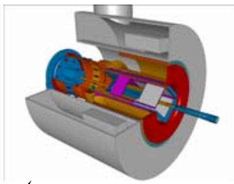
Strahlenschäden in Silizium

Ingrid-Maria Gregor



- Einleitung
- Klassifizierung von Strahlenschäden
  - TID - Total Ionising Dose
  - NIEL - Non Ionising Energy Loss
  - SEE - Single Event Effects
- Strahlentolerante Sensoren
- Deep Submicron
- Zusammenfassung

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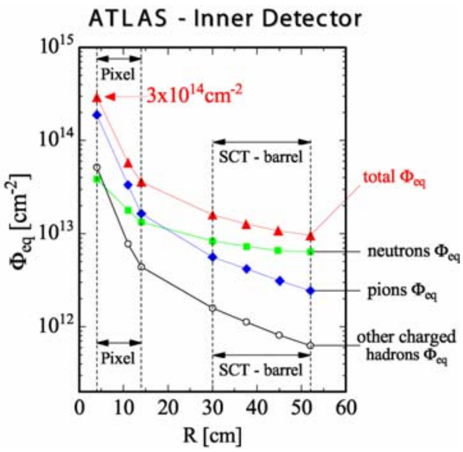
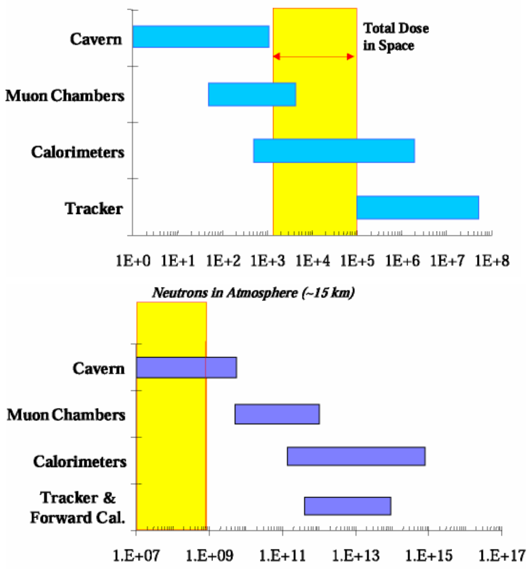
Introduction

- Promising new physical results are related to some very rarely produced particles
  - high event rate (10^9/sec at LHC), very good spatial resolution and fast signal read out required, can be fulfilled with silicon detectors, however:
- Detectors and electronics will be harshly irradiated!
  - ATLAS - Inner Detector: Φ_{eq} up $3x10^{14}$ cm^{-2} per year (1 Billion Lung x-rays)
  - 10 years of operation have to be guaranteed



- What is the impact on silicon ?
- How can it be made harder ?

Comparison with Space Environment



- comparison of total dose and neutral fluence in the space and CMS (LHC)
- total dose and dose rate comparable to those expected in the calorimeter => similar qualification approach (NASA,ESA ...)
- neutron environment not an issue in space appl.
- different apporach for bipolar circuits

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Classification of Radiation Effects

- Surface Defects: Total Ionising Dose (TID)
  - mainly affect electronic circuits
- Bulk Damages: Non Ionising Energy Loss (NIEL)
  - mainly affect sensor like structure (pn junctions)

permanent

- Single event effects (SEE)

transient

- Transient Radiation Effects in Electronics (TREE) associated with detonation of nuclear weapons
- "Radiation sensitive" materials:
  - semi-conductors
  - oxides
  - heavy elements from interconnections (W, Ta, Au, Pb, Pt,....)

