HARDWARE TECHNIQUES FOR ACCURATE READ-OUT OF SOLID-STATE DOSIMETERS

Alberto J. Palma – University of Granada

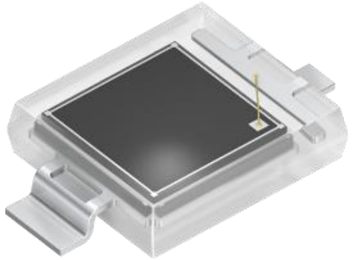
2nd WORKSHOP ELICSIR PROJECT, 9-10.03.2021

Agenda

- Introduction
- Silicon PIN diodes
  - General remarks
  - UGR reader design
- MOSFETs/RADFETs
  - Sensor response and configurations
  - UGR real-time reader
  - CubeSAT URSA MAIOR project

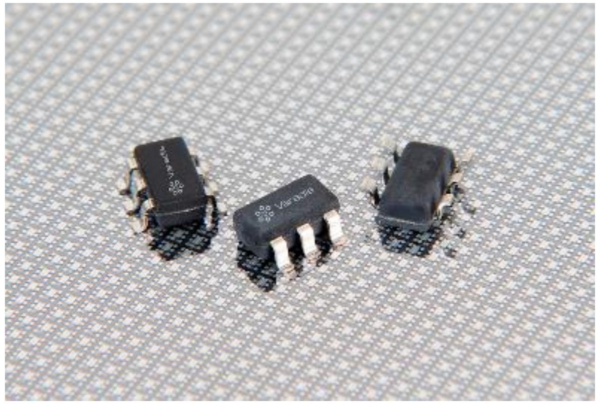
Introduction

- **Talk scope**: Radiotherapy control
  - Dosimeters: Si PIN diodes and MOSFETs/RADFETs
    - Commercial low-cost devices
    - Current and voltage mode sensor output
  - Analog and mixed conditioning electronics
    - Main influential factors: sensors specs. (sensitivity, biasing, output ranges, impedance, noise, …)
    - Design considerations:
      - Portable/Handheld reader (powering, size, weight)
      - Acceptable performance (accuracy, resolution, dynamic response, and ranges)



Si PIN Diode

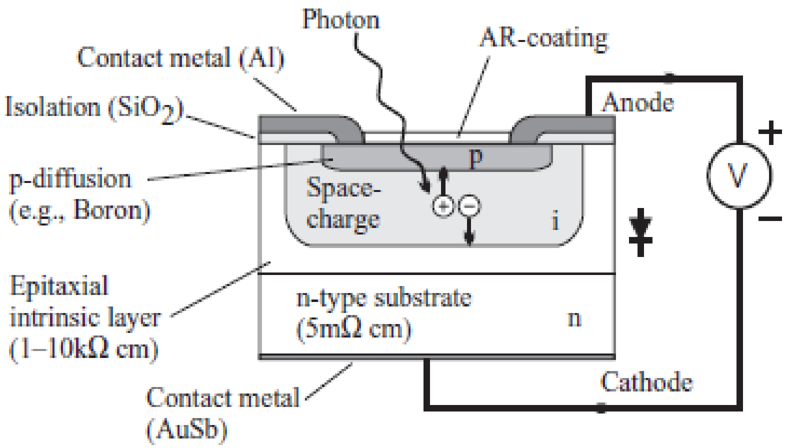
3N163 MOSFET

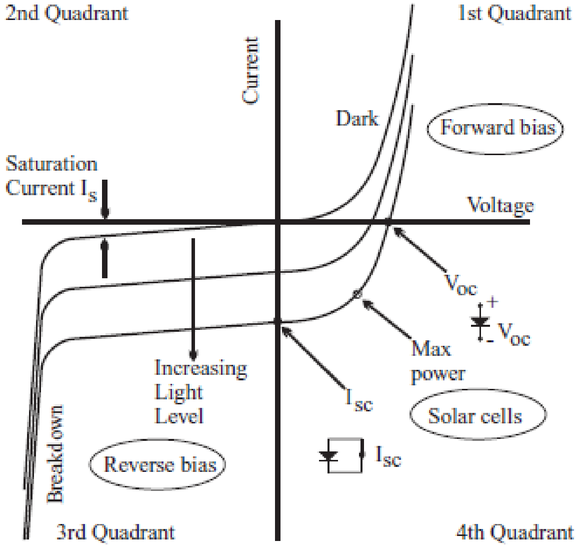


RADFETs by Varidis

Si PIN diodes: Response to radiation

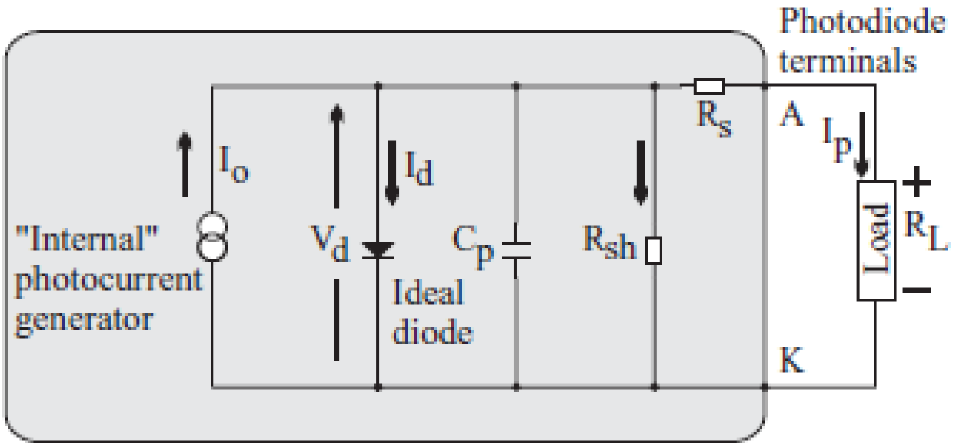
- Structure: diode with an *ad hoc* intrinsic region to extend sensitive volume
- Response:
  - Creation of radiation-induced e-h pairs
  - Separated by depletion-layer electric field
  - Immediate photocurrent in its terminals.
- Photovoltaic mode (Commercial detectors)
  - Diode is not biased
  - Operates as a source (solar cell)
- Photoconductive mode
  - Diode is in reverse bias
  - Operates similarly to a photoconductor (LDR)





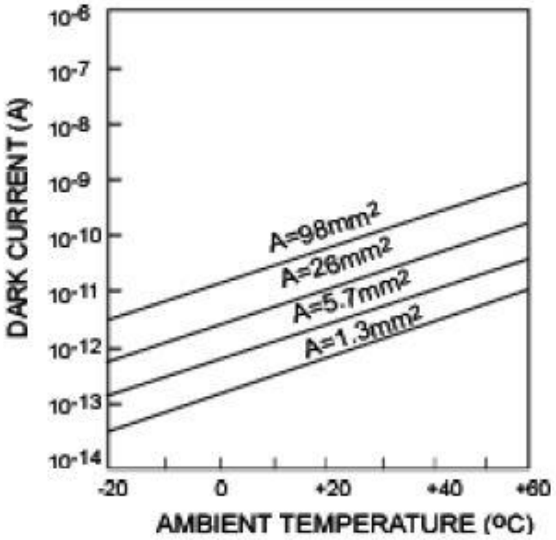
Si PIN diodes: Element of circuit

- **Equivalent circuit**:
  - I_o = dark + photocurrent
  - I_d = direct current (negligible)
  - C_p = junction capacitance (1- 10^3 pF)
  - R_{sh} = shunt resistance (0.1 – 10 GΩ)



- **Noise**: Shunt noise dominates

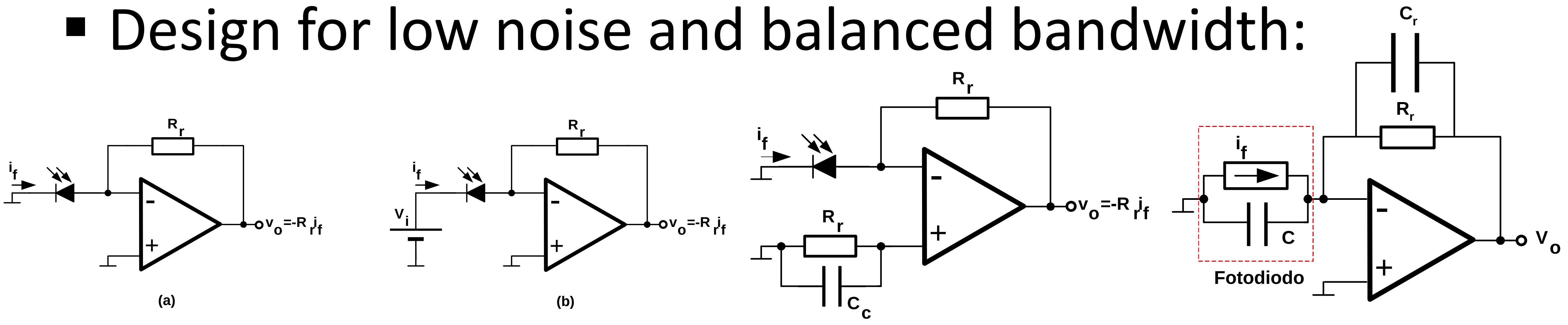
$$i_{nt} = \sqrt{i_{nj}^2 + i_{ns}^2} = \sqrt{\frac{4kTB}{R_{sh}} + 2qI_oB}$$



- **Temperature**: greatly affects dark current

Si PIN diodes: I-V converters

- Design for low noise and balanced bandwidth:



