4th Trento Workshop on Advanced Detectors, 17 February 2009

RD50 studies on radiation induced microscopic disorder

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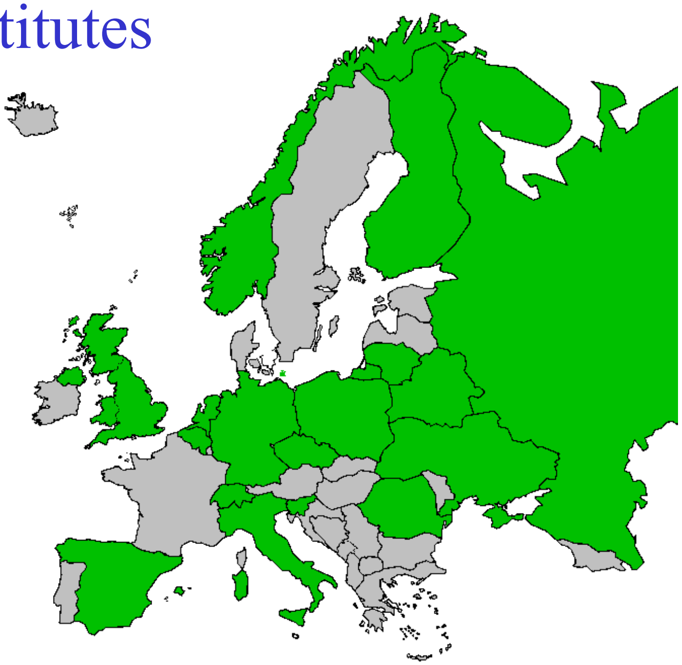
on behalf of RD50

http://www.cern.ch/rd50

RD50 Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

250 Members from 48 Institutes



41 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Glasgow, Lancaster, Liverpool)

8 North-American institutes

Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50

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Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN ECP

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

WODEAN project (G. Lindstroem)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

Pad Detector Characterization
G. Kramberger
(Ljubljana)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irrad.
- Standardisation of macroscopic measurements (A.Chilingarov)

New Structures
R. Bates
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions
- 3D (M. Boscardin)
- Semi 3D (Z.Li)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors
- Comparison of detectors different producers (Eremin)
- pixel group (D. Bortoletto,T. Rohe)

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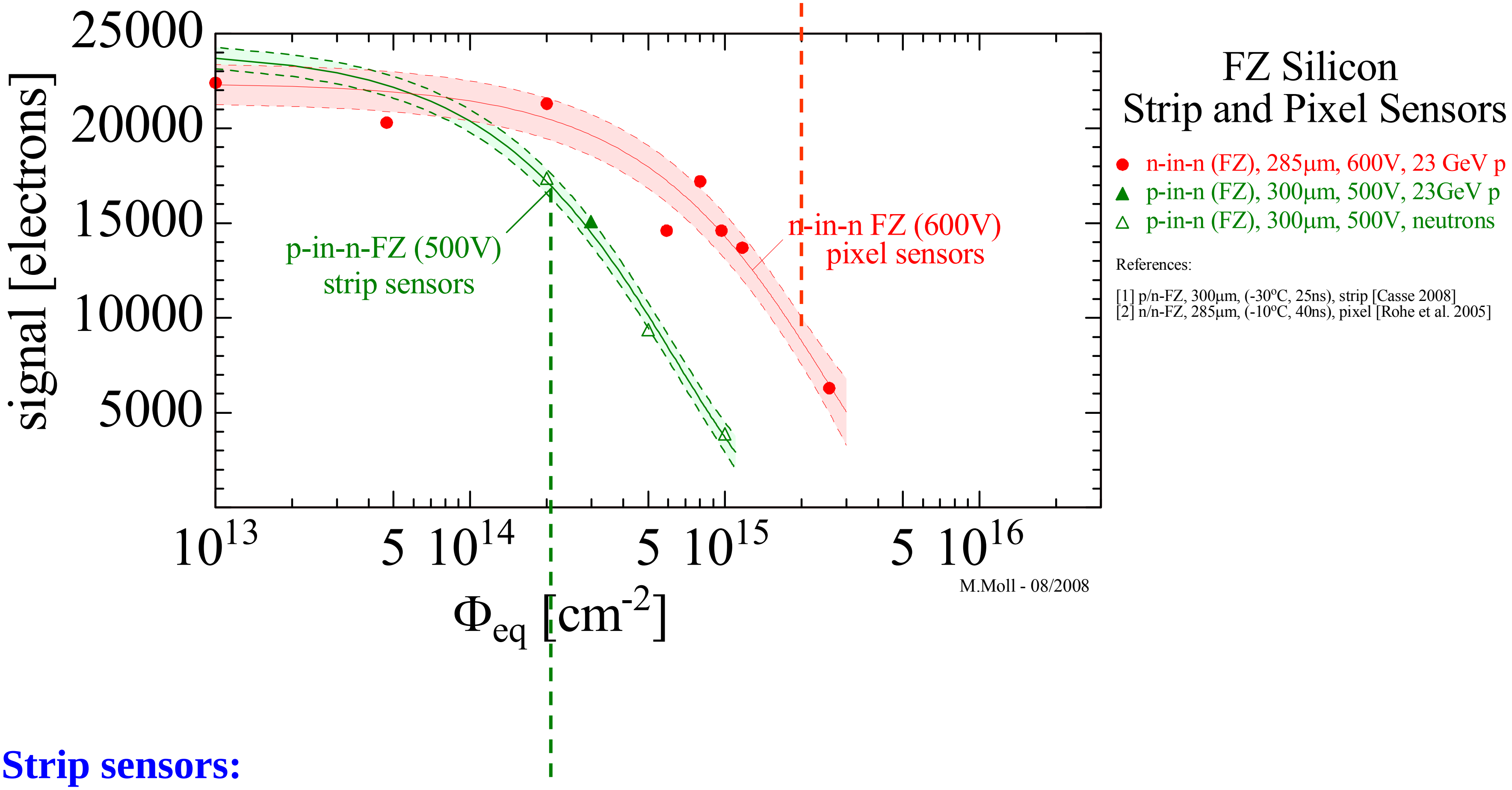
Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC



Strip sensors:

max. cumulated fluence for LHC

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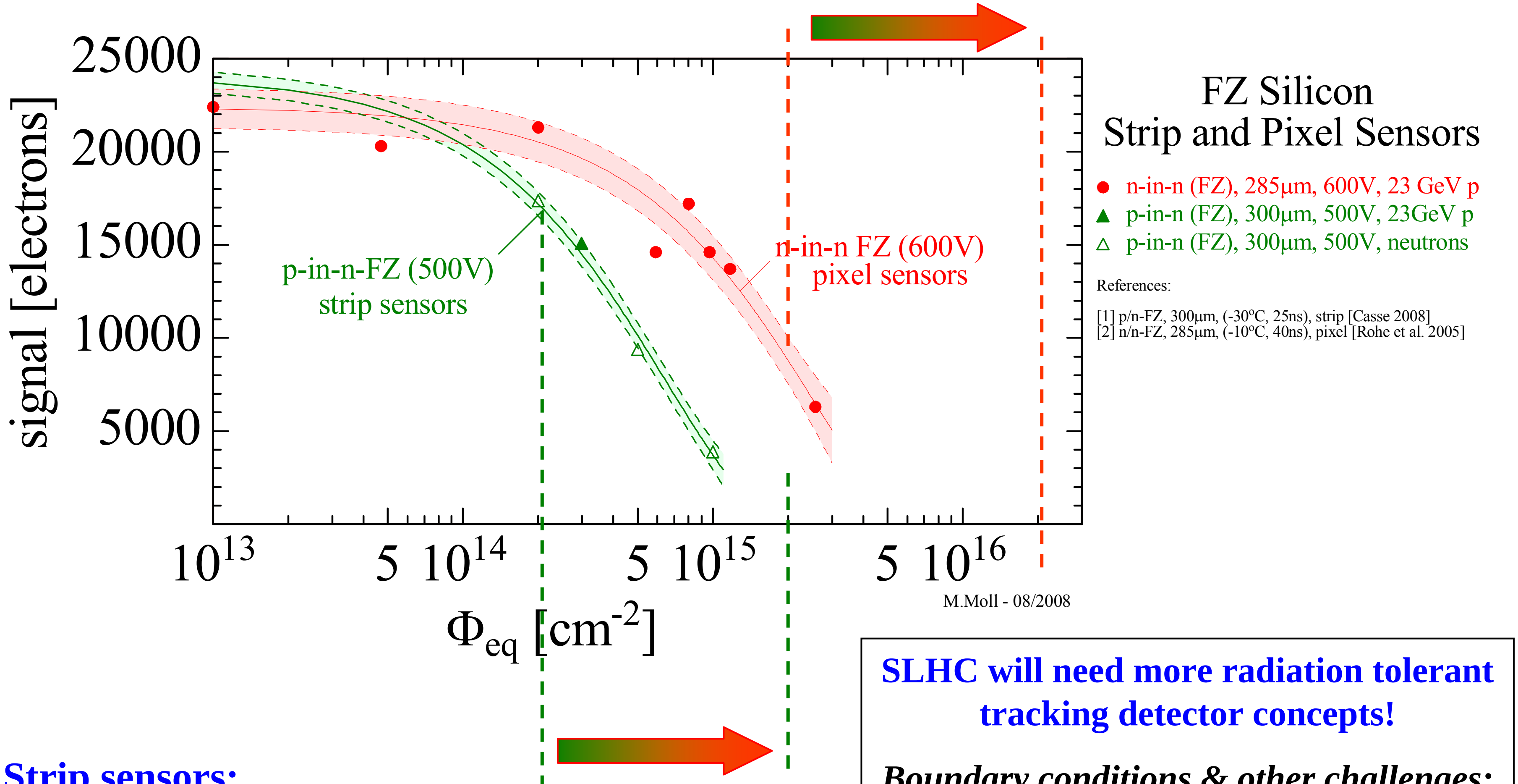
Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC and SLHC



Strip sensors:

max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges:

Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost !

RD50 **Reminder**: Radiation Damage in Silicon Sensors

- **Two general types of radiation damage to the detector materials:**

  - **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –

    I. **Change of effective doping concentration (higher depletion voltage, under- depletion)**

    II. **Increase of leakage current (increase of shot noise, thermal runaway)**

    III. **Increase of charge carrier trapping (loss of charge)**

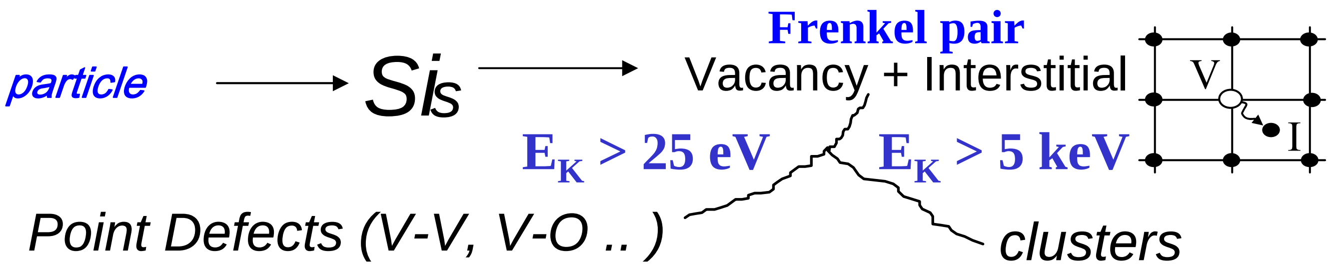
  - **Surface damage due to Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …

- **Impact on detector performance and Charge Collection Efficiency**
  (depending on detector type and geometry and readout electronics!)

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

Radiation - Induced Defects



particle → Si_s →

Frenkel pair

Vacancy + Interstitial

E_K > 25 eV

E_K > 5 keV

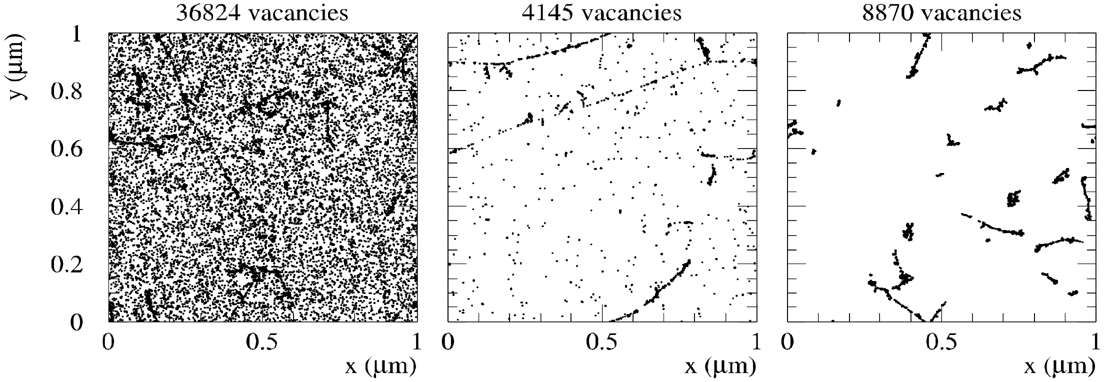
Point Defects (V-V, V-O ..)

clusters

Earlier simulation works: [Mika Huhtinen NIMA 491(2002) 194]

10 MeV protons 24 GeV/c protons 1 MeV neutrons

Initial distribution of vacancies after 10^{14} particles/cm^2

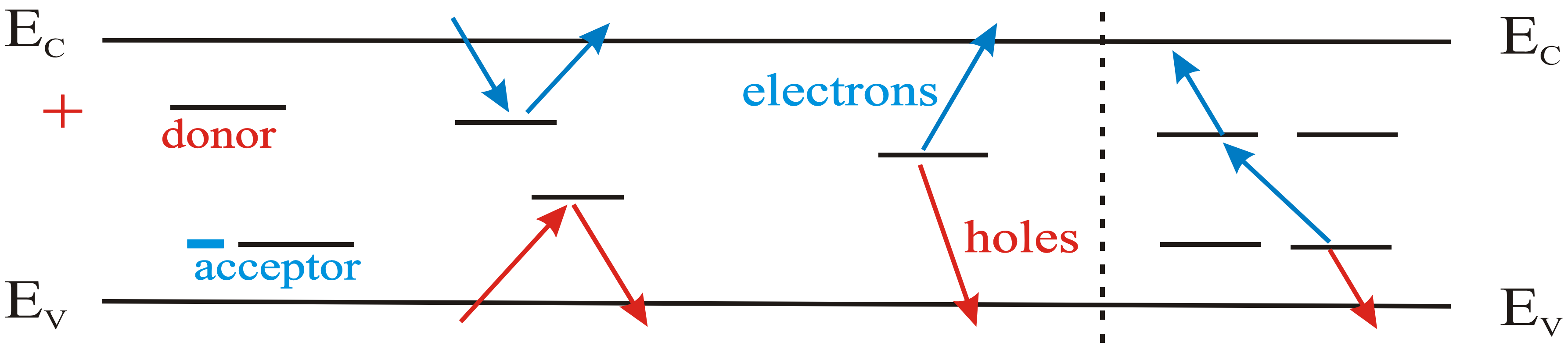


More point defects **Mainly clusters**

RD50 Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)

Inter-center charge
transfer model
(inside clusters only)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

enhanced generation
⇒ leakage current
⇒ space charge

Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

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RD50 approaches to develop radiation harder tracking detectors

- **Material Engineering -- Defect Engineering of Silicon**
  - ➡ **Understanding radiation damage**
    - **Macroscopic effects and Microscopic defects**
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - ➡ **Oxygen rich Silicon**
    - **DOFZ, Cz, MCZ, EPI**
  - Oxygen dimer & hydrogen enriched Silicon
  - Influence of processing technology

- **Material Engineering-New Materials** (work concluded)
  - Silicon Carbide (SiC), Gallium Nitride (GaN)

- **Device Engineering (New Detector Designs)**
  - ➡ **p-type silicon detectors (n-in-p)**
  - ➡ **thin detectors**
  - ➡ **3D detectors**
  - Simulation of highly irradiated detectors
  - Semi 3D detectors and Stripixels
  - Cost effective detectors

- Development of test equipment and measurement recommendations

Available Irradiation Sources in RD50

- ☐ **24 GeV/c protons, PS-CERN**
- ☐ **10-50 MeV protons, Jyvaskyla +Helsinki**
- ☐ **Fast neutrons, Louvain**
- ☐ **26 MeV protons, Karlsruhe**
- ☐ **TRIGA reactor neutrons, Ljubljana**

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Silicon Materials under Investigation

standard for particle detectors

used for LHC Pixel detectors

“new” silicon material

Material	Thickness [μm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	**50,100,150, 300**	**FZ**	**$1–30\times10^3$**	**$< 5\times10^{16}$**
Diffusion oxygenated FZ (n- and p-type)	**300**	**DOFZ**	**$1–7\times10^3$**	**$\sim 1–2\times10^{17}$**
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	**100, 300**	**MCz**	**$\sim 1\times10^3$**	**$\sim 5\times10^{17}$**
Czochralski Si, Sumitomo, Japan (n-type)	**300**	**Cz**	**$\sim 1\times10^3$**	**$\sim 8\text{-}9\times10^{17}$**
Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)	**25, 50, 75, 100,150**	**EPI**	**50 – 100**	**$< 1\times10^{17}$**
Diffusion oxyg. Epitaxial layers on CZ	**75**	**EPI–DO**	**50 – 100**	**$\sim 7\times10^{17}$**

