# RADIATION DAMAGE IN SILICON

LECTURE AT RADHARD SCHOOL (MINI WORKSHOP)

THESSALONIKI-BONN (DAAD PROGRAM)

SEPTEMBER 30, 2024

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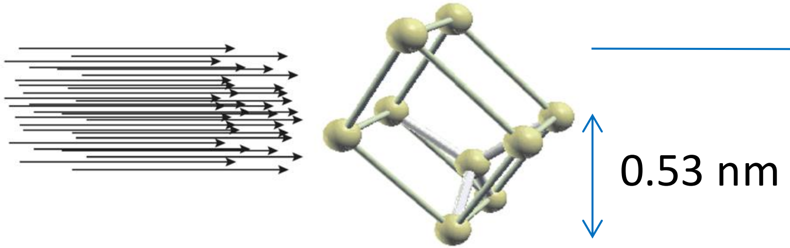
UNIVERSITÄT BONN

# Radiation



- HL-LHC fluence = > every Si lattice cell ”sees” about 50 particles (FCC: 1500 particles)

- From defect understanding -> defect engineering (example: oxygen enrichment)

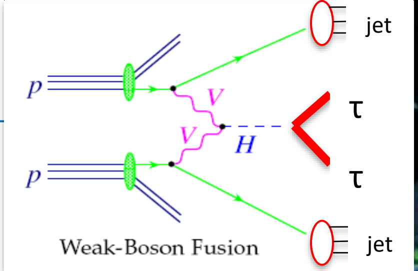
  make VO to happen more likely than VP

  phosphorus = donor

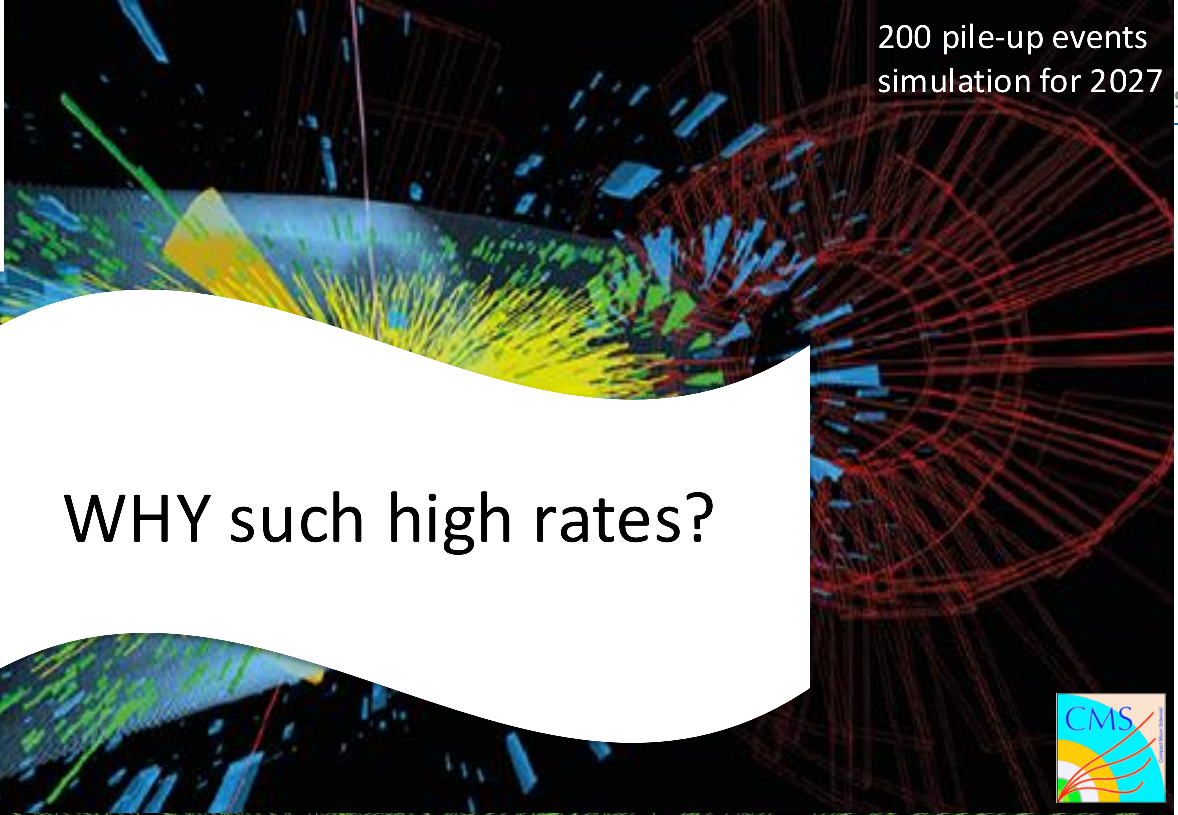
Recipe

- Readout at $n^+$ electrodes ($e^-$ collection)
- Operate at high bias voltages
- Carefully plan the annealing scenario
- Provide proper electrode design and guard rings
- Use p-substrates (rather than n)
- …

... but why?

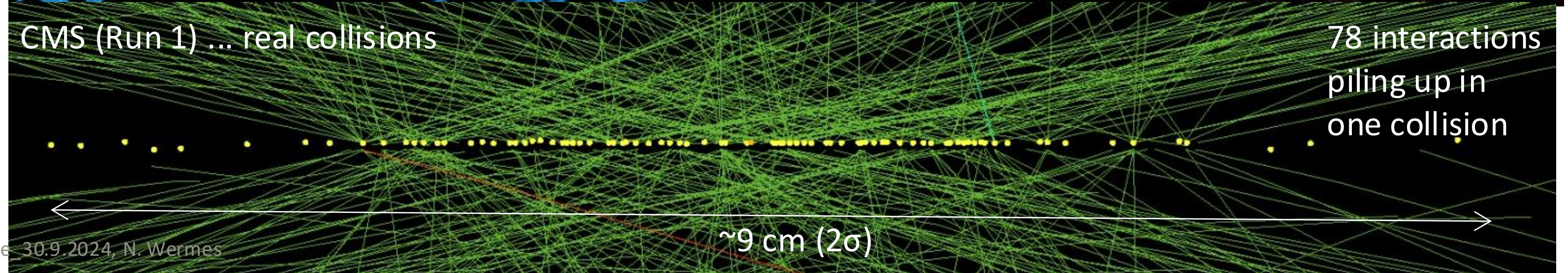


Weak-Boson Fusion



200 pile-up events
simulation for 2027

# WHY such high rates?

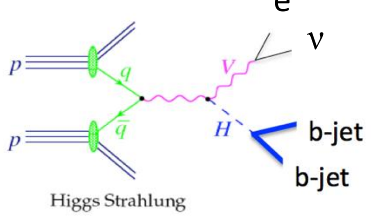


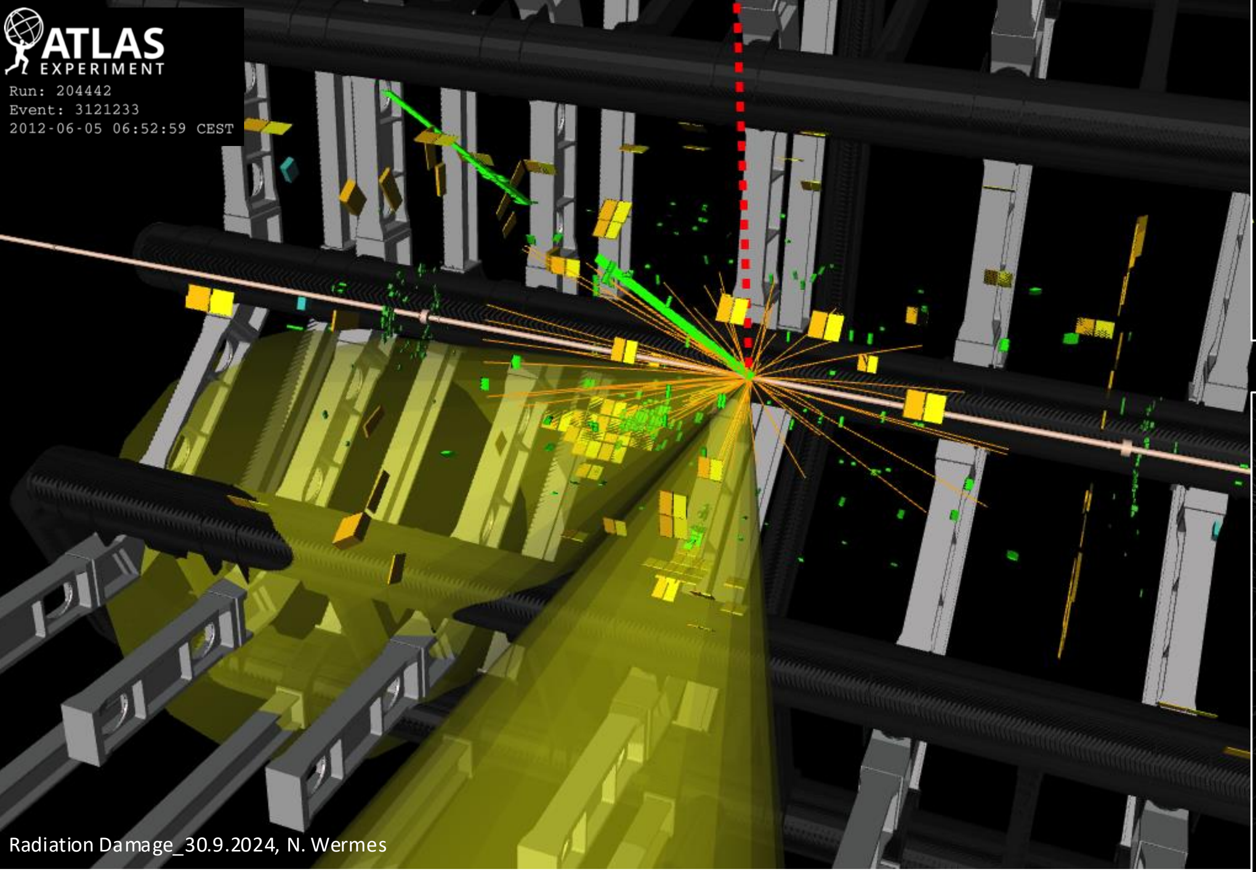
CMS (Run 1) ... real collisions

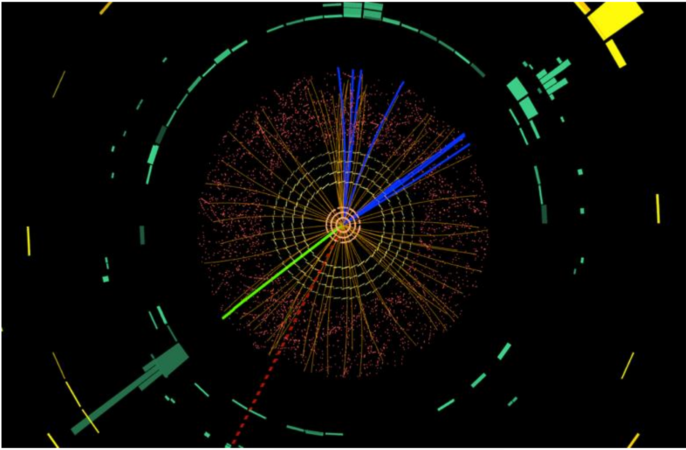
78 interactions
piling up in
one collision

