Radiation Hardened Pixel Development

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Outline

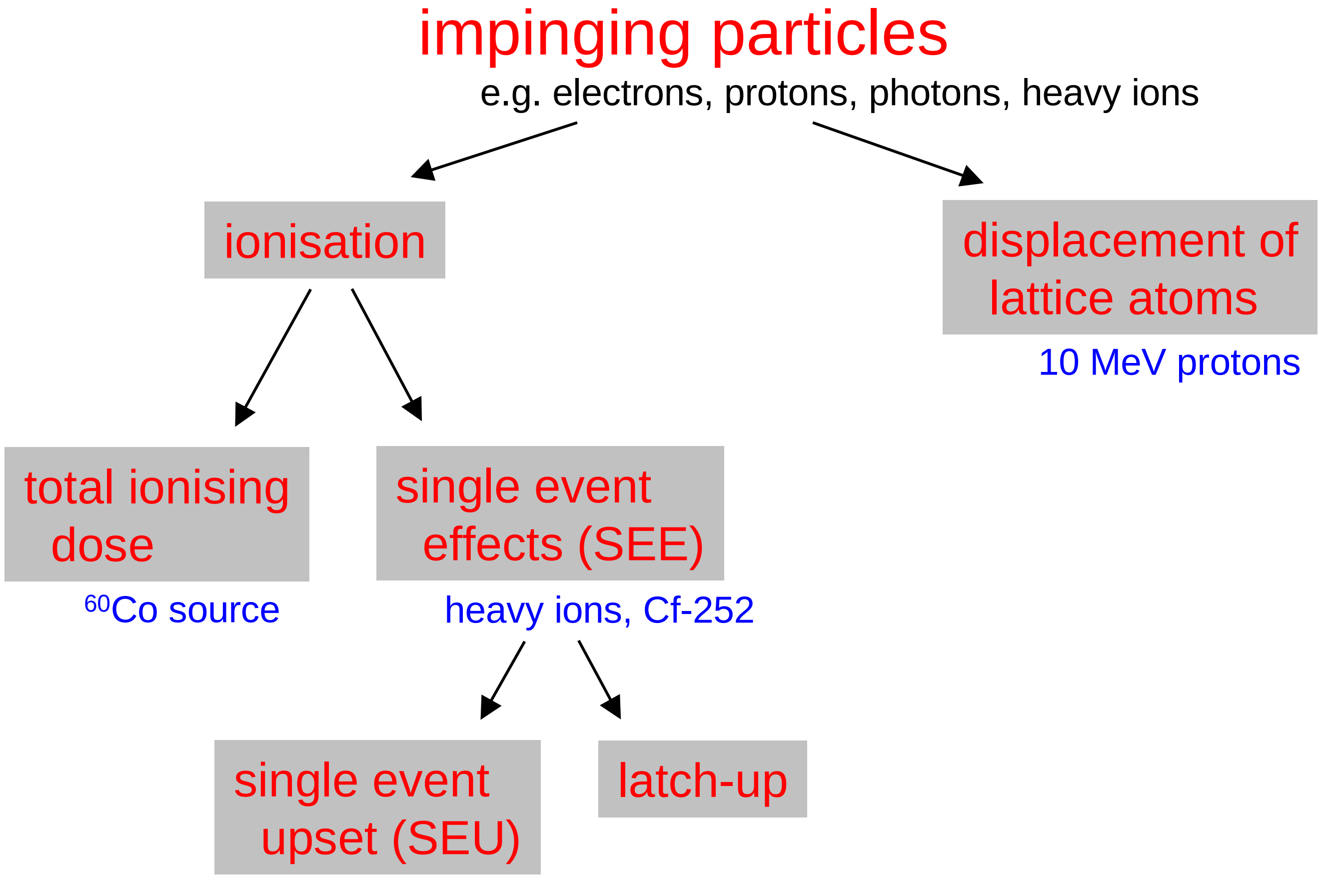
- **Introduction:** radiation effects
- **Total ionising dose effects** (^{60}Co source)
  - standard active pixels
  - solutions for total ionising dose hardening
    - **pMOS based pixel**
    - **radiation-tolerant nMOS pixel**
- **Proton-induced displacement damage** (10 MeV protons)
- **Latch-up experiments**
- **OISL pixel**
- **Conclusions**

Introduction

- CMOS APS with CCD performance
- Operation in the space radiation environment:
  - APS inherently more radiation tolerant than CCDs ?
  - other advantages: low power, on-chip integration, windowing, lower system cost, …

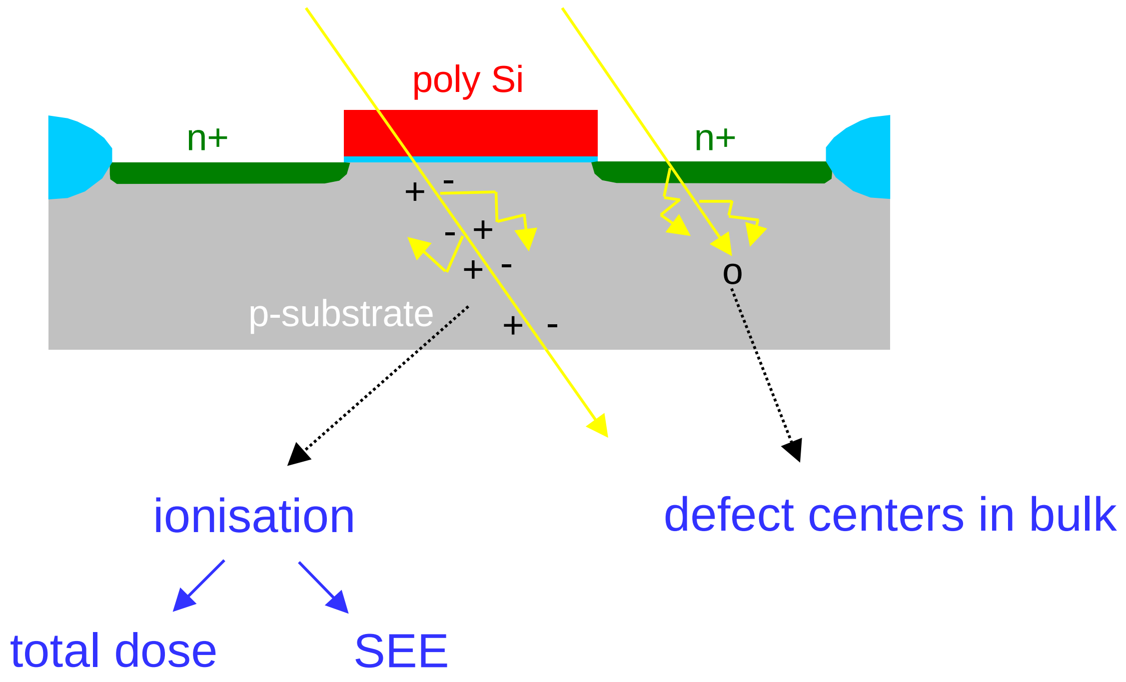
⇒ study and improvement of radiation tolerance of APS

