University of the
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Floating Gate sensor. 1

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Outline

- Motivation
  - Radiation effects on MOS devices
  - RADFET principle
  - Design issues in sub-micron CMOS
- FG sensor
  - FG capacitor
  - FG MOS based current source
  - Current to frequency converter
- Conclusions

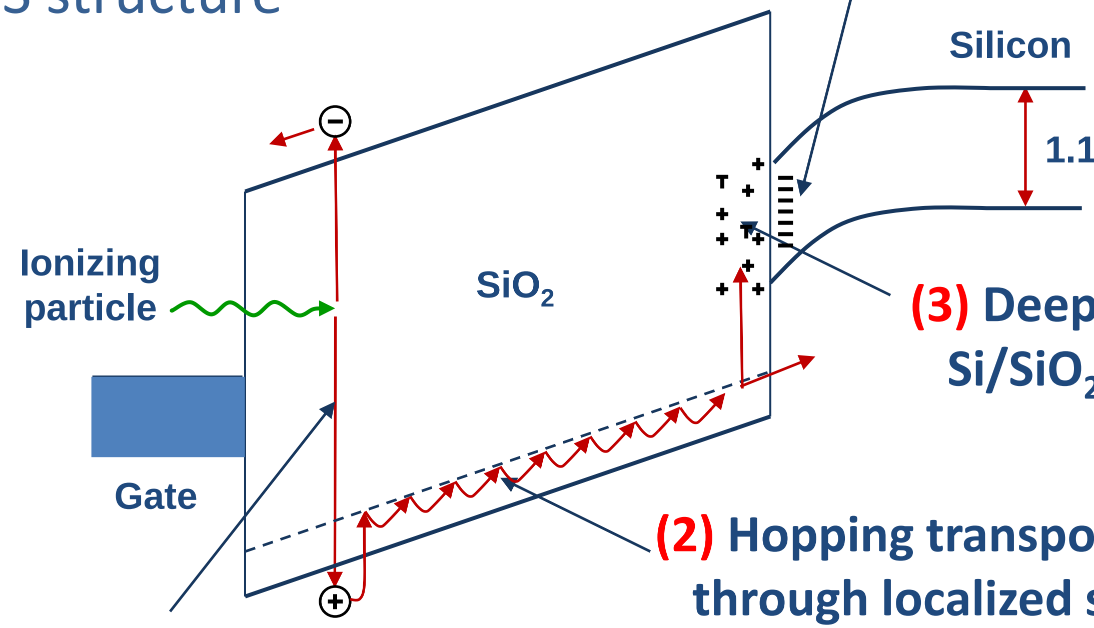
Primary radiation effects in electronic materials and devices

- Charged particles and high energy photons ⇨ ionization effects
  - Total dose effects ⇨ charge buildup in dielectrics
    - Threshold voltage offsets in MOS devices
    - Leakage currents
  - Transient effects ⇨ induced photocurrents
    - Single event upsets (SEU)
    - Current latchup
- Neutrons ⇨ atomic lattice damage (atomic displacements)
  - Induced lattice defects
    - Carrier lifetime degradation