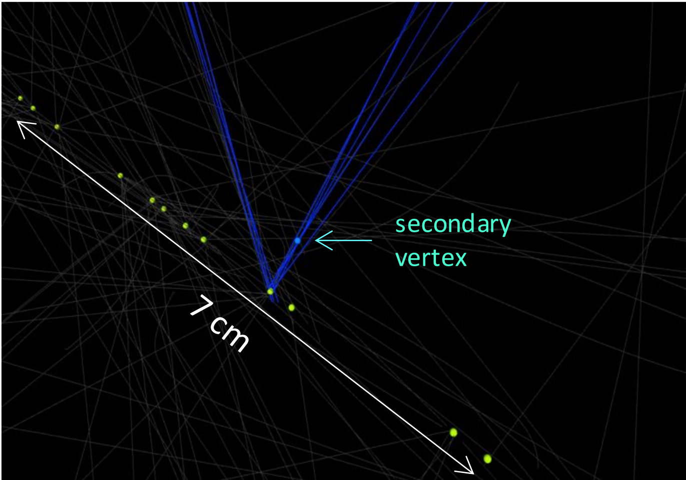
~9 cm (2σ)

# pp -> WH -> $\bar{\nu}$e + bb

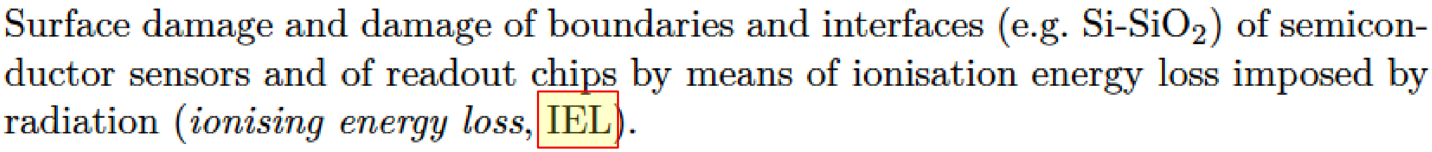






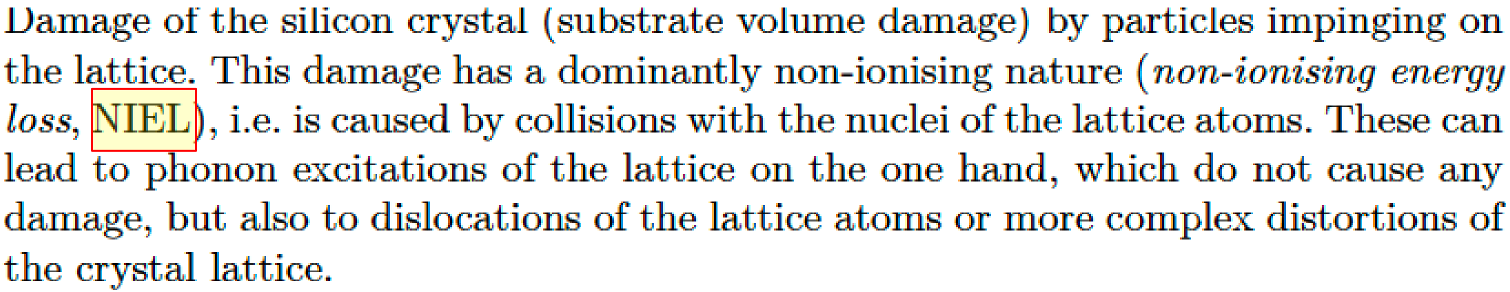


# Distinguish



Surface damage and damage of boundaries and interfaces (e.g. Si-$SiO_2$) of semiconductor sensors and of readout chips by means of ionisation energy loss imposed by radiation (*ionising energy loss*, IEL).

IEL damages sensor surface and electronics



Damage of the silicon crystal (substrate volume damage) by particles impinging on the lattice. This damage has a dominantly non-ionising nature (*non-ionising energy loss*, NIEL), i.e. is caused by collisions with the nuclei of the lattice atoms. These can lead to phonon excitations of the lattice on the one hand, which do not cause any damage, but also to dislocations of the lattice atoms or more complex distortions of the crystal lattice.

NIEL damages the sensor lattice

(whereas ionization damage (IEL) is largely a reversible process in semiconductors)

# Which damage effects?

- Si sensors: lattice => depletion voltage and leakage currents rise
- FE chips: oxide => threshold shifts & parasitic transistors occur

- glue: becomes hard and brittle
- mechanics: material performance degrades
- cooling: larger cooling capacity is needed to cool more needed power

| | Total Ionisation Dose (TID) | | Fluence (ϕ) |
|---|---|---|---|
| LHC | => 100 Mrad (1 MGy) | or | $10^{15}$ $n_{eq}/cm^2$ |
| HL-LHC ≈ LHC x 10 | => up to 2 Grad (20 MGy) | or | 2 x $10^{16}$ $n_{eq}/cm^2$ |
| causing | IEL | | NIEL |

# Pixel Sensors in the LHC radiation environment

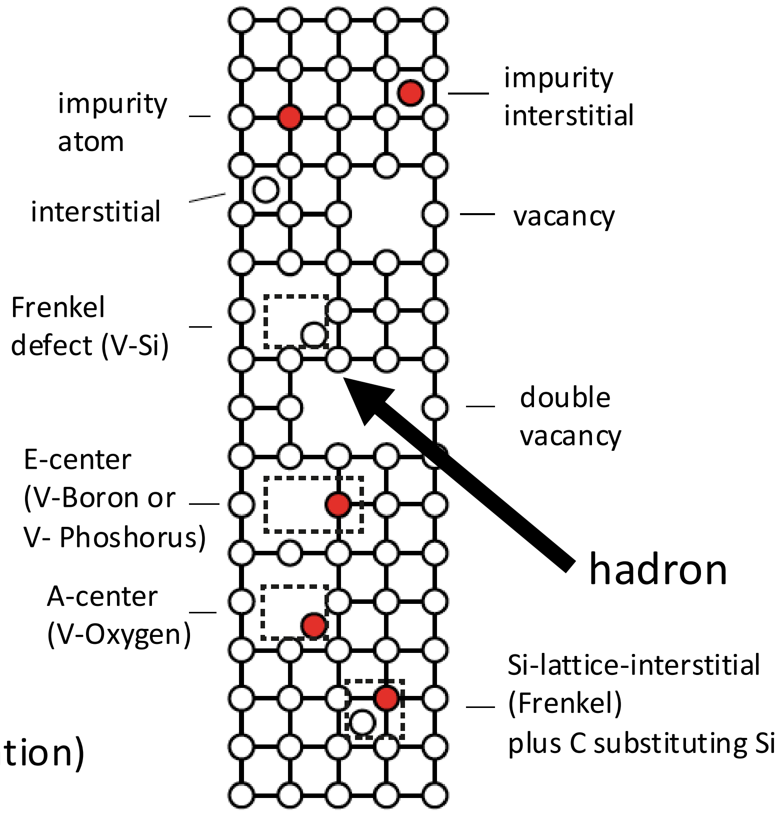
particle interactions with lattice nuclei

NIEL

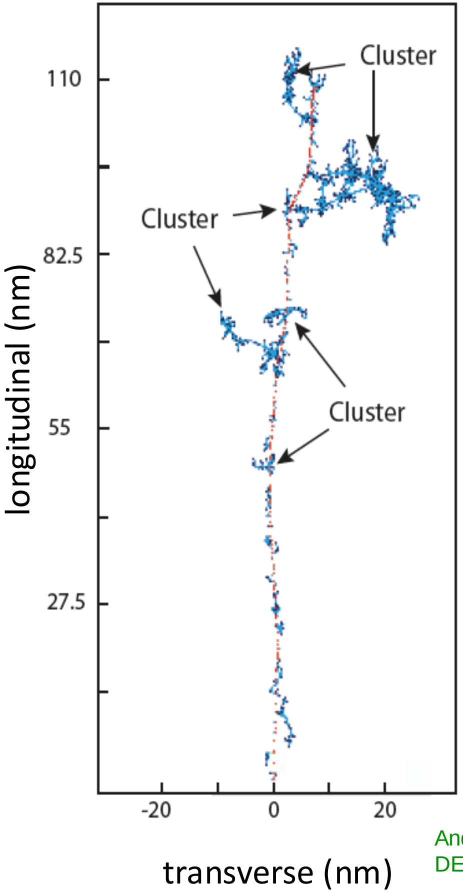
non-ionizing
energy loss
(not reversible)
normalized to
1 MeV neutron damage

recoiling Si-atom can cause further defects
→ defect clusters (10nm x 200nm)

1. generation/recombination levels in band gap
   → increase of leakage current
2. change of space charge in depleted region
   → change of effective doping concentration (VP creation)
3. trapping centers created
   → trapping of signal charge



# Radiation Damage (NIEL)

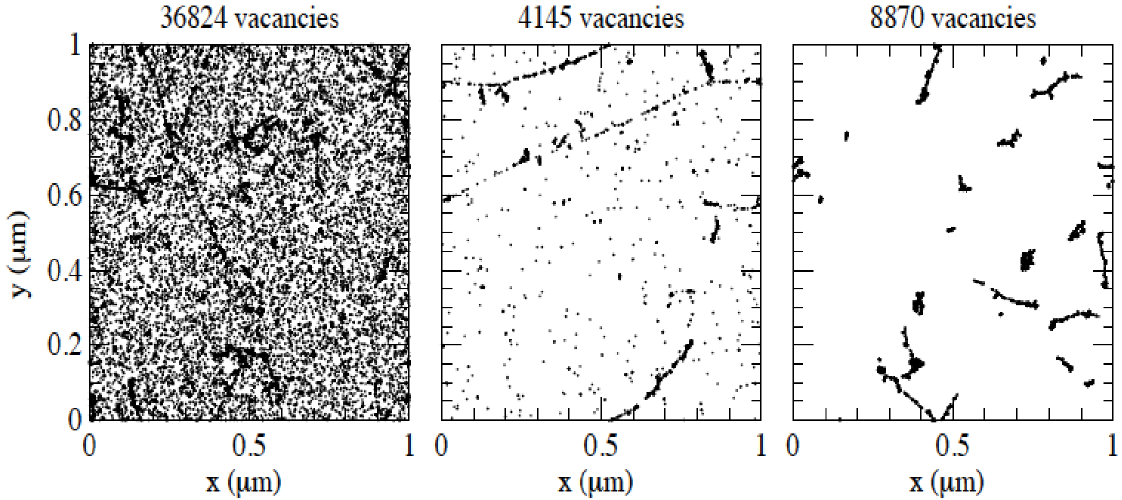


Andrea Junkes, Diss. UHH
DESY-THESIS-2011-031. http

threshold energy to remove a Si-atom from the lattice:

Si: 25 eV, diamond: 43 eV

| damaging particle | 10 MeV p | 24 GeV p | 1 MeV n |
|---|---|---|---|



typical point and cluster defects

M. Huhtinen, NIM-A 491 (2002)

# Physics processes responsible for NIEL

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maximum energy transfer of a particle with mass m and kinetic energy T on a massive atom nucleus M

$$T_{max} = 4\frac{Mm}{(M+m)^2}T$$

remember BBF and $T_{max}$

for electrons
(see BBF, m ⟷ M)

$$T_{max} \approx 2\frac{T_e + 2m_e}{M}T_e$$

for heavy particles
p, n, A, $\pi$, K, also Si-nuclei

kick-off $E_{min}$ in Si
(43 eV in diamond)

**Table 8.4** Comparison of maximum and average energy transfers as well as cross sections (integrated from a threshold energy $T_{min} = 25$ eV to $T_{max}$) for electrons, protons and neutrons as well as for (knocked-off) silicon nuclei with a kinetic energy of 1 MeV. The cross sections for Si nuclei are relevant for the creation of damage clusters (after [957] and references given therein.)

| particle species<br>cross section | electrons<br>Coulomb scat. | protons<br>Coulomb scat. | neutrons<br>elastic scat. | $Si^+$ nuclei<br>Coulomb scat. |
|---|---|---|---|---|
| $T_{max}$ | 155 eV | 134 keV | 134 keV | 1 MeV |
| $\langle T \rangle$ | 46 eV | 210 eV | 50 keV | 265 eV |
| $\sigma$ ($10^{-24}$ cm$^2$) | 44 | 17 950 | 3.7 | 502 500 |

