Silicon Containing Oxygen Dimer

A radiation hard sensor material?

Veronique Boisvert
CERN
Michael Moll

SSD Seminar September 25th

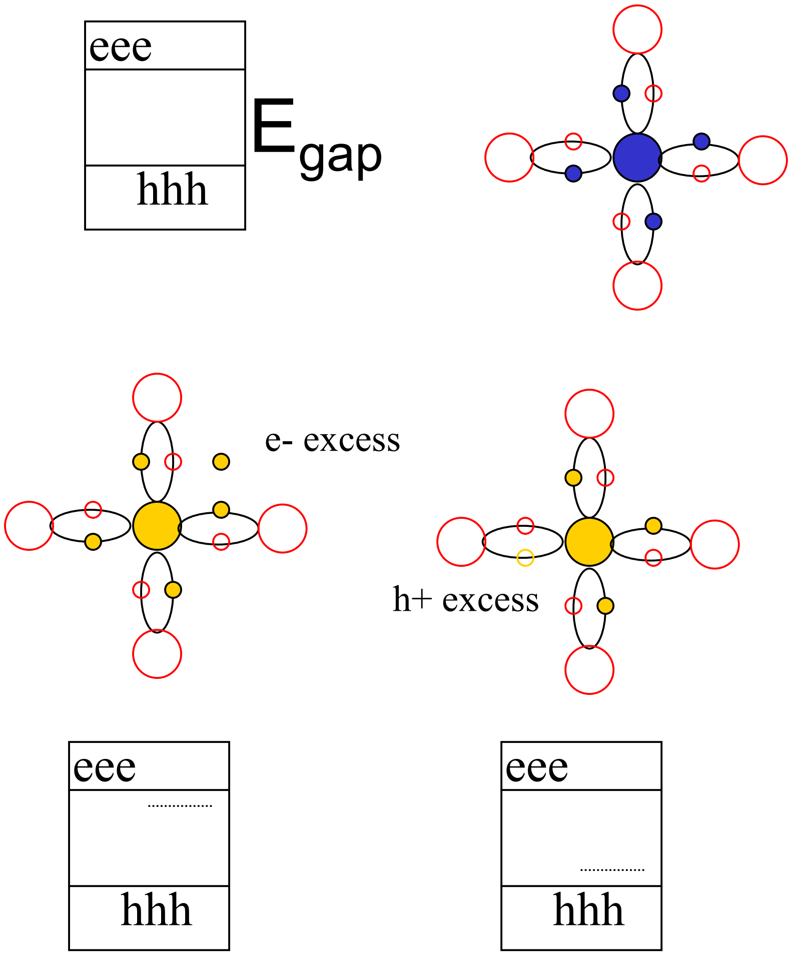
Outline

- Motivation
  - Basic Properties of Silicon detectors
  - Radiation damage
- Evidence of Oxygen dimer
  - How can they be produced?
  - How could they help?
- Proposed Experiment
  - Crude estimates
  - Simulations

