ECsens
Electronic and Chemical sensing solutions

UNIVERSIDAD DE GRANADA

General purpose devices as radiation sensors: MOSFET and photodiodes

M.A. Carvajal, I. Ruiz-García, Juan Román-Raya, M.S. Martínez-García, P. Escobedo, D. Guirado, A.J. Palma

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3rd ELICSIR Training School

Outline

- Our research group
- Introduction and goals
- MOSFET detectors
  - Fundamentals
  - Readout techniques
  - UGR-system
- Dositag: NFC reader
- Photodiode detectors
  - Fundamentals
  - Readout technique
  - UGR-system
- Proton dosimetry with commercial devices
  - MOSFET
  - Photodiodes
  - Results
- Conclusions

Our research group

- **Interdisciplinary Spanish group**:
  - Department of Electronics
  - Department of Atomic, Nuclear and Molecular Physics
  - Radiotherapy Unit of Universitary Hospital “San Cecilio” in Spain (Granada)

Our research group

- **Facilities**
  - **Department of Electronics at the University or Granada**: Laboratory of characterization of electronics devices and printed-circuit-board prototyping. Placed in the Research Centre for Information and Communications Technologies (CITIC-UGR).

Our research group

- **Facilities: Radiotherapy service, University Hospital San Cecilio (Granada, Spain)**: Measurement system for clinical dosimetry based on ionization chambers and diodes. Irradiation sources, LINACs that provide electron beams of energies 6, 9, 12 and 15 MeV and photon beams of 6 and 15 MV.


Elekta Infinity

Siemens

Introduction

- Radiation detection using semiconductor devices

Scanditronix

Based on diode sensors

Best Medical

One Dose

Based on MOSEFT sensors

Motivation

Why use commercial devices not designed to radiation detection?

- Lower cost
- High availability

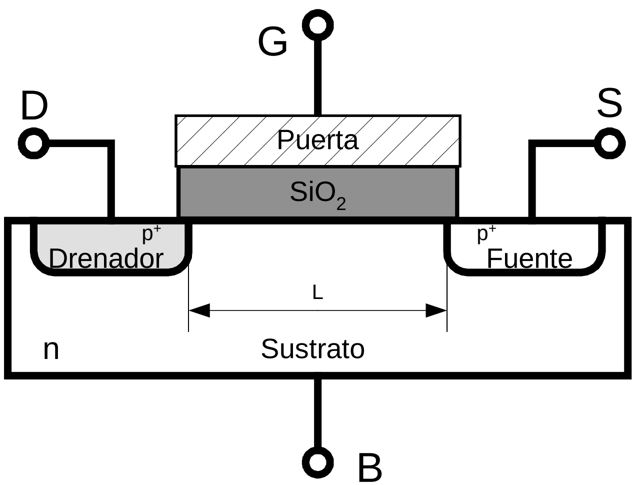
However:

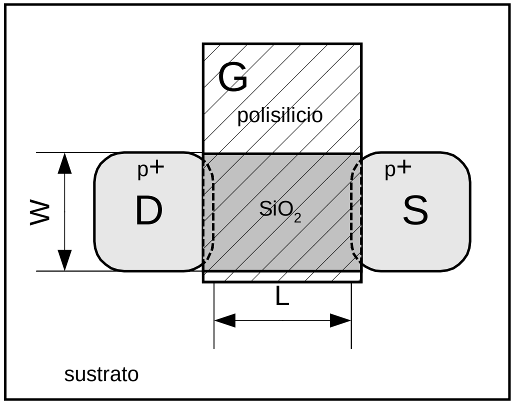
- Lower sensitivity
- Lower linearity (in most of cases)

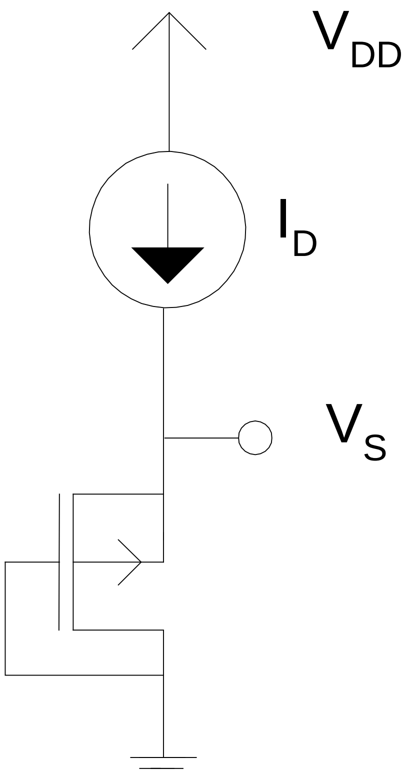
Our goal: To develop instrumentation with amplification, filtering and thermal compensation capabilities to measure ionizing radiation with general "purpose devices".

MOSFET detectors: Fundamentals

- MOSFET basics:





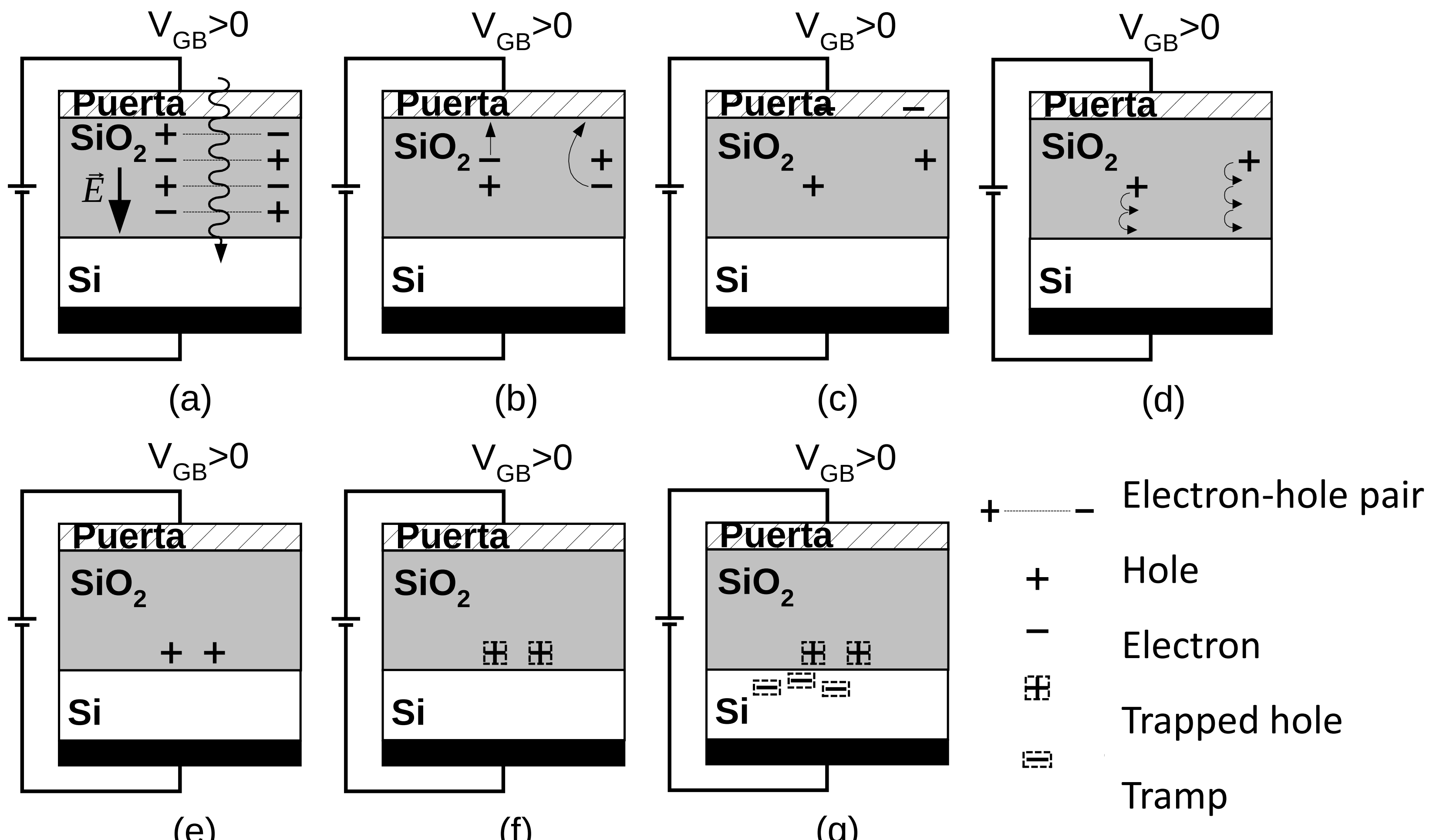


$$\boxed{i_D = -\frac{\beta}{2}\left(v_{GS} - V_t\right)^2}$$

$$With \begin{cases} v_{GS} \leq V_t \\ v_{DS} \leq v_{GS} - V_t \end{cases}$$

MOSFET detectors: Fundamentals

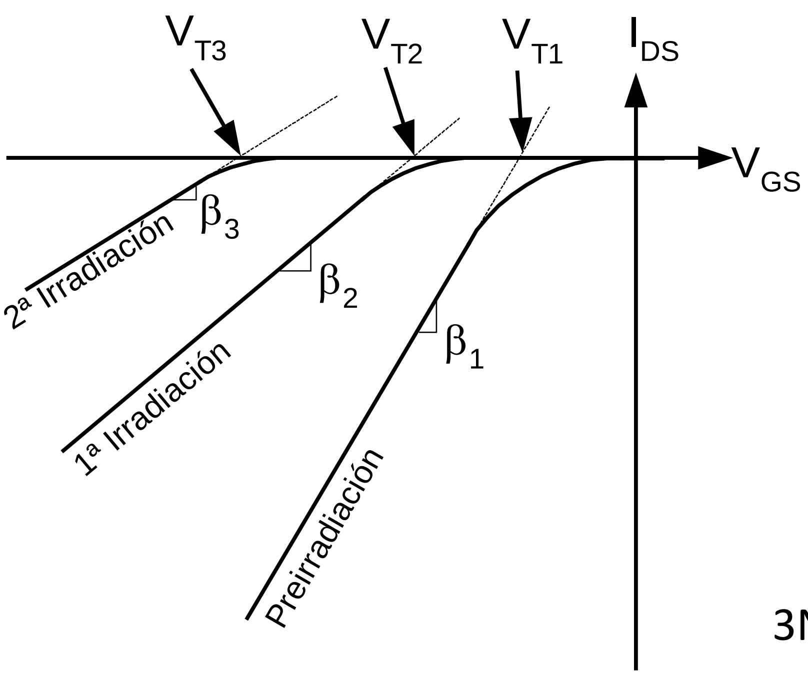
- MOS under irradiation:

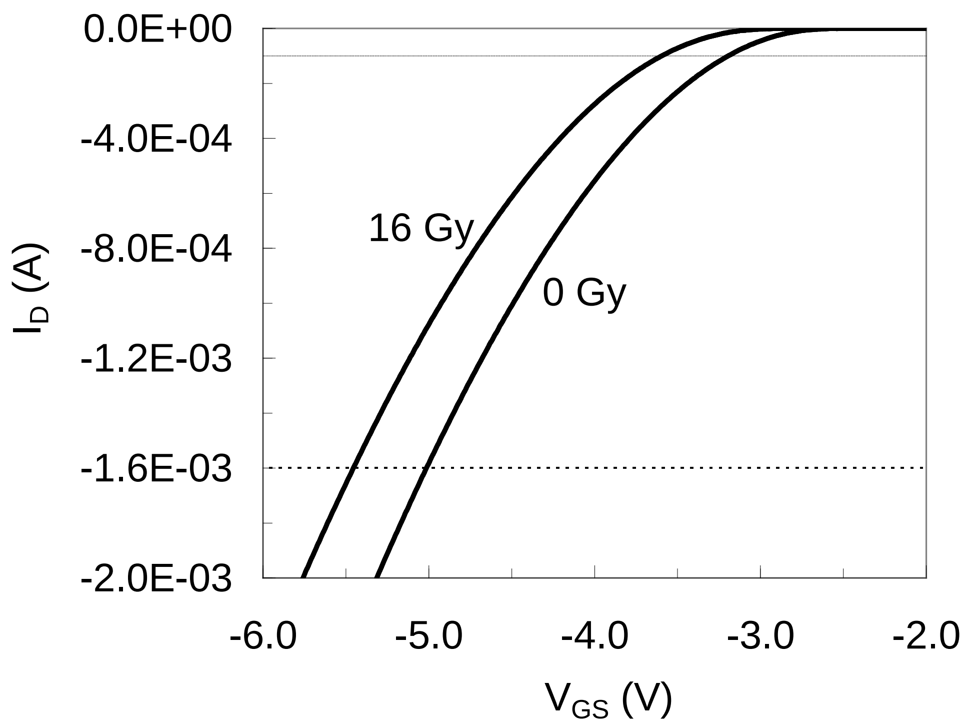


MOSFET detectors: Fundamentals

- Radiation effects in pMOSFET I-V characteristic:

$\boxed{|V_t| \uparrow \quad \beta \downarrow}$



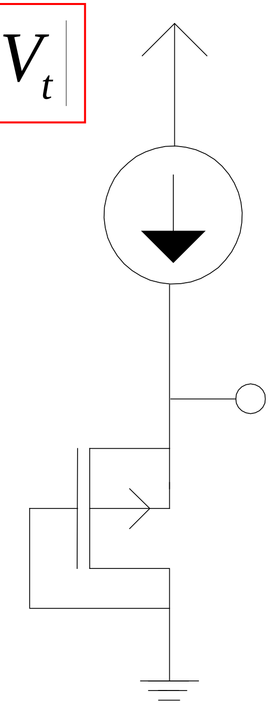


3N163 from Vishay, under ^{60}Co gamma source

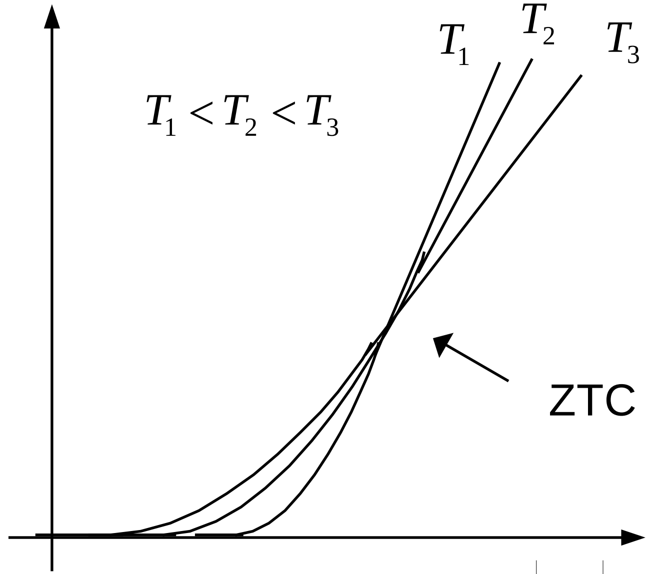
MOSFET detectors: Read out techniques

- Biasing at constant current:

$$\left.\begin{array}{l} i_D = -\dfrac{\beta}{2}\left(|v_{GS}| - |V_t|\right)^2 = cte \\ If \ \ \beta \approx cte \end{array}\right\} \Rightarrow \Delta|v_{GS}| \approx \Delta|V_t| \Rightarrow \boxed{\Delta V_S \approx \Delta|V_t|}$$