Unbiased or reverse biased

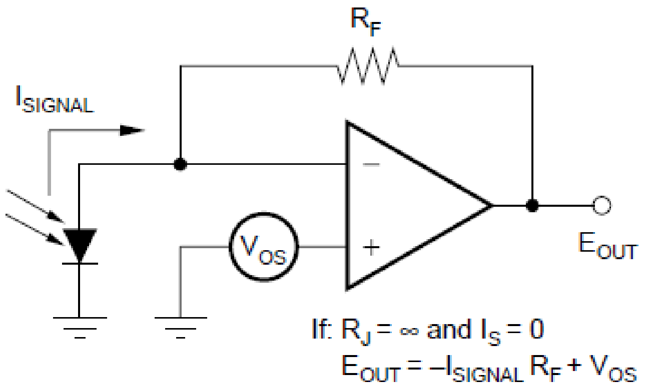
I_B compensation

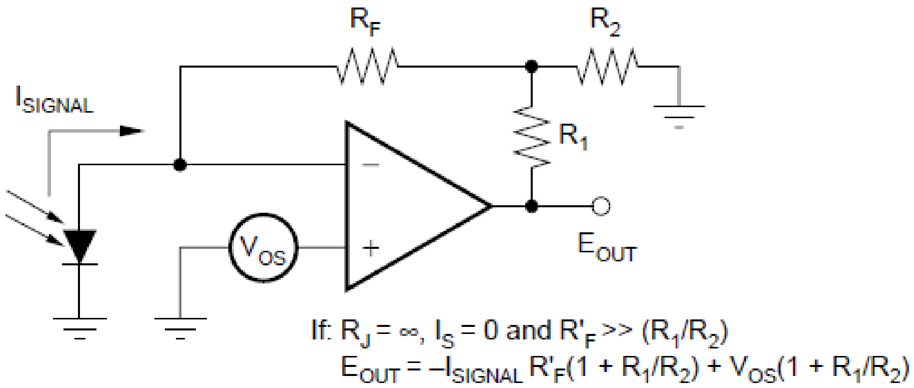
Stability

- Operational amplifier (FET): High input resistance >> R_{sh}.
- R_r also in V^+ for bias current compensation
- C_r: circuit stability and low-pass filtering (not too much)
- Photocurrents 0.1- 50 nA => $R_r \approx$ 0.1-1 GΩ ($V_0 \approx$ 1 V)
  - GΩ resistors: noisy, high tolerance, high thermal drift, short bandwidth

Si PIN diodes: I-V converters

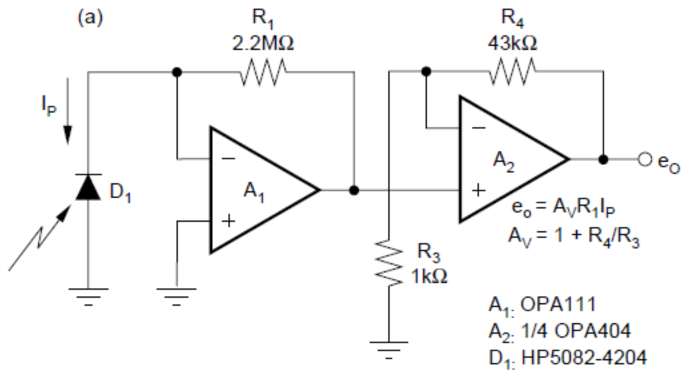
- Solution 1: T-Network

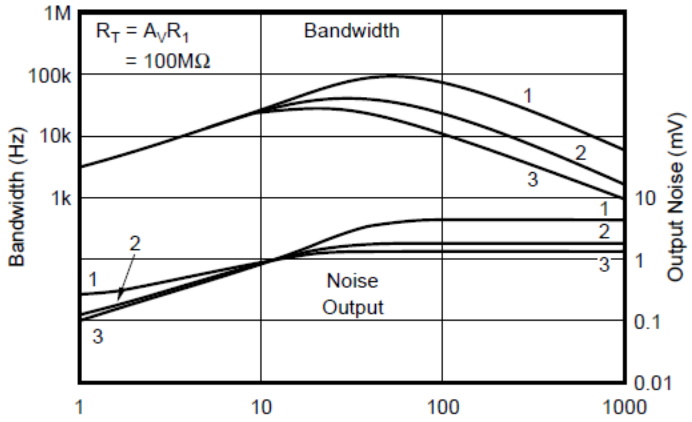




Offset Voltage amplification

Solution 2: Two stages

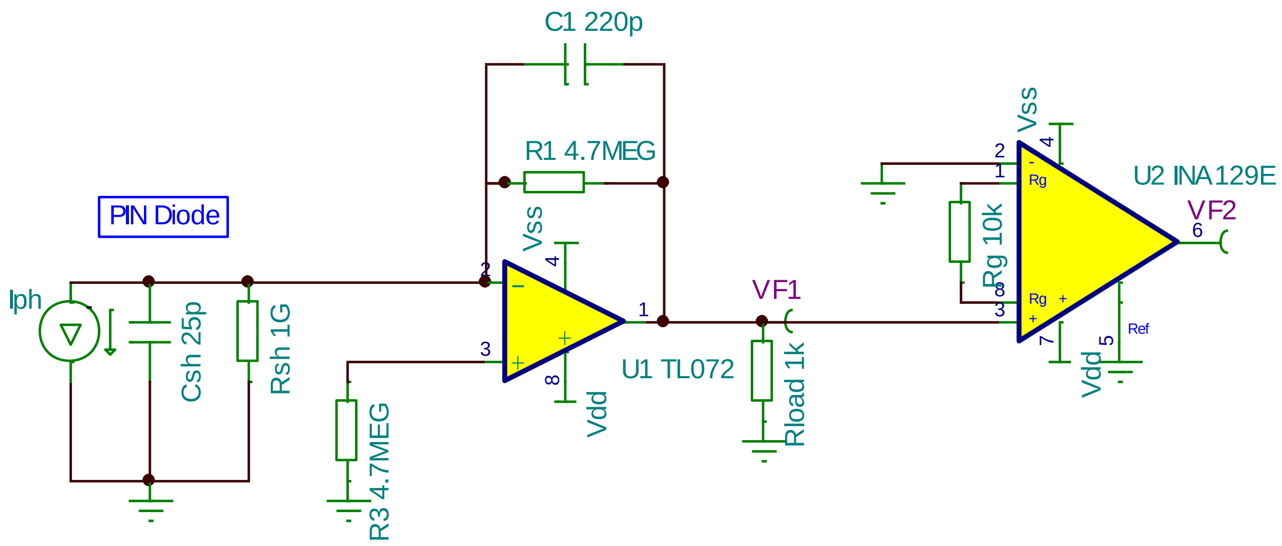




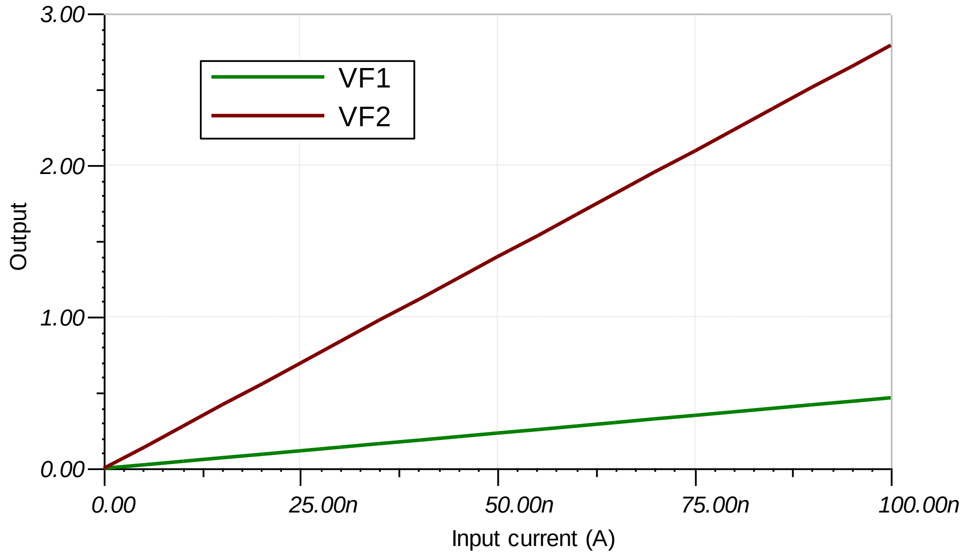
Better BW-noise trade-off

Si PIN diodes: UGR reader

- Solution 2: Two stages
  - I-V converter: $VF1 = 4.7 \cdot 10^6 \cdot I_{ph}$ + Voltage amplifier $Av \approx 20$



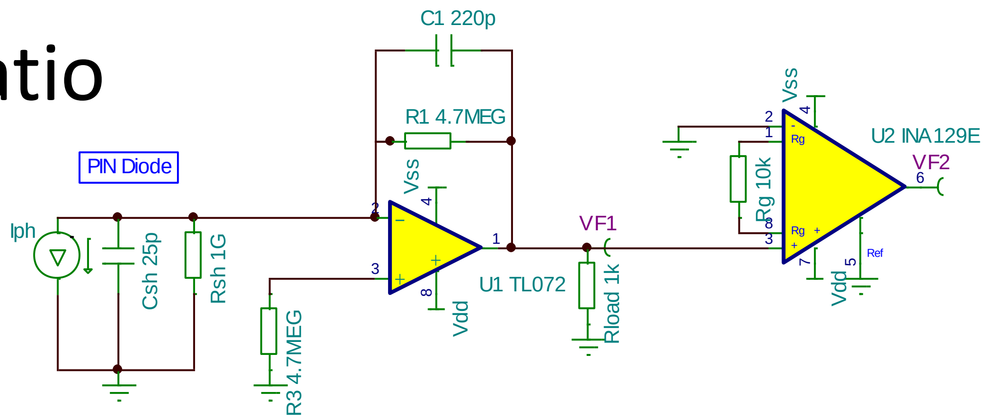
TL072 (FET-input op. Amplifier)
R_i = 1000 GΩ
Low noise : V_n = 18 nV/√Hz @ f = 1 kHz