Total dose related charge build-up process

Energy band diagram of an MOS structure

(4) Radiation induced interface traps within Si bandgap: Q_{it}



(3) Deep hole trapping near Si/SiO_2 interface: Q_{ot}

(2) Hopping transport of holes through localized states in the SiO_2 bulk

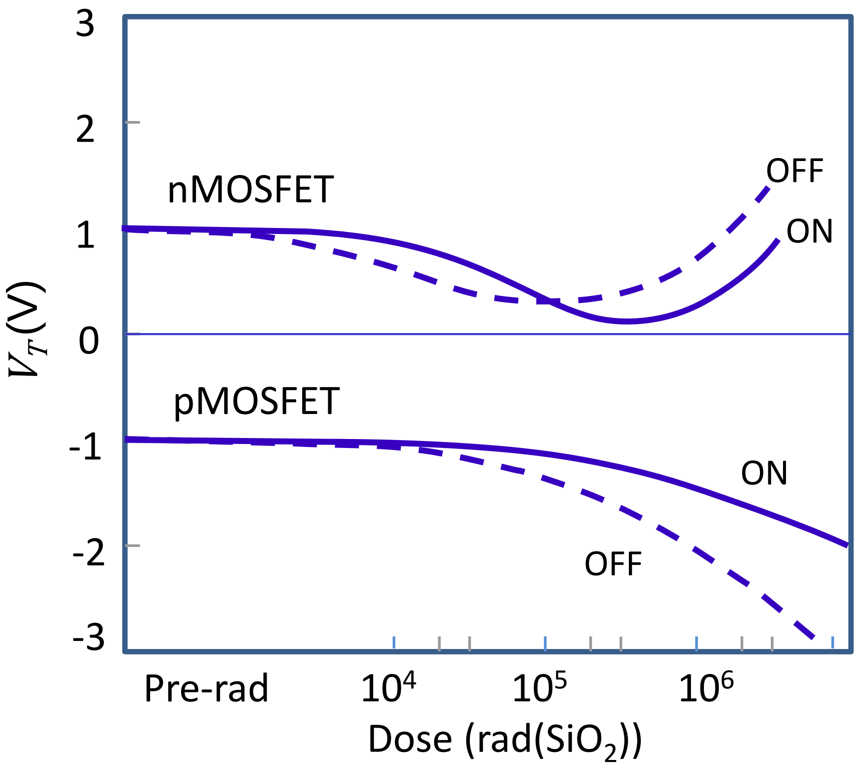
(1) Electron/hole pairs generated by ionizing radiation

RADFET sensor

- Operation principle: based on the MOSFET threshold shift induced by radiation

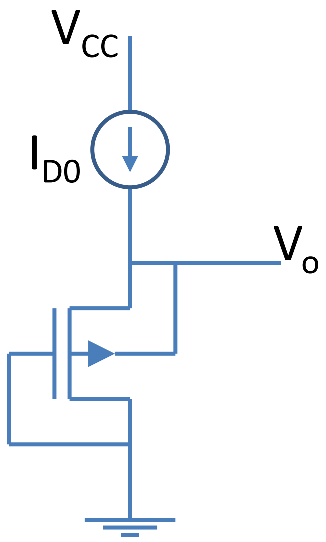
$$\Delta V_T = -\frac{\Delta Q_{ot} + \Delta Q_{it}}{C_{ox}}$$

  - V_T : MOSFET threshold voltage
  - Q_{ot} : charge trapped in the SiO_2 (always positive)
  - Q_{it} : charge trapped in the interface $Si\text{-}SiO_2$ (positive in pMOSFET, negative in nMOSFET)
  - C_{ox}: gate capacitance per cm^2



Source: The NASA ASIC Guide: Assuring ASICS for Space]