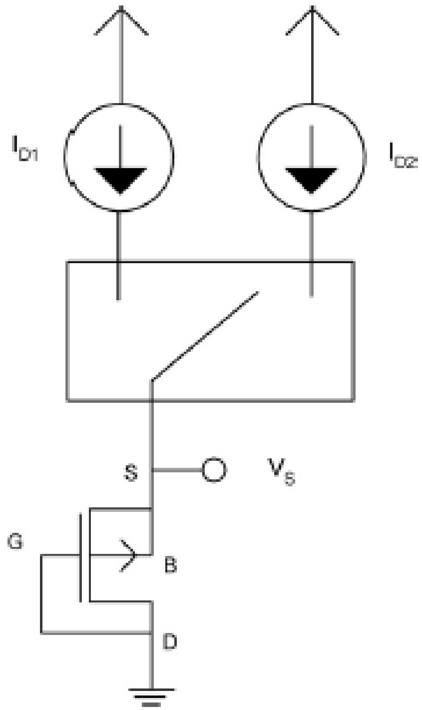


OneDose

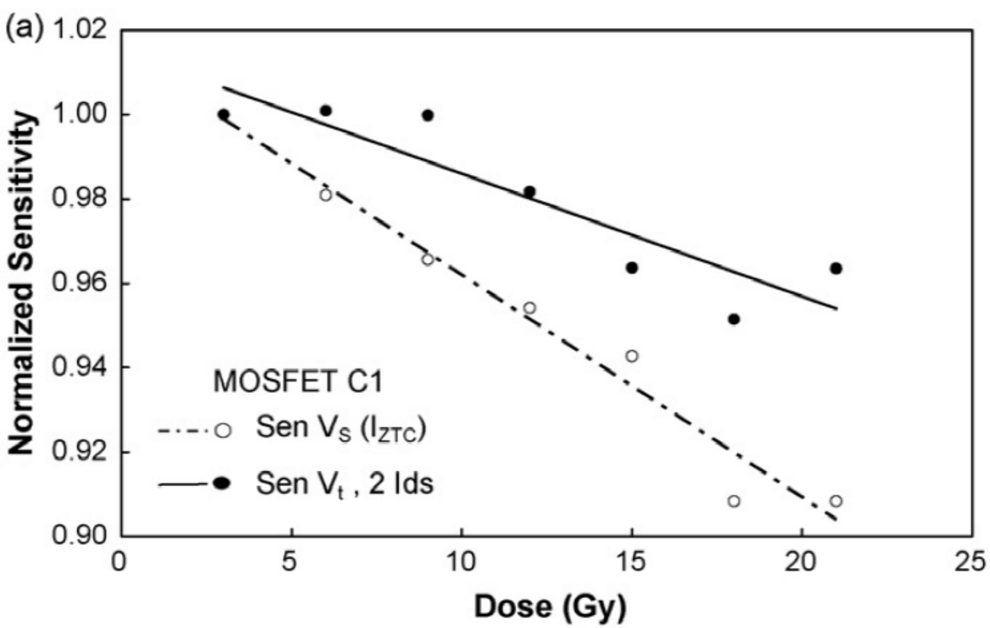


MOSFET detectors: Read out techniques

- Biasing secuentially with two constant current: Reducing the effect of β degradation



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



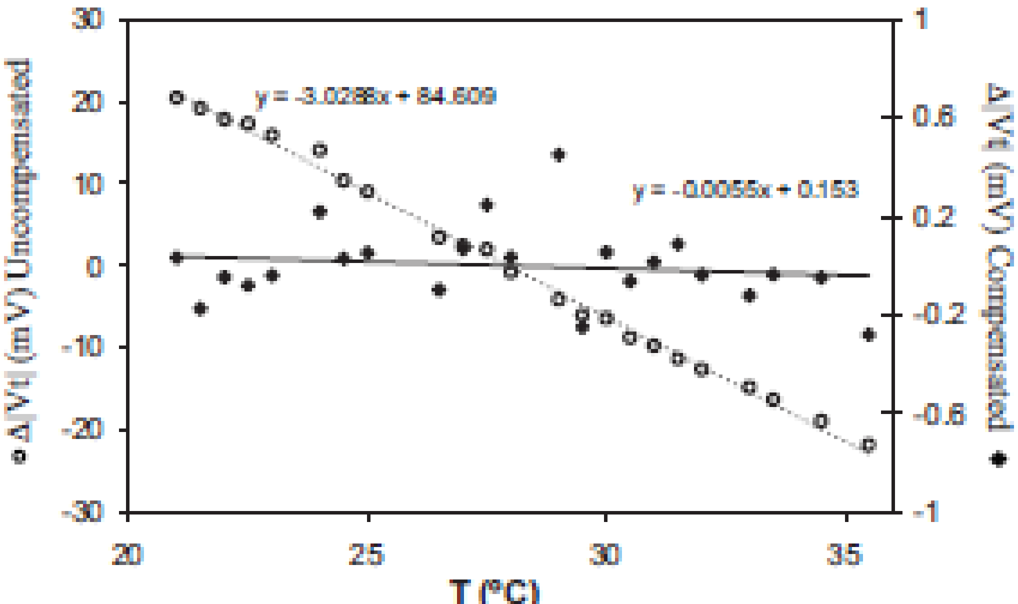
3N163 from Vishay, under ^{60}Co gamma source

M.A. Carvajal et al., Readout techniques for linearity and resolution improvements in MOSFET Dosimeters, Sensors and Actuators A 157 (2010) 178–184

MOSFET detectors: Read out techniques

- Biasing secuentially with three constant current: Reducing the effect of β degradation and thermal compensation.

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

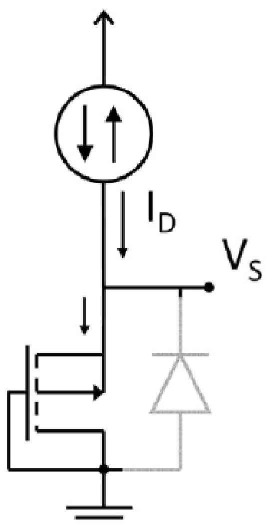


$$\Delta V_{S2}^0 = \Delta V_{S2} + \left(\Delta V_{SC} - \Delta V_{S2}\right)\frac{\sqrt{I_2} - \sqrt{I_{ZTC}}}{\sqrt{I_2} - \sqrt{I_C}}$$

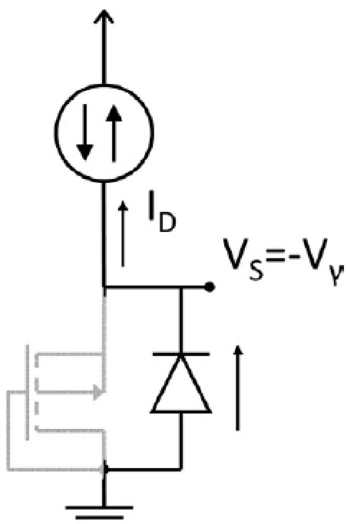
M.A. Carvajal et al., A compact and low cost dosimetry system based on MOSFET for in vivo radiotherapy, Sensors and Actuators A 182 (2012) 146– 152

MOSFET detectors: Read out techniques

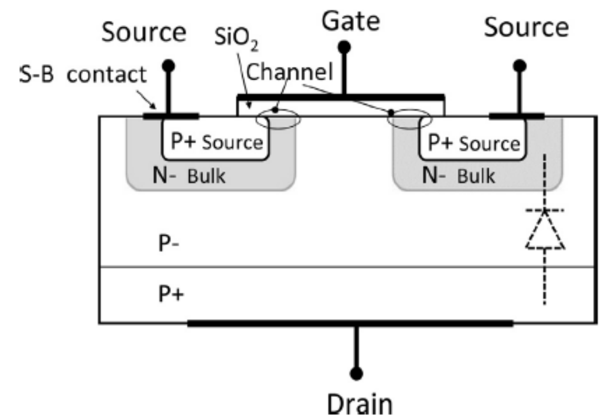
- Thermal compensation using the parasitic diode: The knowledge of I_{ZTC} current is not required

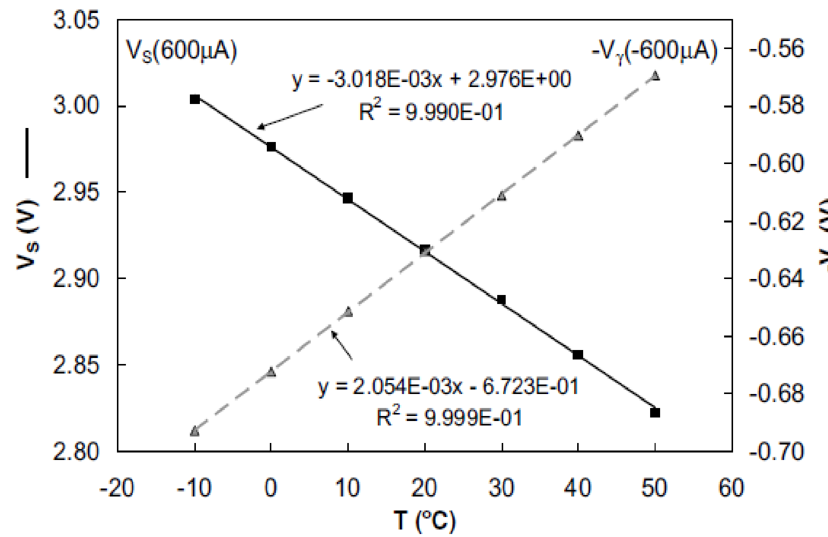


MOSFET is activated



Diode is activated



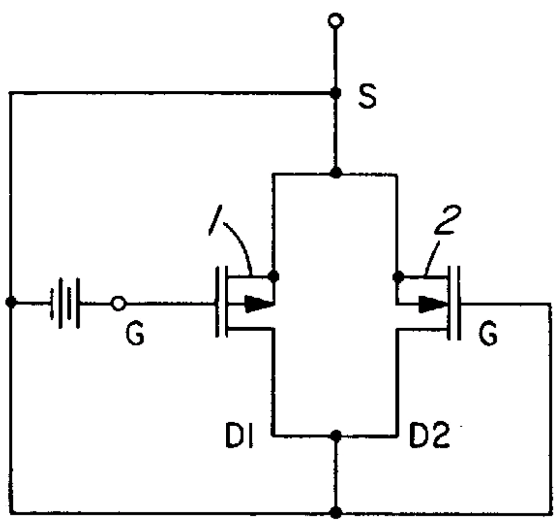


DMOS transistor ZVP3306

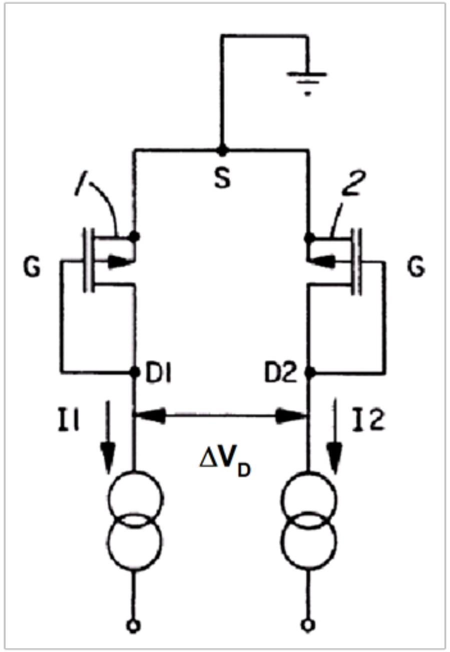
M.A. Carvajal et al., Thermal compensation technique using the parasitic diode for DMOS transistors, Sensors and Actuators A 249 (2016) 249–255

MOSFET detectors: Read out techniques

- Thermal compensation and linearity enhancement applying differential measurements:



Sensing configuration



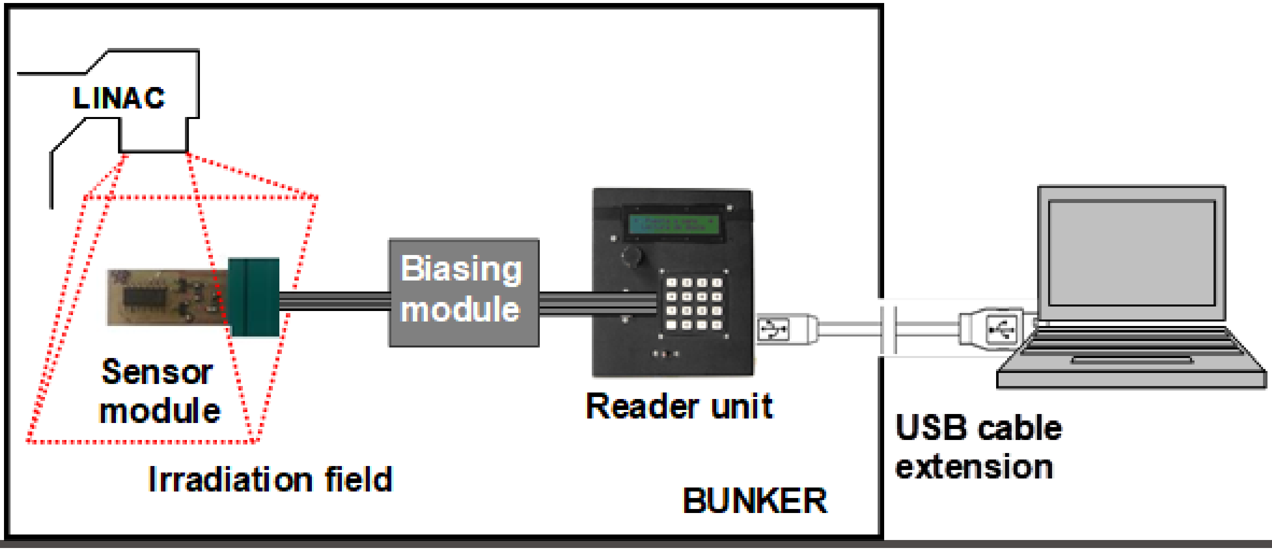
Readout configuration

Best Medical

I. Thomson, Direct Reading Dosimeter, European Patent Office, EP 0471957A2, 02/07/1991.

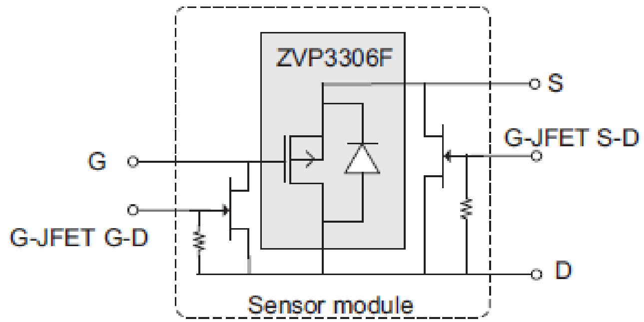
MOSFET detectors: UGR-system

- Our reader unit:
  - Up to 4 currents for sequentially biasing
  - Biased and unbiased mode
  - Sink current to measure Vγ of the parasitic diode.
  - Resolution: 2 cGy
  - Real time measurements