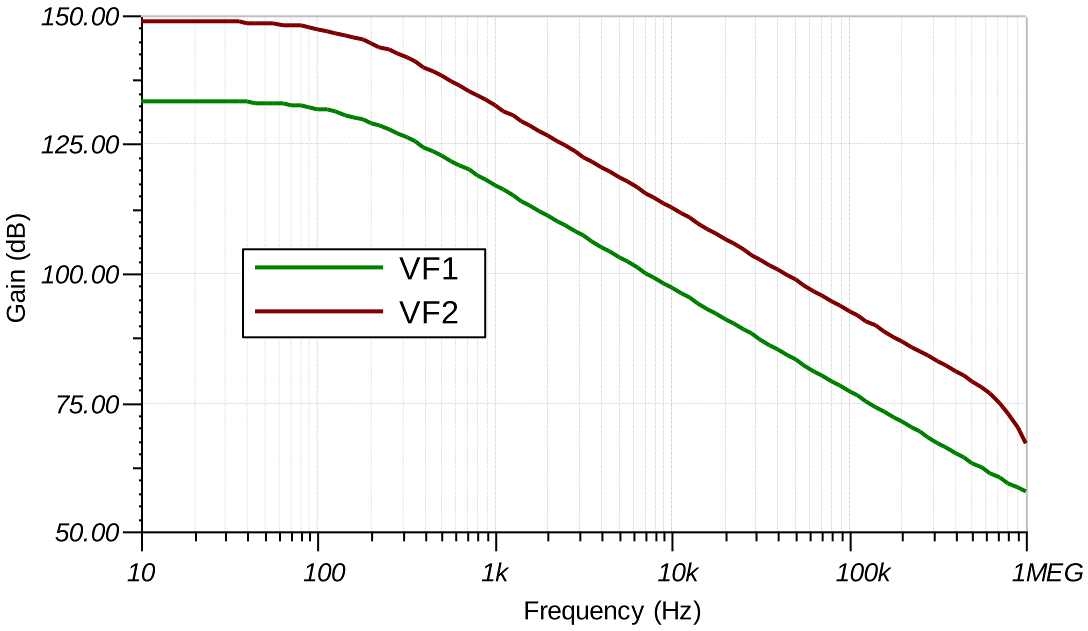


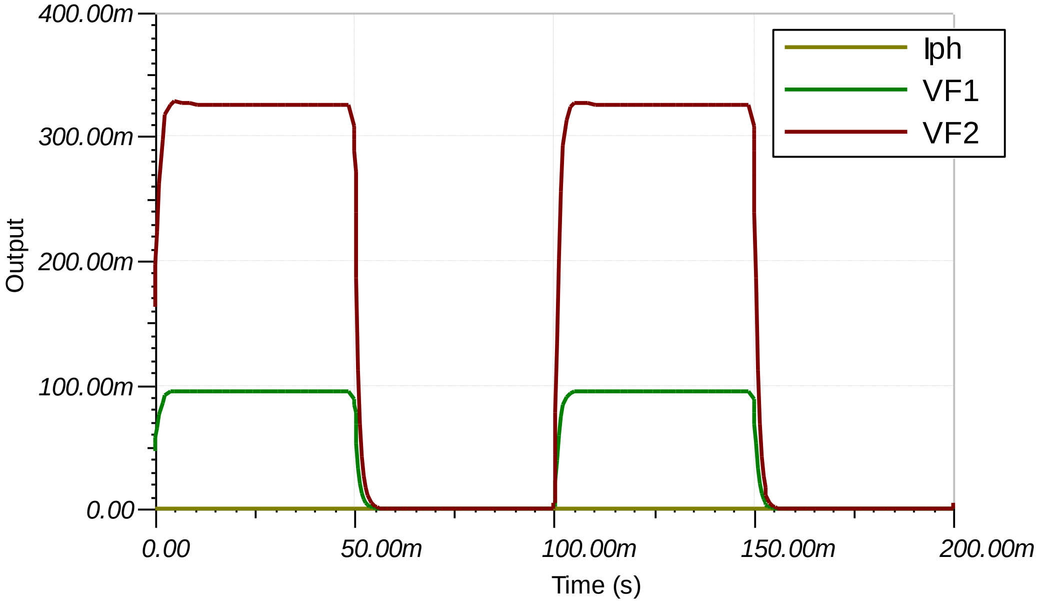
  - Total amplification≈ 0.1 V/nA
  - 16 bits Analog-to-digital converter
  - Error (2·SD): 0.2 nA

Si PIN diodes: UGR reader

- AC behaviour and signal-to-noise ratio
  - BW= 100 Hz
  - SNR > 80 dB (up to 1 kHz) (> 13 bit ADC)
  - Slew rate: 70 V/s

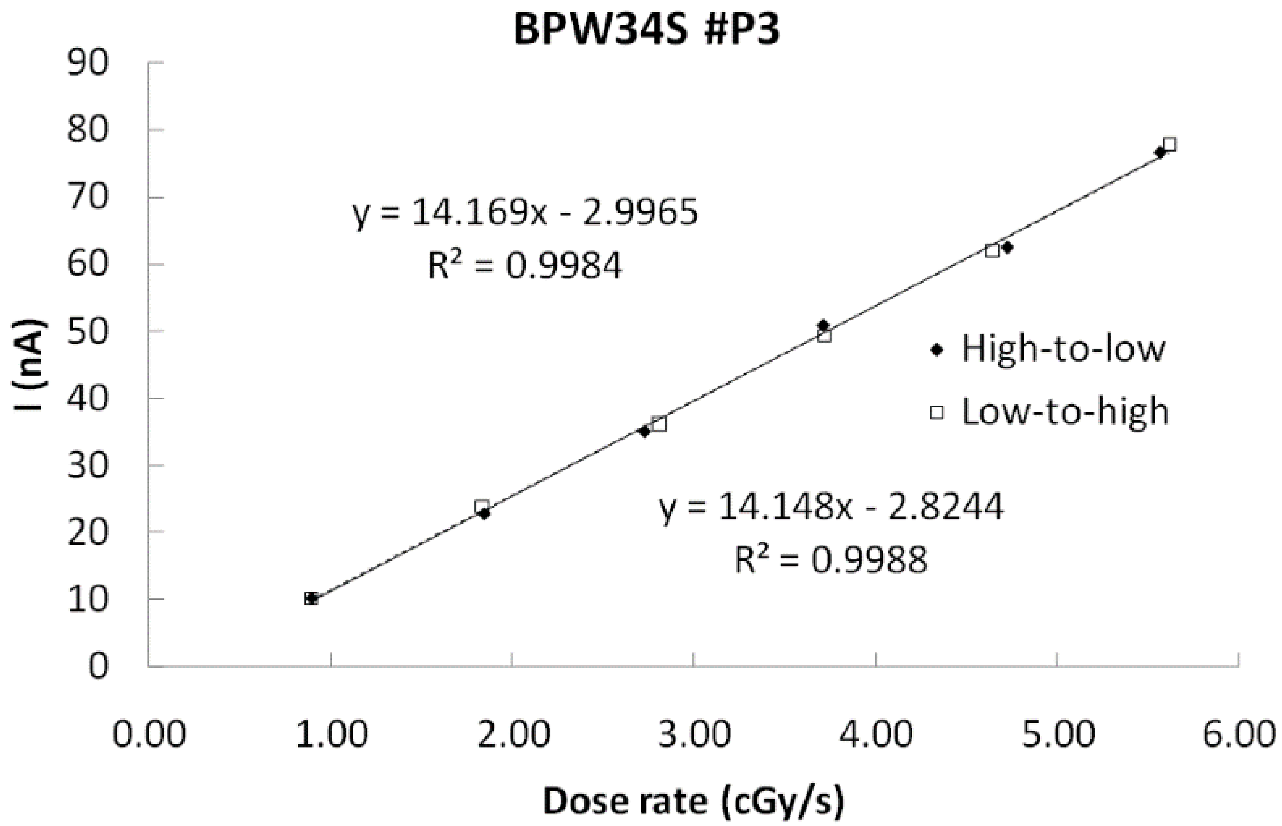






Si PIN diodes: UGR reader

- Some experimental results of BPW34S Si PIN diode:



Studied devices:

- BPW34S
- VTB8440BH

Unbiased and reverse bias

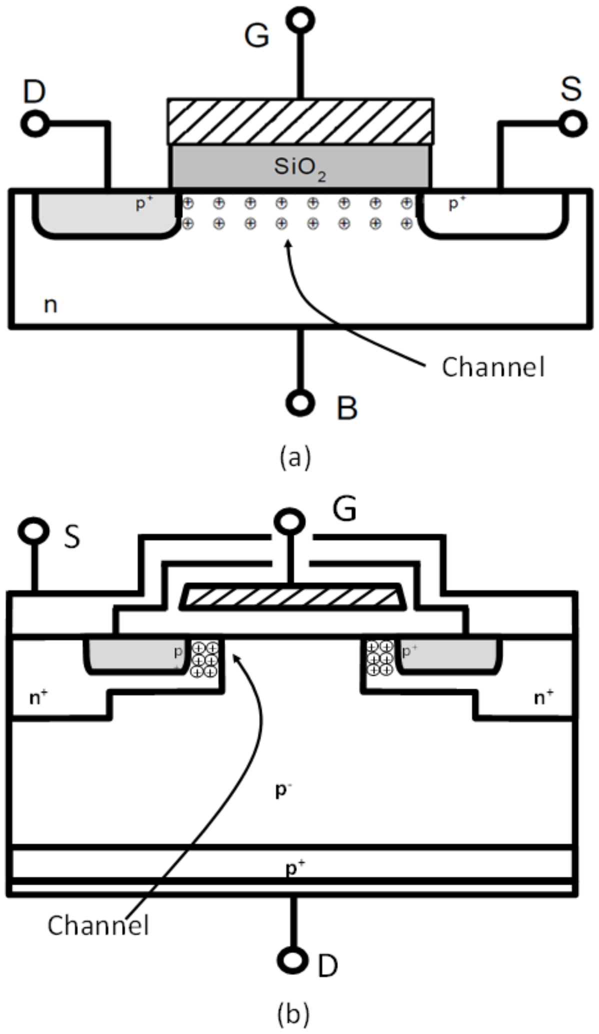
Measured photocurrent versus dose rate in a LINAC (16 MV beams)

MOSFET/RADFET: Structure

- Enhancement p-channel MOSFETs
  - (a) Lateral (RADFET) Higher sensitivity
  - (b) Vertical – DMOS, inexpensive
  - I-V characteristic in saturation region:

$$i_D = -\frac{\beta}{2}(|v_{GS}| - |V_t|)^2$$
$$\Leftrightarrow |v_{GS}| \geq |V_t|, |v_{DS}| \geq |v_{GS} - V_t|$$