Basic Properties of Si detectors

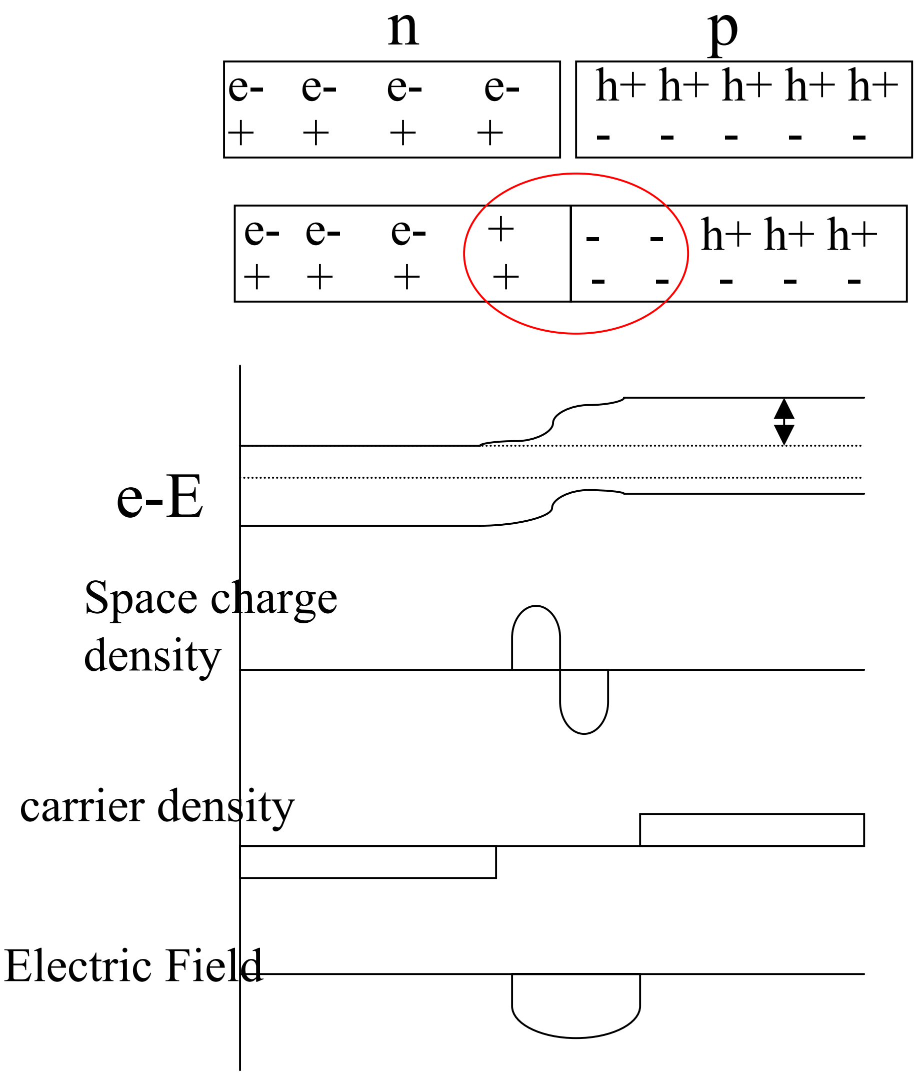
- Pure intrinsic semiconductors:
  - Si RT: E_{gap} =1.1eV
  - $[e,h] \sim 1.5 \times 10^{10} cm^{-3}$
  - →1 in 10^{12} Si atom ionized
- Doped extrinsic sc:
  - ~10^{13} dopant atoms/ cm^3

- Donor impurity:
  - Pentavalent atoms
  - Current: mostly e-, minority:h+
  - n-type (eg P)
- Acceptor impurity:
  - Trivalent atoms
  - Current: mostly h+, minority:e-
  - p-type (eg B)