$\propto 1/E^2$

flat in E

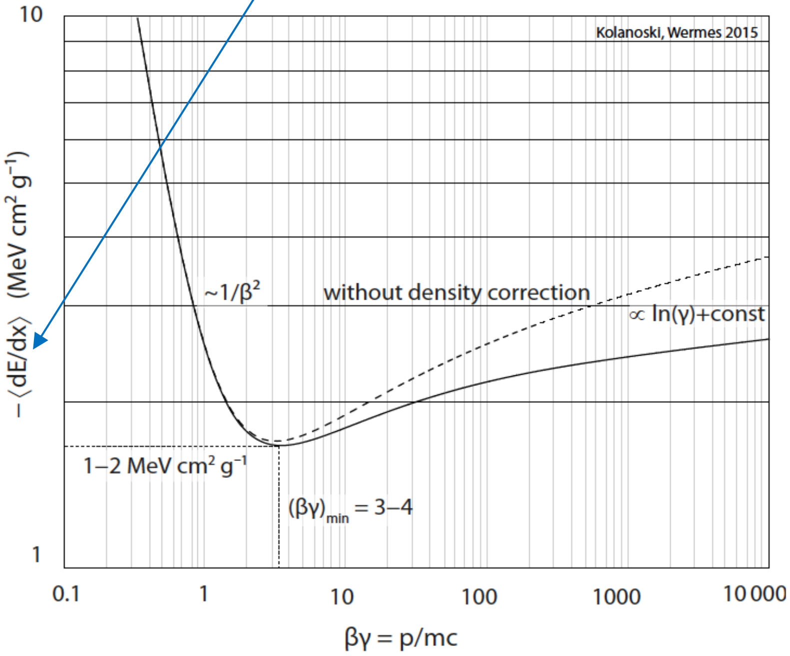
neutrons cause more cluster defects

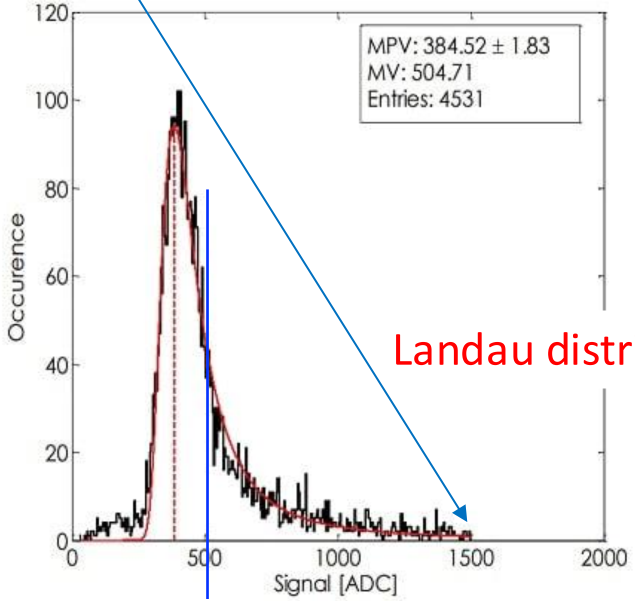
# Energy loss of charged particles by ionisation

Bethe – Bloch formula

$$-\left\langle \frac{dE}{dx}\right\rangle = K\,\frac{Z}{A}\,\rho\,\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\frac{2\,m_e\,c^2\,\beta^2\,\gamma^2\,T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma,\,I)}{Z}\right]$$

average

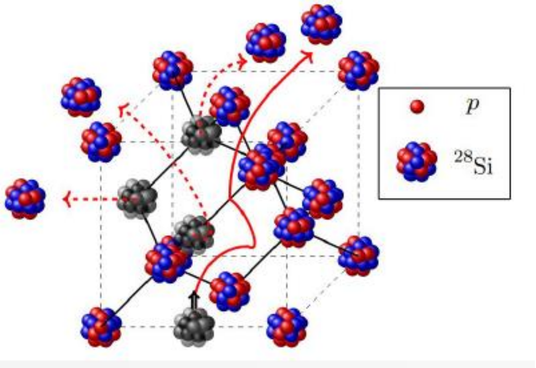


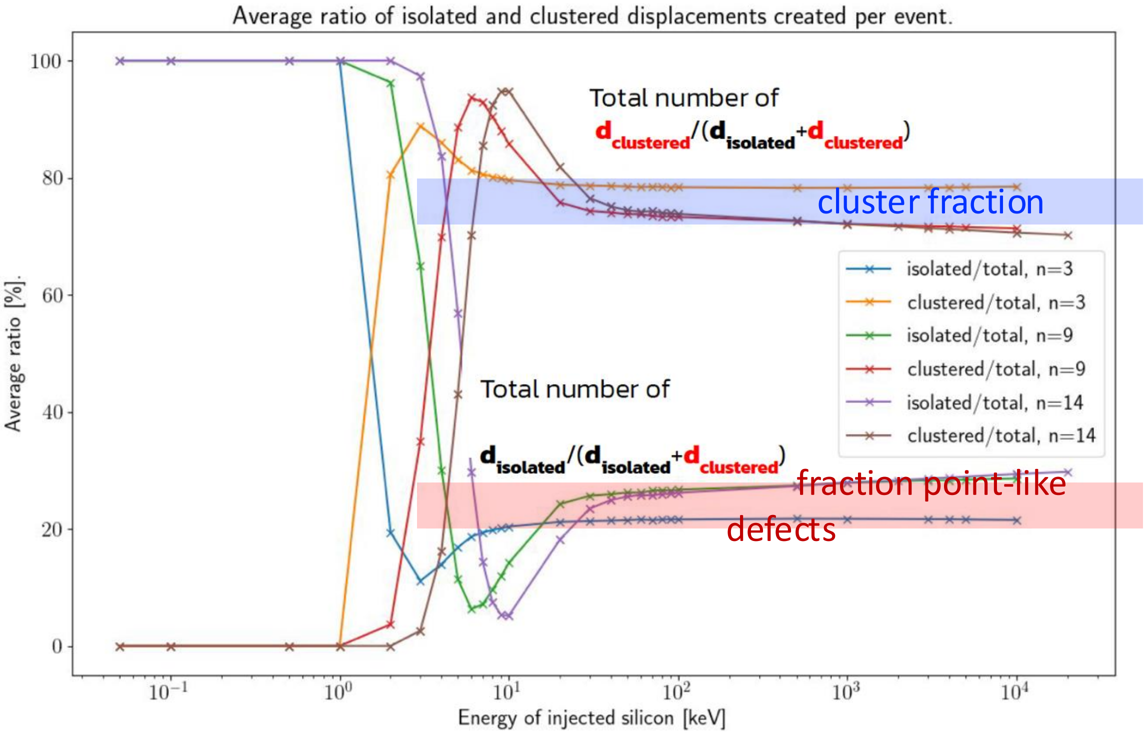


Landau distribution

average

# Point-like versus cluster defects





Total number of $d_{clustered}/(d_{isolated}+d_{clustered})$

cluster fraction

Total number of $d_{isolated}/(d_{isolated}+d_{clustered})$

fraction point-like defects

V. Maulerova-Subert et al., RD50 workshop, Nov. 2022

# The NIEL hypothesis

NIEL = energy lost by a particle in non-ionising interactions mostly leading to lattice displacement damage.

NIEL hypothesis: All lattice damage in Si can be traced back to the abundance of primary defects (point defects and clusters), irrespective of their initial distribution over energy and space. No other origins are considered.

NIEL scaling: All bulk damage caused by a certain fluence of non-ionising radiation can be scaled to an equivalent 1-MeV neutron fluence damage assuming the NIEL hypothesis (i.e. scales for all cases shown e.g. on page 7)

Damage function

particle

recoil atom

partition function

$$D(E) = \sum_i \sigma_i(E) \int_{E_d}^{E_R^{max}} f_i(E, E_R)\, P(E_R)\, dE_R$$

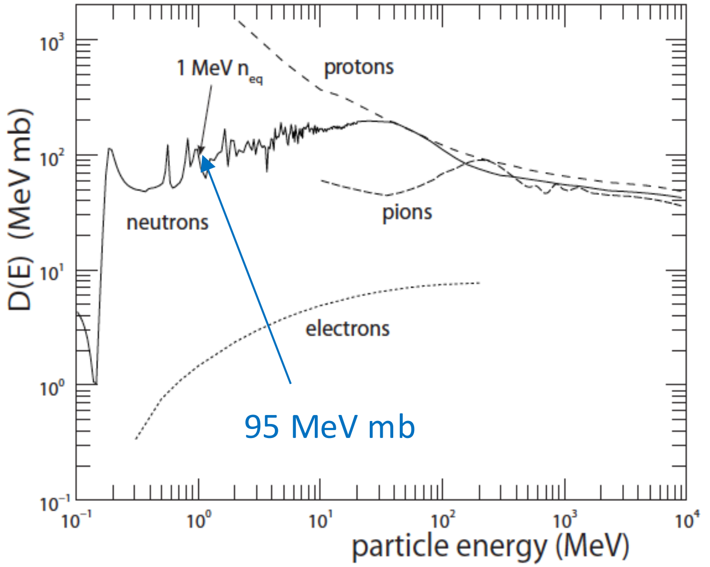
prob

partition fct for $E_{rest}/E_R$

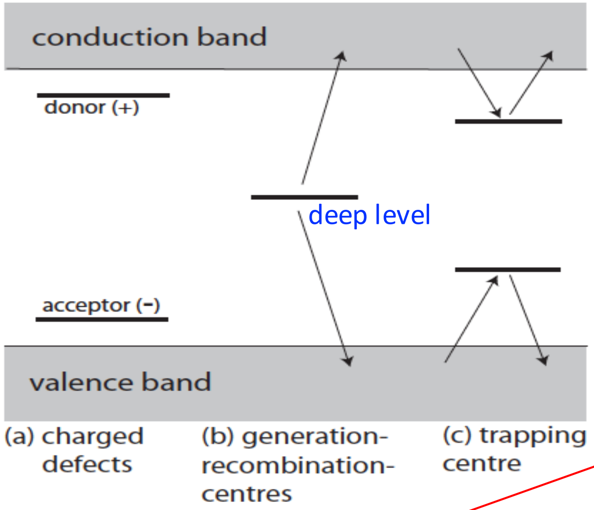
$$\kappa = \frac{\int_{E_{min}}^{E_{max}} D_x(E)\phi(E)dE}{D_n(1MeV)\int_{E_{min}}^{E_{max}} \phi(E)dE}$$

hardness or damage factor

$$\phi_{eq} = \kappa\,\phi$$



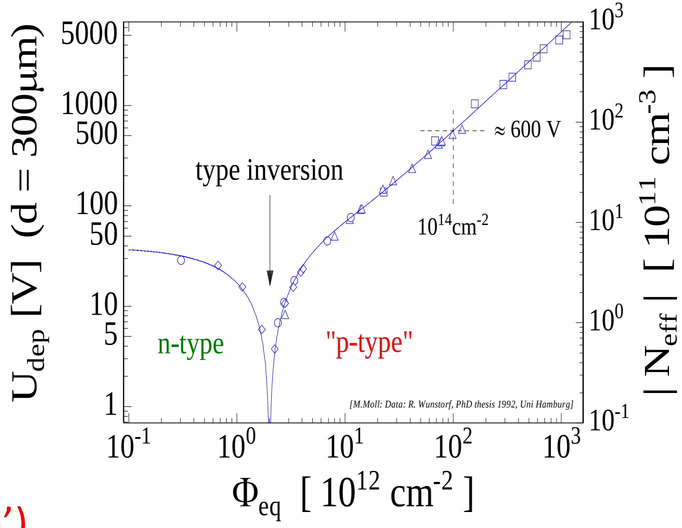
# Three main effects



1. generation/recombination levels in band gap
   → increase of leakage current
2. change of space charge in depleted region
   → change of eff. space charge ('doping concentration')
3. trapping centers created
   → trapping of signal charge

