VERTEX 2019 13-18 October 2019,
Lafodia Sea Resort, Lopud Island, Croatia

Acceptor Removal

Effects of displacement damage involving the shallow acceptor doping in p-type silicon devices

M.Moll, CERN
on behalf of RD50

Outline:

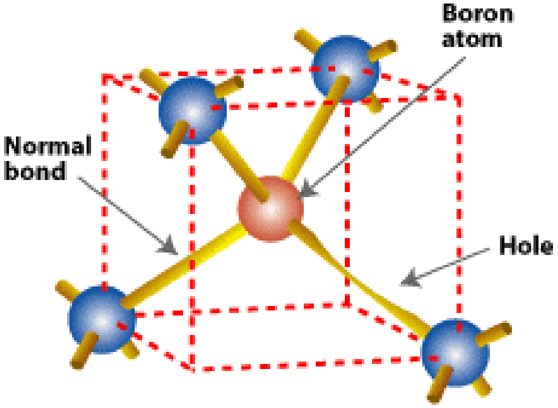
- What is acceptor removal?
- Experimental data
  - Macroscopic effects – Device degradation
  - Microscopic effects – Defect formation an defect kinetics
- Parameterizing the acceptor removal
- Mitigation by defect engineering (example: LGAD sensors)
- Outlook on RD50 activities
- Conclusions

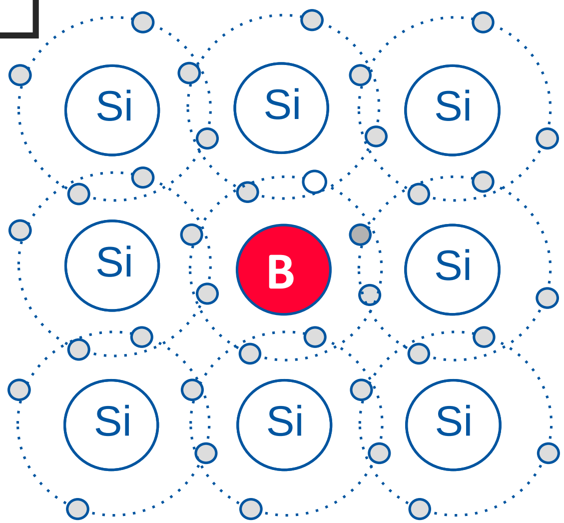
RD50 talks at VERTEX 2019
- RD50 work program: J.Ott
- TCAD simulations: F.R.Palomo
- CMOS sensors: Eva Vilella
- LGAD/Timing: S. Otero Ugobono

Reminder: Doping and p-n junction

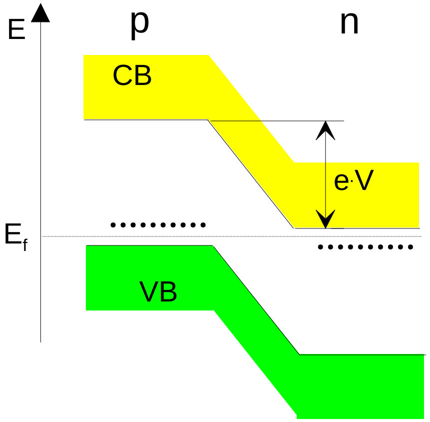
- **Doping: p-type silicon**
  - add elements from IIIrd group ⇒ **acceptors** (B,..)
  - holes are majority carriers
- **Doping**: n-type silicon
  - add elements from Vth group ⇒ **donors** (P, As,..)
  - electrons are majority carriers

Boron substitutional (Bs)





- **p-n junction**



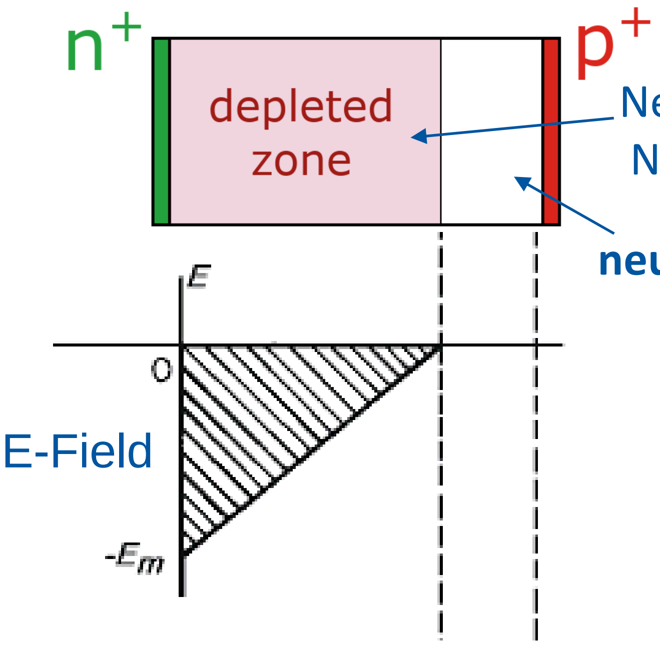
- **resistivity ρ**
  - – carrier concentration *n*, *p*
  - – carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0\left(\mu_n n + \mu_p p\right)}$$

	detector grade	**electronics grade**
doping	**≈ 10^{12} cm^{-3}**	**≈ 10^{17} cm^{-3}**
resistivity ρ	**≈ 5 kΩ·cm**	**≈1 Ω·cm**

Reminder: Space Charge - N_{eff}

- p-type diode below depletion ($V<V_{fd}$)



Negative **space charge**, N_{eff} =[B] (ionized Boron atoms)

neutral bulk (no electric field)

detector thickness d

depletion voltage V_{fd}

$$V_{fd} = \frac{e_0 \cdot |N_{eff}| \cdot d^2}{2\epsilon\epsilon_0}$$

effective space charge density N_{eff} = $[B_s]$ in non-irradiated p-type sensor

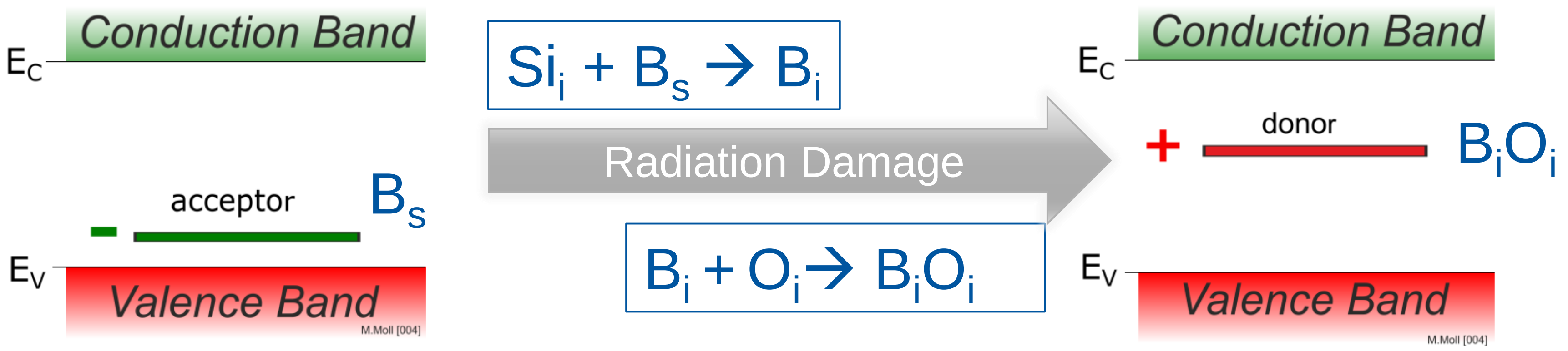
- Depletion Voltage V_{fd}
  - Sensor depleted of free charge carriers
  - Electric field throughout complete device
  - Complete sensor volume sensitive (active)

- p-type silicon:
  - Acceptors (usually Boron) provide free holes that determine conductivity of material
- p-type detectors:
  - Negative space charge (N_{eff}) given by the ionized Boron atoms (B_s = Boron substitutional)

What is acceptor removal?

- The term **“acceptor removal”** is used with different meanings in different context to describe experimental observations:
  - Decrease of the free carrier concentration in p-type silicon
  - Change of the effective doping (space charge) in p-type silicon detectors
  - Nuclear reaction of thermal neutrons with Boron (…the “real” removal)
  - Removal of the acceptor from its substitutional lattice site (i.e. deactivation of shallow dopant properties) [My definition]

- Most typical radiation induced reaction:



$Si_i + B_s \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$

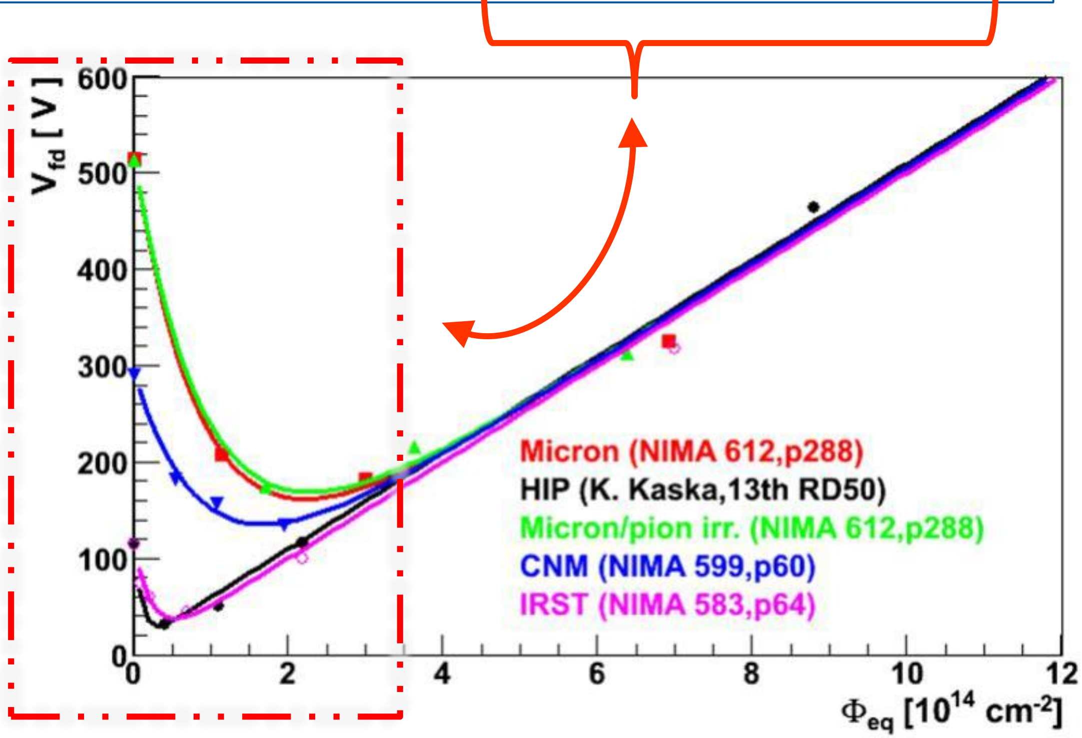
Acceptor removal in Silicon detectors

- N_{eff} is usually extracted from CV measurements
  - Assuming: V_{fd} is a valid parameter to extract N_{eff}
  - Assuming: N_{eff} constant throughout the bulk
- Parameterization of N_{eff}:

$$V_{fd} = \frac{e_0 |N_{eff}| d^2}{2\epsilon\epsilon_0}$$

$$|N_{eff}| = |N_{eff,0}| + g_{eff}\Phi_{eq} - N_{C0}\left[1 - \exp(-c\Phi_{eq})\right]$$

Material:
p-type sensors
with different
resistivity



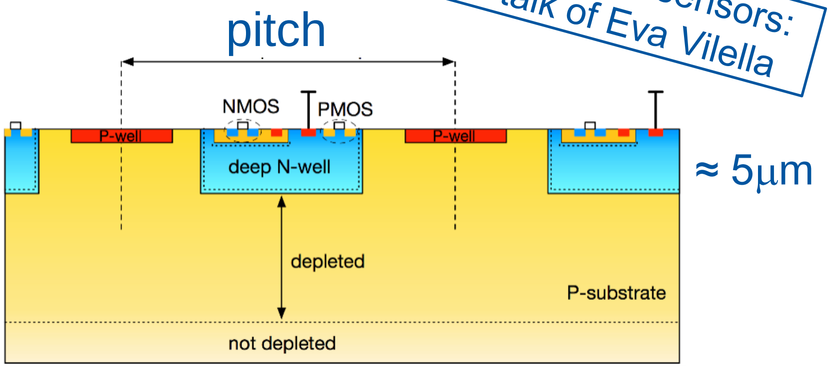
Irradiation:
23 GeV protons
200 MeV pions

[G.Kramberger, JSI, Trento Meeting 2015]

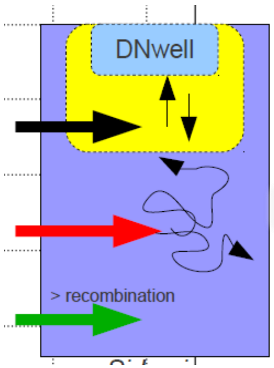
Characterization of CMOS sensors

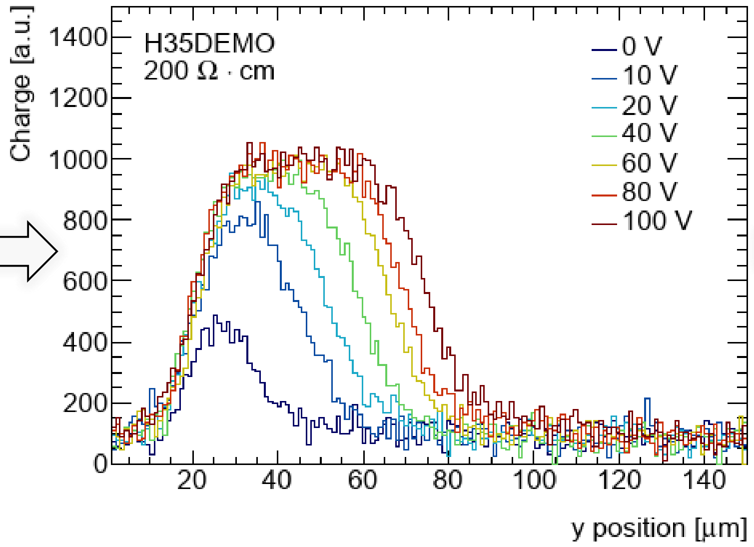
RD50 CMOS sensors: see talk of Eva Vilella

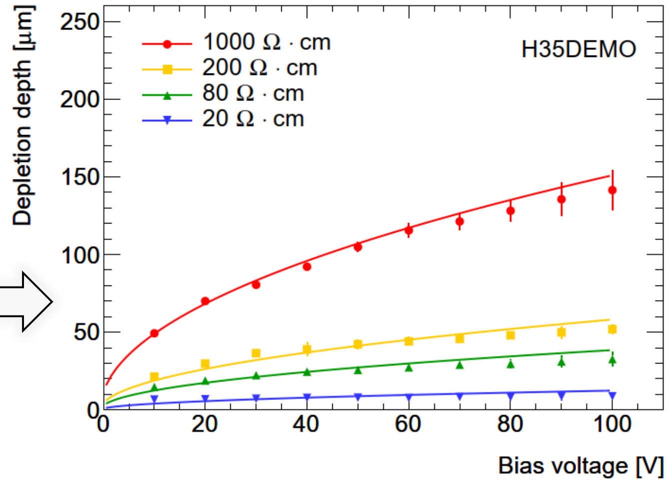
- Typical (HV-)CMOS device
  - Depleted active pixel detectors in CMOS
  - Sensor element is a deep n-well in (usually) low resistivity (~10 Ωcm) p-type substrate; 60 V ~ 10 µm depleted → ~1000 electrons
  - Lower resistivity offers bigger active volume



- CMOS sensor characterization with edge-TCT (before irradiation)
  - Study of depleted volume (as function of voltage) allows to measure N_{eff} ≈ [B]