- Schematic



$$V_o = \sqrt{\frac{2I_{D0}}{\beta}} + |V_T|$$

- Sensitivity

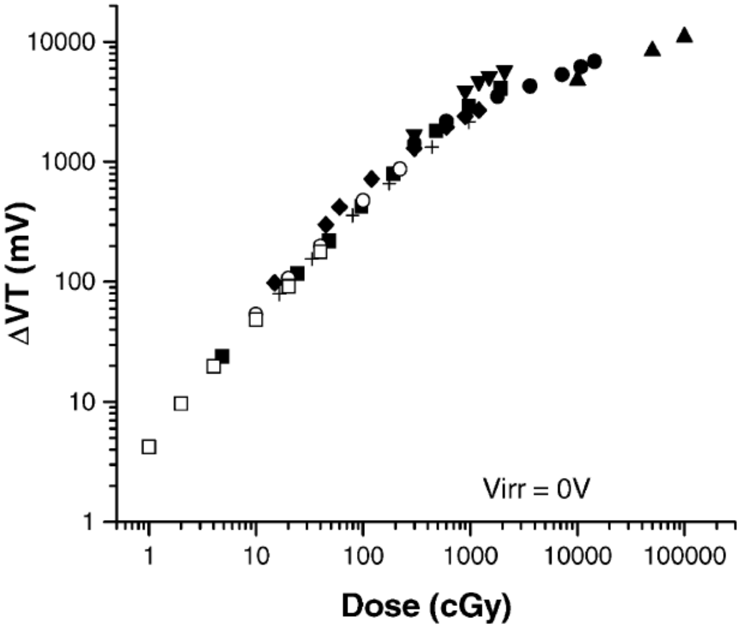


Fig. 2. Radiation response for a single-transistor dosimeter. (Measurements made in different laboratories; RX (10 KeV, 50 KeV), ^{60}Co.)

- I_{DO} selected to achieve minimum dV_o/dT (hundreds of µA)

Design issues in deep submicron CMOS technologies

- Charge build-up (oxide trapped and interface trapped) decreases with d_{ox}

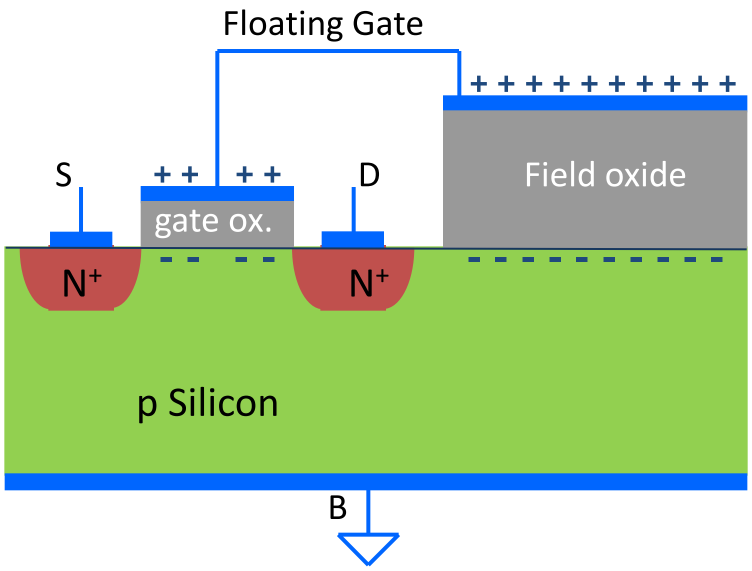
↓

- Devices in deep submicron CMOS technologies can withstand doses up to several Mrads without any specific hardness improvement.
- The achievable sensitivity of the sensor is hampered by gate oxide thickness, which cannot be changed if we want keeping its compatibility with standard technologies

To maintain sensor sensitivity, while keeping its compatibility with deep submicron CMOS technologies, the operating principle has to be changed

Floating gate (FG) radiation sensor

- Operation principle:
  - The sensor is a capacitor that uses the field oxide as dielectric, connected to the electrically "floating" gate of a nMOSFET.
  - Charge can be placed on the floating capacitor prior to the irradiation through an injector.
  - Ionizing radiation generates electron-hole pairs in the field oxide, gradually discharging the capacitor.



$$V_{FG} = V_r\left(\left(1+\frac{V_i}{V_r}\right)\exp\left(-\frac{D}{D_r}\right)-1\right)$$

Operation of the FG radiation sensor

- Dose rate (ζ)

$$\zeta = \frac{Energy\,deposited}{time \cdot mass}$$

$$\frac{Energy\,deposited}{time} = n\left(\frac{pairs\, e^- / h^+}{time}\right) \cdot W_{e-h}$$

$$W_{e-h} = activation\,energy\ (\approx 17 eV) \qquad mass = \rho_{ox} A_{fg} d_f$$