Effects of defect levels mathematically described by Shockley-Read-Hall (SRH) statistics (see e.g. ref[1])

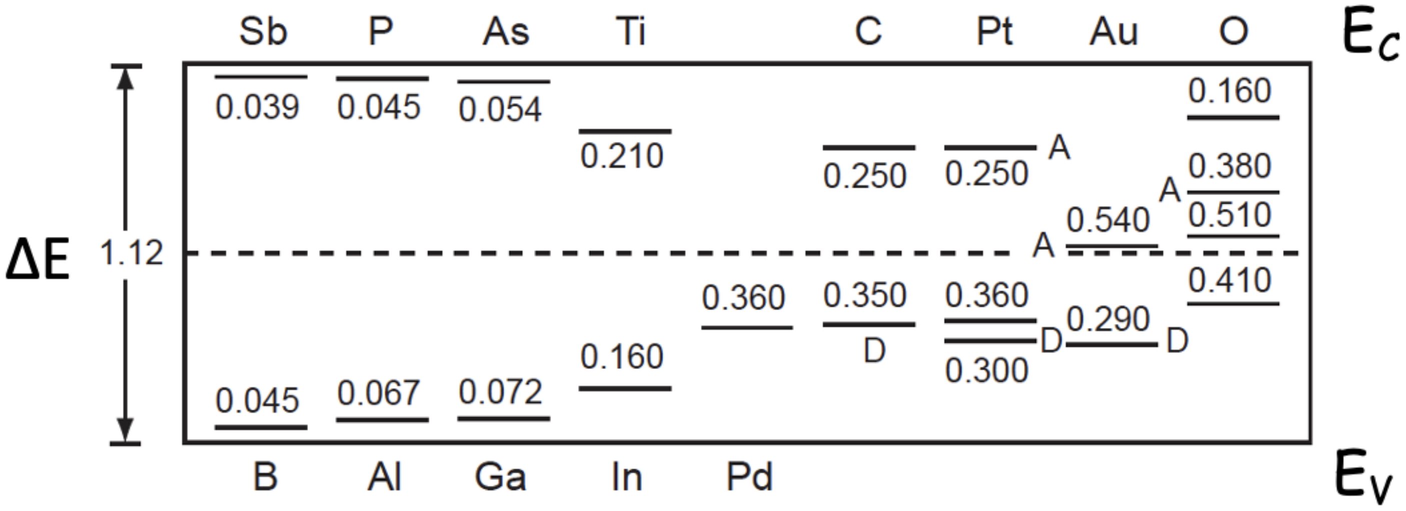
- "Type inversion": $N_{eff}$ changes from positive to negative (space-charge sign-inversion)



- Change of Depletion Voltage $V_{dep}$ ($N_{eff}$)

.... with particle fluence:

# What is “effective space charge”?



When ionised, the “defects” or “impurities” are charged!

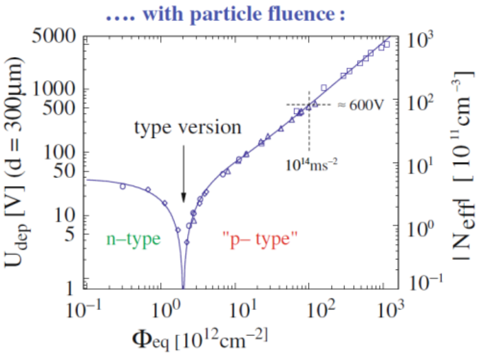
That is … not only the dopants cause the bulk’s charge anymore.

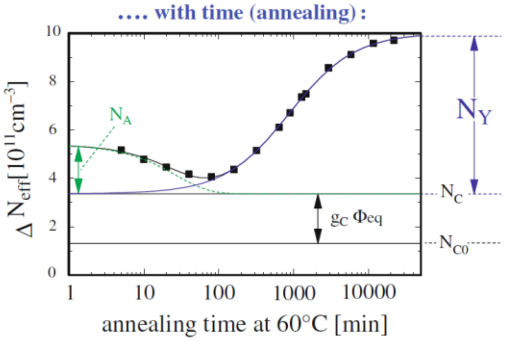
# Implications for detector operation

- change in $N_{eff}$

⇒ “type inversion”
⇒ “reverse annealing”
⇒ need higher $V_{bias}$
⇒ operate in partial depletion
⇒ double junction develops

$$V_{dep} \approx \frac{e|N_{\text{eff}}|d^2}{2\epsilon\epsilon_0}$$





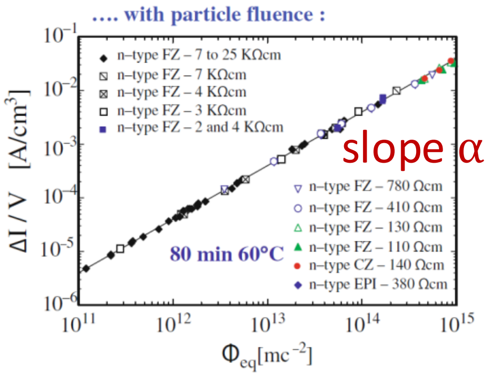
- change in $I_{leak}$

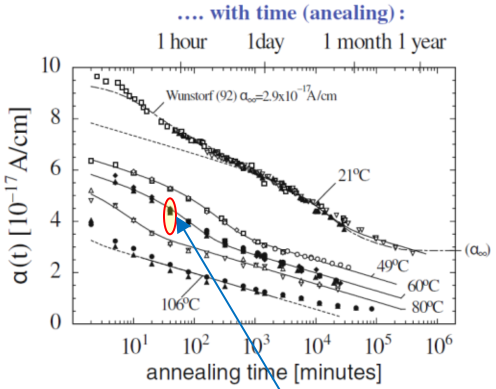
⇒ increased noise
⇒ increased power
⇒ thermal runaway
⇒ increased cooling
⇒ increased material

$$\Delta I_L = \alpha\ \phi_{eq} V$$

$4.0 \times 10^{-17}$ A cm$^{-1}$ (±5%)
@60°C for 80 mins

volume
under
electrode





convention
80 min
60 degrees

- for $\Phi > 10^{15}$ $n_{eq}$/cm$^2$ → charge trapping important: $Q_{tc} \cong Q_0\exp(-t_c/\tau_{tr})$, $1/\tau_{tr} = \beta\Phi$.

CCD becomes smaller than detector thickness (small signal) => need low noise amp@high leakage current

# Implications for detector operation

- change in $N_{eff}$

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⇒ “reverse annealing”
⇒ need higher $V_{bias}$
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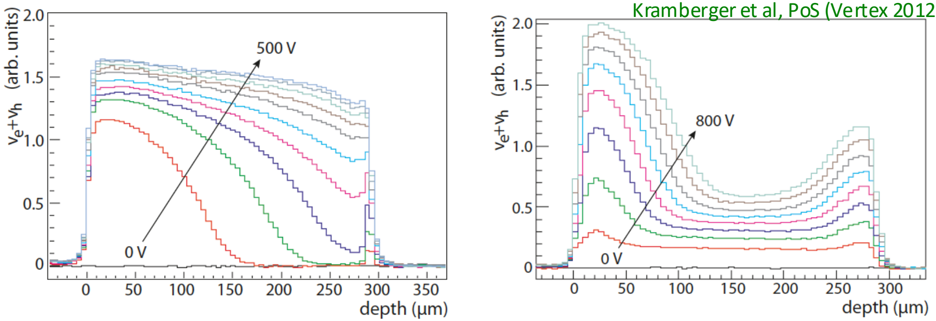
⇒ double junction develops

$$V_{dep} \approx \frac{e|N_{\rm eff}|d^2}{2\epsilon\epsilon_0}$$



(a) Non-irradiated detector (b) Irradiated detector ($\phi_{eq} = 10^{16}\,\mathrm{cm}^{-2}$)

Kramberger et al, PoS (Vertex 2012) 022

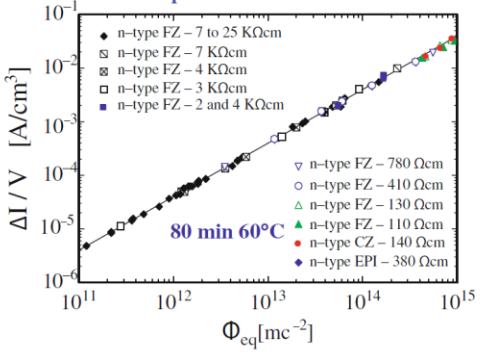
- change in $I_{leak}$

⇒ increased noise
⇒ increased power
⇒ thermal runaway
⇒ increased cooling
⇒ increased material

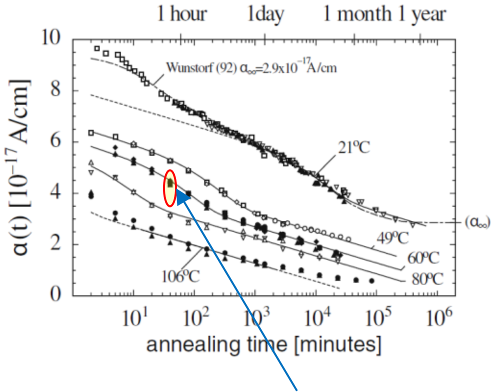
$$\Delta I_L = \alpha\ \phi_{eq}\, V$$

$4.0 \times 10^{-17}$ A cm$^{-1}$(±5%)

…. with particle fluence :



…. with time (annealing) :



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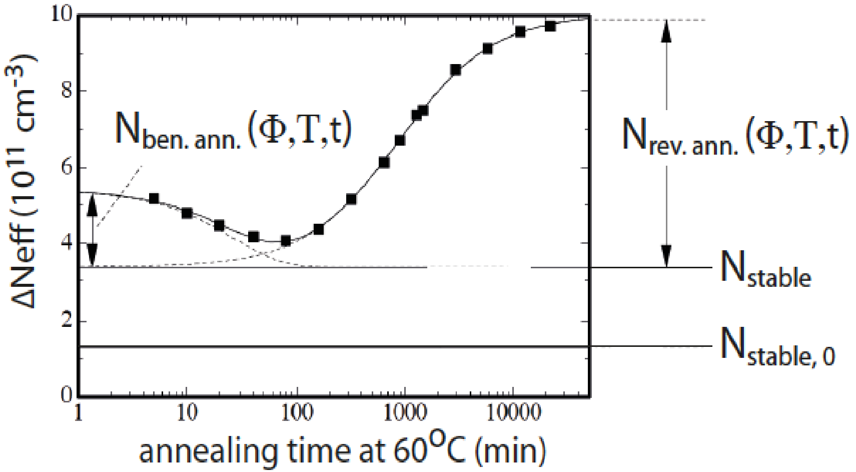
- for $\Phi > 10^{15}\ n_{eq}/cm^2$ → charge trapping important: $Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$

CCD becomes smaller than detector thickness (small signal) => need low noise amp@high leakage current

# Measures for radiation hardening

## Annealing

- shaking the lattice => beneficial annealing
- too long at a high temperature => defects, that did not harm so far, become active => reverse annealing
- hence: keep detectors cool @ -5 to -20° C



$$\Delta N_{\text{eff}}(t;\phi,T) = N_{\text{eff}} - N_{\text{eff}}^{\phi=0} = N_A^{\text{ben}}(t;\phi,T) \;+\; N_C(\phi) \;+\; N_Y^{\text{rev}}(t;\phi,T)$$

fitted with 3 components: beneficial stable reverse

$g_A$, $g_C$, $g_Y$ introduction rates

$\tau_A$, $\tau_Y$ annealing time constants

$\propto \exp(E_a/kT)$ (Arrhenius eq.)