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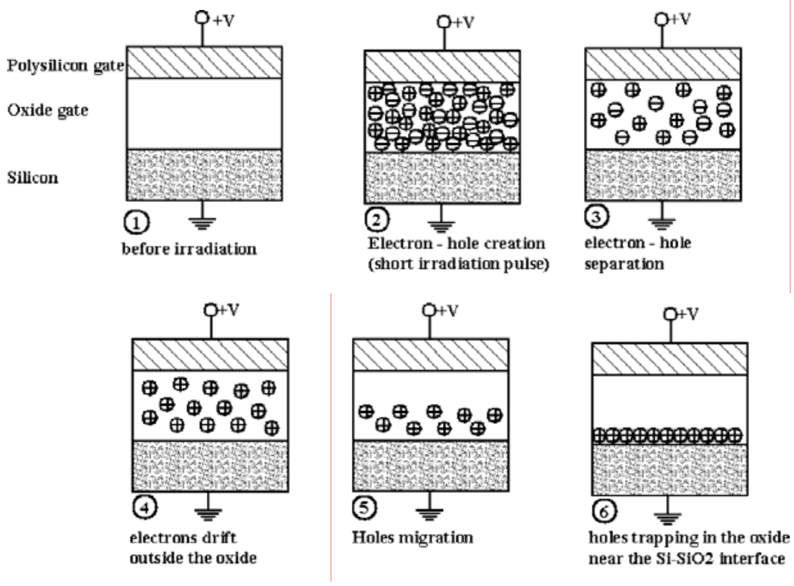
TID: Ionisation in Si or SiO_2

- Direct mechanism:
  - incident photon => absorption
  - incident charged particle => ion. along track
- Indirect mechanism:
  - incident heavy particle =elastic collisions or nuclear reaction => ionisation along the track of secondary particles
- Ionisation:
  - electron-hole pair creation
  - partial recombination (strong if no electrical field)
  - electron: high mobility =>leave oxide
  - holes: very low mobility=>mostly trapped
- Result: net pos. charge trapped in oxide
- long term trapping at room temperature

TID: Cumulated Ion. in a MOS Oxide

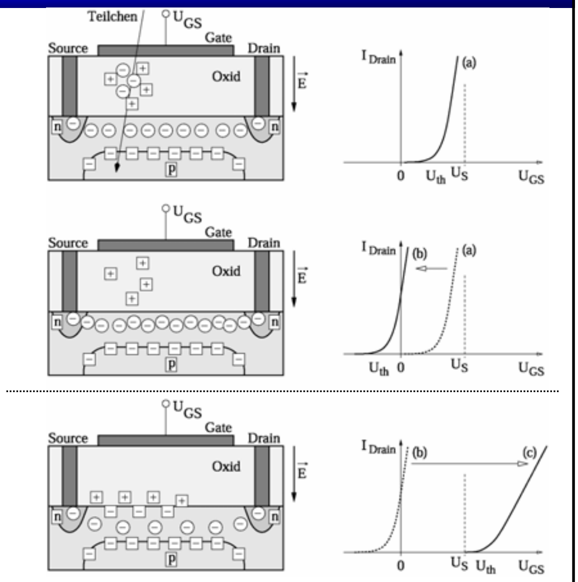


TID: Surface Damages

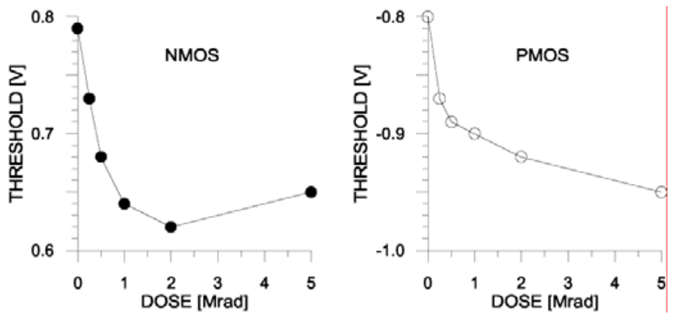
- Defects induced by space charge buildup
  - speed of a circuit decreases due to the decrease of the conductivity
  - dynamic current consumption rises; rise and fall time of signals increase
  - threshold characteristics of transistors change and transistor might stop to switch
- Device degradation scale approx. with the total energy deposited by irradiation -> total ionising dose (TID)
- TID may change the device electrical characteristics for a dose as low as 10Gy=1kRad!! (HERMES Si RD ~200kRad)
- Damage is depending on dose, radiation duration, applied voltage, layout and size of device --> testing is essential

TID: NMOS-Transistor

- Gate bias $U_{GS} > U_{th}$
  -> n-conducting channel between source and drain
- a) typical behaviour
- b) after direct damages
  - n channel increases
  - constructive field added
- c) with charge trapping field
  - deconstructive field (for very high doses)