Typical biasing region when used as radiation detector

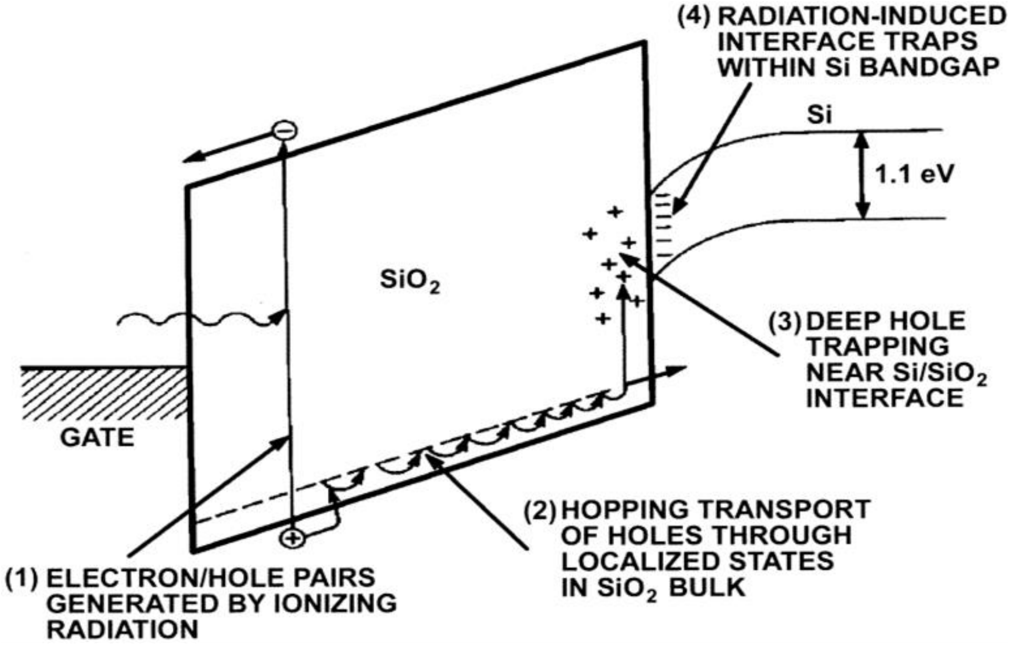


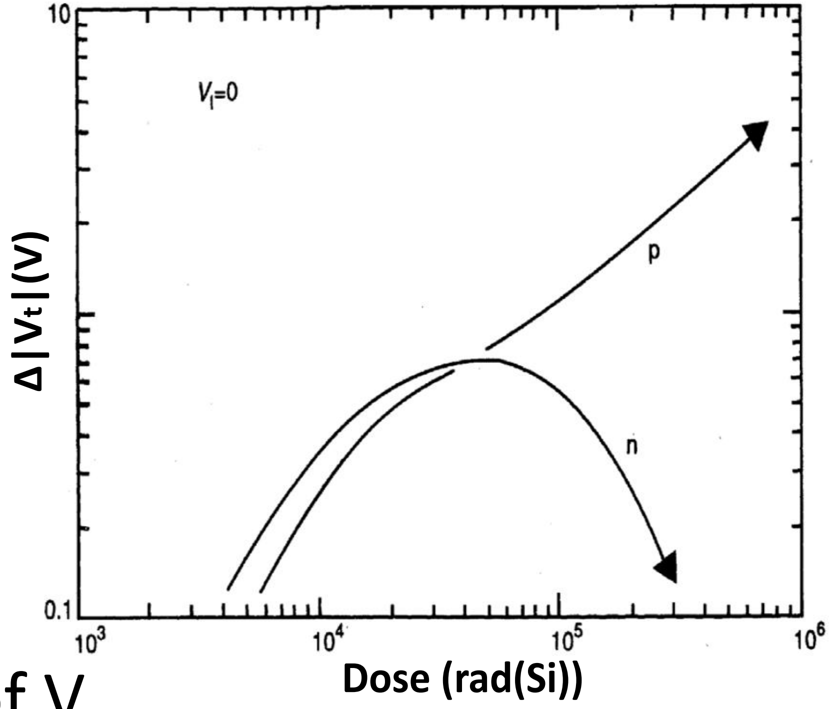
(a) (b)

MOSFET/RADFET: Response to radiation

- Positive charge trapped near the interface
- Interface traps in the interface

$$\Delta V_t = -\frac{Q_{ss}}{C_{OX}} = -\frac{1}{C_{OX}}(\Delta Q_{OT} + \Delta Q_{IT})$$

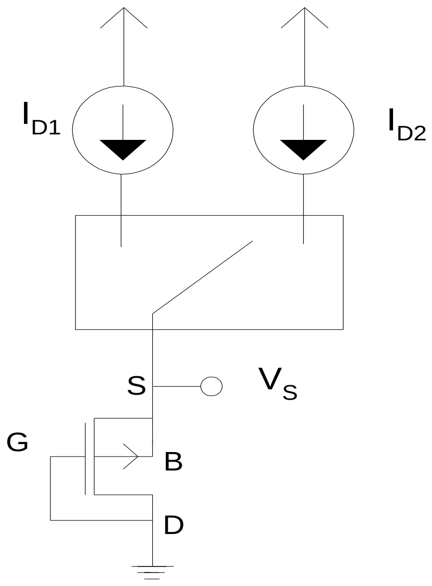


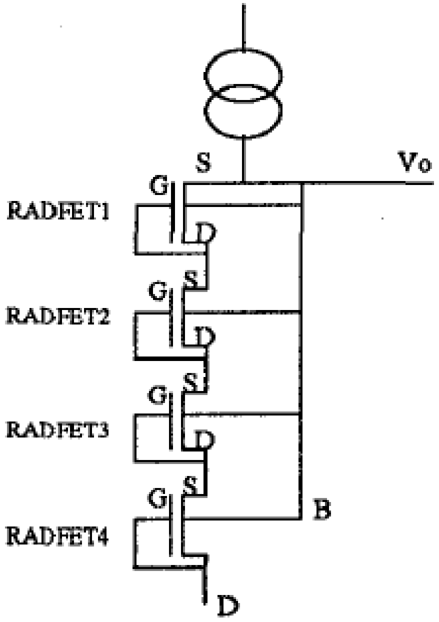


Storage charge mode operation: Monitoring of V_t

MOSFET/RADFET: Configurations as dosimeter

- Unbiased/Biased gate-source voltage
- Single or stacked devices





Measure V_S with constant current method

Saturation region V_{GD}=0

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

Considering β≈ cte => $\Delta|v_{GS}| \approx \Delta|V_t|$

Gate to ground V_G=0

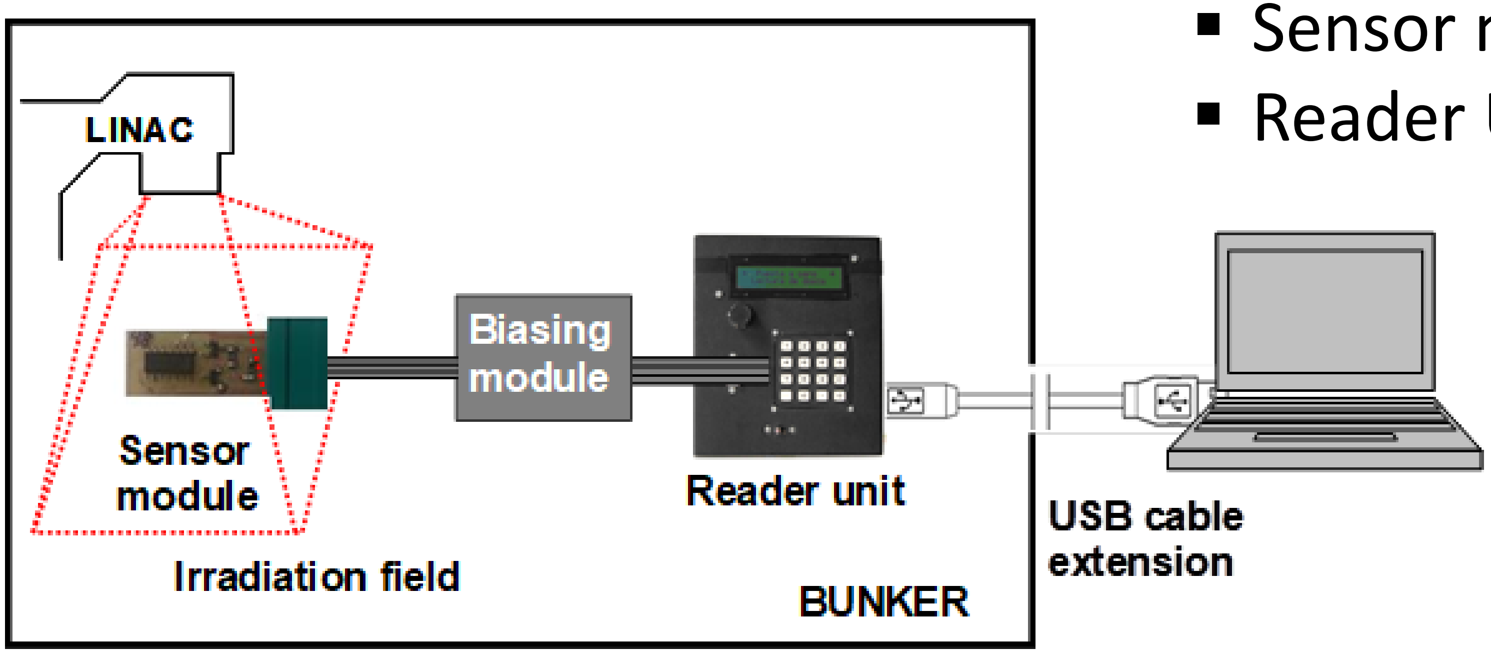
$$\boxed{\Delta|V_S| \approx \Delta|V_t|}$$