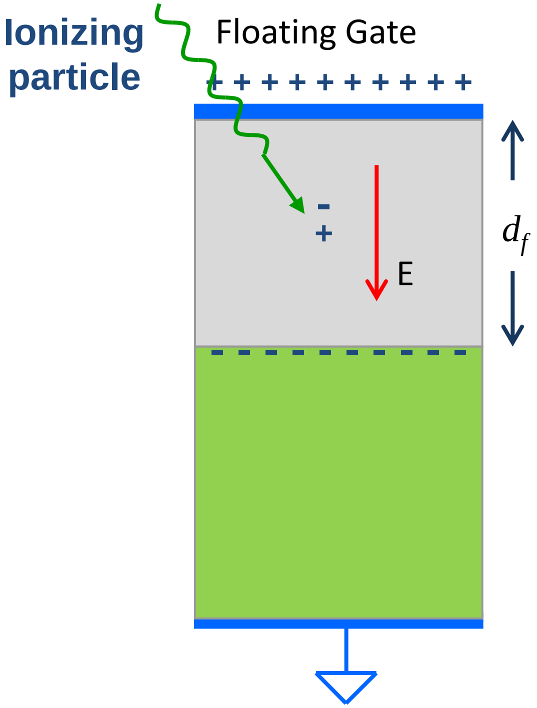
- Radiation induced current (I_r)

$$I_r = q \cdot n \cdot f$$

$$q = electron\ charge \qquad f = fractional\ \ yield$$

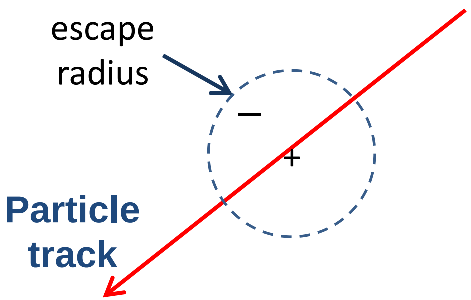
- Floating gate voltage (V_{FG})

$$V_{FG} = V_i - \frac{1}{C_T}\int_0^t I_r\, dt$$

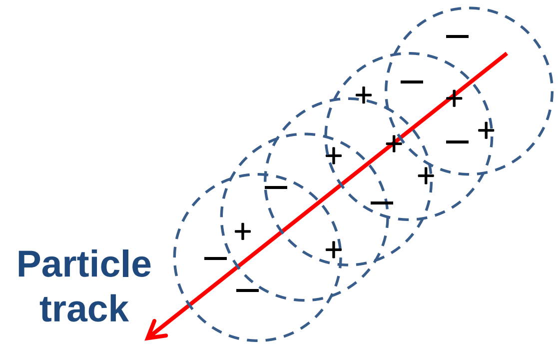


Fractional yield

- Geminate theory



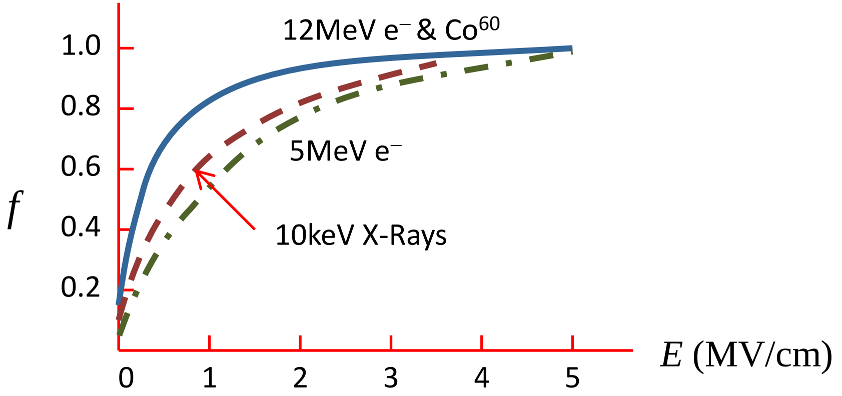
- Columnar theory



- Experimental results

Fitting for Co^{60} and low E

$$f = f_o(1+\frac{E}{E_r})$$



Response of the FG radiation sensor

- Floating gate voltage (V_{FG})

$$V_{FG} = V_i - \frac{1}{C_T}\int_0^t I_r\,dt \quad \Rightarrow \quad \frac{V_{FG}}{dt} = -\frac{q}{C_T}\frac{\rho_{ox}A_{fg}d_f}{W_{e-h}} f_o\left(1+\frac{V_{FG}}{d_f E_r}\right)\zeta$$

$$V_{FG} = V_r\left(\left(1+\frac{V_i}{V_r}\right)\exp\left(-\frac{D}{D_r}\right)-1\right)$$