Basic radiation effects (1)



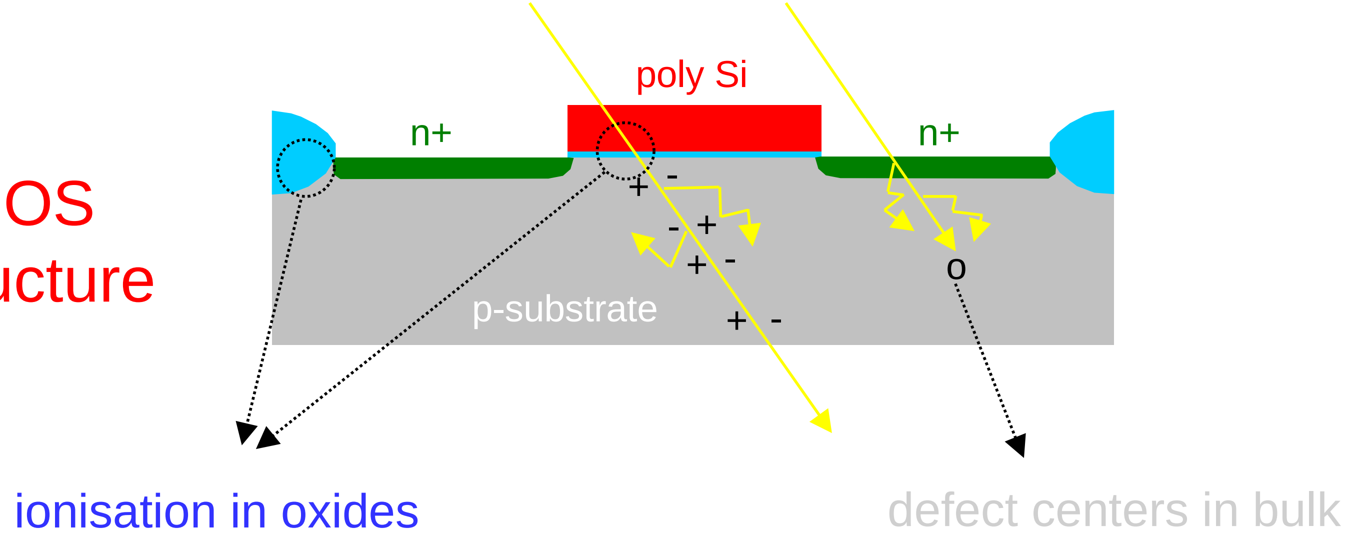
Basic radiation effects (2)

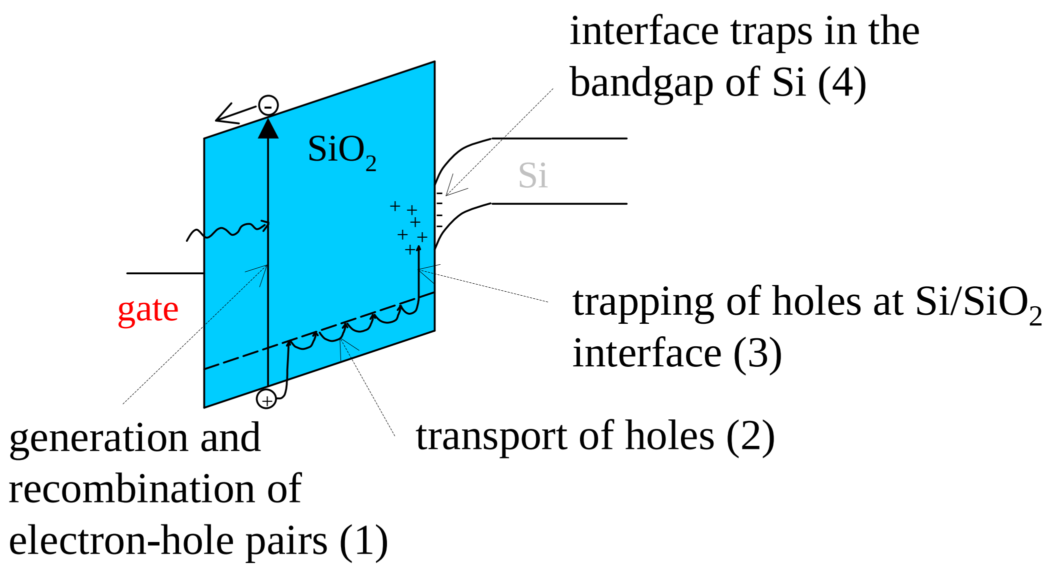
MOS structure



Basic radiation effects (2)