if you want longer times => operate cooler

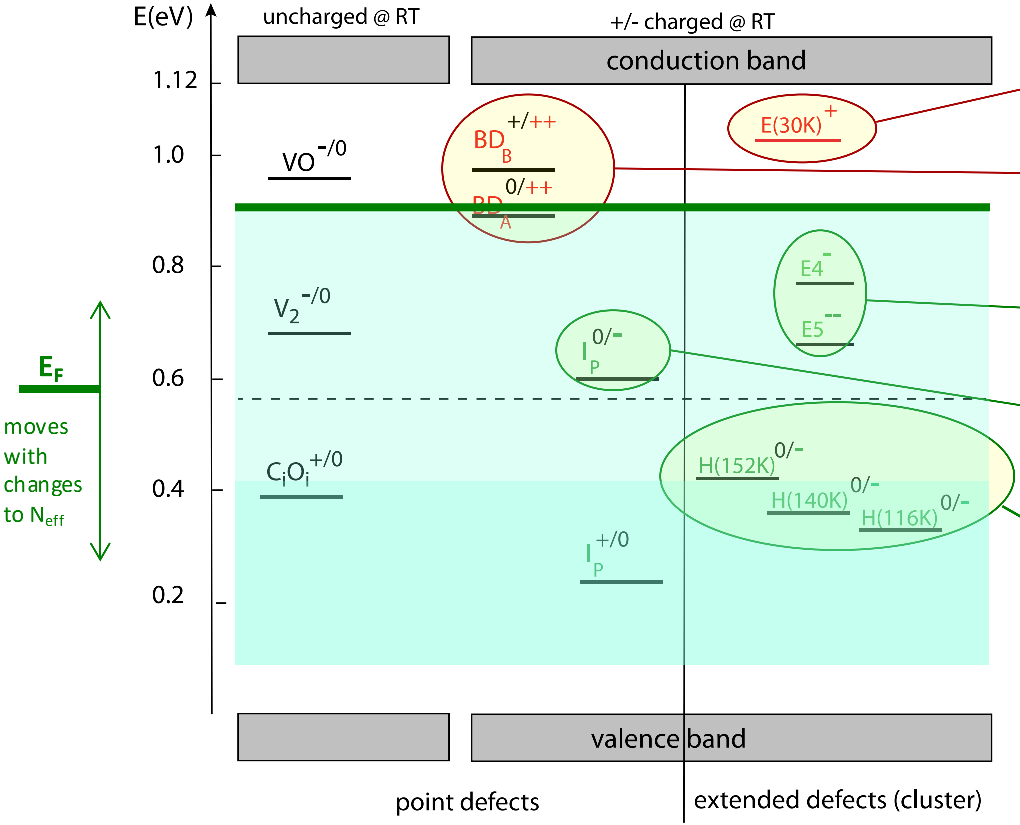
$$N_A(t;\phi,T) = g_A \exp\left(-\frac{t}{\tau_A}\right)\phi\,,$$

$$N_C(t;\phi) = N_{C,0}\left(1-\exp\left(-c\phi\right)\right) + g_C\phi\,,$$

$$N_Y(t;\phi,T) = g_Y\left(1-\exp\left(-\frac{t}{\tau_Y}\right)\right)\phi\,.$$

# Detailed studies and progress in understanding radiated Si-sensors

defects become effective for $N_{eff}$ when charged



e- trap
**positive space charge**
higher conc. after proton than neutron irradiation
depends on oxygen content

BD=bistable donor (e- trap)
**positive space charge**
strongly produced in oxygen rich DOFZ material

triple vacancy, small cluster
**negative space charge**
-> **high leakage current**

$V_2O$ complex (?)
**negative space charge**
causes **leakage current**,
strongly produced in oxygen lean STFZ

extended acceptor defects produced equally by n,p
**negative space charge**
-> **reverse annealing**

most defects act as acceptors
=> $N_{eff}$ becomes more negative (more p)

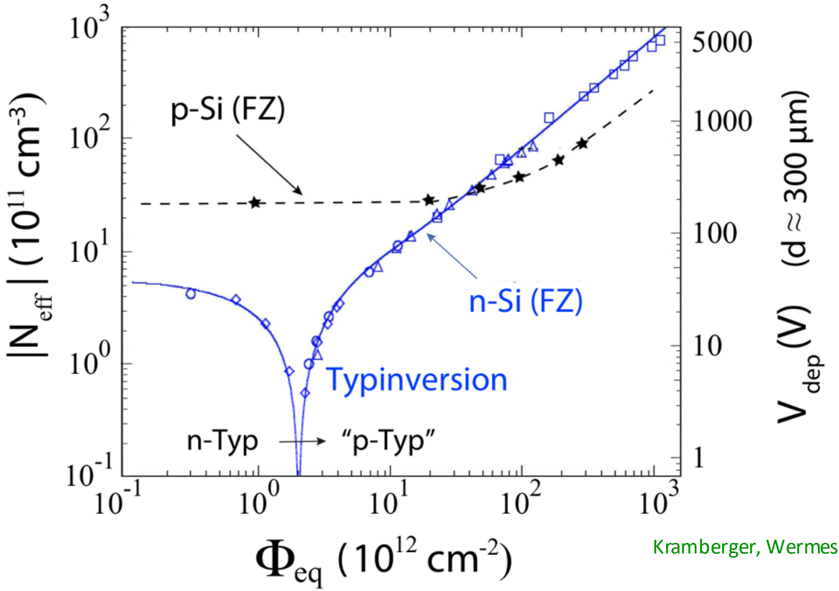
- most defects show linear fluence dependence
- cooling helps to keep $I_{leak}$ and rev. annealing smaller
- $N_{eff}$ changes

Radu et al., J. Appl. Phys. 117, 164503 (2015)
RD50, M. Moll et al., PoS (Vertex 2013) (2013) 026

# … a word on type inversion

Note
p-type Si does NOT type-invert, since most defects act as "acceptors" (negative space charge) and p-substrate is already negative.

Nevertheless
Both donor and acceptor removal IS a problem .... especially also in more highly doped junction applications like LGADs (gain is affected)

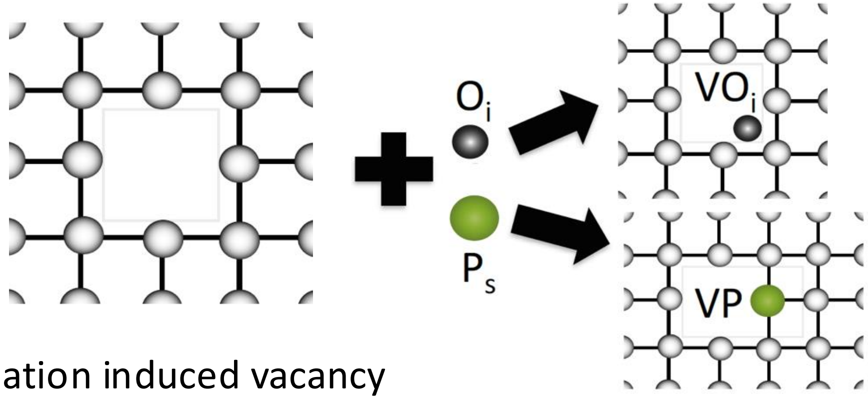


Kramberger, Wermes, 2023

# … and cures (defect engineering example) ... simplified description

- for n-type Si: donors (P) are removed by forming a VP complex (=> donor removed)

  - oxygenated silicon
  - low temperature (-10 °C) operation



radiation induced vacancy
(mobile even below RT)

harmless
$VO_i$ defect

harmful
removes donor (P)
decreases $N_{eff}$

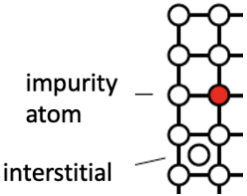
⇩

$[O] \gg [P]$

A. Junkes, PoS Vertex 2011 (2011) 035
I. Pintilie et al., Nucl.Instrum.Meth. A611 (2009) 52-68

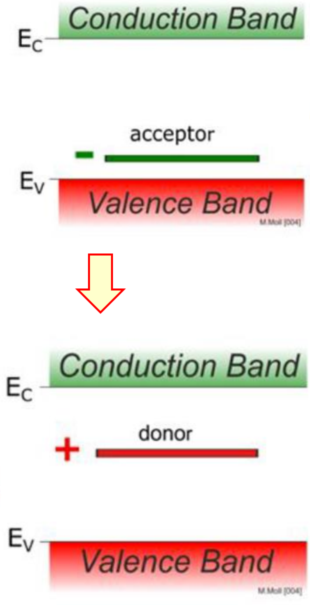
# … and cures (defect engineering example) … again (too?) simplified

- for p-type Si: acceptors (B) are removed by forming $B_iO_i$ complex (i=interstitial)



… the process is, however, a bit more complex

- ○ interstitial defects are highly reactive
- ○ electrically active ("substitutional") boron $B_s$ on its lattice site is removed by an (interstitial) $Si_i$ – atom
- ○ Now B is $B_i$ (interstitial) and "highly reactive"
- ○ $B_i$ then causes $B_iO_i$ complexes whereby boron atoms are absorbed into an electrically active defect (a donor) => acceptor is removed space charge is increased by **two** units.



$Si_i+B_s \rightarrow B_i$

$B_i+O_i \rightarrow B_iO_i$

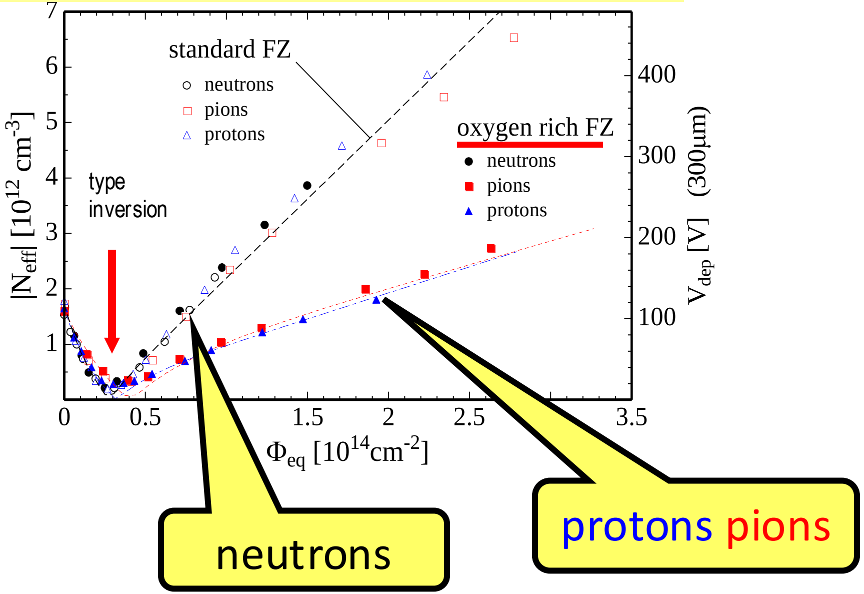
Cure …

Carbon enrichment such that $[C] \gg [Si_i]$:
Then $C_iS_i$ complexes are built instead and the $Si_i$ that has initiated the above reaction chain is "eaten" away.
The $C_iS_i$ complex is electrically neutral (I believe).