- In all cases, source-drain voltage read-out under constants I_D

MOSFET/RADFET: UGR real-time reader system

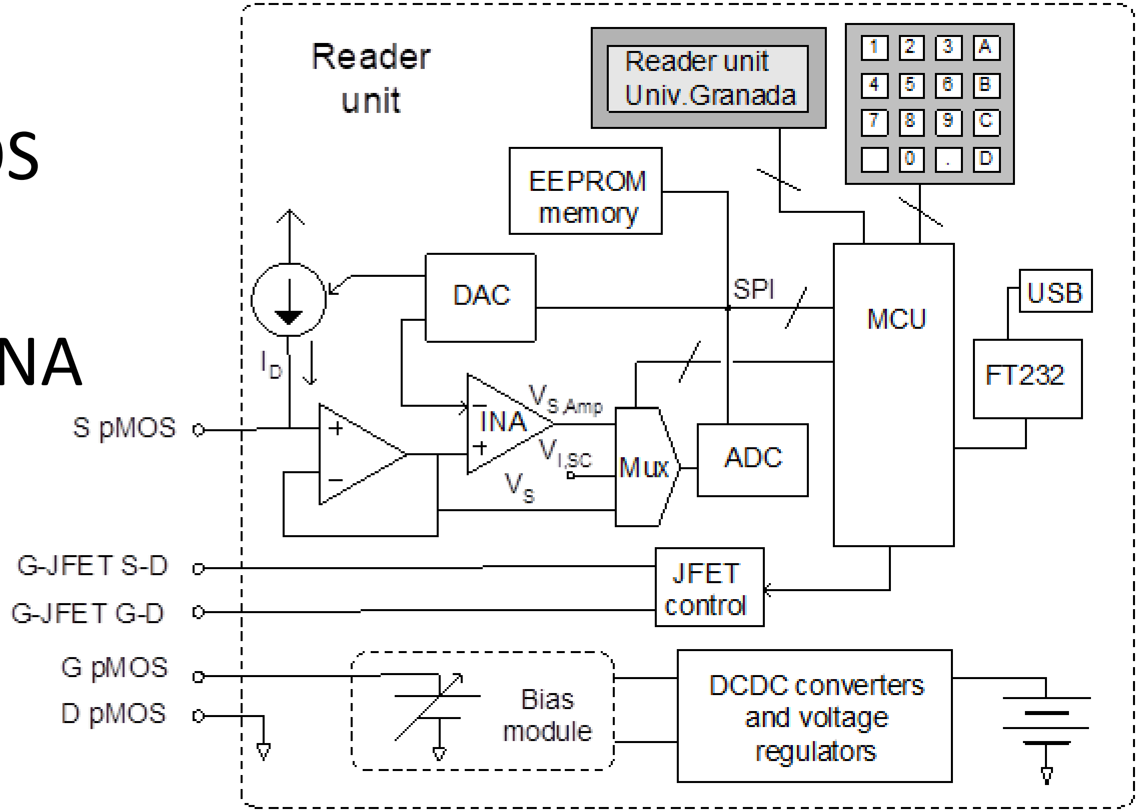
- Compact electronic reader able to read in real time:
  - Unbiased/Biased pMOS
  - Up to 2 stacked devices

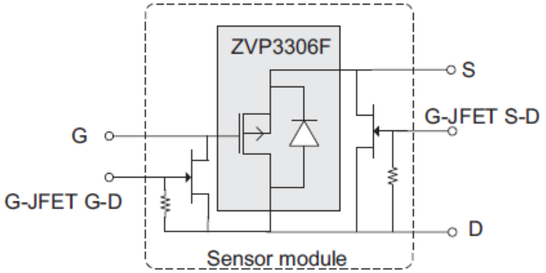
Two modules:
- Sensor module
- Reader Unit + biasing module



MOSFET/RADFET: UGR real-time reader system

- **General features:**
  - Sensor modules for 1 or 2 pMOS
  - Programmable current source
  - Dual V_S recording with zeroed INA
  - 16-bit A/D converter (ADC)
  - MCU data averaging (512)
- **Powering electronics:**
  - 7.4 V ion-Li battery
  - DC-DC boosted to 24 V (analog circuit)
  - V_{SDmax} readable 17 V



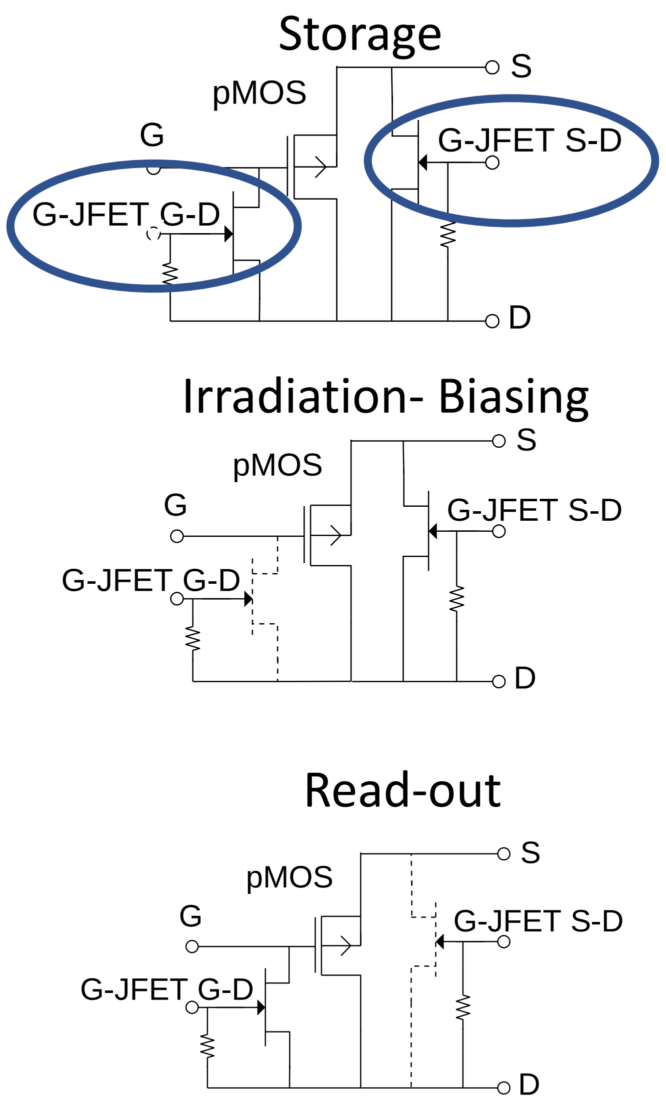


MOSFET/RADFET: UGR real-time reader system

- **Sensor module: 1 pMOS** (ESD protection and selective pin biasing)
- **JFET S-D switch allows pMOS reading**
  - ON: gate short-circuited during irradiation and storage
  - OFF: during read-out
- **JFET G-D switch allows pMOS biasing**
  - ON: unbiased pMOS mode
  - OFF: biased pMOS mode

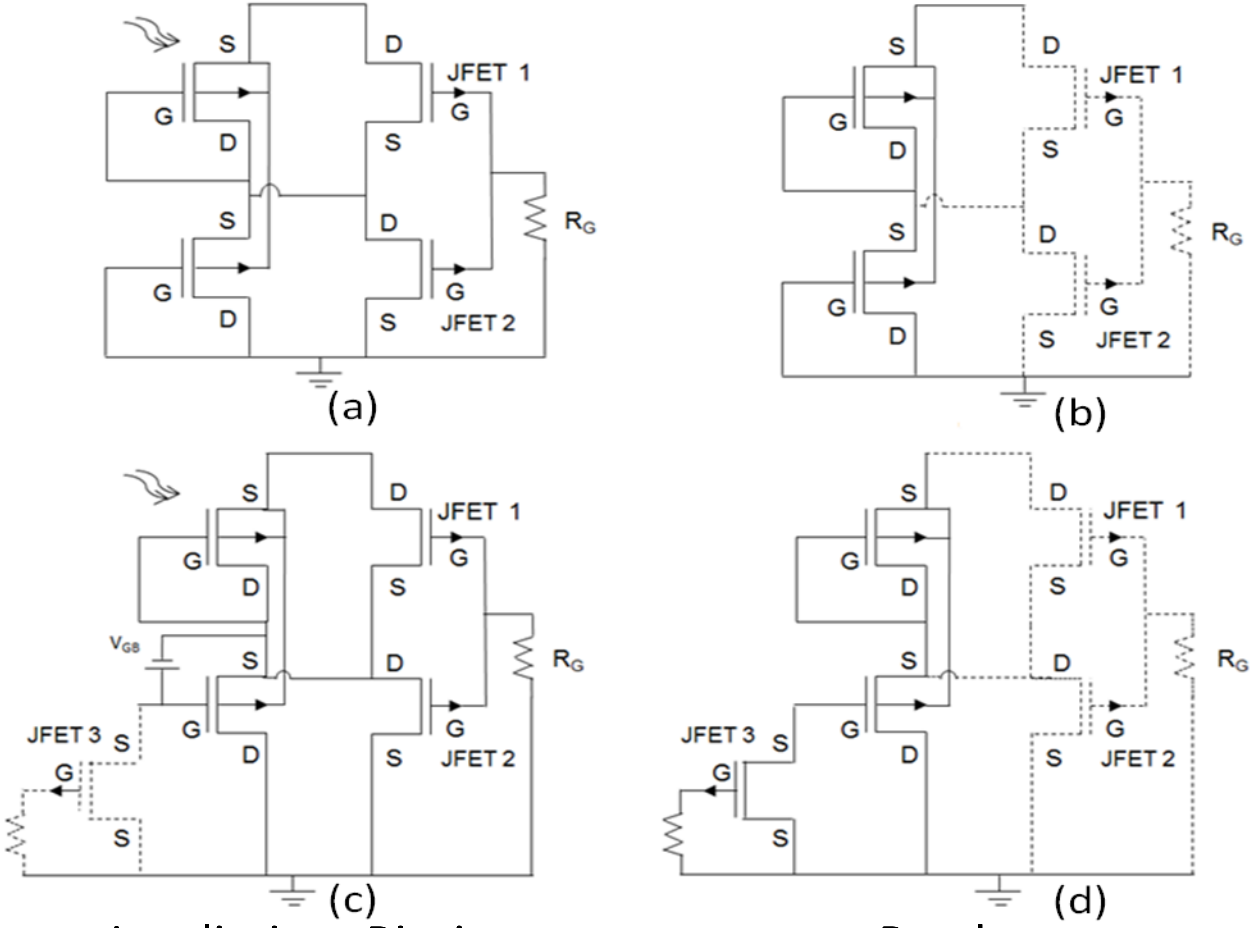
JFET: MMBF4391
Normally ON
R(ON) = 30 Ω
V_{cutoff} = -10 V