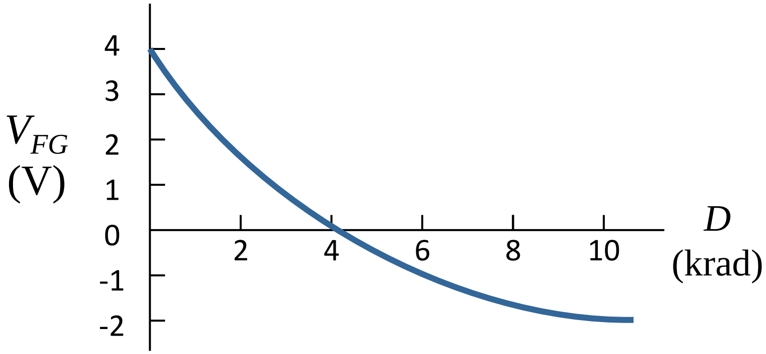
where D is the **cumulated dose**

$$D \equiv \int \zeta\,dt$$

and V_r D_r are sensor parameters

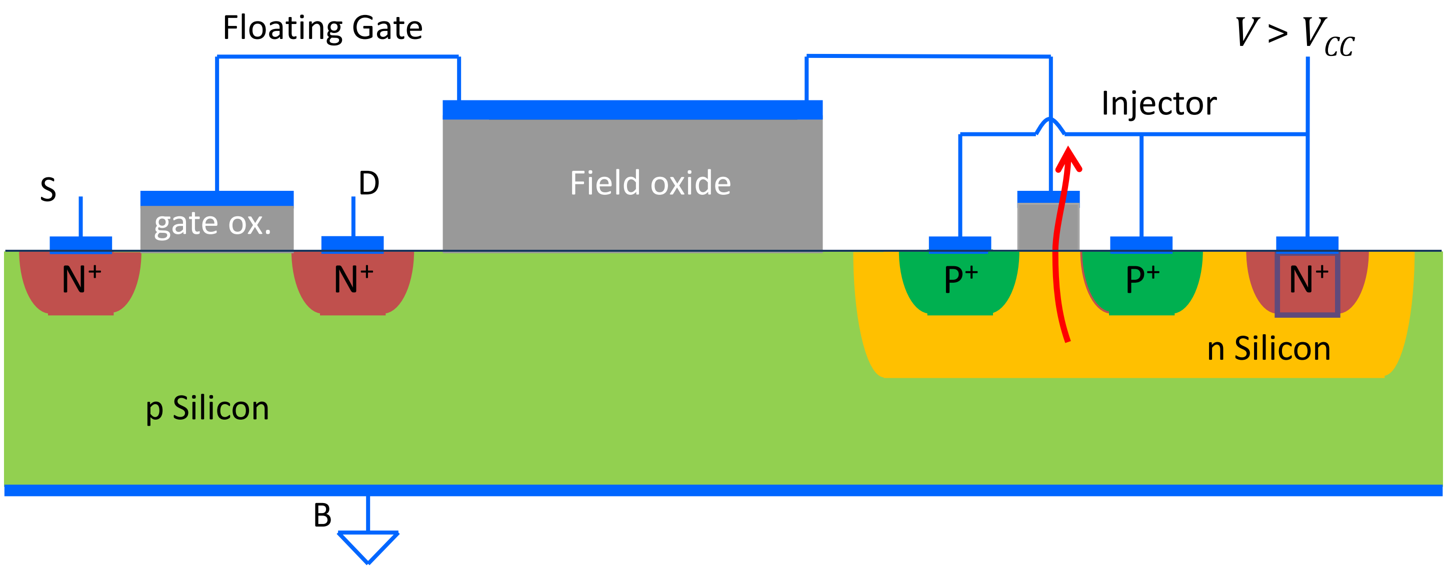
$$V_r \equiv E_r d_f$$

$$D_r = \frac{W_{e-h}E_r C_T}{q A_{fg}\rho_{ox} f_o}$$



FG radiation sensor. Injector

- The injector is a small pMOSFET which has its gate bonded to the FG and the drain, source and bulk short-circuited



- The FG is charged by applying sufficiently large positive voltage to the injector electrode to cause tunneling through the gate oxide.