# Proven **success ... for LHC1: oxygenation of n-type Si**

## solution: oxygenated FZ silicon (for n-type substrate)

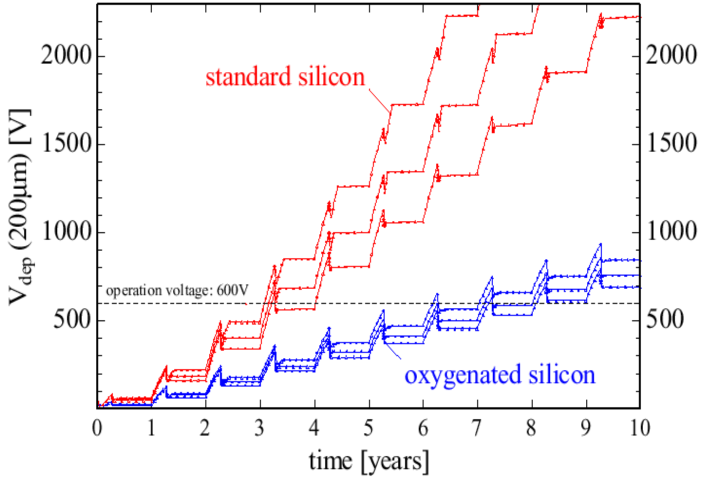
radiation tolerant to $10^{15}\ n_{eq} / cm^2$ (60 Mrad)



neutrons

protons pions

necessary voltage for full depletion



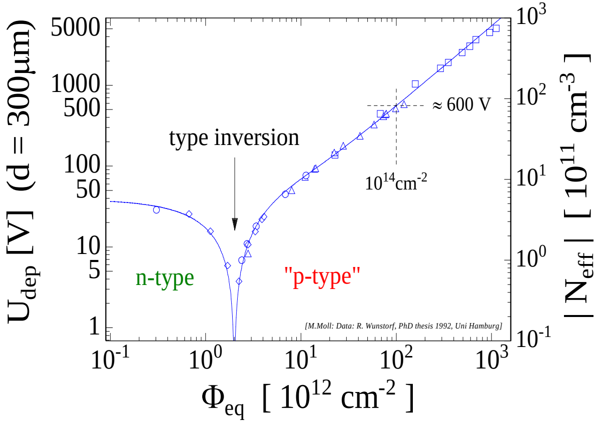
RD50, G. Lindström et al.
NIM-A 465 (2001) 60-69

Reason: complex interaction of various (point+cluster) defects: need “shallow donor” (BD = point defect) to replace donor removal. For neutrons, however, mainly clusters contribute to radiation damage.
For LHC upgrades mostly p-type substrates will be used (no type-inversion).

# Pixel Sensors in the LHC1&2 radiation environment (why $n^+$ in n?)

- Change of Depletion Voltage $V_{dep}$ ($N_{eff}$)

.... with particle fluence:

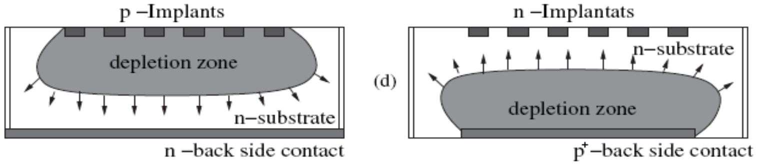


- "Type inversion": $N_{eff}$ changes from positive to negative (Space Charge Sign Inversion)

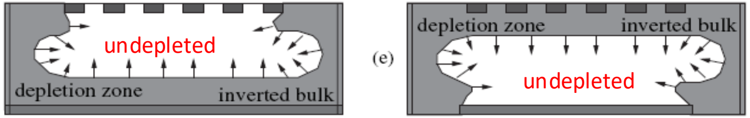
fluence (NIEL) > $10^{15}$ $n_{eq}/cm^2$
total dose > 600 kGy

$p^+$ in n "normal"

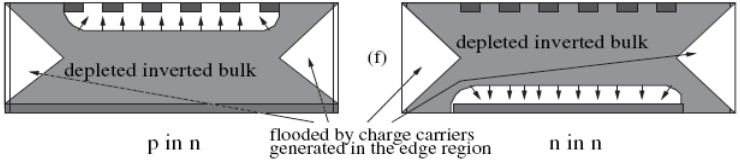
$n^+$ in n



before type inversion



after type inversion

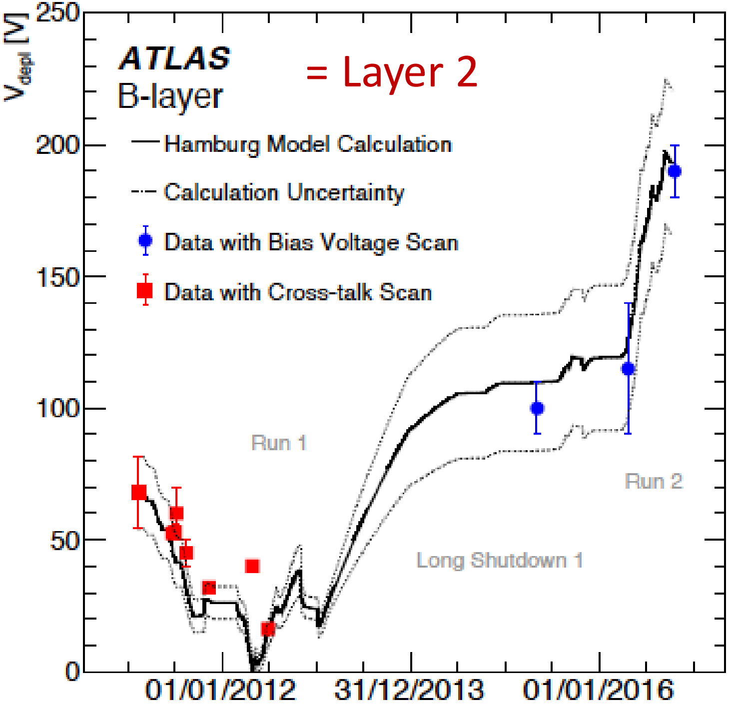


after heavy radiation damage

L. Andricek et al, NIM-A 409 (1998) 184-193

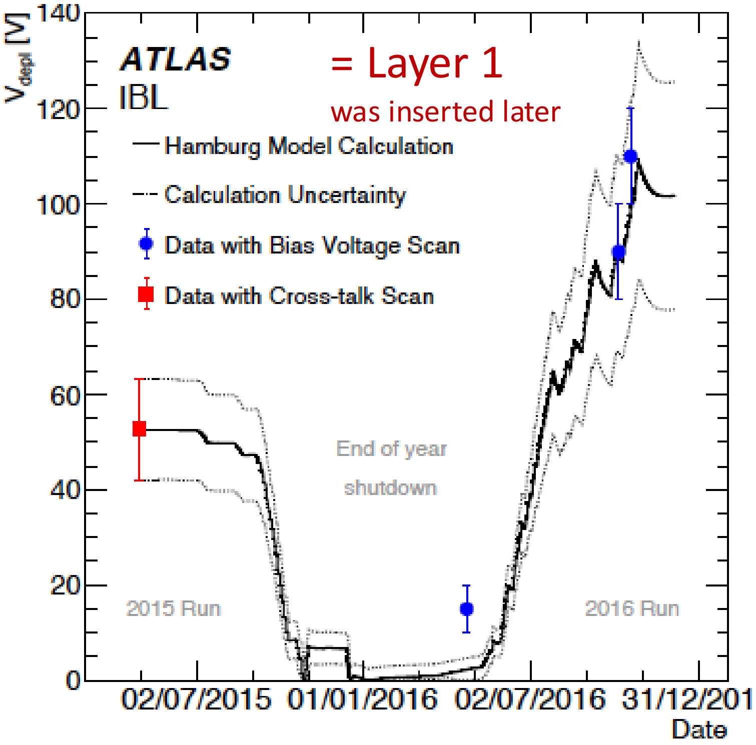
# Type inversion has been observed at LHC

ATLAS Pixels



= Layer 2

summer 2012



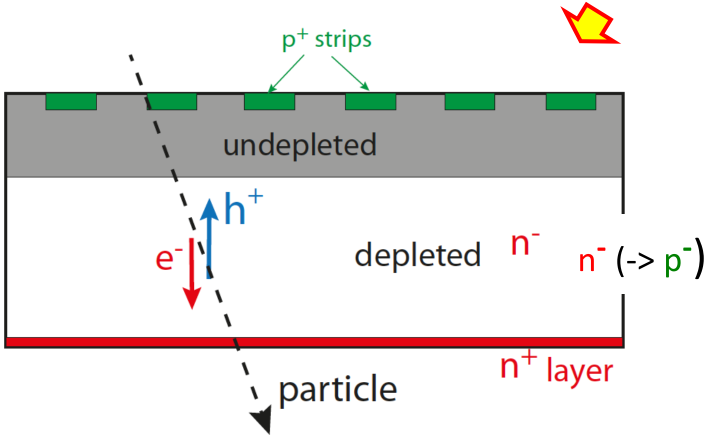
= Layer 1

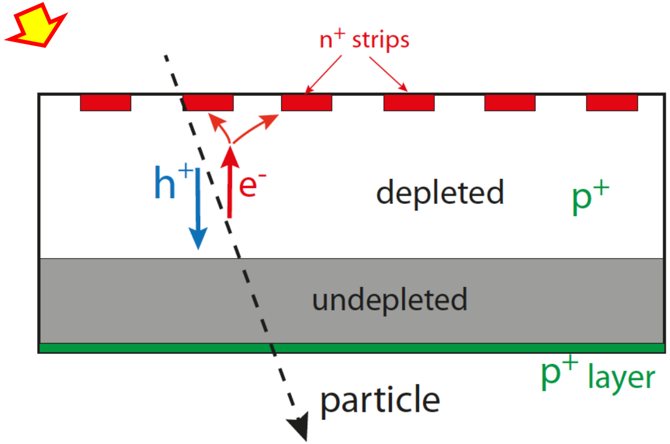
was inserted later

# For upgrades: p-type silicon substrates

- classic choice (for strips): **$p^+$ in n**
- for HL upgrade: **$n^+$ in p** or **$n^+$ in n (-> p)**

after high irradiation





consequences:

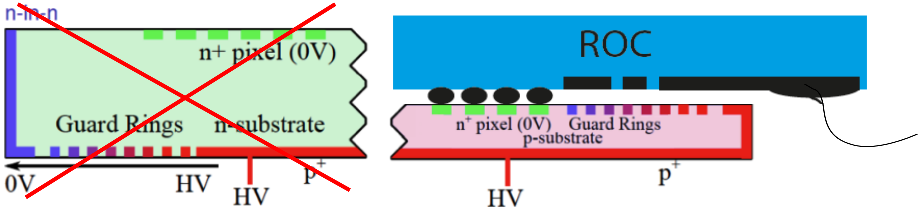
- signal loss
- resolution degradation (spreading of induced charge)

advantages:

- faster charge collection (electrons)
- signal and CCE degradation less & smoother

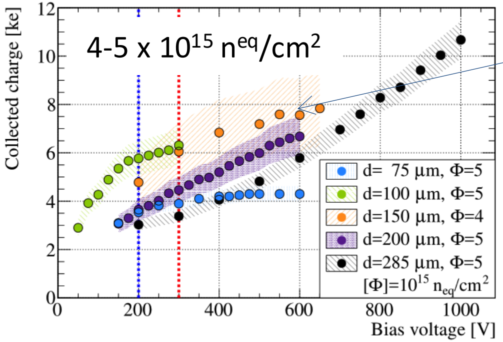
p – type substrates for strips and for pixels (easier to fabricate, single sided processing)

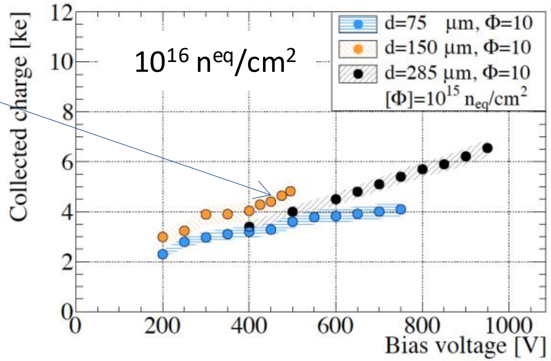
# For very high fluences -> thin planar (pixel) sensors