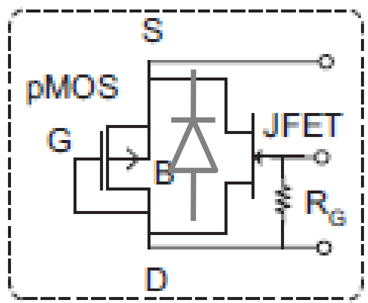


MOSFET detectors: UGR-system

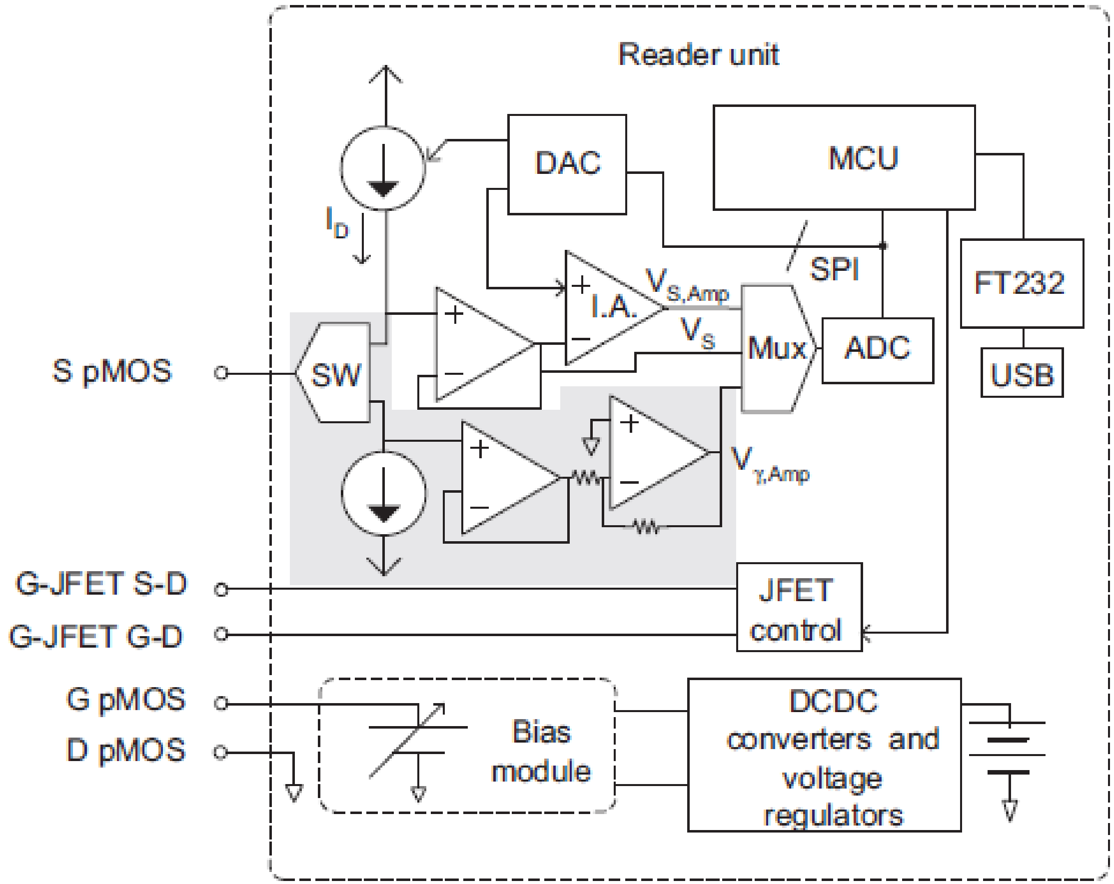
- Electronics details



Biased mode



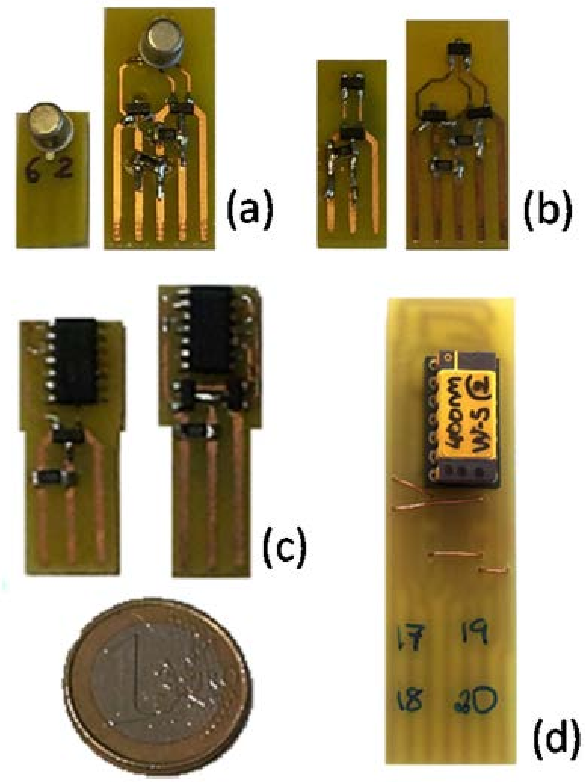
Unbiased mode

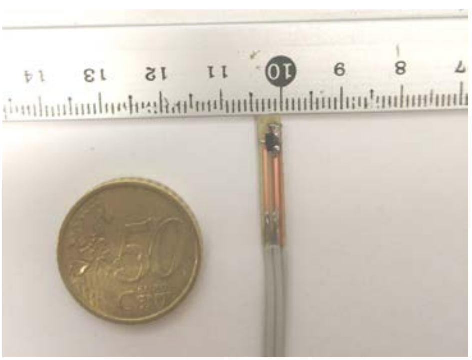


M.A. Carvajal et al., Thermal compensation technique using the parasitic diode for DMOS transistors, Sensors and Actuators A 249 (2016) 249–255

MOSFET detectors: UGR-system

- Sensor modules
  a) 3N163 Vishay
  b) ZVP3306 Zetex
  c) CD4007 Texas Instruments
  d) RADFET 400nm from Tyndall
  e) Miniaturized probe based on ZVP3306

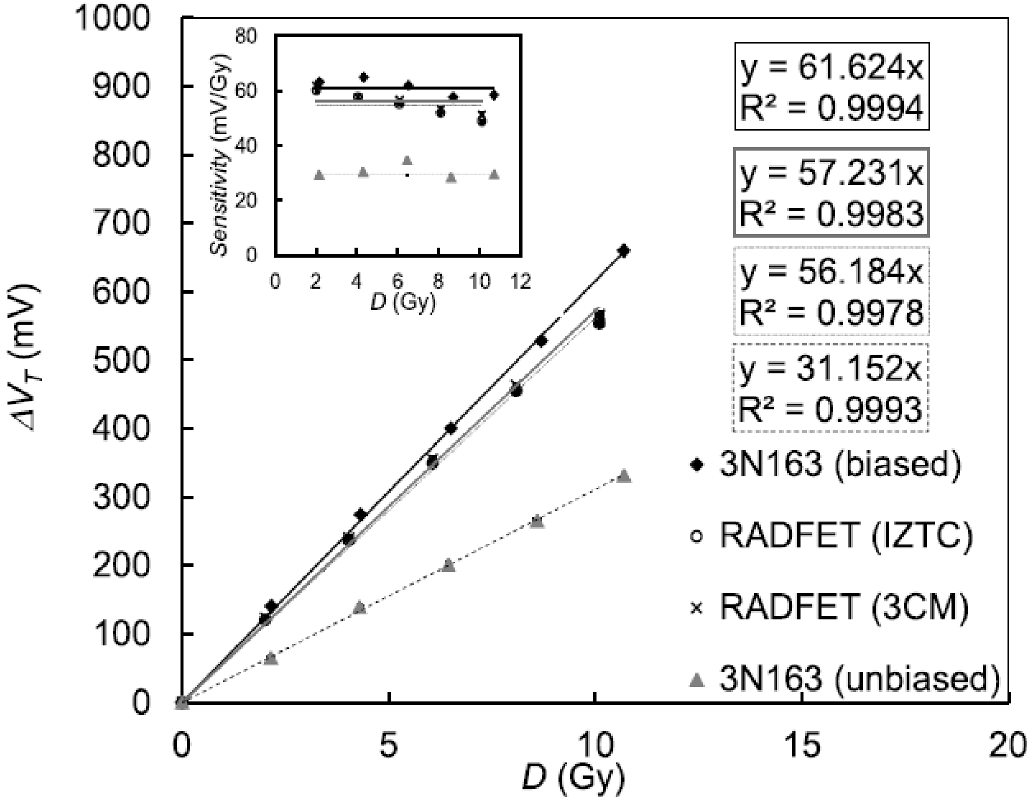


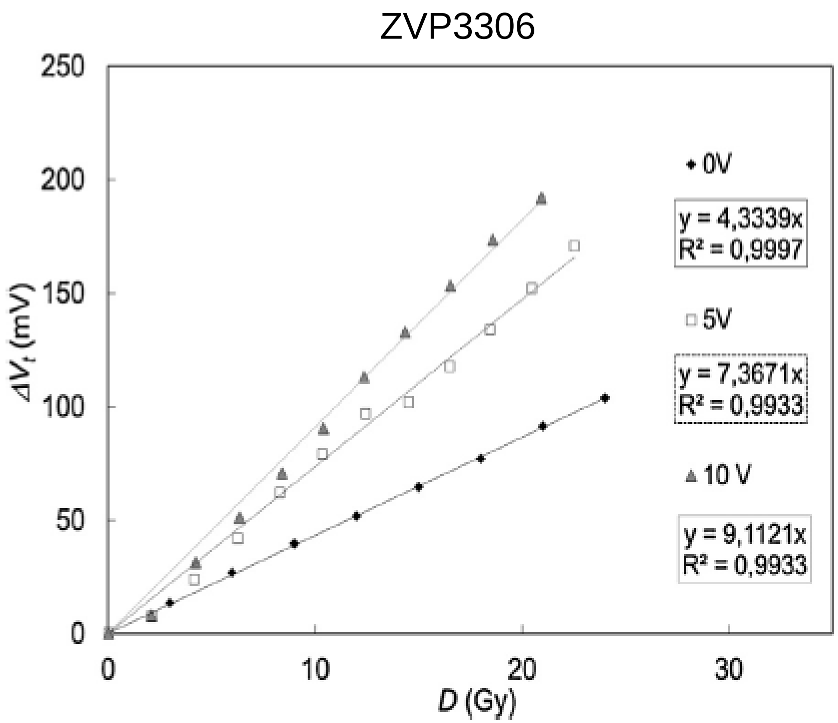


M.S. Martínez-García et al.," Response to ionizing radiation of different biased and stacked pMOSstructures", Sensors and Actuators A 252 (2016) 67–75

MOSFET detectors: UGR-system

- Sensor modules sensitivities (photons):



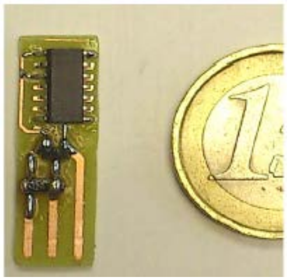


Radiation beam: 6MV photons provided by a LINAC Mevatron KDS (Siemens),

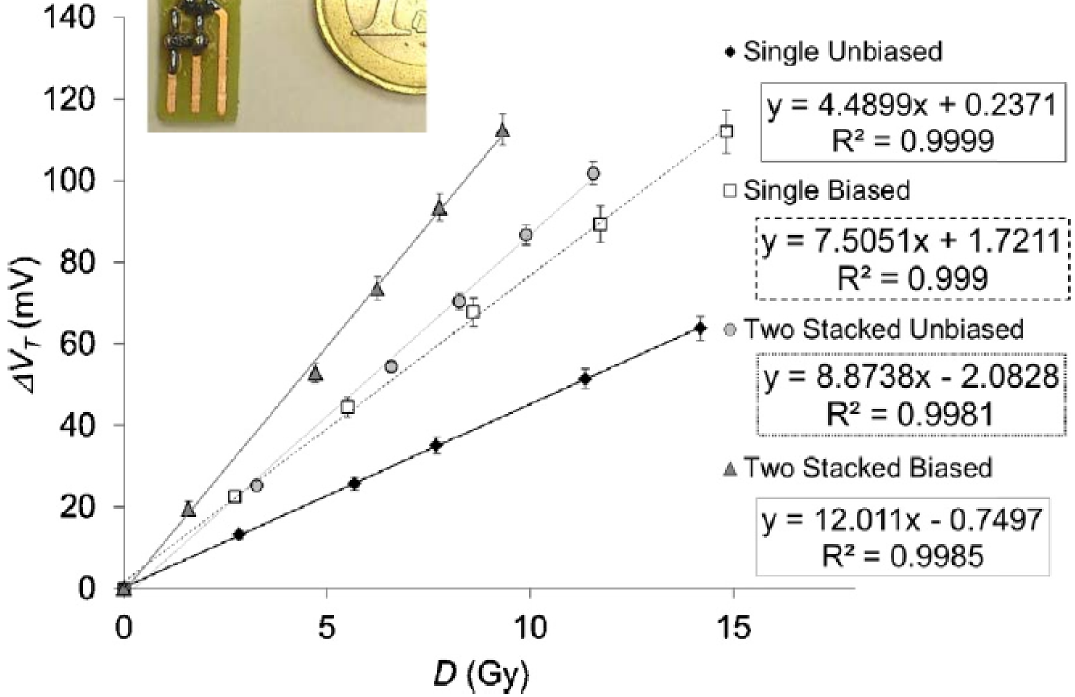
M.S. Martínez-García et al.," Response to ionizing radiation of different biased and stacked pMOS structures", Sensors and Actuators A 252 (2016) 67–75

MOSFET detectors: UGR-system

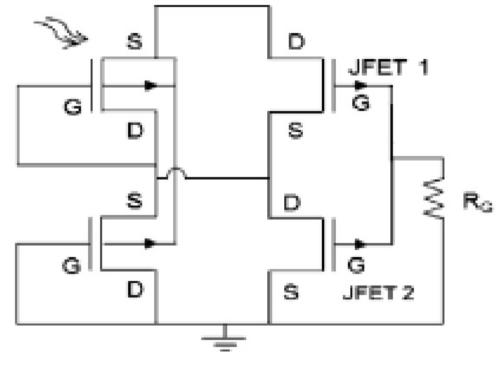
- Sensor modules sensitivities (electrons):



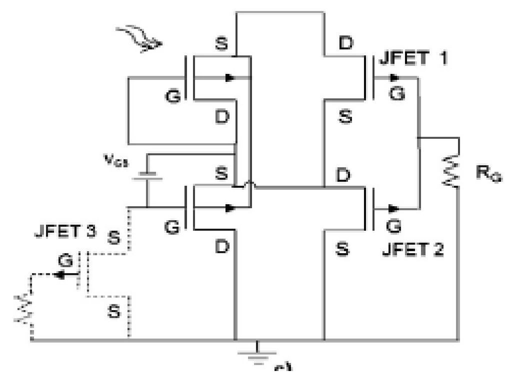
CD4007



Two stacked unbiased



Two stacked biased



Radiation beam: 6MV electrons provided by a LINAC Mevatron KDS (Siemens)

