Improving the sensitivity of passive RADFET detectors

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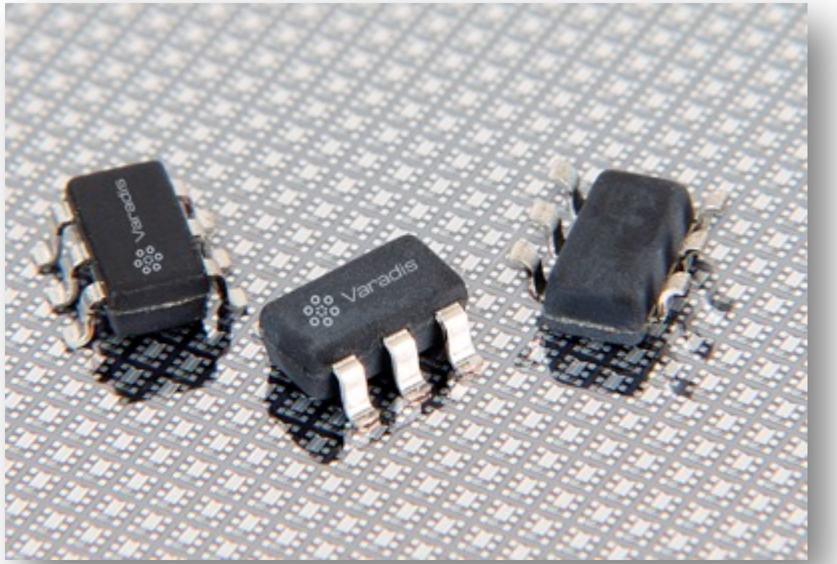
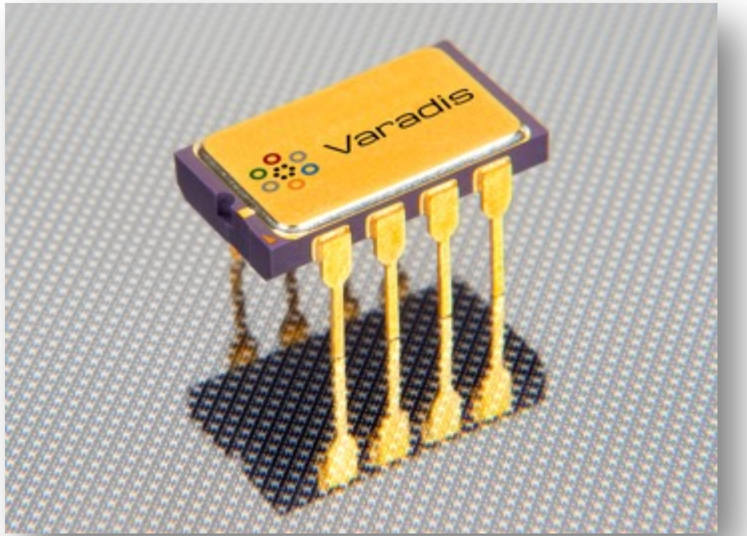
3rd ELICSIR Summer School in University of Granada

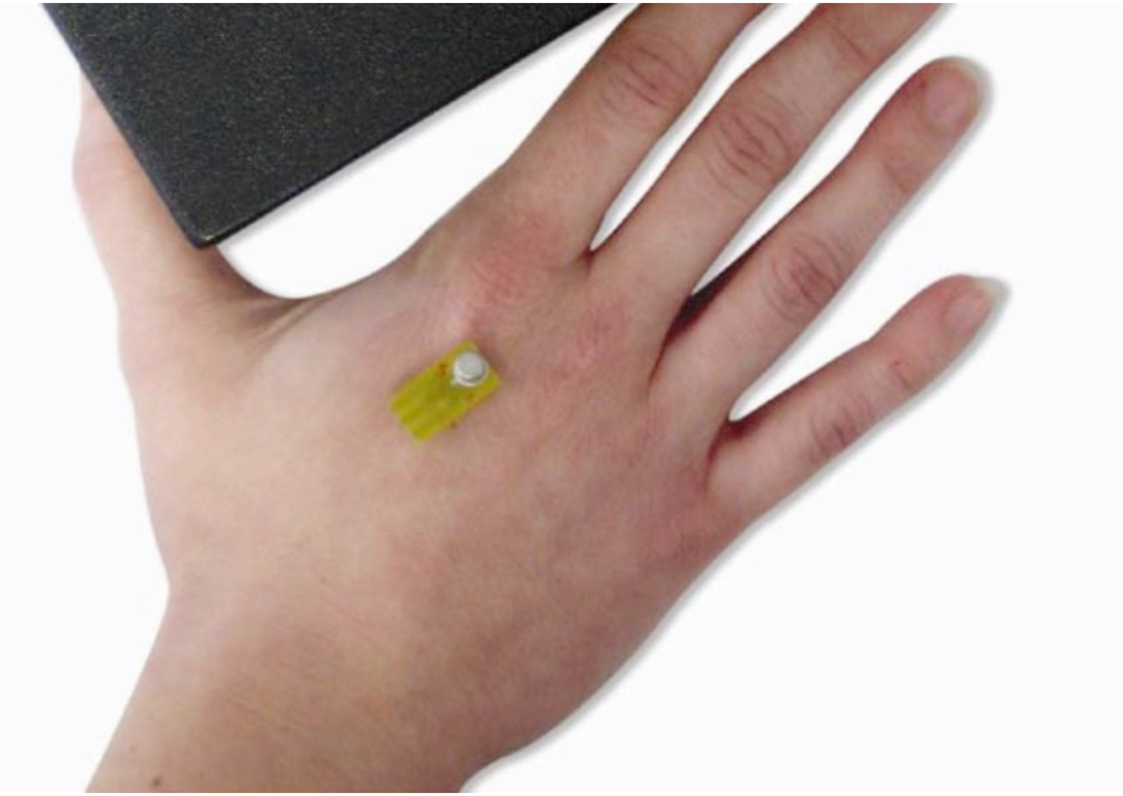
Tyndall company Varadis – custom RADFETS

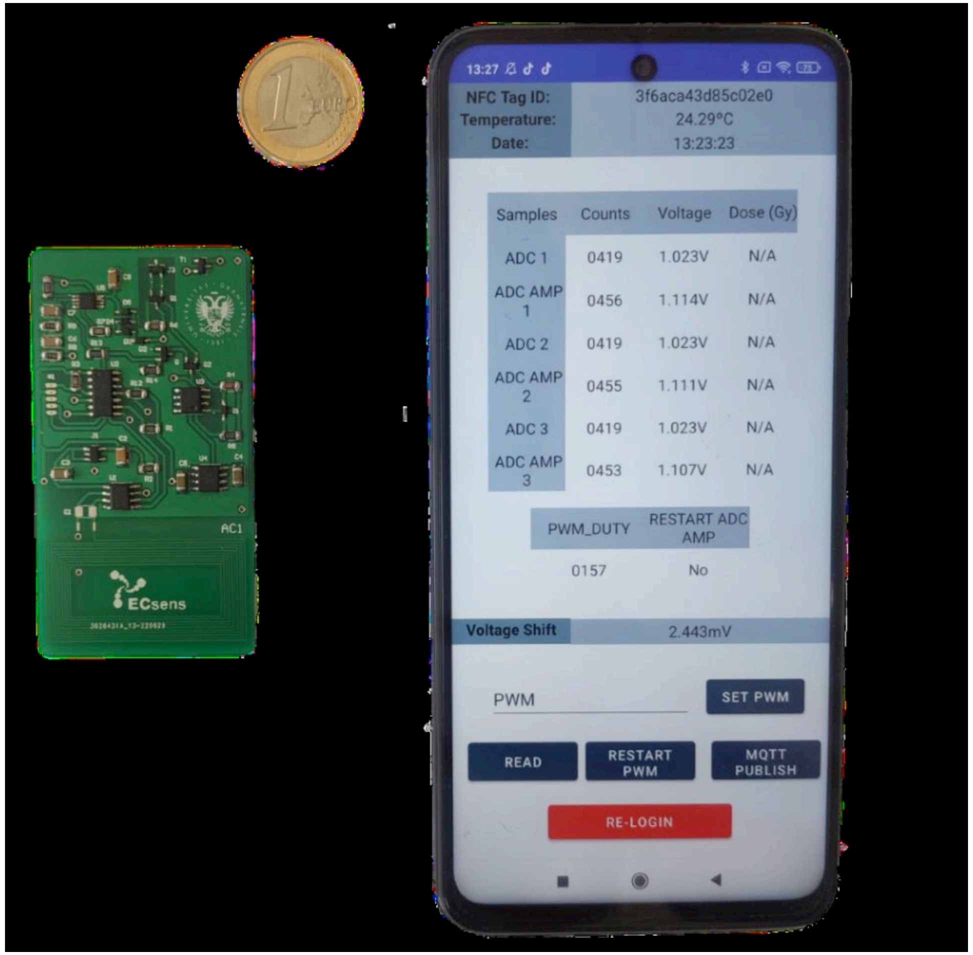




- Space – ESA, NASA, JAXA, Satellites

Passive RADFET patches/tags for radiotherapy





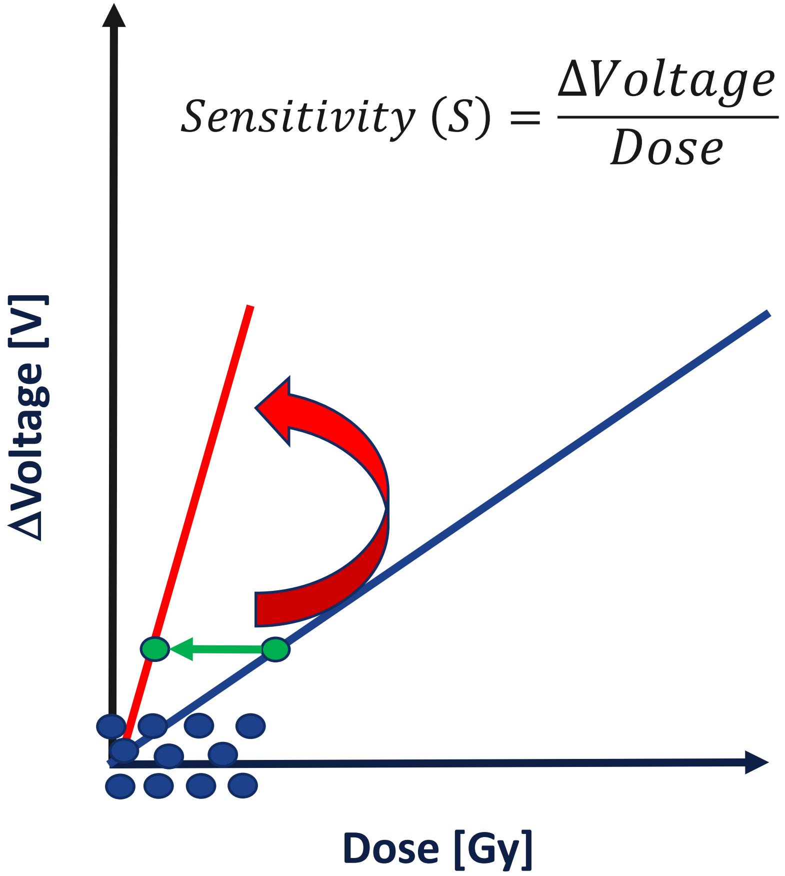
Passive RADFET Patches for lower doses

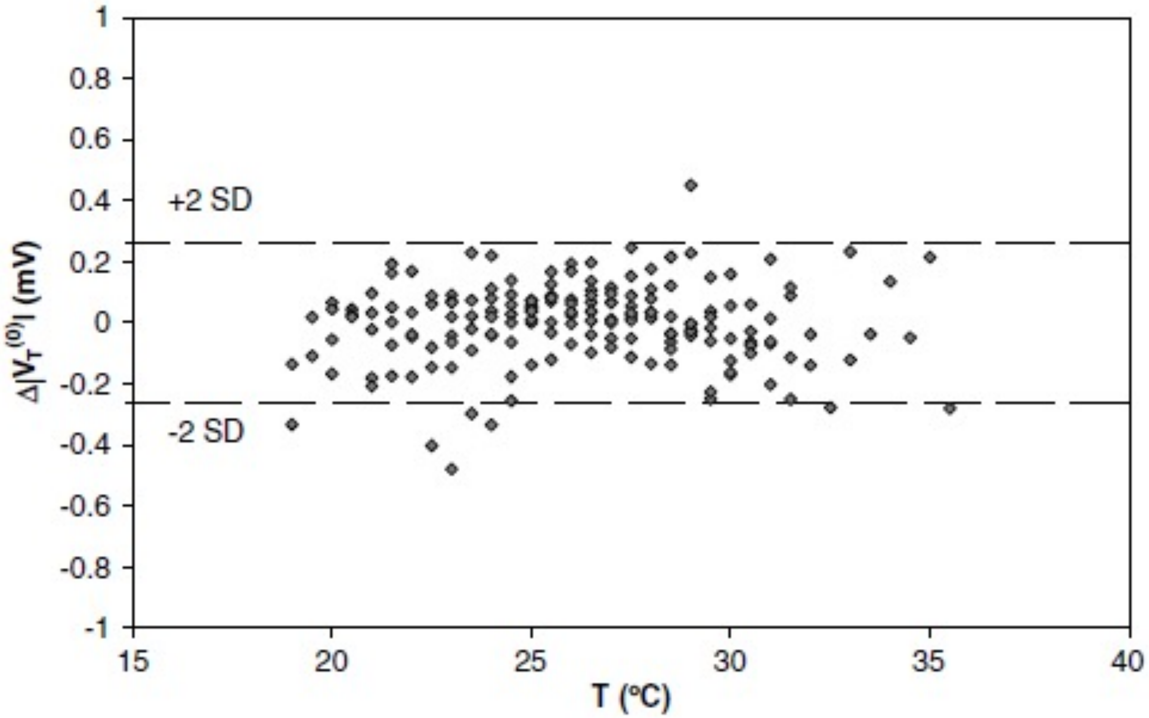
Electrogenics Labs

- Radiotherapy
- Interventional Radiology
- CT Scans

Lower Doses

How can higher RADFET Sensitivity help?





Uncertainty of +/- 0.25mV in voltage reading

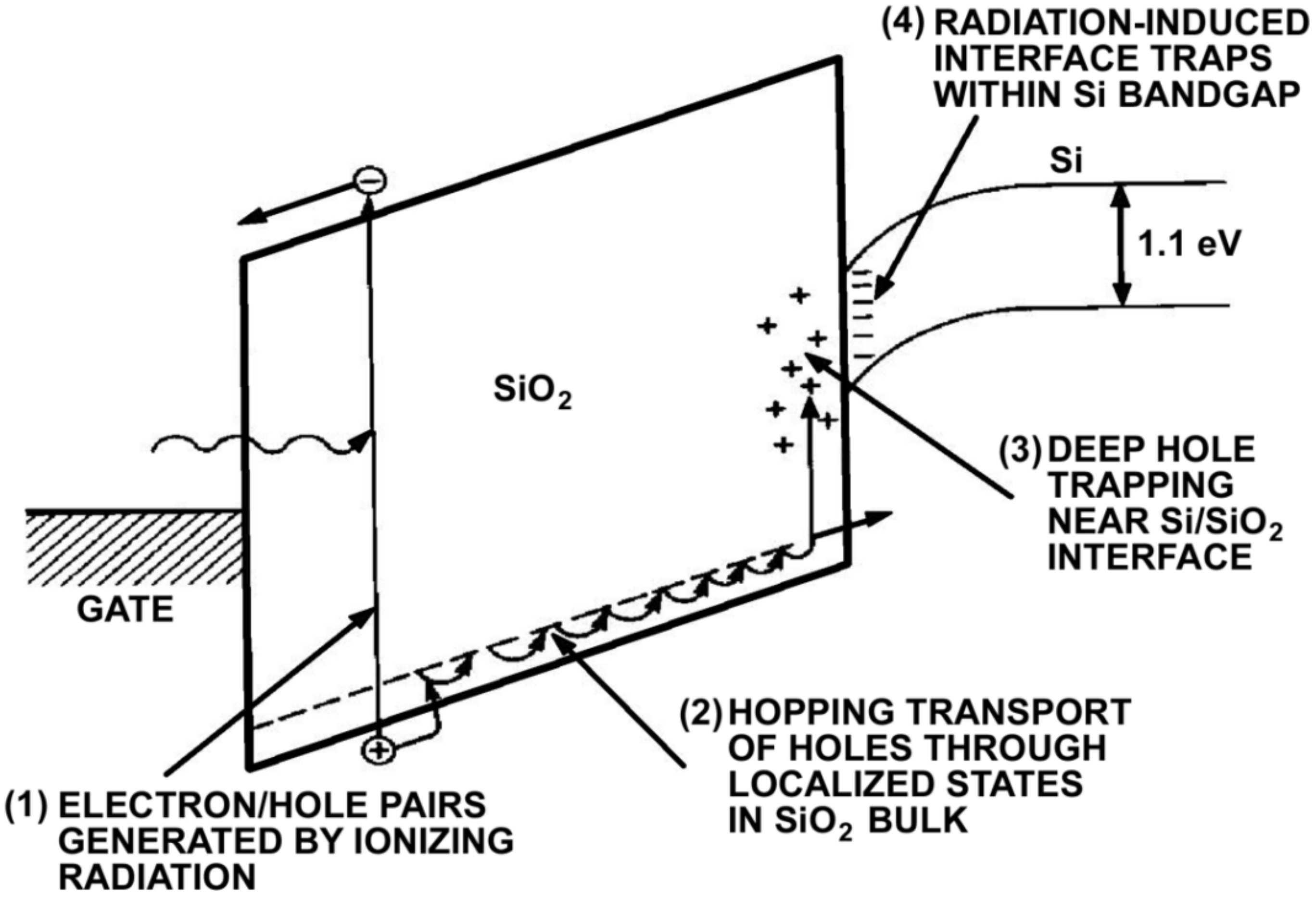
M A Carvajal *et al* 2011 *Phys. Med. Biol.* **56** 3535

Higher RADFET Sensitivity Detects Lower Doses if Electronic Noise/Drift remains same