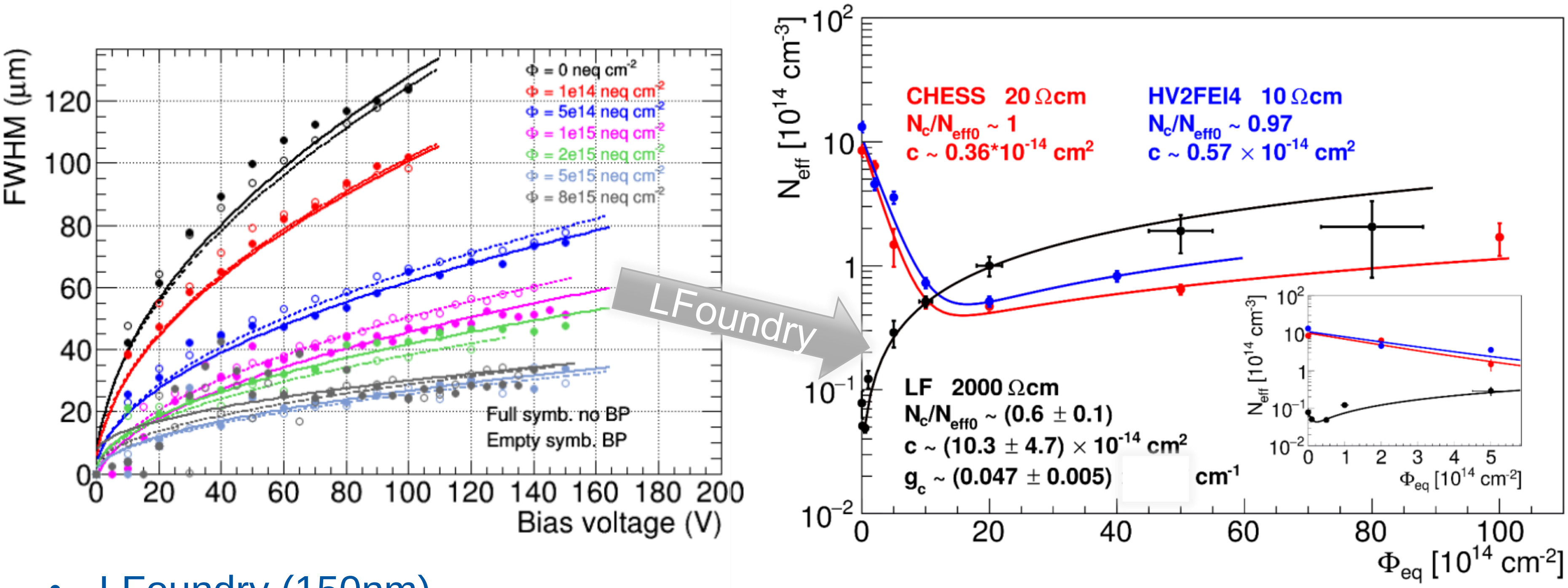


[J.Anders et al.2018 JINST 13 P10004]

$$w - w_0 = \sqrt{2\epsilon\epsilon_0 V \Big/ e_0 N_{eff}} = \sqrt{2\epsilon\epsilon_0 \mu_p \rho}$$

Acceptor removal in CMOS sensors

- Measure N_{eff} with edge-TCT (see previous slide) on irradiated sensors
  - Example: neutron irradiation of CMOS sensors



[I.Mandic, 2017 JINST 12 P02021]

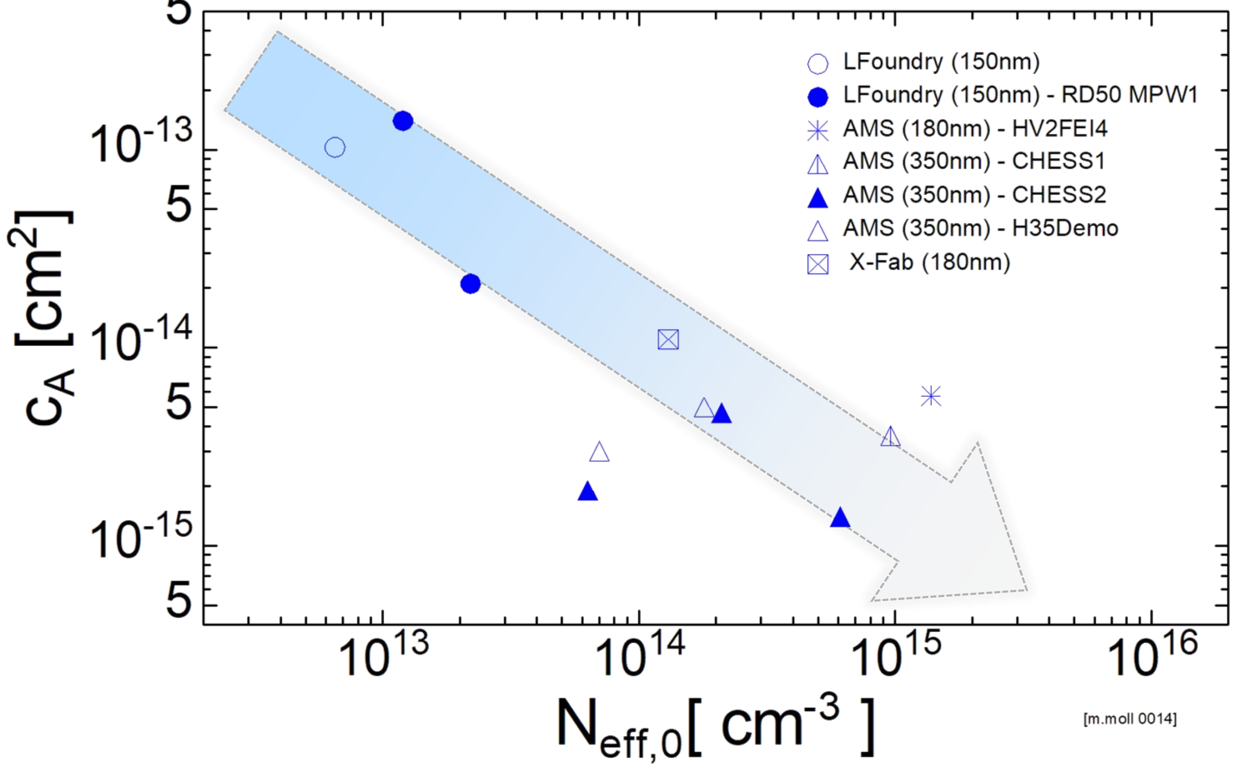
- LFoundry (150nm)
  - 2kΩcm substrate
  - Passive sensors; 50x250μm^2 pixel (no CMOS circuitry in n-well)

Fit including “removal coefficient” c :

$$|N_{eff}| = |N_{eff,0}| + g_c\Phi_{eq} - N_C[1-\exp(-c\Phi_{eq})]$$

Acceptor removal in CMOS sensors

- Acceptor removal coefficients reported in literature (CMOS sensors)
  - Note: all given data obtained after neutron irradiation;
    there are significant differences towards proton irradiations!



- Observation: c parameter drops with increasing doping concentration (decreasing resistivity)
- ➔ "faster removal for higher resistivity" if we take parameterization strict:
- ..but, is the removal really following an exponential decay? (see later)

$$N_B = N_{B0}\,\exp(-c_A\Phi)$$

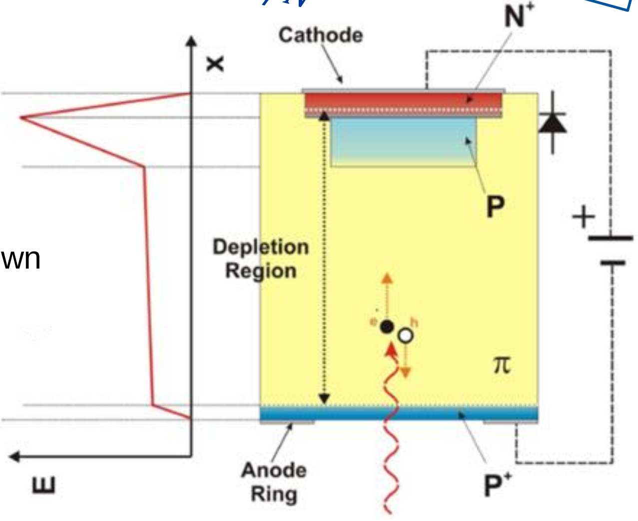
[References and more details: I.Mandic et al. RD50 Meeting Nov.2018]

LGAD: Low Gain Avalanche Detectors

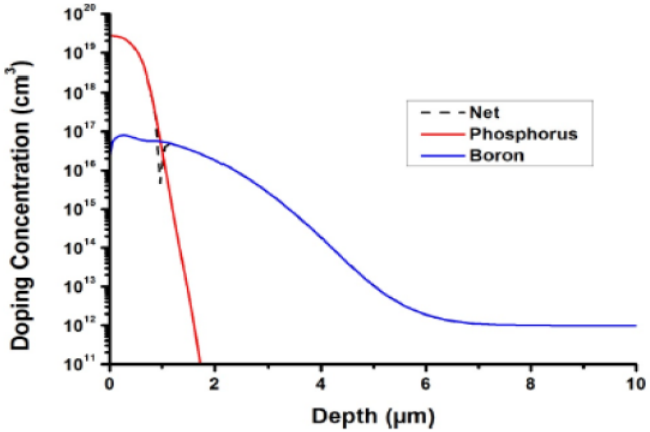
RD50 LGAD sensors:
see talk of
S.Otero Ugobono

$$\sigma_{jitter}{}^{2} = \frac{Noise}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

- **Origin:** Pioneered by RD50 with CNM,Barcelona (and later also FBK,Trento)
  - RD50 working on LGADs since ≈2010 (≈ 50 production runs)
- **Application:** LGAD for timing detectors
  - Intrinsic gain of devices allows for excellent timing performance (<50ps)
  - Time-tagging of particle tracks in order to mitigate pile-up effects
  - To be implemented in ETL(CMS) and HGTD(ATLAS)
- **Concept:** similar to APD but lower gain O(10)
  - Impact ionization in p^+-implant (multiplication layer) produces gain
  - Tailored multiplication layer ([B]~10^{17}cm^{-3}); challenge: optimize gain vs. breakdown
- **Foundries:**
  - CNM (Barcelona, ES), FBK(Trento,IT), HPK (Japan), IHEP(Bijing, China), Micron(UK), BNL(USA) and soon CIS(Erfurt, Germany)



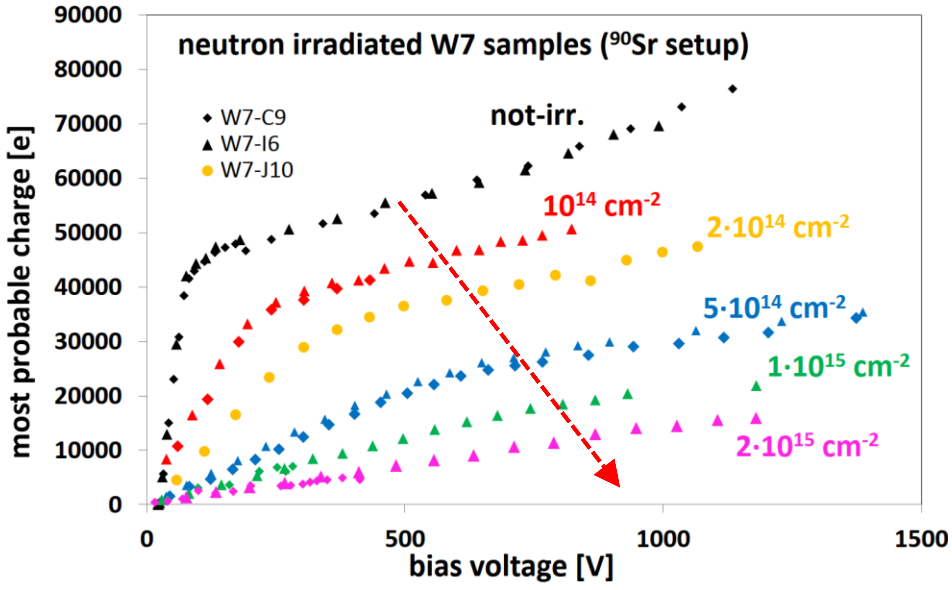
- **Areas of LGAD developments within RD50**
  - **Timing performance**
    - Optimization: sensor thickness, gain layer profile and signal homogeneity
  - **Fill factor and signal homogeneity**
    - Gain layer needs protection against breakdown (JTE) causing non-efficient area
    - Mitigation: New and optimized LGAD concepts investigated
  - **Radiation Hardness:**
    - Problem: Field in gain layer dropping due to "acceptor removal"
      - Defect Engineering of the gain layer
      - Modification of gain layer profile



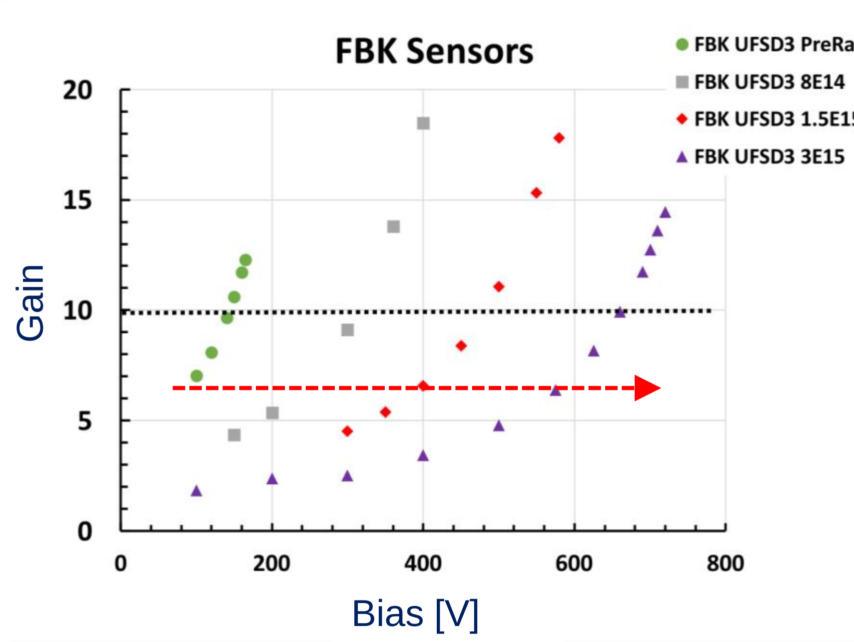
Radiation damage to LGADs

- Decrease of signal gain with increasing particle fluence
  - Main reason: Radiation induced degradation of the gain layer
  - Gain layer is (usually) a Boron implant that is suffering from “acceptor removal”
  - Mitigation: Increase of voltage to enhance the impact ionization

[G.Kramberger et al., JINST 10 P07006, 2015]



Loss of signal gain with increasing fluence



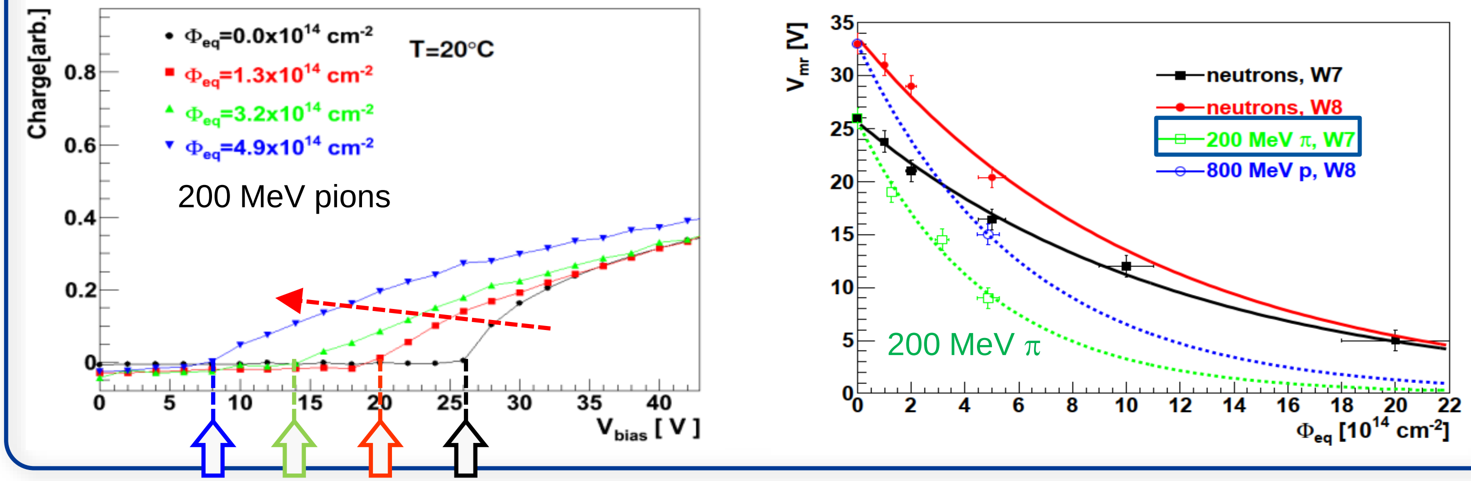
[CMS TDR of the MTD, 2019]

Increasing voltage needed to reach a gain of 10

Acceptor removal in LGADs

- Determination of acceptor concentration in the gain layer
  - Shift of the onset voltage V_{mr} for amplification (depletion of gain layer)
    - Assumption: The onset voltage is a clear measure for N_{eff} (i.e. [B]) within the gain layer
    - Measurement methods: (I) Analyze the "foot" in a CV curve
      (II) Analyze signal vs. voltage using TCT, beta CCE, test beam, ..