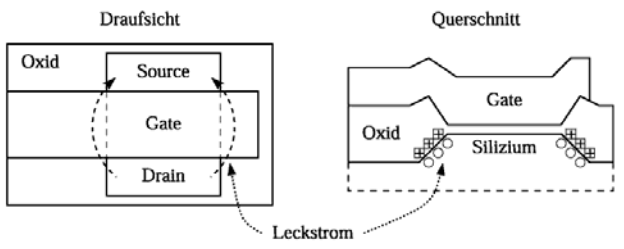


TID: Threshold Voltage Shifts



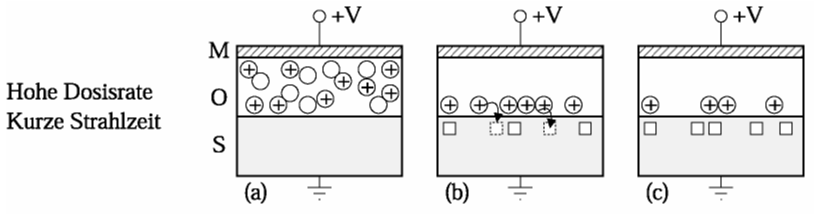
- slight upturn: reflects buildup of interface states
- about 70% of the threshold shift occur during the first 250kRad

TID: Increase of Leakage Current



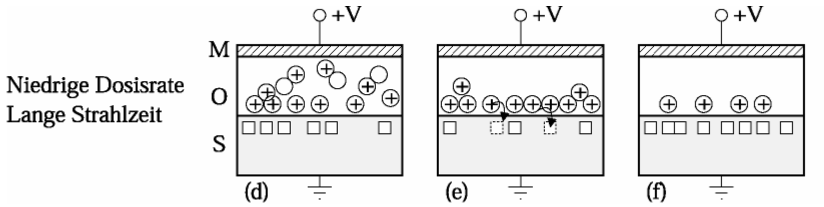
- the conductivity along the SiO2 layer is increased due to the additional permanent charges at the interface (source drain leakage current)
- seems to be independent of lateral isolation techniques in NMOS gates
- leakage current within a transistor but also between adjacent transistors

TID: Dose Rate Effect, Example:NMOS



- high dose rate:
  - 2nd order effect: recombination. Each electron is surrounded by numerous holes
    - → large recombination
    - → reduced density of trapped holes in SiO_2
  - 1st order effect: time. Short time irradiation => only a part of the trapped holes leave SiO_2
  - Result: only small shift in characteristics

TID: Dose Rate Effect, Example:NMOS



- low dose rate:
  - 2nd order effect: recombination. Each electron is surrounded by few holes
    - small recombination
    - high density of trapped holes in SiO2
  - 1st order effect: time. Long time irradiation => most of the trapped holes leave SiO2
  - Result: large shift in characteristics
- Low dose can reduce the failure dose of CMOS or BiCMOS circuit by a factor of 5 or more !!

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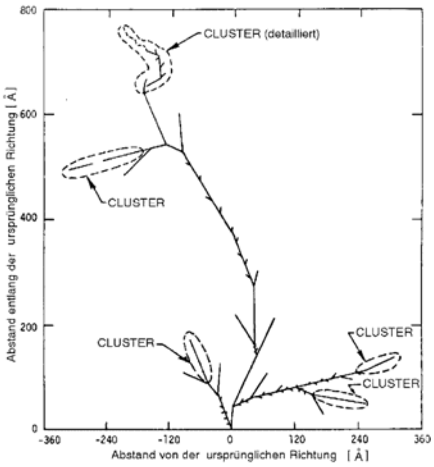
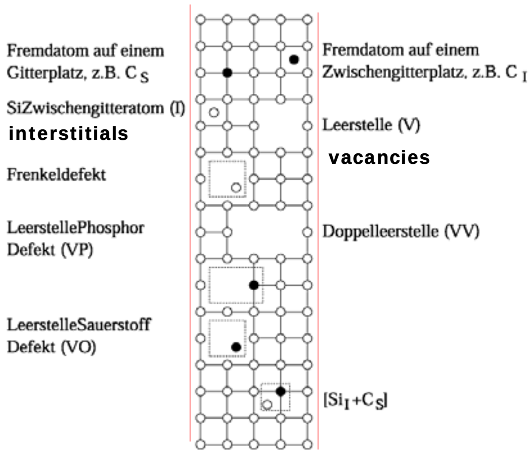
Bulk Damages (NIEL)