R_G for discharging of JFET gate capacitance



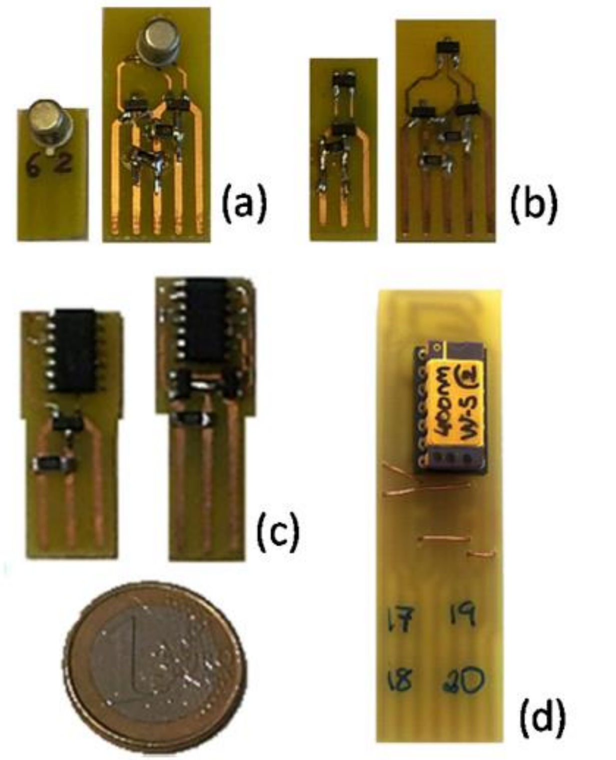
MOSFET/RADFET: UGR real-time reader system

- **Sensor module: 2 stacked pMOS configuration**



Irradiation- Biasing

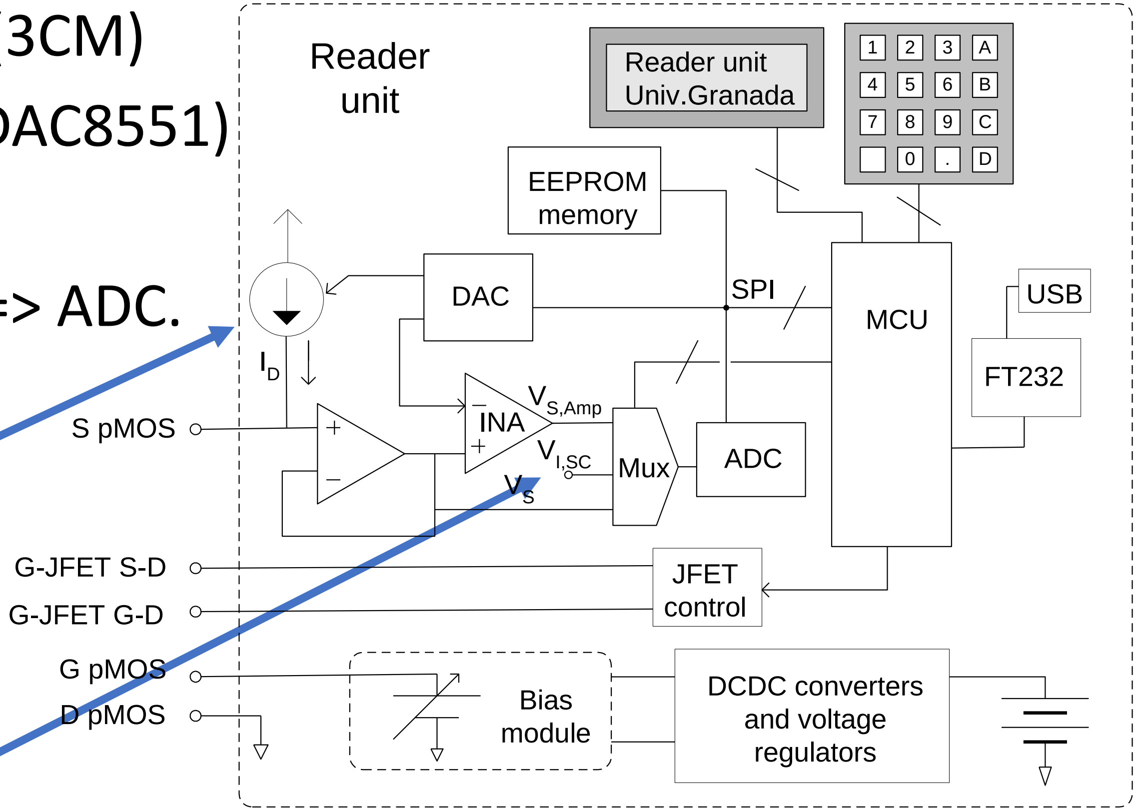
Read-out

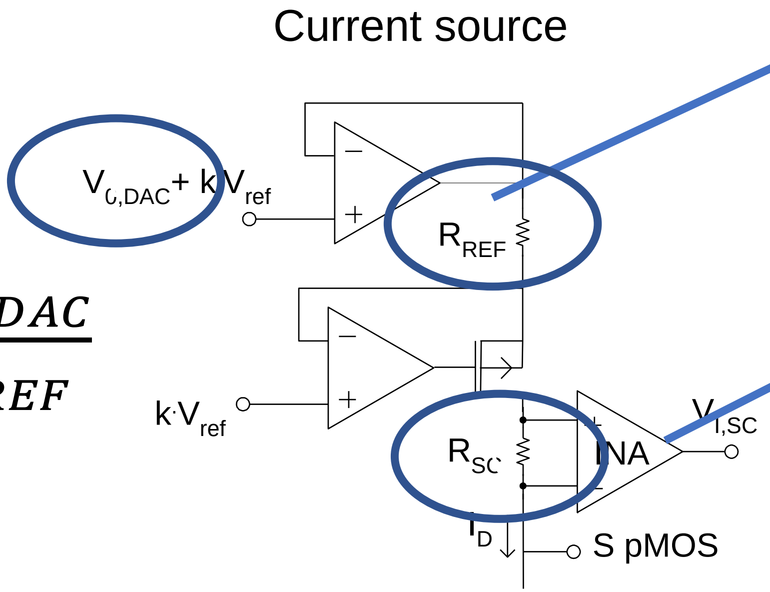


Sensor modules: 3N163, a DMOS, CD4007 and Tyndall RADFET

MOSFET/RADFET: UGR offline reader system

- **Reader unit: programmable drain current source**
  - To implement the **three current method** (3CM)
  - 16 bit digital-to-analog converter (DAC) (DAC8551)
  - Range: 10 µA – 1 mA. Resolution: 60 nA
  - I_D checked by R_{SC} and amplifier (INA114) => ADC.