Method II: Signal (example: TCT; red front)



[G.Kramberger et al., JINST 10 P07006, 2015]

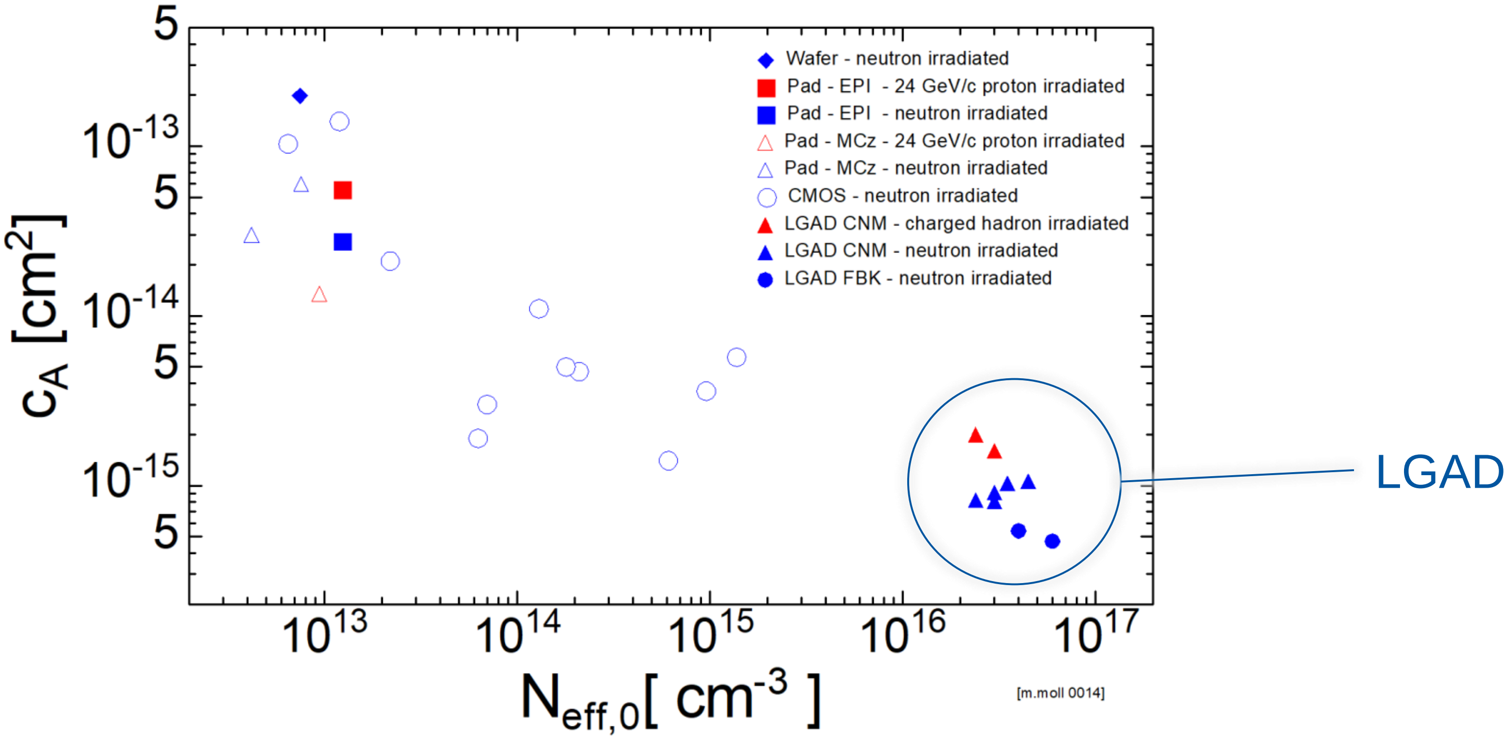
- Analyses for acceptor removal:

$$V_{mr} \approx V_{mr,0} \times \exp(-c\Phi_{eq}) \Rightarrow N_A \approx N_{A,0} \times \exp(-c\Phi_{eq})$$

- **Shortcomings:** The gain layer has not a constant doping; it has an implant profile
  The electric field in the sensor bulk can influence the measurement

Acceptor removal in Boron doped silicon

- Acceptor removal coefficients reported in literature
  - Values obtained after charged hadron irradiation and neutron irradiation



[m.moll 0014]

- c parameter drops with increasing doping concentration (decreasing resistivity)
  - ..but, is the removal really following an exponential decay?
- Strong scattering of data:
  - Different measurement techniques used; different devices; different Silicon (e.g. [O])

$$N_B = \mathrm{N}_{\mathrm{B0}} \exp(-c_A \Phi)$$

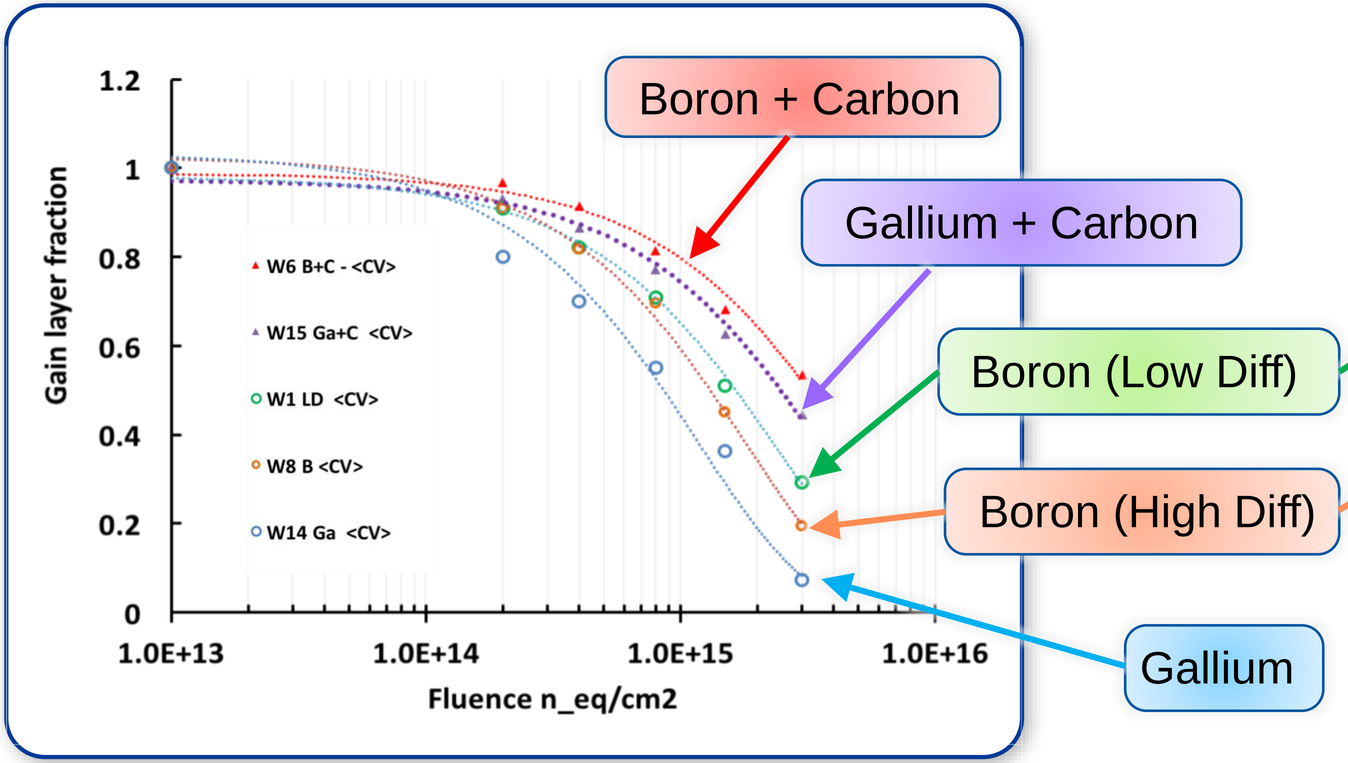
LGAD: Gain layer engineering

Defect Engineering of the gain layer

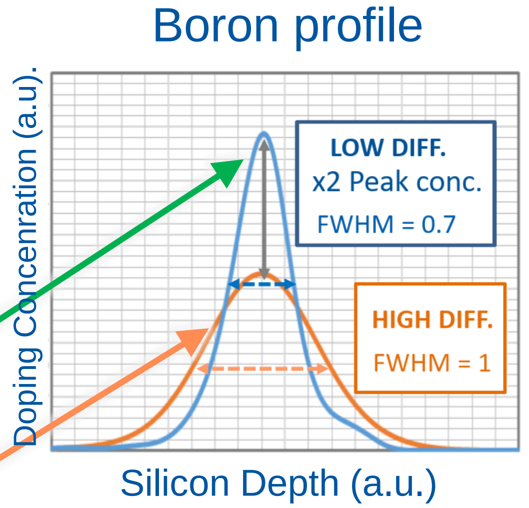
- **Carbon** co-implantation mitigates the gain loss after irradiation
- Replacing Boron by **Gallium** did not improve the radiation hardness

Modification of the gain layer profile

- Narrower **Boron doping profiles** with high concentration peak (Low Thermal Diffusion) are less prone to be inactivated



[G.Paternoster, FBK, Trento, Feb.2019]

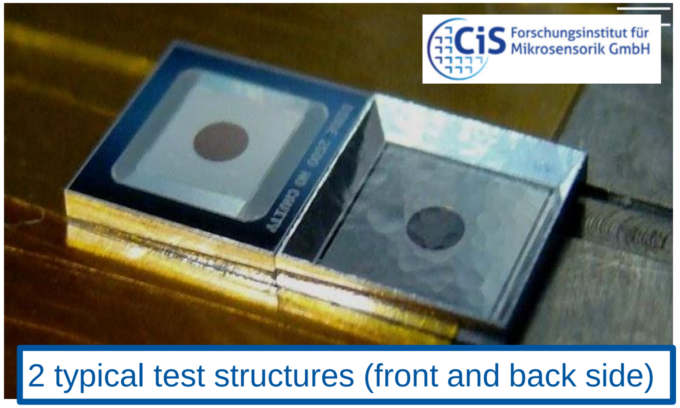


..latest c_A vs. N_A plot for LGAD in Annex of this talk

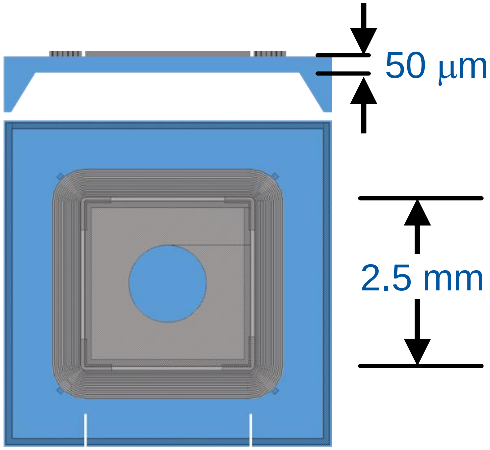
A dedicated acceptor removal study

RD50

- Production of test structures (diodes) from various p-type Silicon materials
- Material
  - **Epi Silicon (50 μm grown on CZ) 10, 50, 250 and 1000 Ωcm**
  - FZ Silicon (100 – 285 μm)
  - Cz/MCz Silicon (50-200 μm)
- Samples
  - Mainly diodes (CiS & Minsk)
    - Metal opening for light injection
    - Thinned for TSC and TCT
- Characterization
  - CV, IV, TCT
  - TSC, DLTS
- Irradiations
  - Protons (23 GeV; 230 MeV)
  - Neutrons (reactor)
  - Electrons (3.5 MeV)
  - Gammas (^{60}Co)
  - Alphas (5.15 MeV)


CiS Forschungsinstitut für Mikrosensorik GmbH

2 typical test structures (front and back side)



Proton irradiation

CERN | IRRAD Proton Facility — **24 GeV /c**

Boston General Hospital — **230 MeV**

Neutron irradiation

Institut "Jožef Stefan"
50 let REAKTORJA TRIGA

Reactor neutrons

Gamma - irradiation

BGS IDEEN PLUS ENERGIE — **^{60}Co**

50 kGy, 200 kGy and 1 MGy

Electron irradiation

BELARUSIAN STATE UNIVERSITY

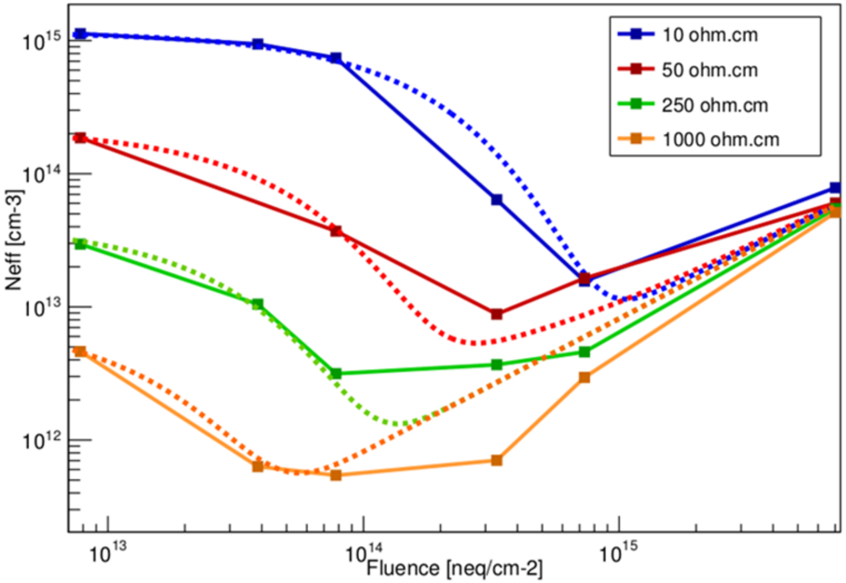
3.5 MeV and 5.5 MeV

CERN | EP-DT-DD Detector Technologies Detector Development
IFCA Instituto de Física de Cantabria
UH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG
BELARUSIAN STATE UNIVERSITY
INFN
AIDA 2020

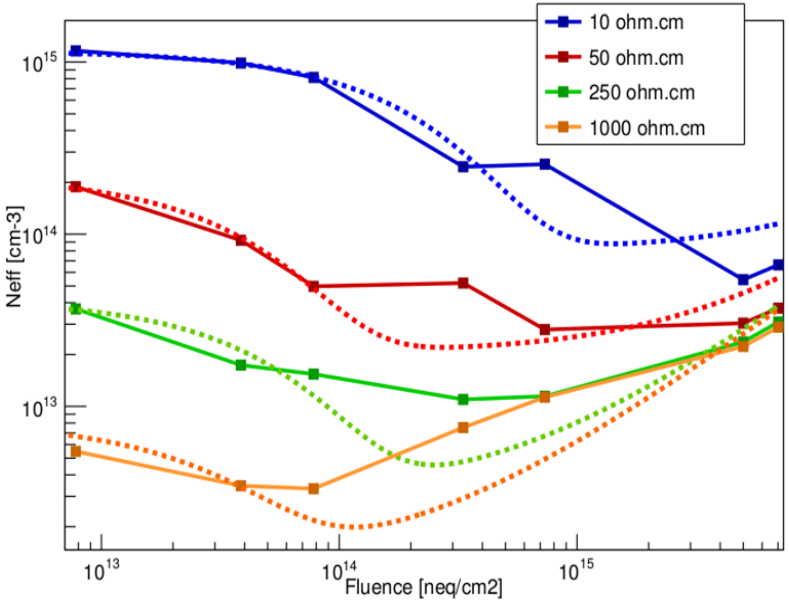
Macroscopic Damage: N_{eff}

- N_{eff} extracted from CV measurements
  - beware: can be affected by errors for highly irradiated sensors!