- bulk damages maybe caused by neutral and charged particles
- ihigh energy particle interacts with an atom in the silicon lattice, enough energy maybe transfered to dislodge the atom from its position (Si: 25eV)
- primary knock on atom (PKA) looses its energy due to energy or displacement of further atoms until it stops --> cascade
- different local point defects
- high energy --> complexes
- defects induce several energy levels in the bandgap of the semiconductor



NIEL :Typical Defects in Silicon Lattice

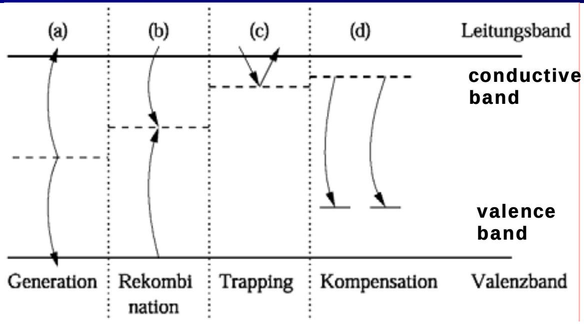
- Doping materials Phosphor and Bor acting as donators and acceptors
- impurities as oxygen or carbon in lattice due to process
- interstitials and vacancies are primary defects



NIEL: Bulk Damages

- additional energy-levels in the bandgap have consequences on the physical behaviour of the device

1



- flat energy band (c): majority carriers might be trapped and detrapped with a delay (decrease in carrier lifetime)
- results in a partial loss of the signal charge because of the decrease in the charge collection efficiency (cce)
- cce is indirectly depending on the depletion voltage -> effect can be compensated by increasing the depletion voltage
- small effect compared to the next two

NIEL: Bulk Damages

2

- energy level in the middle of forbidden bandgap act as generation (a) and recombination centres (b)
- can cause a change of the carrier density -> increase in leakage current
- mainly due to radiation induced defect cluster

$$\Delta I = \alpha \cdot \phi_{eq} \cdot V$$

α	describes damage constant
ϕ_{eq}	fluence of damaging particles
V	depletion voltage

- leakage current is also depending on temperature

$$I_{leak} \sim T^2 \exp(-\frac{E_g}{2k_B T})$$

- cooling the device is necessary to keep the leakage current low

NIEL: Bulk Damages

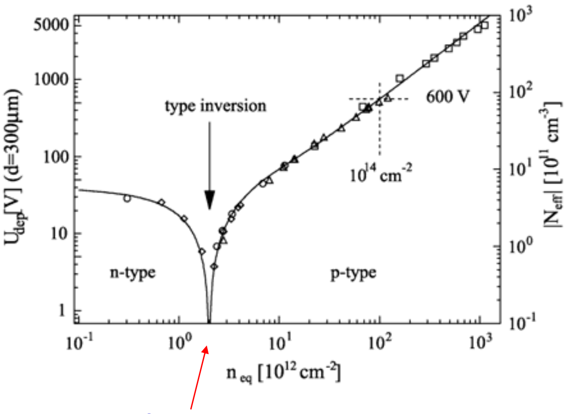
3

- compensation (d) of donators or acceptors
- results in change of majority carriers and the effective doping concentration
- direct impact on depletion depth and on the sensitive volume of a pn-junction
- donator and acceptor-like defects are deactivated and at the same time acceptor like levels are created (prop. to the fluence)
- type inversion 1.2 10^{12} 1MeV equivalent neutrons
- field gradient in pn-junction inverses (as well as the spreading direction)

- because of their large depletion depth (hundreds of microsns) detector diodes are very sensitive to bulk damage

NIEL: Bulk Damages

Change in the effective doping concentration depending on the 1MeV equivalent neutron fluence