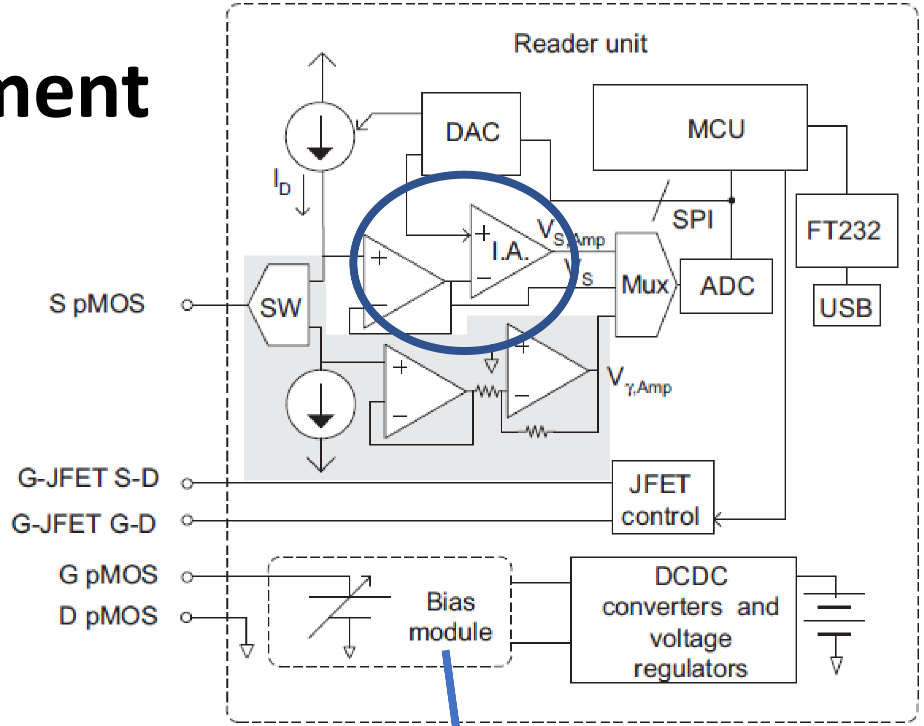


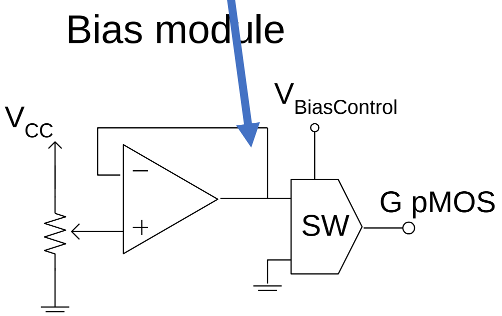


- $$I_D = \frac{V_{o,DAC}}{R_{REF}}$$

MOSFET/RADFET: UGR offline reader system

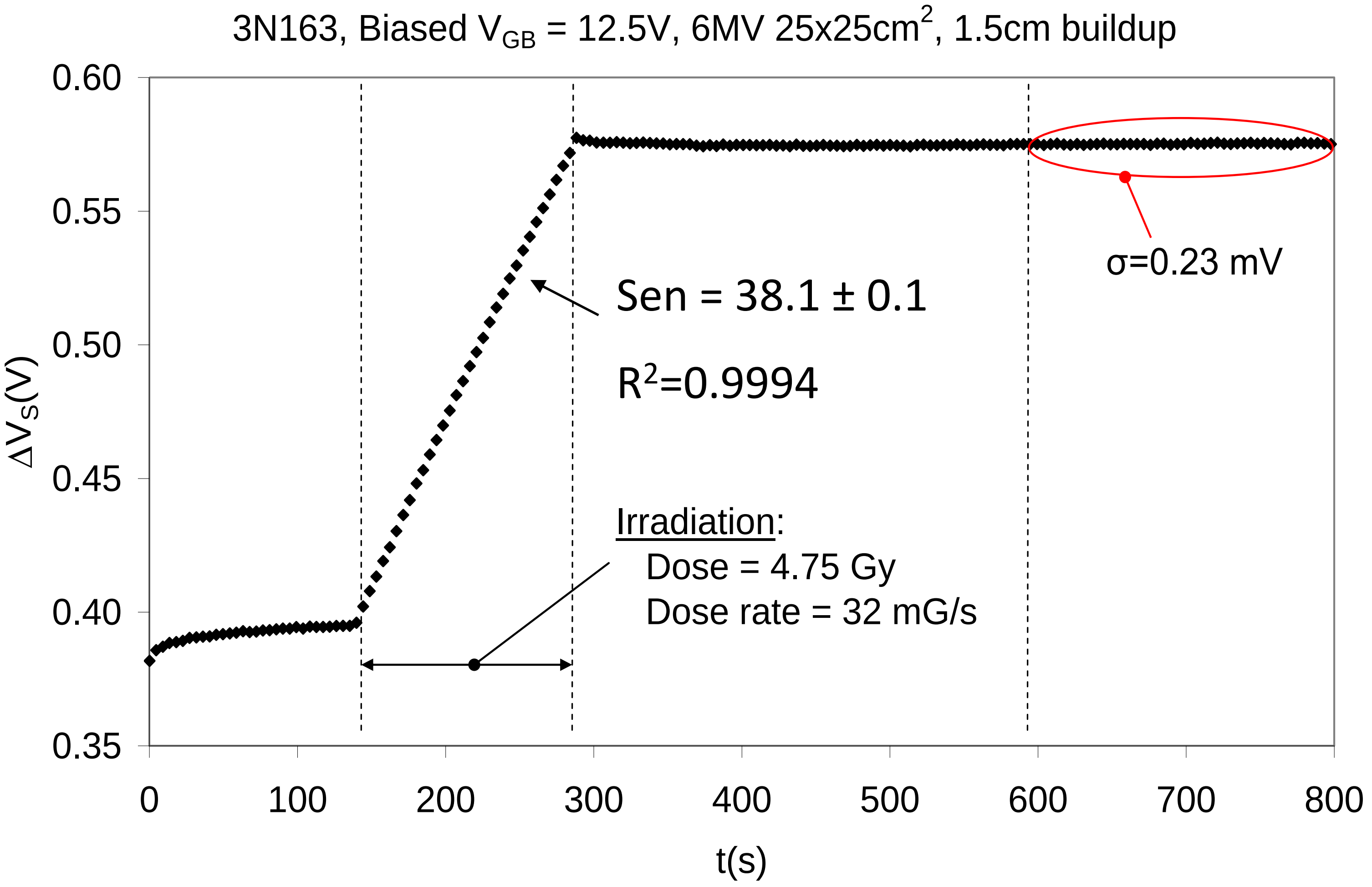
- **Reader unit: Source voltage measurement**
  - Directly from MOSFET (buffer + ADC)
  - Amplified (INA + ADC)
  - V^- (INA) set to 80 mV by DAC
  - Resolution (16-bit ADC and INA Gain ≈ 4)
    - $\Delta V_{SD} = 20\ \mu V/LSB$
- **Biasing module:**
  - Digital potentiometer for providing up to 22 V
  - Analog buffer for impedance matching
  - Switch controlled by MCU for biasing control





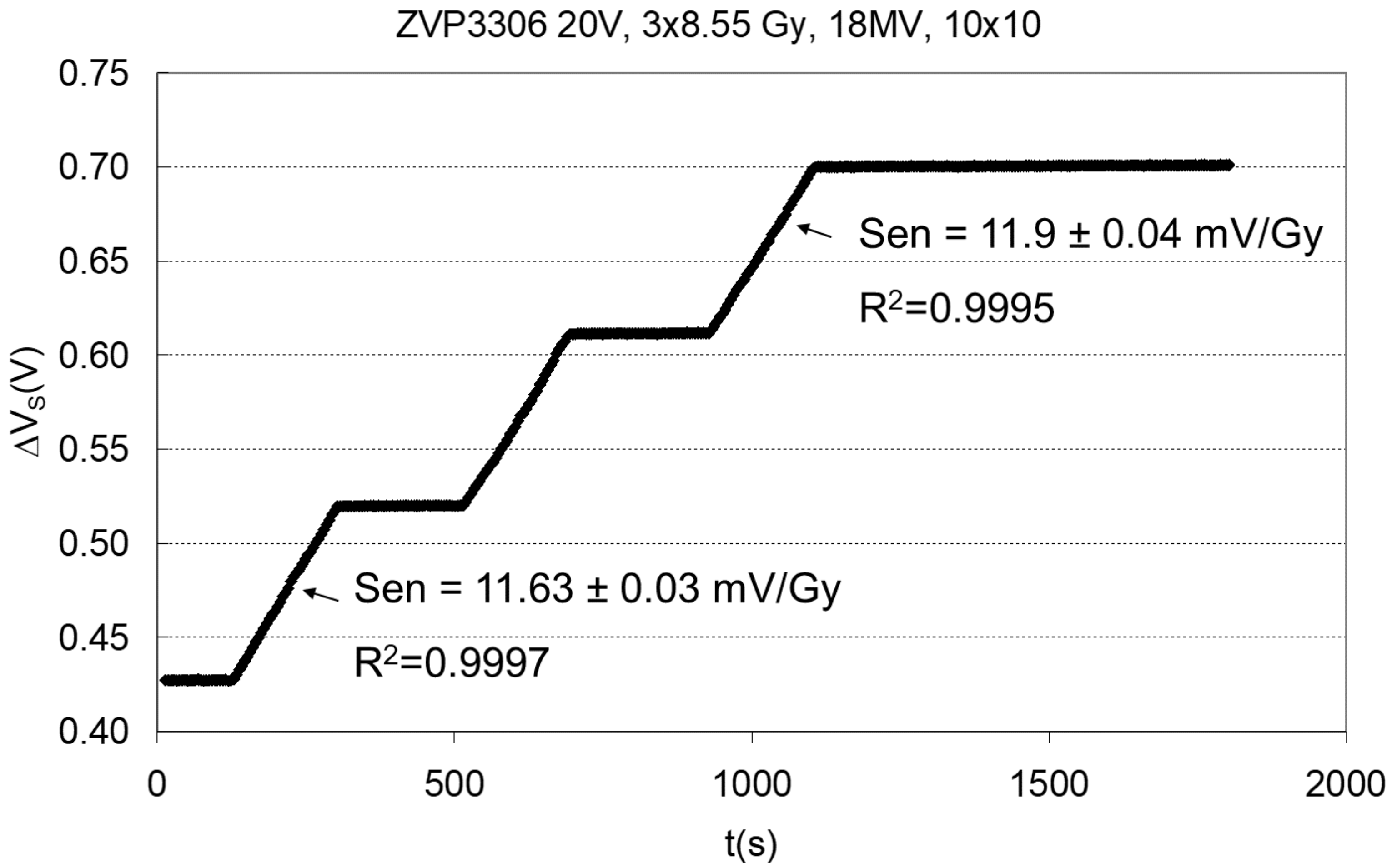
MOSFET/RADFET: UGR offline reader system

- **Some examples of real-time measurements: 3N163**



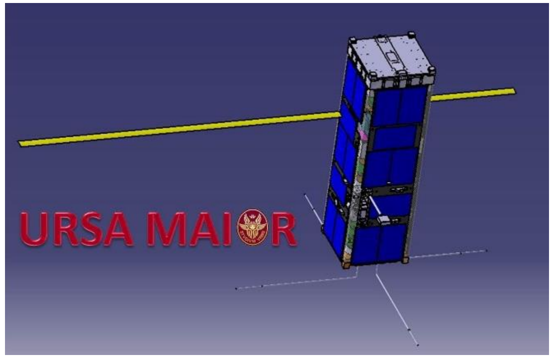
MOSFET/RADFET: UGR offline reader system

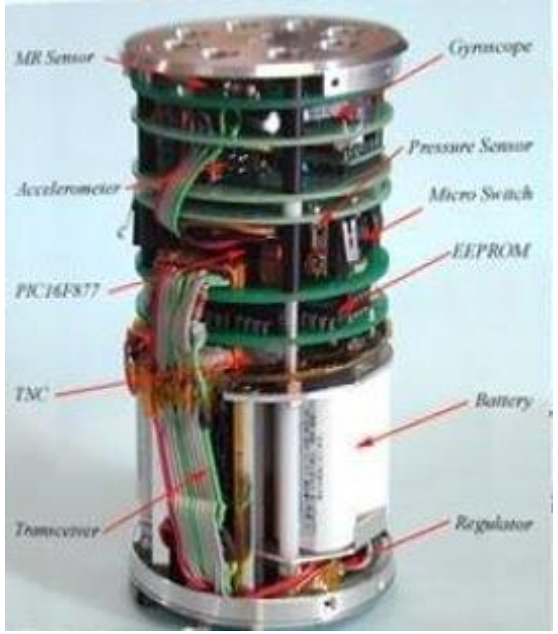
- **Some examples of real-time measurements: a DMOS**



MOSFET/RADFET: CubeSat URSA MAIOR

- **QB50:** European network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere **(FP7-EU)**
- **URSA MAIOR (**University Sapienza- Rome)
- **Challenge:** To include a **small printed circuit board** with radiation sensors for dosimetry inside the Satellite with high T stress (0-40°C)
- **Main board:**
  - DC supply
  - Microprocessor with built-in ADC



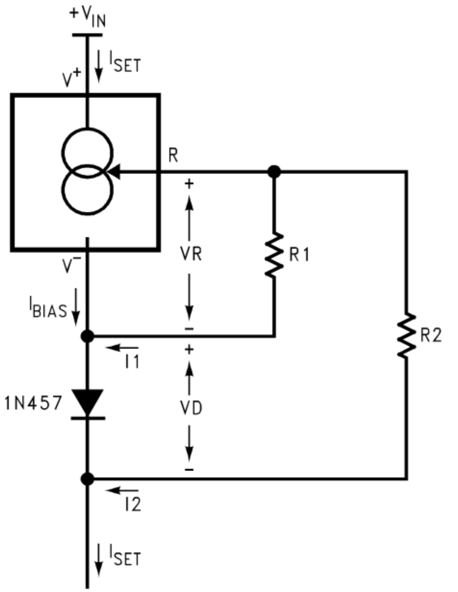


MOSFET/RADFET: CubeSat URSA MAIOR

- **4 sensors selected biased a I_{ZTC} :** to cover different sensitivities
  - JFET protected:
    - Radiation cycles: all terminals short-circuit (99%)
    - Reading period: JFET cut-off (1%)