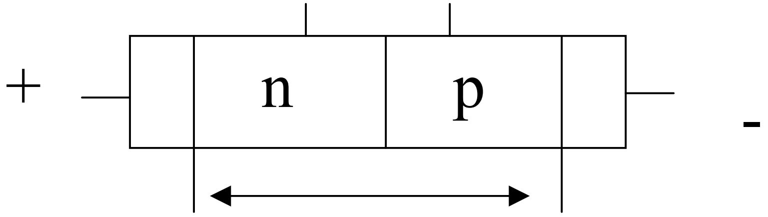
Basic Properties of Si detectors

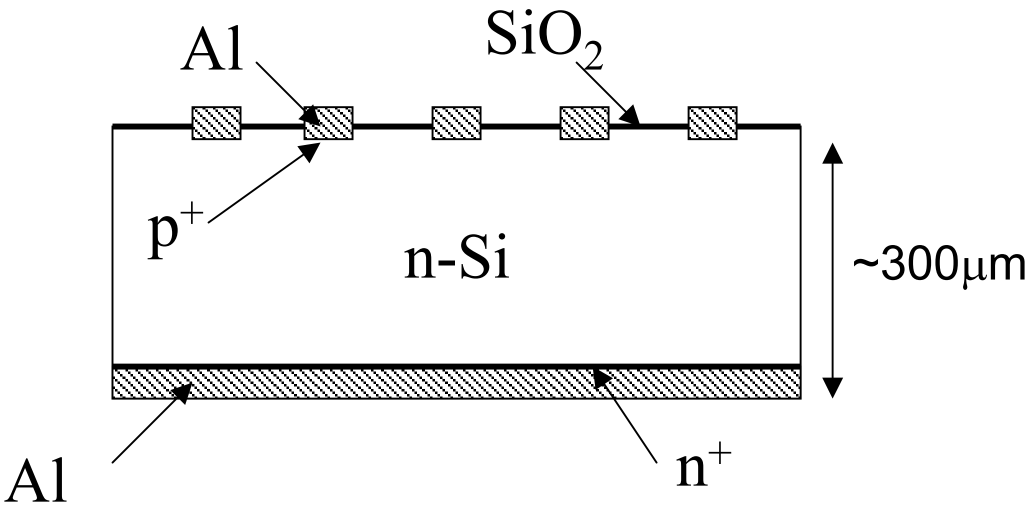
- np Junction
  - Contact is difficult
  - Depletion depth:
    - No charge carriers
    - For Si~74μm (small)
  - Main issues:
    - Intrinsic E too small for good charge collection efficiency
    - Too small depletion depth
    - Small thickness →large C →noise increase



Basic Properties of Si detectors

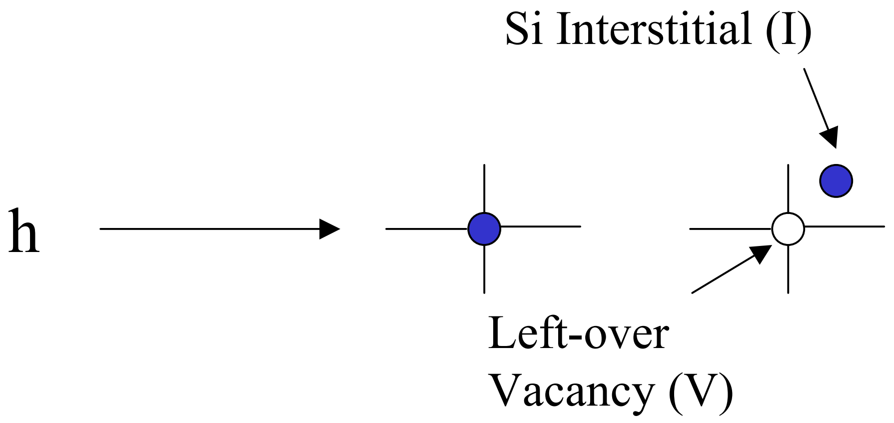
- Reversed Bias Junction
  - Apply –V on p side
    - Higher voltage → greater d
    - More efficient cc
    - High resistivity Si~5mm
      - High purity needed
- Microstrip Detectors
  - V full depletion~160V
  - Resolution ~5μm
  - ~100 e-h pairs/μm





Radiation Damage

- Damage mechanism
  - particle incident on PKA
    - If E>~25eV: Frenkel pair
    - If E>~5keV: cluster
  - Particle type dependence:
    - Neutrons:
      - If E~185eV: Frenkel
      - If E~35keV: cluster
    - Electrons:
      - If E~255keV: Frenkel
      - If E~8MeV: cluster
    - CO^{60} γ: e- from Compton sc.
      - E~1MeV → only Fr. pairs



