QFG Transistors Radiation Damage Effects

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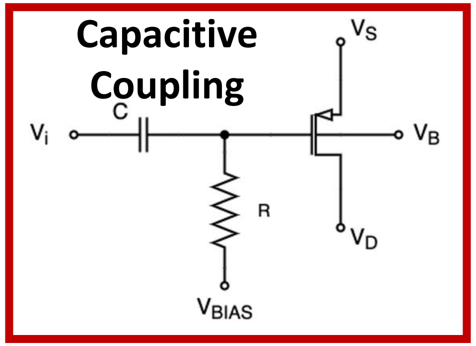
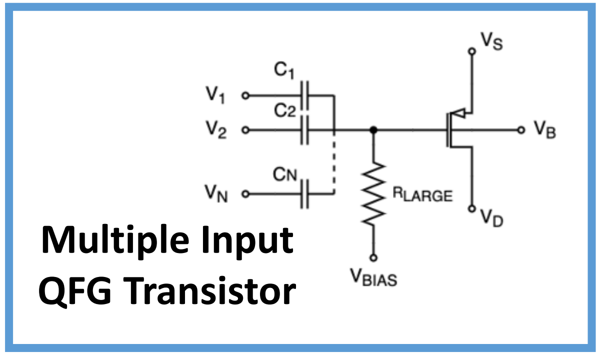
In a Nutshell

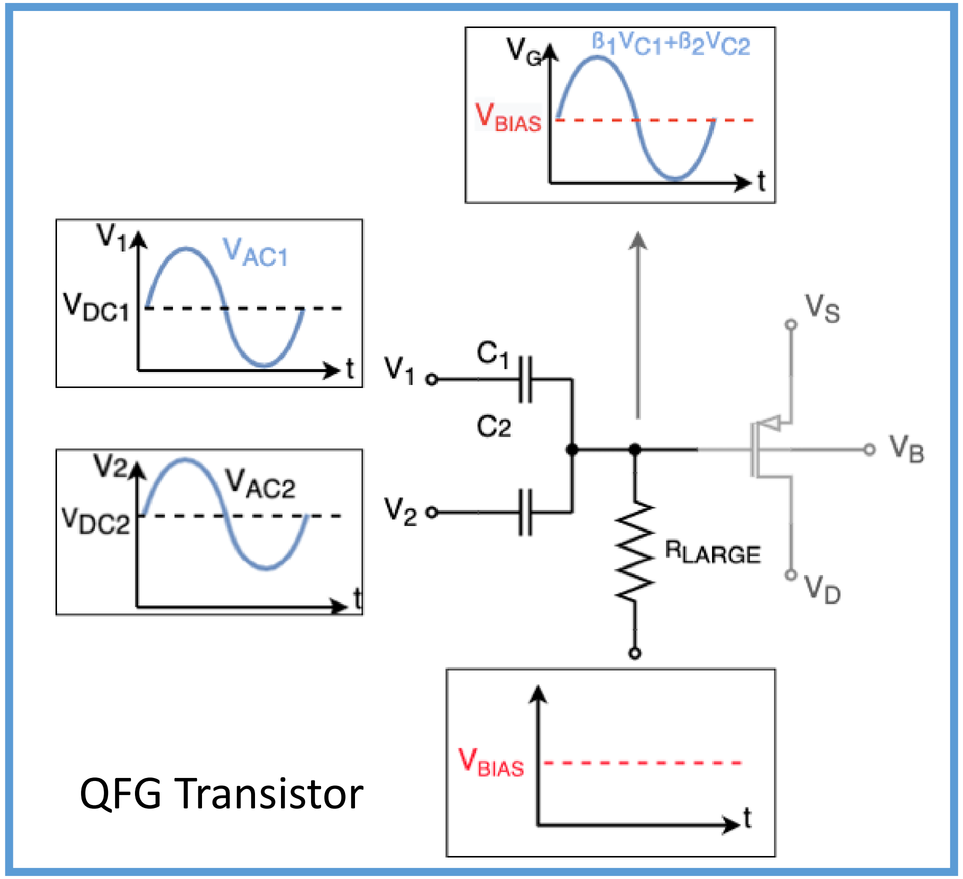
- **What are QFG Transistors?**
- **"Quasi Infinite Resistors" as reverse biased pmos diodes**
- **Radiation Damage in QFG Transistors**
- **Experimental Gamma Irradiation**
- **Results**

QuasiFloating Gate Transistors

- Classical capacitive coupling is widely used in analogue and mixed signal design.
  - This technique is not suitable for relatively low frequency because requires R and C with such high values that it is impossible to integrate.
  - It is restricted to narrow RF signals
- Quasi-Floating Gates (QFG) is an **area efficient and versatile alternative**.
  - Comprises a **pseudoresistor** (replaces the passive resistor) and **one or several low value capacitors.**
  - A pseudoresistor is an active element based on MOS transistors that operates in the **cut-off** or in the **subthreshold region** to provide an extremely large resistance (depending on the implementation, from GΩ to TΩ)
  - **Operating Principle**
    - DC Operation: C1 and C_2 act as open circuits, the DC components of the input signals are filtered. The current across the pseudoresistor is negligible so the transistor gate is biased at V_{bias}.
    - AC Operation: the capacitors couple the input signal to the transistor gate, weighted by a factor $\beta_i = C_i/\Sigma C_i$

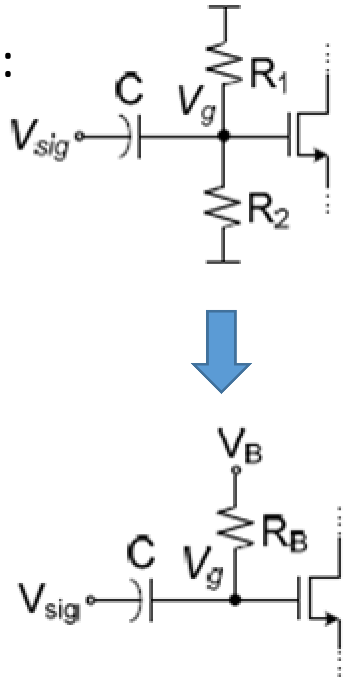

Capacitive Coupling


Multiple Input QFG Transistor


QFG Transistor

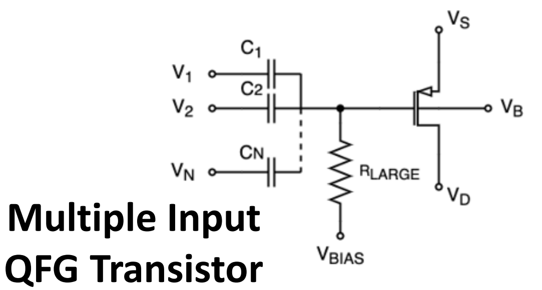
QuasiFloating Gate Transistors

- Widely used by designers in solutions to achieve:
  - Low voltage and/or rail-to-rail operation
  - High Linearity
  - Class AB behaviour
  - Improved Gain-Bandwidth product
  - Bulk-driven+Gate-driven behaviour



- Succesfully applied to:
  - Analog Switches
  - Opamps and OTAs
  - ADCs and DACs
  - Mixers
  - Filters
  - Track & Holds
  - Logic families

The simplest (but not the more useful) example of QFG is the bias of a transistor. Changing the R_1,R_2 resistor divider by a huge R_B avoids the static power consumption