Talk Outline

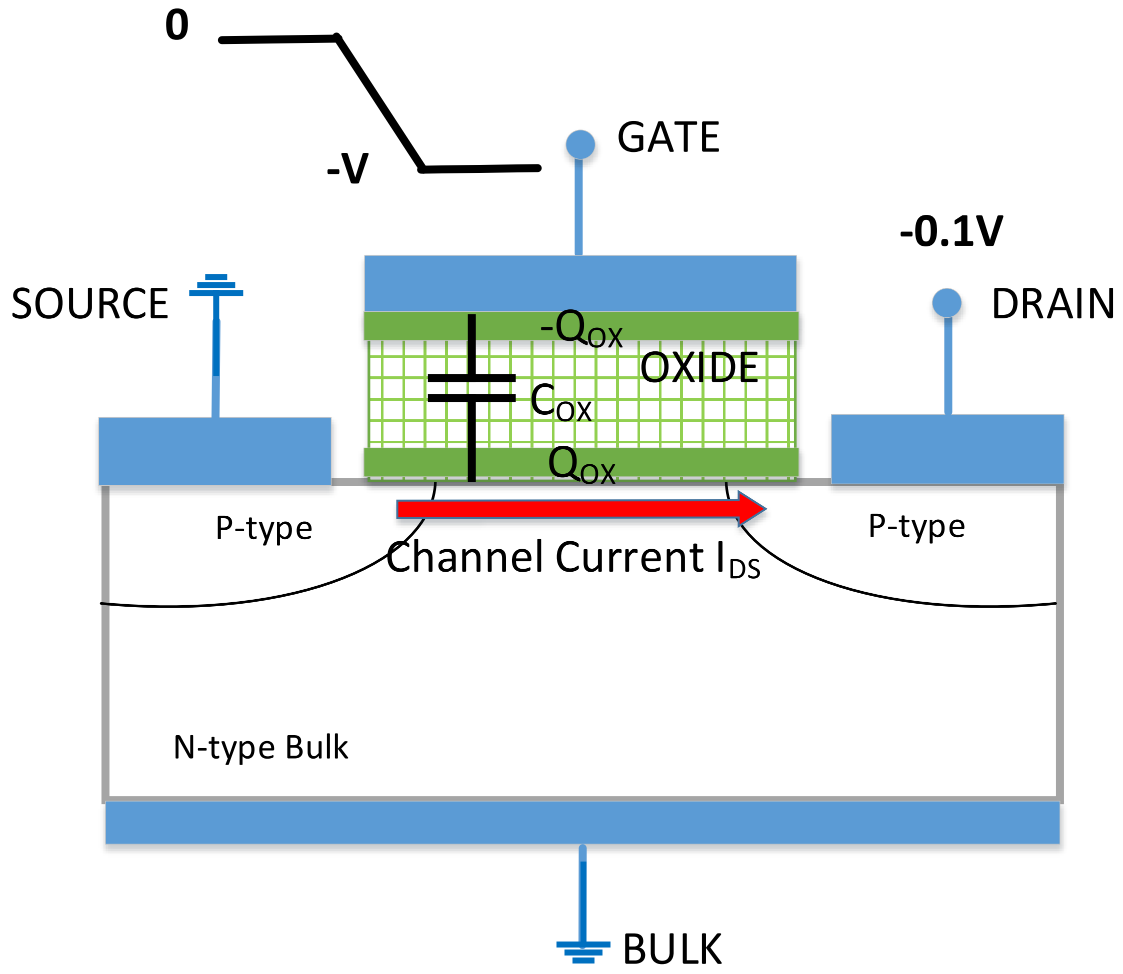
- RADFET Sensitivity Review
- How to increase RADFET Sensitivity
  - Geometry
  - Material
  - Readout

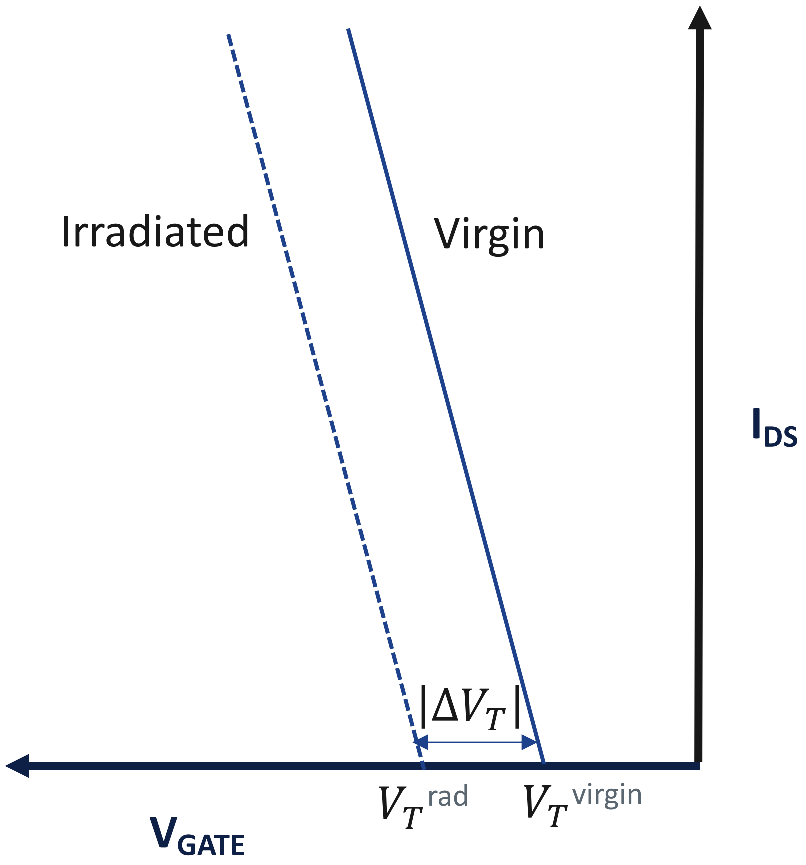
How is biased RADFET sensitive to radiation?



Tim Oldham, Basic Mechanisms of TID and DDD response in MOS and Bipolar Microelectronics, IEEE NSREC Course 2011

RADFET – PMOSFET Transistor

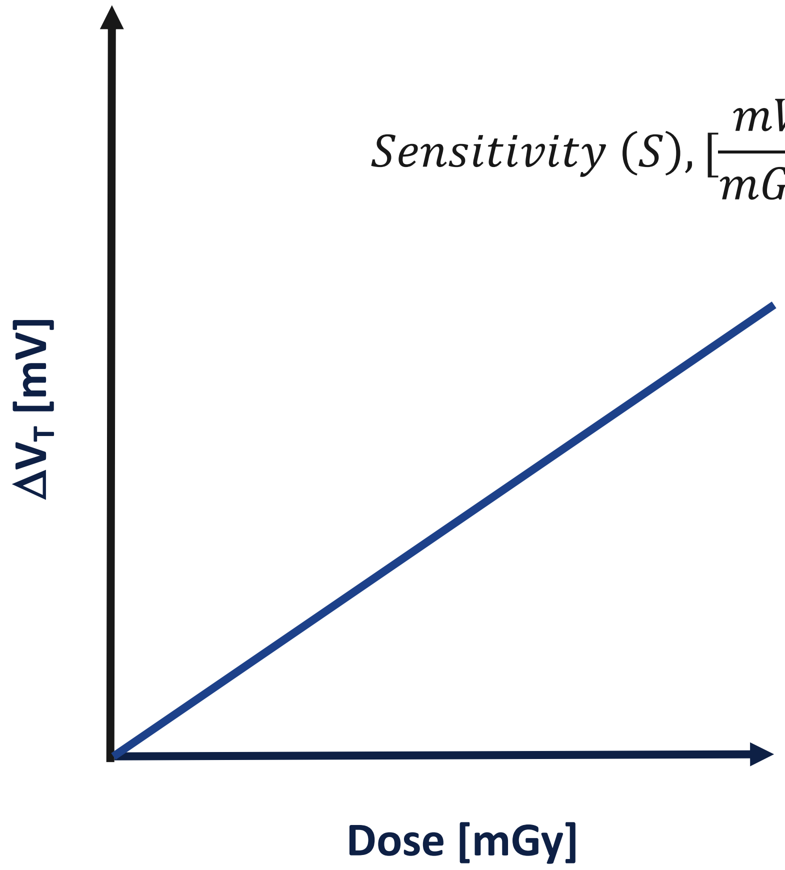


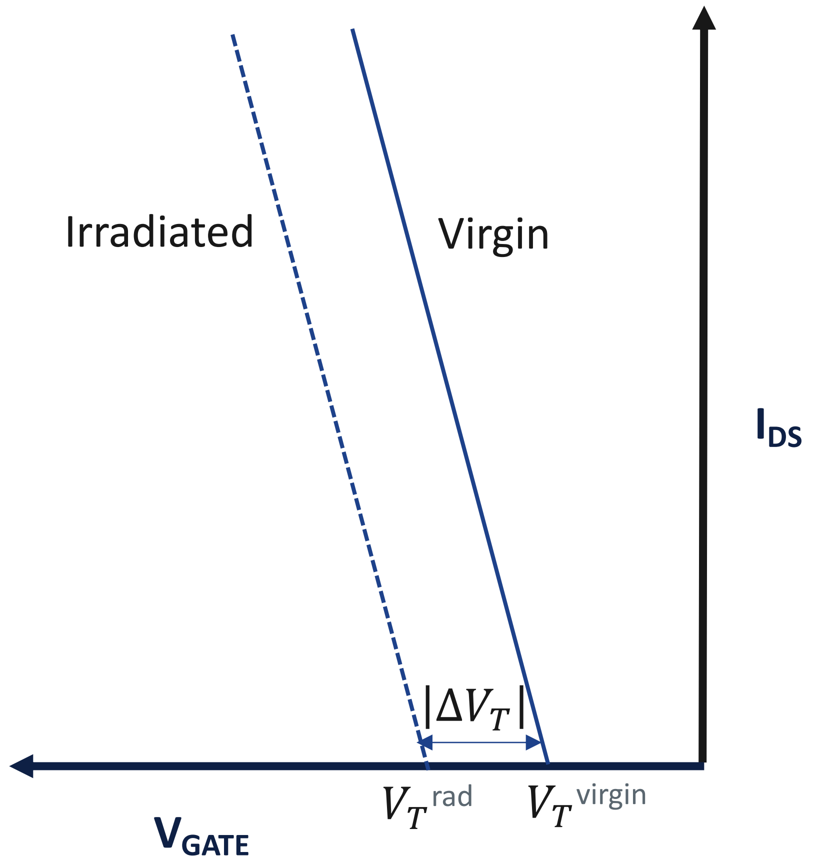


$$|\Delta V_{GATE}| = |\Delta V_T| = \frac{|\Delta Q_{OX}|}{C_{OX}}$$

RADFET – PMOSFET Transistor

$$Sensitivity\ (S), [\frac{mV}{mGy}] = \frac{\Delta V_T}{Dose}$$





$$|\Delta V_{GATE}| = |\Delta V_T| = \frac{|\Delta Q_{OX}|}{C_{OX}}$$

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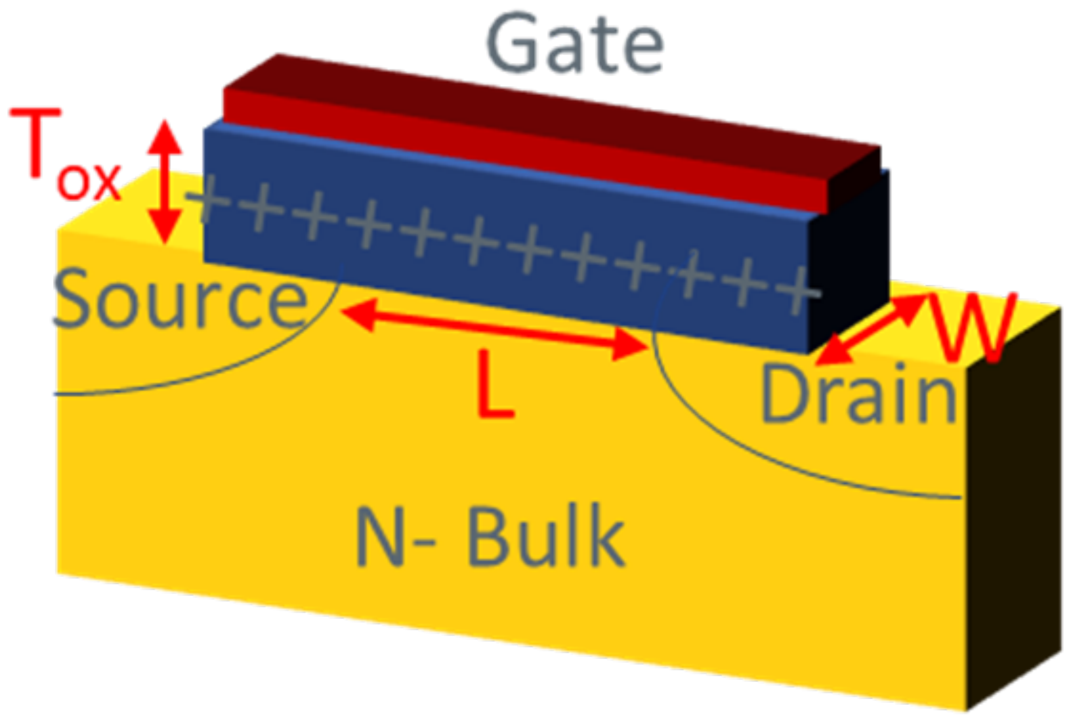
RADFET Geometry



Geometry Effect – Width, Length

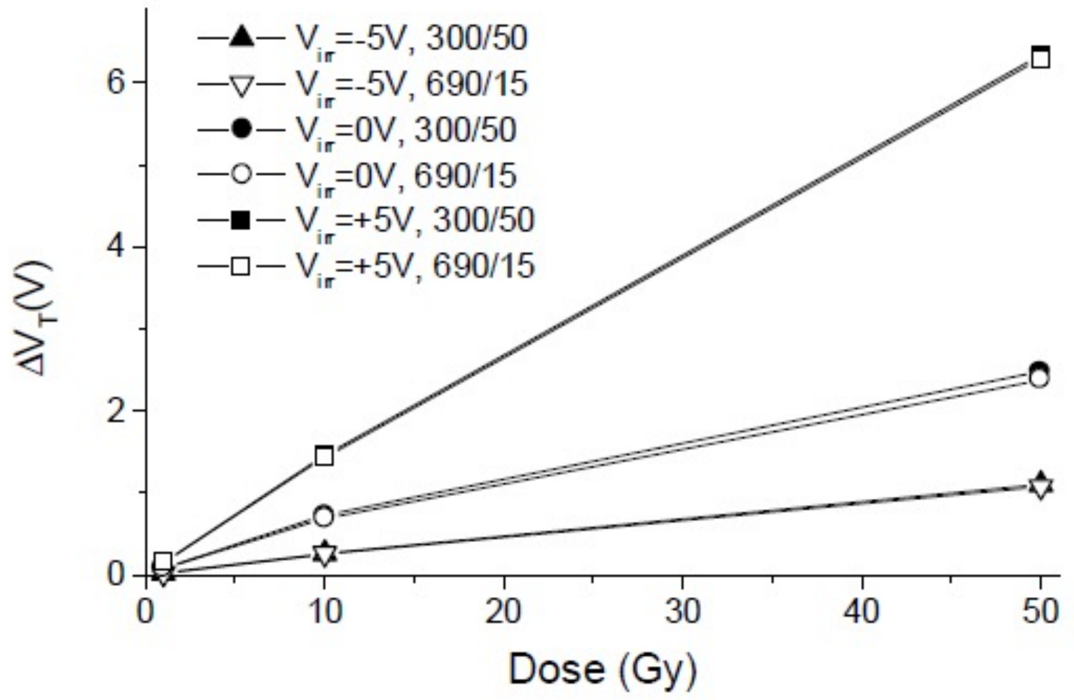


Fig. 3. ΔV_T during irradiation with negative, zero and positive gate bias for RADFETs with different W/L; W and L in μm.