- **DOFZ silicon** - **Enriched with oxygen on wafer level, <u>inhomogeneous</u> distribution of oxygen**
- **CZ/MCZ silicon** - **high Oi (oxygen) and O_{2i} (oxygen dimer) concentration (<u>homogeneous</u>)**
  - **formation of shallow Thermal Donors possible**
- **Epi silicon** - **high O_i , O_{2i} content due to out-diffusion from the CZ substrate (inhomogeneous)**
  - **thin layers: high doping possible (low starting resistivity)**
- **Epi-Do silicon** - **as EPI, however additional O_i diffused reaching <u>homogeneous</u> O_i content**

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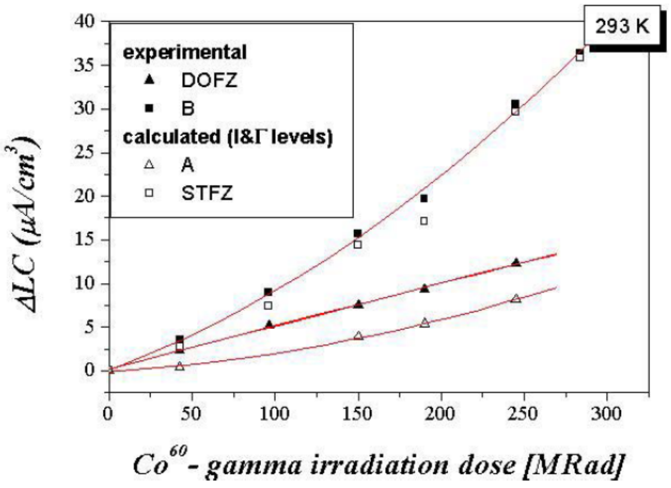
Earlier Works: γ Co^{60} irradiation

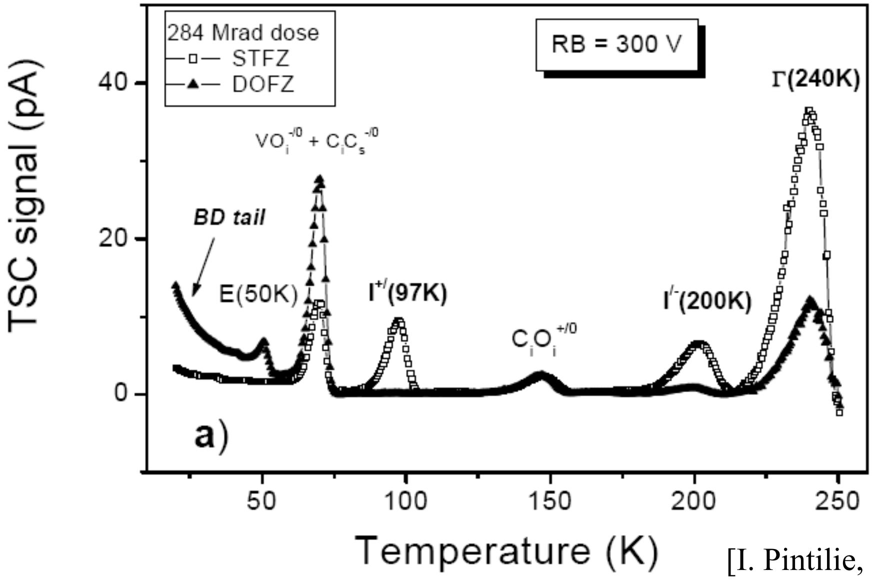
2003: To investigate only point defects; Main focus on differences between standard and oxygen enriched material and impact o the observed defect generation on pad detector properties.

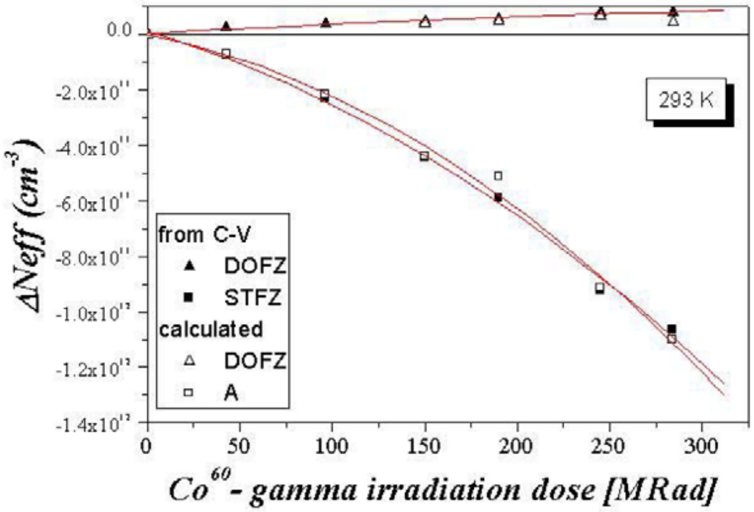
Beneficial oxygen effect consists in:

(a) suppressing deep acceptors responsible for the type inversion effect in oxygen lean material. So called I and Γ close to midgap acceptor like levels and are generated in higher concentrations in STFZ silicon than in DOFZ;

(a) shallow donors (BD) creation as well;





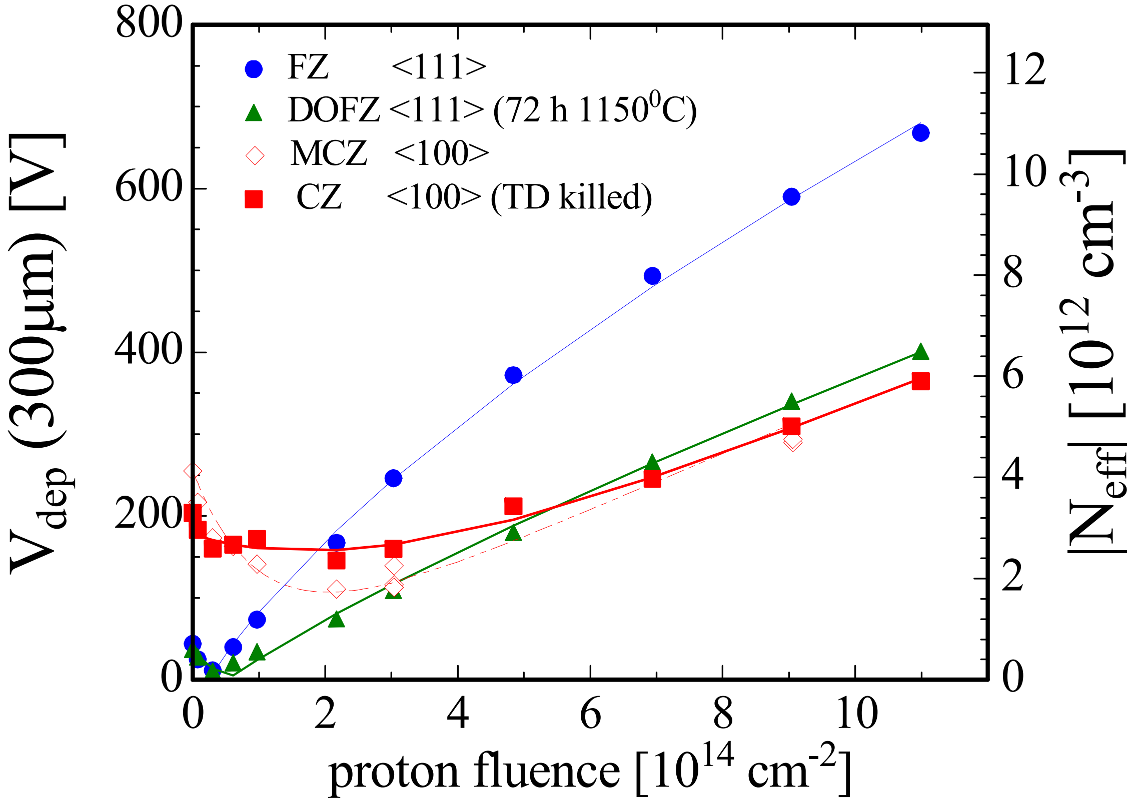


[I. Pintilie, APL, 82, 2169, March 2003]

RD50 Proton irradiation: FZ, DOFZ, Cz and MCz Silicon

- **Strong differences in V_{dep}**
  - **Standard FZ silicon**
  - **Oxygenated FZ (DOFZ)**
  - **CZ silicon and MCZ silicon**
- **Strong differences in internal electric field shape**
  (type inversion, double junction,…)
- **Different impact on pad and strip detector operation!**

24 GeV/c proton irradiation (n-type silicon)



- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

RD50 Earlier Studies - proton irradiated silicon detectors I

2004: Levels responsible for depletion voltage after 23 GeV proton irradiation:

Almost independent of oxygen content:

- **Donor removal**
- **“Cluster damage”** ⇒ **negative charge**

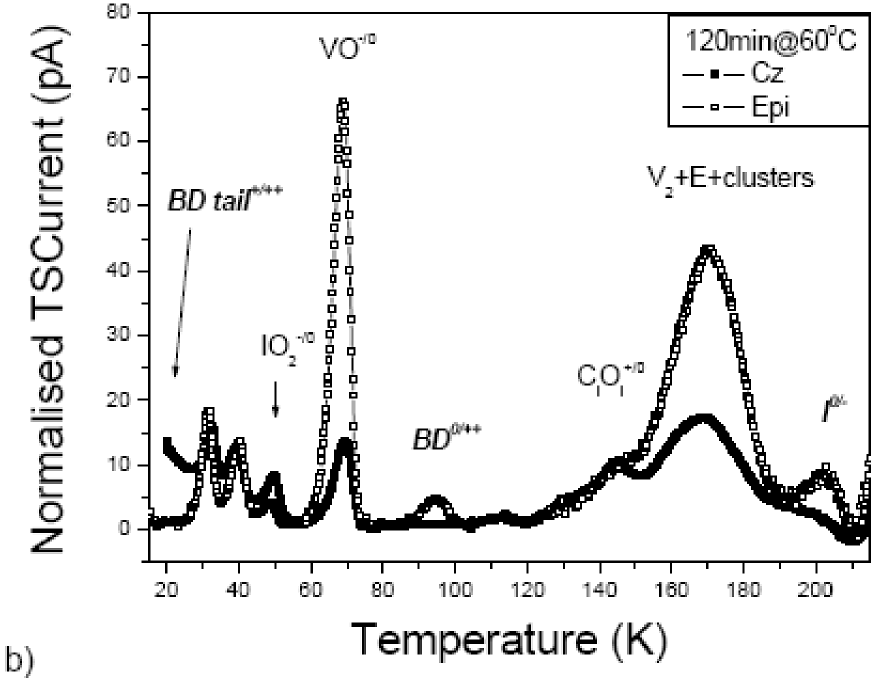
Influenced by initial oxygen content:

- deep acceptor level at E_C-0.54eV
  (good candidate for the V_2O defect)
  ⇒ **negative charge**

Influenced by initial oxygen dimer content (?):

- **BD-defect:** bistable shallow thermal donor
  (formed via oxygen dimers O_{2i})
  ⇒ **positive charge**

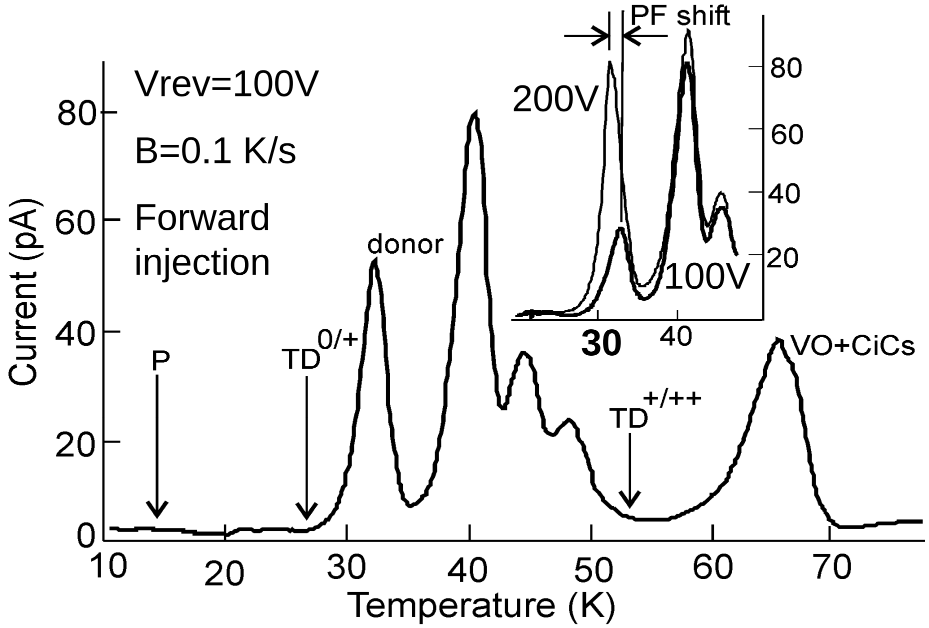
[I.Pintilie, RESMDD, Oct.2004]

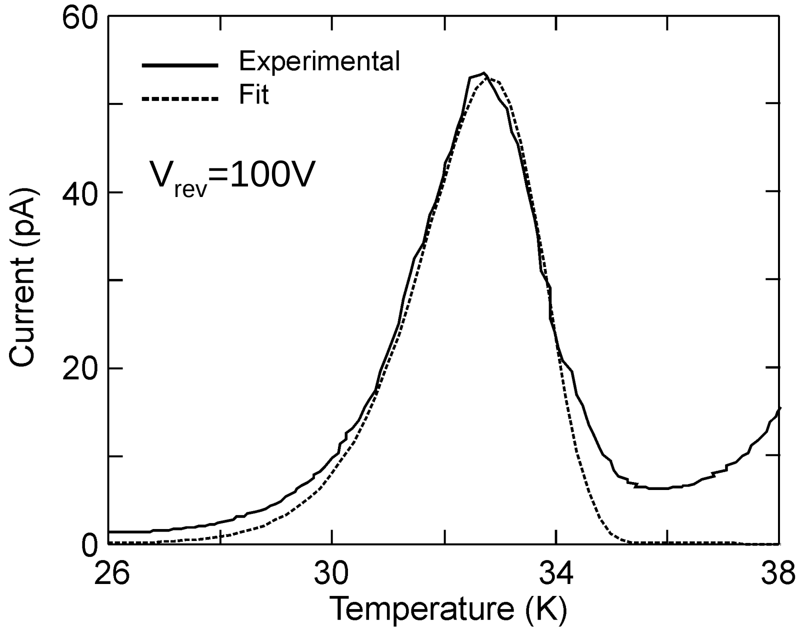


TSC after irradiation with 23 GeV protons with an equivalent fluence of 1.84×10^{14} cm^{-2} recorded on Cz and Epi material after an annealing treatment at 600C for 120 min.

RD50 Earlier Studies - proton irradiated silicon detectors II

1) No TDs.
2) Shallow Donor close to 30 K peak (PF shift evidences its donor-like nature)



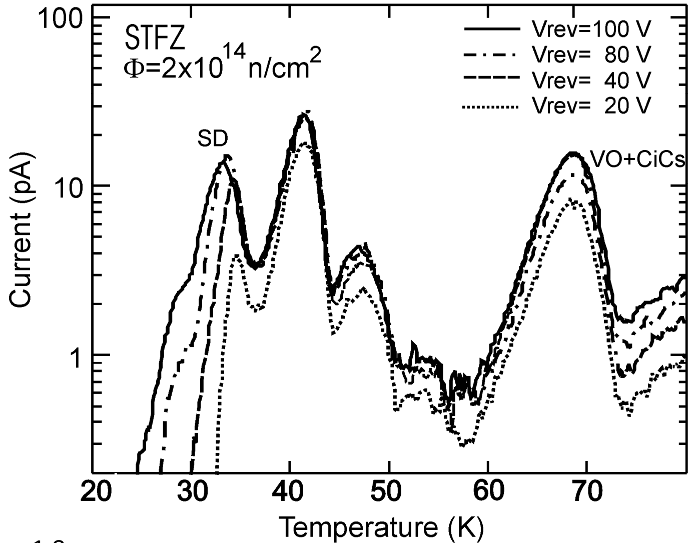


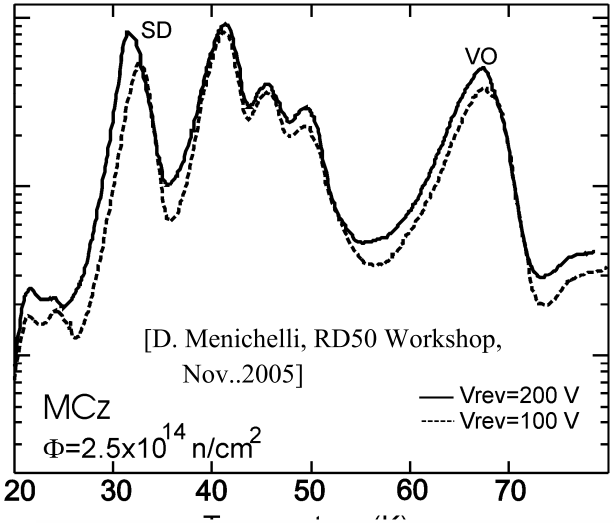
M. Bruzzi et al., NIM A 552 (2005) pp. 20-26.
N-type MCz Si – SMART
24GeV/c p up to 4x10^{14}p/cm^{2}
Annealing: 1260min at 60°C

M. Scaringella et al.
NIM A 570 (2007) 322–329

RD50 Earlier Studies - proton irradiated silicon detectors III

- 2005: Shallow donor generated by proton irradiation in MCz and Epitaxial silicon