23 GeV proton irradiated



Neutron irradiated



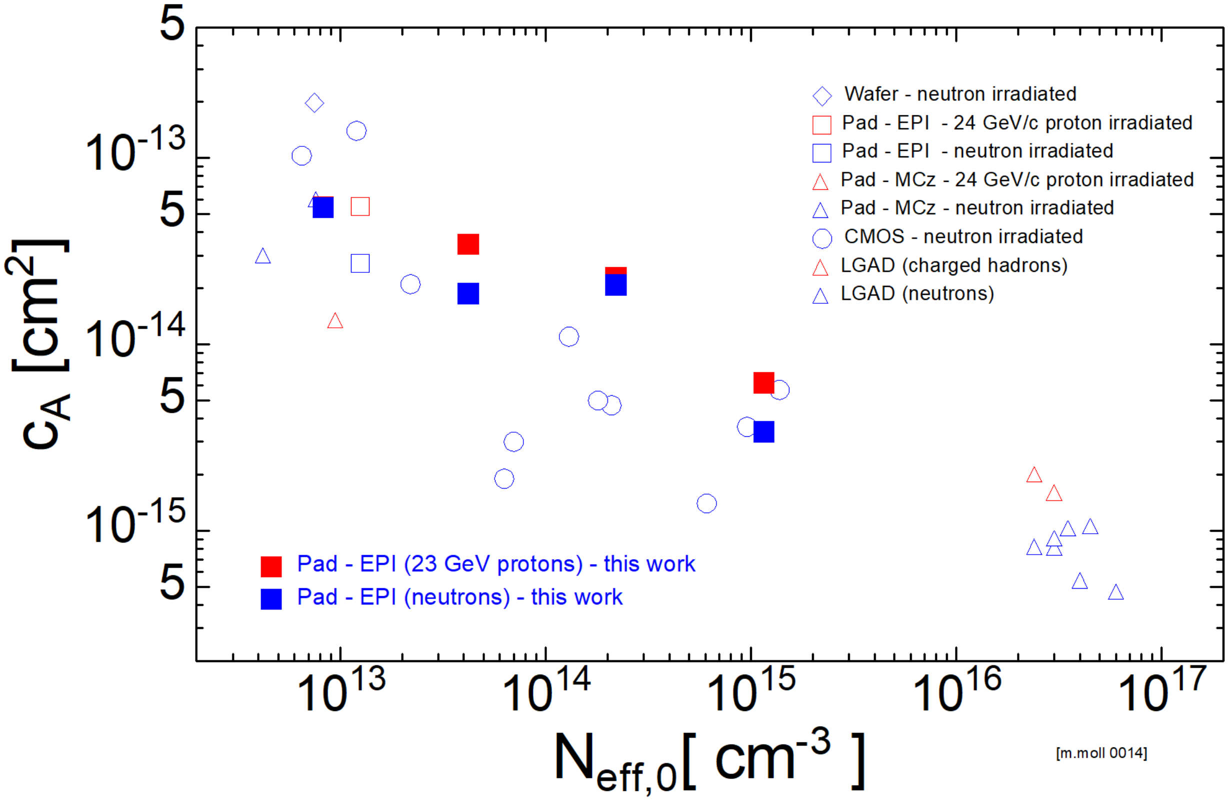
P. Almeida et al, 32nd RD50 workshop (2018)

- **Observation:** Samples differing by more than 2 orders in magnitude in initial resistivity behave very similar after very high radiation levels
- **Note:** Very complex behavior after proton irradiation (“type inversion”; see backup slides)
- Parameterization of data gives a “removal coefficient” c for every resistivity

$$\boxed{N_{eff}(\Phi_{eq}) = N_{eff,0} \cdot \exp(-c\Phi_{eq}) + g_c\Phi_{eq}}$$

Acceptor removal in Boron doped silicon

- Acceptor removal coefficients reported in literature
  - Values obtained after charged hadron irradiation and neutron irradiation

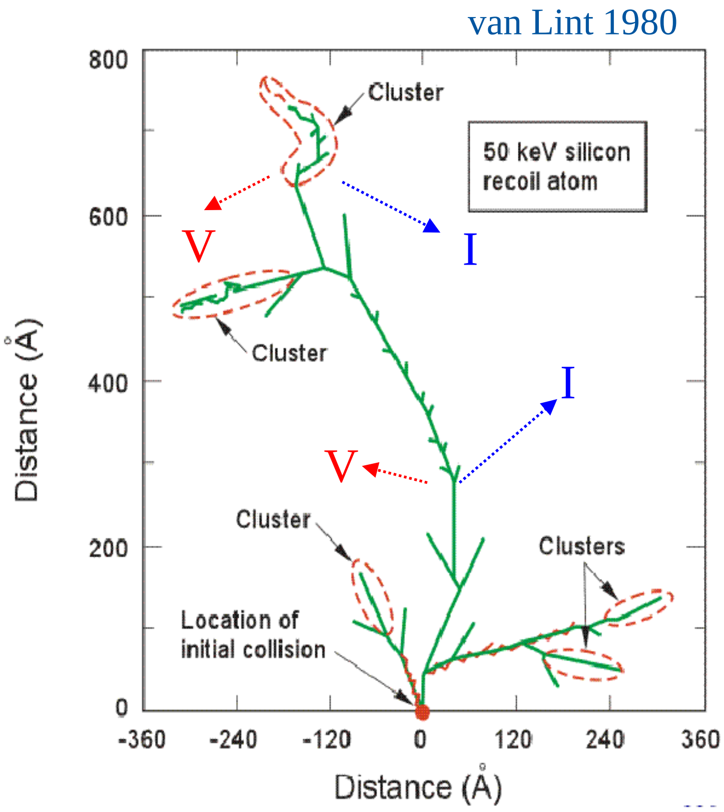


- c_A parameter drops with increasing doping concentration (decreasing resistivity)
  - ➔ “faster removal for higher resistivity” if we take parameterization strict:

$$\boxed{N_B = \mathrm{N_{B0}}\,\exp(-c_A \Phi)}$$

Displacement Damage

- Mechanism:
  - Primary interaction generates displacements (vacancies & interstitials)
  - Vacancies and Interstitials migrate, either recombine (~90%) or migrate and form stable defects (point and cluster defects)


van Lint 1980

- Secondary defect generation due to migration of I - Silicon Interstitial and V – Vacancy
- Reacting with impurities in silicon: Oxygen (O_i), Carbon (C_s), Boron (B_s)……

$I+C_s \rightarrow C_i \Rightarrow C_i+C_s \rightarrow C_iC_S$

$C_i+O_i \rightarrow C_iO_i$

$\mathbf{I+B_s \rightarrow B_i} \Rightarrow B_i+C_s \rightarrow B_iC_S$

$B_i+O_i \rightarrow \mathbf{B_iO_i}$

$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$

$V+O_i \rightarrow VO_i \Rightarrow V+VO_i \rightarrow \underline{V_2O_i}$

$V+P_s \rightarrow VP_s$

…and many more reactions ……

Parameterization of the c parameter: Torino

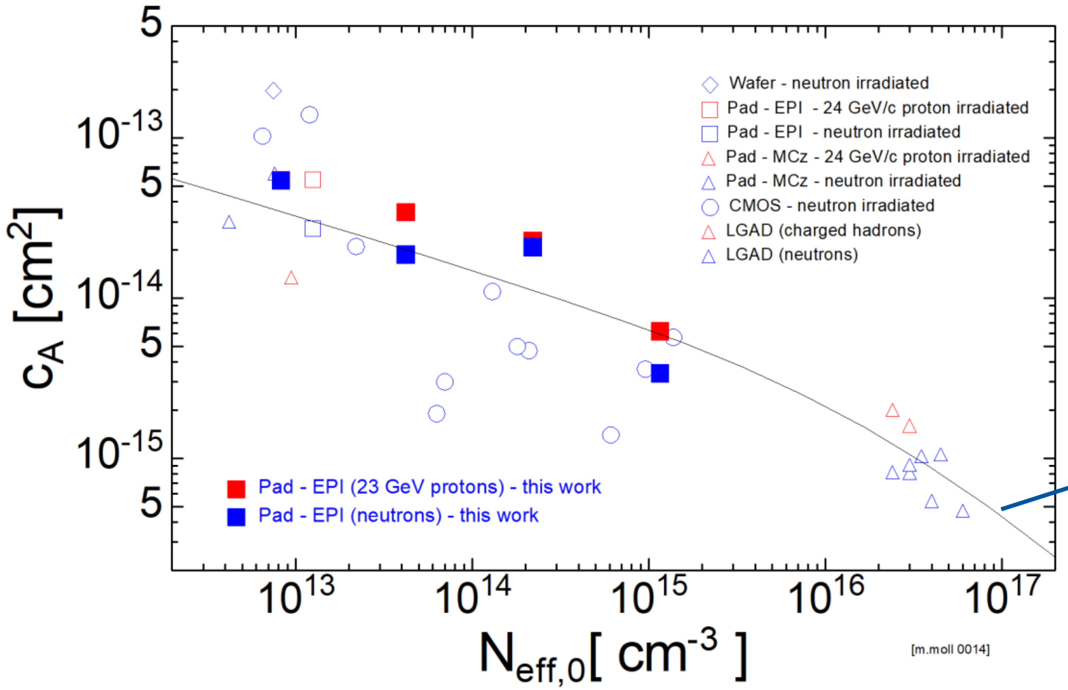
- Based on a estimation of the average number of interstitials (N_{Int}) created in the particle interaction (with cross section σ_{Si} and the silicon of atomic density N_{Si}). Fit gives: $g_{Interstitials} \approx 60\ cm^{-1}$

$$N_A = N_A(0)\exp(-c\Phi_{eq})$$

$$c = k_{cap}\frac{N_{Si}\ N_{Int}\ \sigma_{si}}{0.63\ N_A(0)}\left(1+\left(\frac{N_{A0}}{N_A(0)}\right)^{2/3}\right)^{-1}$$

$$k_{cap}\cdot N_{Int}\cdot\sigma_{Si} = 7.6\times10^{-22}cm^2$$
$$N_{Si} = 5\cdot10^{22}\ cm^{-3}$$
$$N_{A0} = 2.5\cdot10^{16}\ cm^{-3}$$

- **Fit parameter N_{A0}** and the corresponding term in the equation describe the probability to remove an acceptor with an interstitial; the higher $N_A(0)$ the lower the chance that interstitials interact elsewhere
- The **parameter k_{cap}** accounts for the impurity content (i.e. variations in different Si materials)



[m.moll 0014]

"Torino parameterization"

[M.Ferrero et al., Radiation resistant LGAD design, NIMA 919 (2019)16-26]

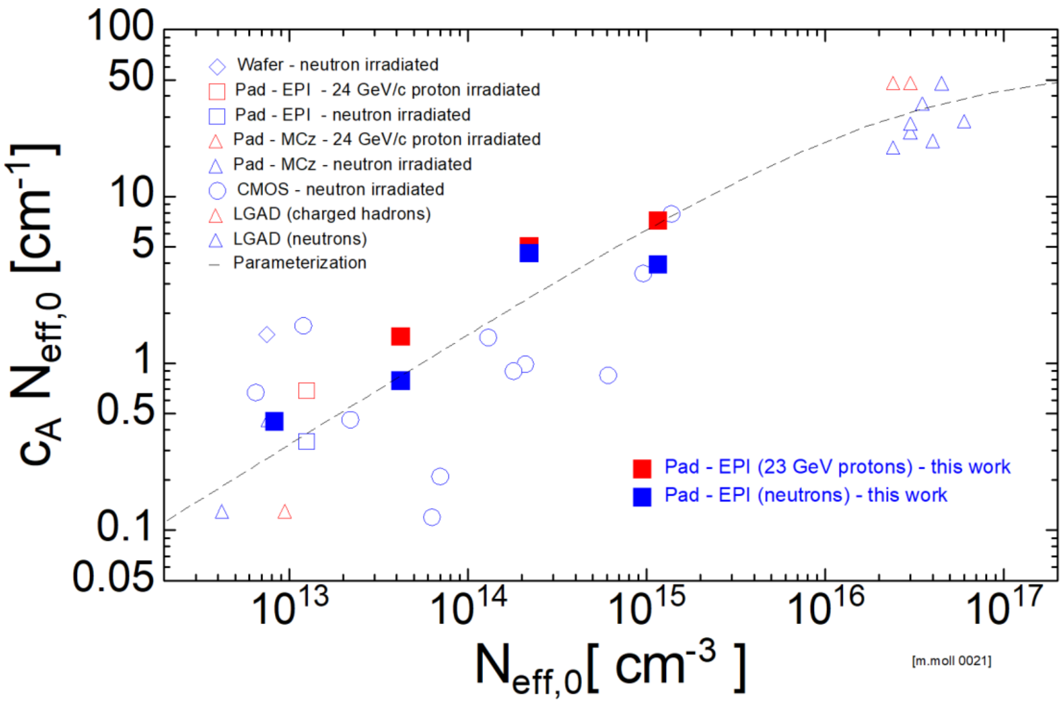
Acceptor removal in Boron doped silicon

- Initial acceptor removal rate ($g_A = c_A N_{A,0}$) at small fluences

$$N_A = \mathrm{N}_{\mathrm{A0}} \exp(-c_A \Phi) \;\approx\; \mathrm{N}_{\mathrm{A0}} - c_A \mathrm{N}_{\mathrm{AO}} \Phi + \;\ldots$$

$$g_A \equiv c_A \mathrm{N}_{\mathrm{eff,0}}$$

Number of “removed” acceptors per incident particle (normalized to NIEL)



≈ 60 cm^{-1}

≈ 0.1 cm^{-1}

- Is acceptor removal “faster” for lower or higher acceptor concentration?
  - Faster in absolute numbers: The higher the acceptor concentration, the more acceptors get removed
  - Slower in relative numbers: The higher the accepter concentration, the smaller is the removed fraction