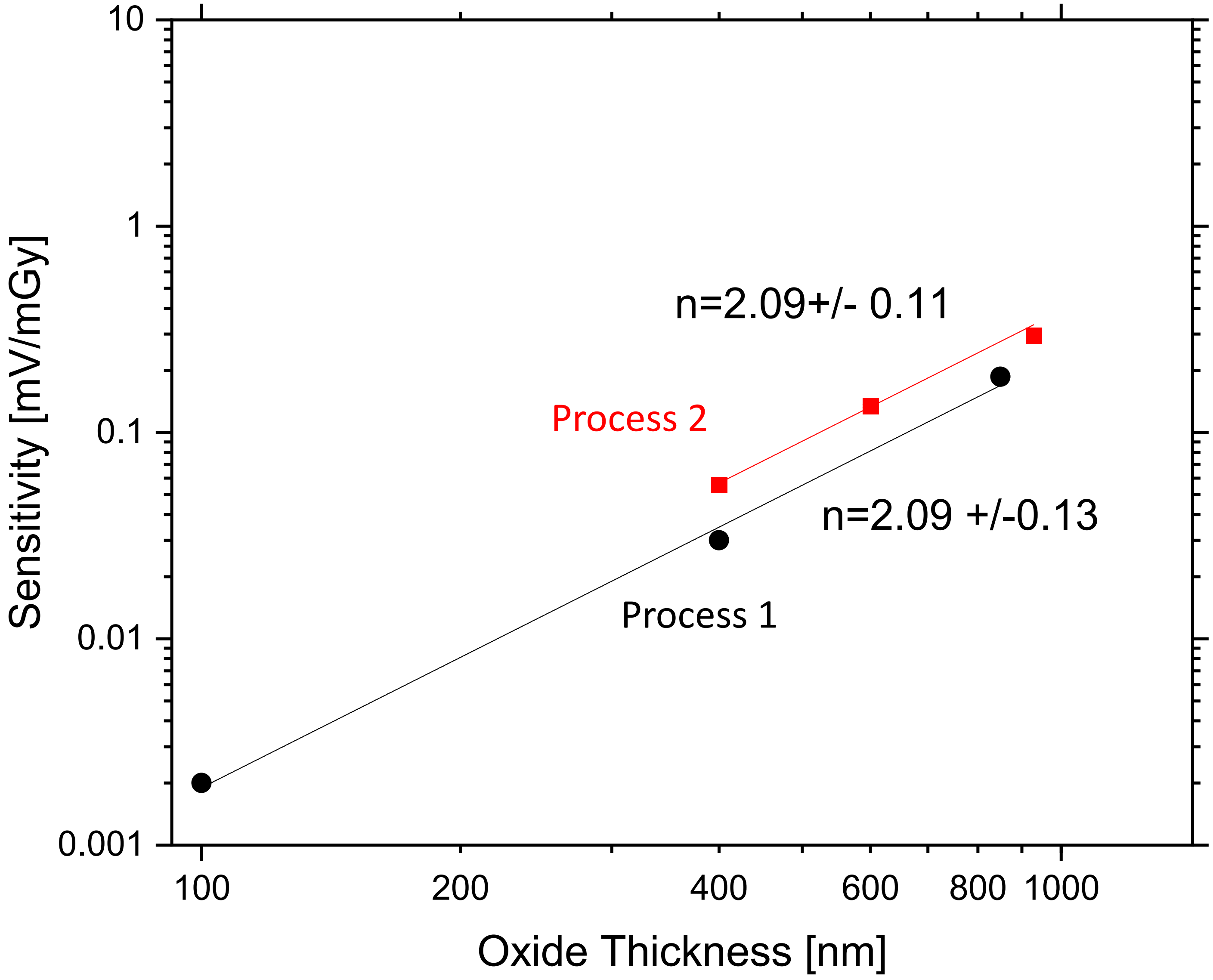
*MOSFET Area=W*L um²*

$$|\Delta V_T| = \frac{|\Delta Q_{OX}|}{C_{OX}} = \frac{A * Q'_{OX}}{\frac{A * \varepsilon_{OX}}{T_{OX}}} = \frac{Q'_{OX} * T_{OX}}{\varepsilon_{OX}}$$

➢ **Uniform charge trapping in W and L dimension**

A. Jaksic, G. Ristic, M. Pejovic, A. Mohammadzadeh and W. Lane, "Characterisation of radiation response of 400 nm implanted gate oxide RADFETs," 2002 23rd International Conference on Microelectronics. Proceedings (Cat. No.02TH8595), 2002, pp. 727-730 vol.2, doi: 10.1109/MIEL.2002.1003360.

T_{ox} Dependence– Passive (0V during irradiation)

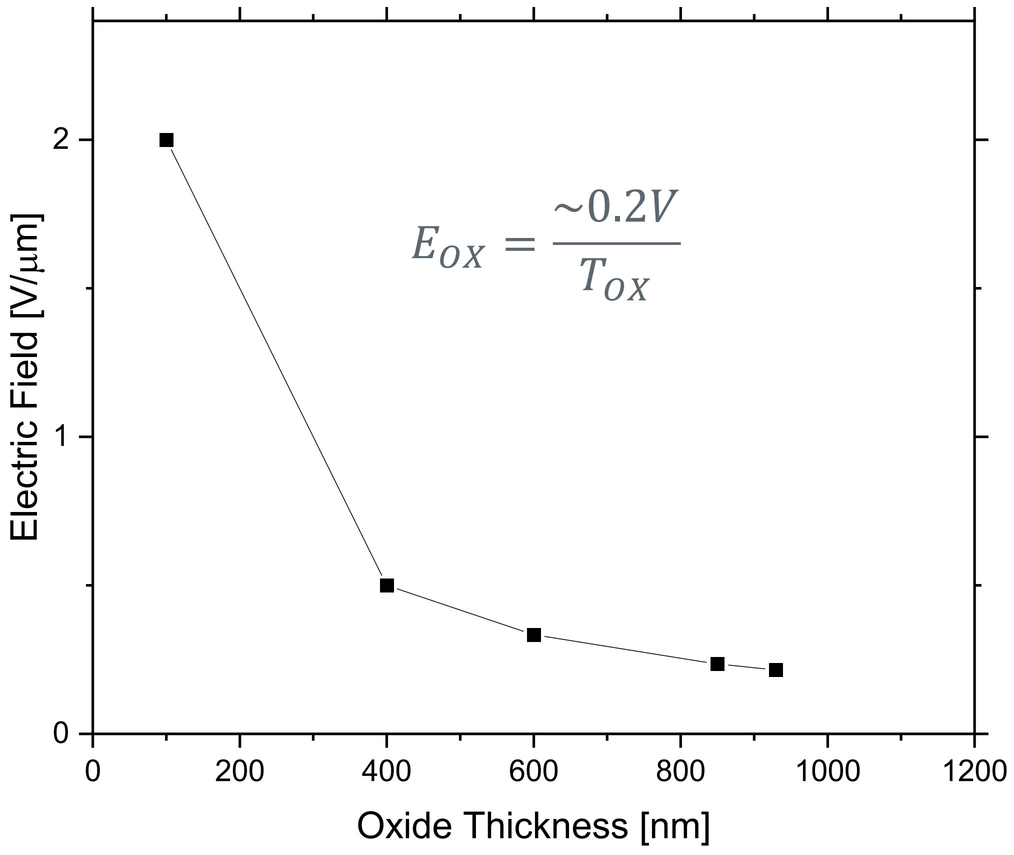


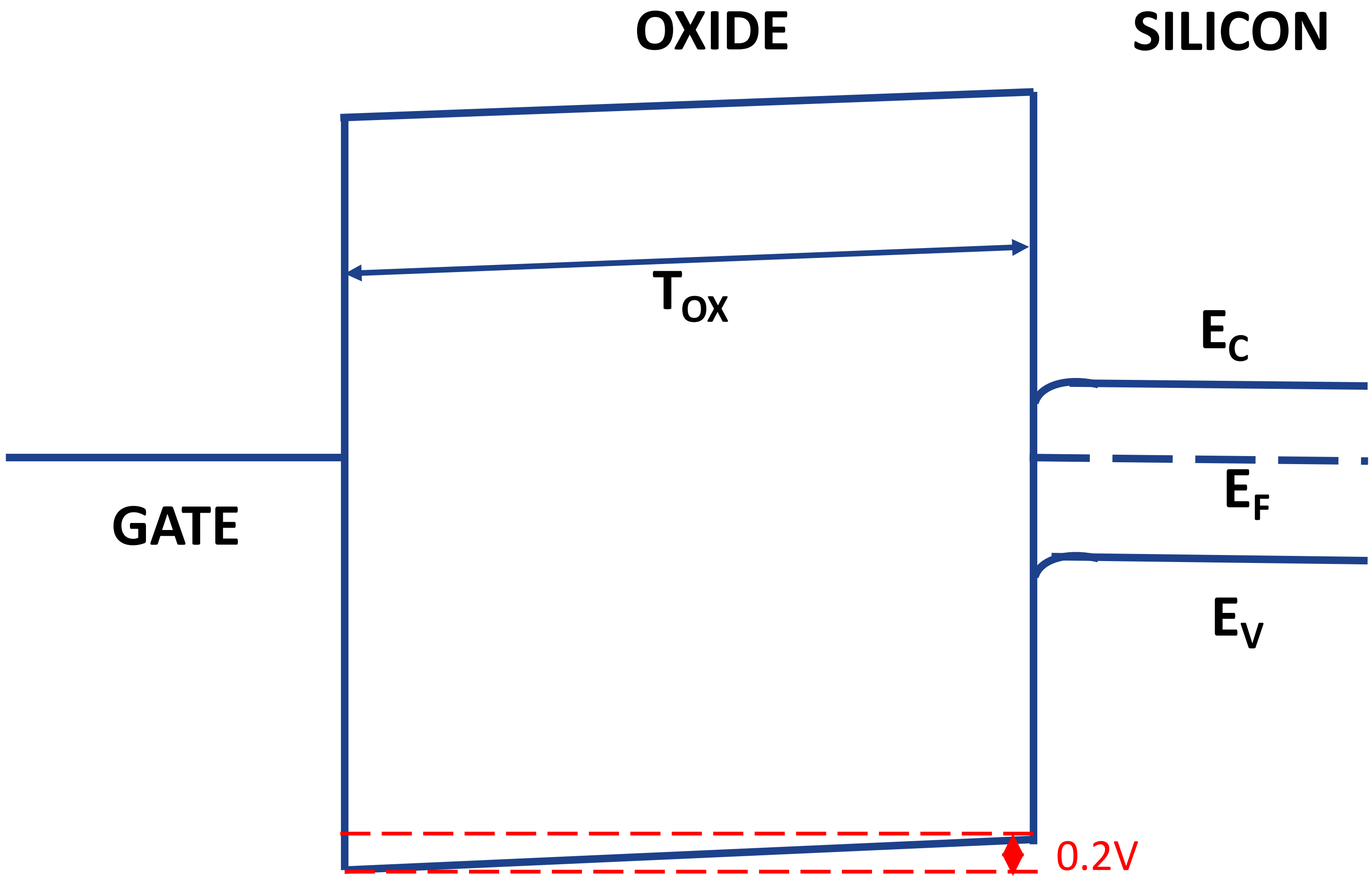
$$Sensitivity\ (S) \approx A * T_{OX}^{2}$$

Sensitivity measured in linear regime

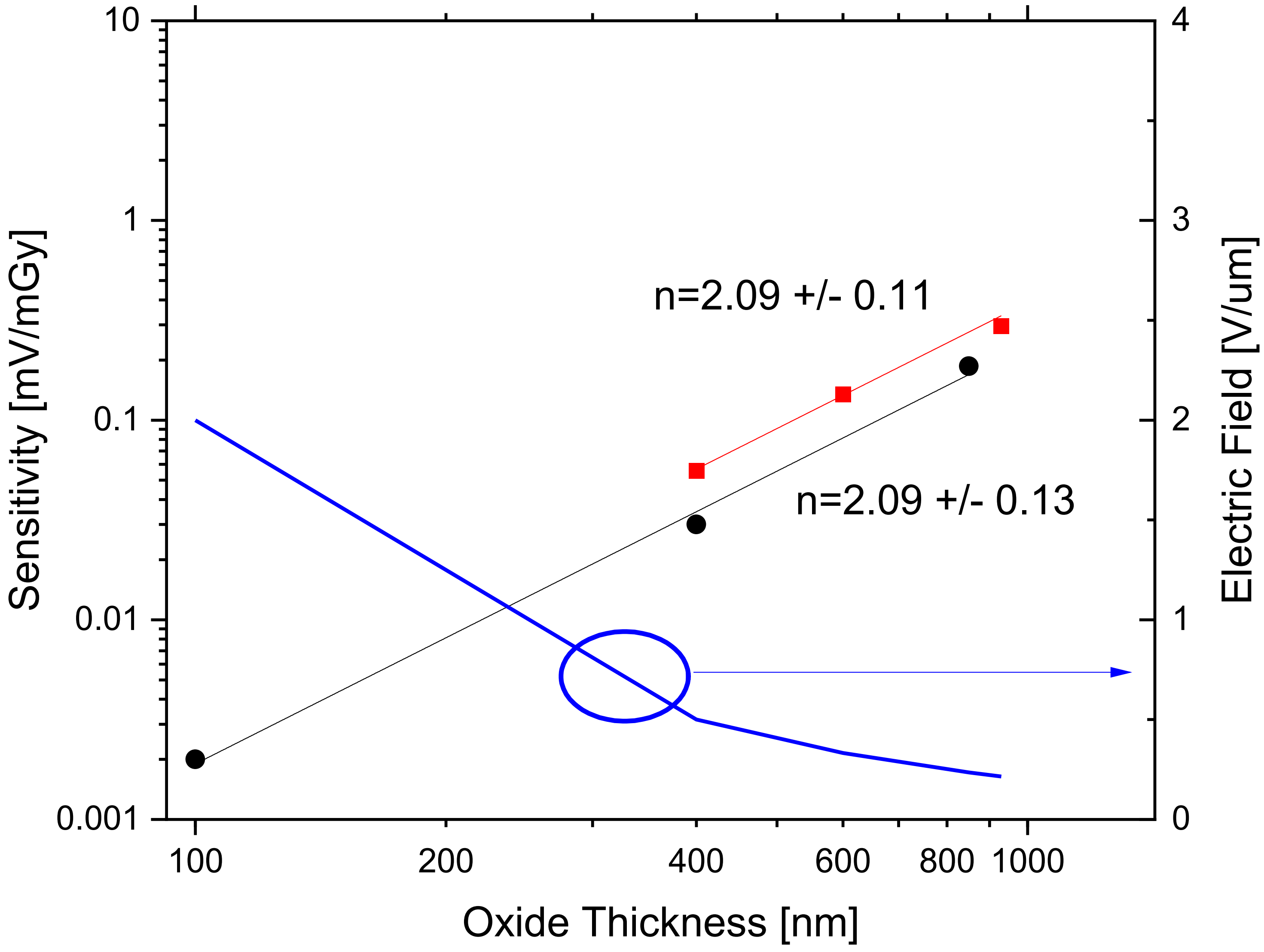
Co60 source in Vinca except for one expt @ 6MV

Electric Field in Passive RADFET @0V

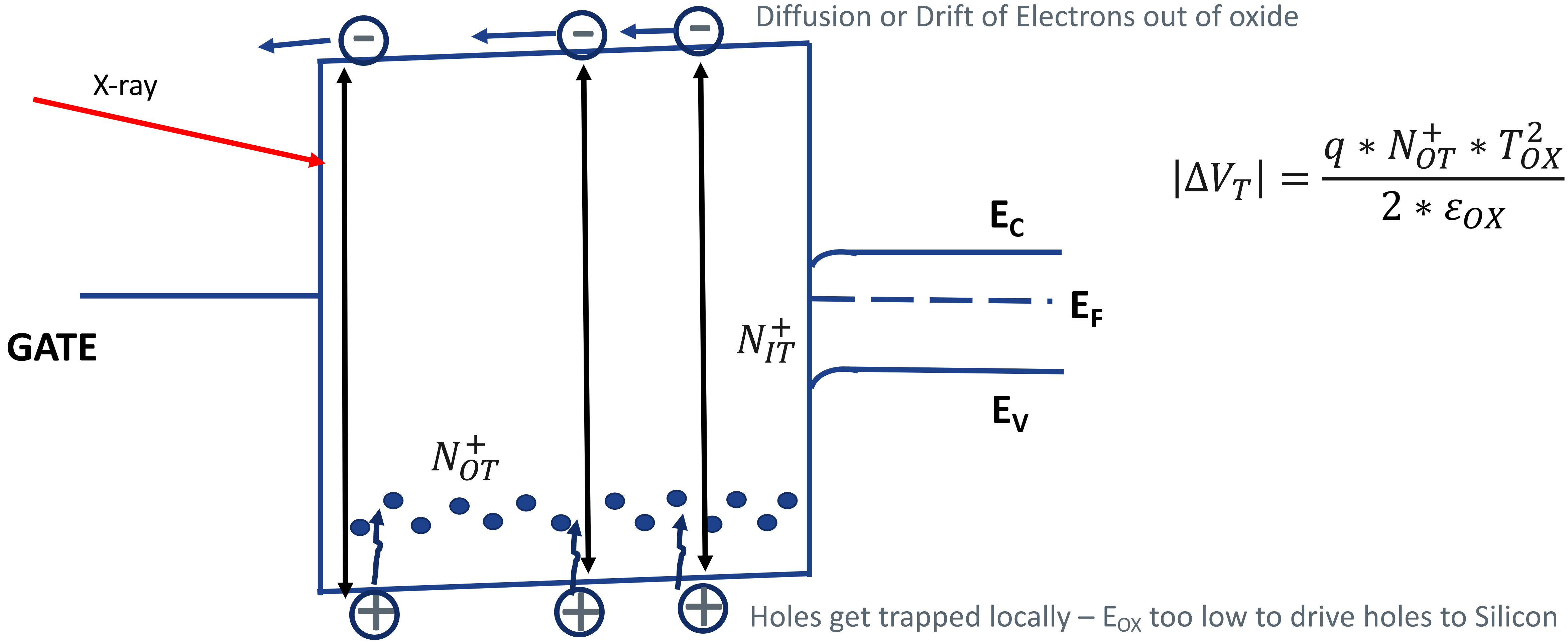




What is causing Sensitivity increase?