60% annihilate

Rest: combine with each other or impurities

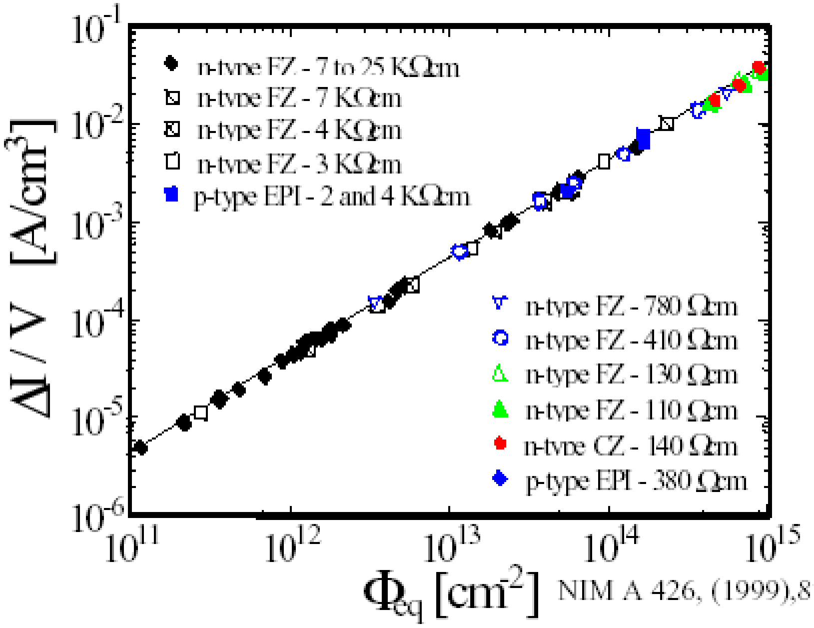
→ Macroscopic deterioration

Radiation Damage

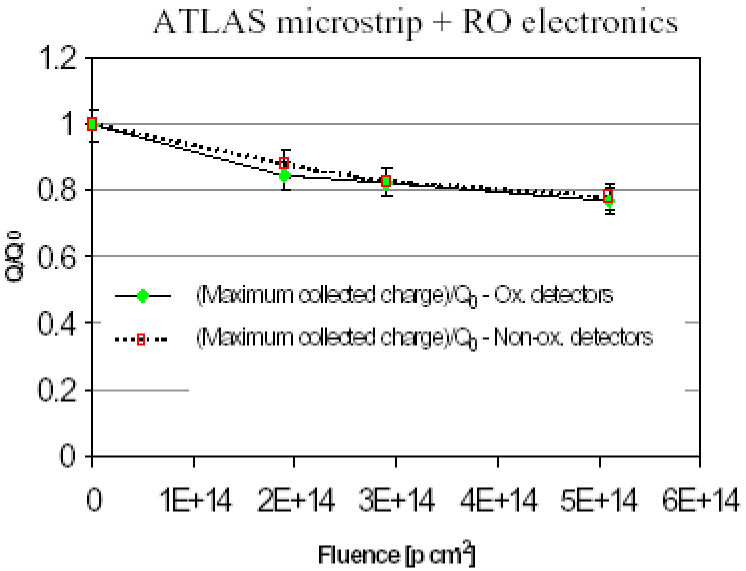
- Future of HEP:
  - LHC: design $L=10^{34}$ cm^{-2} s^{-1} $\phi(R=4cm) \sim 3x10^{15} cm^{-2}$ after 10 years
    - Then need replacement
  - LHC upgrade: $L=10^{35} cm^{-2}$ s^{-1} $\phi(R=4cm) \sim 1.5x10^{16} cm^{-2}$
    - Present detectors can not sustain this fluence
  - Linear Collider:
    - High doses of e- and γ!
- What are Macroscopic effects at those fluences?

Radiation Damage

- Increase in Leakage current
  - I/Volume = $\alpha \phi_{eq}$
  - $\alpha \sim 3\times10^{-17}$ A/cm
  - RT: I/V~30mA/cm^3 for $\phi=10^{15}$cm^{-2}
- Deterioration of the charge collection efficiency
  - Dramatic deterioration for $\phi>10^{14}$cm^{-2}