M.S. Martínez-García et al.," General purpose MOSFETs for the dosimetry of electron beams used in intra-operative radiotherapy", Sensors and Actuators A 210 (2014) 175–181

Dositag V1

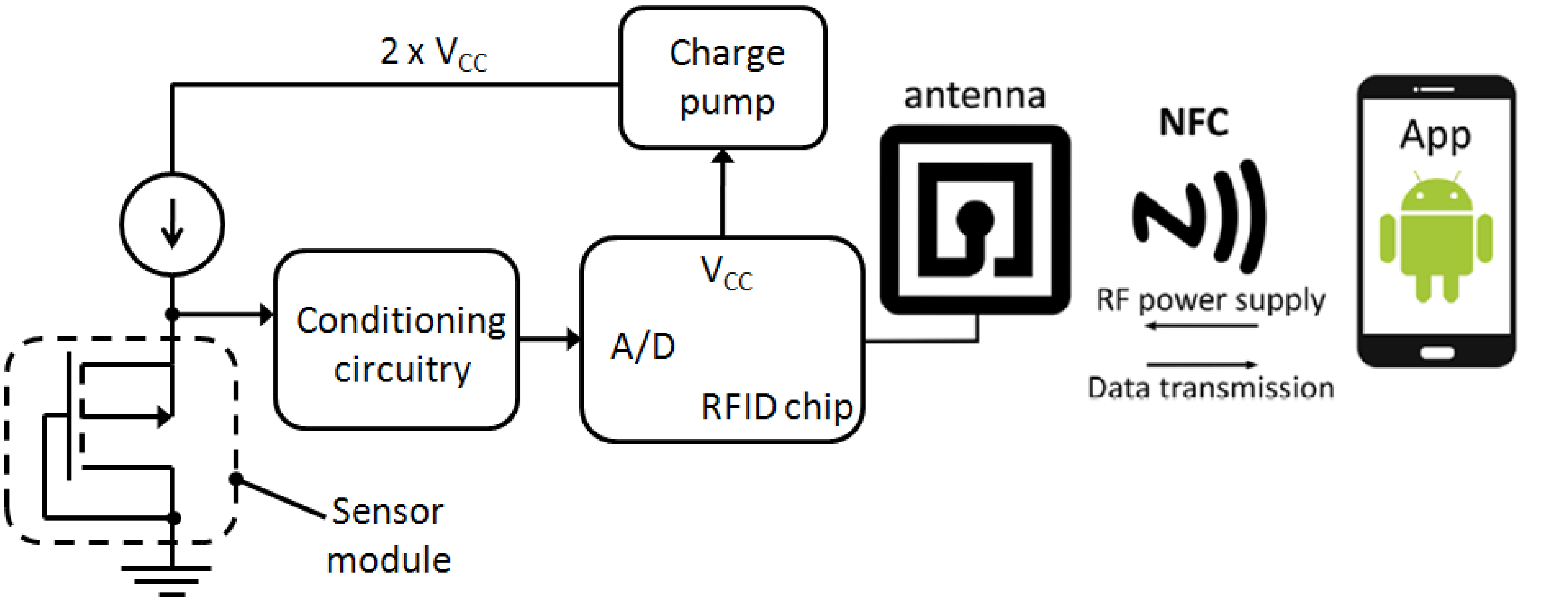
Our goal

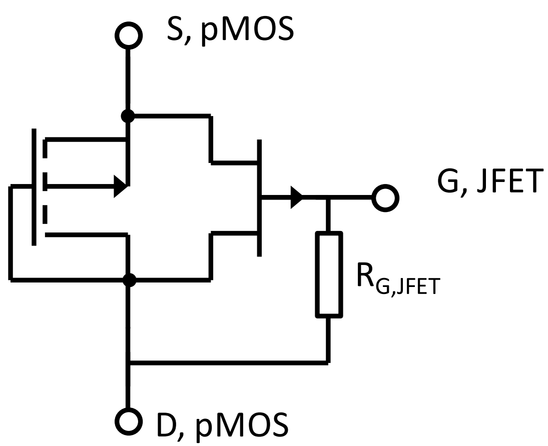
- To develop a passive NFC reader for MOSFET dosimeters

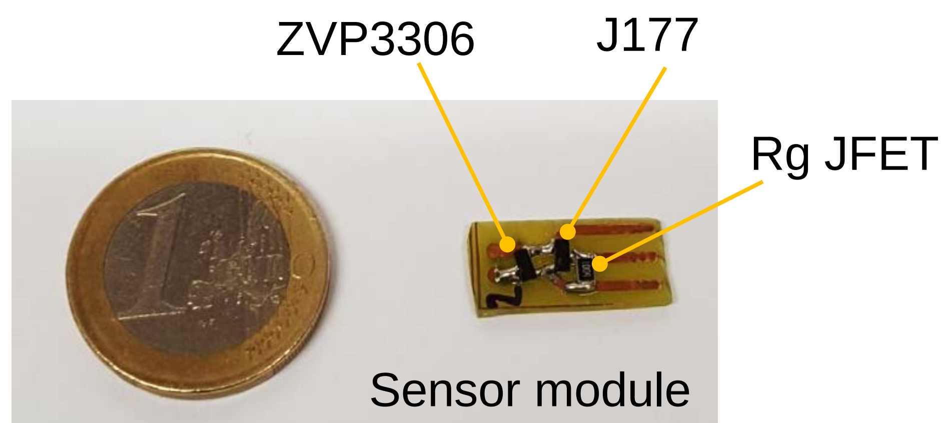
- **Why a NFC reader for MOSFET dosimeters?**
- Most of smartphones include a NFC reader
- Passive tags without battery with sensing capabilities
- Cost saving and easy to use
- Android devices are very popular

M.A.Carvajal et al.," A compact dosimetric system for MOSFETs based on passive NFC tagand smartphone", Sensors and Actuators A 267 (2017) 82–89

Dositag V1







M.A.Carvajal et al.," A compact dosimetric system for MOSFETs based on passive NFC tagand smartphone", Sensors and Actuators A 267 (2017) 82–89

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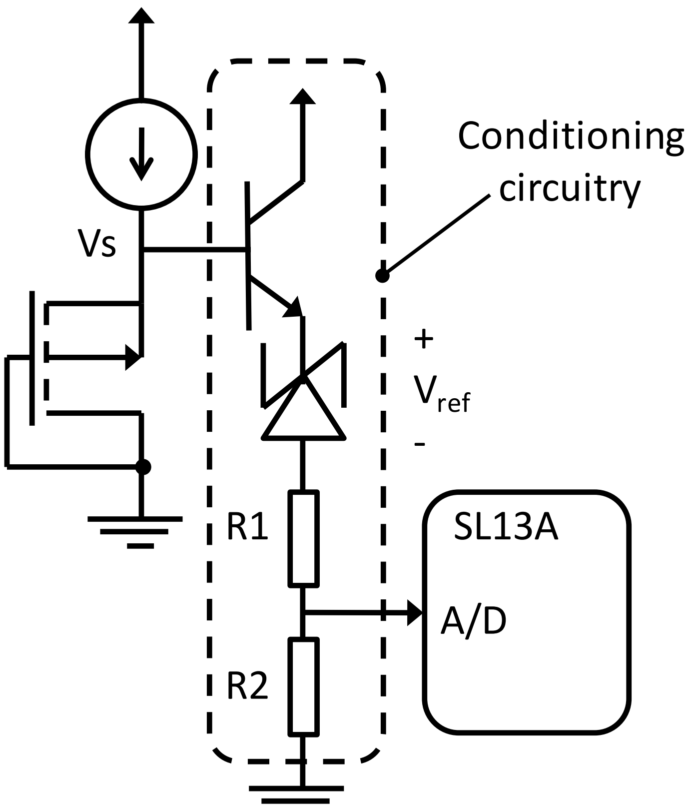
Dositag V1



$$V_{in}^{ADC} = \frac{R_2}{R_1 + R_2}\left(V_S - V_{BE} - V_{ref}\right)$$

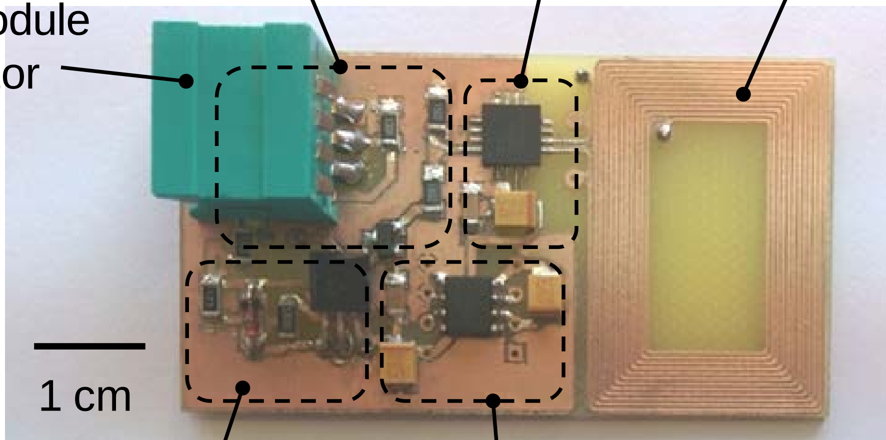
$$\left.\begin{aligned} \Delta V_{in}^{ADC} &= \alpha \Delta T \\ \Delta V_S &= \alpha_S \Delta T \\ \Delta V_{BE} &= \alpha_{BE} \Delta T \end{aligned}\right\}$$

$$\boxed{\alpha = \frac{R_2}{R_1 + R_2}\left(\alpha_S - \alpha_{BE}\right)}$$

	I (µA)	α (mV/ºC)	Δα (mV/ºC)
VBE_BJT	30	-2.332	0.013
Vs_MOSFET	220	-2.30	0.12

M.A.Carvajal et al.," A compact dosimetric system for MOSFETs based on passive NFC tagand smartphone", Sensors and Actuators A 267 (2017) 82–89

Dositag V1



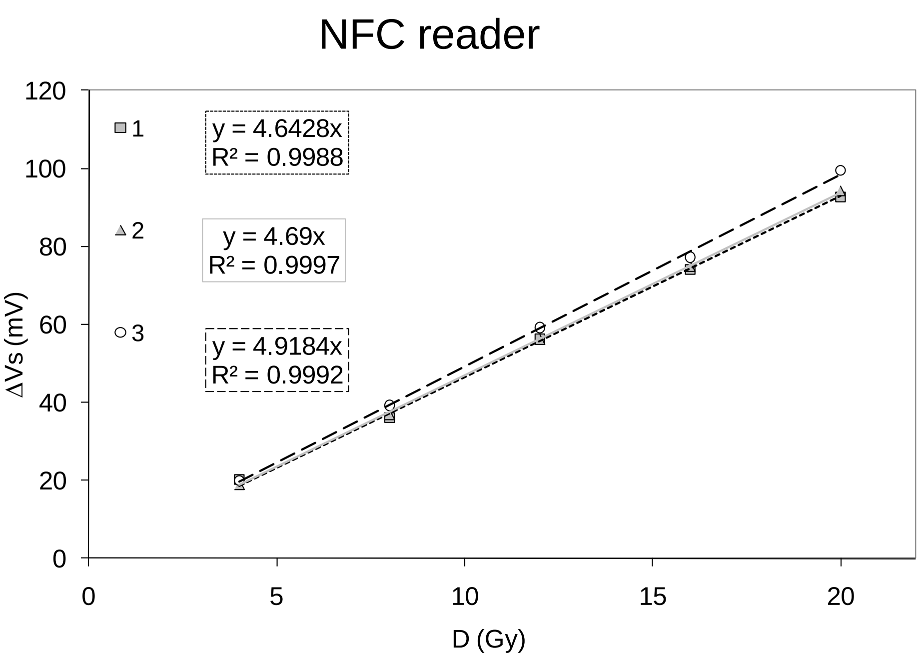
- Compact
- Passive tag, **no battery** is required

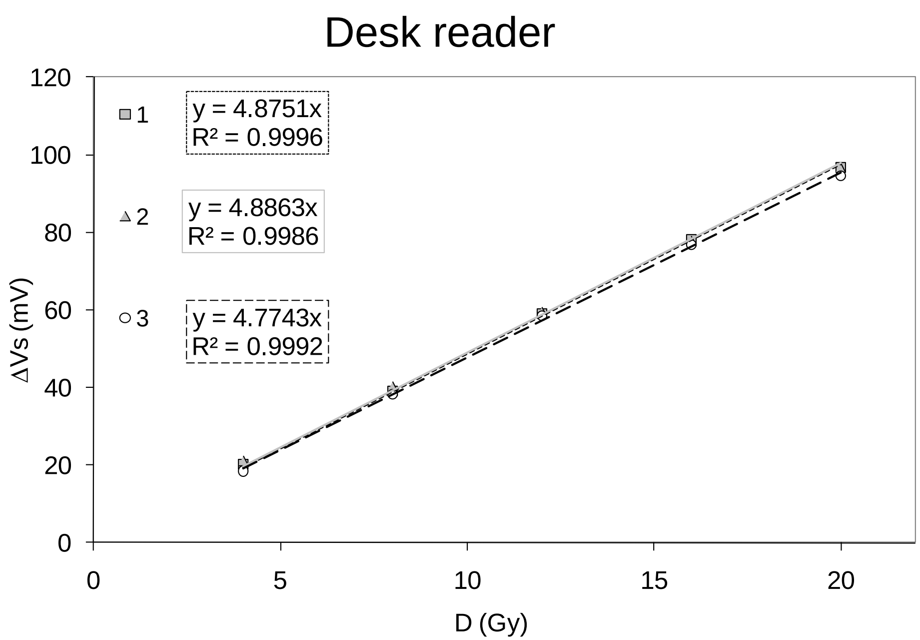
Experimental setup:

- LINAC Siemens Artiste: Photon beans of 6 MV irradiation field of 10x10 cm^2.
- 1.5 cm of solid water as buildup layer.
- 5 sessions of 4 Gy.