Passive RADFET Model



$$|\Delta V_T| = \frac{q * N_{OT}^{+} * T_{OX}^{2}}{2 * \varepsilon_{OX}}$$

- ➢ Geometry results indicate uniform trapped charge generation over the volume of the dielectric at low doses

R. C. Hughes, "Theory of response of radiation sensing field effect transistors", Journal of Applied Physics 58, 1375-1379 (1985) https://doi.org/10.1063/1.336110

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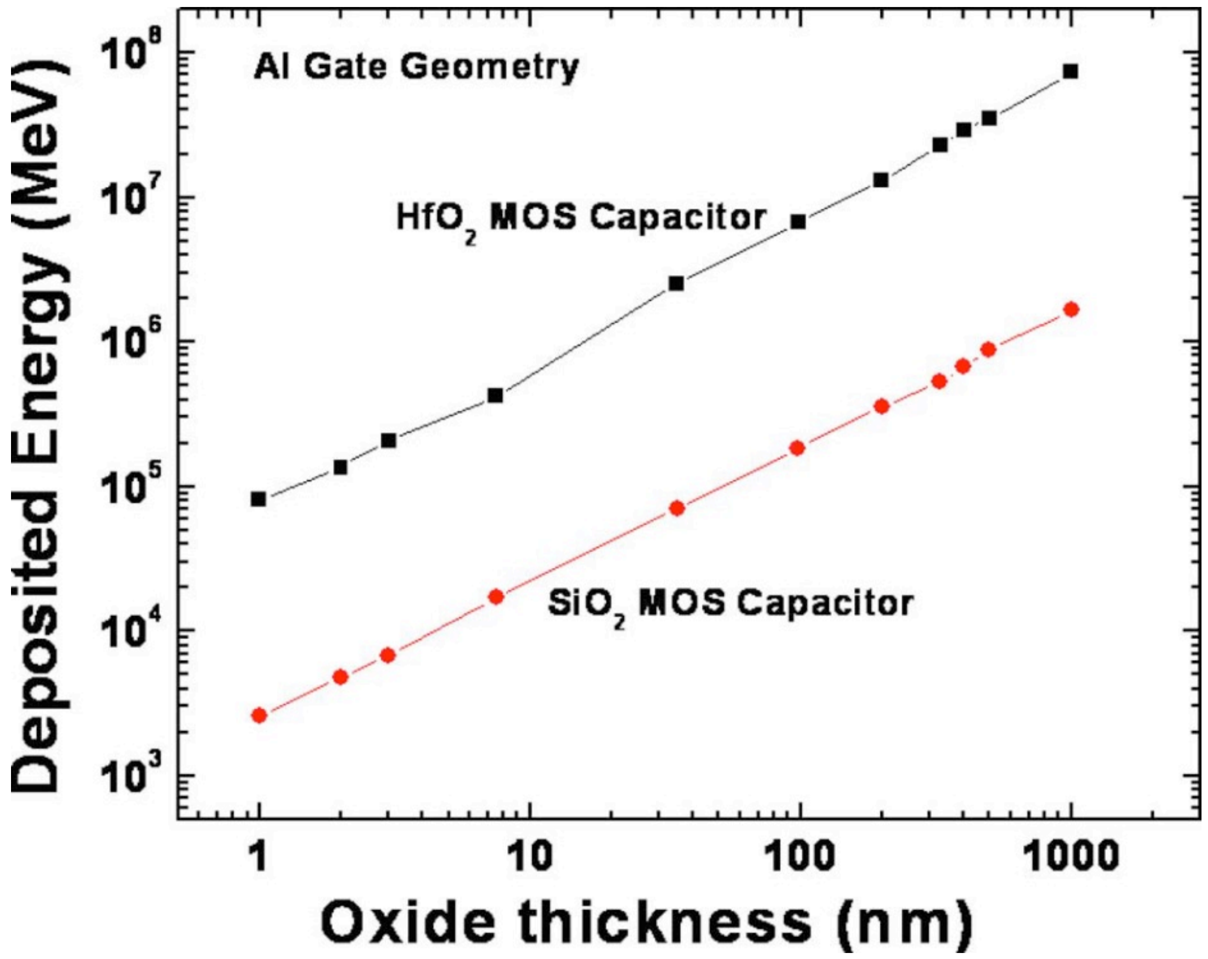
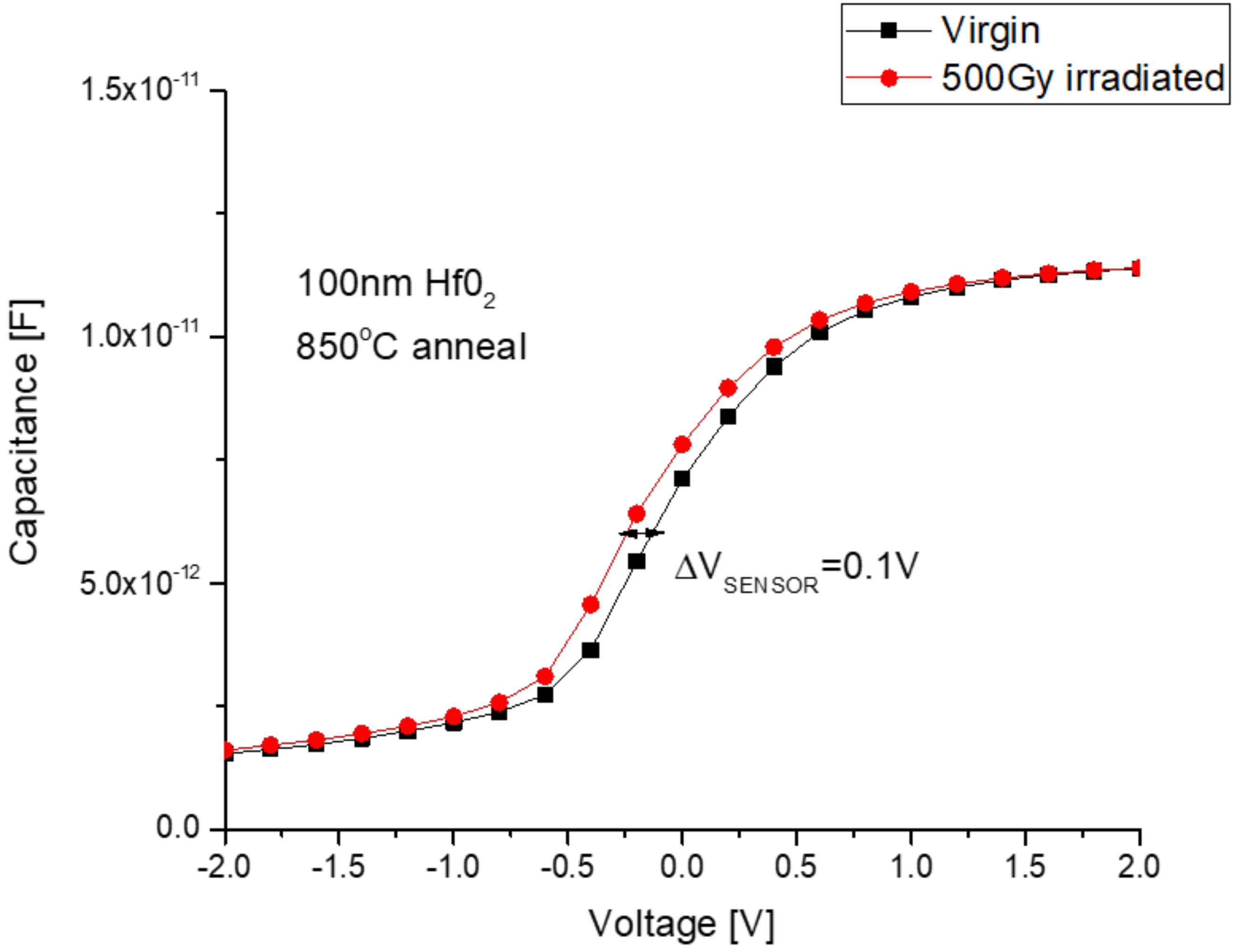
High k Dielectrics



More energy is deposited in $Hf0_2$ than SiO_2 @400kev

A. Dasgupta, D. M. Fleetwood, R. A. Reed, R. A. Weller, M. H. Mendenhall and B. D. Sierawski, "Dose Enhancement and Reduction in SiO 2 and Hih- κ MOS Insulators," in *IEEE Transactions on Nuclear Science*, vol. 57, no. 6, pp. 3463-3469, Dec. 2010

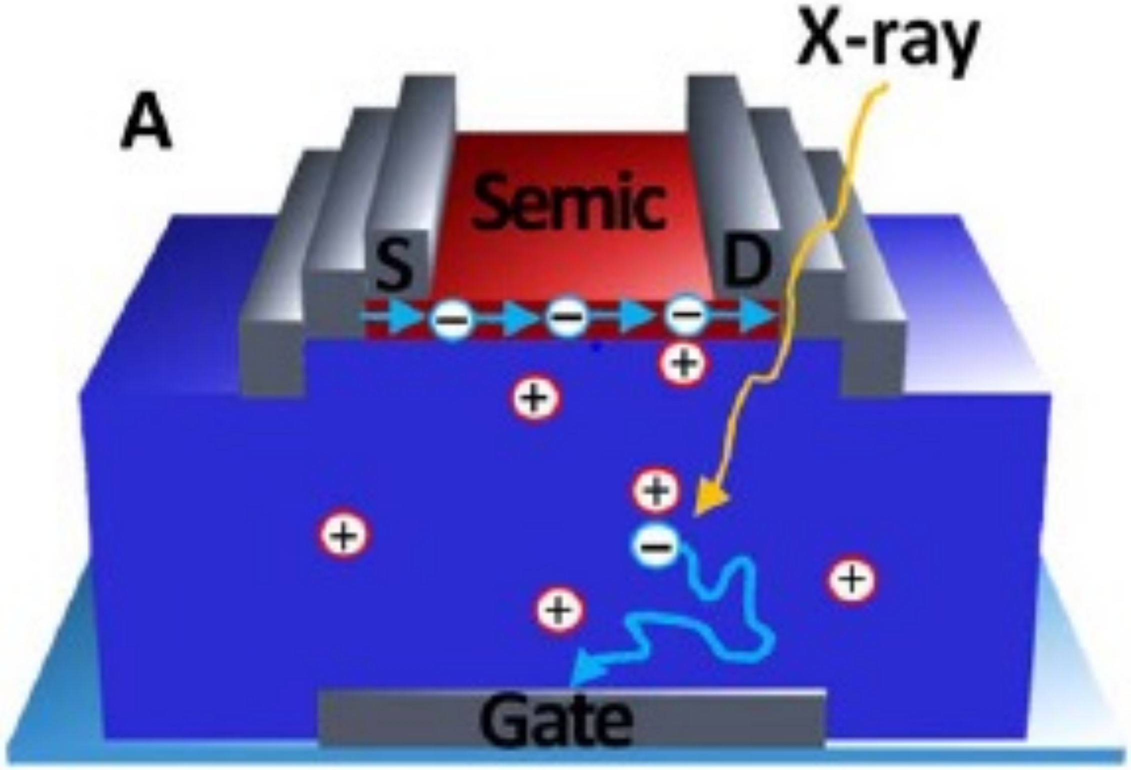
Tyndall results



50% Q_{ox} vs SiO_2

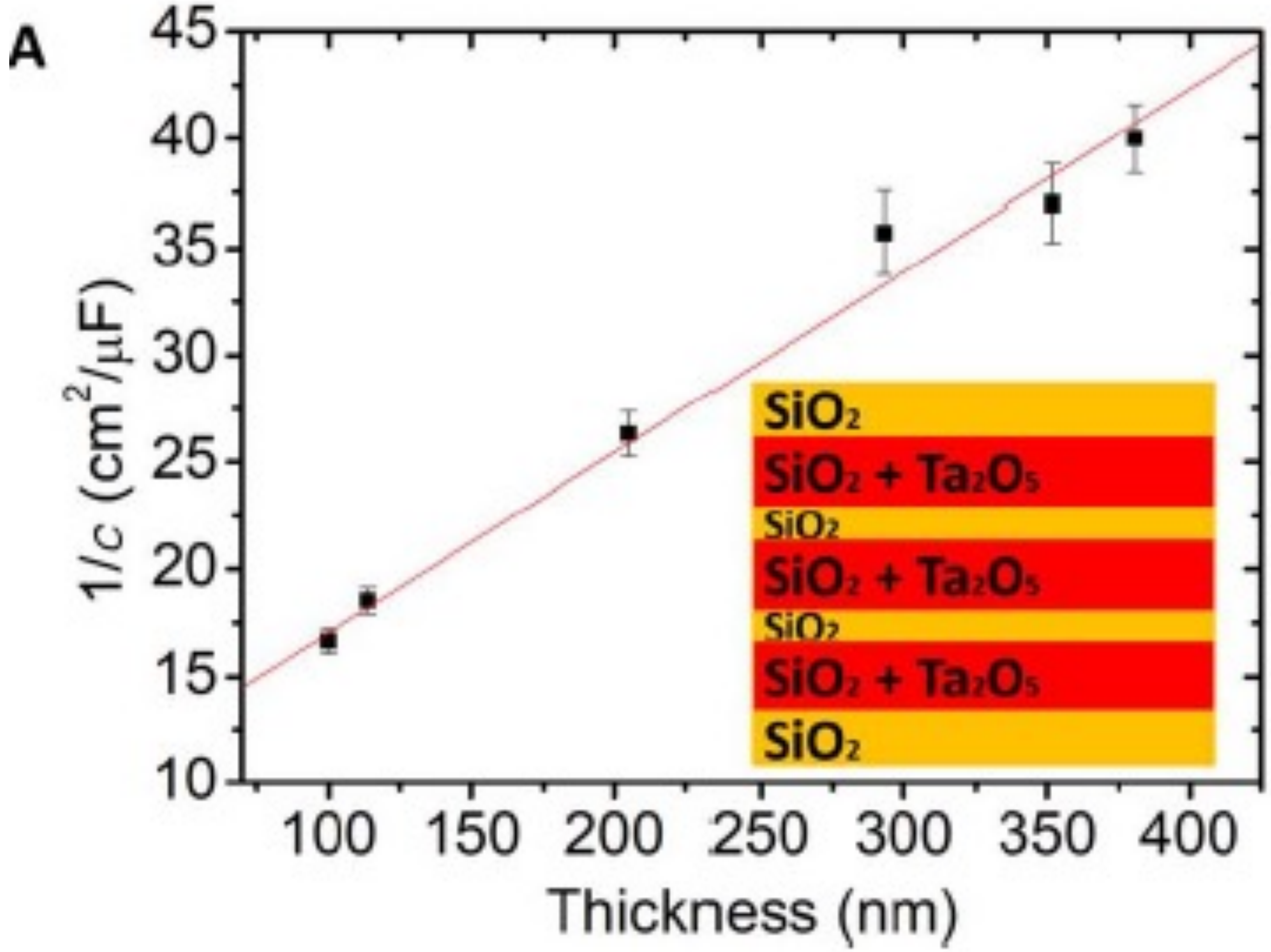
Co60 source in Vinca

High k MOSFET (ROXFET)



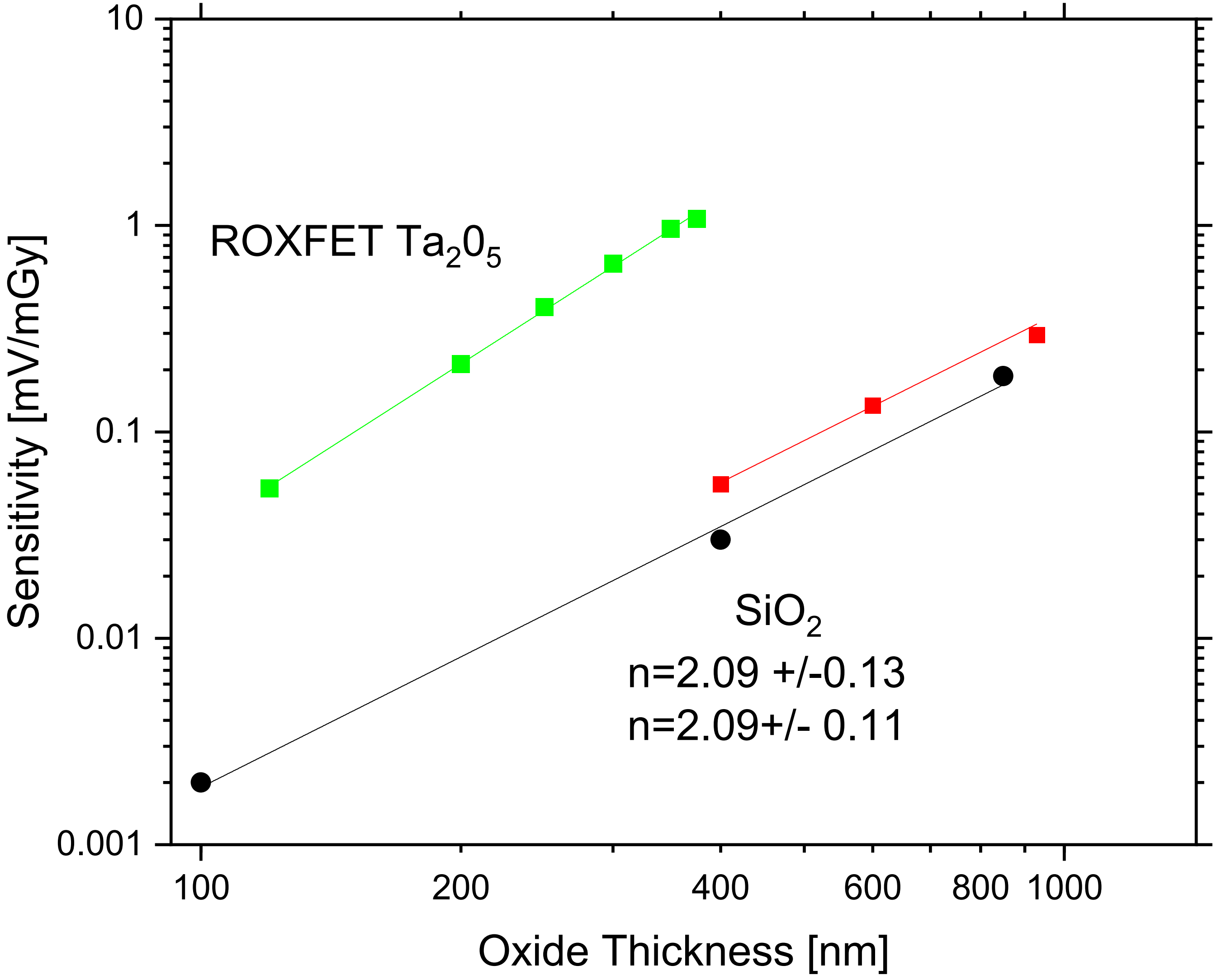
T. Cramer, I. Fratelli, P. Barquinha, A. Santa, C. Fernandes, F. D’Annunzio, C. Loussert, R. Martins, E. Fortunato, B. Fraboni, Passive radiofrequency x-ray dosimeter tag based on flexible radiation-sensitive oxide field-effect transistor. Sci. Adv. 4, eaat1825 (2018).