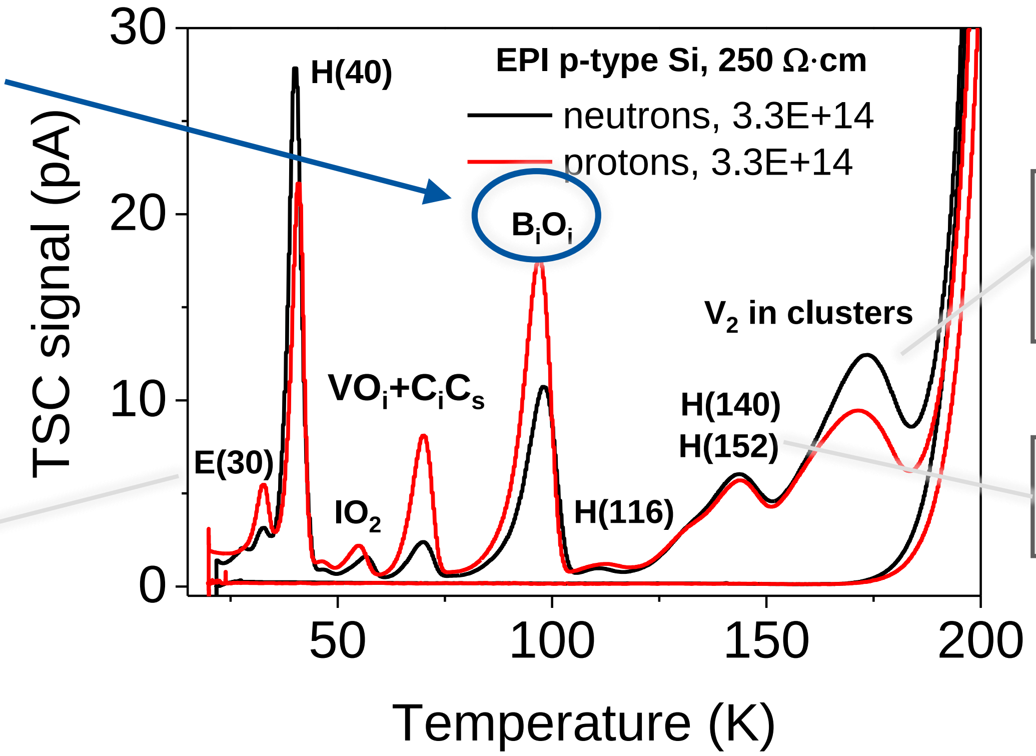
Defect Characterization

- *Example: TSC (Thermally Stimulated Currents) measurement*
  - Comparing damage after proton and neutron exposure

More about defects: see talk of F.R.Palomo: RD50 TCAD simulations

B_iO_i defect (acceptor removal)

E30 donor (positive charge) proton vs. neutron damage



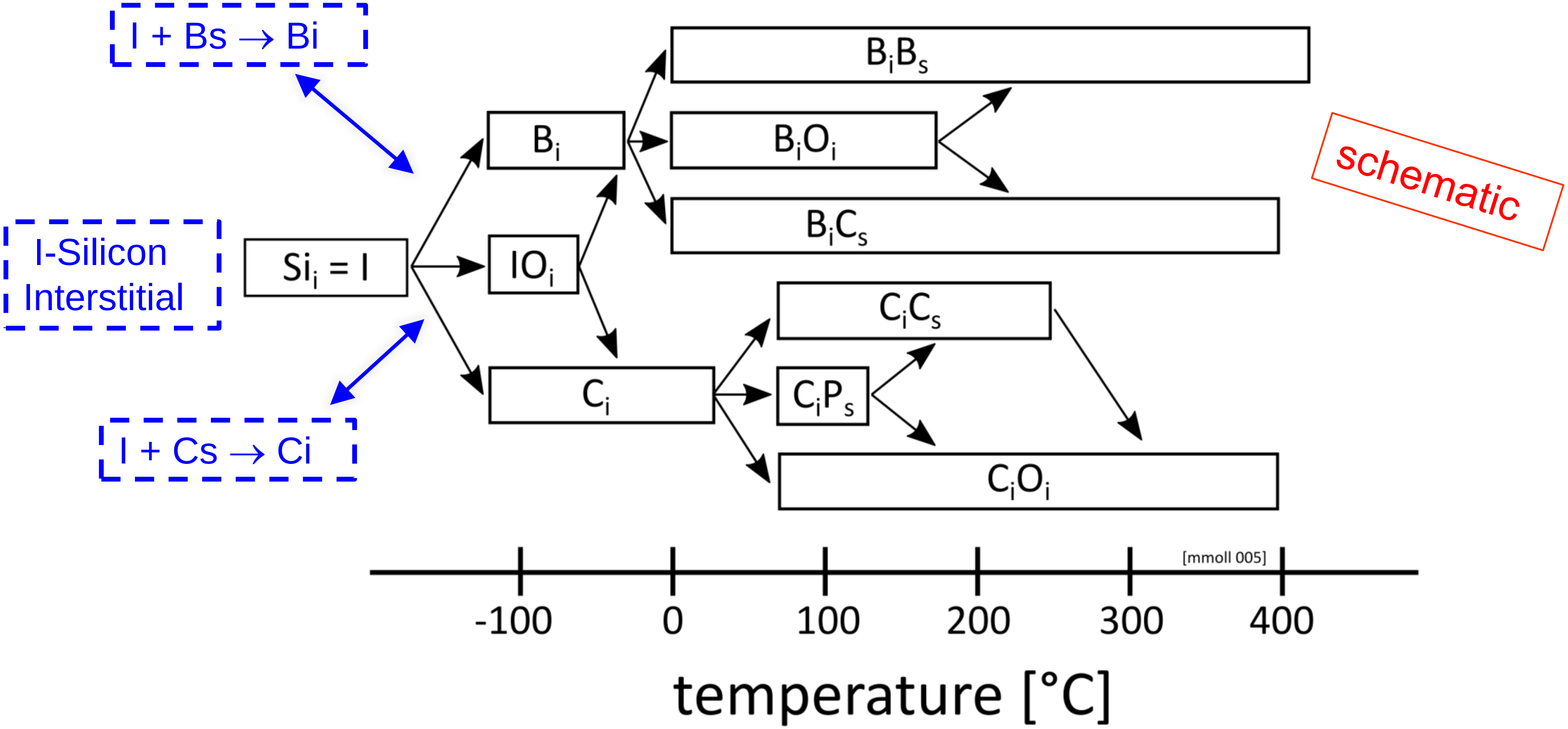
Cluster related defects (leakage current)

H(1xx) - acceptors (reverse annealing)

- More point defects and higher [BiOi] after proton irradiation
- In agreement with stronger acceptor removal (i.e. higher c_A value for same $[B_S]$) after proton exposure (for same NIEL).

[Y.Gurimskaya et al., 2019 https://doi.org/10.1016/j.nima.2019.05.0]

Boron defect kinetics



I + Bs → Bi

I-Silicon Interstitial

I + Cs → Ci

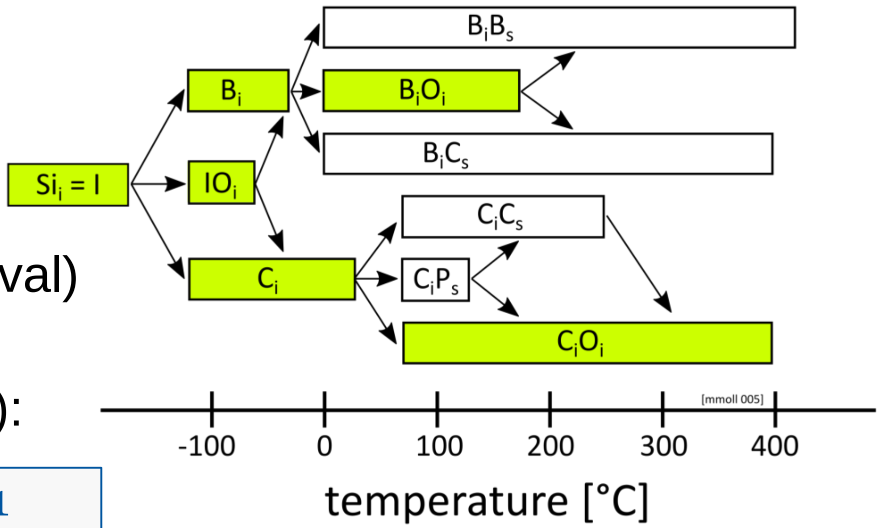
schematic

[Moll 1999, PhD thesis]

- Boron and Carbon competing for Interstitials
- High rho silicon: [O] >> [C] >> [B] leading to production of mainly C_iO_i
- Increasing Carbon content will “protect” Boron from removal

Back of envelope approach

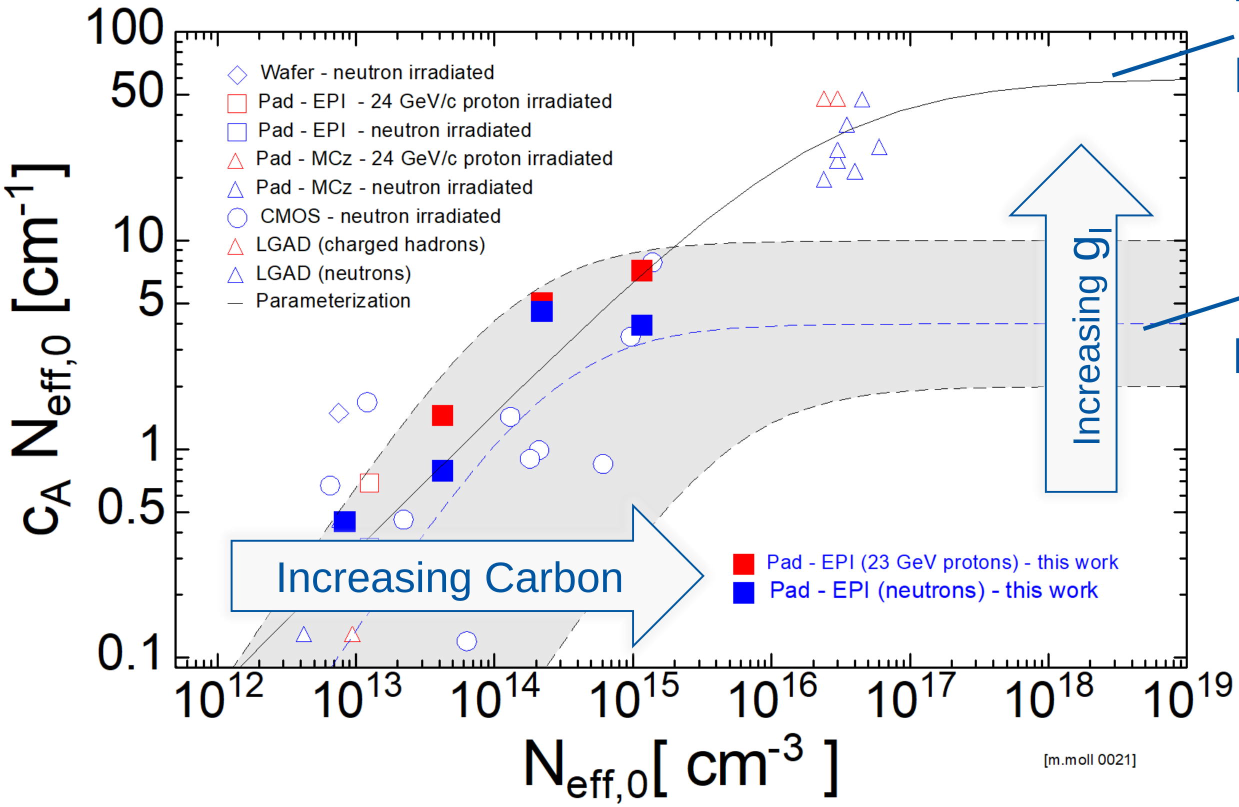
- Assumptions: [O] >> [B],[C]
  - Boron is removed by the reaction
    I+Bs→ Bi → Bi+Oi→BiOi
  - Interstitials (I) are “shared” between Cs and Bs (i.e. Cs protects Bs from removal)
  - Initial Boron removal rate
    (i.e. rate of BiOi formation at low fluence):



$$g_B = g_{BiOi} \approx g_I \left(1 + \frac{k_{IC}[C_s]}{k_{IB}[B_s]}\right)^{-1}$$

- BiOi is a donor (i.e. contributes positive space charge)
  - For every removed Boron an acceptor is lost and a donor is created (factor 2 !)
- From literature and our own measurements (see Annex of talk):
  - Generation of interstitials (outside clusters): $g_I \approx$ 1-3 cm^{-1} (high resitivity silicon)
  - Sharing of interstitials between Bs and Cs: $k_{IB}/k_{IC} \approx$ 1-7
  - $[C_s] \approx 1 - 5 \times 10^{15}$ cm^{-3}

Modeling approaches



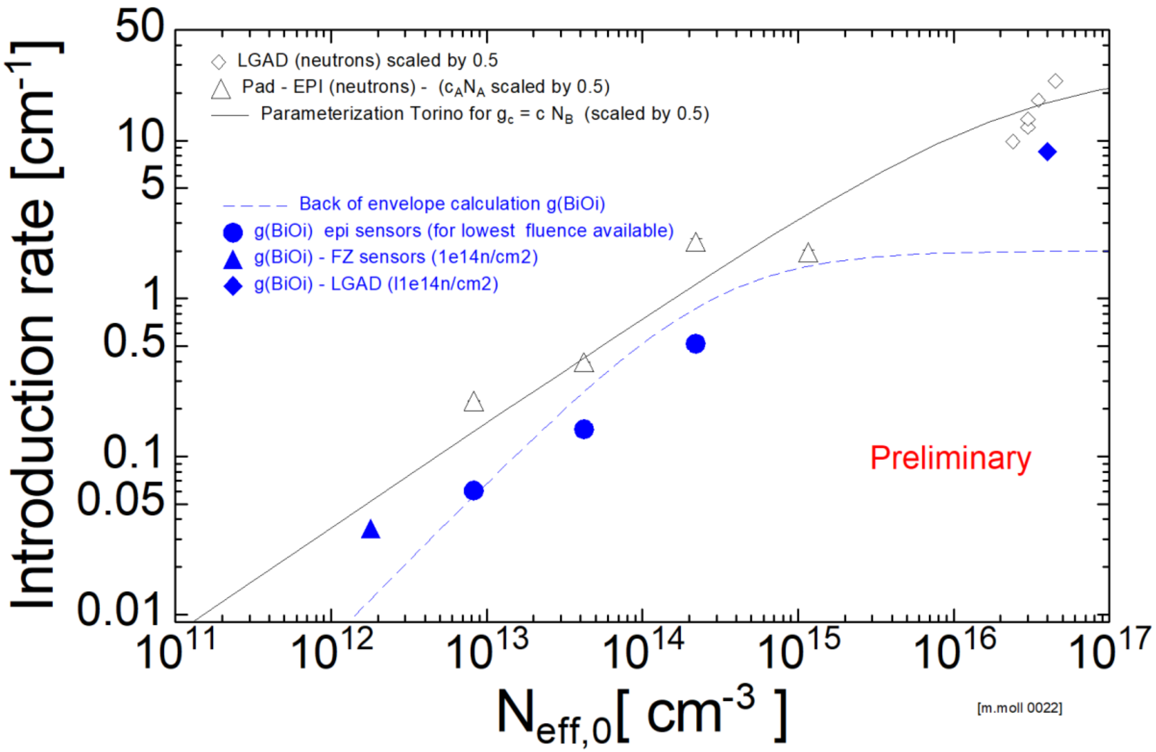
"Torino parameterization"

Expectation from simple defect kinetics modelling

- Model I (Torino parameterization)
  - Fit to data, requires an introduction rate of $g_I = 60$ cm^{-1} and interstitial gettering center in silicon that is not leading to visible defects and does not react with other defects like Ci and Bi.
  - Fits the data set over 6 orders of magnitude !
  - Shortcoming: Not in line with defect/defect kinetics studies which do not indicate an "invisible" gettering center
- Model II (Back of envelope defect kinetics calculation):
  - Simplistic model ignoring defect kinetics complexity; g_I based on experimental data of defect introduction rates
  - Shortcoming: Does not cover the data and can not explain the LGAD data (low resistivity) at all

BiOi – Introduction Rates

- Compare [BiOi] introduction to “acceptor removal rate”



- **Missing a factor of 2-4 in defect concentration of [BiOi]** to explain the macroscopic acceptor removal
- Contrary to many other effects like e.g. reverse annealing for which we can calculate the macroscopic change in V_{fd} from the microscopic defect concentrations

Conclusions

- Radiation induced acceptor removal effect leads to performance changes (mostly degradation) in LGAD, CMOS and standard p-type detectors.
  - It is the limiting factor for LGAD sensor application in high radiation fields!
- **Parameterization of acceptor removal existing** and covering the range [B]=10^{12} to 10^{18} cm^{-3} (10 kΩcm to 5 mΩcm)
  - i.e. damage prediction can be done
- **Defect engineering: Carbon enrichment reduces “removal speed”**
  - LGAD sensors can gain a factor of order 2-3 in fluence reach by gain layer engineering
- **Microscopic understanding remains incomplete**
  - Measured defect concentration does not explain the observed acceptor removal effect
  - Two modelling approaches presented (both lacking some consistency with data)
    - Model I (Torino): Good parameterization to all experimental data measured on macroscopic scale. Can be used for damage predictions. Difficult to include in the microscopic picture as we need an invisible sink for interstitials (“dark interstitial sink”)
    - Model II (Defect formation): We can explain the BiOi formation in high resistivity materials up to 10 Ωcm but not beyond (i.e. the strong BiOi formation in LGAD sensors).
- **Need more data/models: Dedicated RD50 projects started and ongoing**

Annex

Annex – Spare Slides

- Acceptor removal on wafer level
- LGAD: Gain layer defect engineering
- LGAD: Boron is not removed by nuclear reactions
- EPI silicon:
  - SIMS and SR profiling
  - Type inversion after proton irradiation
- Summary: Defects with impact on sensor performance
- Determination of oxygen concentration from defect kinetics after irradiation
- Determination of carbon concentration from defect concentrations after irradiation

Acceptor removal on wafer level

Example: Doping removal in high resistivity wafers (1996 R.Wunstorf et al.)