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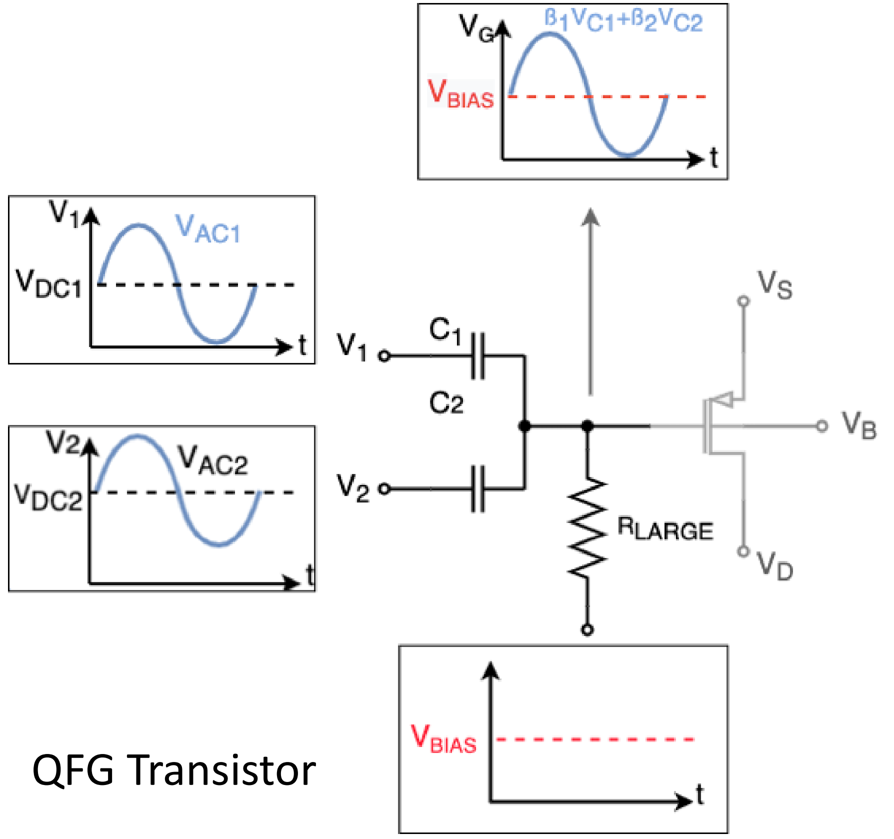
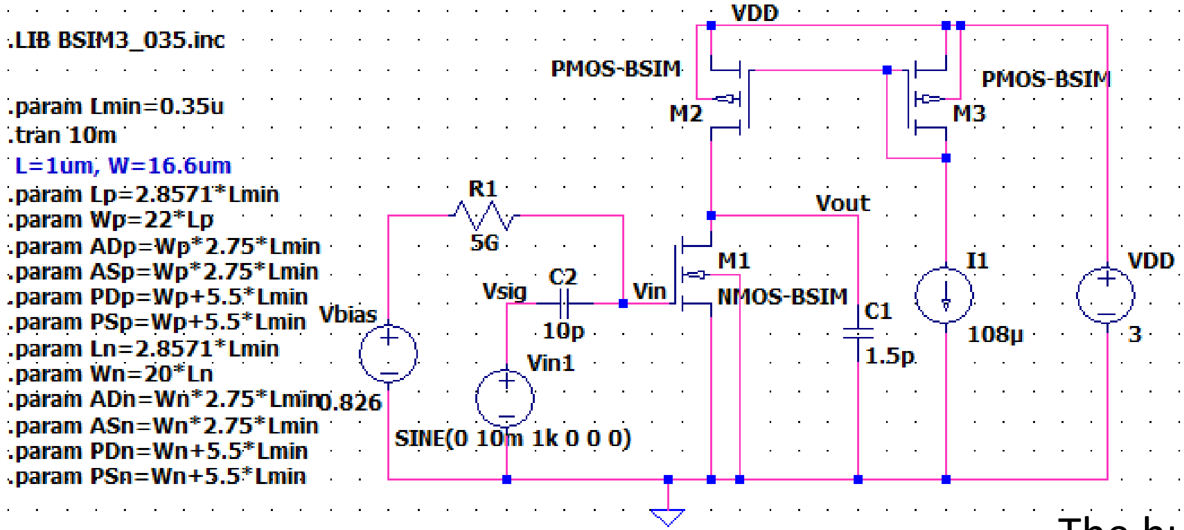


QFG Transistor

S. Pourashraf, J. Ramirez-Angulo, A. J. Lopez-Martin, R. Gonzalez-Carvajal,and J. M. Algueta-Miguel, “An Op-Amp Approach for Bandpass VGAswith Constant Bandwidth,” IEEE Transactions on Circuits and SystemsII: Express Briefs, vol. 65, no. 9, pp. 1144–1148, 2018

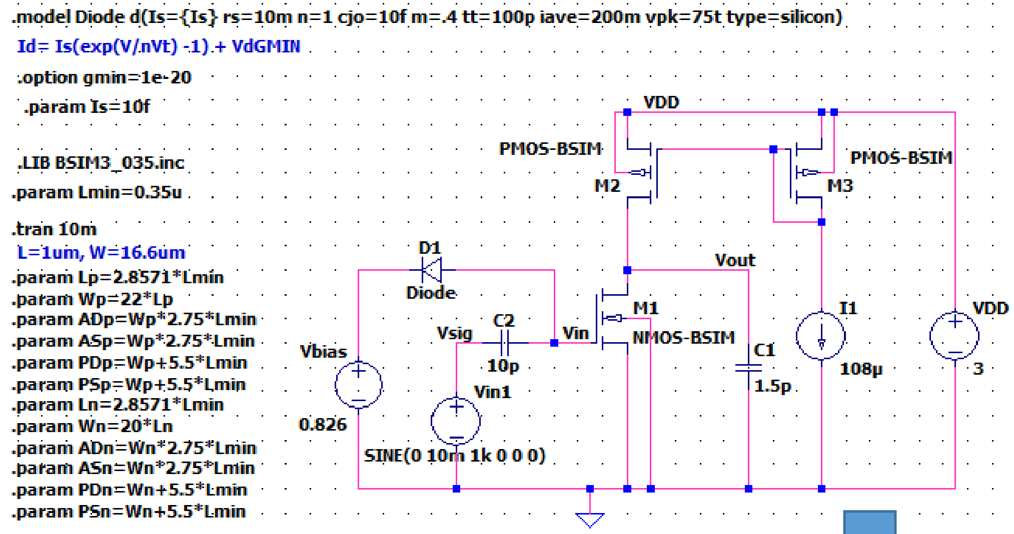
C. Garcia-Alberdi, A. J. Lopez-Martin, L. Acosta, R. G. Carvajal and J. Ramirez-Angulo “Tunable class AB CMOS Gm-C filter based on quasi-floating gate techniques,” IEEE Transactions on Circuits and Systems I: Regular Papers,vol. 60, no. 5, pp. 1300–1309, 2013Tunable class AB CMOS Gm-C filter based on quasi-floating gate techniques,”

QFG simple example: Class A Amplifier simulations



```
.LIB BSIM3_035.inc

.param Lmin=0.35u
.tran 10m
L=1um, W=16.6um
.param Lp=2.8571*Lmin
.param Wp=22*Lp
.param ADp=Wp*2.75*Lmin
.param ASp=Wp*2.75*Lmin
.param PDp=Wp+5.5*Lmin
.param PSp=Wp+5.5*Lmin
.param Ln=2.8571*Lmin
.param Wn=20*Ln
.param ADn=Wn*2.75*Lmin
.param ASn=Wn*2.75*Lmin
.param PDn=Wn+5.5*Lmin
.param PSn=Wn+5.5*Lmin
```