ROXFET High K Dielectric Stack



k =13.5

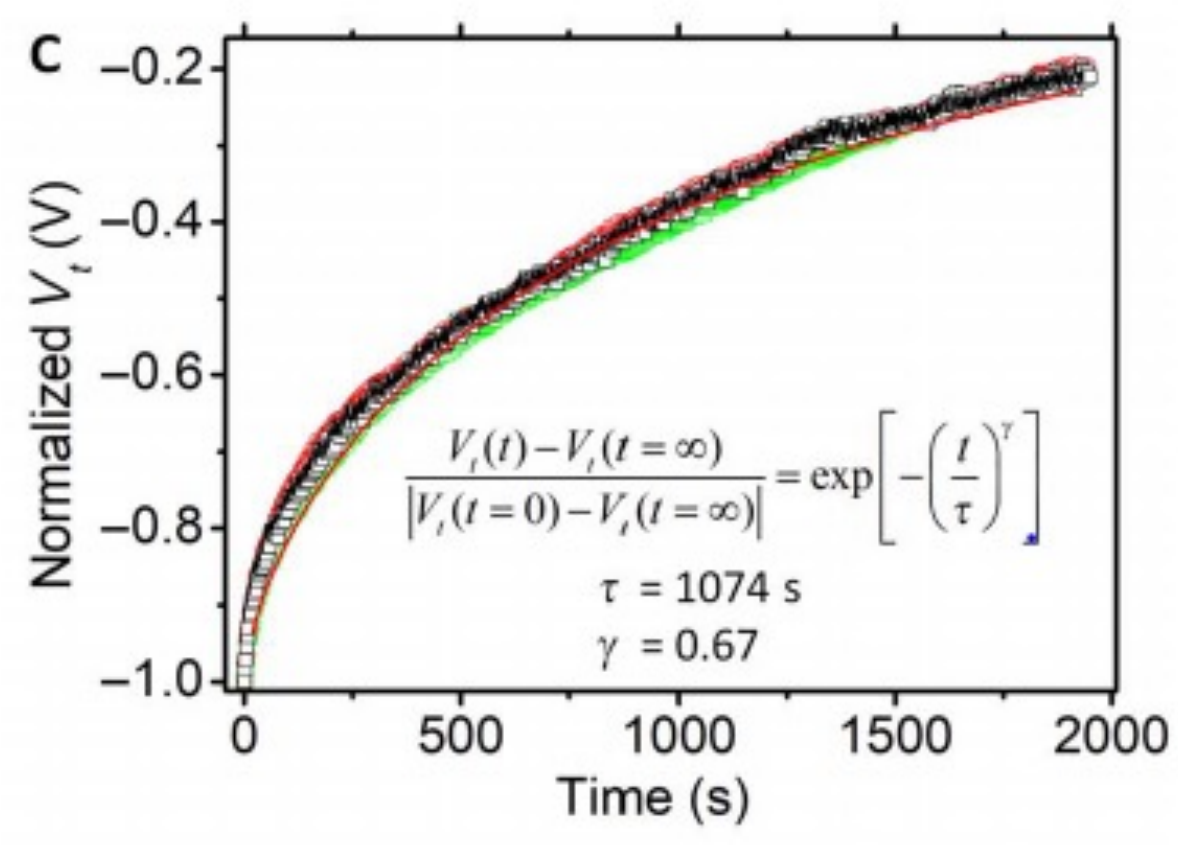
Sensitivity Comparison



- Published ROXFET sensitivity @35kV Xray
- I reduced by factor of 3 to estimate Co60 response

- >10 times increase in sensitivity versus RADFET

ROXFET Fading of Charge



80% of charge fades after 2000 seconds

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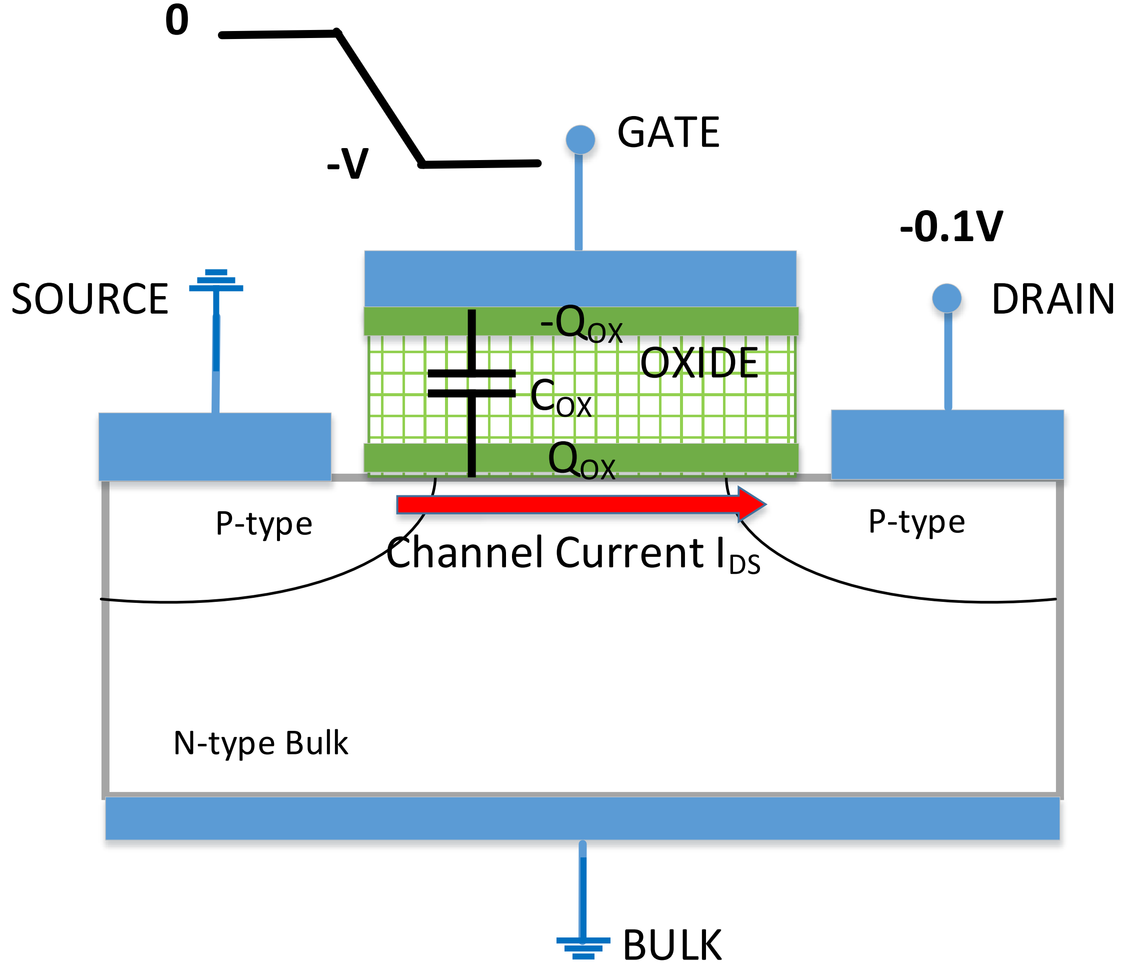
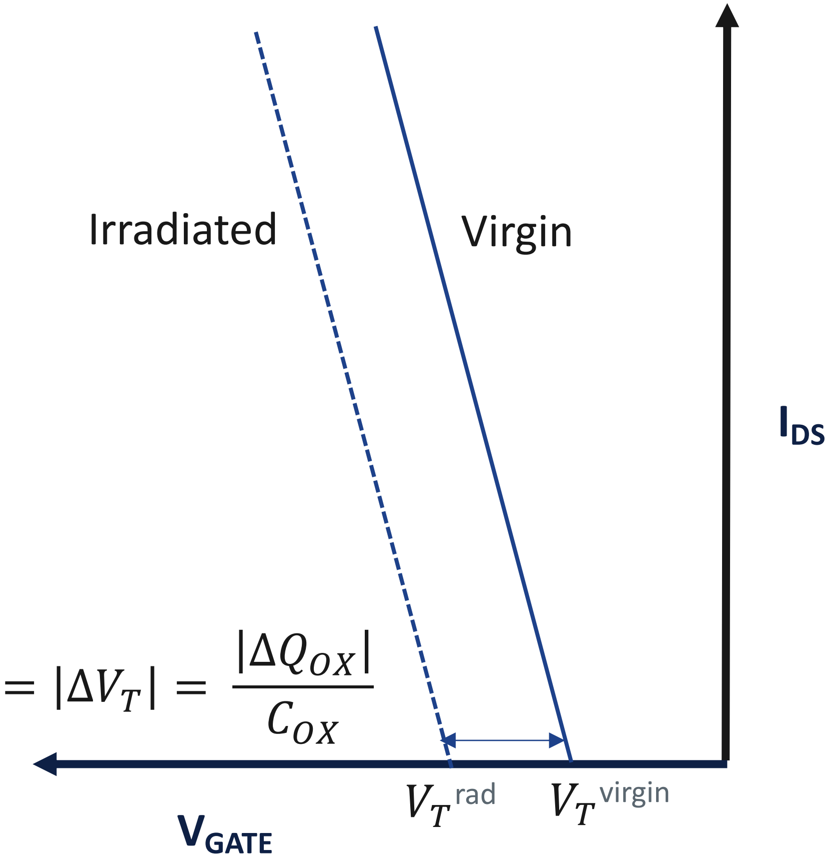
RADFET – PMOSFET Transistor

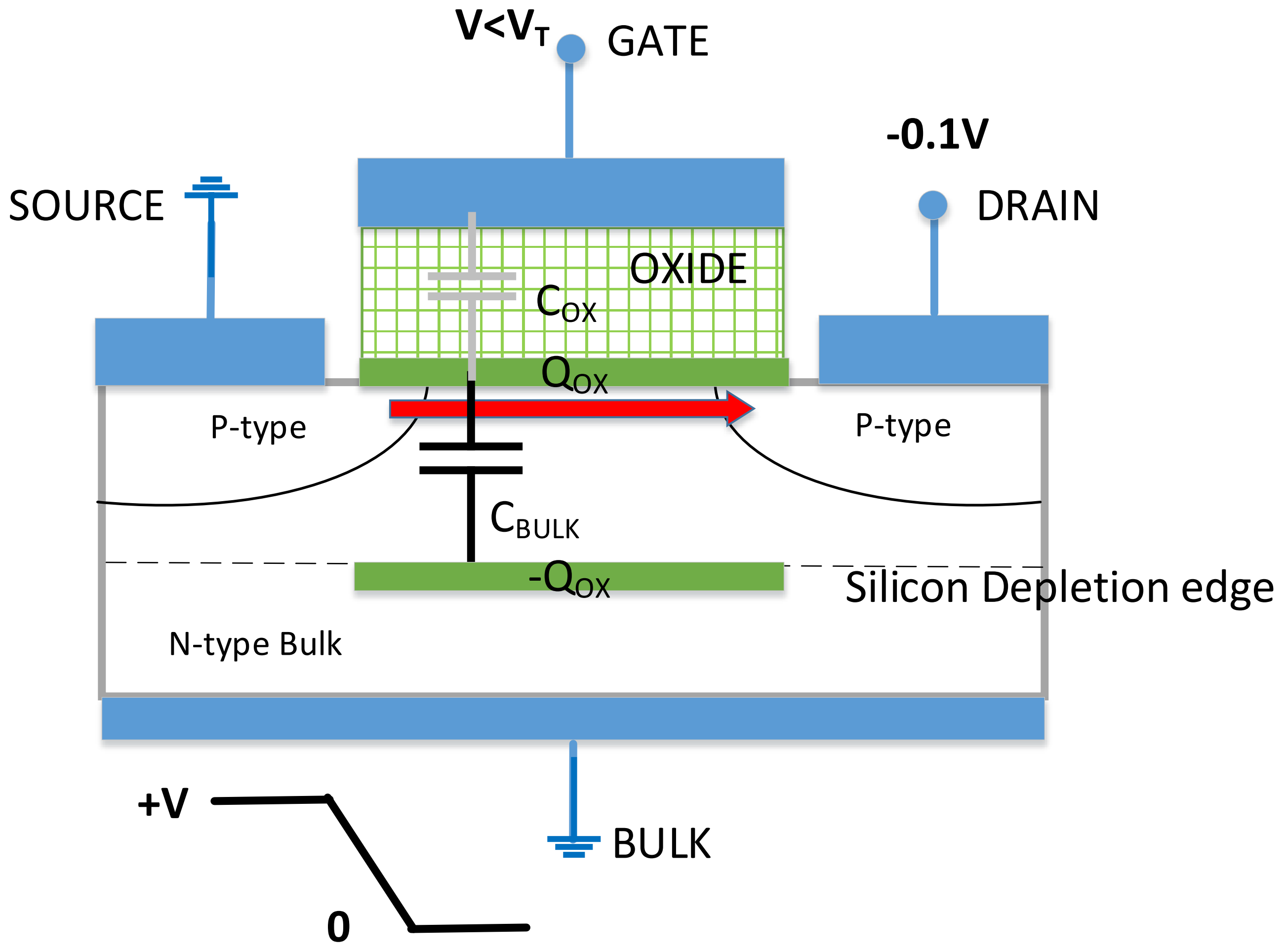


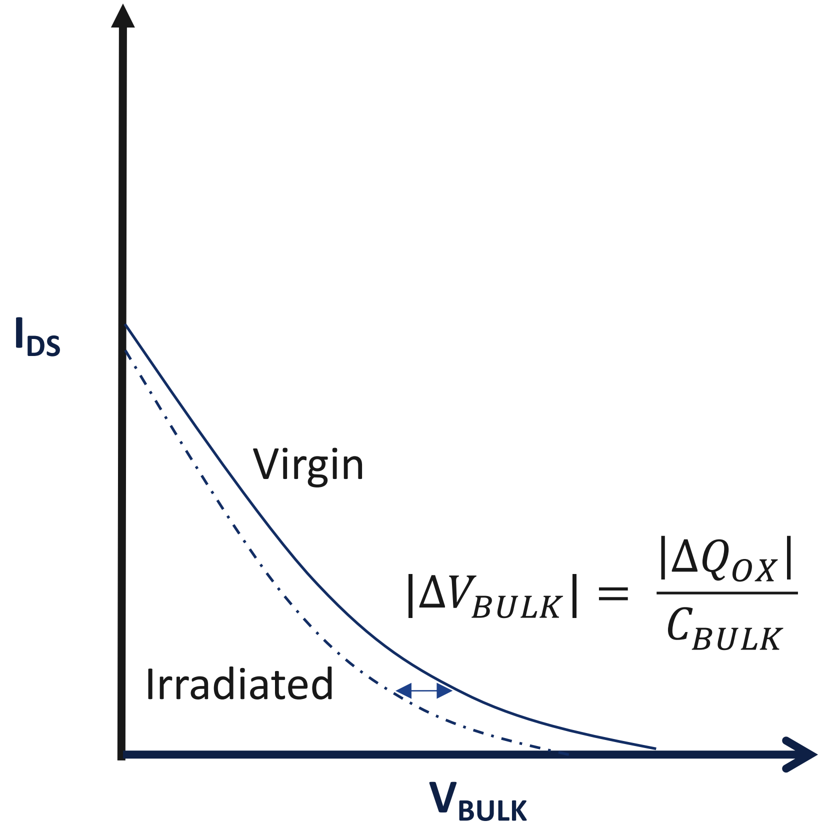


$$|\Delta V_{GATE}| = |\Delta V_T| = \frac{|\Delta Q_{OX}|}{C_{OX}}$$

$$Voltage\ Sensitivity\ (S), [\frac{mV}{mGy}] = \frac{\Delta V_T}{Dose}$$

Bulk Silicon as Back Gate ; Silicon as Dielectric

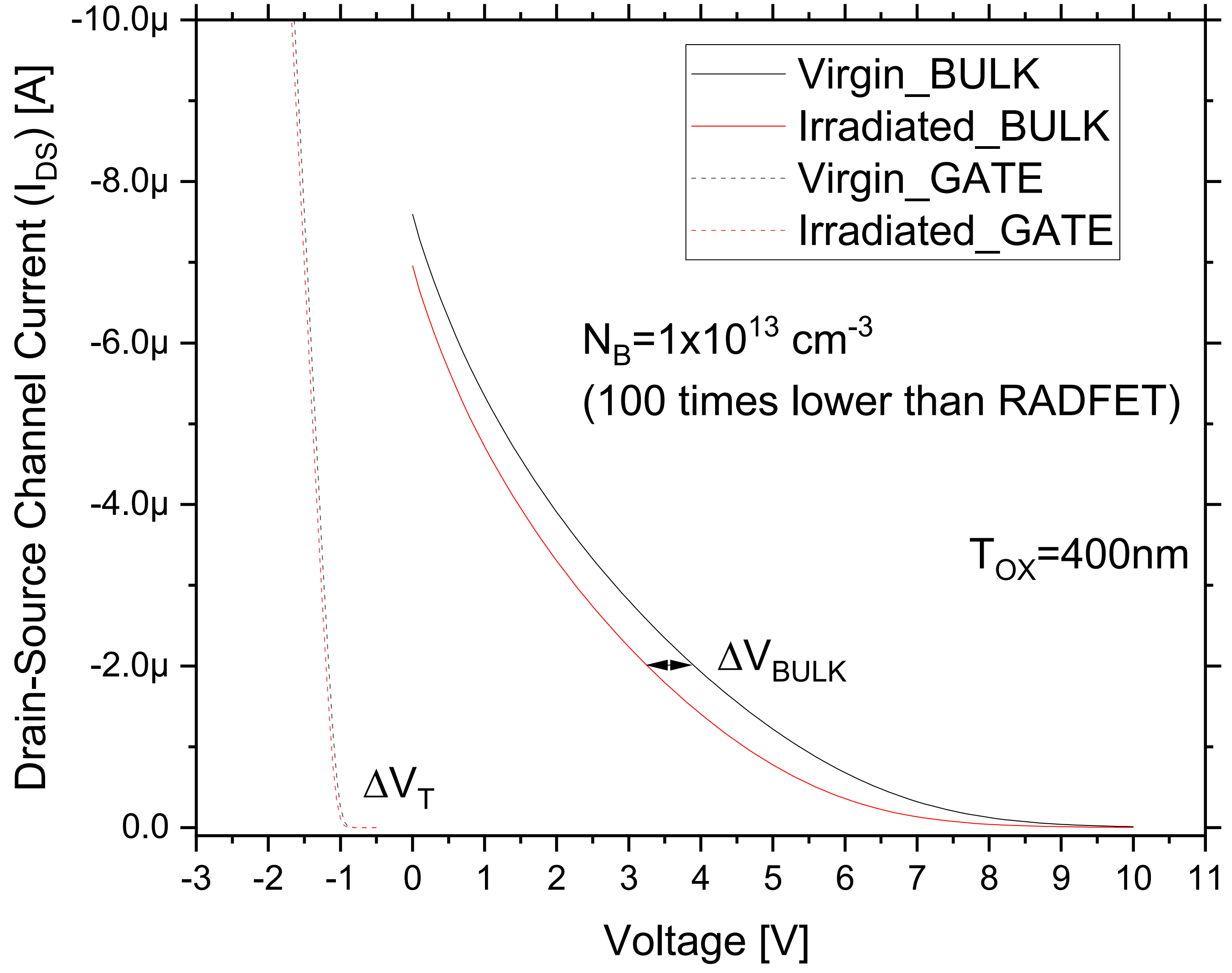




$$|\Delta V_{BULK}| = \frac{|\Delta Q_{OX}|}{C_{BULK}}$$

$$\text{@constant IDS ; } |\Delta V_{BULK}| = \frac{|\Delta Q_{OX}|}{C_{BULK}} = \frac{|\Delta Q_{OX}|}{\sqrt{\frac{q\epsilon_s N_{BULK}}{2V_{BULK}}}}$$