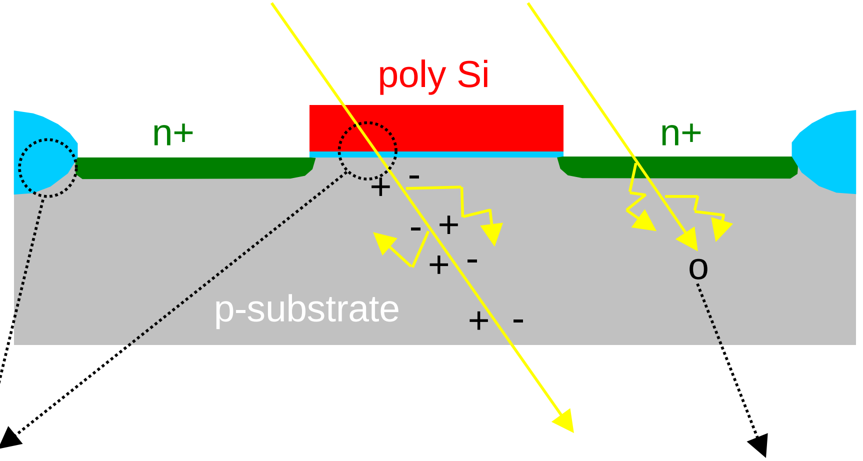
MOS structure



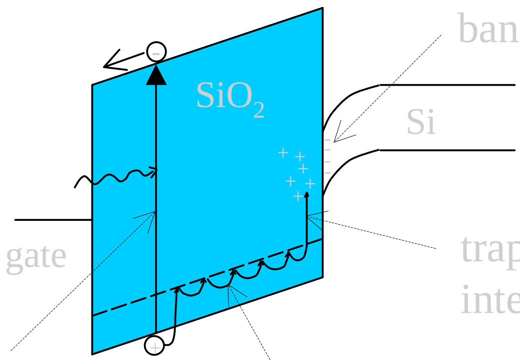


Basic radiation effects (2)

MOS structure



ionisation in oxides



interface traps in the bandgap of Si (4)

trapping of holes at Si/SiO_2 interface (3)

transport of holes (2)

generation and recombination of electron-hole pairs (1)