ATLAS after one year

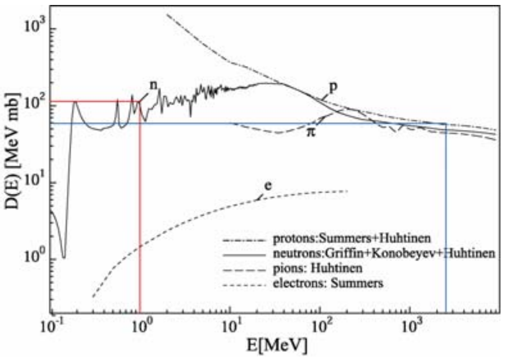
donator and acceptor-like defects are deactivated and at the same time acceptor-like levels are created (prop. to the fluence)

Non Ionising Energy Loss (NIEL)

- NIEL hypothesis: possible way of correlation and unification of the experimental data in radiation hardness studies
- NIEL scaling: any particle fluence can be reduced to an equivalent 1MeV neutron fluence producing the same bulk damage in a specific semiconductor
- based on hypothesis, that generation of bulk damage is due to non-ionising energy transfer to the lattice

Damage Function D(E) with an Example

Displacement damage functions for NIEL scaling in silicon



1 MeV n 24 GeV p

D(E)(1MeV n) ~ 100 MeV mb
=>NIEL=2.144 keV cm2/g

D(E)(24GeV p) ~ 60 MeV mb
=>NIEL=1.265 keV cm2/g

$$\frac{NIEL(1MeVn)}{NIEL(24GeVp)} = 1.7$$

- have to apply 1.7 times as many 24GeV protons to reach same damage as with 1MeV neutrons
- count only for silicon !

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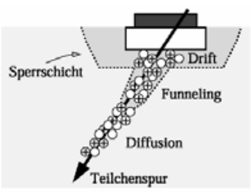
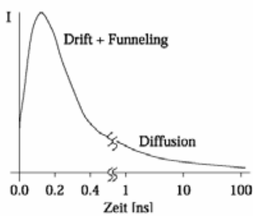
Single Event Effects

- Serious concern for space electronics (solar flares)
- Radiation induced errors in microelectronic circuits
  - caused when charged particles lose energy by ionising the medium through which they pass
  - leaving behind a wake of electron-hole pairs
  - bias across the oxide => transient current across the oxide



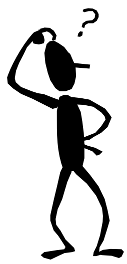


- track of an ionising particle through a reverse bias pn-junction
- along the track the field is verzerrt
- collection of charge due to drift, funneling and diffusion
- resulting a short current puls

- With forthcoming LHC --> important issue for high energy physics community

Mitigation Techniques

- Goal of radiation-hard design
  - obtain a system whose characteristics do not change under irradiation (hardly possible)
  - maintain required performance over the lifetime of the system
- start out with superior characteristics
- best mitigation technique -> avoid problem by shielding or by reducing the electronics in the radiation environment



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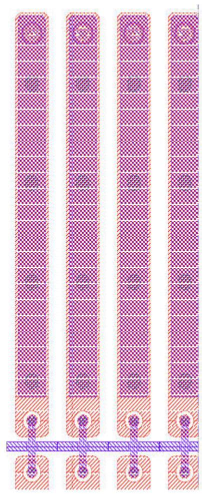
Design of Radiation “Hard” Sensor

- Example: ATLAS Pixel sensor
- right now one of the “hardest” designs
- pixel size 50µm x 400µm
  - 50 µm pitch
  - 12µm diameter bump connection
- total active area 1.75m^2 (1700 modules)
  - high yield
  - testability
- 10 years operation
  - fault tolerance
- harsh radiation environment
  - up to 10^{15} cm^{-2} (1 MeV neutron eq.)
  - radiation hard technology and design



Radiation Damages in Sensor

Bulk Damage:

- Increase bulk generation current
  - limited by low operation temperature and small pixel size
- Increase acceptor like defects
  - type conversion and increase of depletion voltage
  - in case ATLAS bias voltage V_{dep} limited to 600V
  - would be only partially depleted =>smaller signal
- Increase of trapping centres
  - charge loss => small compared to above

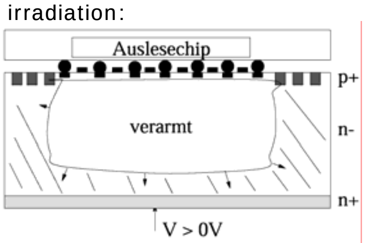
Surface Damage:

- Creation of positive charges in the oxide and additional interface states
- electron accumulation layer
  - increase of interstrip capacitance
  - pin-holes

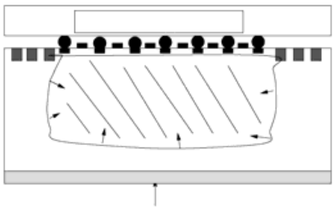
ATLAS Sensor Concept

p-on-n

before irradiation:



after irradiation:

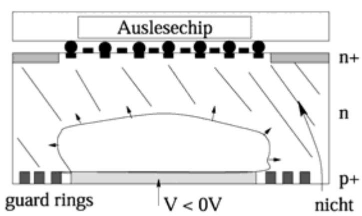


- have to be operated (almost) fully depleted
- potential drop on the read out side
- only single sided processing necessary

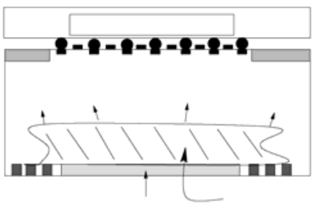
ATLAS Sensor Concept

n-on-n

before irradiation:



after irradiation:

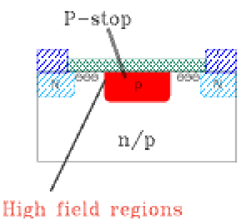


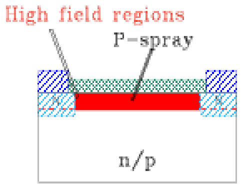
- can be operated partially depleted
- potential drop on the back side
- double sided processing needed

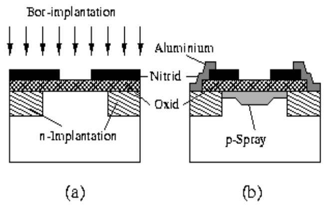
- choice: n^+-in-n devices with only one guard ring structure => keeps n-side including the edges of the sensor on ground => prevents sparking into FE

Isolation techniques

p-stop	p-spray	moderated p-spray







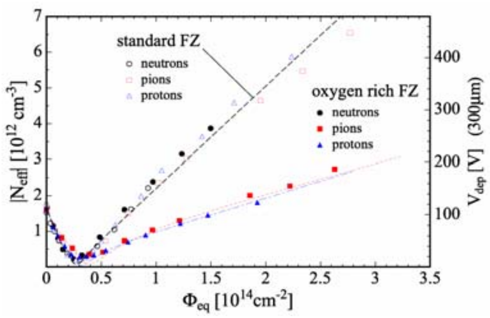
	p-stop	p-spray	moderated p-spray
before irr. :	low E-field	high E-field	low E-field
after irr. :	high E-field	low E-field	low E-field

- choice: moderated p-spray

Crystal Alteration

Rose collaboration:

- alter defect kinetics by controlled introducing individual impurities in silicon crystal (oxigenation)
- radiation studies with 24GeV protons, 192MeV pions and reactor neutrons
- strong improvement for pions and protons
- no improvement for neutrons
- improvement due to point defects (caused by an introduction of donator like defects)



Oxigenation

- reduction of stable damage
- reduction of amount of reverse annealing
- deceleration of reverse annealing

Result: Sensor concept

- $50*400\ \mu m^2$ pixel size
- n on n pixel
- moderated p-spray isolation
- oxigenated silicon
- 3 sensor tiles per wafer
- various tests and process monitor structures
- radiation hardness >50MRad and $1x10^{15}n_{eq}$

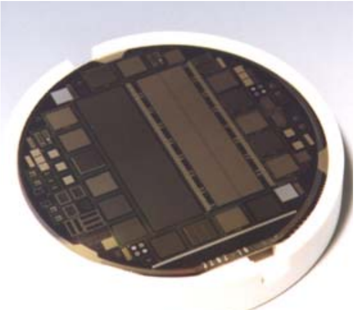


Photo of Prototype 1 Wafer

- Further solutions to allow reasonable operating voltages even after high fluences and annealing:
  - low resistive silicon
  - thin detectors
  - <100> to reduce interstrip capacitance