Numerical Simulations

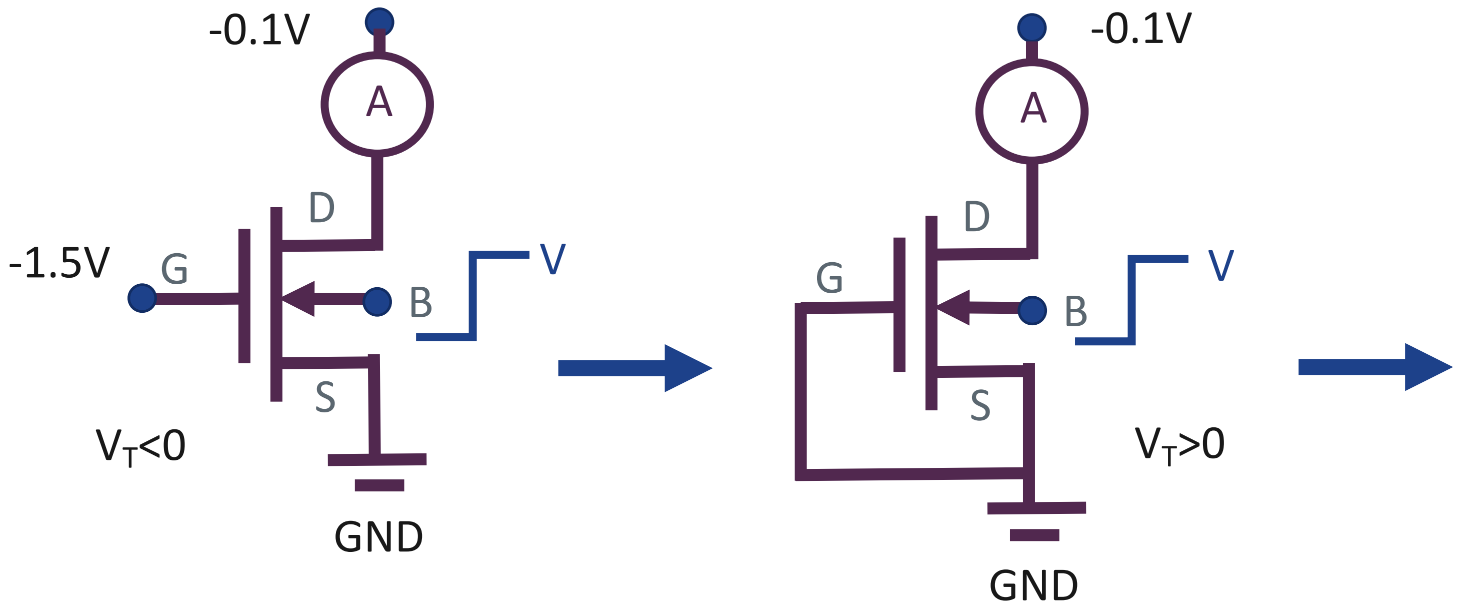


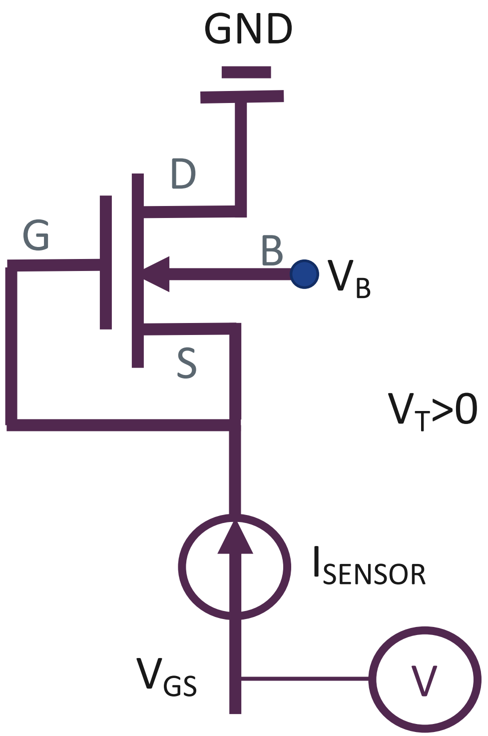
$$|\Delta V_B| = \frac{|\Delta Q_{OX}|}{C_{BULK}} = \frac{|\Delta Q_{OX}|}{\sqrt{\frac{q\epsilon_s N_{BULK}}{2V_{BULK}}}}$$

$$|\Delta V_G| = |\Delta V_T| = \frac{|\Delta Q_{OX}|}{C_{OX}}$$

- Using Bulk as Gate with low N_B
  - ➢ Good charge sensor
  - ➢ Poor transistor

Device/Circuit Architecture





RADFET: V_T=-1V

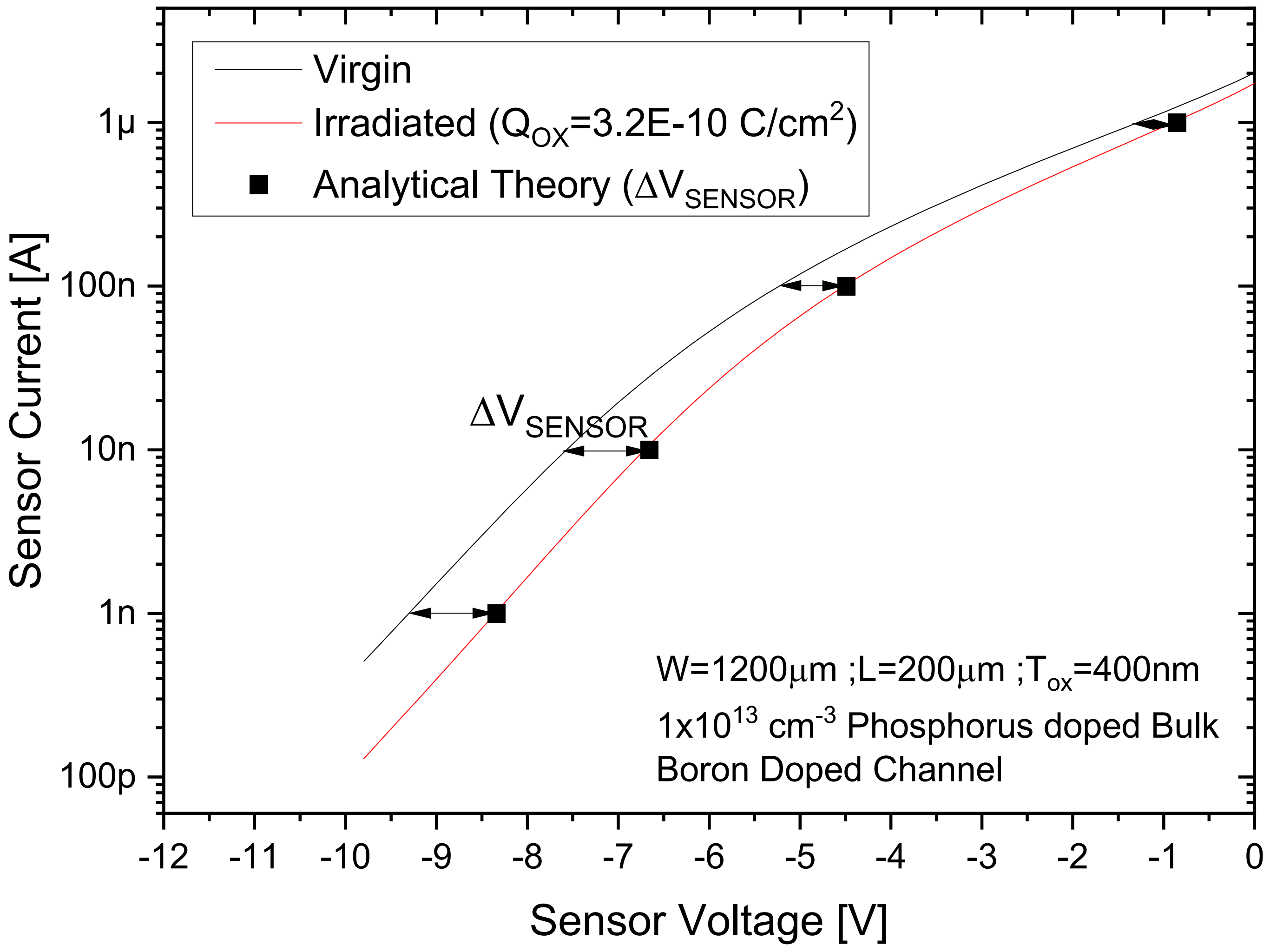
PMOS Charge Sensor: V_T>0

Channel Doping Design

- $V_{GS} < V_T$ to ensure channel current

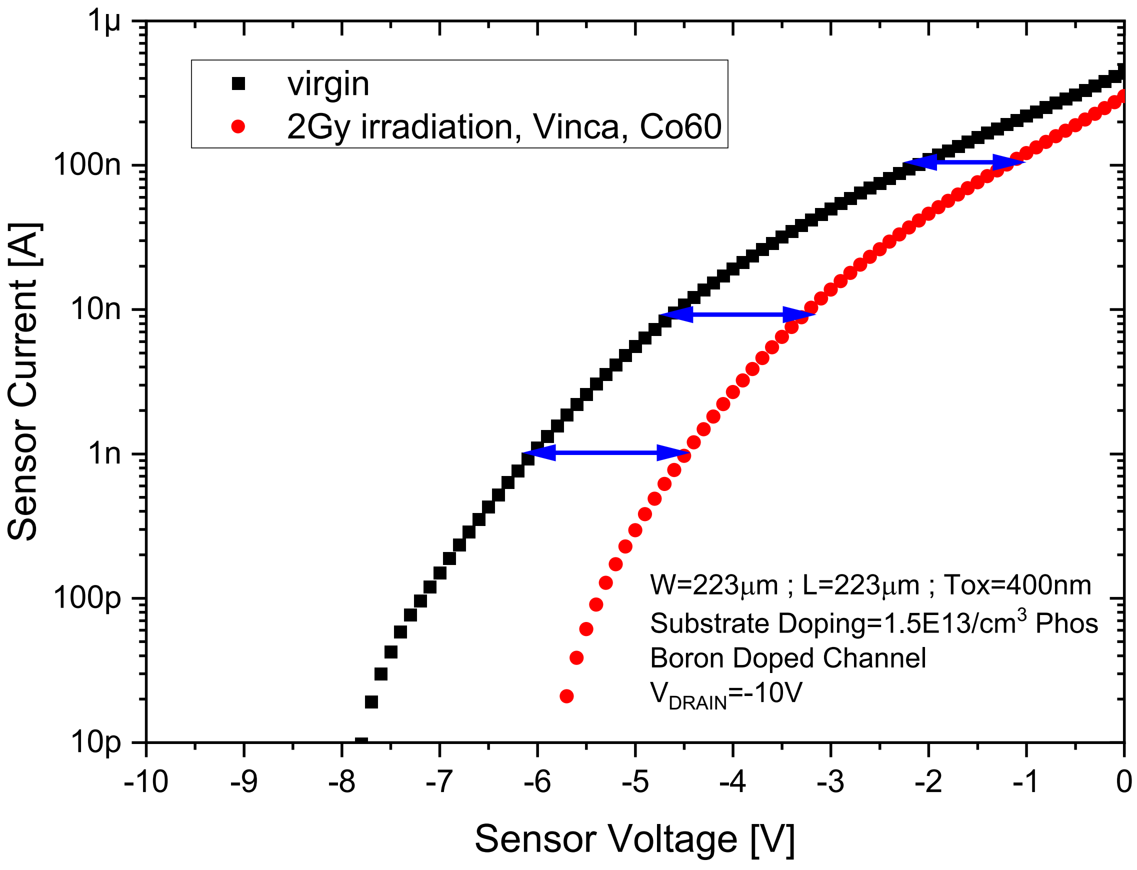
$$|\Delta V_{GS-B}| = |\Delta V_{SENSOR}| = \frac{|\Delta Q_{OX}|}{C_{BULK}}$$

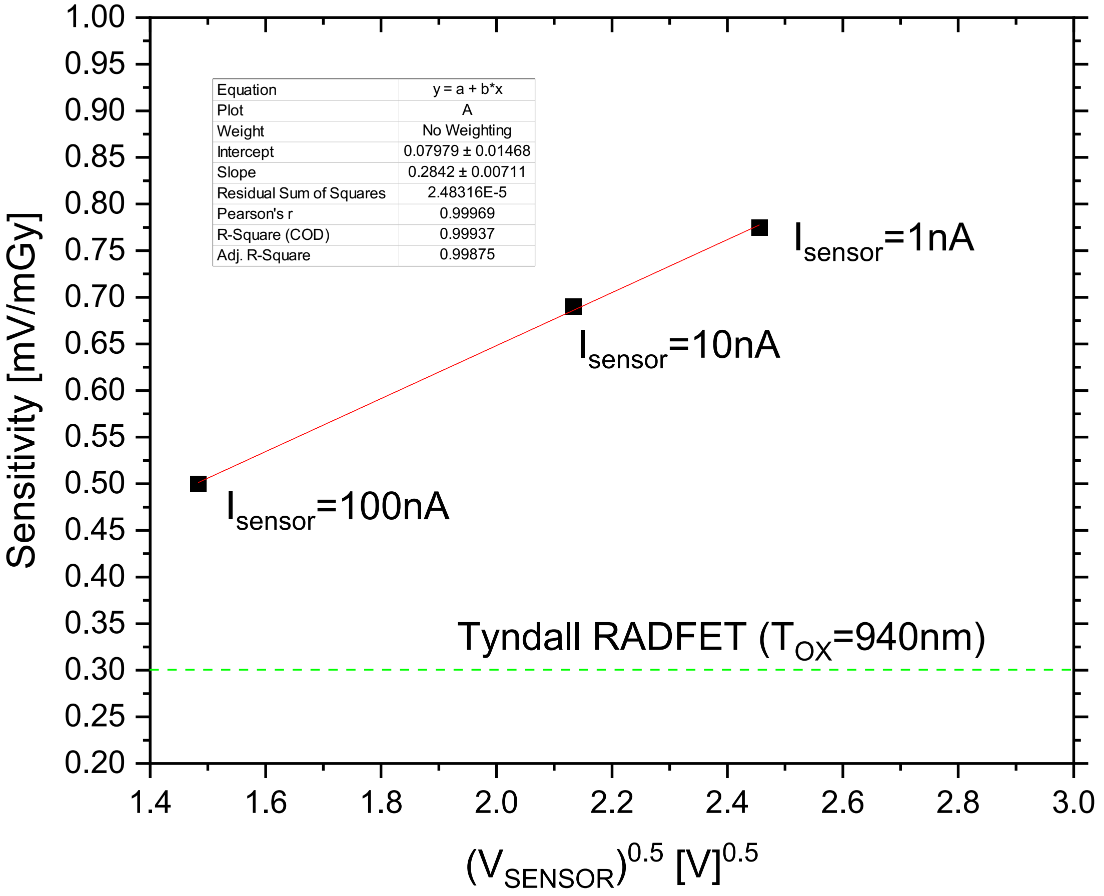
Analytical Theory vs Numerical Simulation



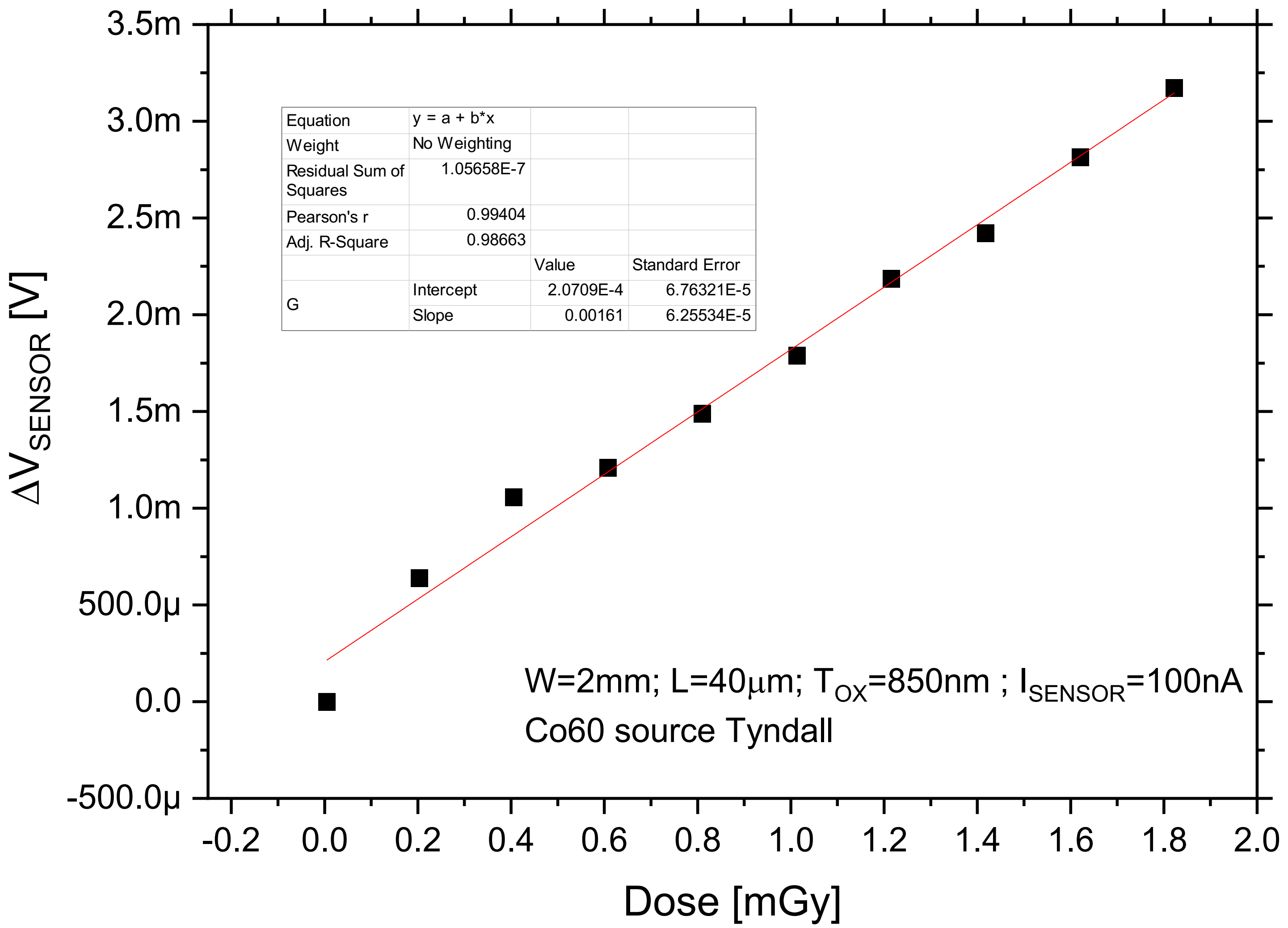
$$|\Delta V_{SENSOR}| = \frac{|\Delta Q_{OX}|}{C_{BULK}} = \frac{|\Delta Q_{OX}|}{\sqrt{\frac{q\epsilon_s N_{BULK}}{2V_{SENSOR}}}}$$