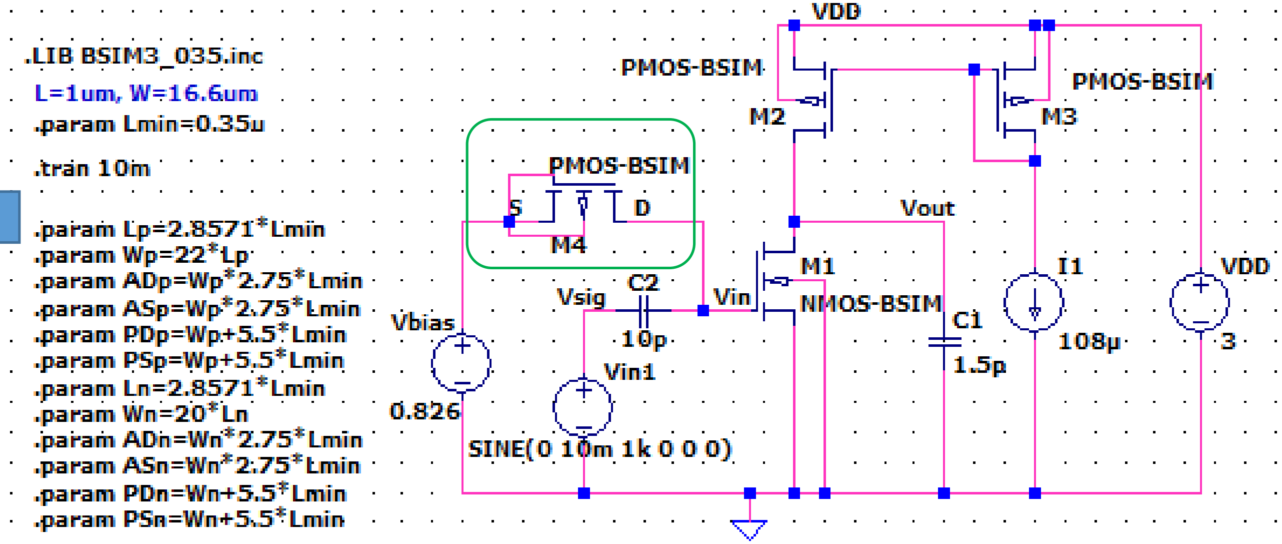


```
.model Diode d(Is={Is} rs=10m n=1 cjo=10f m=.4 tt=100p iave=200m vpk=75t type=silicon)
Id= Is(exp(V/nVt) -1) + VdGMIN
.option gmin=1e-20
.param Is=10f

.LIB BSIM3_035.inc
.param Lmin=0.35u

.tran 10m
L=1um, W=16.6um
.param Lp=2.8571*Lmin
.param Wp=22*Lp
.param ADp=Wp*2.75*Lmin
.param ASp=Wp*2.75*Lmin
.param PDp=Wp+5.5*Lmin
.param PSp=Wp+5.5*Lmin
.param Ln=2.8571*Lmin
.param Wn=20*Ln
.param ADn=Wn*2.75*Lmin
.param ASn=Wn*2.75*Lmin
.param PDn=Wn+5.5*Lmin
.param PSn=Wn+5.5*Lmin
```

The huge R is implemented by a pmos wired as a body diode so microelectronics is still possible



```
.LIB BSIM3_035.inc
L=1um, W=16.6um
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.param PDp=Wp+5.5*Lmin
.param PSp=Wp+5.5*Lmin
.param Ln=2.8571*Lmin
.param Wn=20*Ln
.param ADn=Wn*2.75*Lmin
.param ASn=Wn*2.75*Lmin
.param PDn=Wn+5.5*Lmin
.param PSn=Wn+5.5*Lmin
```
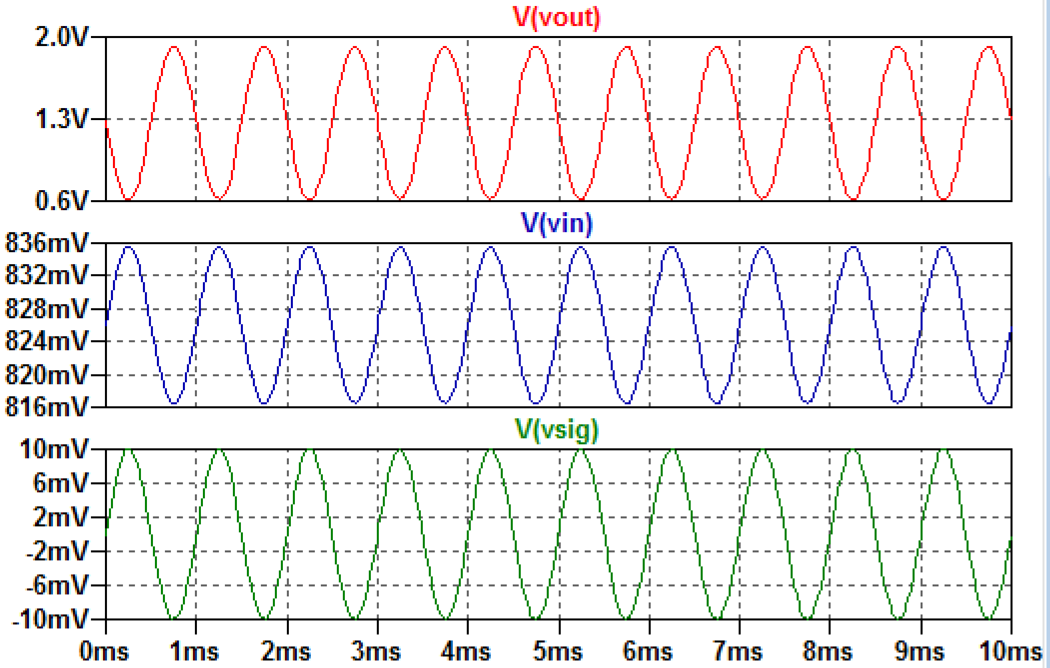



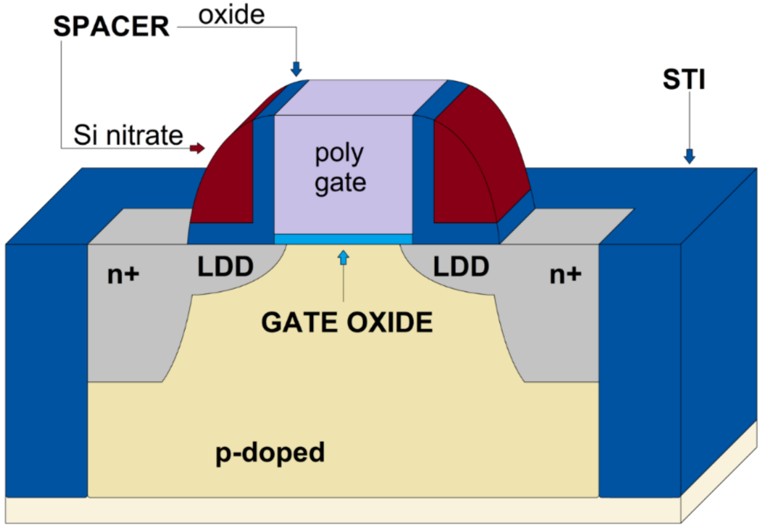
QFG technique for ionizing radiation environments?

Since the 2003 seminal paper* on QFG, the technique is widely used, for low power analog microelectronics in challenging applications as portable/wearable and wireless communications or biomedicine.

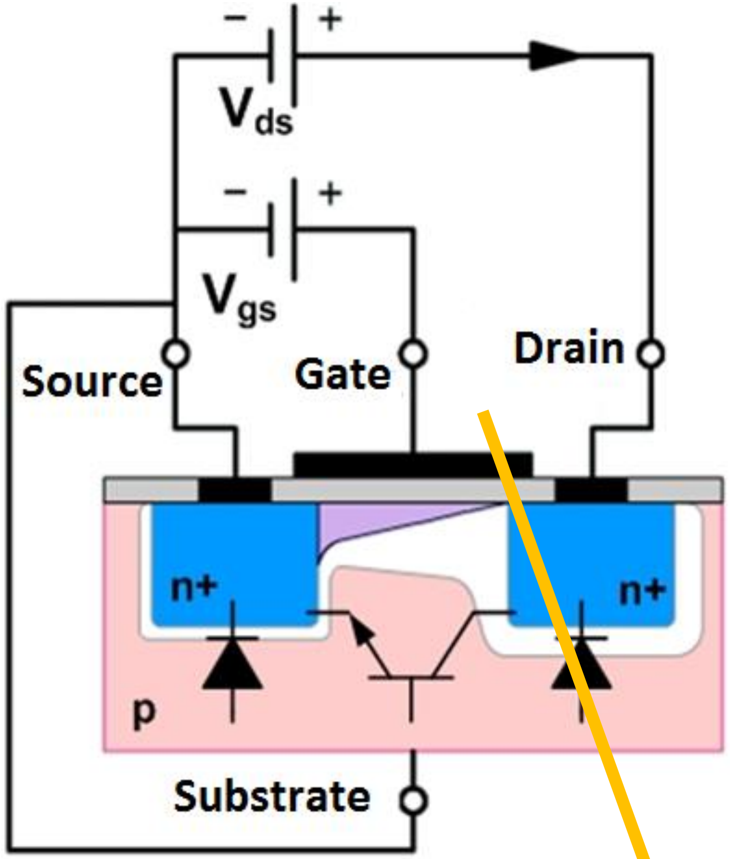
Microelectronics for High Energy Physics is now following the same highly integrated and low power route so a natural question appears: **is a QFG transistor radiation resistant?**

Conventional wisdom says that MOS transistors at very high integrated scales are sensitive to Total Ionization Dose and Single Event Effects but not to Radiation Damage. The reason: the channel is very shallow (50nm or less) and the blocking diodes are very small. Before any detectable Radiation Damage effect you have TID (ΔVth, Δgm, I_{leak}) or SEE (SET, SEU) very visible in your design.