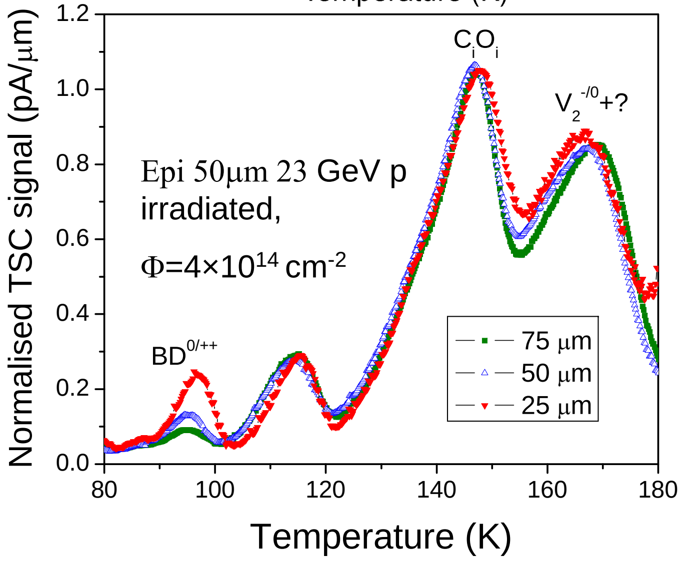


[D. Menichelli, RD50 Workshop, Nov..2005]

MCz n-type 26 MeV p irradiated, $\Phi=4\times10^{14}$ cm^{-2}

$[SD]_{MCz}/[SD]_{FZ} > 5$

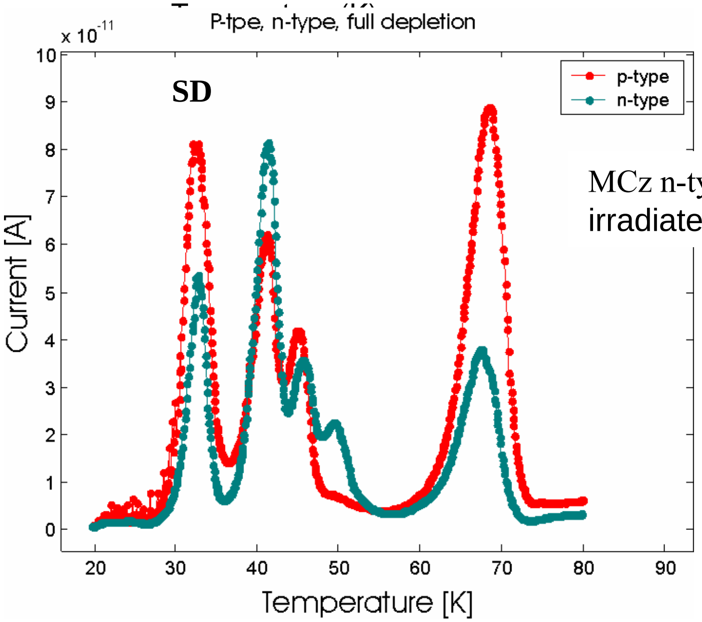
M. Scaringella et al.
NIM A 570 (2007) 322–329



Epi 50µm 23 GeV p irradiated,

$\Phi=4\times10^{14}$ cm^{-2}

[G. Lindstroem, RD50 Workshop, Nov..2005]



MCz n-type and p-type 24 GeV p irradiated, $\Phi=4\times10^{14}$ cm^{-2}

[M. Bruzzi, Trento Workshop, Feb. 2005]

The WODEAN Project

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G.Lindstroem, Hamburg)
  - **Aim: Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}**
  - **Method: Defect Analysis on identical samples performed with the various tools available inside the RD50 network:**
    - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
    - **I-DLTS** (Current Deep Level Transient Spectroscopy)
    - **TSC** (Thermally Stimulated Currents)
    - **PITS** (Photo Induced Transient Spectroscopy)
    - **FTIR** (Fourier Transform Infrared Spectroscopy)
    - **RL** (Recombination Lifetime Measurements)
    - **PC** (Photo Conductivity Measurements)
    - **EPR** (Electron Paramagnetic Resonance)
    - **TCT** (Transient Charge Technique)
    - **CV/IV**
  - **~ 240 samples irradiated with protons and neutrons**
  - **first results presented on 2007 RD50 Workshops, further analyses in 2008 and publication of most important results in in Applied Physics Letters**

11 Institutes/Institutions Involved

CERN
Bucharest NIMP
Florence University
Hamburg University
Ljubljana JSI
London King's College
Minsk University
Minsk NAS
Oslo University
Warsaw ITME
Vilnius University

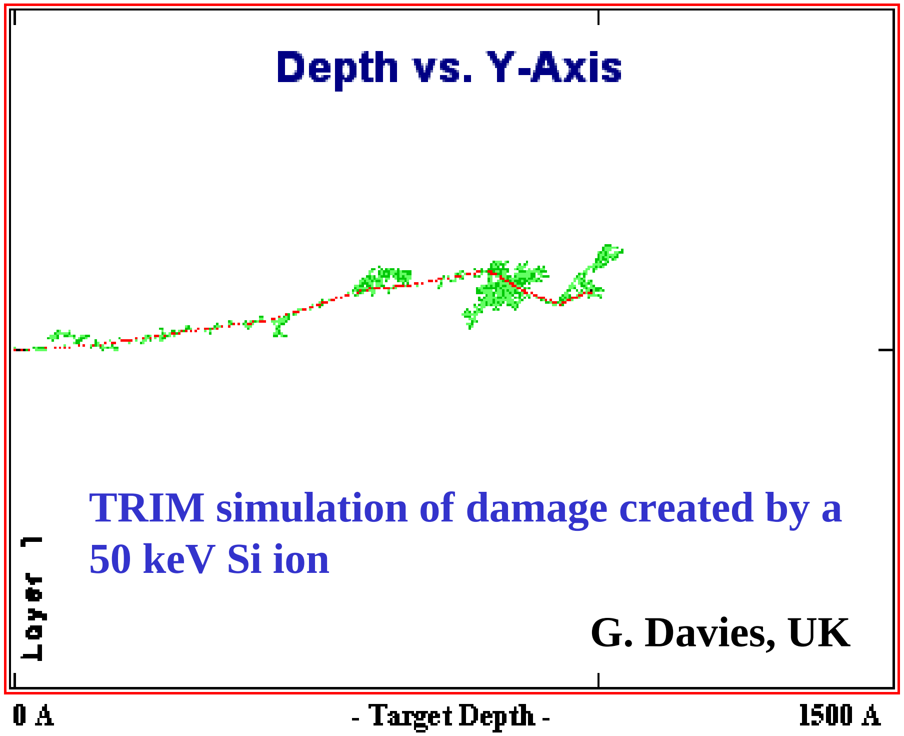
RD50 Open problem: Clusters evaluation

Use TRIM as a guide to the amount of damage.

Neutron fluence of 3×10^{16} cm^{-2} gives 3×10^{15} cm^{-3} tracks.

Typical knock-out energy of Si atom is 50 keV.

Each track has about 700 vacancies.



TRIM simulation of damage created by a 50 keV Si ion

G. Davies, UK

- **Most of the damage (95%) is in the large disordered regions (clusters).**
- **But 5 % is in small damage events (point defects), with have well-defined energy levels, so *can be measured accurately*.**

- G. Davies, RD50 Workshop, Ljubljana, June 08

RD50 Recent Literature on Defects in neutron irradiated silicon

V_2 has two charge states at 0.24 and 0.43 eV below *Ec* corresponding to 135 K and 233 K transitions. A large 233 K peak is the hallmark of neutron-damaged silicon, related to clusters; electron irradiation, which produces more uniform displacement damage, shows two nearly equal peaks at 135 and 233 K.

Two bistable configurations of the defects.

1. either immediately after irradiation or after forward bias (12.5 A/cm^2 at 300 K for 20 min). Increase in the 233 K peak and appearance of the 195 K peak/shoulder. After neutron , but not electron irr., decrease in the shallow V_2 peak at 135 K.
2. after sample at 350 K for 60 min either shorted or reverse biased or after the sample has been at room temperature for months. Lower 233 K peak, a much lower 0.36 eV trap signature, and a larger shallow *V*2 peak (neutron irr.)

Change in the $V_2^{=/-}$ intensity (neutron irr.) explained as partial filling of the level due to band bending within a cluster.