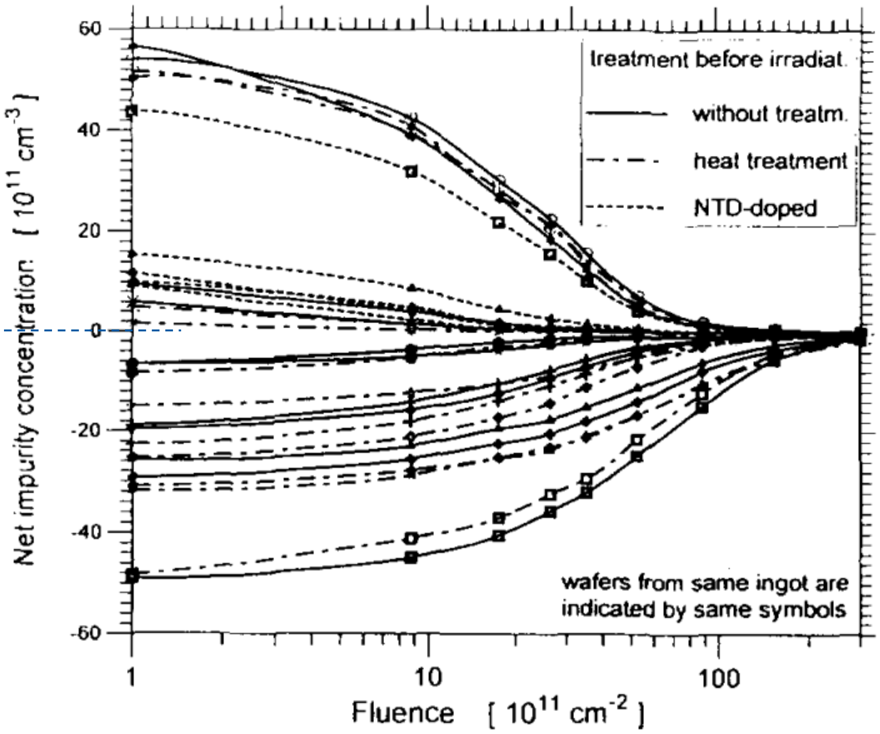
- Material:
  - Neutron Transmutation Doped (NTD) FZ Silicon
  - Wafers only differing in Phosphorus content
- Measurement: Resistivity as obtained with 4 point probe

$$^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P$$

[R. Wunstorf et al. NIMA 377, 228–233 (1996)]

n-type

p-type



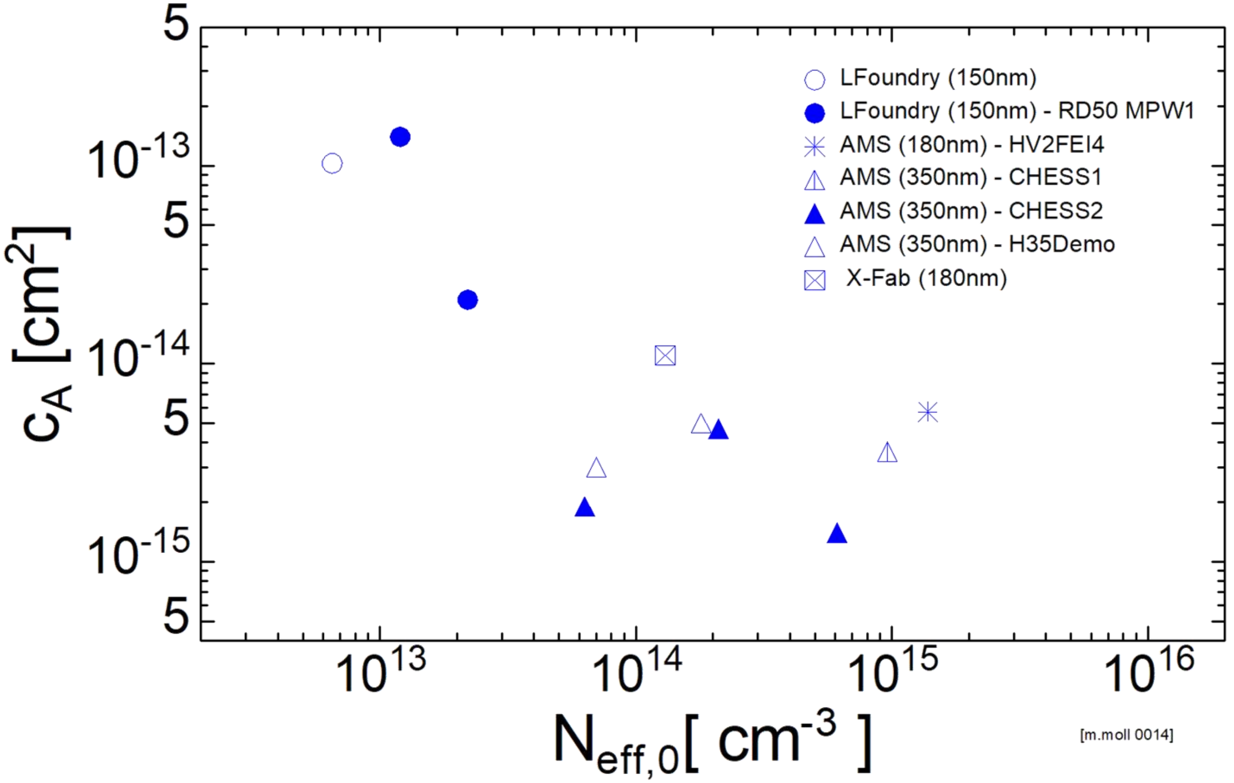
experiment targeted n-type silicon but gave also result for p-type

$$N_B = \mathrm{N_{B0}} \exp(-c_A \Phi)$$

$$c_A = 1.98 \times 10^{-13} cm^2$$

Acceptor removal in CMOS sensors

- Acceptor removal coefficients reported in literature (CMOS sensors)
  - Note: all given data obtained after neutron irradiation;
    there are significant differences towards proton irradiations!



- Observation: c parameter drops with increasing doping concentration (decreasing resistivity)
- ➔ "faster removal for higher resistivity" if we take parameterization strict:
- ..but, is the removal really following an exponential decay? (see later)

$$N_B = N_{B0}\exp(-c_A\Phi)$$

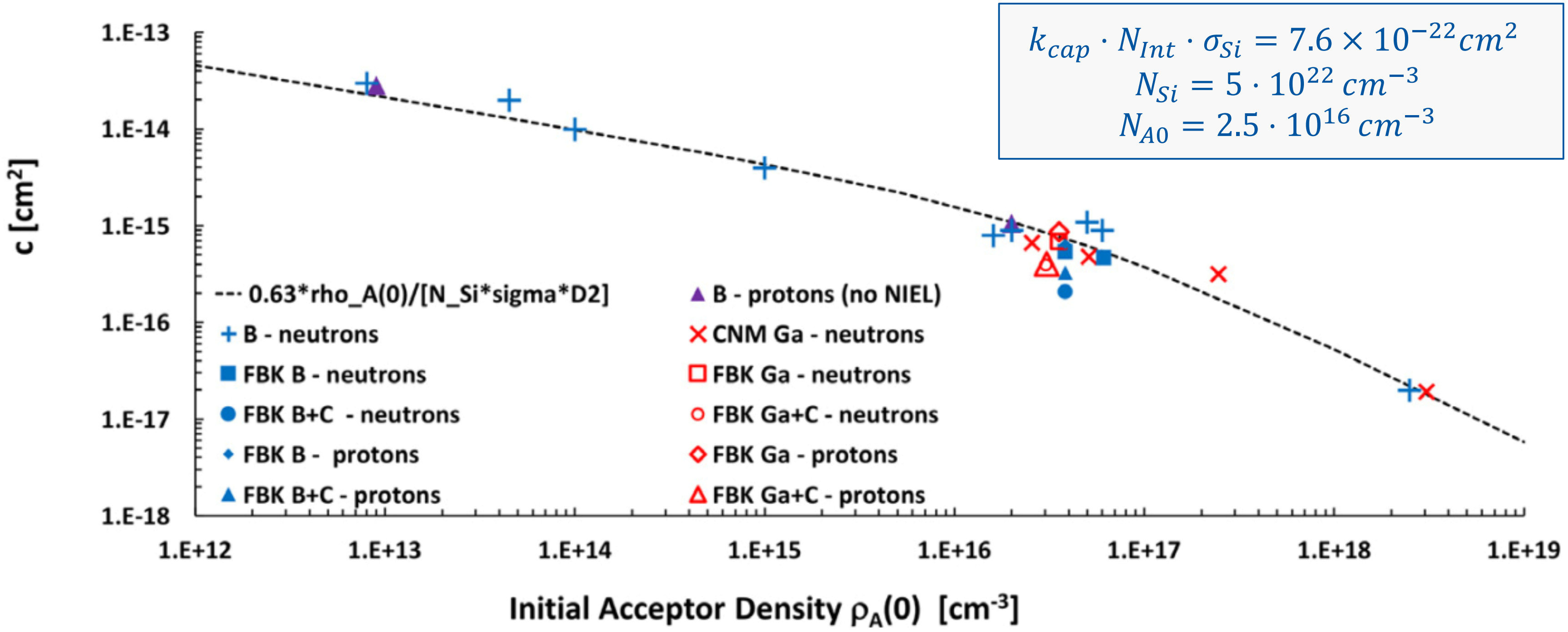
[References and more details: I.Mandic et al. RD50 Meeting Nov.2018]

Parameterization of the c parameter: Torino

$$N_A = N_A(0)\exp(-c\Phi_{eq})$$

$$c = k_{cap}\frac{N_{Si}\,N_{Int}\,\sigma_{si}}{0.63\,N_A(0)}\left(1+\left(\frac{N_{A0}}{N_A(0)}\right)^{2/3}\right)^{-1}$$

- Based on a calculation of the average number of interstitials (N_{Int}) created in the particle interaction (with cross section σ_{Si}) and the silicon (of atomic density N_{Si}).
- Fit parameter N_{A0} and the corresponding term in the equation describe the probability to remove an acceptor with an interstitial; the higher $N_A(0)$ the lower the chance that interstitials interact elsewhere
- The parameter k_{cap} accounts for the impurity content (i.e. variations in different Si materials)



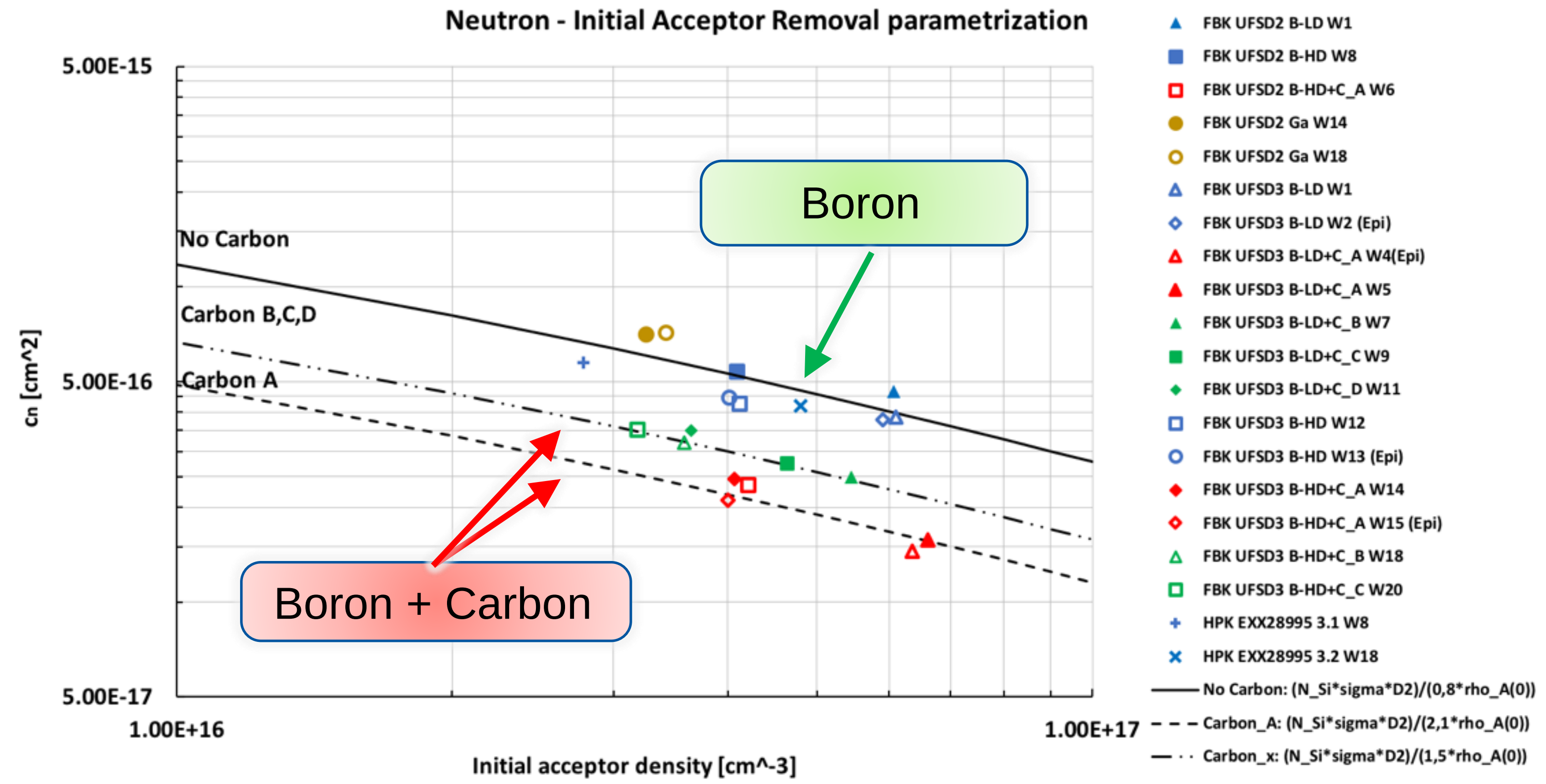
$$k_{cap}\cdot N_{Int}\cdot\sigma_{Si} = 7.6\times10^{-22}\,cm^2$$
$$N_{Si} = 5\cdot10^{22}\,cm^{-3}$$
$$N_{A0} = 2.5\cdot10^{16}\,cm^{-3}$$

[M.Ferrero et al., Radiation resistant LGAD design, NIMA 919 (2019)16-26]