defect centers in bulk

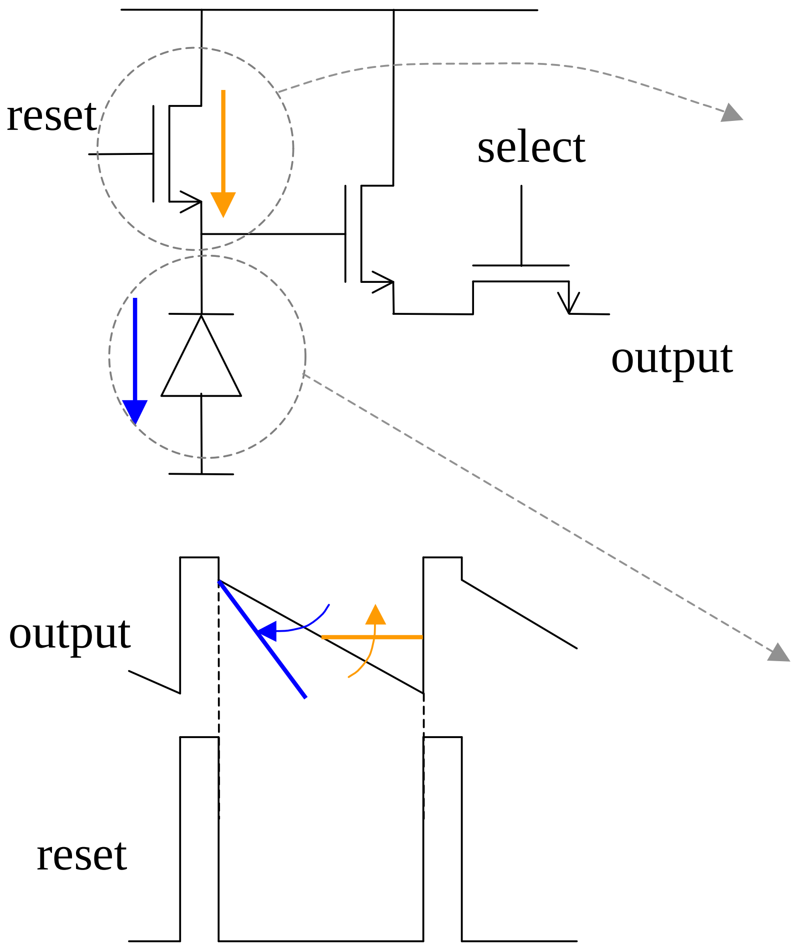
★ generation

★ recombination

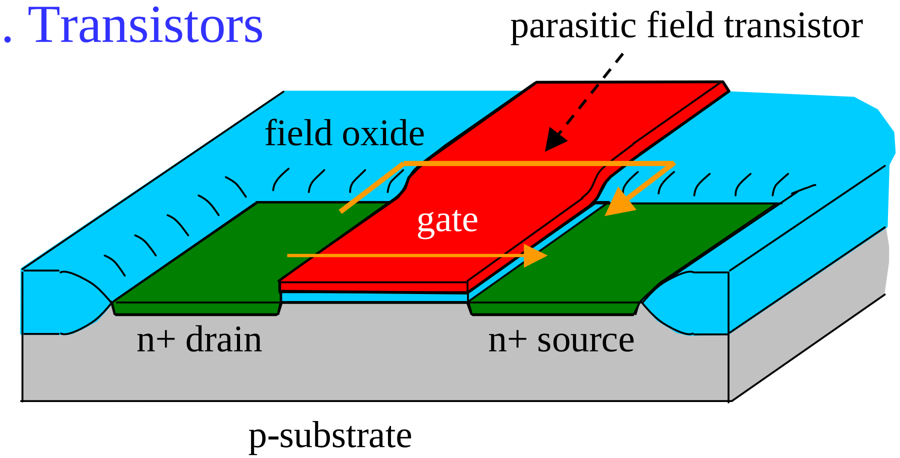
★ trapping

Total dose: standard active pixels

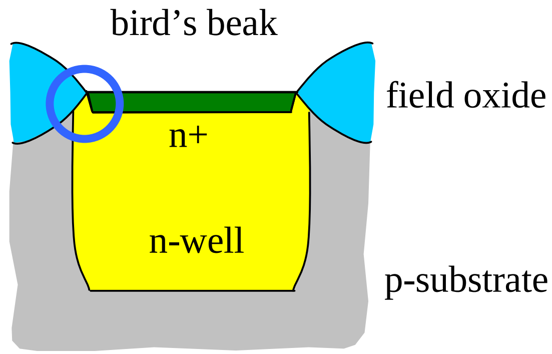
Radiation induced surface damage



1. Transistors



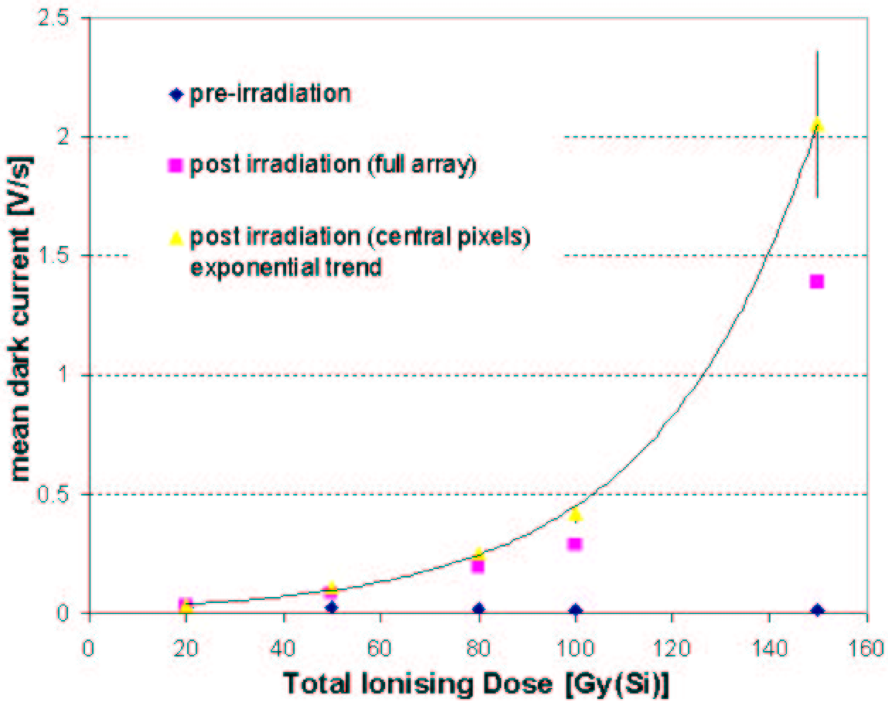
2. Photodiode



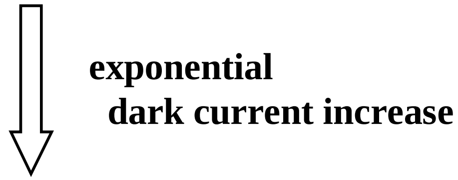
3. Interconnections

Mean dark current increase

Co-60 measurements on IRIS-2 chips



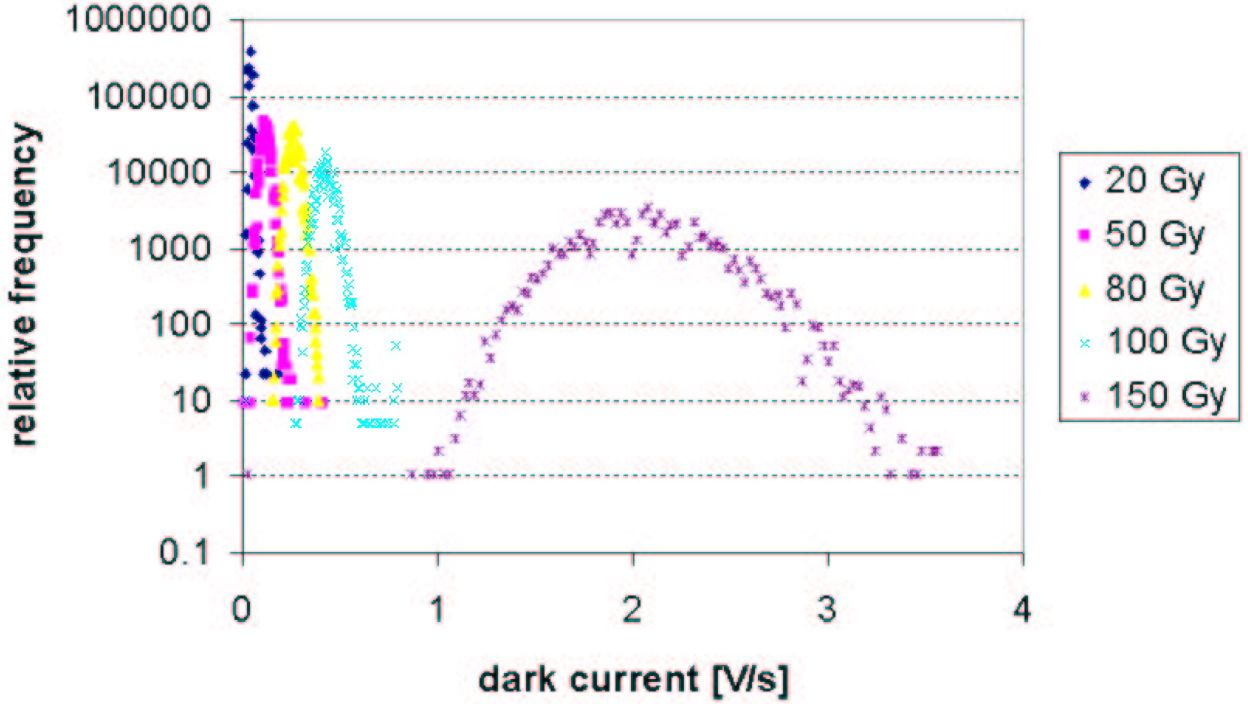
★ pre-irradiation value: ± 20 mV/s



★ post-irradiation value: 150 Gy(Si): ± 2 V/s

Dark current non-uniformity

Co-60 measurements on IRIS-2 chips



dark current non-uniformity increases with total ionising dose

Radiation-tolerant active pixels