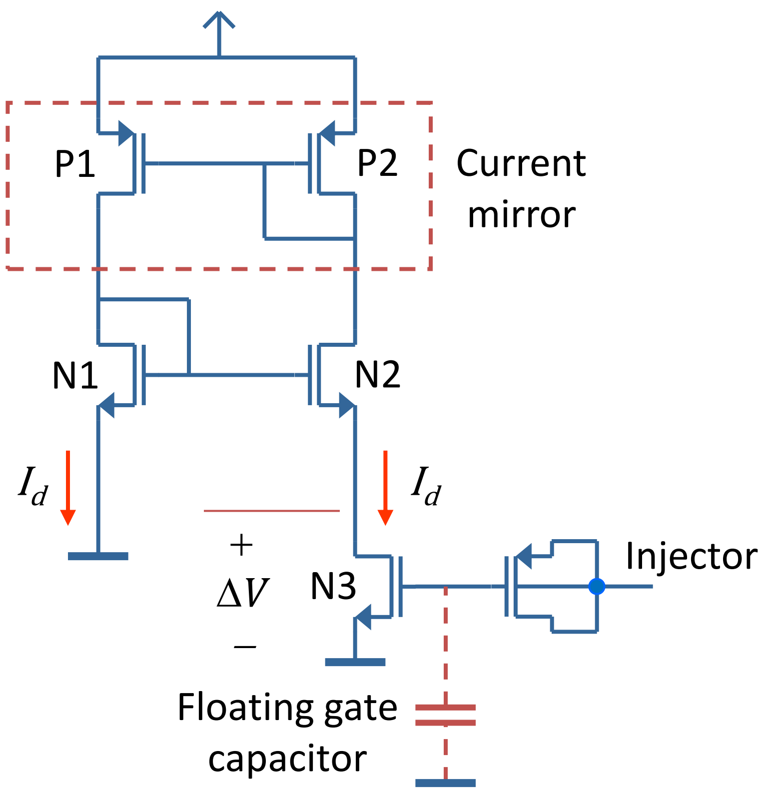
FG radiation sensor. Schematic

- Schematic:
  - P1-P2 and N1-N2 form a current mirror that force N1 and N2 to drive the same current
  - because N1-N2 have different aspect ratios, they have different gate-source voltages

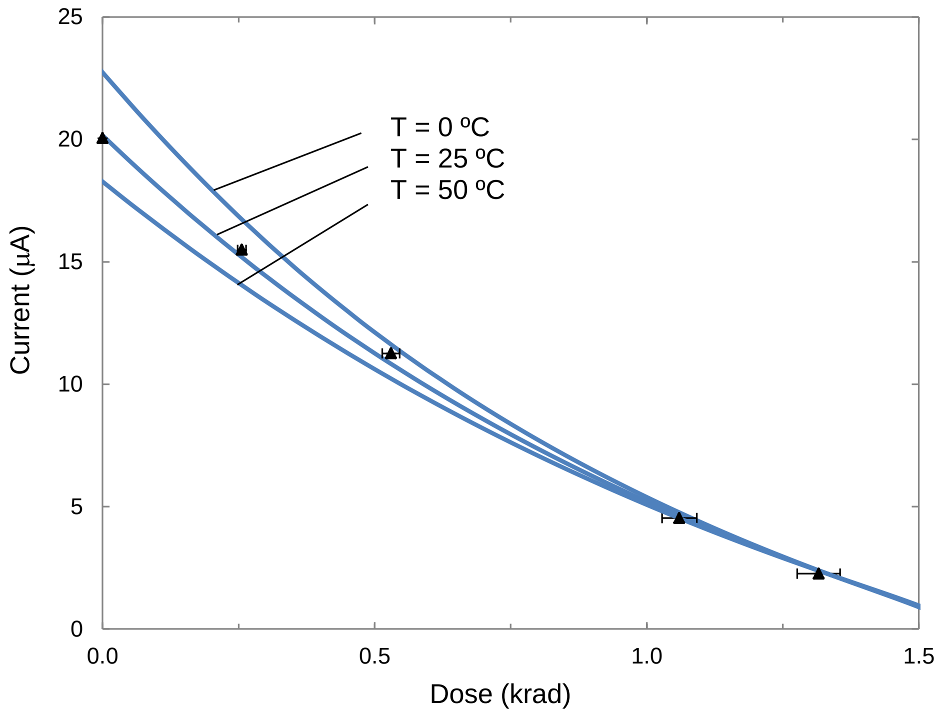
$$\Delta V = V_{GS}(\text{N1}) - V_{GS}(\text{N2})$$