Oxides can trap holes, in particular if their thickness is bigger than 10nm. TID is an issue in particular at the STI field oxides and the silicon nitride spacers.



Ionizing radiation damage in 65 nm cmos technologies: influence of geometry, bias and temperatura at ultrahigh doses, G.Borghello et al., Microelectronics Reliability, 116 (2021) 114016



Single Event Effects are activation of the blocking diodes or the body bipolar transistor due to the ionization track of a charged particle.

[Radiation Handbook for Electronics (Rev. A) - TI.com](https://www.ti.com/seclit/eb/sgzy002a/sgzy002a.pdf)
https://www.ti.com/seclit/eb/sgzy002a/sgzy002a.pdf

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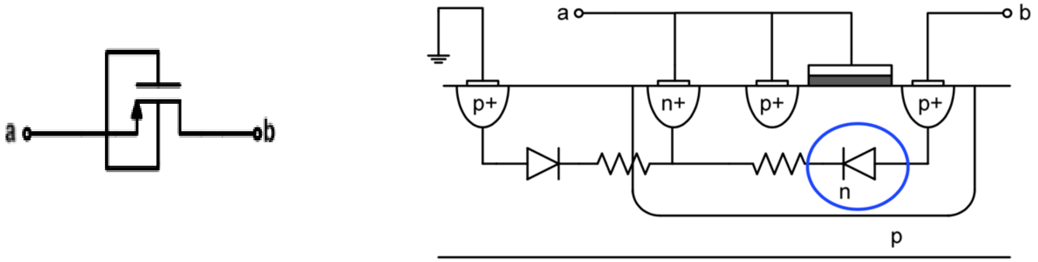
*A new family of very low-voltage analog circuits based on quasi-floating-gate transistors J. Ramírez-Angulo et al. IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing, vol. 50, no. 5, pp. 214–220, 2003

But QFG implements QIR with reverse biased body diodes...

We know that irradiated reversed diodes (aka detectors) show radiation damage effects : pmos body diodes have to be sensitive to radiation damage as well.



Reverse biased n-well PN junction (QIR)

A QIR synthetized as a reversed pmos body diode means that the diode saturation current, I_s, needs to be minimal (fA) to operate like a **very high value resistor with minimum physical size.**

When irradiating the pmos QIR with γ rays (so no SEE) we know that point defects must appear in the pmos body due to Compton electrons. Those Compton electrons hit Primary Knock-on Atoms (PKA) with energy enough to produce a Frenkel Pair.

From the simplest generation-recombination models we also know that deep trap levels in reverse biased diodes are responsable of an increase on the saturation current, I_s.

So we need to determine, experimentally, on QIR diodes, the saturation current after irradiation to know if they are still big enough equivalent resistors and the QFG transistor is viable in a radiation environment.

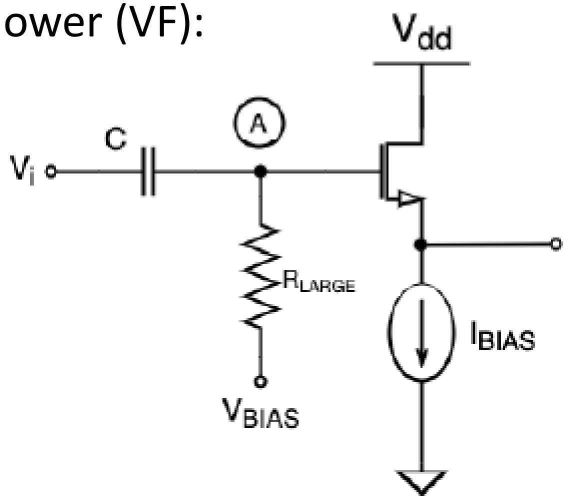
I. Pintilie, E. Fretwurst, G. Lindstr¨om, and J. Stahl,"Results on defects induced by 60Co gamma irradiation in standard and oxygen-enriched silicon," Nuclear Instruments and Methods in Physics Research, A, vol. 514, no. 1, pp. 1561–1582, 2003.

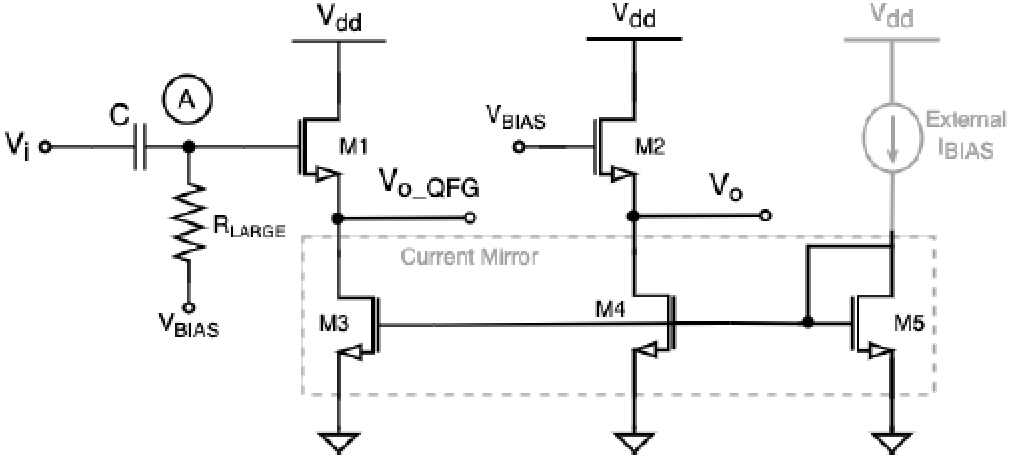
I. Pintilie, G. Lindstroem, A. Junkes, and E. Fretwurst, "Displacement damage in silicon detectors for high energy physics," Nuclear Instruments and Methods in Physics Research, A, vol. 611, no. 1, pp. 52–68, 2009.

M. Moll, "Displacement damage in silicon detectors for high energy physics,"IEEE Transactions on Nuclear Science, vol. 68, no. 8, pp. 1561–1582, 2018.

Device Under Test (DUT)

To evaluate the equivalent resistance of the QIR at a QFG transistor we need to observe the transient response at the QFG gate. The simplest way to measure the equivalent resistance is to apply the QFG technique to the transistor acting as a Voltage Follower (VF):





The device under test comprises a QFG VF plus a conventional VF, both matched (M1 with M2 and M3, M4 with M5) to avoid discrepancies. Both VF has the same size and biasing. TID will affect homogenously to the whole DUT but only the Rlarge, implemented as a pmos body diode, is sensitive to Displacement Damage.