M.A.Carvajal et al.," A compact dosimetric system for MOSFETs based on passive NFC tagand smartphone", Sensors and Actuators A 267 (2017) 82–89

Dositag V1





	#1	#2	#3	Average
NFC reader	4.64 ± 0.03	4.69 ± 0.02	4.92 ± 0.03	**4.75 ± 0.15**
Desk Reader	4.88 ± 0.02	4.89 ± 0.04	4.77 ± 0.03	**4.85 ± 0.07**

M.A.Carvajal et al.," A compact dosimetric system for MOSFETs based on passive NFC tagand smartphone", Sensors and Actuators A 267 (2017) 82–89

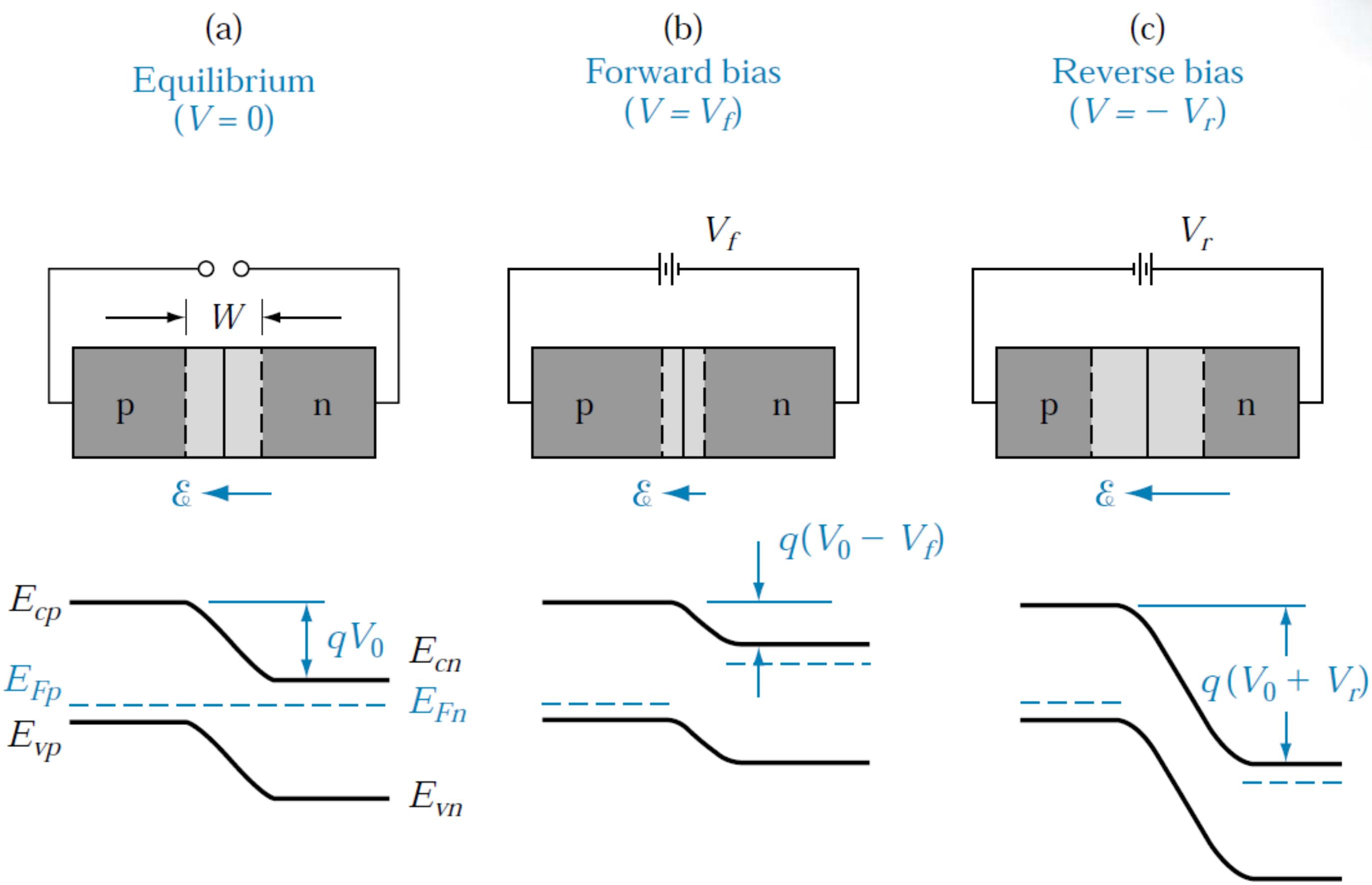
MOSFET detectors: UGR-system

MOSFET summary

Commercial MOSFETs have been successfully tested for dosimetry in radiotherapy for photon and electron beams

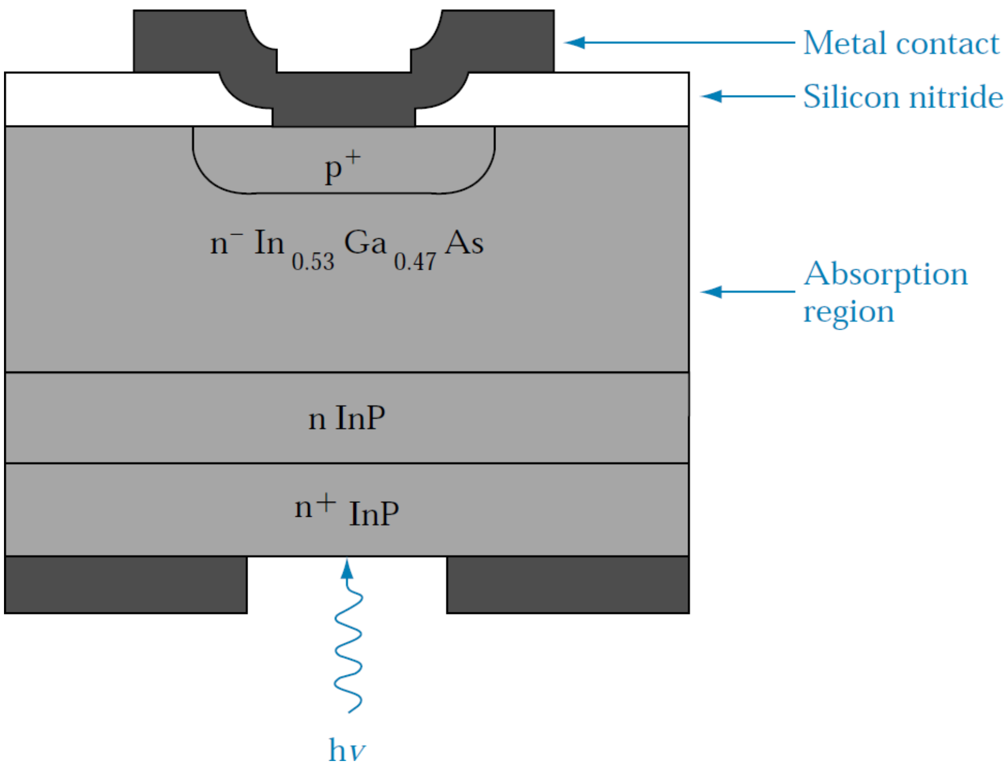
Photodiode detectors: Fundamentals

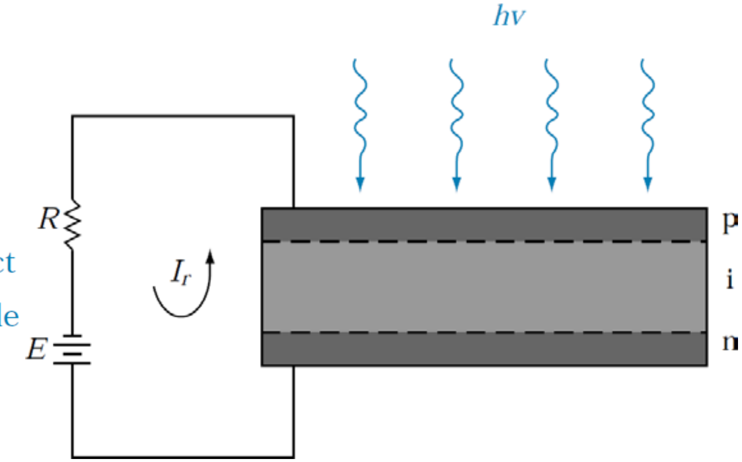
- P-N junction:

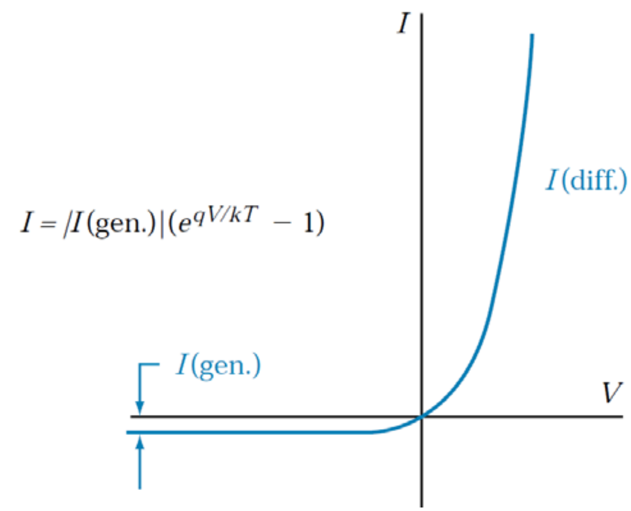


Photodiode detectors: Fundamentals

- PIN diodes:

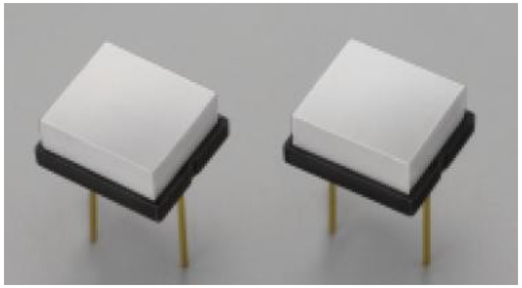


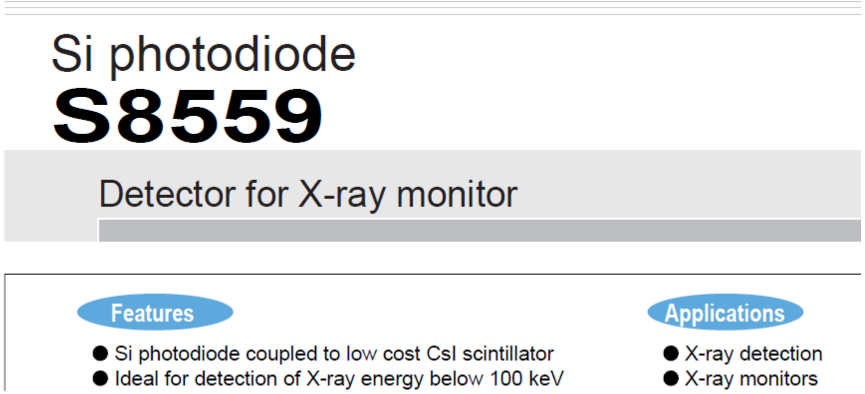




Photodiode detectors: Fundamentals

- PIN diodes
  - For gamma or x ray detection a scintillator over the photodiode can be used.

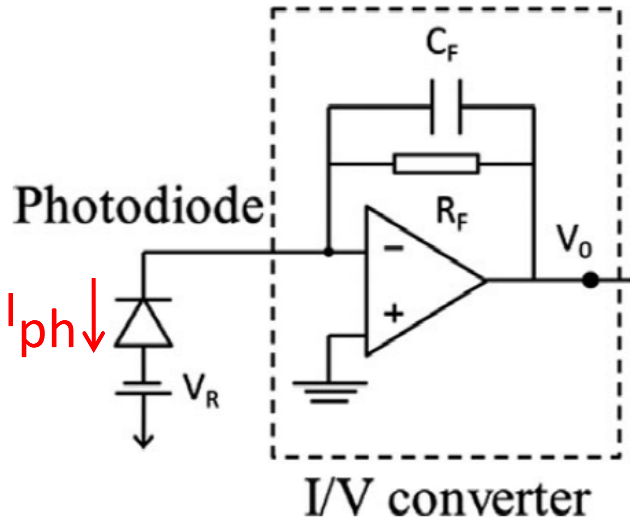




Our goal: To measure gamma rays without scintillator material using a PIN commercial photodiode designed to visible light detection.

Photodiode detectors: readout techniques

- IV converter based on an operational amplifier

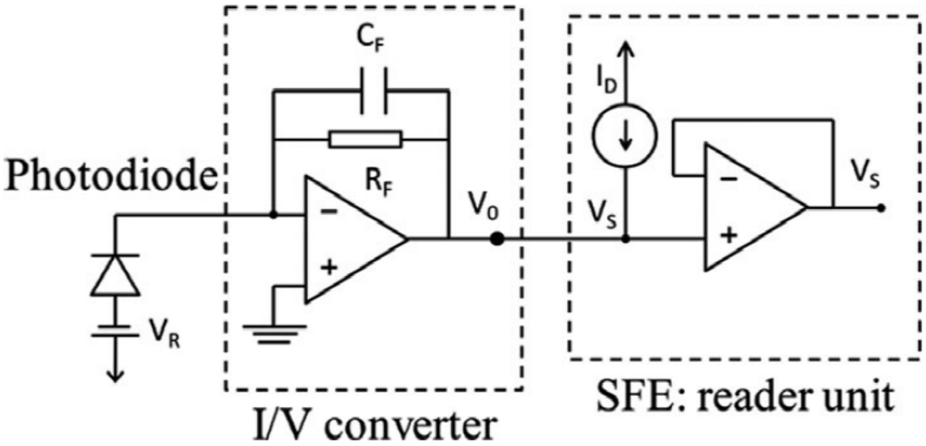


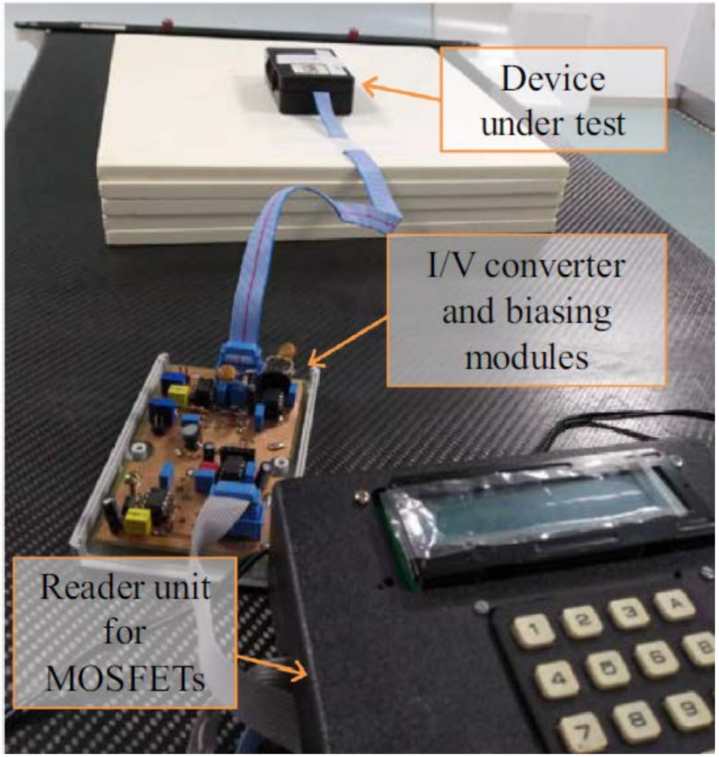
$$V_o = R_f I_{\text{ph}}$$

- Increasing the V_R voltage the sensitivity is improved and the dark current as well.

Photodiode detectors: UGR-system

- External module connected to MOSFET reader unit.