- thin **n⁺ in p** sensors after high fluences (neutrons)

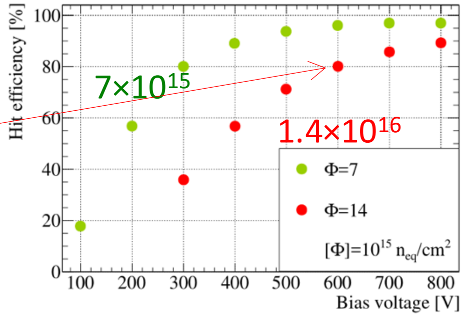
best (150 µm)





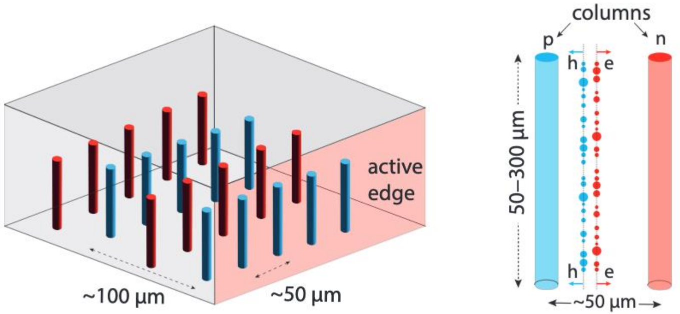
- **6000 – 7000 e-**
  for 100 - 200 µm sensors @ 300 V – 600 V bias

- hit efficiencies still reasonable at Φ > $10^{16}$



Macchiolo, Nisius, Savic, Terzo, NIM A831:111–115, 2016.
Terzo, Andricek, Macchiolo, Nisius et al, JINST 9 (2014) C05023

# Radiation hard Si sensors -> 3D-Si sensors

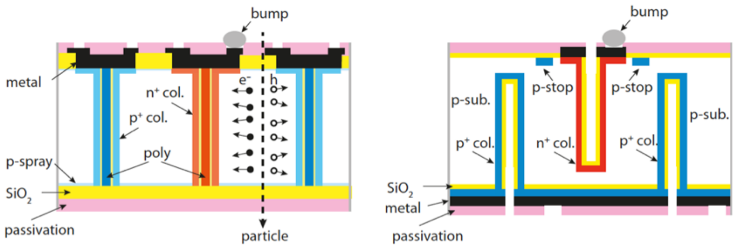


S. Parker, C. Kenney, J. Segal, ICFA Instrum.Bull. 14 (1997) 30-50
C. Da Via, et al., NIM A49 (2005) 122-125 and NIM A 699 (2013) 18

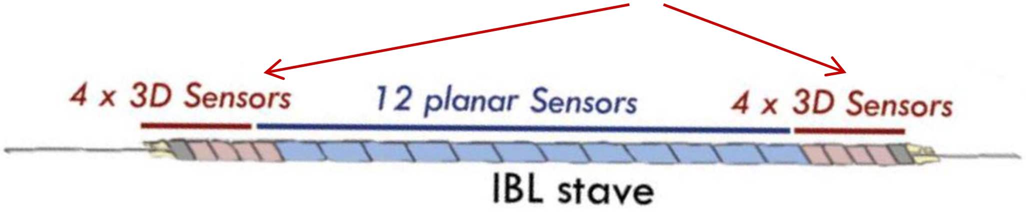
- particle path (signal) different from drift path
- high field w/ low voltage

-> radiation tolerance
-> Q still 50% @ $10^{16}$ cm$^{-2}$

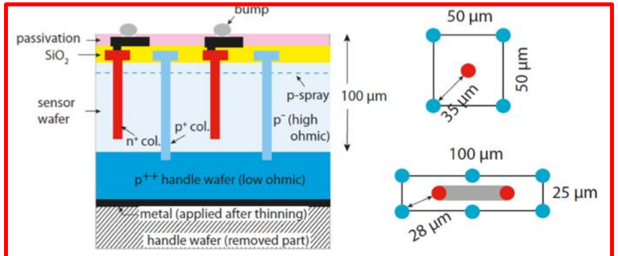
- slightly larger $C_{in}$ (noise)
- now also in diamond, CdTe



(a) 3D-Si: penetrating columns (b) Partial 3D-Si (double sided)



**Development for HL-LHC:**
- thin (100 µm)
- 6" wafers
- electrodes thin (5µm) & narrowly spaced
- slim or active edges



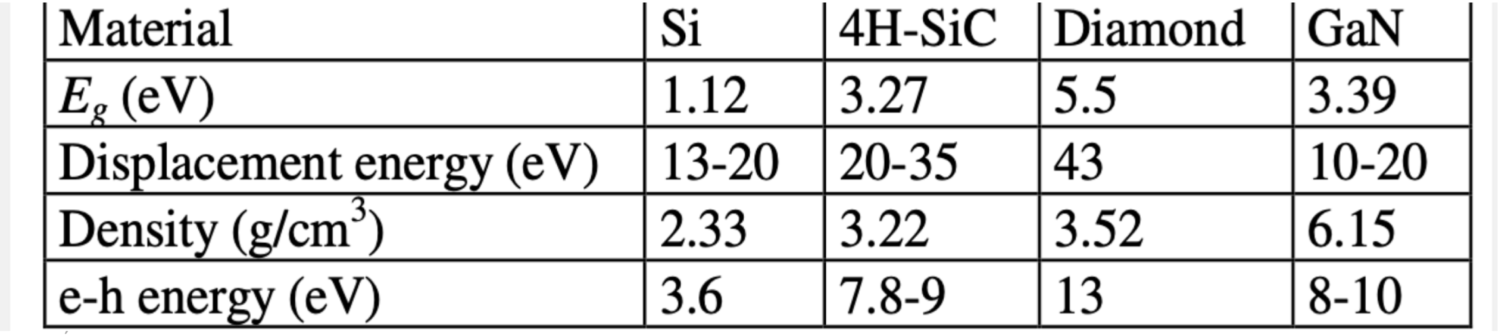
(c) HL-LHC design

- 3D sensors have been put to reality in ATLAS IBL detector since 2015 -> so far reliable and well performing

# Other radhard material developments

- CVD diamond
  - stronger bonds than Si (43 eV versus 25 eV)
  - no leakage current due to large band gap (5.5 eV)

- newly SiC & GaN
  - wider bandgap and other nice features like density, displacement energy
  - They have regained attention after the material quality has improved much due to an industrial push coming from power devices and LEDs.
  - So far, charge collection degrades faster with radiation fluence than for Si and diamond, however.

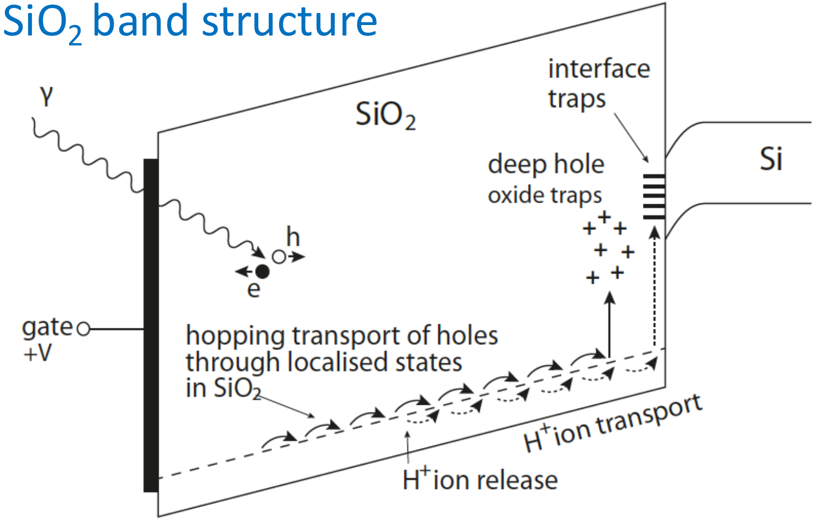


| Material | Si | 4H-SiC | Diamond | GaN |
|---|---|---|---|---|
| $E_g$ (eV) | 1.12 | 3.27 | 5.5 | 3.39 |
| Displacement energy (eV) | 13-20 | 20-35 | 43 | 10-20 |
| Density (g/cm$^3$) | 2.33 | 3.22 | 3.52 | 6.15 |
| e-h energy (eV) | 3.6 | 7.8-9 | 13 | 8-10 |

# Radiation damage to the FE-electronics see also ref[1]

Responsible for main damage effect: ionising radiation (IEL)

## $SiO_2$ band structure



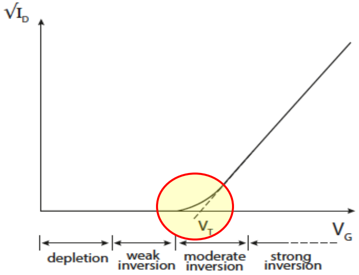
1. in $SiO_2$: $\mu_h \lll \mu_e$ => **self trapped holes** (polarons)
   - slowly hopping holes **meet oxygen vacancies,** being dense near the interface, and are trapped.
   - also believed: polaron hopping releases impurity **$H^+$ ions** which move and form traps at the interface bonds

=> neg. threshold shifts in NMOS and PMOS

2. traps @ Si – $SiO_2$ interface bonds:
   - traps have E-levels in band gap and can act as donors or acceptors (charge dep. on bias)
   - NMOS and $V_{bias}$ pos. => **traps -> negative**
   - PMOS and $V_{bias}$ neg. => **traps -> positive**

=> effect 1. is decreased (NMOS)
or increased (PMOS)

- net effects:
  threshold shifts
  parasitic currents



# Radiation damage to the FE-electronics … and cure

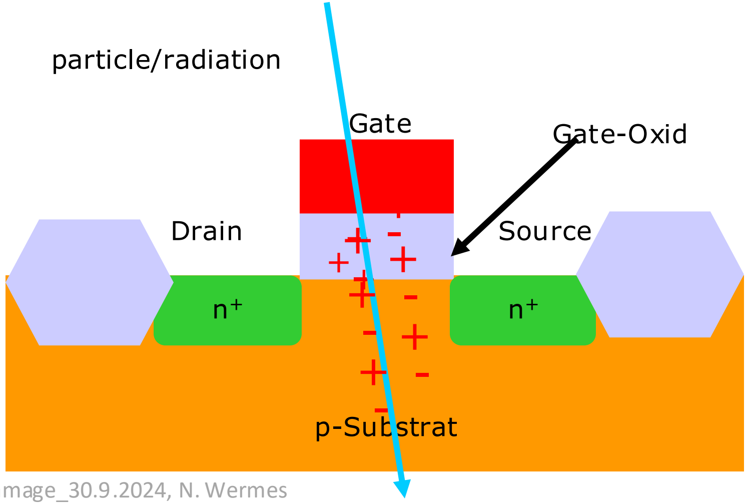
generation of positive charges in $SiO_2$ and defects in Si - $SiO_2$ interface cause …

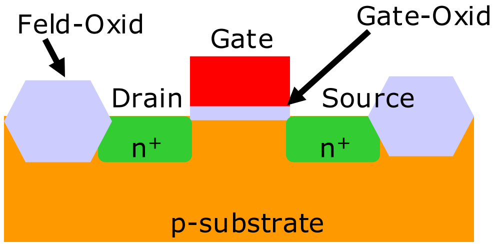
**1. Threshold shifts of transistors**

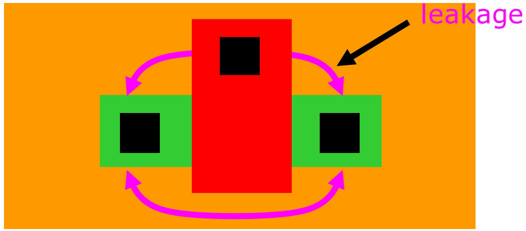
➔ Deep Submicron CMOS technologies with small structure sizes (≤ 250 nm) and thin gate oxides ($d_{ox}$ < 5 nm) => holes tunnel out