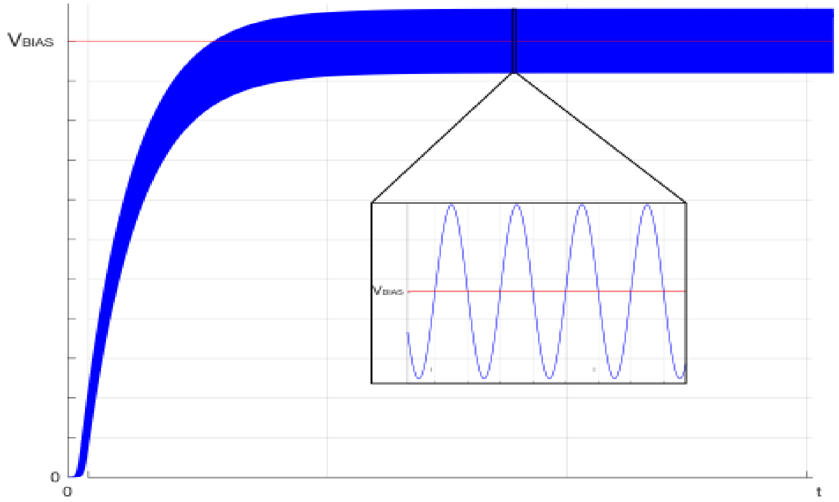
For a conventional VF:

$$v_o = \frac{g_m r_o}{1+g_m r_o+g_{mb} r_o} v_i \approx \frac{g_m}{g_m+g_{mb}} v_i$$

For the QFG voltage follower:

$$v_o|_{QFG} \approx \frac{g_m}{g_m+g_{mb}} \cdot \frac{sR_{LARGE}C}{1+sR_{LARGE}C} v_i$$

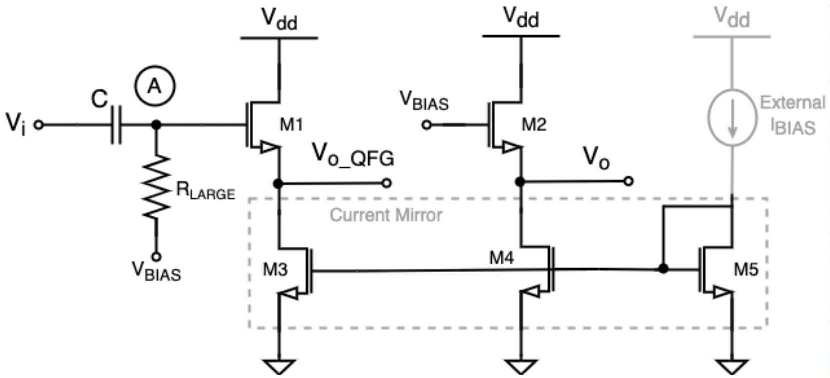
The QFG-VF reaches its final DC value with a settling time $\tau = R_{large}C$



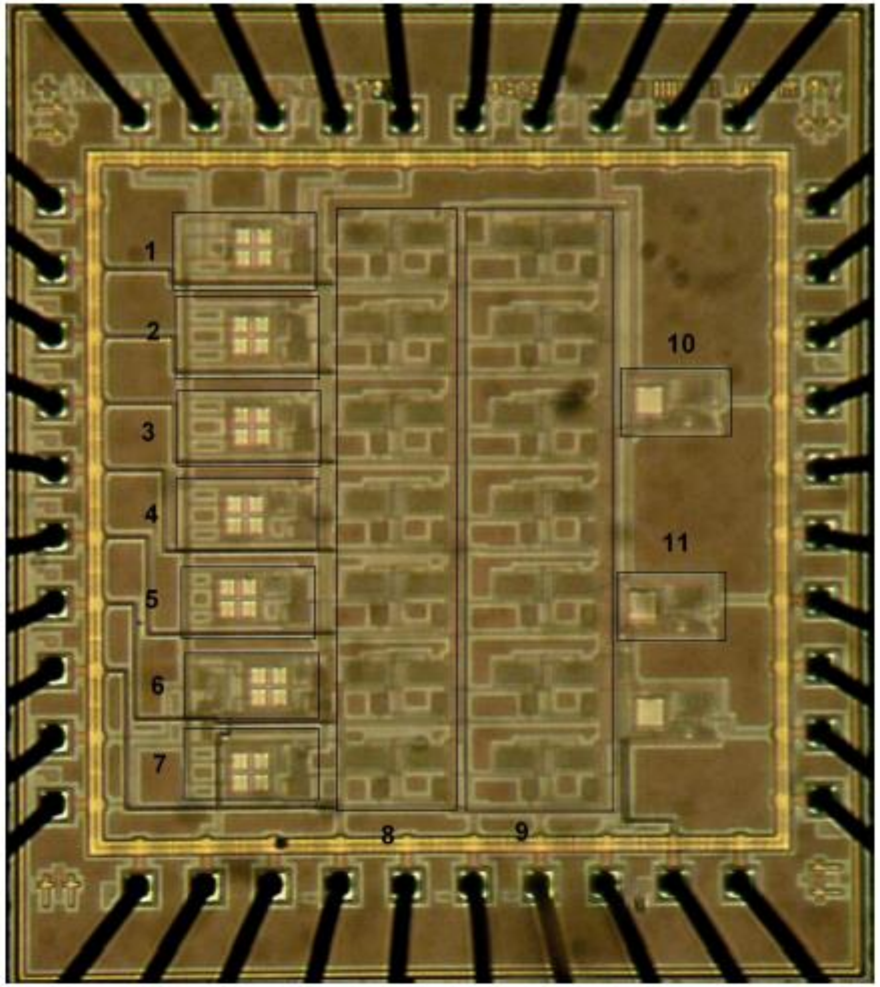
The expected output for the same Vbias for Vo_QFG (blue) and Vo (red) . The conventional VF reaches the same final DC value in a neglible time. Initially C is discharged so the expected Vo_QFG will rise exponentially from 0 to final value V_{bias}-V_{gs} . A low amplitude sinuosoidal signal is superimposed to test the QFG under radiation as in a real application.

Test Chip

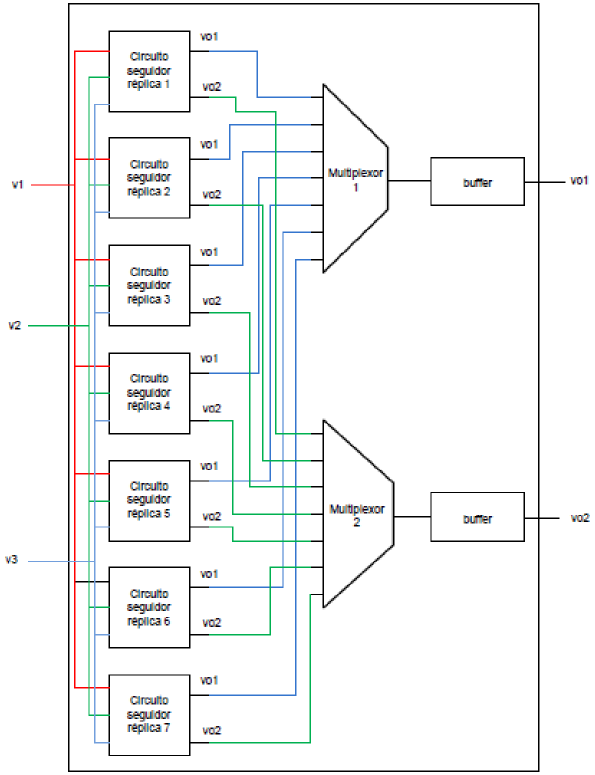
Transistor	W [µm] / L [µm]
M1,M2	50,1/1,05
M3,M4,M5	100,2/1,05
M_{LARGE}	15/1,2



As the value of the capacitors are not modified by radiation, the QFG-VF settling time $\tau = R_{large}C$ is an indirect measurement of the (average) value of Rlarge.



The chip is made in AMI C5N 500 nm technology, with well known TID behavior*, TID resistant up to 2Mrad. There are seven identical DUTs in a chip.



Multiplexers and output buffers route signals to the pads.