  - N3 acts as a resistance, R, controlled by the voltage at the floating-gate capacitor

$$I_d = \frac{\Delta V}{R}$$



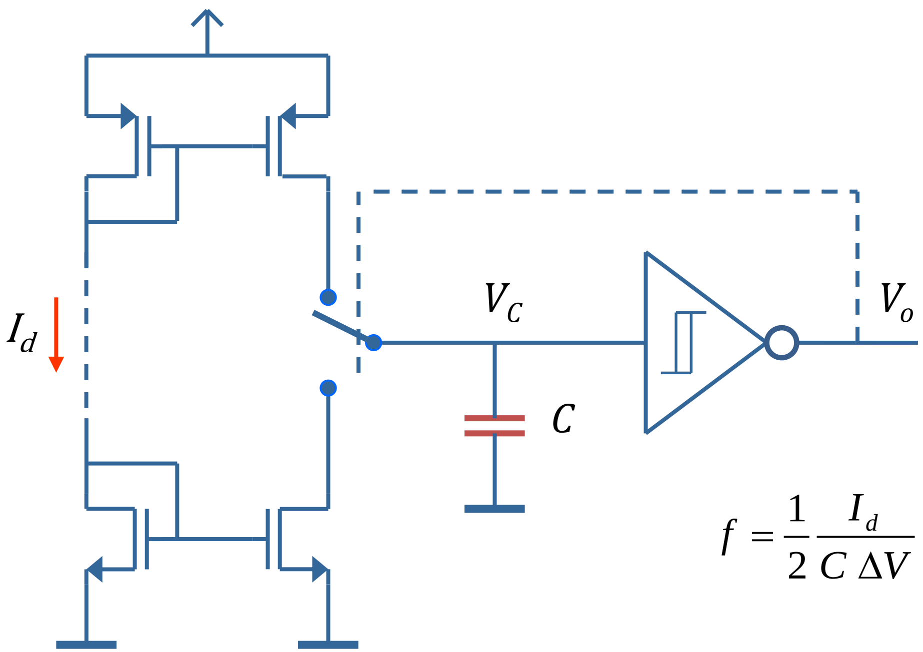
FG radiation sensor. Response



- γ radiation, ^{137}Cs source
- Curves obtained by HSPICE simulation
- Experimental points @ 25 ºC