- **The pMOS based pixel**

  + no parasitic field transistors

  + area

  - low sensitivity, fill factor

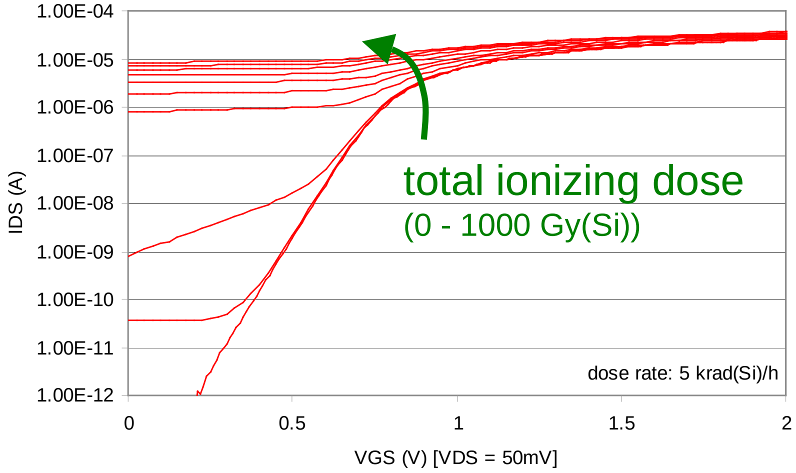
- **Radiation-tolerant nMOS pixel**

  - **TID tolerance: > 200 kGy(Si) (dose rate: 350 Gy(Si)/h)**
  - **area:**

technology	minimal pixel pitch
0.7 µm	20 µm
0.5 µm	15 µm
0.35 µm	8 µm

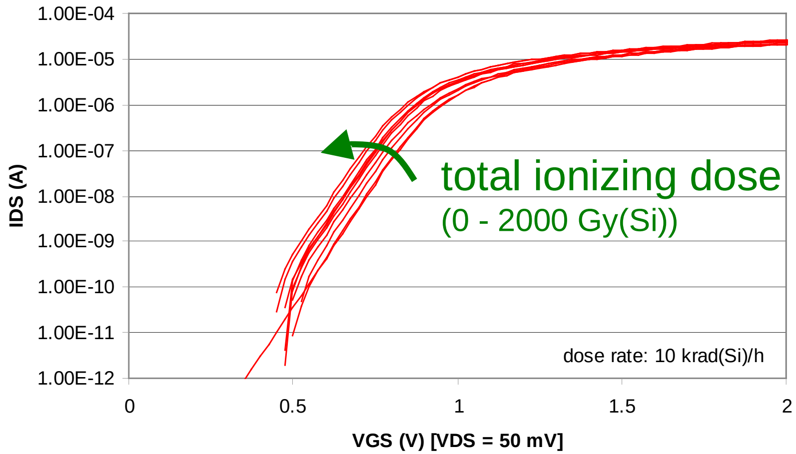
Radiation-tolerant nMOS pixel

Input characteristics of nMOS transistors



Standard nMOS layout:

- large leakage current increase due to parasitic field transistor
- typical TID threshold: 200 - 400 Gy(Si)



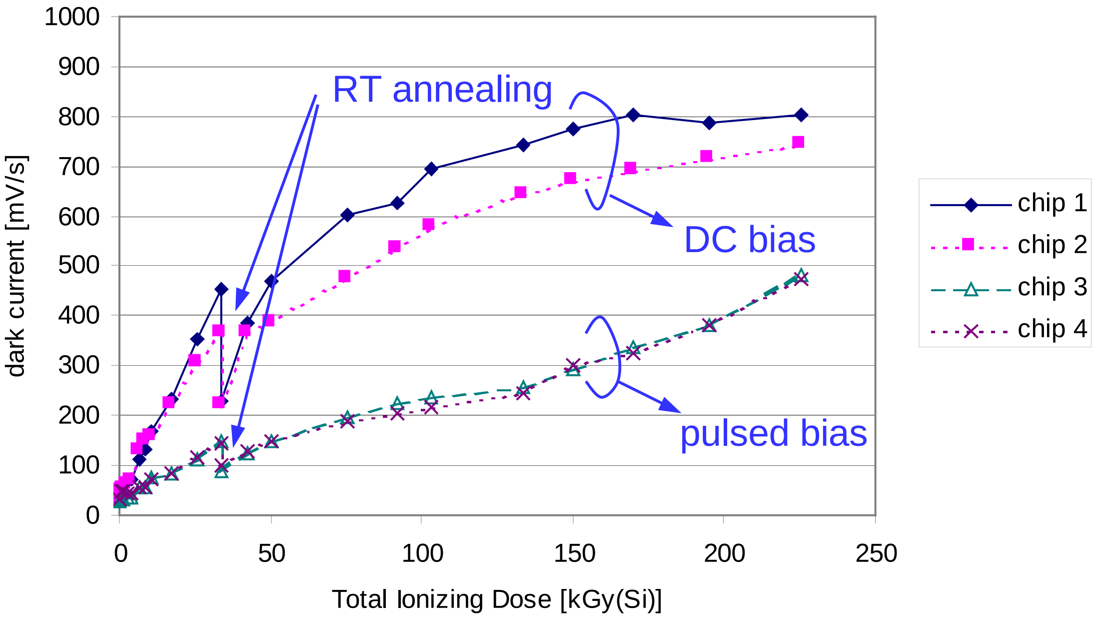
Radiation-tolerant nMOS layout:

- no leakage current increase
- small threshold voltage shift

  t_{oxide} dependence !