TYPE OF SENSOR	SELECTED Id(μA)
CD4007	137
3N163	230
Tyndall RADFET (x2)	10

LM334
Output current: 1 μA - 10 mA
Biased from 1 V to 40 V

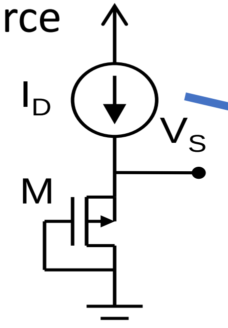


  - Current source based on thermal compensated LM334:
    - If R2=10·R1 =>LTC ≈ 0 => I_{SET}**=0.134V/R1**

MOSFET/RADFET: CubeSat URSA MAIOR

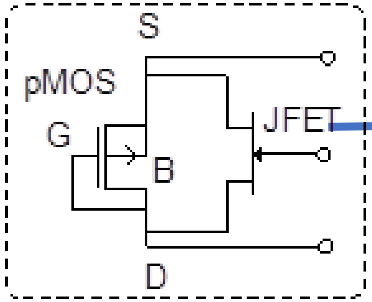
- **Circuit design:**

Current source

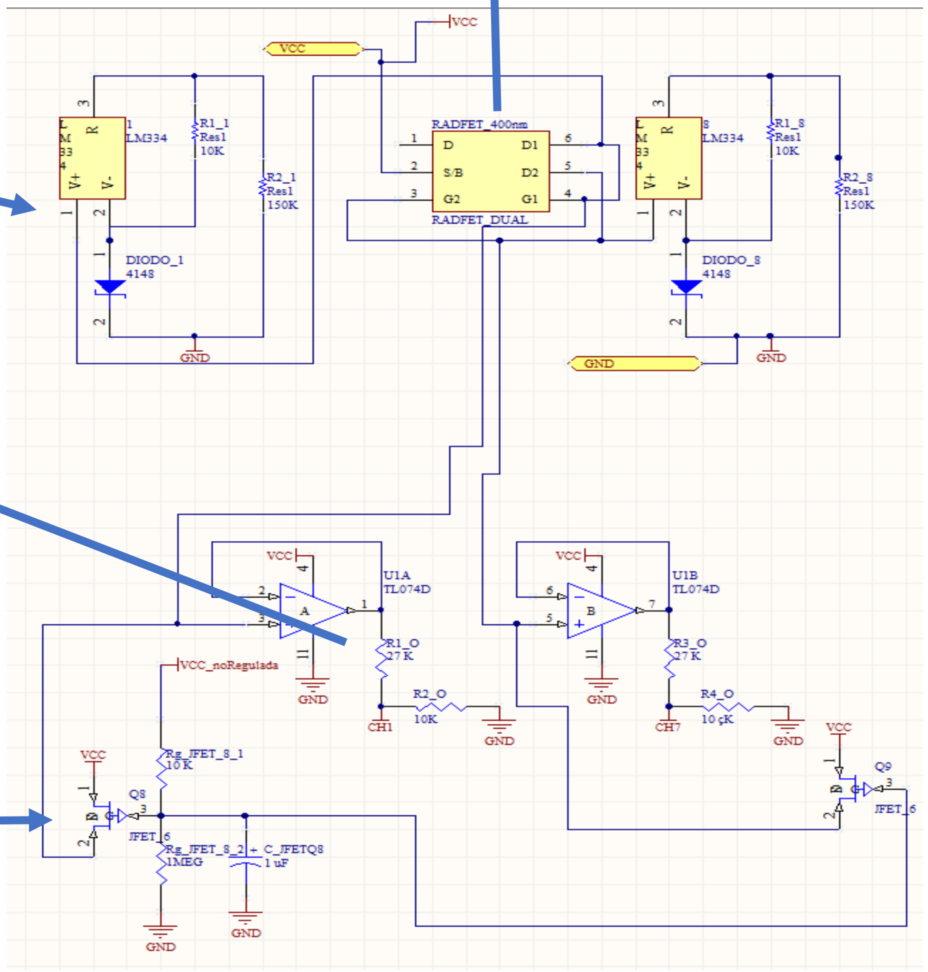


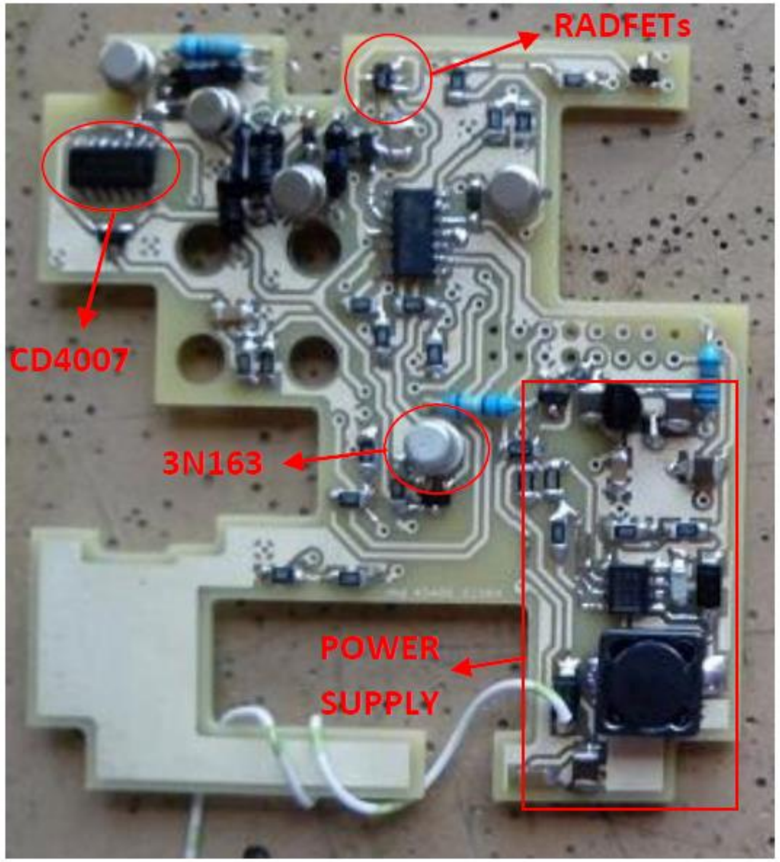
Vs level shifting

JFET for switching



RADFETs



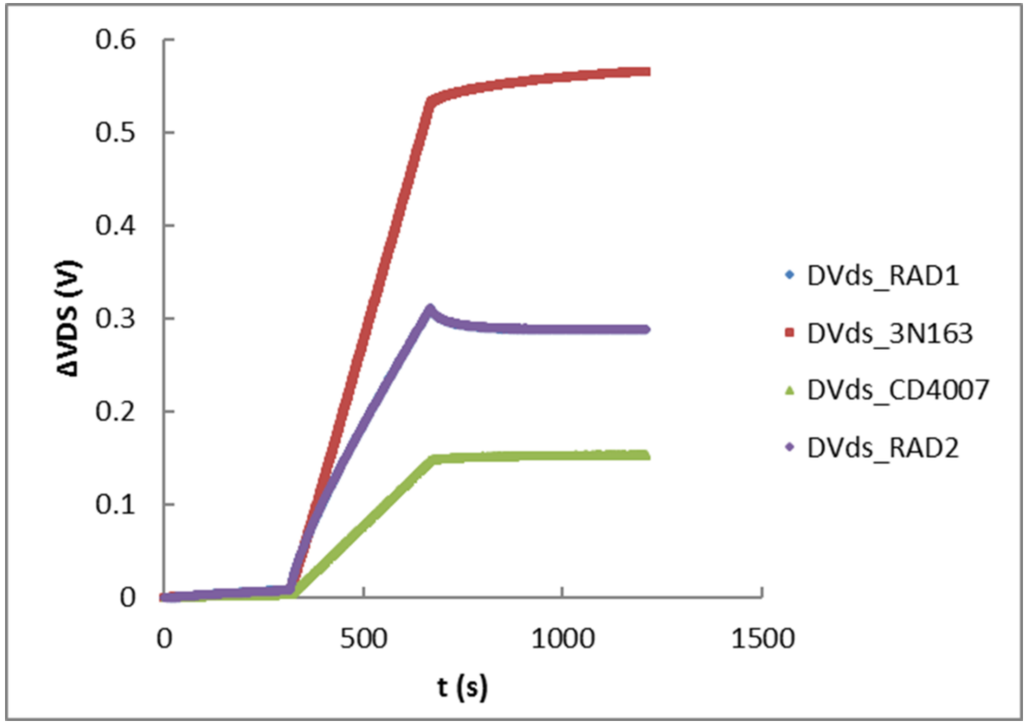


Picture of the printed circuit board

MOSFET/RADFET: CubeSat URSA MAIOR

- **Thermal and irradiation tests before launching:**
  - **Irradiation set-up**
    - LINAC Mevatron (Siemens, Germany)
    - Normal Beam 15 MV up to 115 Gy
  - **Temperature stress**
    - Climate chamber between 0 and 40ºC
  - **Results**

MOSFET	Sensitivity (mV/Gy)	SD Sensitivity (mV/Gy)	Thermal drift (mV/K)
CD4007	5.0	0.1	0.13
3N163	17.90	0.07	0.36
RADFET 1	20.6	0.1	0.3
RADFET 2	20.8	0.1	0.4



Sensor responses for 115 Gy of accumulated dose

- **Communication lost after launching:** no data received

CONCLUSIONS AND FUTURE WORK

- Reliable and high performance dosimetry systems for real-time monitoring were designed, fabricated and tested for PIN diodes and pMOS.
- However, as any electronic system need to be constantly revised and redesigned to include new features or to improve existing ones.
- We are working in adapting it to different kind of solid-state dosimeter beyond pMOS.
- It would be advisable to take it to the market
- Any collaboration in this regard will be very welcome.

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THANK YOU FOR YOUR ATTENTION- QUESTIONS?