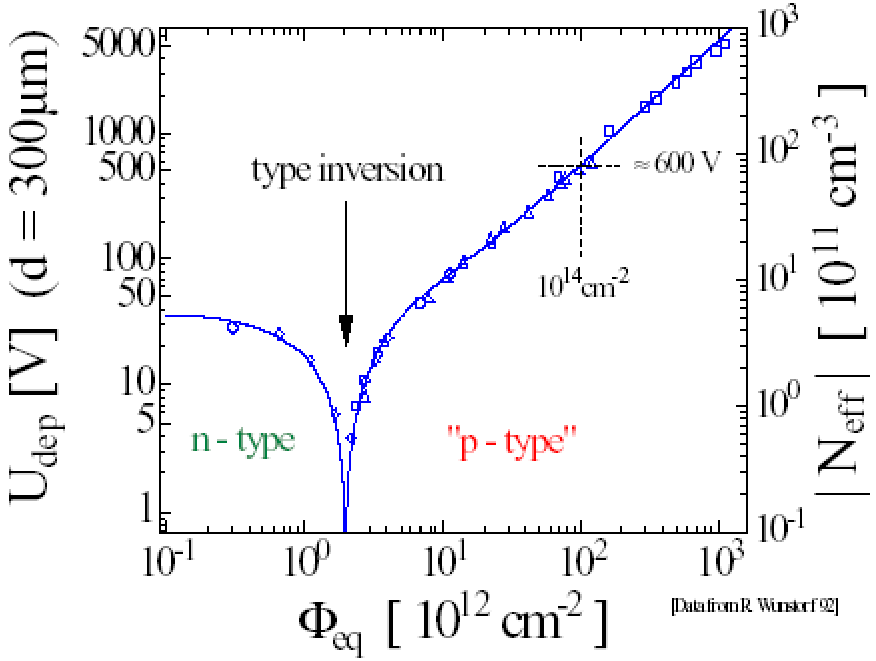
NIM A 426, (1999),87



Data: Gianluigi Casse: 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders; CERN; 28-30 November 2002

Radiation Damage

- Type Inversion, Change of the effective doping
  - n-type becomes effective p-type
  - Need to apply a greater voltage for full depletion

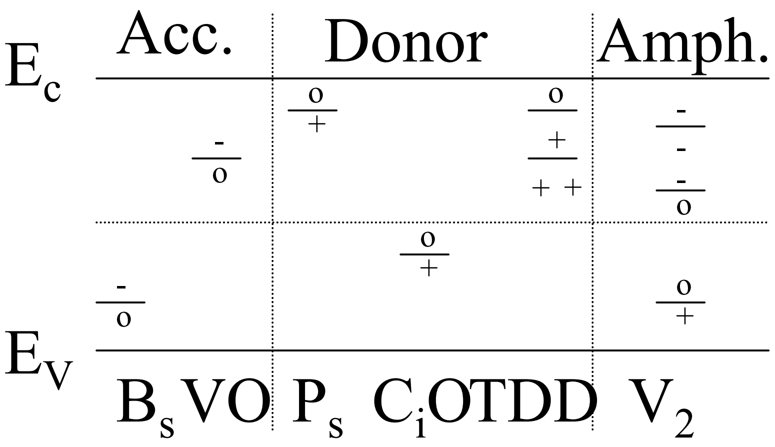


[Data from R. Wunstorf 92]

- Need Improvements in Radiation Hardness!

Radiation Damage

- Classification of Defects
    - Acceptor defect:
        - Negative when occupied by e-
    - Donor defect:
        - Neutral when occupied by e-
    - 1defect can have more than 1 level
    - Amphoteric defect:
        - Acceptor and donor levels
    - Actual charge state depends on Fermi level



→Typically:

VO, C_iO: neutral

B_s, P_s: -,+ space charge

Radiation Damage

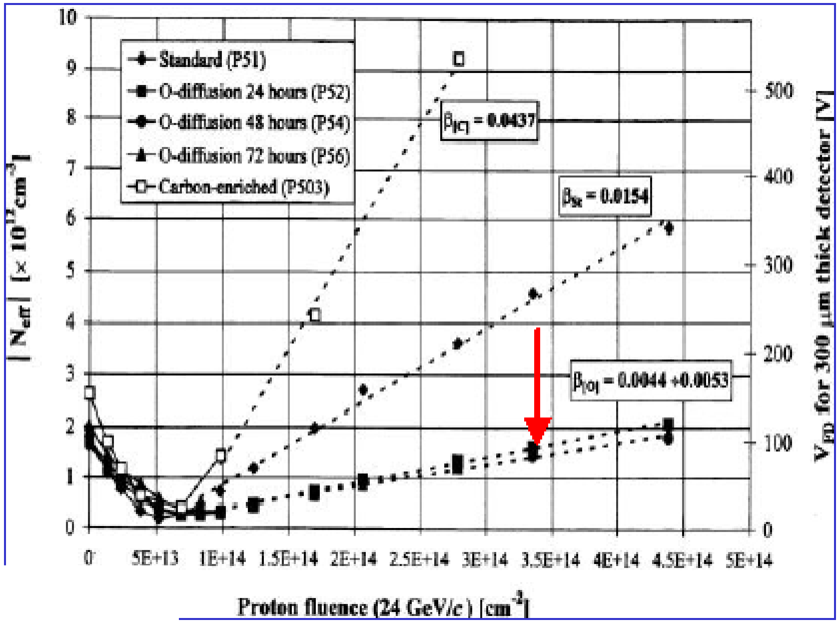
- Impact of defects on detector properties
  - Leakage Current:
    - Defects close to middle of band-gap: generation centers
  - Deterioration of charge collection efficiency:
    - Trapping: deep defects trap drifting e-h
      - If time for reemission > ro time → loss of efficiency
      - Trapping probability $\propto$:
        - Capture coeff. Of defects
        - Concentration of defects
        - Fraction of defects not occupied with e,h

Radiation Damage

- Impact of defects on detector properties
  - Type inversion, change of Vdep:
    - Initially: n, shallow donor, turns into p: many defects that act like acceptors
    - Vdep a |Neff|: effective doping concentration
      - Mobile defects that react with dopants → changes Neff
- Conclusion:
  - Since defects react with impurities → need high purity in Si bulk
  - OR: Defect Engineering!

Radiation Damage

- Example of Defect Engineering: DOFZ material
  - V_2 is likely charged
  - VO is likely neutral
  - V_2O is acceptor close to mid gap
  - → hypothesis: more O leads to more VO than V_2 and V_2O ?
- Atlas and CMS pixels are using DOFZ Si!



Evidence for Oxygen Dimers

- Another Defect Engineering possibility:
  - Oxygen Dimers: O_2
- How could they help?
  - V_2O_2 and VO_2 : neutral
  - Vs V_2, VO, V_2O: could be charged
- How to create them?
  - $V+O \rightarrow VO$
  - $VO+O \rightarrow VO_2$, $V+VO_2 \rightarrow V_2O_2$
  - $I+VO_2 \rightarrow O_2$, $V+O_2 \rightarrow VO_2$

Evidence for Oxygen Dimers

- Lindstrom et.al.:
  - Irradiation using fast electrons (E=2.5MeV)
  - Samples:
    - n-Cz Si (P), 50Ωcm
    - Carbon-lean
    - High [O]~10^{18}cm^{-3}
  - $[O_2]$=
    - Before: ~$1\text{x}10^{15}$cm^{-3}
    - After: ~$5\text{x}10^{16}$cm^{-3}>>[VO]
- E vs Co^{60} or Cs^{137}:
  - Uniform I-V
  - V_2=V/50