Radiation-tolerant nMOS pixel

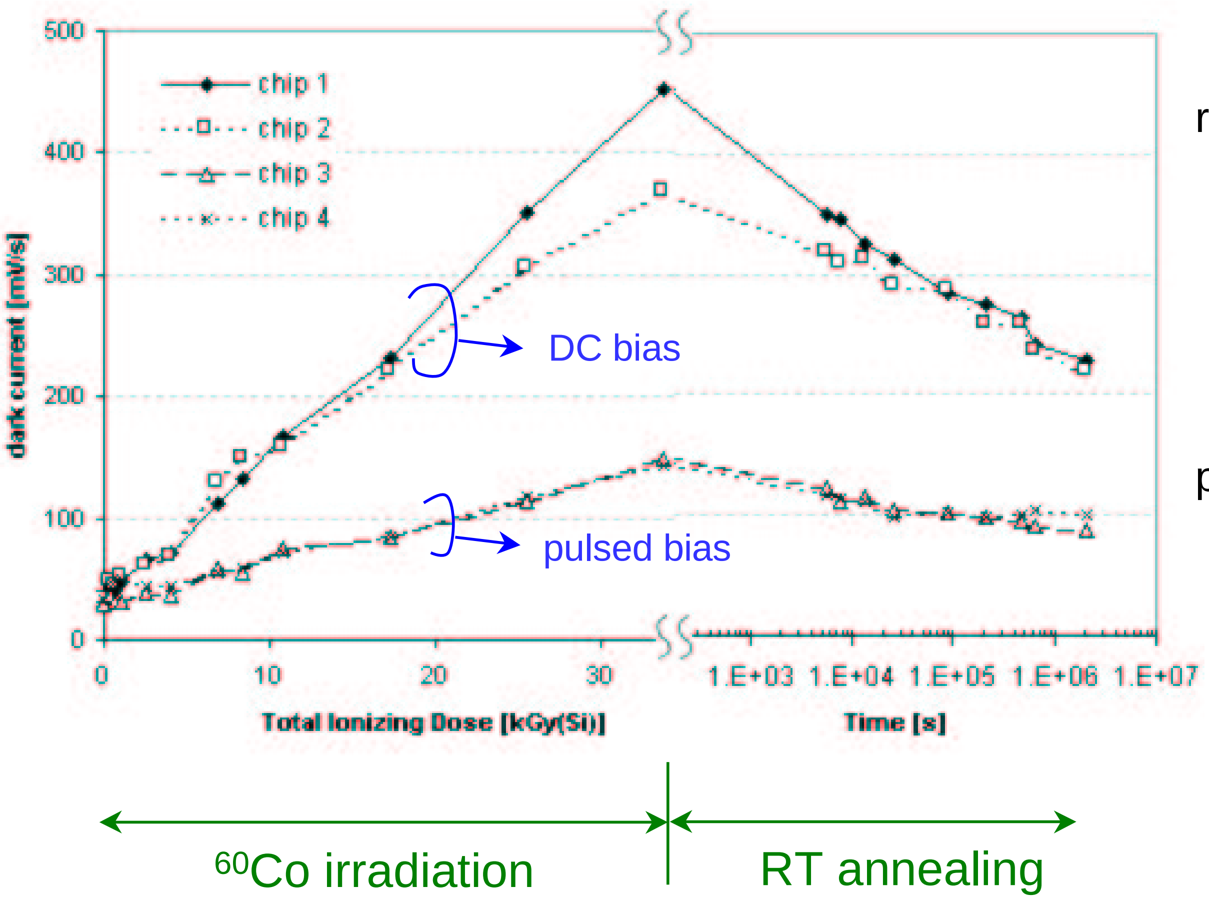
Dark current of radiation-tolerant nMOS pixel
(0.7 µm technology)



- very low dark current increase compared to standard active pixels
- dark current radiation-tolerant nMOS pixel < dark current pMOS based pixel
- 'DC bias' is the worst case scenario

Radiation-tolerant nMOS pixel

Dark current of radiation-tolerant nMOS pixel



room temperature annealing:

- why?
- log(time) annealing

⇓

dark current increase is probably small in low dose rate space environment

Displacement damage (1)

• **Devices:** 5 Ibis4 CMOS APS from FillFactory

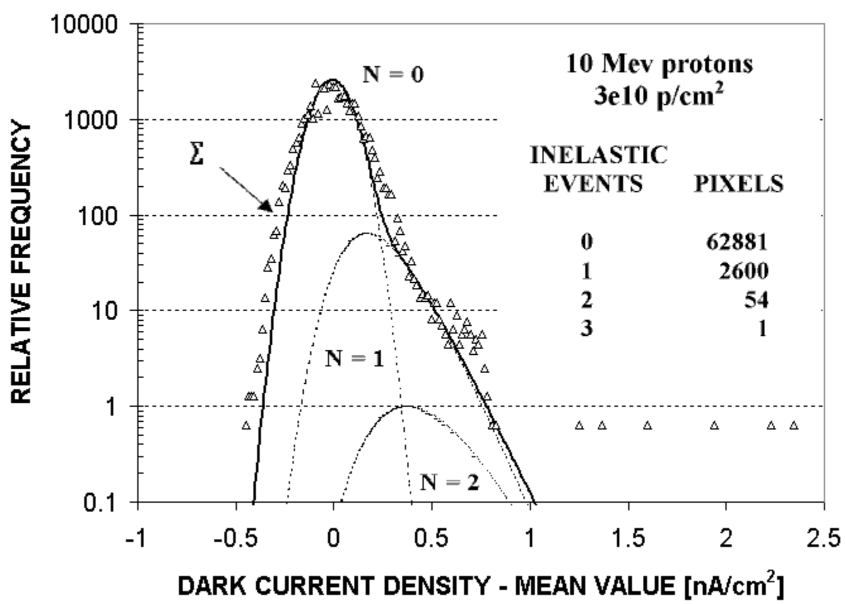
• **Irradiation:** 10 MeV protons
3×10^{9}, 1×10^{10}, 3×10^{10}, 1×10^{11}, 3×10^{11} protons/cm^2

• **Displacement damage effects:**

- **mean value and variance of the dark current density increase**
- **distributions become more skewed**
- **anomalously high dark current spikes:**
  field-enhanced emission

Displacement damage (2)

Histogram of dark current density



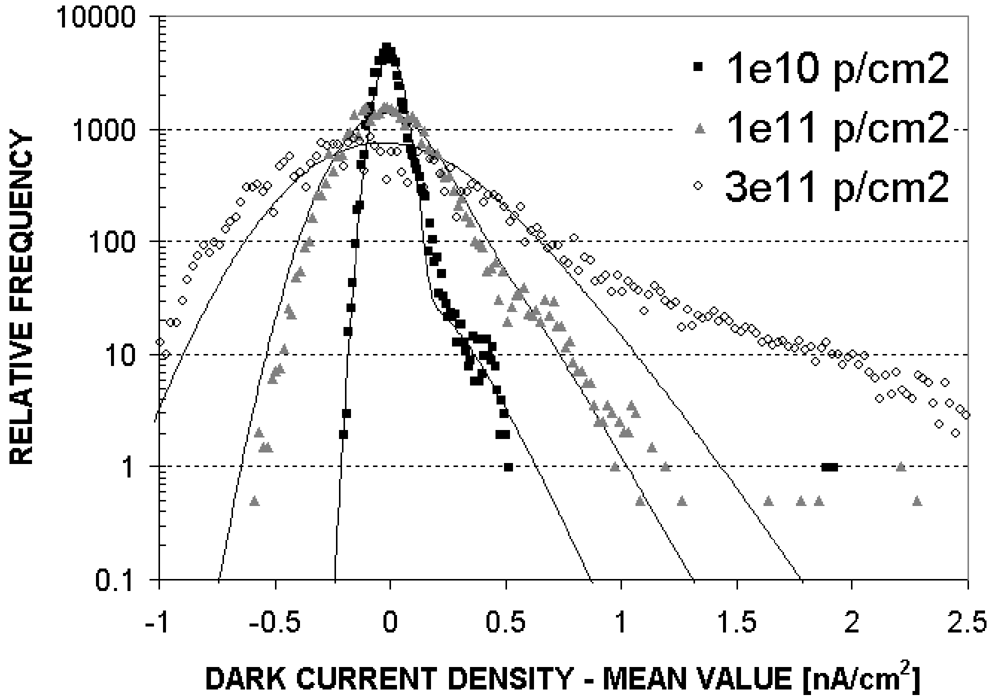
- 256x256 window
  3x10^{10} protons/cm^2 (10 MeV)
- pixel sensitive volume:
  45 µm^3
  (typically 1000 µm^3 for CCDs, CIDs)
- elastic interactions:
  416 per pixel
  inelastic interactions:
  0.138 per pixel