I. Ruiz-García et al., "Commercial photodiodes and phototransistors as dosimeters of photon beams for radiotherapy", Med. Phys. 48 (9), September 2021

Photodiode detectors: UGR-system

- DUT:
  - Photodiodes: VTB8440BH and BPW34S
  - Phototransistors: BPW85B and OP505A
- A symmetrical staggered irradiation cycle (2 Gy per stage)
  - Six-step decreasing the averaged dose rate (ADR) staircase from 3 to 0.5 Gy/min
  - A six-step increasing ADR rate staircase from 0.5 to 3 Gy/min.

I. Ruiz-García et al., “Commercial photodiodes and phototransistors as dosimeters of photon beams for radiotherapy”, Med. Phys. 48 (9), September 2021

Photodiode detectors: UGR-system

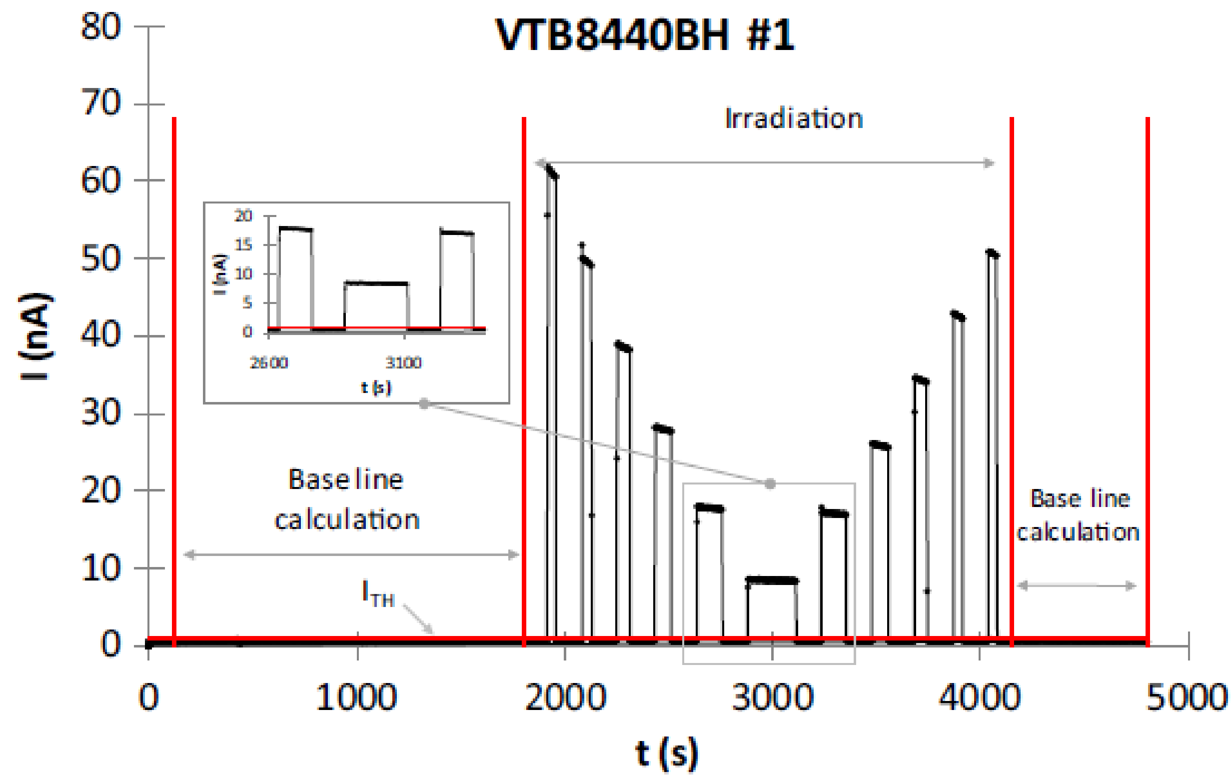
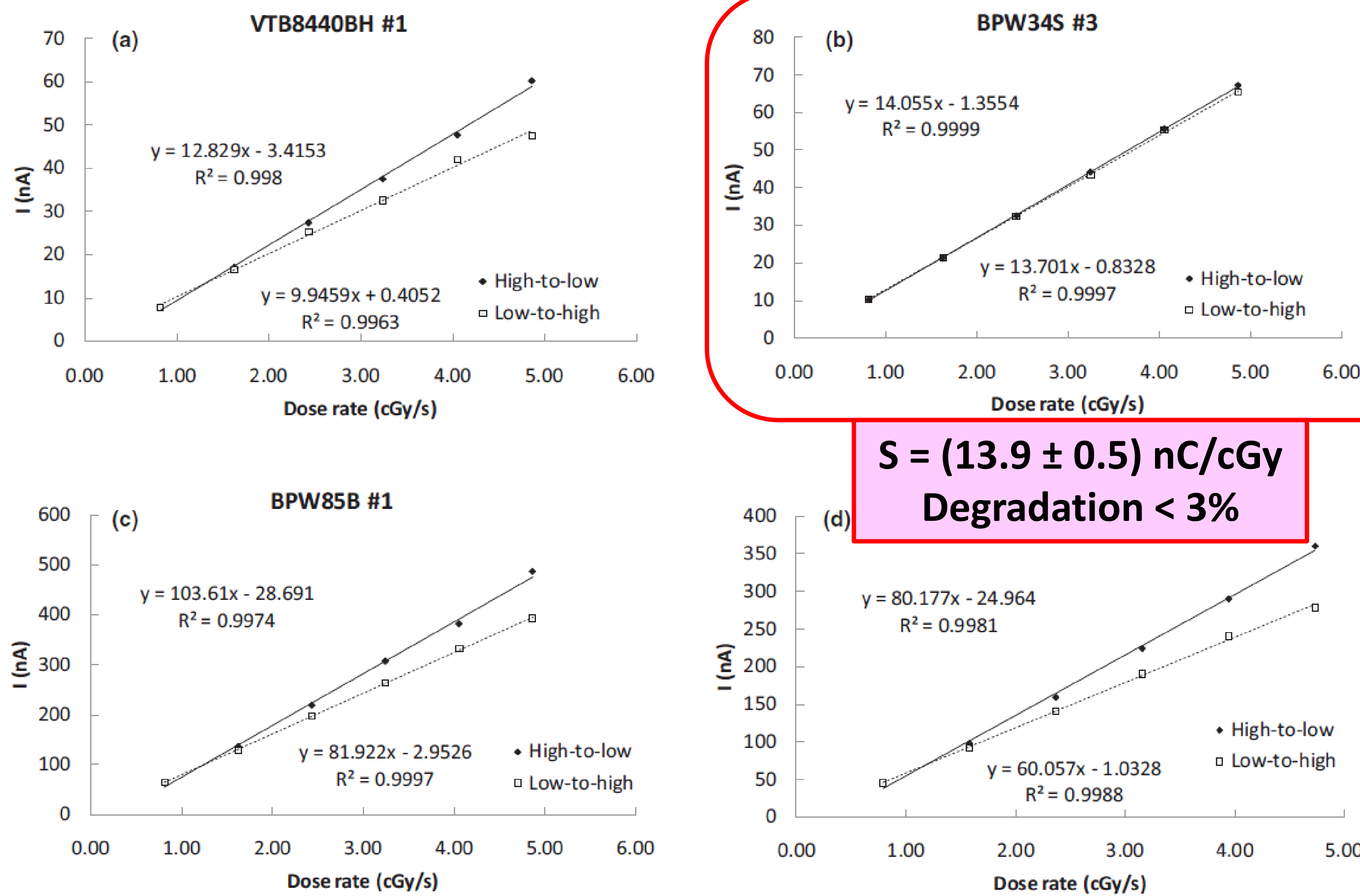


FIG. 3. Measured current during the characterization of the sample number #1 of the model VTB8440BH showing the proposed complete irradiation cycle. [Color figure can be viewed at wileyonlinelibrary.com]

Photodiode detectors: UGR-system

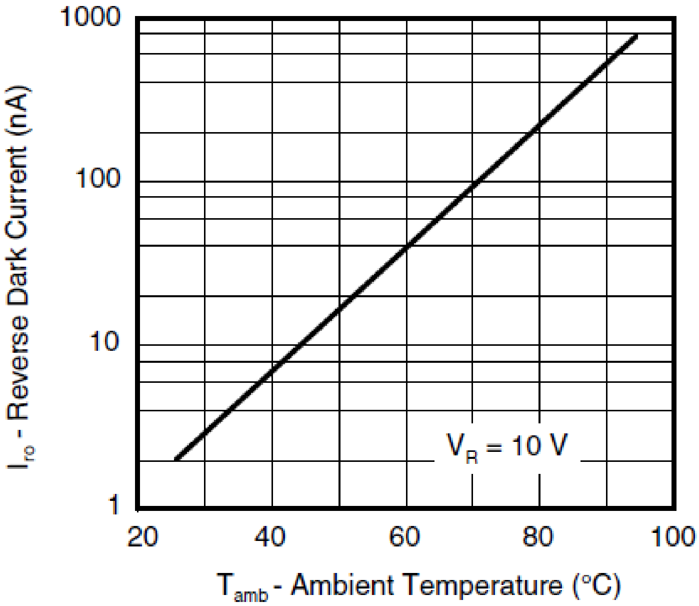


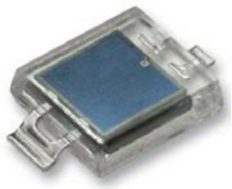
S = (13.9 ± 0.5) nC/cGy
Degradation < 3%

I. Ruiz-García et al., "Commercial photodiodes and phototransistors as dosimeters of photon beams for radiotherapy", Med. Phys. 48 (9), September 2021

Photodiode detectors: UGR-system 2

- **Problem:** The dark current of photodiodes present an exponential dependence with temperature → A thermal compensation method is mandatory to be used as radiation detectors.

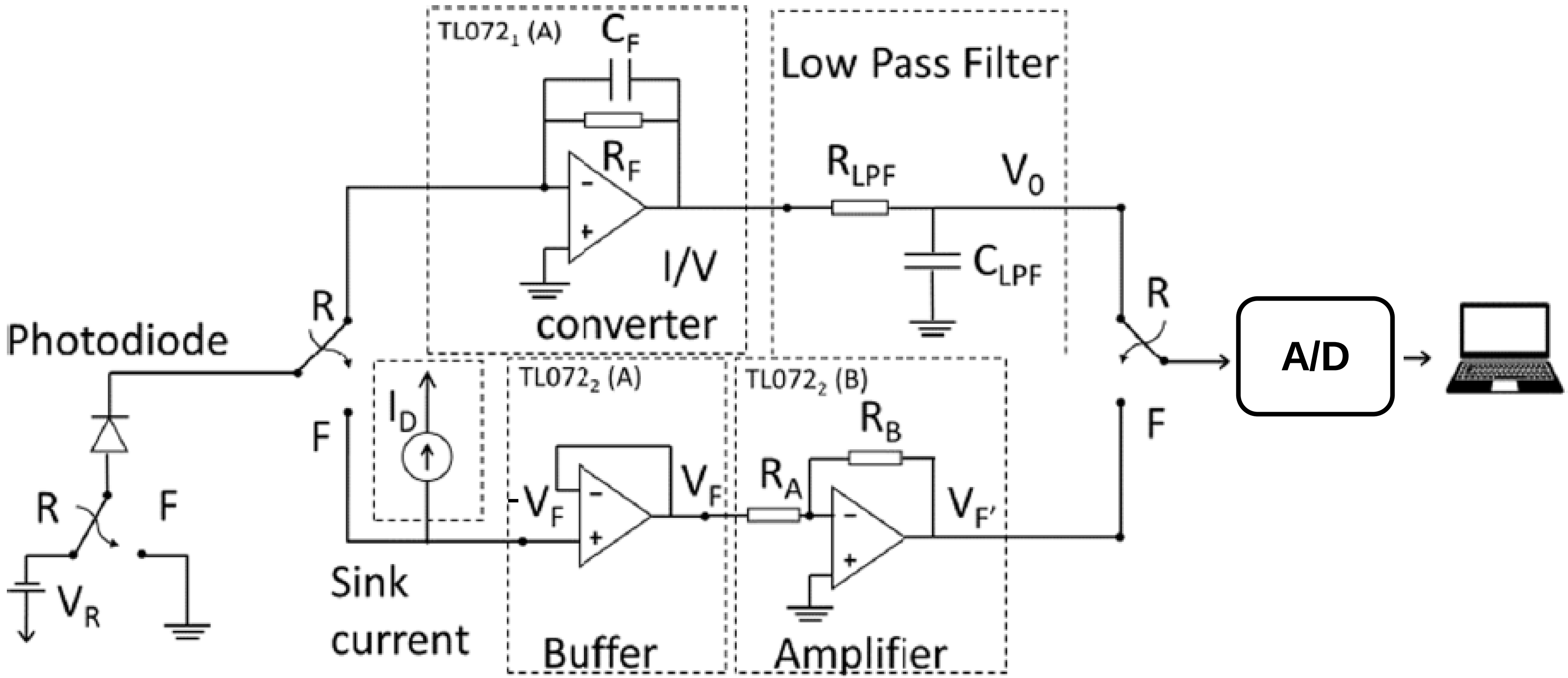




- **Our proposal:** To switch the operation mode of the device from photodiode, biased with reverse voltage, to a PIN diode biased with a forward constant current. The temperature of the silicon die is measured via the forward voltage .