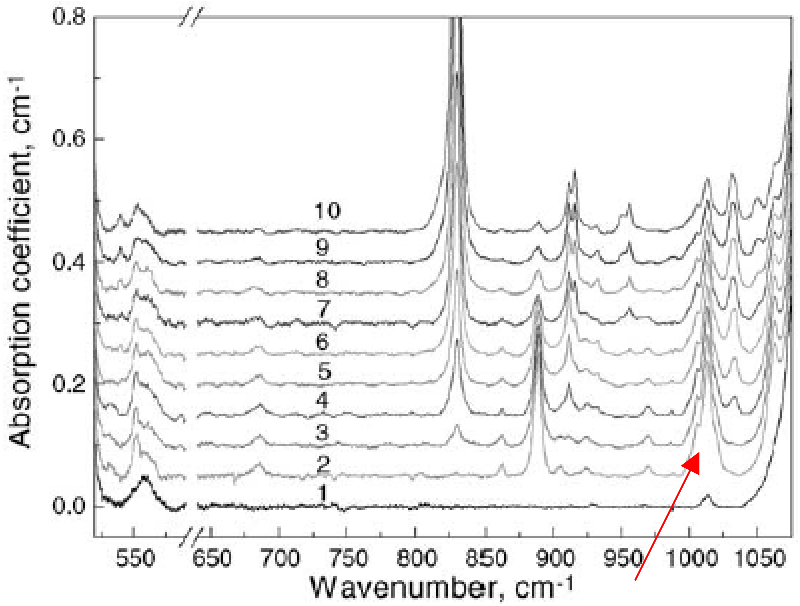


Fig. 1. Room temperature absorption spectra for C-lean n-Cz–Si ($\rho = 50\,\Omega\,$cm): (1) as-grown; (2) after electron irradiation at 350°C, $F = 8 \times 10^{17}$ cm^{-2}; (3–10) after RT irradiation. F(cm^{-2}): (3) 1×10^{16}, (4) 5×10^{16}, (5) 10^{17}, (6) 2×10^{17}, (7) 4×10^{17}, (8) 7×10^{17}, (9) 1.1×10^{18}, (10) 6×10^{18}.

Proposed Experiment

- 1) Dimering Process:
  - Different samples: Cz, (DO)FZ
  - Use p+ as irradiation
    - But 2.5MeV 350C, F=8x10^{17}e/cm^2 correspondence?
    - know 8.6x10^{13} 1 MeV e/cm^2 dose → 6x10^{12} A-centers (Brotherton)
    - If 8x10^{17}e/cm2 →5.6x10^{16} A-centers
    - Know with protons 1 unit fluence → 0.5 unit A-center
    - So need fluence of 1.12x10^{17} cm^{-2} →400 days! (1day = 2.8x10^{14}cm^{-2})
    - Wrong assumption: Temperature dependence

Proposed Experiment

- Simulations:
  - 1st step: RT reactions:

I	V	C_i
$I+C_s \rightarrow C_i$	$V+V_2 \rightarrow V_3$	$C_i+C_s \rightarrow CC$
$I+CC \rightarrow CCI$	$V+O \rightarrow VO$	$C_i+O \rightarrow CO$
$I+CCI \rightarrow CCII$	$V+VO \rightarrow V_2O$	
$I+CO \rightarrow COI$		
$I+COI \rightarrow COII$		
$I+V_2 \rightarrow V$		
$I+VO \rightarrow O$		