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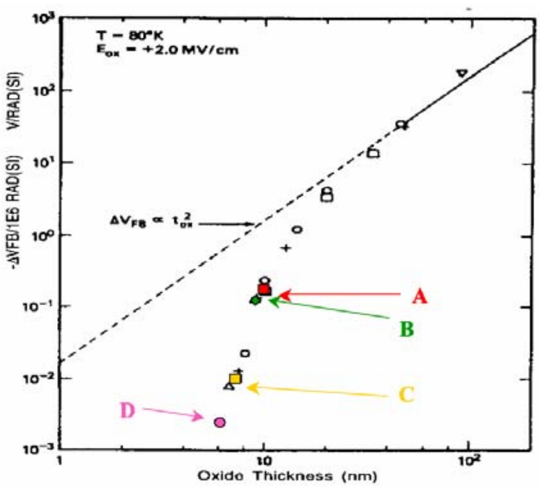
The Solution: Deep Submicron

- Economic Considerations:
  - MUST follow the technological trends otherwise no suppliers
- Radiation tolerance of thin gate oxide
  - rad-induced holes removal by e-tunneling
  - very few interface traps
- Features of deep submicron technology
  - large scale integration density -> acceptable density for radiation tolerant design
  - performance -> speed, noise and matching are good
  - low power
  - main stream, large volume process -> high yield, low cost
  - attractive for pixel readout chip
  - radiation tolerance

- main radiation tolerance limitation of deep submicron: leakage currents originating from charge trapping in thick oxides

Principles of rad-tol design

(1) Gate oxide scaling

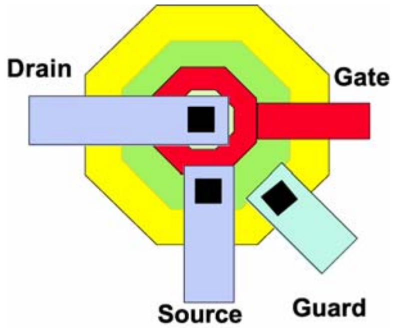


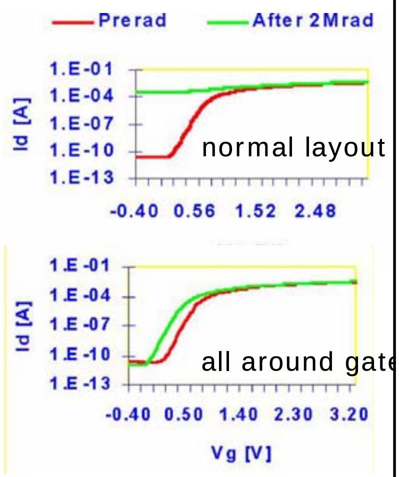
- reducing of the gate oxide thickness greatly improves the rad. resistance
- thinner gate oxides are required for small channel length -> higher density processes tend to improve the rad. resistance
- Total Dose effects such as V_t shifts, are naturally reduces in deep submicron processes
- Electro tunneling neutralises trapped holes in thin oxides

Principles of rad-tol design

(2) Thin Gate oxides + gate all around layout

- Min-size NMOS layout
- edge less structure minimises eliminates leakage via parasitic edge transistor
- higher capacitance of gate all-around structure improves SEU tolerance





leakage within transistor eliminated

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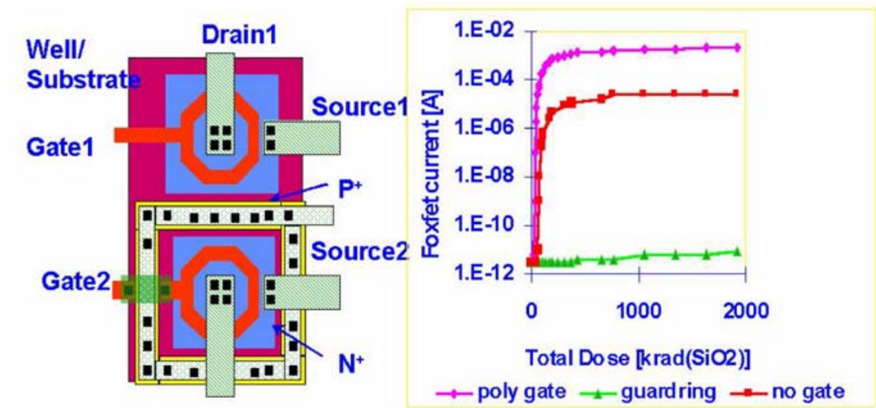
Guard Rings