Photodiode detectors: UGR-system 2

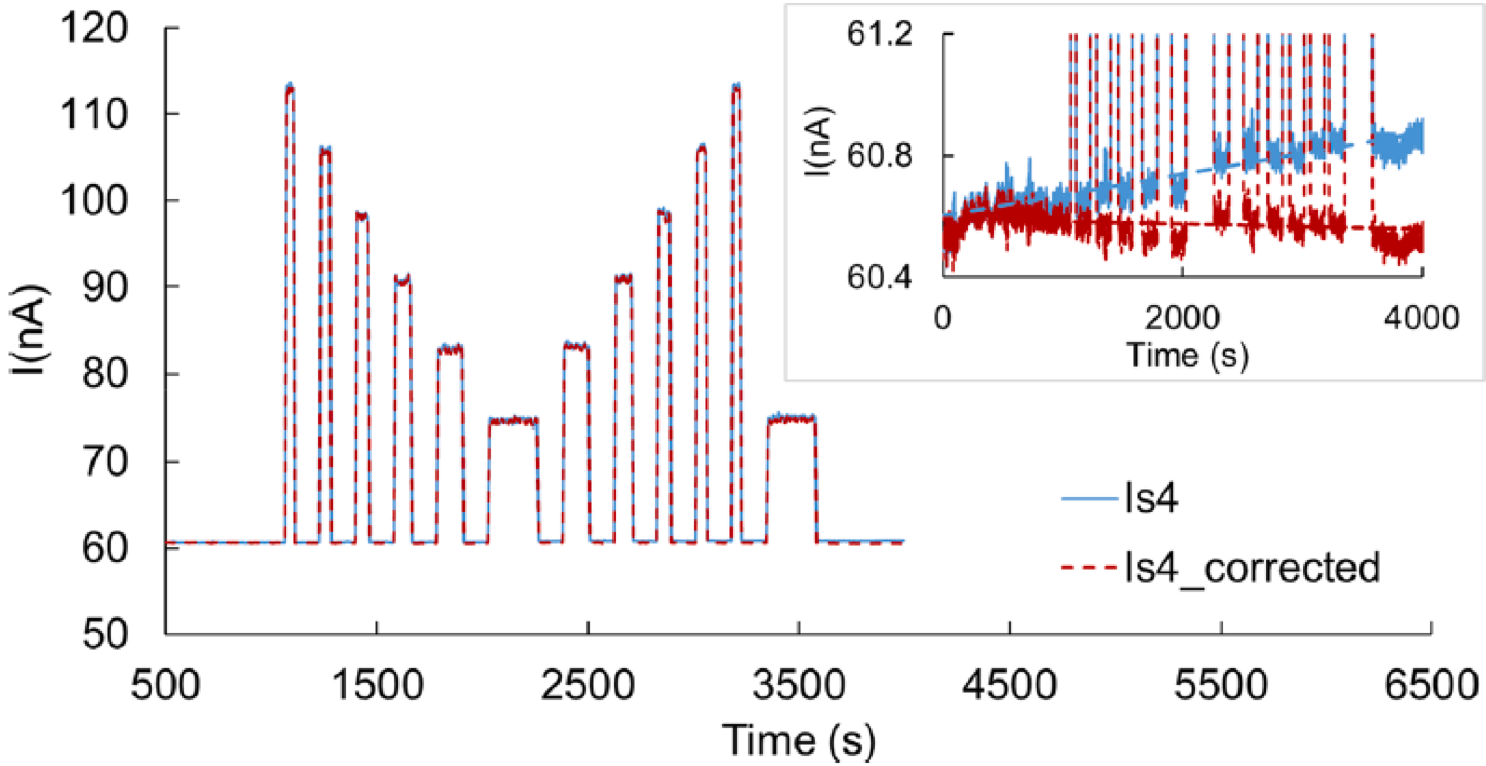
- A new reader unit for photodiode sensors has been developed. A sink current has been included to bias forward the photodiode.



I. Ruiz-García et al., “Thermal drift reduction in photodiode dosimeters with switching bias”, Measurement 199 (2022) 111538

Photodiode detectors: UGR-system 2

- The dark current (base line) can be thermal compensated.
- A reduction factor 7 of t the thermal coefficient has been reached.
- The average sensitivity has been reduced (10%) : (12 ± 2) nC/cGy



Photodiode detectors: UGR-system 2

Photodiode summary

- A commercial photodiode has been successfully tested as dose-rate sensor in the range from 0.5 to 3.0 Gy/min.
- A thermal compensation technique has been implemented.

Proton dosimetry with commercial devices

- **Introduction:** Proton therapy has become a real alternative to conventional high-energy photon beam therapy and shows up as an increasingly common treatment tool in radiotherapy centers.

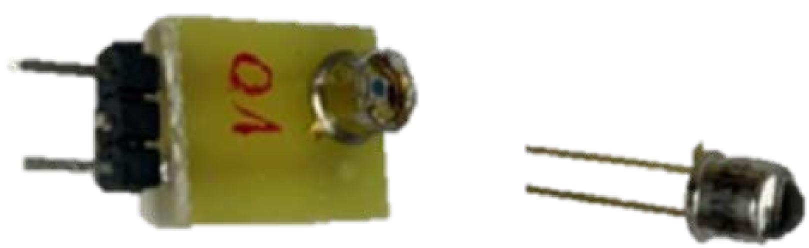
- **Motivation:** Radiation detectors based on general purpose devices would reduce the costs and improved the availability.

- **Proton source:** Accelerator capable to provide protons of 5.6 MeV

Proton dosimetry with commercial devices

- Experimental setup
  - Device under test (DUT) modification:
    - The BPW34S, characterized previously didn’t respond to proton beams due to the low penetration power of protons of 5.6MeV.
    - The top of the housing has to be removed, so a different photodiode was characterized.

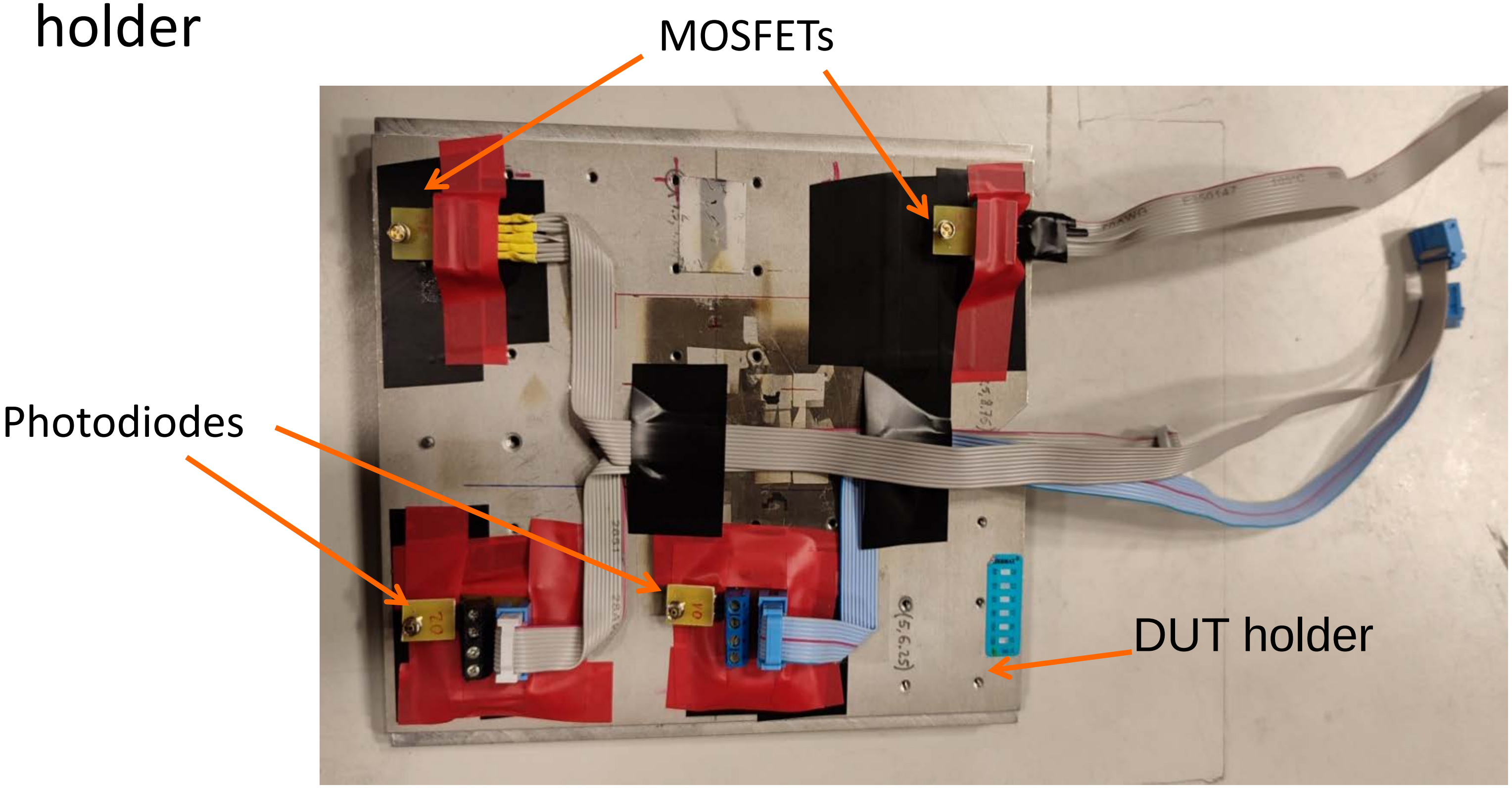
MOSFET 3N163 (Vishay) decapsulated



BPW24 (Vishay) decapsulated and original

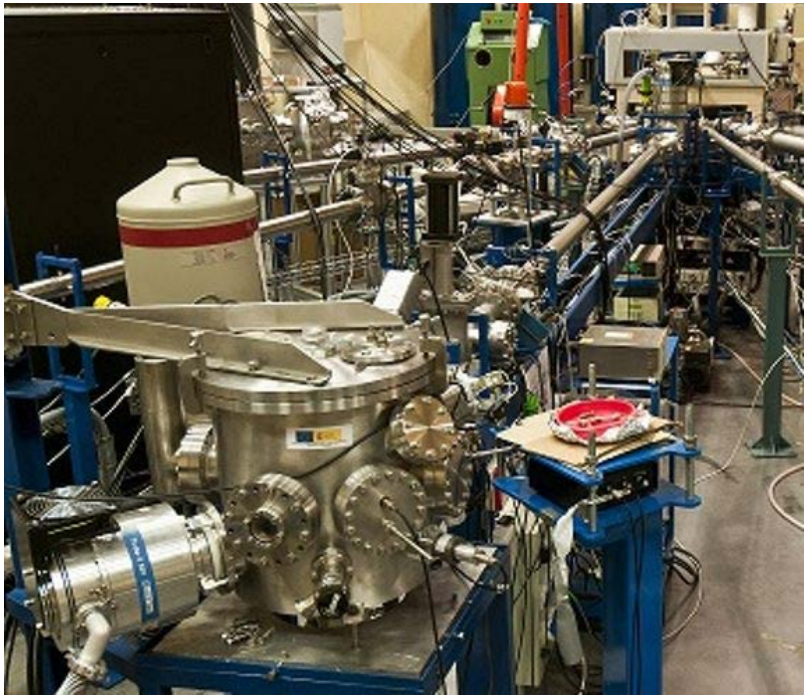
Proton dosimetry with commercial devices

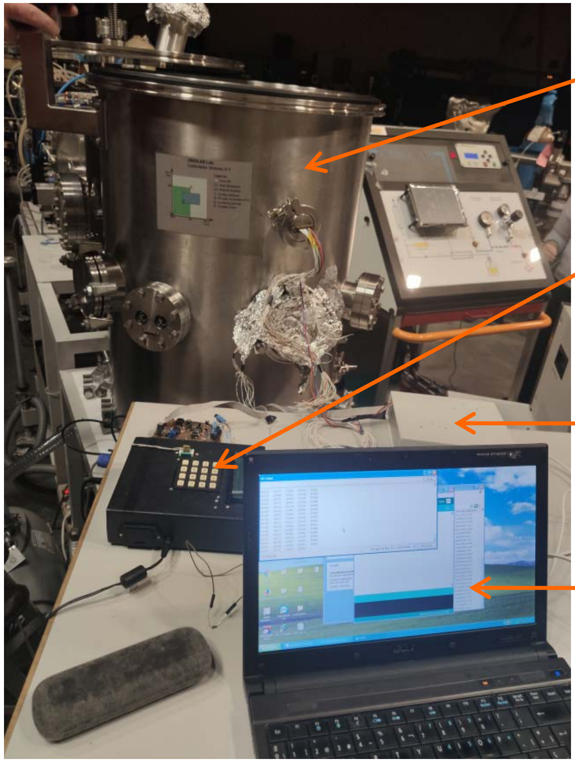
- Experimental setup:
  - DUT placements: Two MOSFETs and two photodiodes in the holder



Proton dosimetry with commercial devices

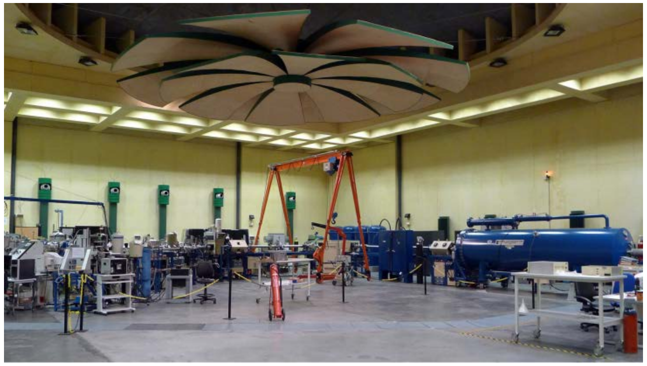
- Irradiation facility: National Accelerator Centre, CNA (Sevilla, Spain)
  - Tandem Accelerator capable of generating proton beam of 5.6 MeV.

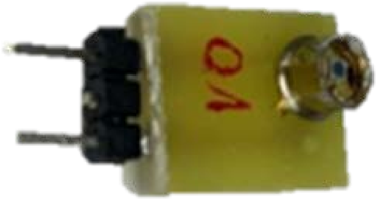




Proton dosimetry with commercial devices

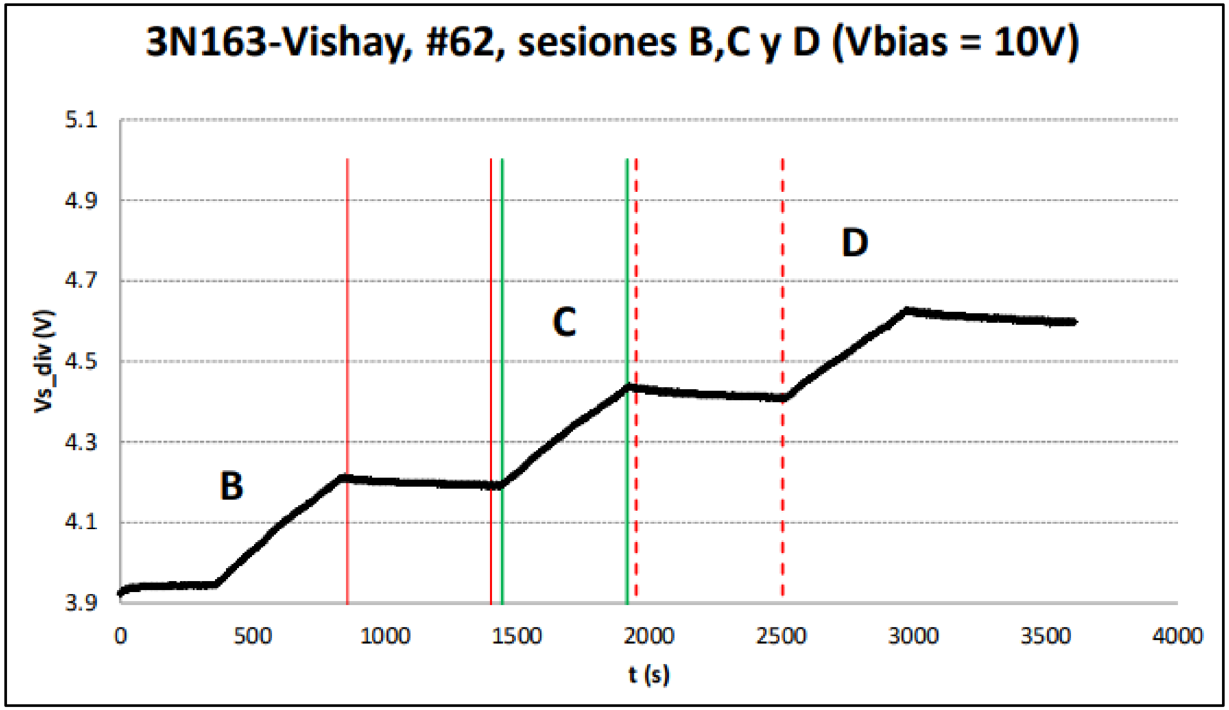
- Irradiation conditions:
  - MOSFET:
    - Irradiation sessions of 2 minutes with sweeps of 10x10 cm and rest about 8 minutes -> Average dose rate of 11.2 cGy(Si)/s.
  - Photodiodes:
    - Irradiation sessions of 2 minutes with sweeps of 2x2 cm and rest about 8 minutes -> Average dose rate of 8.69 Gy(Si)/s.