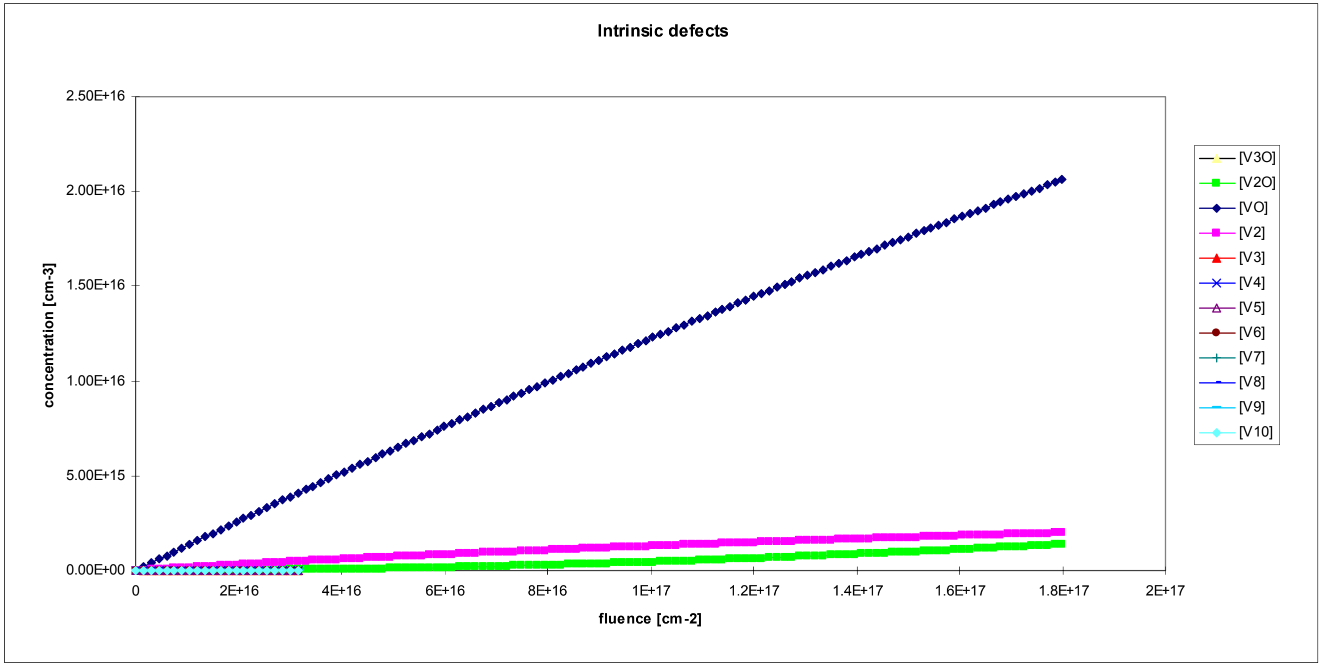
$$P(V,O)=\frac{R(V,O)[O]}{R(V,V_2)[V_2]+R(V,O)[O]+R(V,VO)[VO]}$$

Proposed Experiment

- Assumptions:
  - Damage process occur in increments:
    - 5×10^{11} cm^{-3} V produced << [O]
  - At each increment $[D]=\eta_V f_i P$
  - V_2 is primary defect not secondary
  - All used every increment: V, I, V_2, C_i
  - V gets updated: $V_i=\eta_V f_i+V_{i-1}$
  - O and C get updated
  - C_i mobile right away

Proposed Experiment

- Needed ingredients:
  - Introduction rates: I,V,V_2
  - All the trapping radius ratios
- End result: Concentration of defects for a given fluence
  - It works!



Proposed Experiment

- 2nd step: Simulation at 350C
  - VO is moving! Additional reactions:

I	V	Ci	VO, VO2
I+VO2 →O2	V+VO2 →V2O2	Ci+VO2 →CsO2	VO+O →VO2
I+O →IO	V+O2 →VO2		VO2+O →VO3
I+IO →I2O	V+IO2 →O2		
I+O2 →IO2			
I+IO2 →I2O2			

Proposed Experiment

- 2) IR measurement of pre-irradiated sample
  - See which samples contain dimers!
- 3) get diodes, characterize them (resistivity, [],…), apply same dimering process
- 4)After dimering process make measurements:
  - CV/IV, DLTS, etc…
- 5)Proton irradiation
  - LHC+ fluence
  - Monitor depletion Voltage vs fluence
  - Various annealing procedures
  - DLTS, CV/IV, etc.

Proposed Experiment

- Needed facilities:
  - p+ irradiation: CERN PS
  - γ irradiation: GIF
  - CV/IV: CERN
  - DLTS: possibly ISOLDE
  - IR: Lindstrom…

Conclusion

- Defect Engineering has a lot of potential in increasing the radiation hardness of Si sensors.
- A lot need to be understood:
    - Microscopic characterization
    - Standardization
- Oxygen Dimers carry a lot of potential
    - Might improve radiation hardness
    - Might shed light on microscopic processes