- guard ring eliminates leakage between devices and provides latch-up protection

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SEE effects in Deep Submicron

- Single event gate rupture
  - occurs when a highly ion. particle causes an avalanche breakdown of the transistor gate.
  - irreversible damage
  - never observed in the 0.25 µm process
- Single event latch up
  - occurs when a parasitic thyristor is switched on by power supply spikes or ionising radiation
  - reversible or irreversible
  - never observed in deep submicron
- Single event upset
  - highly ion. particle deposits charge near a low capacitance node
  - soft error
  - IS a risk and should be protected with redundant architecture

Current status of rad tol design

- Proven design methodology (RD49)
  - Extreme TID hardness, good SEE immunity
  - Excellent analouge and digital performance
- 0.25µm CMOS supported for LHC designs
  - Blanket Pirchase Contract for LHC
  - Export licences (USA, Japan, Canada)
  - Support by CERN & RAL (Design kit, libraries,MPWs)
  - Authorised "design centres"
    CERN, RAL, INFN, IN2P3, Nikhef, PSI, Heidelberg, FNAL, LBL, UPenn, Columbia
  - Experience: good yield, reproducibility, low cost

Summary

- Total Ionising Dose
  - surface damages induced by ionisation
  - space charge buildup leads to changes in threshold characteristics and leakage current
- Non Ionising Energy Loss
  - bulk damages due to high energy transfer
  - decrease in charge collection efficiency
  - increase in leakage current
  - type inversion
- and SEE
  - passage of particle can cause transient current across oxide

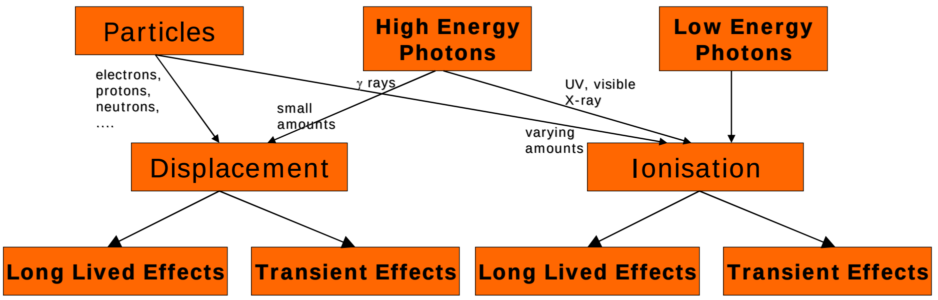
Summary

- design of radiation “hard” sensors
  - possible by following certain rules and by introducing individual impurities
- radiation tolerant (hard) processes
  - present deep submicron technologies are rad. tolerant provided special layout rules are obeyed
  - must maintain significant effort in the assessment of radiation problems in new technologies
  - scaling of CMOS opens new challenges for vertex detectors
  - a reasonable infrastructure and level of competence must be maintained within HEP if we want to remain at the cutting edge of development

References

- “Complete” collection of talks:
  - atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.html
  - look for Tutorials on Radiation Effects
  - check out the CERN training 2000 (Dentan and Moll)
- Overview paper:
  - www-physics.lbl.gov/~spieler/rad_tutor.pdf
  - effects are nicely explained, mitigation techniques are a bit outdated !
- Deep Submicron technology
  - Michael Campbells talk @ Vertex2000
  - www.physics.purdue.edu/vertex/presenation.html

Summary of rad. induced degradation effects



Displacement – Long Lived Effects
- Increased defect concentration
- Decreased carrier lifetime
- Decreased carrier mobility
- Decreased carrier concentration
- Local disorder leading to dilation & stress

Displacement – Transient Effects
- Rapid annealing of minority carrier lifetime

Ionisation – Long Lived Effects
- Charged excitation: altered population of traps (colour centre formation)
- Charge transport: charge sheet build-up, oxidation reduction reactions,
- Bonding changes: bond scission, cross linking, etc.
- Decomposition: gas evolution

Ionisation – Transient Effects
- photocurrents l. to transient voltage
- changes at terminal letching conditions in bistable circuits
- breakdown effects leading to abnormally high local currents in gas or solid states
- production of short lived centres