Irradiation experiment (T_{OX}=400nm)



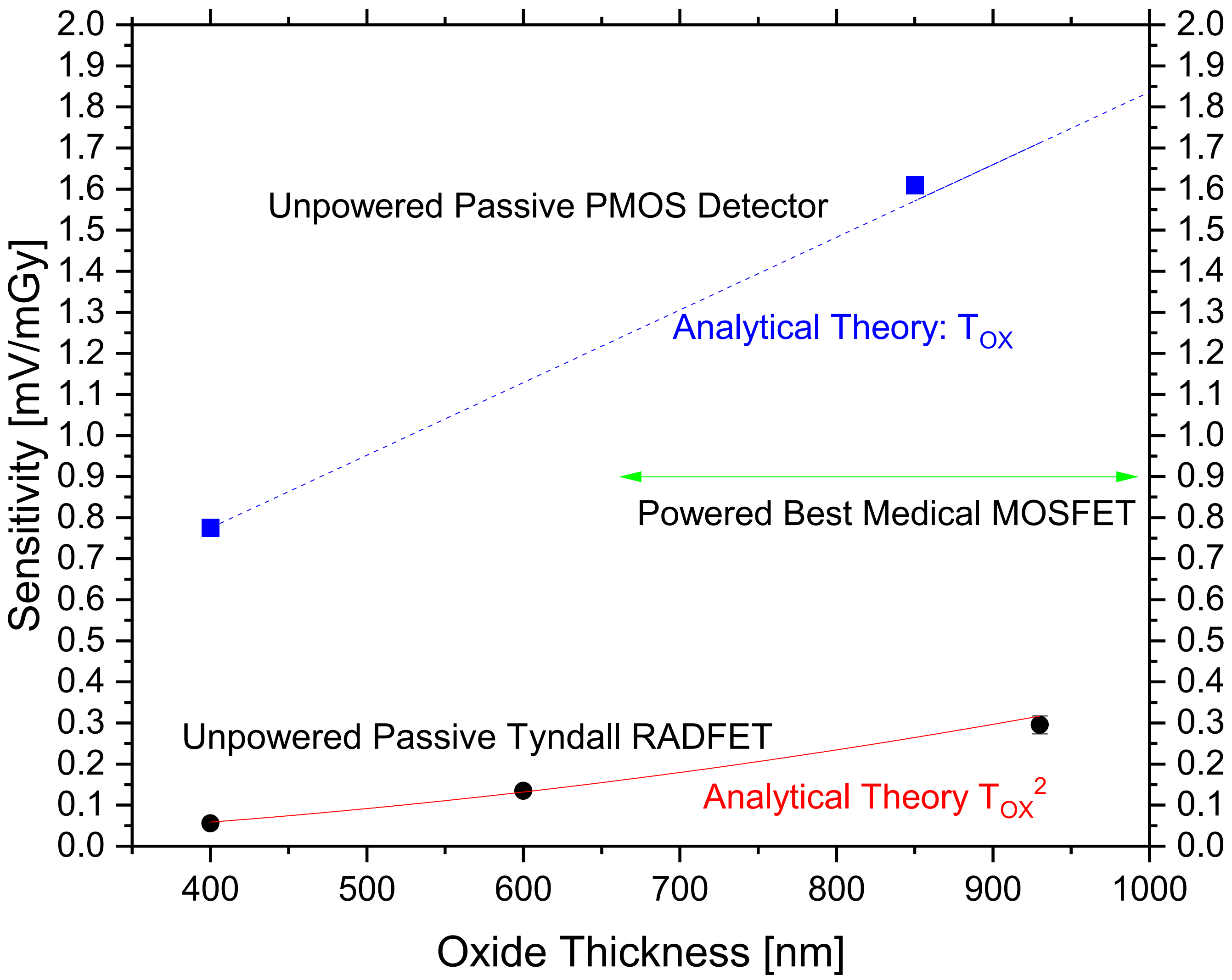


Irradiation experiment (T_{OX}=850nm)

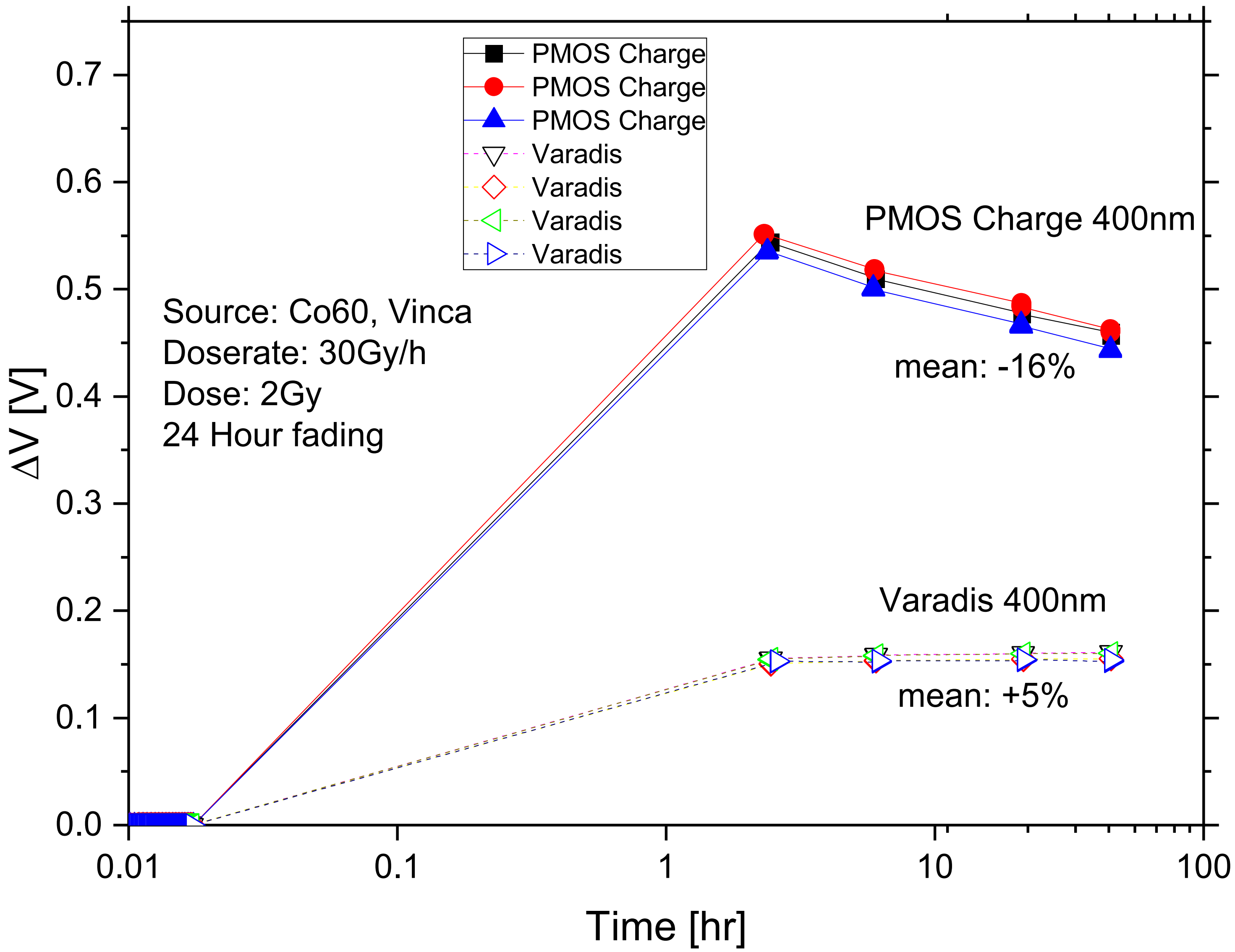


- Sensitivity = 1.6mV/mGy
- Detect sub mGy doses using low activity Co60 source

Comparison with Best Medical



Fading experiment (T_{OX}=400nm)



Summary

- Passive RADFET Sensitivity can be increased a number of ways:
  - Dielectric Thickness and SiO_2 process
  - High k Dielectric Material to generate more charge
  - Bulk electrode as a back-gate to enhance voltage sensitivity

➢ Increased sensitivity is possible with High k and new readout but so far at expense of increased fading

➢ Fading and noise floor of both these approaches needs to be carefully examined

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Thank you for your attention.
Questions?

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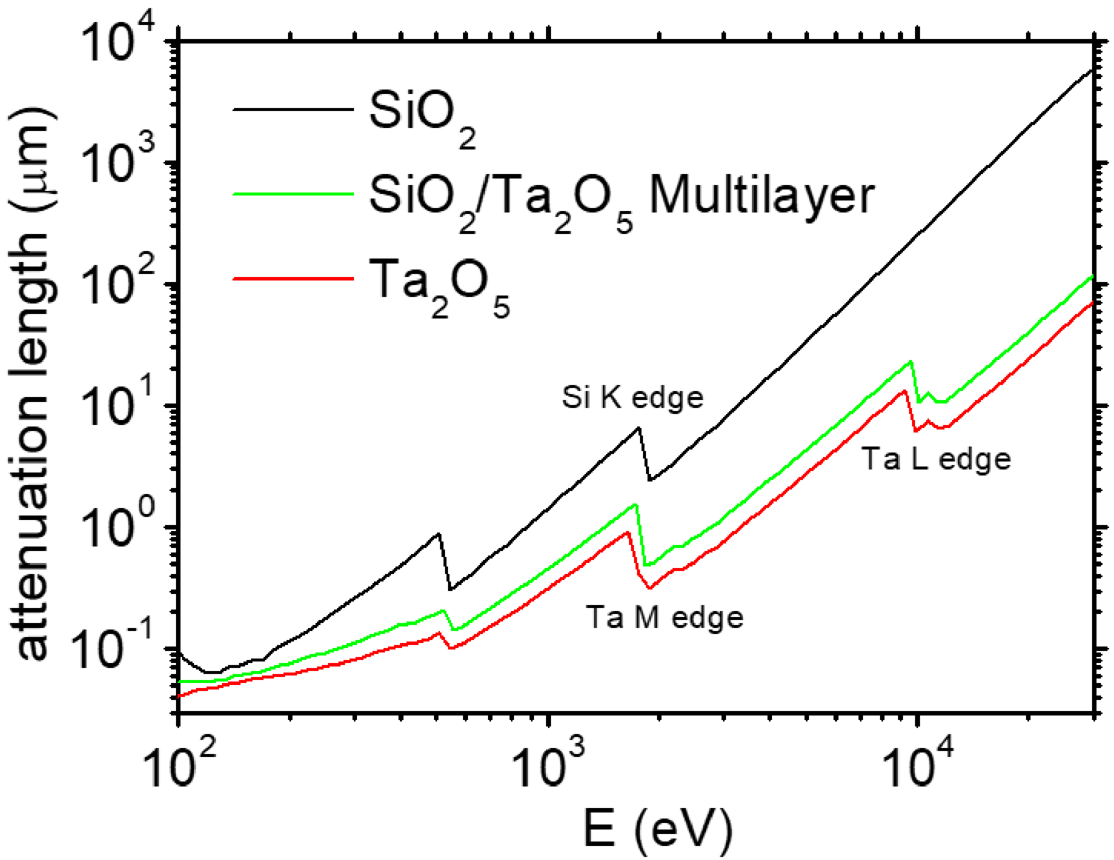
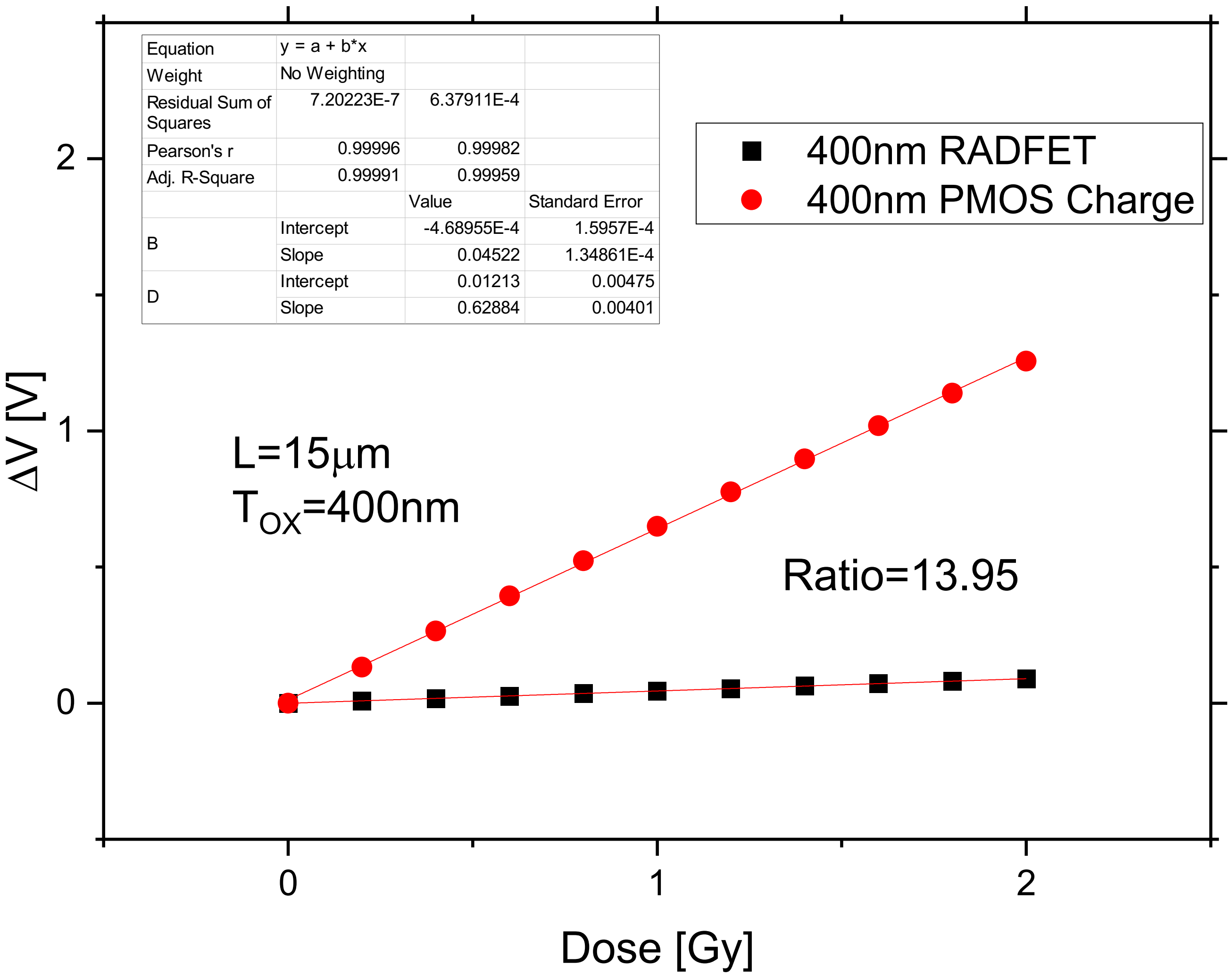
ROXFET Dielectric – Attenuation Length