*Deep submicron CMOS technology for the LHC experiments, P.Jarron et al. Nuclear Physics B, 78, 1999, 625-634

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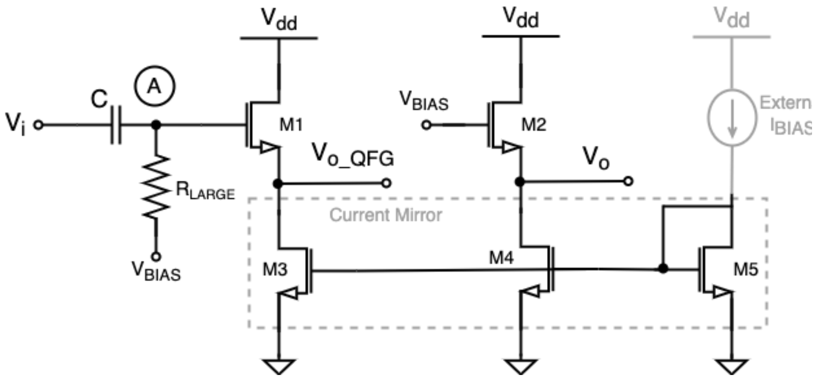

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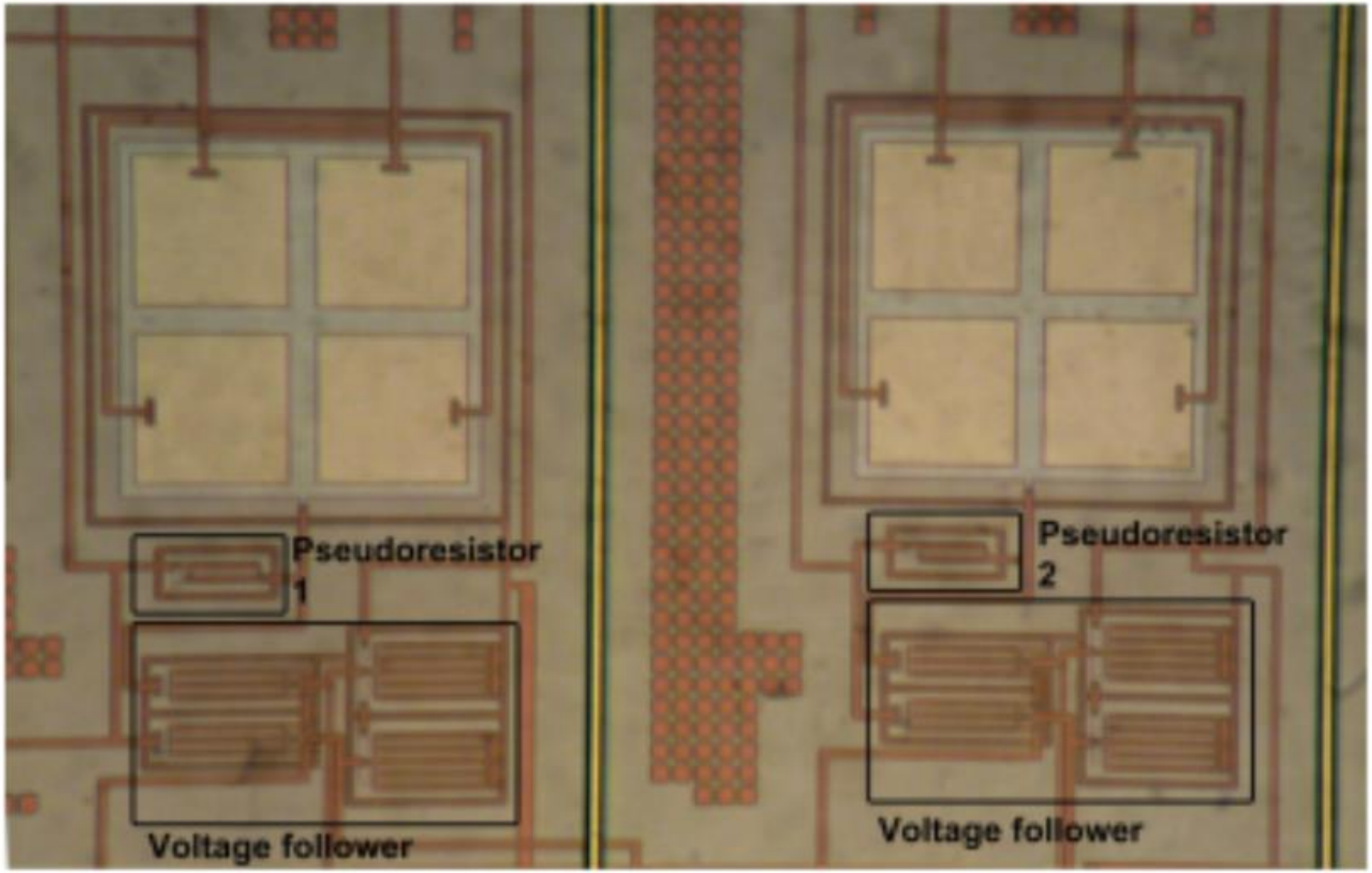
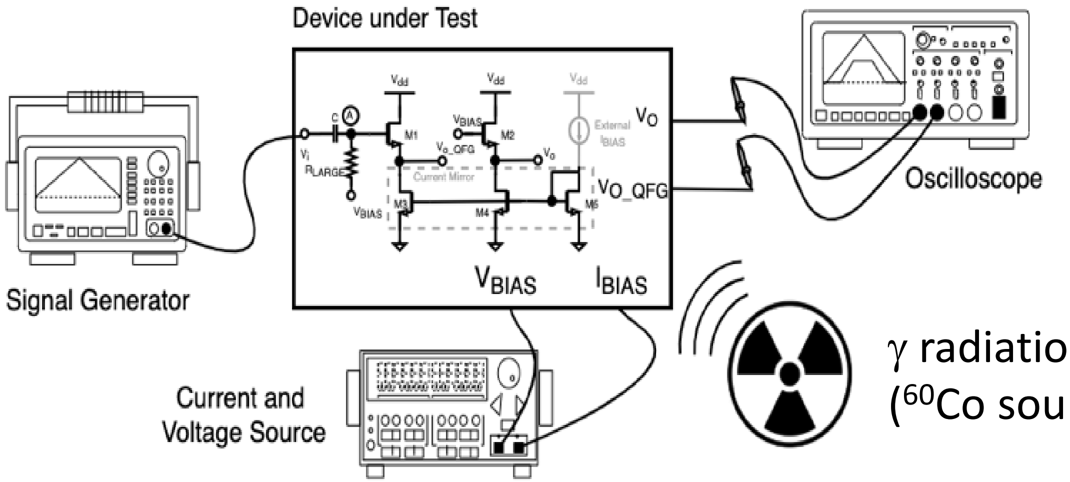
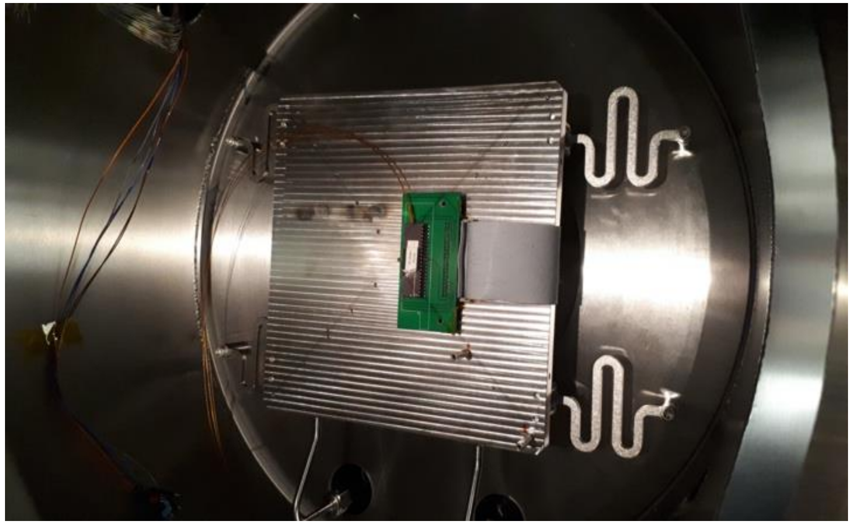


*Deep submicron CMOS technology for the LHC experiments, P.Jarron et al. Nuclear Physics B, 78, 1999, 625-634

