standard	Standard	3 mV/ R	Diagnostic X-ray
Standard	High	9 mV/ R	Diagnostic X-ray
Standard Linear 5ive Array	Standard	0.98 mV/cGy	^{192}Ir
Standard Linear 5ive Array	High	1.38 mV/cGy	^{192}Ir

High Sensitivity Dosimeter models TN-1002RD, TN-1002 RDM, TN-502LA5 & TN-1002LA5

Dosimeter	Bias Supply Setting	Nominal Sensitivity	Energy Source
High Sensitivity	Standard	3 mV/ cGy	^{60}Co with buildup
High Sensitivity	High	9 mV/ cGy	^{60}Co with buildup
High Sensitivity	Standard	10 mV/ R	Diagnostic X-ray
High Sensitivity	High	30 mV/ R	Diagnostic X-ray
High Sensitivity Linear 5ive Array	Standard	11.1mV/cGy	^{125}I
High Sensitivity Linear 5ive Array	High	15.2 mV/cGy	^{125}I
Extreme Sensitivity Linear 5ive Array	Standard	25.8 mV/cGy	^{125}I
Extreme Sensitivity Linear 5ive Array	High	37.2 mV/cGy	^{125}I

Our **> 40 mV/cGy**

LabFisDisp

Comparison with commercial sensors

FEATURES & SPECIFICATIONS	ONE DOSE SICEL	RT Dose (MOSFET) Best Medical Canada	Diff **Fox**
Surface/Skin Dose Measurements	YES	YES	YES
Depth-Dose Measurements (Dmax) w/ Build-up for radiotherapy	NO. Limited	YES for all Photon and Electron Energies using Brass and Solid Water Caps	YES
Reusable Dosimeter	NO. Single Use	YES. Multiple use	YES. Multpl use
Number of Dose Fractions per Dosimeter	1 fraction	100 to 200 fractions	**100000 fractions**
Cost per Dose Fraction	~15 $	< 1 $	**< 0.001 $**
Dosimeter Size	6 mm wide	1 mm & 2 mm options MicroMOSFET fits inside 5 or 6 Fr catheter	1 mm side
Dose Points in Real-Time	1 dose point off-line	Up to 40 dose points on-line in real-time	1 point/5 sec real time. ilim.
Dose Readout Mode	Single read mode	Single or Continuous readout mode at variable time intervals	Single or continuous
Energy Dependence	NO	NO	NO
Isotropic for 360°	NO 2% at 0°-45°*	YES ±2% for 360°	....
Accuracy	±5% typical	±2% on High Setting	+/- 2%
Temperature Dependence	YES "Accuracy only within ±5 C variance"*	NONE 0.5% from 20 to 40 C	0.27 mGy/C

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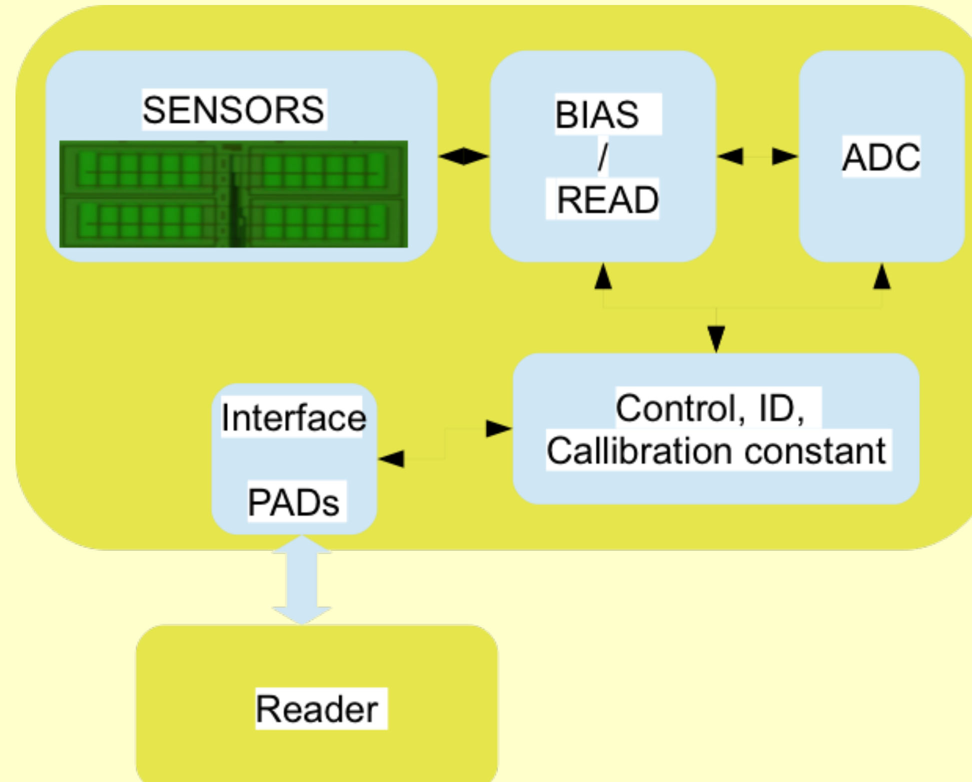
Future steps in the integration of sensors

- OPAMP with FOXFET differential input pair, correction of non-linearities with feedback.
- Then integration of ADC and reading electronics on chip, for a SoC.
- RFID front end for an offline dosimeter.
- Study of interaction of radiation with packaging.



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Thanks

Thanks!

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