**2. Leakage currents under the field oxide**

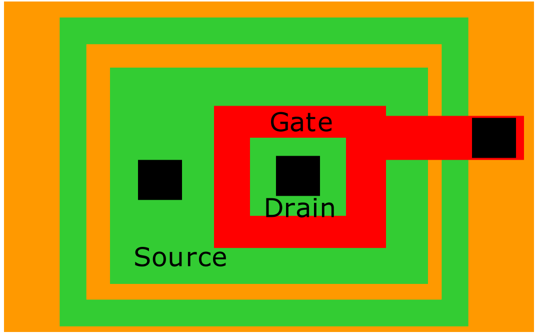
➔ Layout of annular transistors with annular gate-electrodes + guard-rings







enclosed (”round”) transistors (ELT)



# Radiation damage to the FE-electronics … and cure

radiation induced bit errors

("single event upsets" SEU)

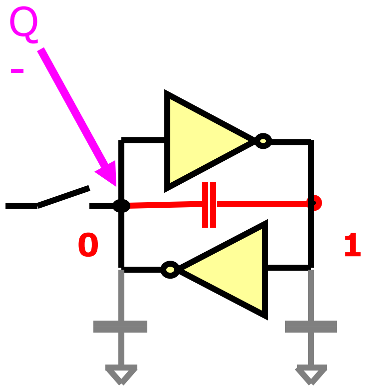
large amounts of charge on circuit nodes
- by nuclear reactions, high track densities -
can cause "bit-flip"

2 examples of error resistant logic cells

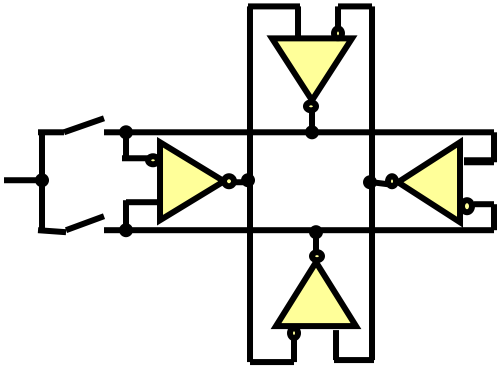
➔ enlarge storage capacitances in SRAM cells:

$Q_{crit} = V_{threshold} \cdot C$

➔ storage cells with redundancy (DICE SRAM cell)



standard SRAM cell



SEU tolerant DICE SRAM cell

information and its inverse stored on 2+2 independent and cross-coupled nodes → temporary flip <u>of one node</u> cannot permanently flip the cell.

# Pixel R/O-Chip for HL-LHC rates (and radiation)

ATLAS

**FE-I3**

< 100 MHz/cm²
< 100 Mrad

250 nm technology

pixel size 400 × 50 µm²

3.5 M transistors

pixel Run1

**FE-I4**

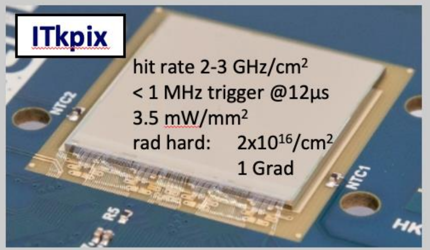
hit rate < 400 MHz/cm²
1.8 mW/mm²
rad hard: 5x10¹⁵/cm²
200 Mrad

130 nm technology

pixel size 250 × 50 µm2

70 M transistors

pixel IBL



**ITkpix**

hit rate 2-3 GHz/cm²
< 1 MHz trigger @12µs
3.5 mW/mm²
rad hard: 2x10¹⁶/cm²
1 Grad

65 nm technology

pixel size 50 × 50 µm²

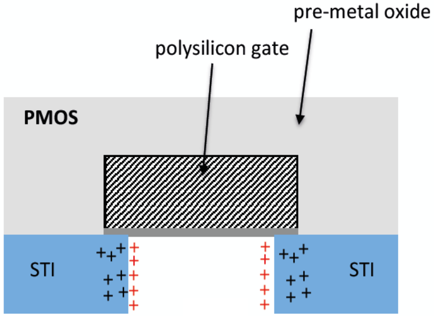
~ 1000 M transistors

pixel HL-LHC

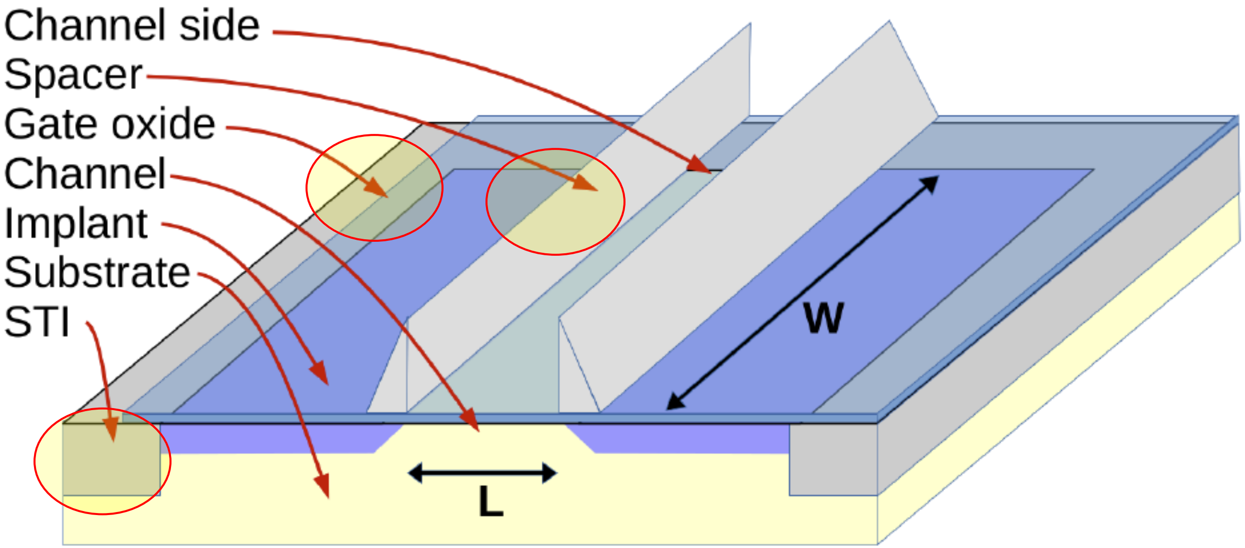
- Deep submicron (250 nm & 130 nm) saved LHC pixel R/O chips
- 65 nm has its own – geometry induced – radiation effects to deal with
- Requires long and tedious study program ...

RINCE = Radiation Induced Narrow Channel Effects

RISCE = Radiation Induced Short Channel Effects



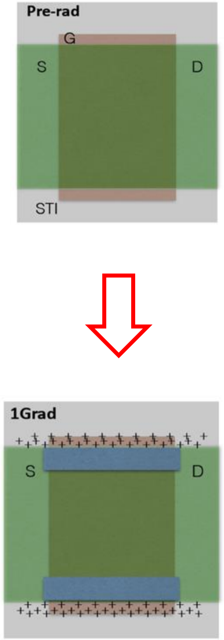
# Three dangerous oxides



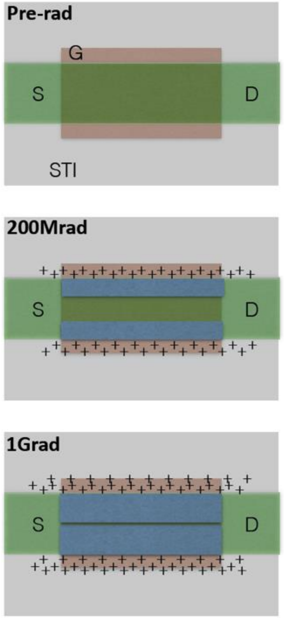
(more details in ref [7] of intro-lecture)

# Radiation effects in 65 nm CMOS small channel devices (see ref [7] of intro)

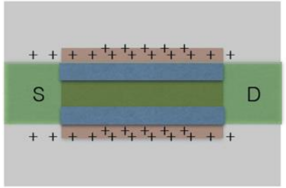
W = moderate size



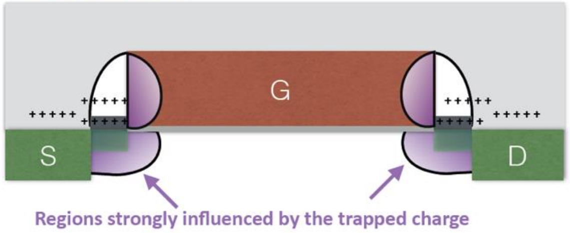
W = minimum size



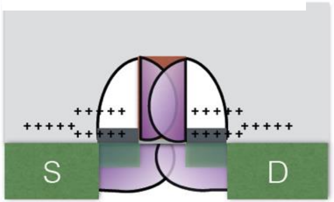
heating trap release



L = moderate size



L = minimum size



RINCE = RI narrow channel effect parasitic lateral gating

cartoons: F. Faccio, TWEPP2015

RISCE = RI short channel effect

# Pop-up questions

- Which type of radiation harmful for detectors do you know? Which respective quantity quantises them.
  - NIEL (affects lattice), measured as fluence (neq/cm^2), IEL (affects surfaces&oxide), TID (Gy)
- What does the NIEL hypothesis state? And what is NIEL scaling?
  - All you need to know is the abundance of point defects and cluster defects, irrespective of their initial distribution over energy and space. Bulk damage can be scaled to that of 1 MeV n.
- What is type inversion and how (and why) is it different for n- and p-type substrates?
  - Space charge change due to radiation induced defects causes n -> p inversion, since dominantly acceptors are created. In p-type material space chare is already negative, but damage still is creating effects.
- What are the cures?
  - n-type: oxygenation prevents P removal. p-type: carbonisation helps against B removal
- Which effects does IEL cause in transistors? Cures?
  - threshold shifts and parasitic current flows, cures = thin oxides, ELTs, special digital cells

UNIVERSITÄT BONN

# Thank you very much for your attention

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# Content of lecture based on ...

- Particle Data Group Review (2024)

  **35.9 Low-noise detector readout**

  Revised November 2021 by N. Wermes (Bonn U.), revised November 2013 by H. Spieler (LBNL).

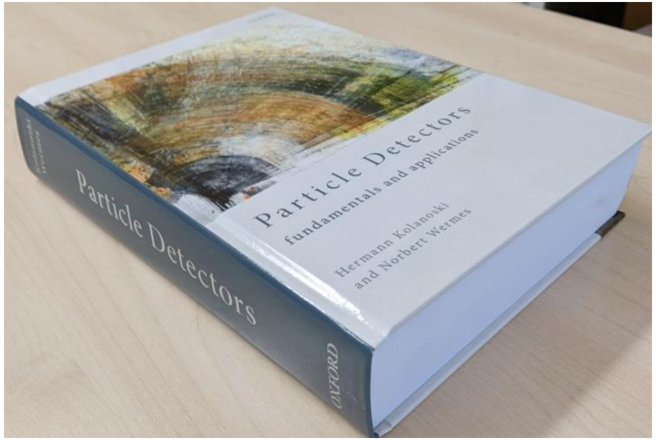
Hermann Kolanoski
Norbert Wermes

Teilchendetektoren

Grundlagen und Anwendungen

Springer Spektrum

new edition
to appear 2025



- Kolanoski, H. und Wermes, N.
  Teilchendetektoren – Grundlagen und Anwendungen
  (Springer/Spektrum 2016)

- Kolanoski, H. and Wermes, N.
  Particle Detectors – fundamentals and applications
  (Oxford University Press 2020)

  = ref [1]