LGAD: Gain layer engineering

Defect Engineering of the gain layer

- **Carbon** co-implantation mitigates the gain loss after irradiation



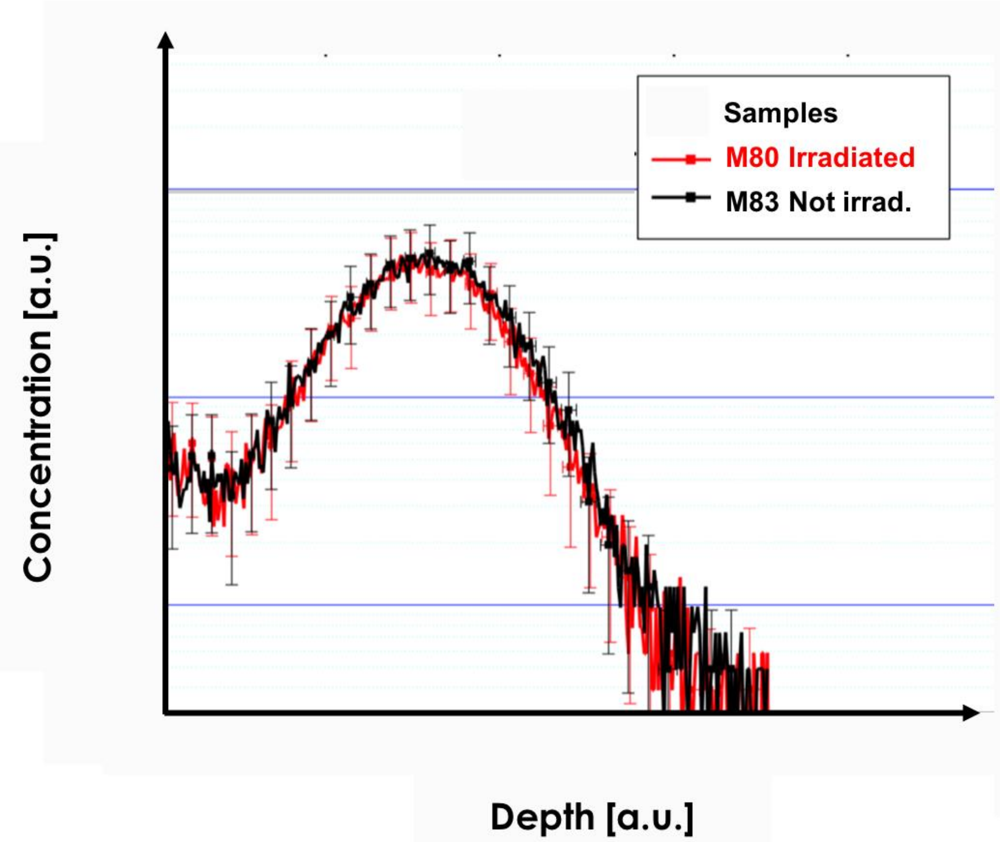
Boron

Boron + Carbon

[N.Cartiglia, Torino, private communication, October 2019 to be presented on IPRD19, Siena by Marco Ferrero]

SIMS before and after irradiation

- SIMS = Secondary Ion Emission Spectroscopy
  - Measurement of Boron profile before and after irradiation with neutrons (10^{16} n_{eq}/cm^2) – no difference

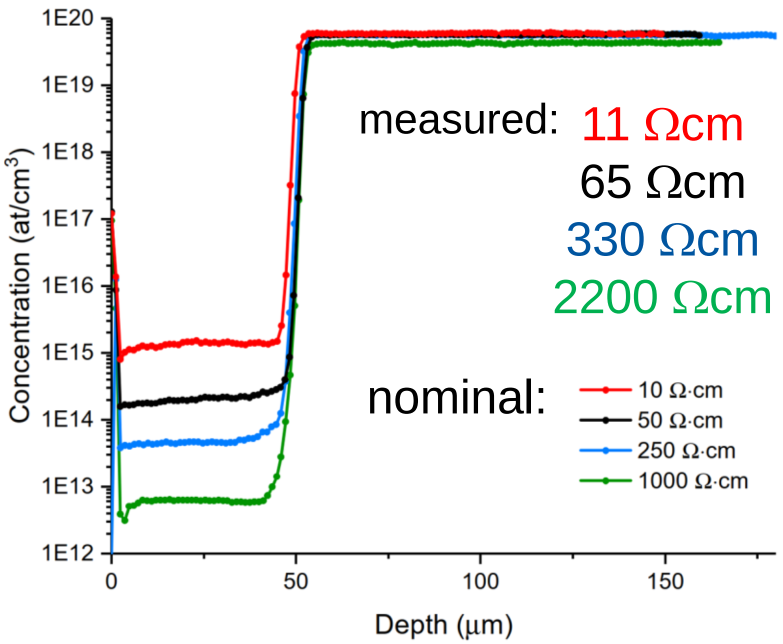


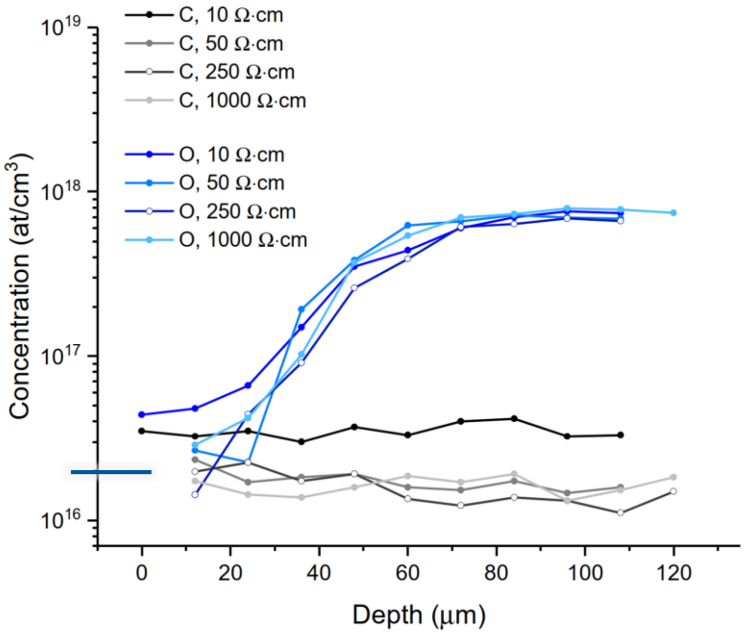
[M.Ferrero et al., Radiation resistant LGAD design, NIMA 919 (2019)16-26]

Epitaxial Silicon Sensors

- Systematic study on epitaxial p-type silicon
  - All wafers produces in same facility/process on same substrate (low resistivity Cz); wafers differ only in Boron content (i.e. resistivity)
  - all wafers processed together and all samples irradiated together

- Characterization on processed devices (destructive)
  - SR (Spreading Resistance) and SIMS (Secondary Ion Emission Spectroscopy)



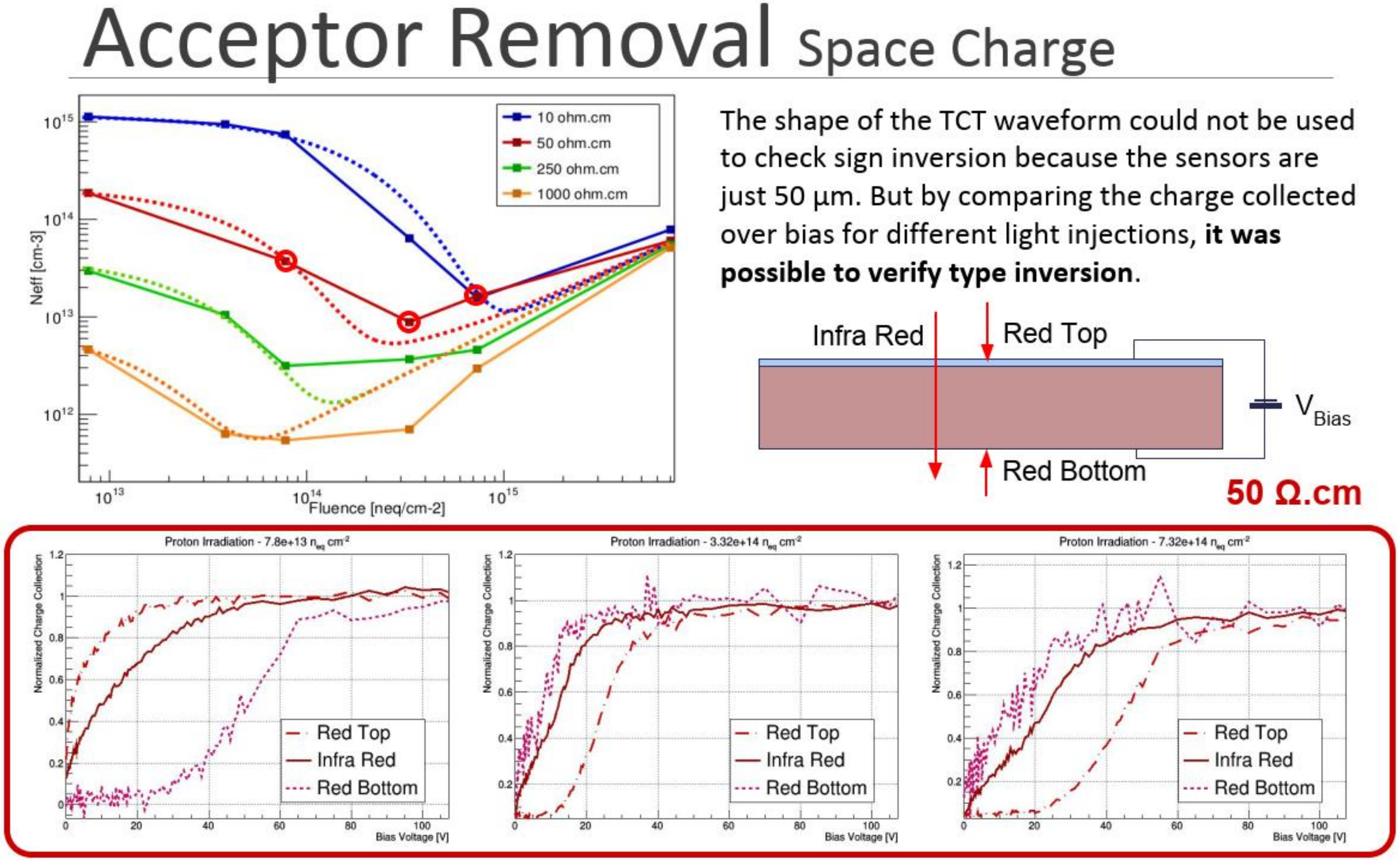


[SR and SIMS: ITME and ITE, Warsaw, Poland]

$$\rho = {}^{1}\!/_{e_0 \mu_p [B]}$$

Type inversion of epi sensors

- Observation of type inversion (negative space charge to positive space charge after 24 GeV/c proton irradiation)



Acceptor Removal Space Charge

The shape of the TCT waveform could not be used to check sign inversion because the sensors are just 50 µm. But by comparing the charge collected over bias for different light injections, **it was possible to verify type inversion**.

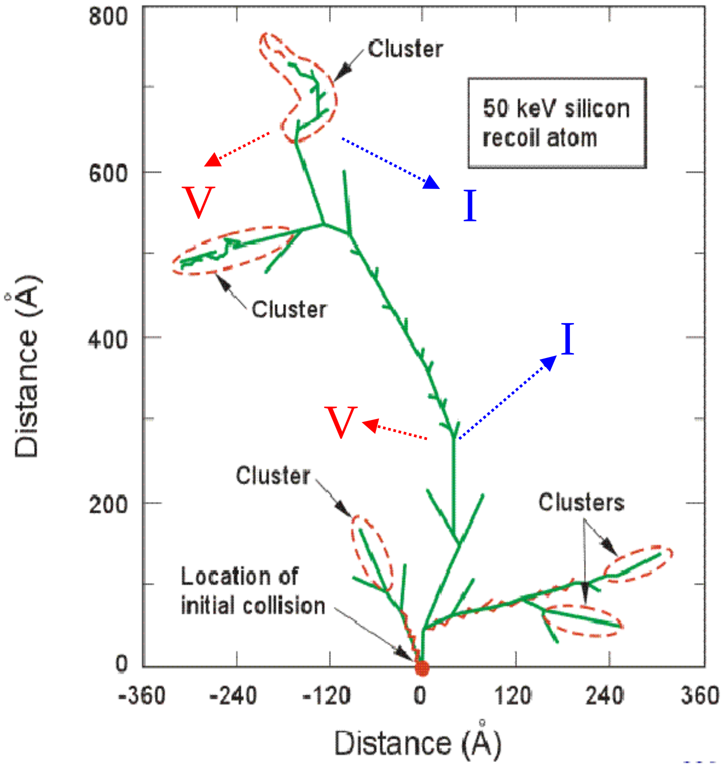
50 Ω.cm

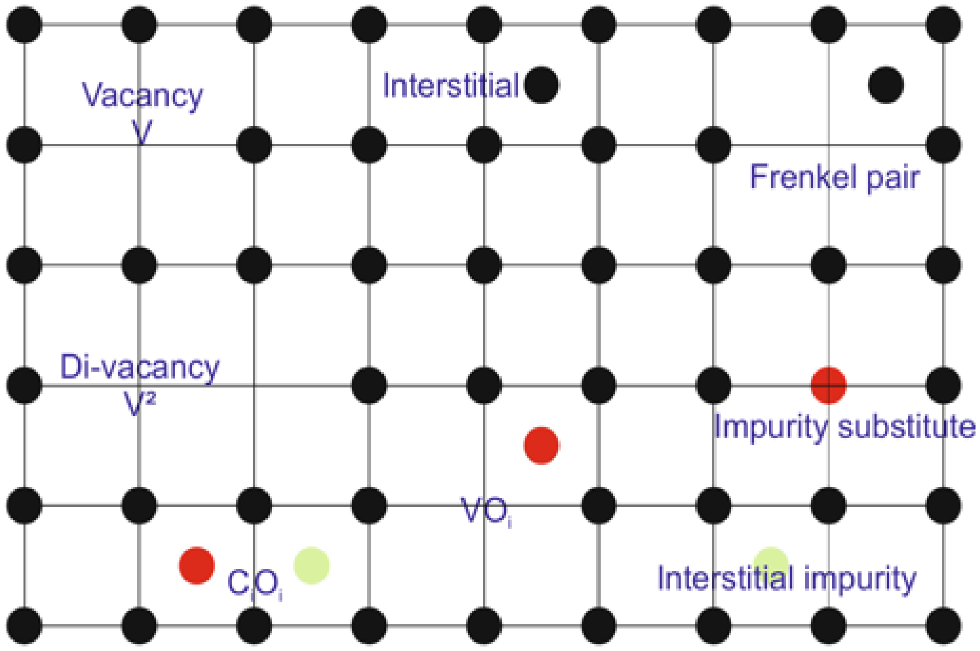
[P.Almeida et all. RD50 Workshop 6/2018, Hamburg]

Displacement Damage

- Mechanism:
  - Primary interaction generates displacements (vacancies & interstitials)
  - **V**acancies and **I**nterstitials migrate, either recombine (~90%) or migrate and form stable defects (point and cluster defects)

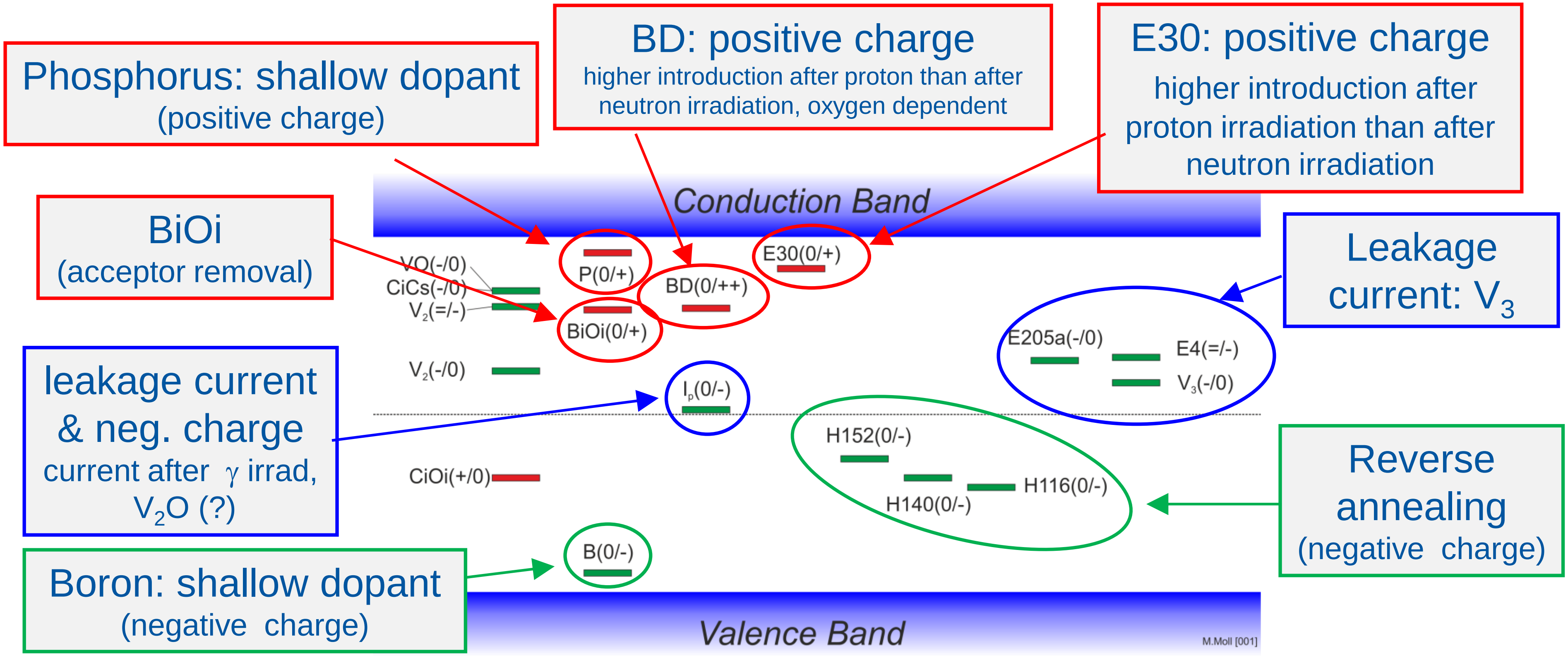
van Lint 1980





Radiation induced defects with impact on device performance

RD50 map of most relevant defects for device performance near room temperature:



Phosphorus: shallow dopant
(positive charge)

BD: positive charge
higher introduction after proton than after neutron irradiation, oxygen dependent

E30: positive charge
higher introduction after proton irradiation than after neutron irradiation

BiOi
(acceptor removal)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad, V_2O (?)