Test Setup

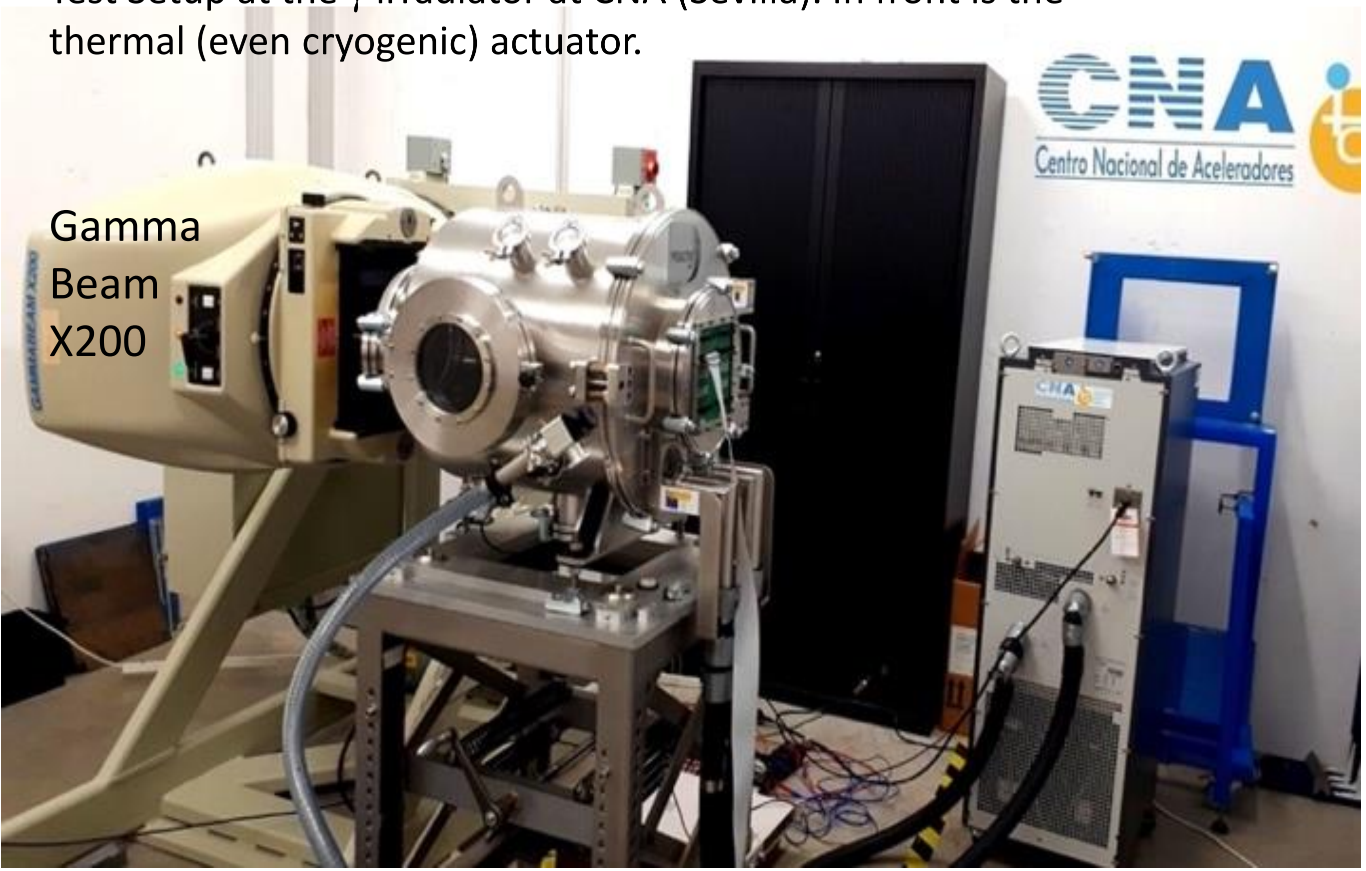


γ radiation
(^{60}Co source)



The chip is on a thermal chuck to ensure constant temperature during test

Test Setup at the γ irradiator at CNA (Sevilla). In front is the thermal (even cryogenic) actuator.



Gamma
Beam
X200

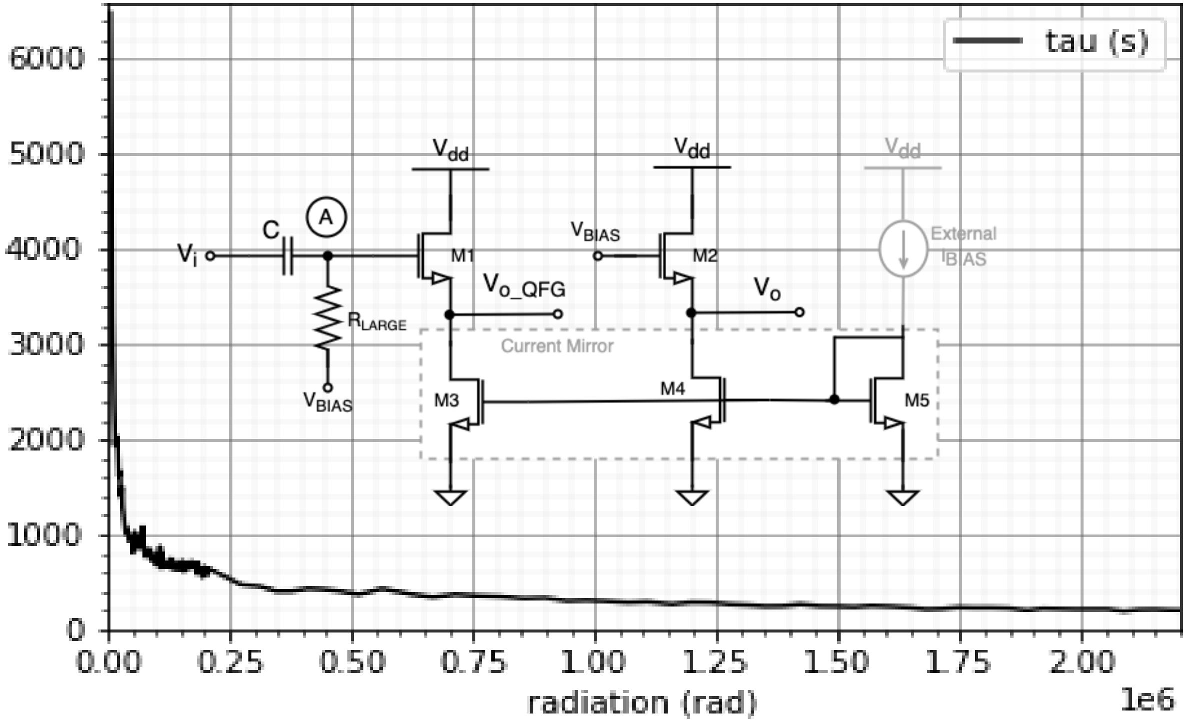
We made two irradiation legs

- Up to 207 krad (218 rad/h, 949h)
- Up to 2.045 Mrad (14,611 krad/h, 140h)
- Room Temperature annealing for 2200h

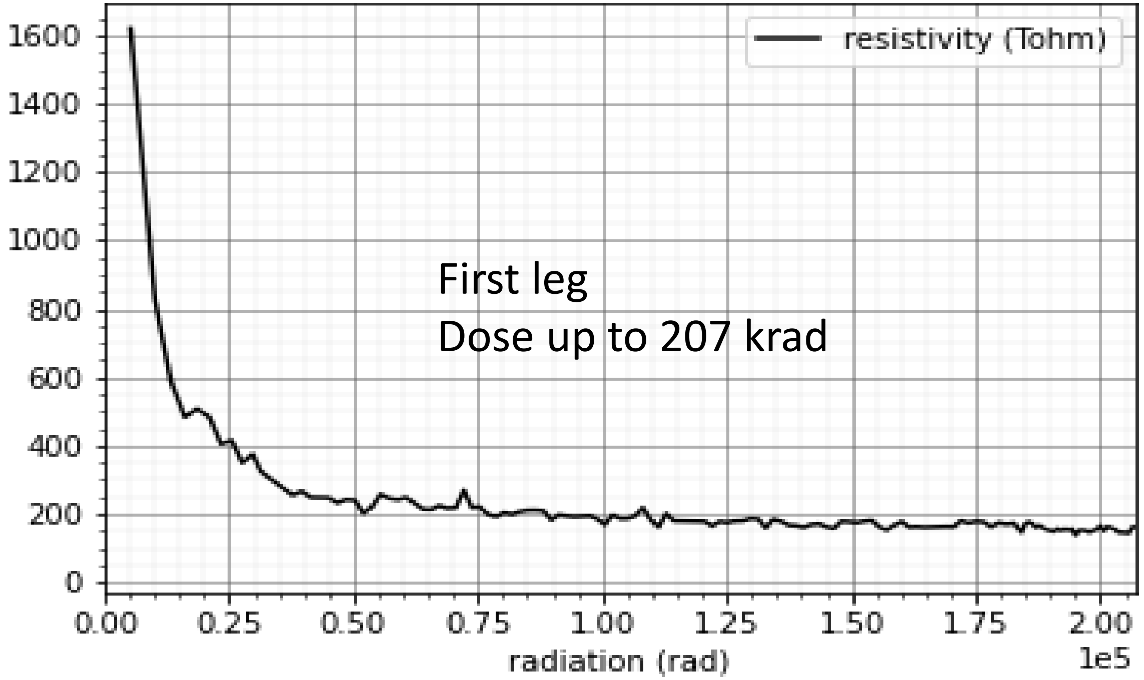
Two irradiated samples, one chip “on”, the other “off” to compare