10 MeV proton recoil spectrum parameters (Marshall et al.) ⇒

Cross section (10^{-24} cm^2)	Mean damage energy (MeV)	Variance of damage energy (MeV^2)
ELASTIC EVENTS		
1847.5	1.784 x 10^{-4}	*4.77 x 10^{-6}
INELASTIC EVENTS		
0.6127	0.06021	1.30976 x 10^{-3}

Displacement damage (3)

Histogram of dark current density at different fluences

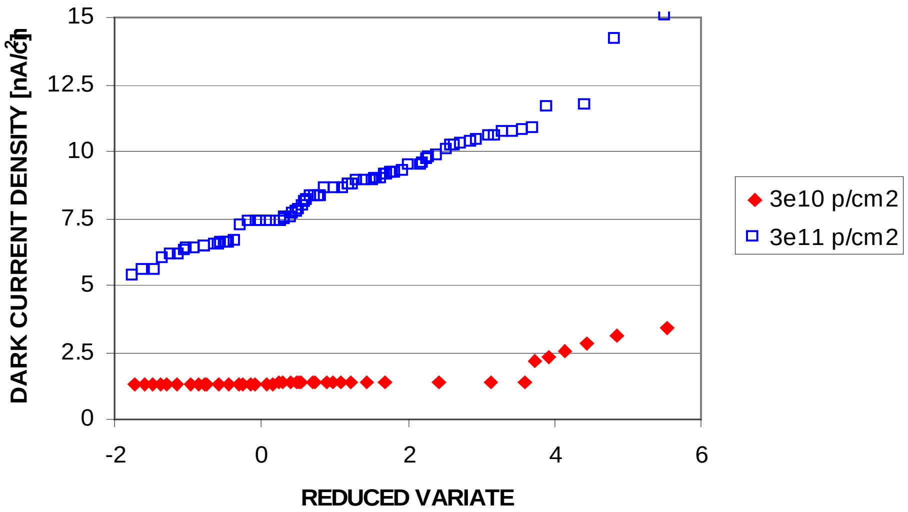


- mean value has a component due to ionisation damage
- mean value and variance of the dark current density increase with increasing proton fluence

Tail on distributions:

- infrequent, highly damaging inelastic collisions
- spikes: field-enhancement

Displacement damage (4)



- 256 x 256 window subdivided: 256 bins of 256 pixels each
- extreme value statistics:

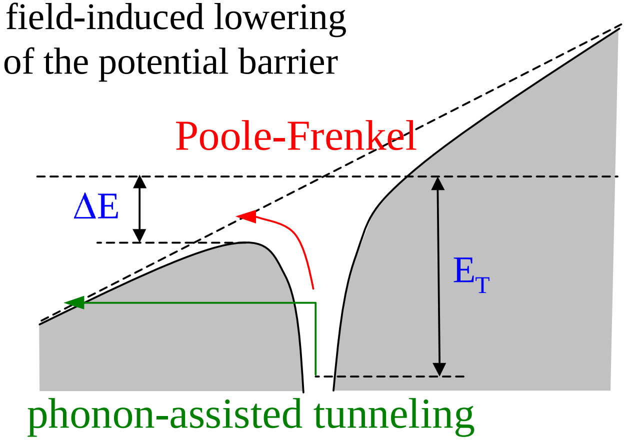
  largest dark current values do not follow the normal distribution

⇓

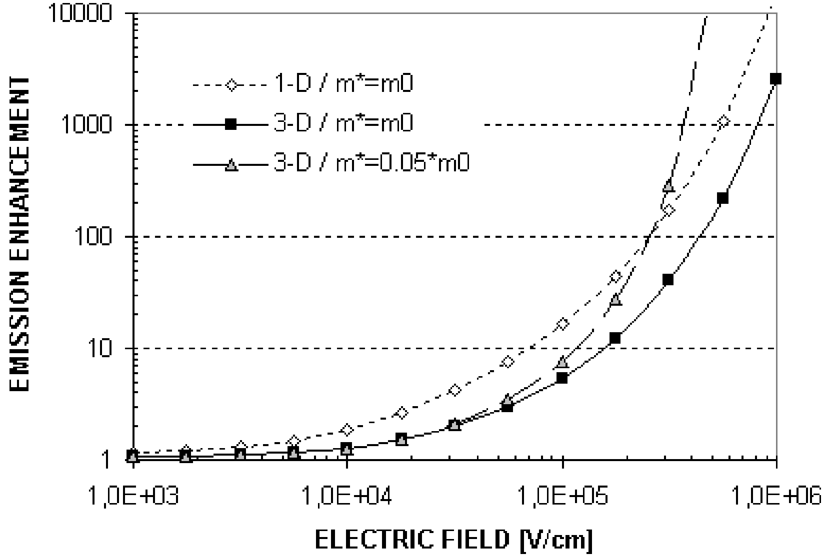
FIELD-ENHANCED EMISSION

- Poole-Frenkel effect
- phonon-assisted tunneling

E_T = energy level of the trap
ΔE = field-induced lowering of the potential barrier



Displacement damage (5)



emission enhancement factor (Coulombic potential):

± 10 @ 10^5 V/cm

- very small area in sensitive volume
- induced by other defect

Latch-up experiments

- **ASCoSS sensor (Sira, heavy ions)**

latch-up threshold	**~ 19.9 MeV/mg/cm^2**	**(ADC)**
	> 28 MeV/mg/cm^2	**(analog core)**

- **IRIS-2 (Cf-252)**

latch-up (43 MeV/mg/cm2) (only in digital core)