Proton dosimetry with commercial devices

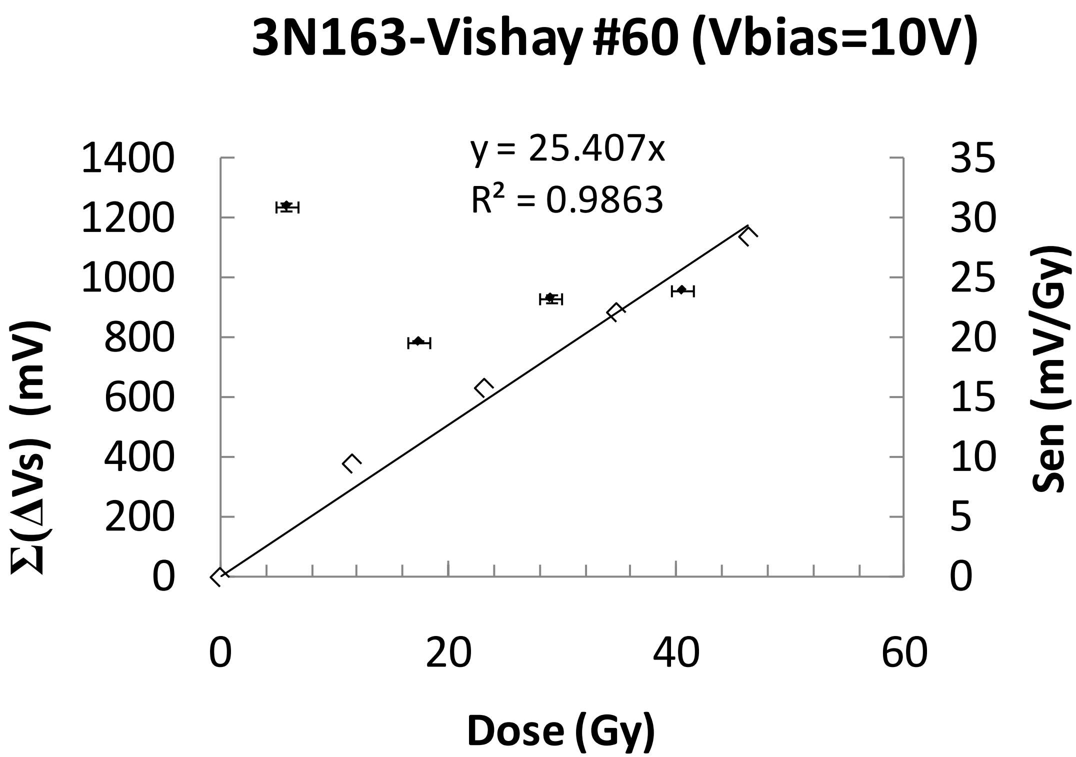
- Results



- **During irradiation** (between **green lines**), the MOSFET source **voltage increases**, while during **rest periods** (between **red lines**) it is **slightly reduced** (short term fading).

Proton dosimetry with commercial devices

- MOSFET Results
  - **Sensitivity** has been calculated from the **the slope** and the rate of absorbed dose in silicon.



Proton dosimetry with commercial MOSFET

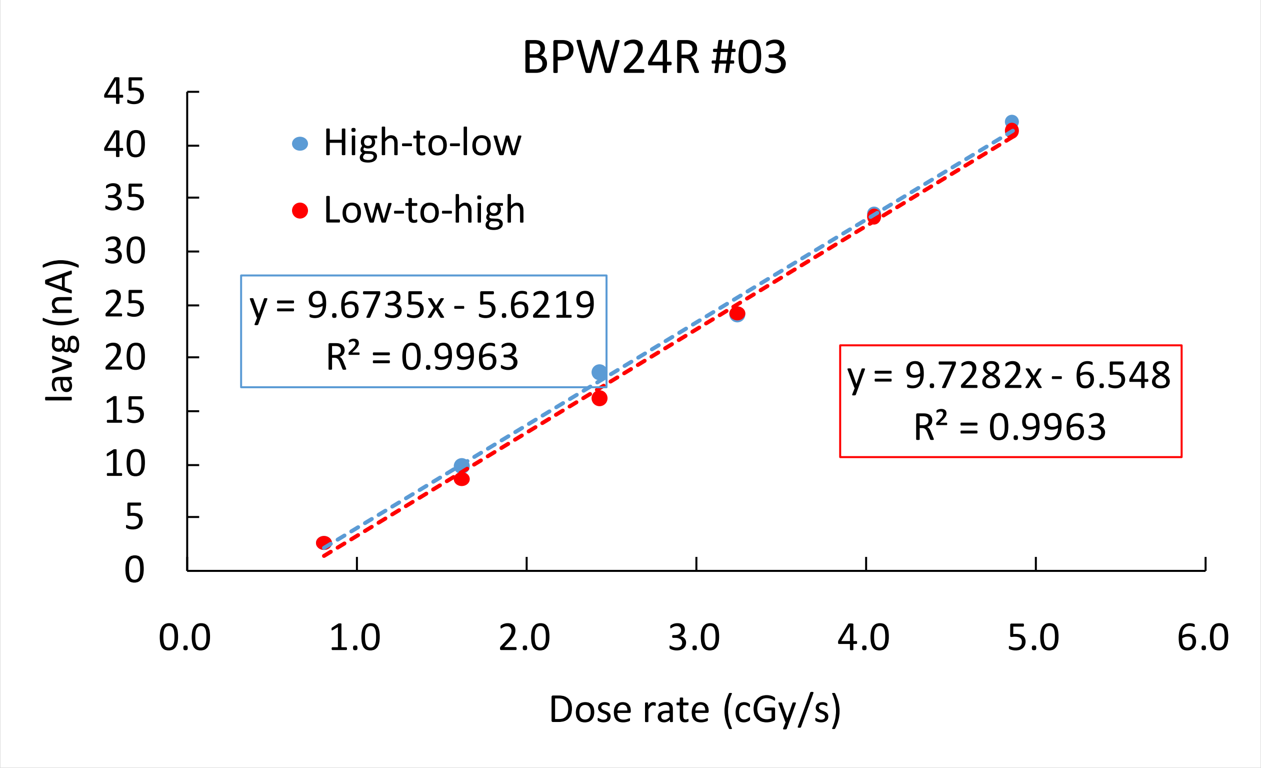
- Results

	Sen (mV/Gy)	SD (mV/Gy)
62	21.4	0.7
61	21.1	0.8
60	25.4	0.8
AVG	**23**	**3**

- Conclusion:
  - The 3N163 transistor from Vishay presents a promising response as a dosimeter for proton beams.
- Current and future tasks:
  - A completed characterization with other bias voltage will be carried out to study the sensitivity, the sensitivity decay, and the fading among others parameter.

Proton dosimetry with commercial photodiode

- Characterization with photons: Three samples of BPW24R were studied using the same experimental setup used for the model BPW34S.

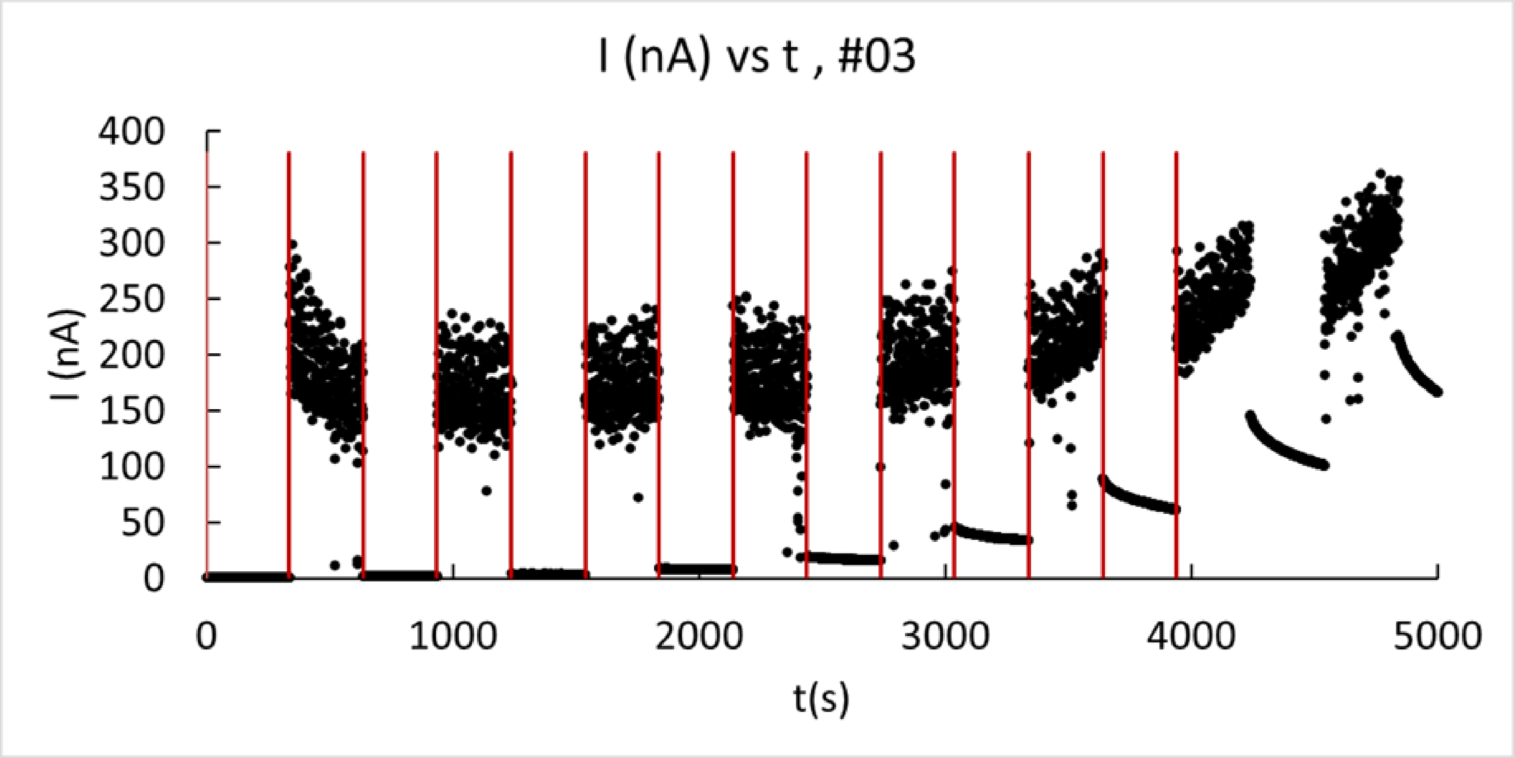


BPW34S
S = (13.9 ± 0.5) nC/cGy
Degradation < 2%

BPW24R
S = (9.7 ± 0.6) nC/cGy
Degradation < 3%

Proton dosimetry with commercial photodiode

- Results
  - Very high dose: 1.04 kGy per irradiation session.
  - The dark current has increase with high doses.



Proton dosimetry with commercial photodiode

- Results
  - Very high dose: 1.04 kGy per irradiation session.
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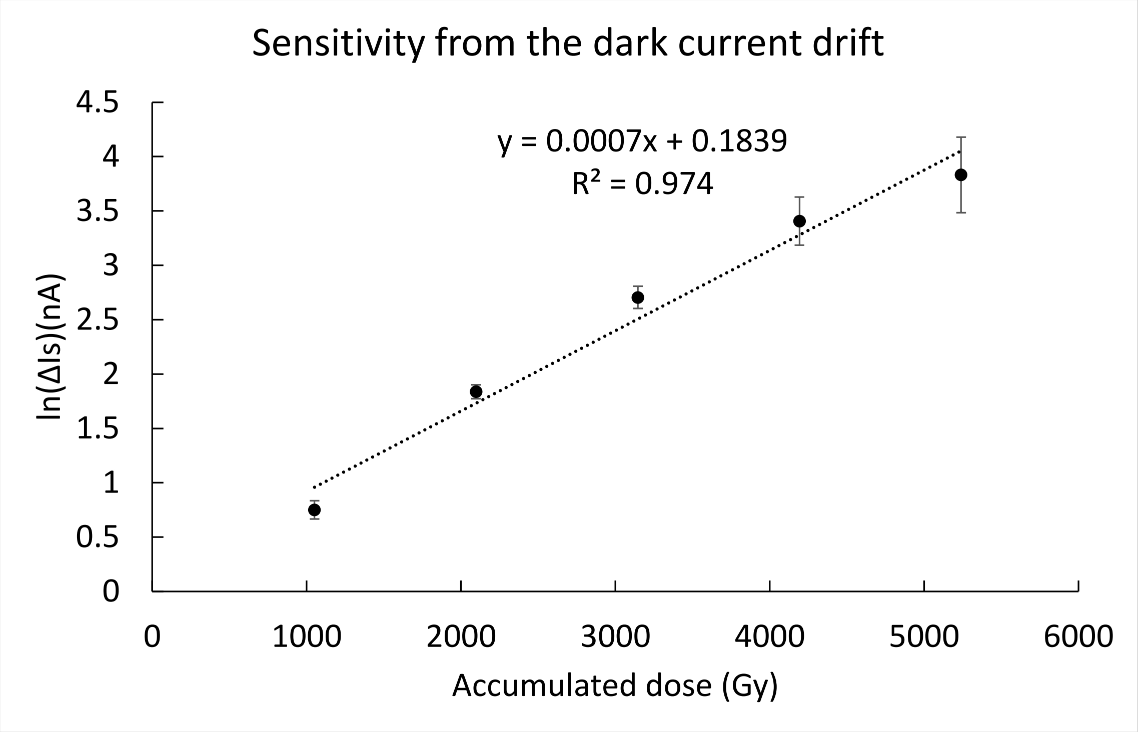

Proton dosimetry with commercial photodiode

- Conclusion:
  - After this preliminary study, the dark current of the BWP24S could be a dosimetric parameter for very high doses, upto 5kGy.
- Future and current task:
  - To test the BWP24S with sweeps of 2x2 to reduced the dose per session, and then, study the degradation and the fading of the sensor.
  - To design a photodiode matrix and a new reader unit to study the sweep of the photon bean in the irradiation field.

Conclusions

- Devices not designed to ionizing radiation detection can be use as radiation sensors with the correct bias, amplification and thermal compensation techniques in radiotherapy treatments (dose higher than 1 Gy).
- Commercial devices has been successfully tested for electron and photons beams as radiation sensors for radiotherapy typical doses.

- **Future task**: To enhancement the study the response with proton beams of commercial photodiodes and MOSFETs.

ECsens
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General purpose devices as radiation sensors: MOSFET and photodiodes

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