R. M. Fleming,a C. H. Seager, D. V. Lang, E. Bielejec, and J. M. Campbell, APL, 90, 172105 2007

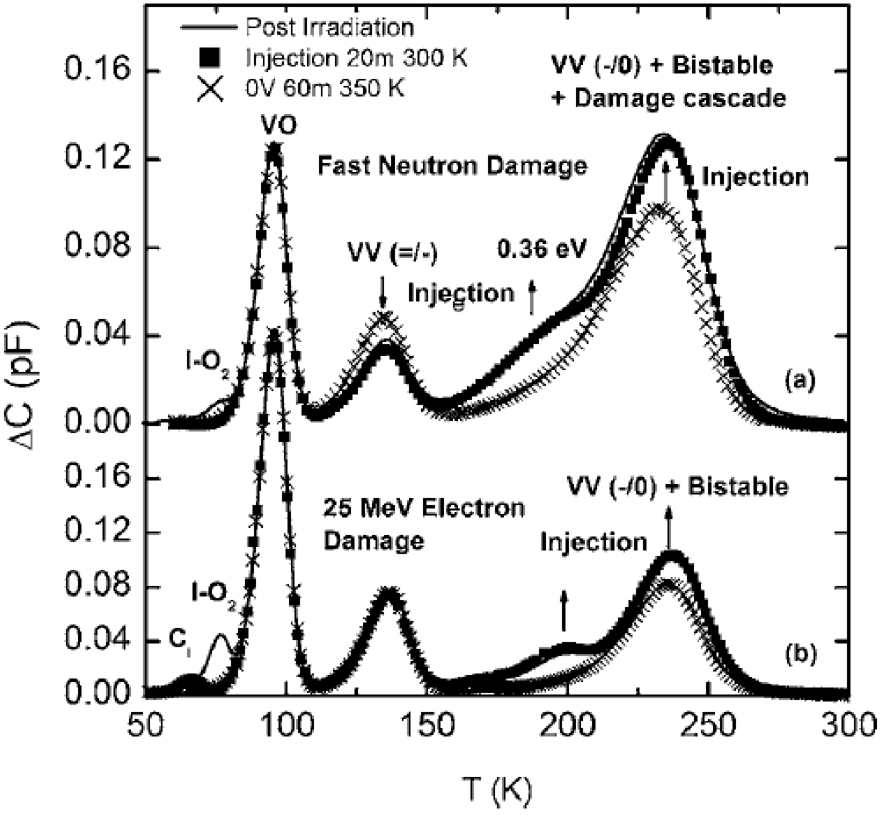


FIG. 1. DLTS of the base-collector diode of radiation damaged *n-p-n* transistors. The DLTS spectrum can be cycled between two limiting cases, a higher defect state (immediately after irradiation or after forward bias at 300 K) and a lower defect state (after zero or reverse bias at 350 K). (a) Fast neutrons and (b) 25 MeV electrons.

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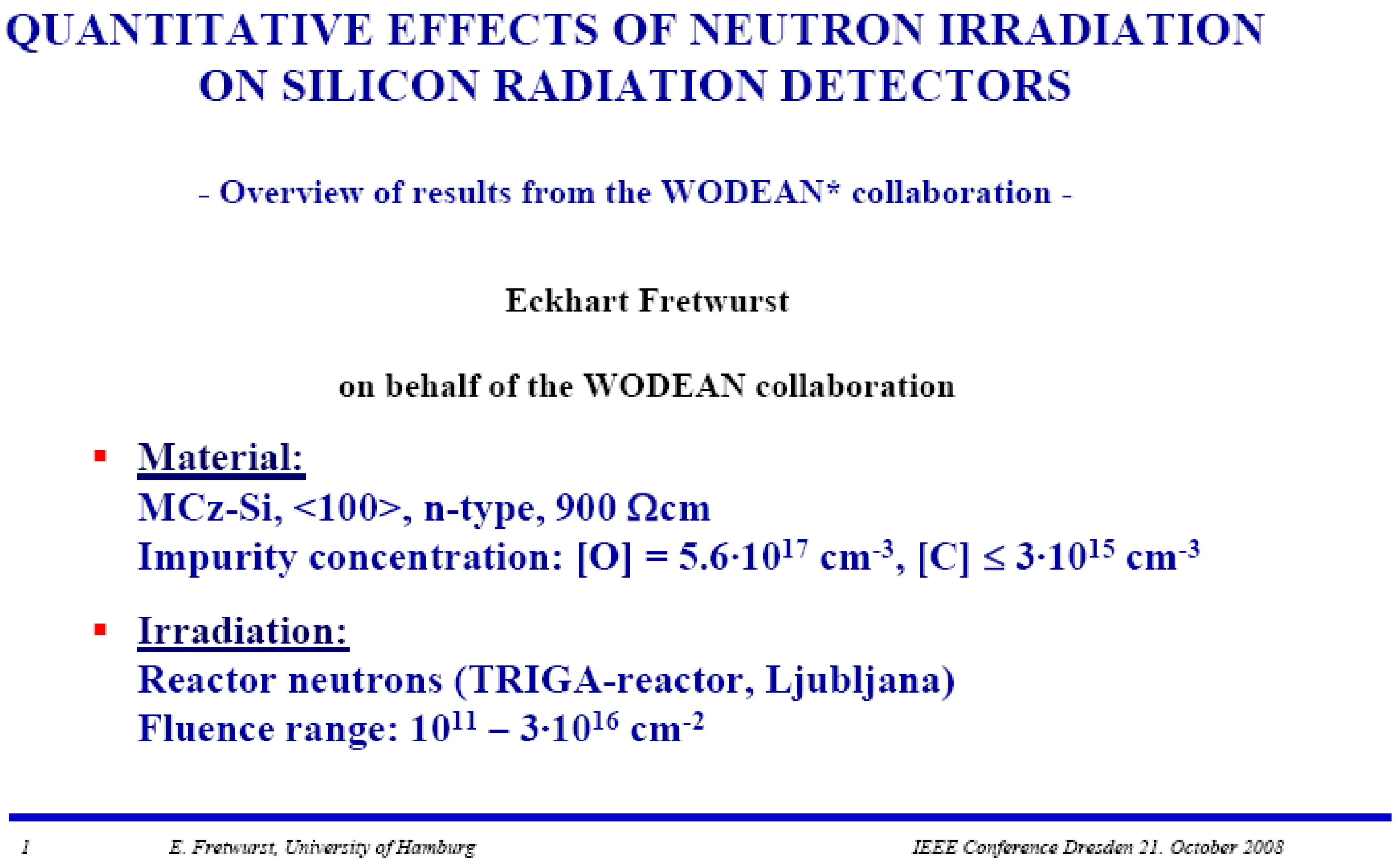
WODEAN : Latest achievements



QUANTITATIVE EFFECTS OF NEUTRON IRRADIATION ON SILICON RADIATION DETECTORS

- Overview of results from the WODEAN* collaboration -

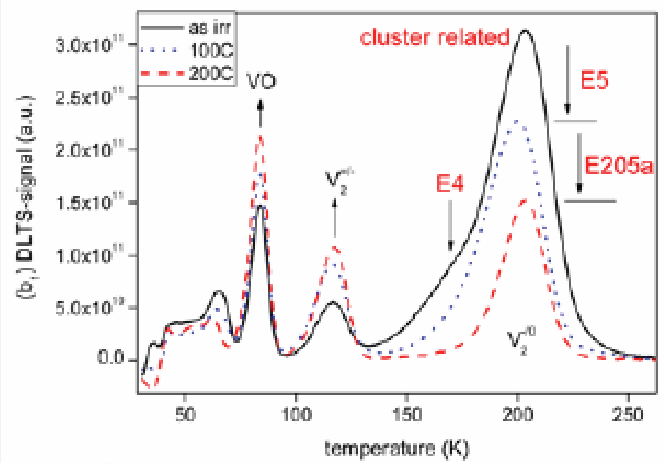
Eckhart Fretwurst

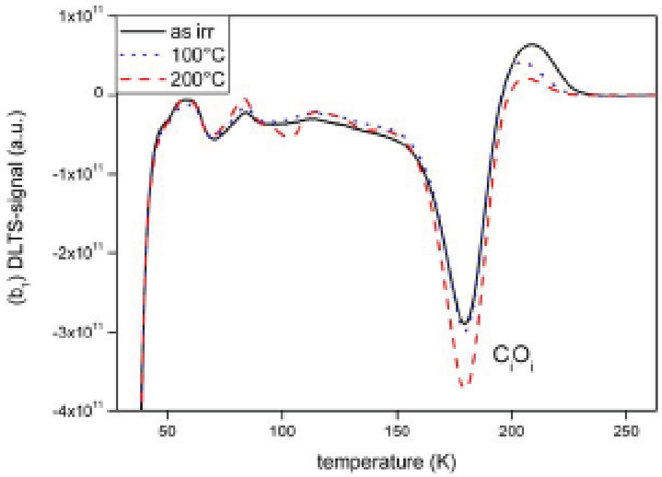
on behalf of the WODEAN collaboration

- **Material:**
  MCz-Si, <100>, n-type, 900 Ωcm
  Impurity concentration: [O] = $5.6 \cdot 10^{17}$ cm^{-3}, [C] $\leq 3 \cdot 10^{15}$ cm^{-3}
- **Irradiation:**
  Reactor neutrons (TRIGA-reactor, Ljubljana)
  Fluence range: $10^{11} - 3 \cdot 10^{16}$ cm^{-2}