OISL pixel

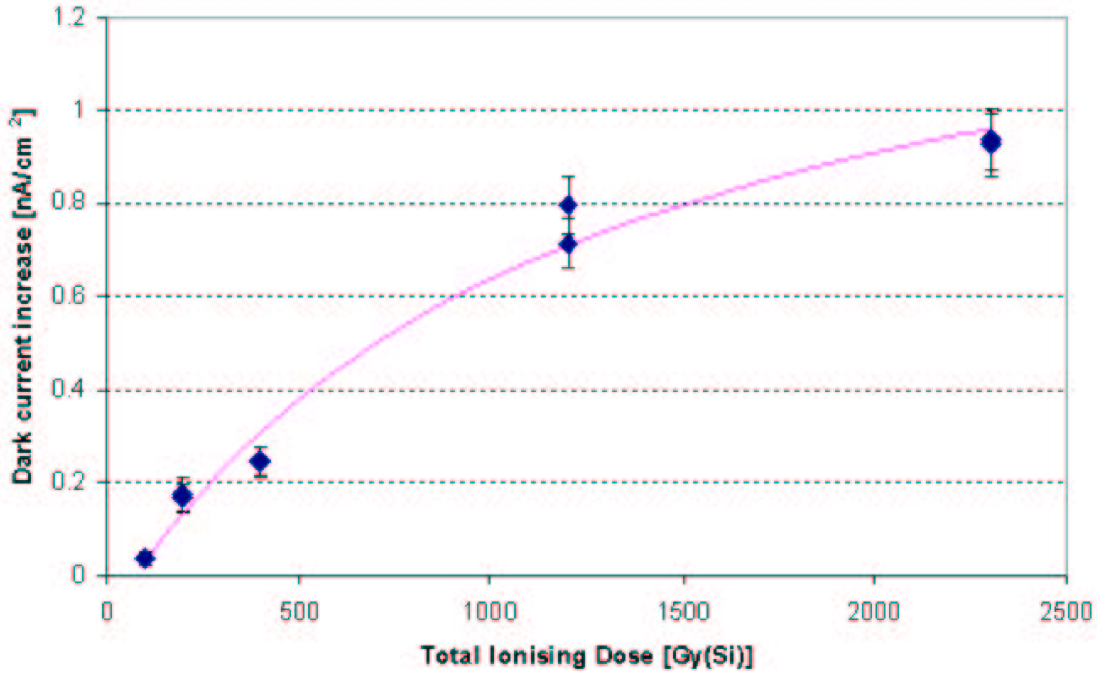
- **OISL = CMOS Active Pixel Sensor for Optical Inter-Satellite Link**

  (details in presentation D. Uwaerts, FillFactory)

- **radiation-tolerant design:**
  - **0.5 µm technology**
  - **^{60}Co irradiation (50 Gy(Si)/h):**
    - 10 devices
    - total ionising dose: 100, 200, 400, 1200, 2300 Gy(Si)
    - ongoing irradiation >50 kGy(Si)

Dark current density increase

Co-60 measurements on OISL



★ pre-irradiation value:
$\pm$ 0.2 nA/cm^2
($\pm$ 45 mV/s)

saturating dark current increase

★ post-irradiation value:
2300 Gy(Si):
$\pm$ 1.1 nA/cm^2

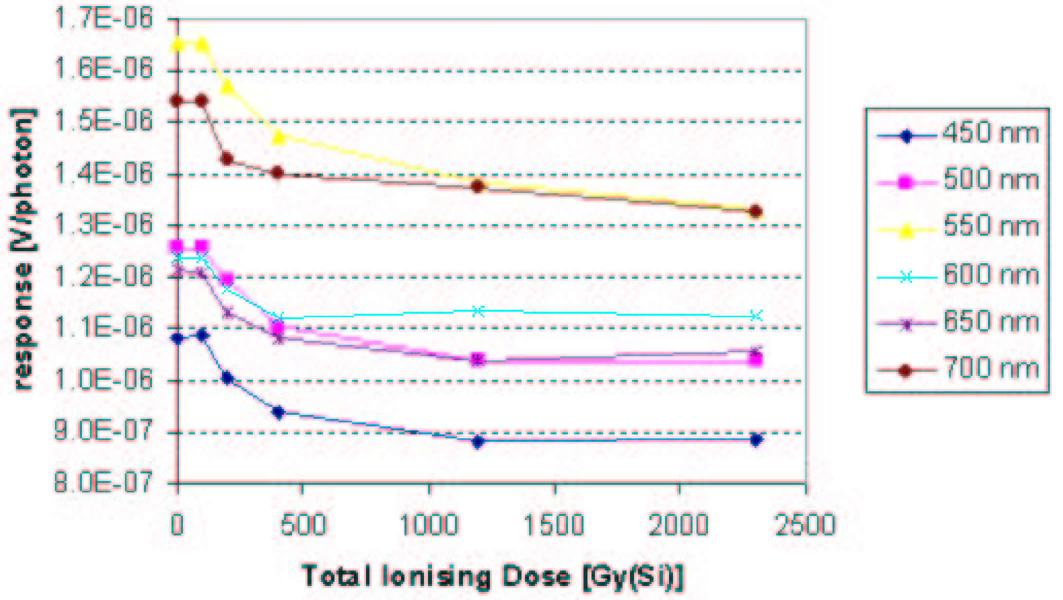
Fixed pattern noise

Co-60 measurements on OISL

FPN not affected by Co-60 irradiation:
no degradation in column amplifiers

Photo-response

Co-60 measurements on OISL



decrease of responsivity (wavelength dependent)

- increased absorption in overlaying layers?

- decrease of QE?

After 20 kGy(Si) (2 Mrad(Si))!

Conclusions (1)

- **Ionising radiation:**
  - **large impact at the surface in standard active pixels**
    - nMOS leakage current
    - increase in dark current
  - **radiation tolerant pixels can be obtained** (> 200 kGy(Si))
- **Displacement damage:**
  - **mean and variance**
  - **tail on histograms:** - inelastic nuclear collisions
    - field-enhanced emission

Conclusions (2)

- **Comparison with CCDs**
  - **radiation tolerance in standard CMOS technology**
  - **large operating window**
  - **no problems with CTE**
  - **mean dark current and amplitude of dark current spikes is lower:**

    ⇒ smaller sensitive volume

- **Design of OISL:**

  Probably the best radiation-tolerant CMOS imager in the world...