Total Dose not even close to dose for significant TID (~10 Mrad) in 500nm transistors

Experimental Results

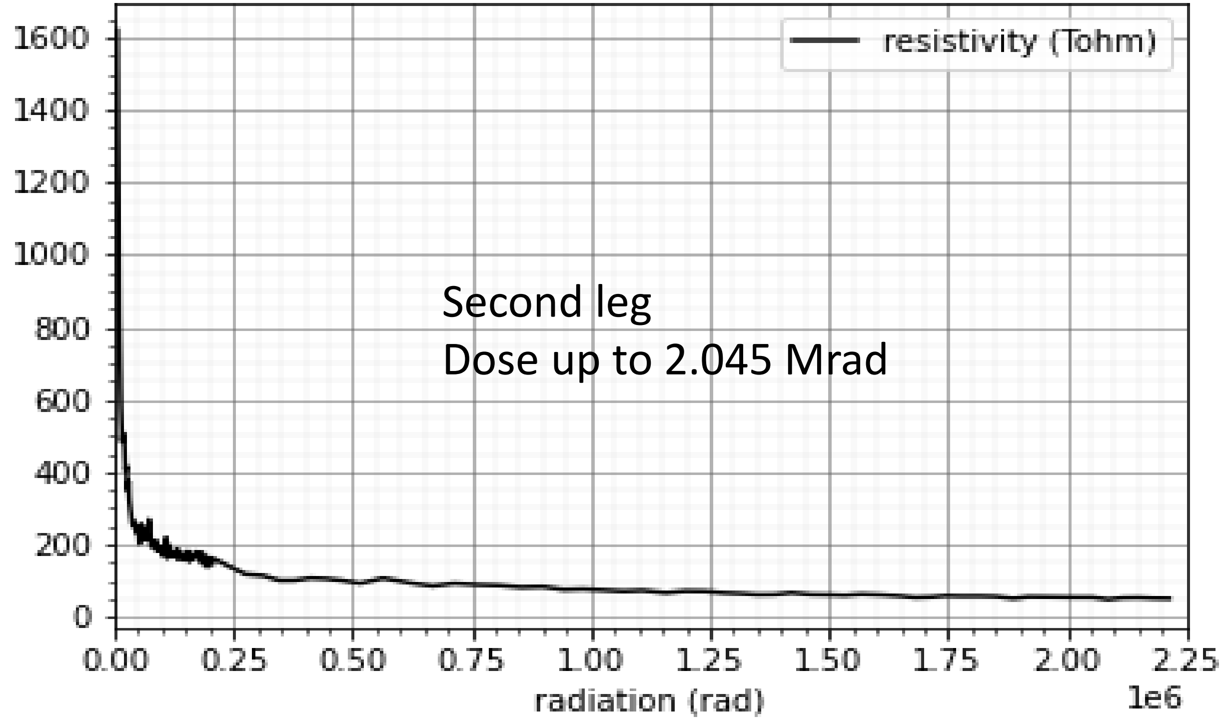


The settling time, τ, is how long it takes for the QFG-VF to reach its final value (Vbias-Vgs$_{|M1}$) at output V_{o_QFG} . Before irradiation, for all practical purposes, the final value is never reached. During irradiation it is very clear that the settling time is switfly reduced (even at low doses) and reaches a plateau.

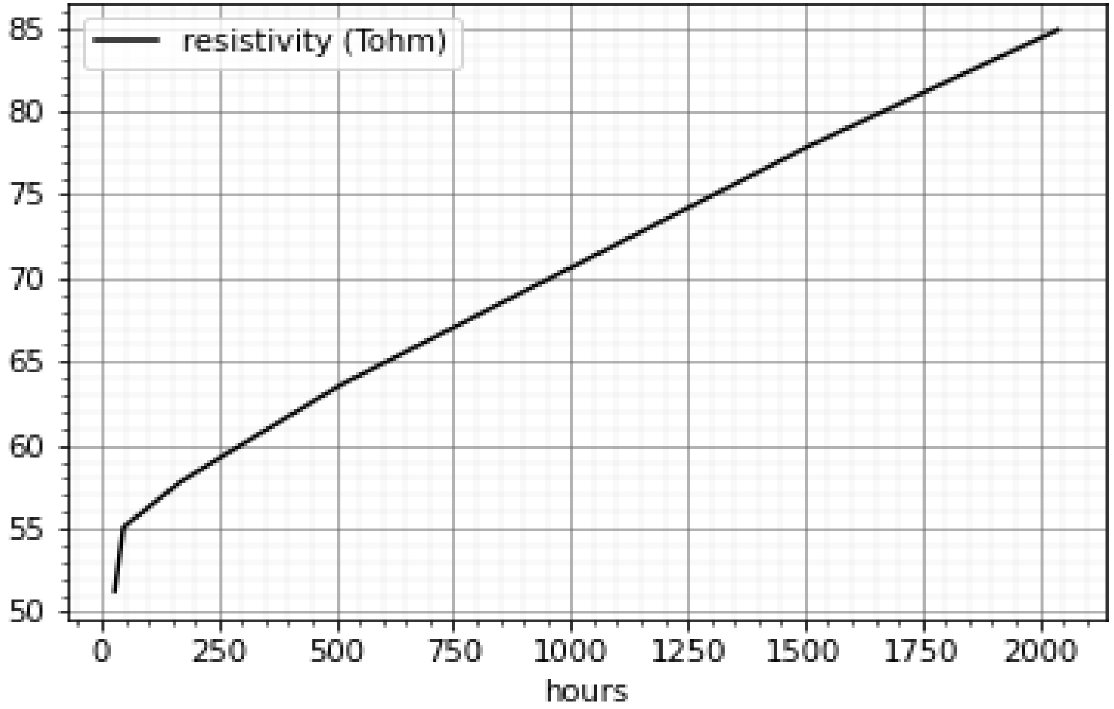


The first irradiation leg was up to 207 krad, well down the threshold of the TID effects. Considering that the input capacitor C has no radiation damage, the settling time data is translated to equivalent resistivity for the QIR (pmos wired as a reverse diode).
Rlarge falls from “almost infinity (1600 TΩ)” to 200 TΩ in the first 50 krad.

Experimental Results



Second leg
Dose up to 2.045 Mrad



The second leg was from 207 krad to 2.045 Mrad, still down the TID security margins but not for too much. The data shows the same result: the equivalent resistance of the QIR is strongly reduced, reaching a plateau after 50 krad, with a very mild resistance reduction from 200 TΩ to 55 TΩ in the second leg. This is intepreted as an increment in the saturation current, Is, of the QIR (a pmos reverse diode), in agreement with a crystalline radiation damage due to secondary Compton electrons.

Annealling at room temperature (2400h) is not very beneficial, we recover from 55 TΩ equivalent resistance to a maximum of 85 TΩ at the QIR (Rlarge).

Conclusions

- QFG technique to synthetize big equivalent resistors with small silicon area is blooming
- The QIR shows Radiation Damage effects, not very usual in VLSI electronics
- That Radiation Damage is in agreement with what we know from detector diodes
- As it must be because QIR’s, as in this work, are implemented tipically as diodes

Prospects

Is still useful the QFG technique in radiation environments?

- For the simplest QIRs (this work, reverse pmos diodes) the QFG technique is still useful at 50-80 TΩ of equivalent Rlarge (real designs are happy at GΩ)
- The observed dependence of Is with γ dose could be compensated in a real design operating a lower temperature (to be researched)
- We are preparing new studies at nanometric technologies, more TID resistant (for example at 65 nm scale) in order to increase the safe (noTID) dose span.

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Thanks for your attention

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