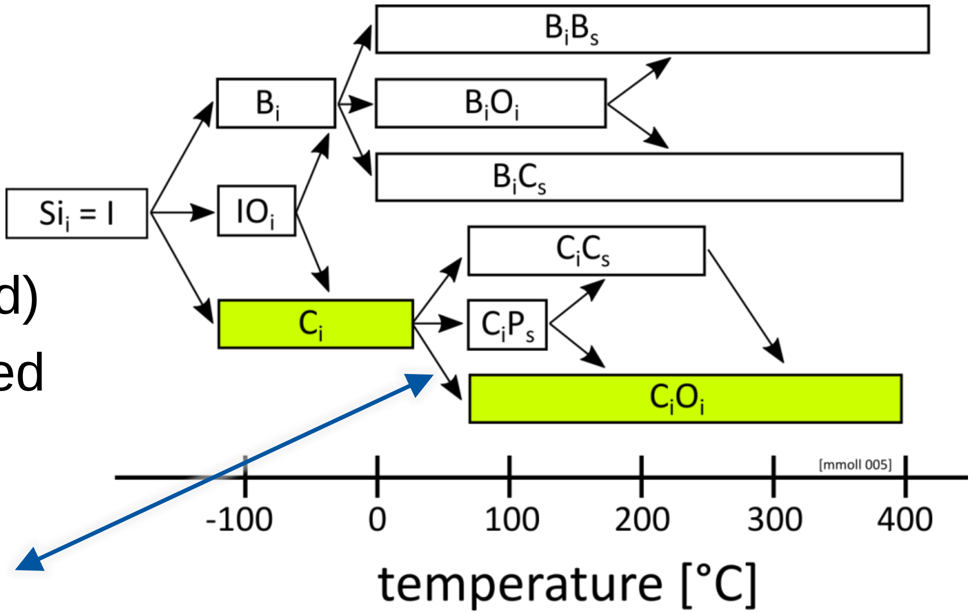
Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

- Trapping: Indications that E205a and H152K are important (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and energy, and some on material!

Determine $[O_i]$ from defect kinetics

- Assume [O] >> [B],[C]
  - valid for high ρ silicon
  - mainly B_iO_i and C_iO_i formed (other reactions can be neglected)
  - Ci, C_iO_i and B_iO_i can be measured with the DLTS or TSC technique



[More details: L.Makarenko et al., JAP 2007 101,113537]

- Study reaction $C_i + O_i \rightarrow C_iO_i$

$$\frac{d}{dt}[C_iO_i] = -\frac{d}{dt}[C_i] = 4\pi R_{CO} D_{Ci}\,[O_i][C_i]$$

⇨

$$[C_i](t) = [C_i](0)\ \exp(-{}^{t}/_{\tau_{CO}})$$

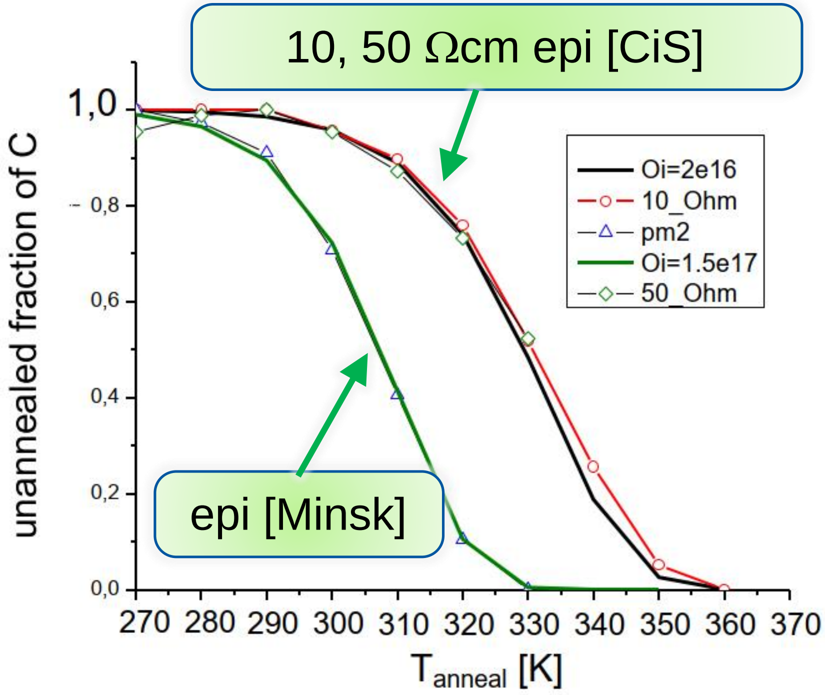
with

$${}^{1}/_{\tau_{CO}} = k_{CO}[O_i] = 4\pi R_{CO} D_{Ci}[O_i]$$

- With known parameter k_{CO} the oxygen content $[O_i]$ can be determined from the annealing kinetics of the interstitial Carbon C_i

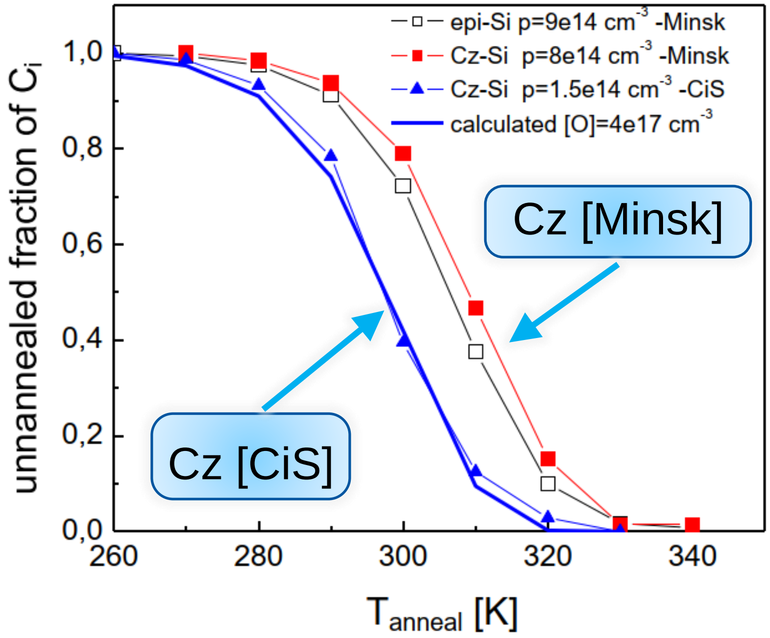
Determine $[O_i]$ from defect kinetics

- Irradiation: electrons (3.5 MeV, 5.5 MeV), alphas (5.5 MeV)
- Isochronal annealing study
  - isochronal: stepwise T increase ($\Delta T=10°C$); fixed annealing time (30 min)
  - Study of reaction $C_i + O_i \rightarrow C_iO_i$ with DLTS ; Data shown: Decrease of $[C_i]$



10, 50 Ωcm epi [CiS]

epi [Minsk]



Cz [Minsk]

Cz [CiS]

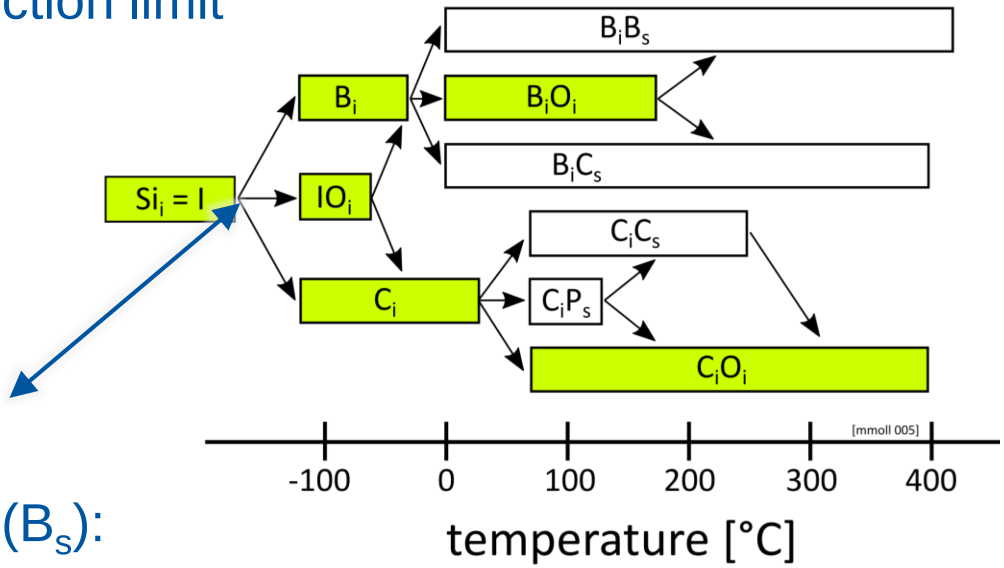
[L.Makarenko et al., GADEST 2019]

- Ci defect reaction faster in samples produced at CiS than in samples produced in Minsk
- Conclusion: [Oi] depending on foundry, i.e. processing (for identical substrate wafers)
  - Produced in Minsk: $[O_i] \approx 1.5 \times 10^{17}$ cm^{-3}
  - Produced at CiS, Erfurt: $[O_i] \approx 2 \times 10^{16}$ cm^{-3}

Note: There is a [O] profile
(average value determined)

Determine [C_s] from defect kinetics

- Carbon usually below SIMS detection limit
- Assume [O] >> [B],[C]
  - valid for high ρ silicon
  - mainly B_iO_i and C_iO_i formed (other reactions can be neglected)
  - C_iO_i and B_iO_i can be measured with the DLTS or TSC technique
- Study sharing of interstitials (Si_i) between Carbon (C_s) and Boron (B_s):



$$[1] \quad Si_i + B_s \xrightarrow{k_{IB}} B_i \quad ⇨ \quad [1]\ B_i + O_i \xrightarrow{k_{BO}} B_iO_i$$

$$[2] \quad Si_i + C_s \xrightarrow{k_{IC}} C_i \quad ⇨ \quad [2]\ C_i + O_i \xrightarrow{k_{CO}} C_iO_i$$

$$\eta_{BC} = \frac{[C_i]}{[B_i]} = \frac{k_{IC}[C_s]}{k_{IB}[B_s]} \approx \frac{[C_iO_i]}{[B_iO_i]}$$

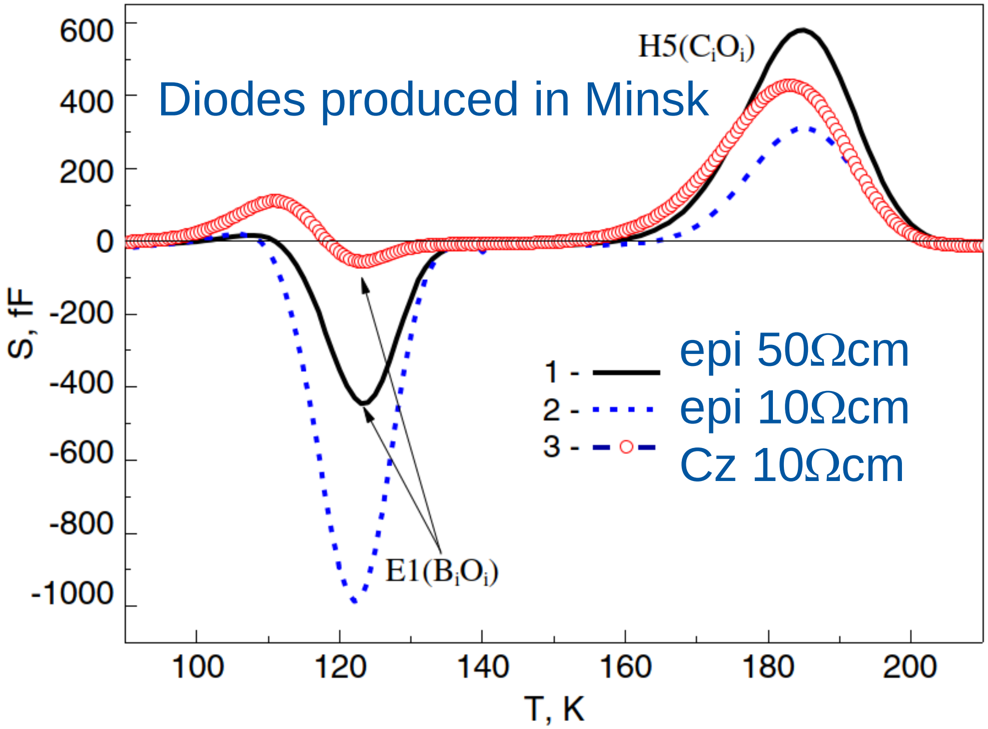
$$⇨ \quad [C_s] \approx \frac{k_{IB}}{k_{IC}} \frac{[C_iO_i]}{[B_iO_i]} [B_s]$$

- With known parameter k_{IB}/k_{IC} (≈7) the carbon content [C_s] can be determined from the ration [CiOi]/[BiOi] and the Boron concentration [B_s]

[More details: L.Makarenko et al., JAP 2007 101,113537]

Determine [C_s] from defect kinetics

- Assume $$[C_s] \approx \frac{k_{IB}}{k_{IC}} \frac{[C_iO_i]}{[B_iO_i]} [B_s]$$ (see last slide)



- MC-DLTS (minority carrier injection)
  - Peak heights give concentrations [CiOi] and [BiOi]
  - Resistivity (i.e.CV measurement) gives [Bs]
  - $k_{IB}/k_{IC} \approx 7$ from literature
- Calculated [Cs]
  - epi 50Ωcm [Cs] ≈ 1.5-2×10^{15} cm^{-3}
  - epi 10Ωcm [Cs] ≈ 1.5-2×10^{15} cm^{-3}
  - Cz 10Ωcm [Cs] ≈ 3×10^{16} cm^{-3}

[L.Makarenko et al., Phys. Status Solidi A 2019,216,1900354]

- Significantly more Carbon in our Cz samples compared to the epi samples