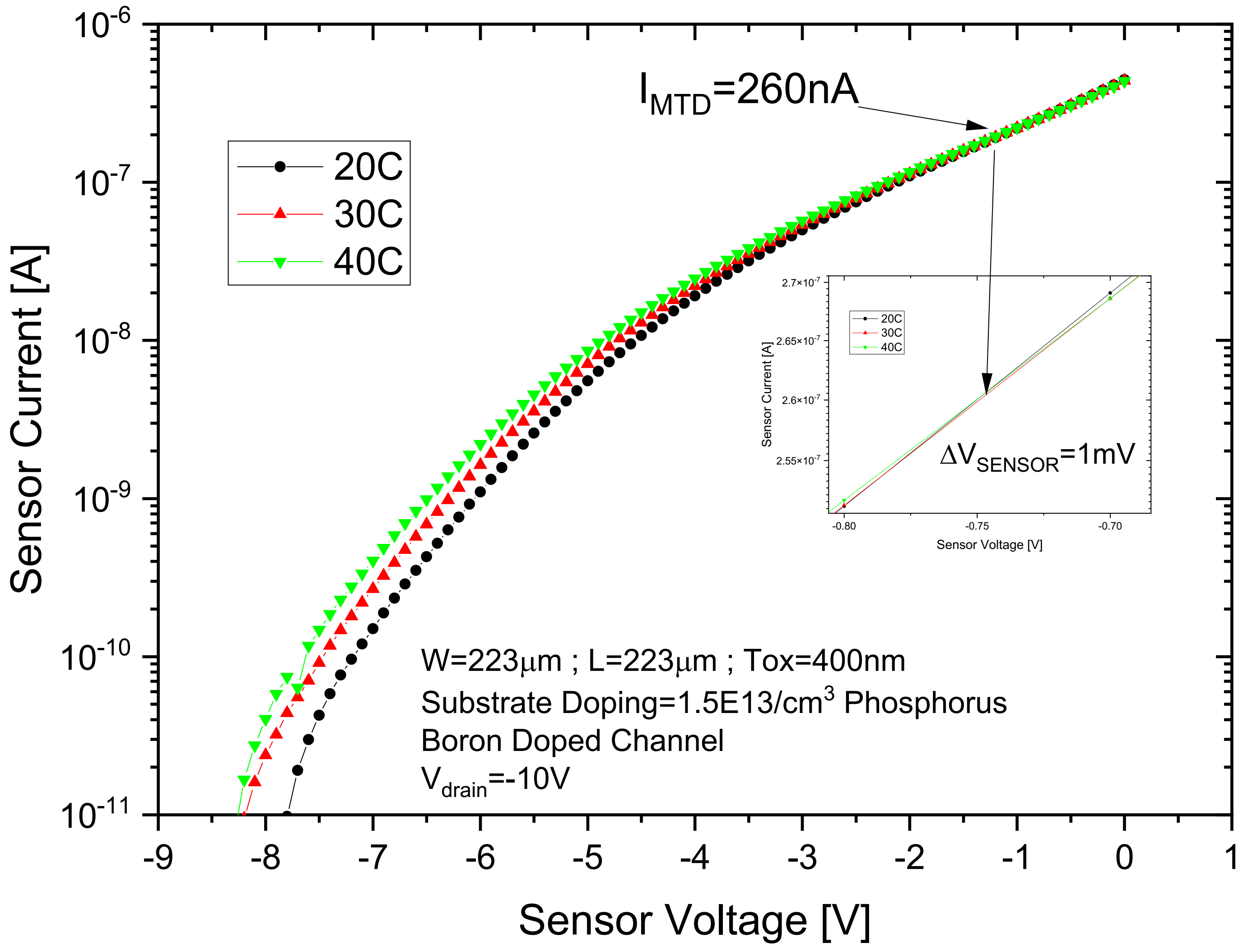


X-ray Irradiation: 35kV Molybedium Tube

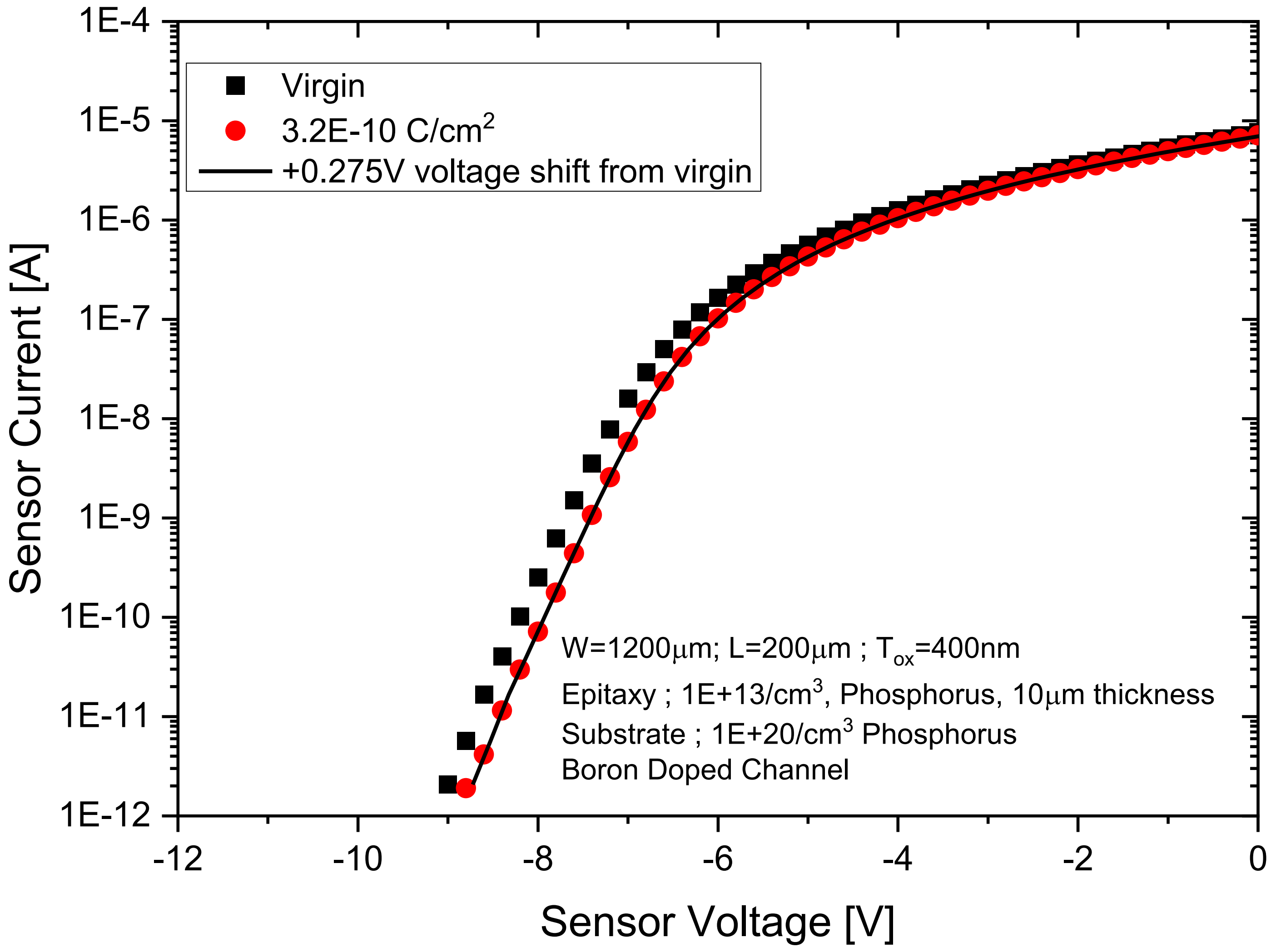
Linearity with Diode Temperature Compensation



Measured Current-Voltage vs Temperature

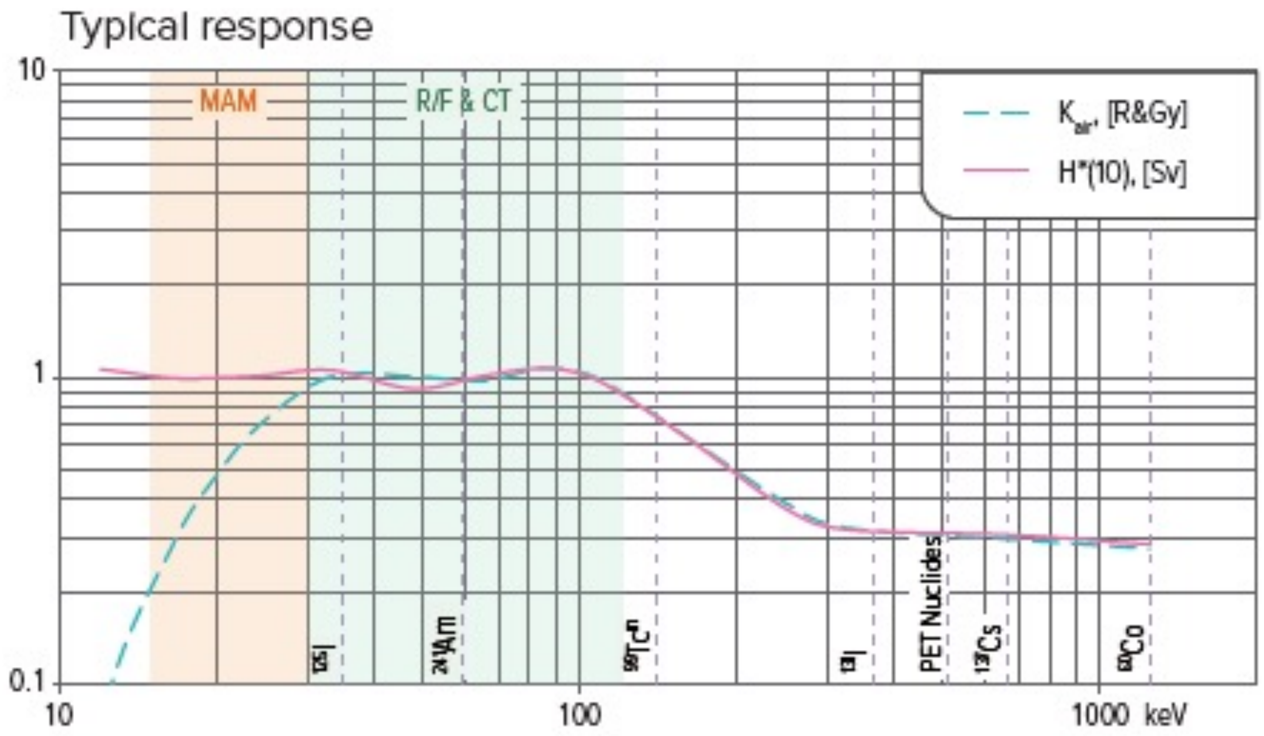


New Materials improve performance

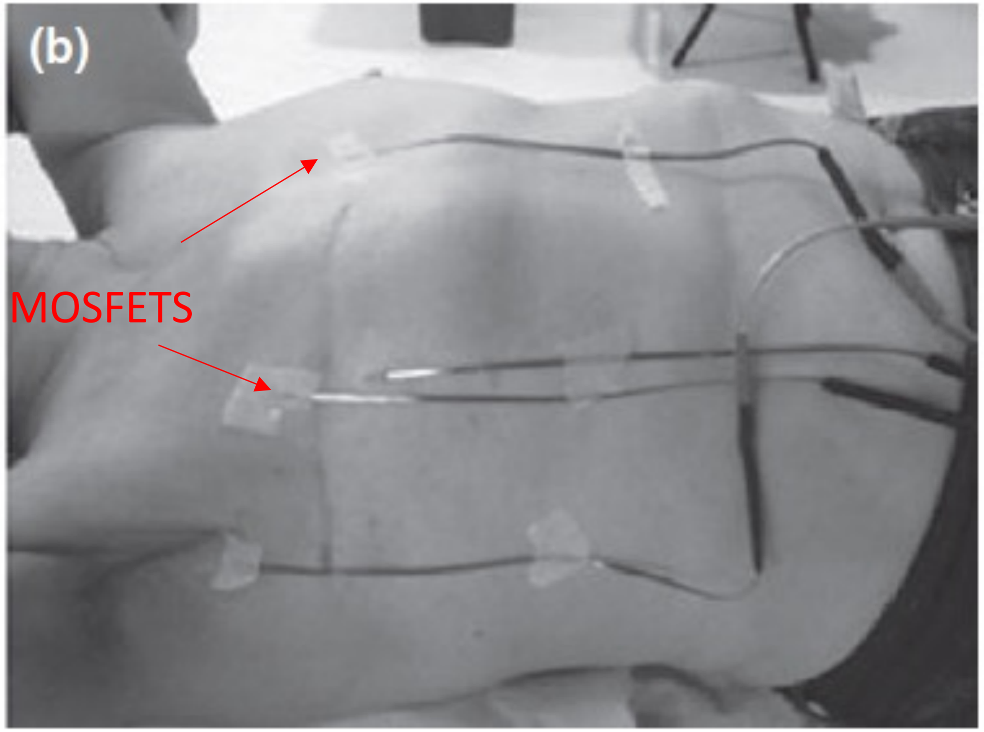


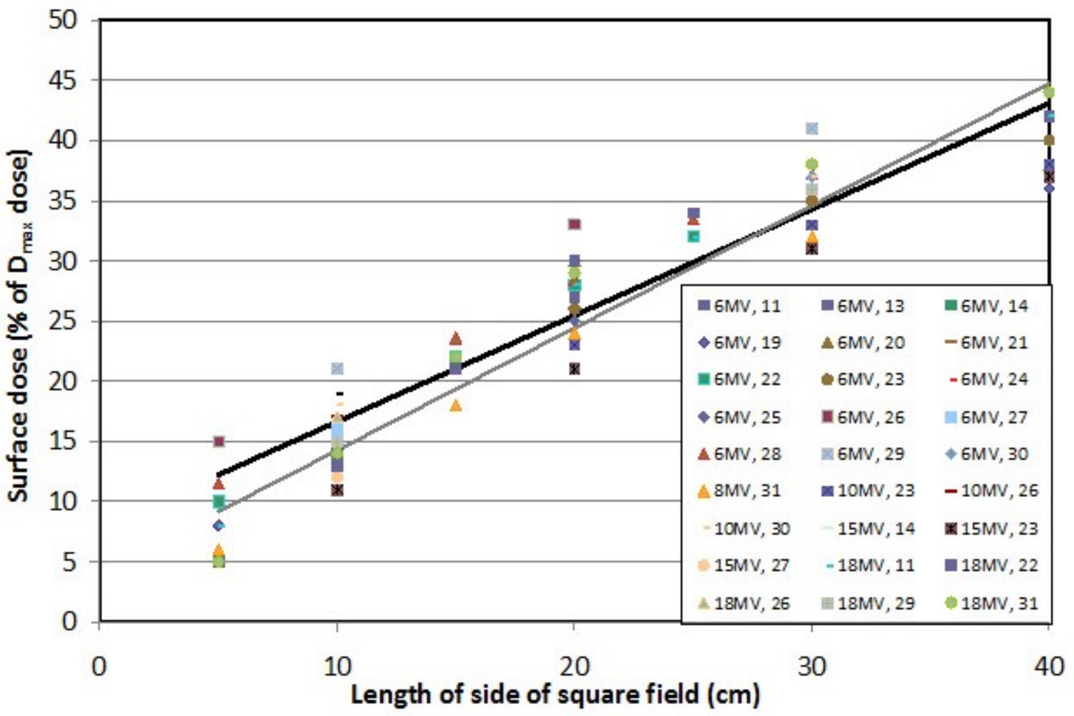
$$|\Delta V_{SENSOR}| = \frac{|\Delta Q_{OX}|}{C_B}$$

Energy Dependence



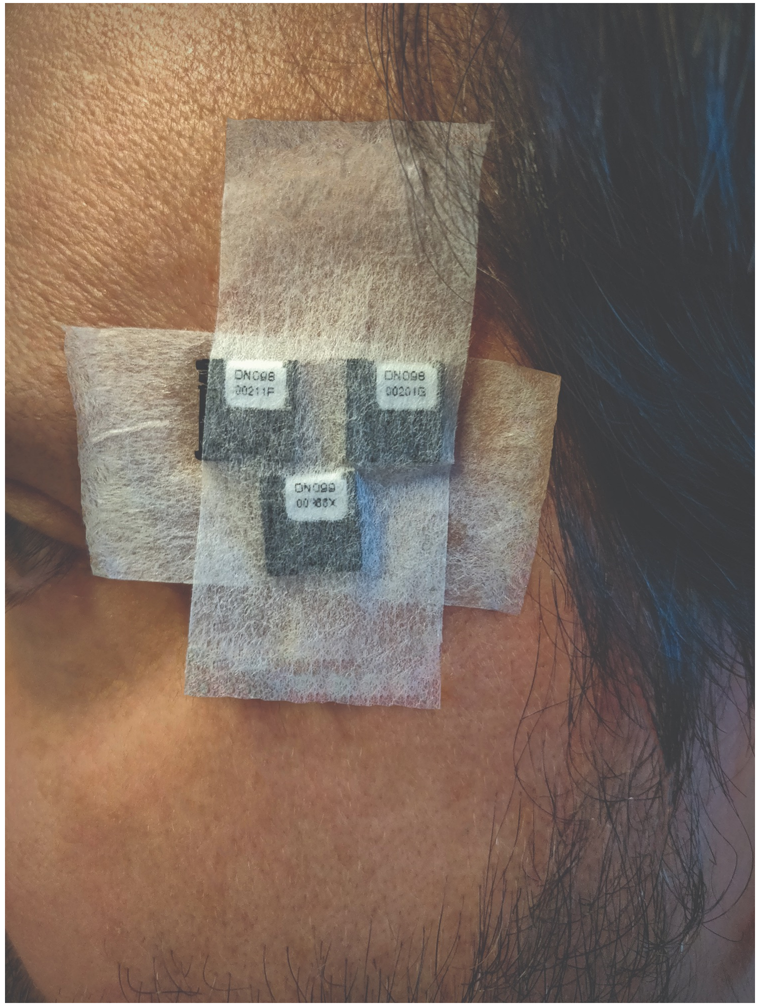
Dose levels





Typical Fraction =2Gy
5% is 100mGy

Wire Free (Passive) Single use dosimeters



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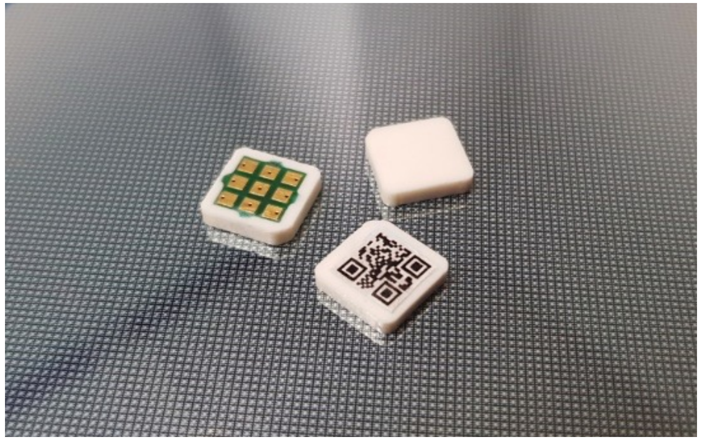
Our patch



Nikola Vasovic
Now in Varadis