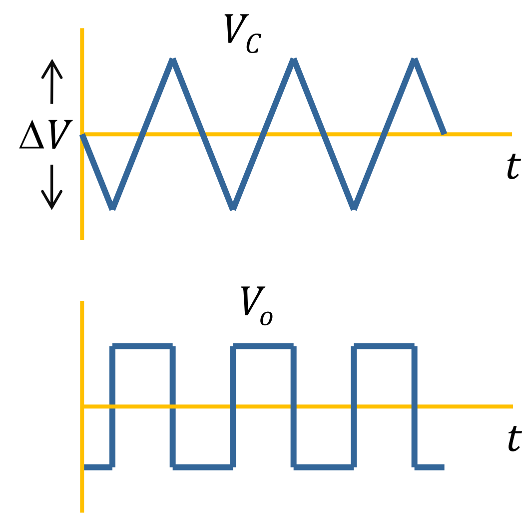
Current to frequency converter

- Schematic

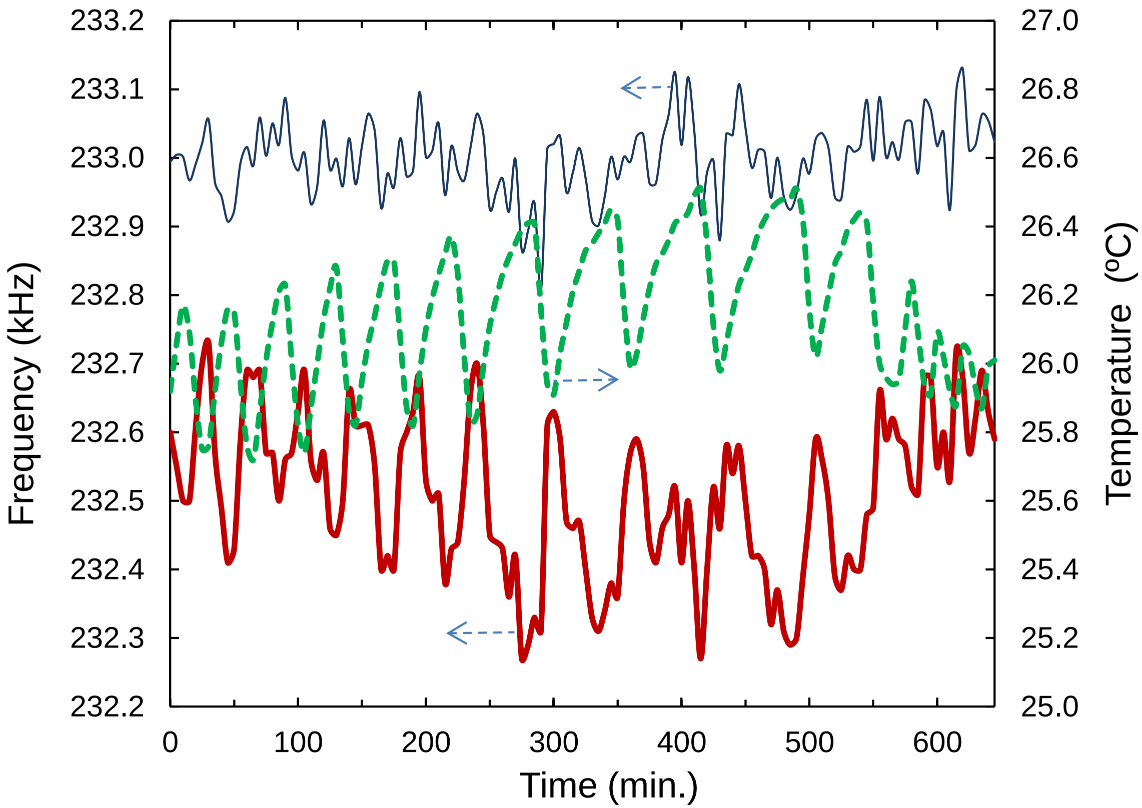


$$f = \frac{1}{2}\frac{I_d}{C\,\Delta V}$$

- Waveforms



Current to frequency converter



- Linear temp correction

Summary & conclusions

- Our gamma radiation dosimeter is intended to be embedded in CMOS integrated circuits: it has low power consumption and require little silicon area
- Its output is a square wave signal of radiation dependent frequency
- Lowest detectable dose ~ 1 rad. Sensitivity of the current source ~ 20 μA/krad
- Higher sensitivity → lower range. **But the charge in the FG capacitor, can be reset again**.
- Temperature sensitivity is high, which practically imposes external temperature compensation.