1 *E. Fretwurst, University of Hamburg* *IEEE Conference Dresden 21. October 2008*

C-DLTS studies – fluence $3 \cdot 10^{11}$ cm^{-2}



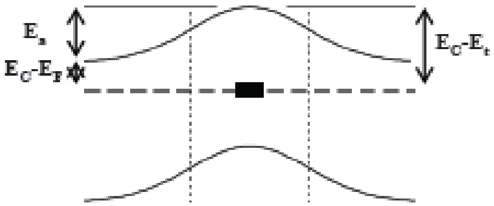


C-DLTS requires $N_t \ll N_d$ → low fluence only

Electron traps:

- **VO at T=80 K**
- **V_2(=/-) at T=120 K → strongly suppressed due to potential barrier surrounding cluster**
- **V related defects in cluster at T=170-220 K, V_2(-/0), E4/E5, E205a**

Band structure in a disordered region

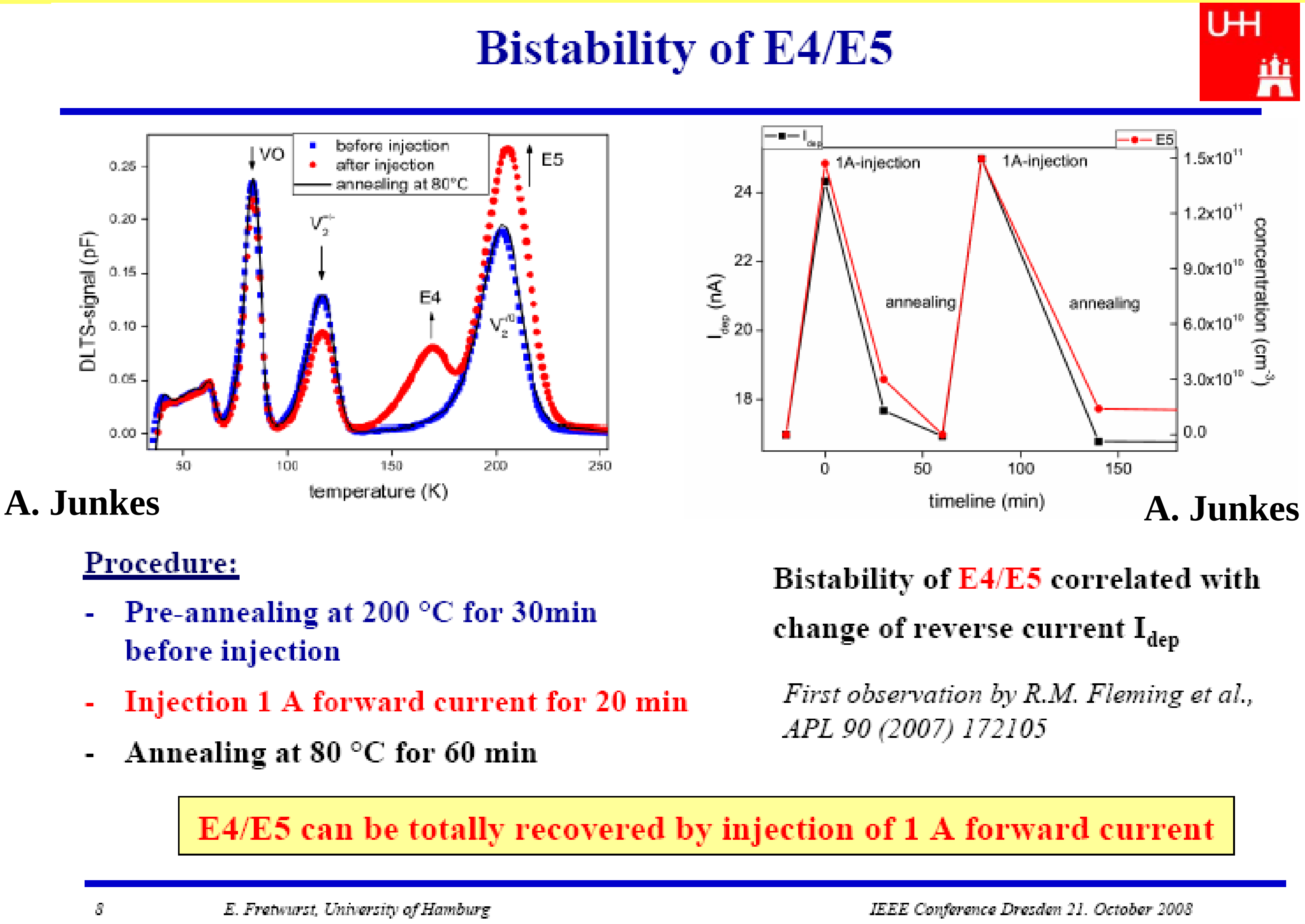


Hole trap:

- **C_iO_i at T=180 K**

Increasing temperature: Cluster dissolution
→ "Cluster-peak" at 200 K decreases
→ potential barrier drops
→ V_2(=/-) and VO increase

RD50 Bistability of E4/E5 correlated wit reverse current in neutron irradiated Si



Bistability of E4/E5

A. Junkes

A. Junkes

Procedure:

- Pre-annealing at 200 °C for 30min before injection
- Injection 1 A forward current for 20 min
- Annealing at 80 °C for 60 min

Bistability of E4/E5 correlated with change of reverse current I_{dep}

First observation by R.M. Fleming et al., APL 90 (2007) 172105

E4/E5 can be totally recovered by injection of 1 A forward current

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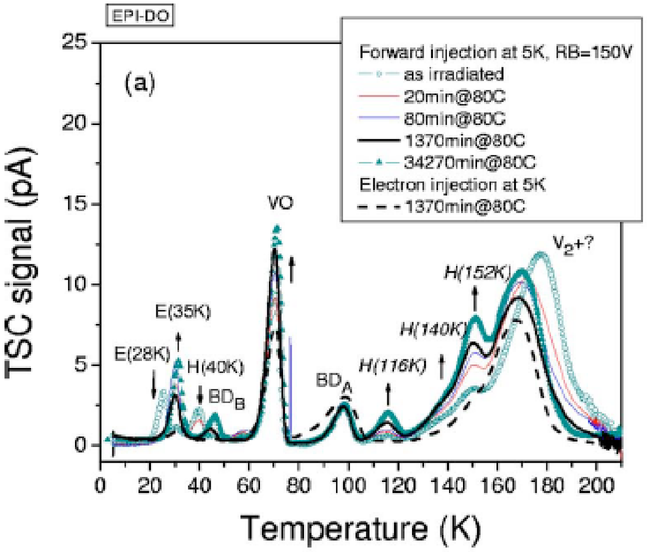
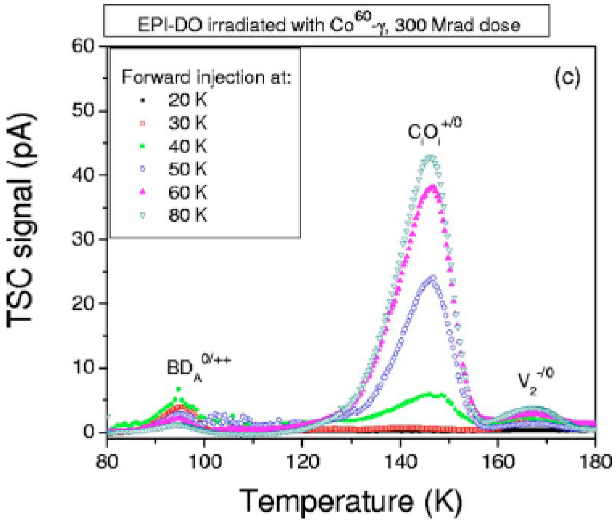
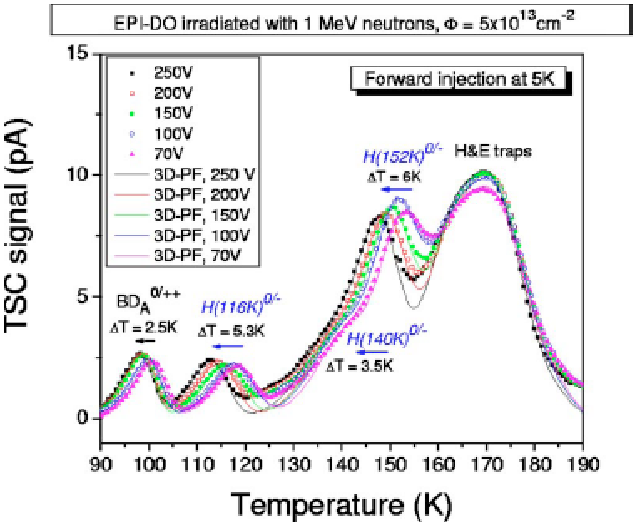
Cluster related hole traps as source for long term annealing

Hole traps *H*116 K, *H*140 K, and *H*152K, cluster related defects (not present after γ-irradiation) observed in neutron irradiated *n*-type Si diodes during 80 °C annealing. To be observed by TSC it is necessary to deactivate C_iO_i, through filling with forward injection at very low initial temperature.







I. Pintilie, E. Fretwurst, and G. Lindström, APL **92**, 024101 2008

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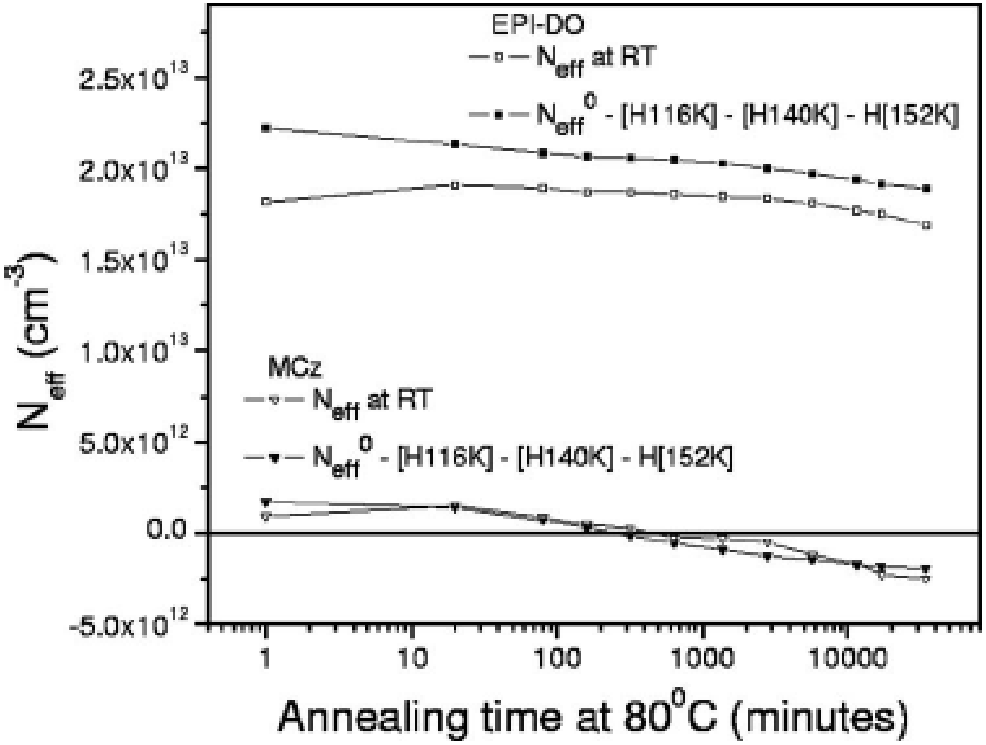
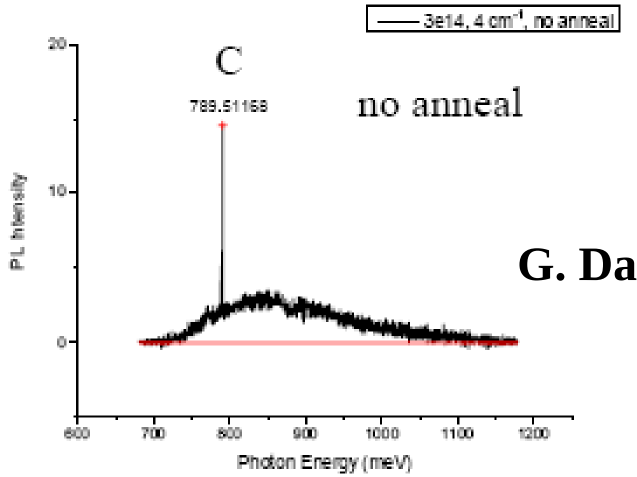
Hole traps *H*116 K, *H*140 K, and *H*152K concentration in agreement with Neff changes during 80 °C annealing, they are believed to be causing the long term annealing effects.

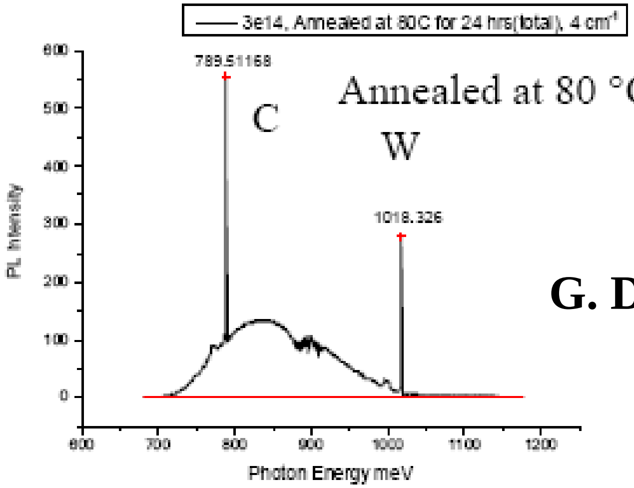


I. Pintilie, E. Fretwurst, and G. Lindström, APL **92**, 024101 2008

Photoluminescence Spectroscopy



G. Davies



G. Davies

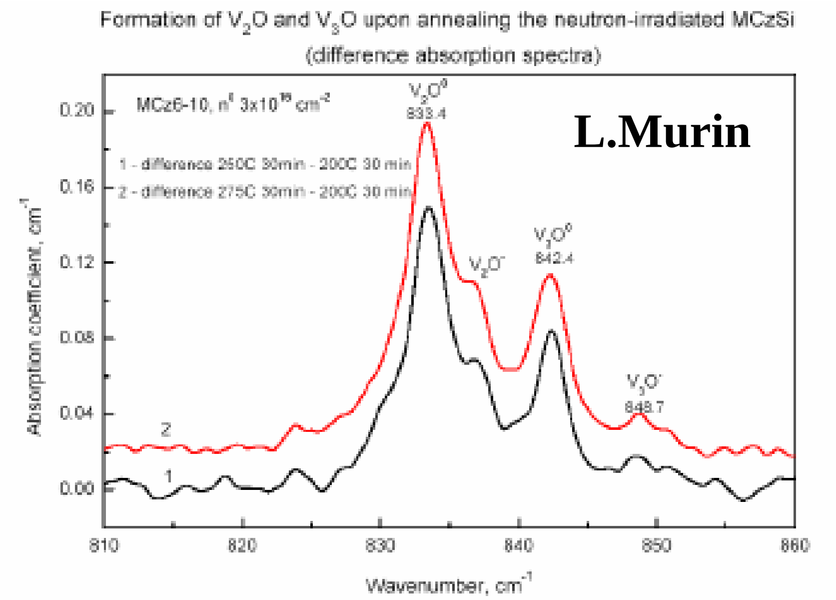
PL properties:

- Very high spectral resolution, typical 0.1 meV at 1000 meV
- More sensitive to I related defects than V related defects
- Extraction of concentrations difficult
- PL quenched by V-clusters or other defects

Visible defects:

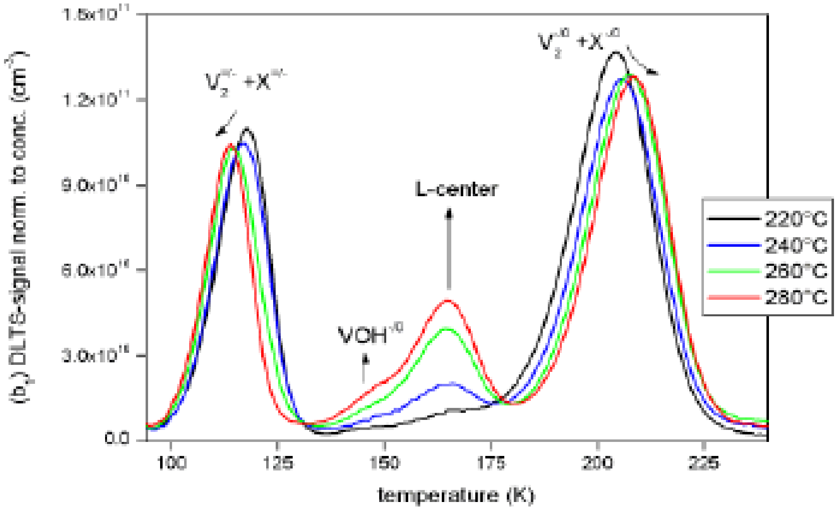
- C-line at 789 meV = C_iO_i
- W-line at 1018 meV = I_3,
  only seen after annealing at T > RT
  grows with annealing time
- Broad band:
  attributed to disordered region

FTIR-annealing compared with DLTS


Formation of V_2O and V_3O upon annealing the neutron-irradiated MCzSi (difference absorption spectra)

L.Murin

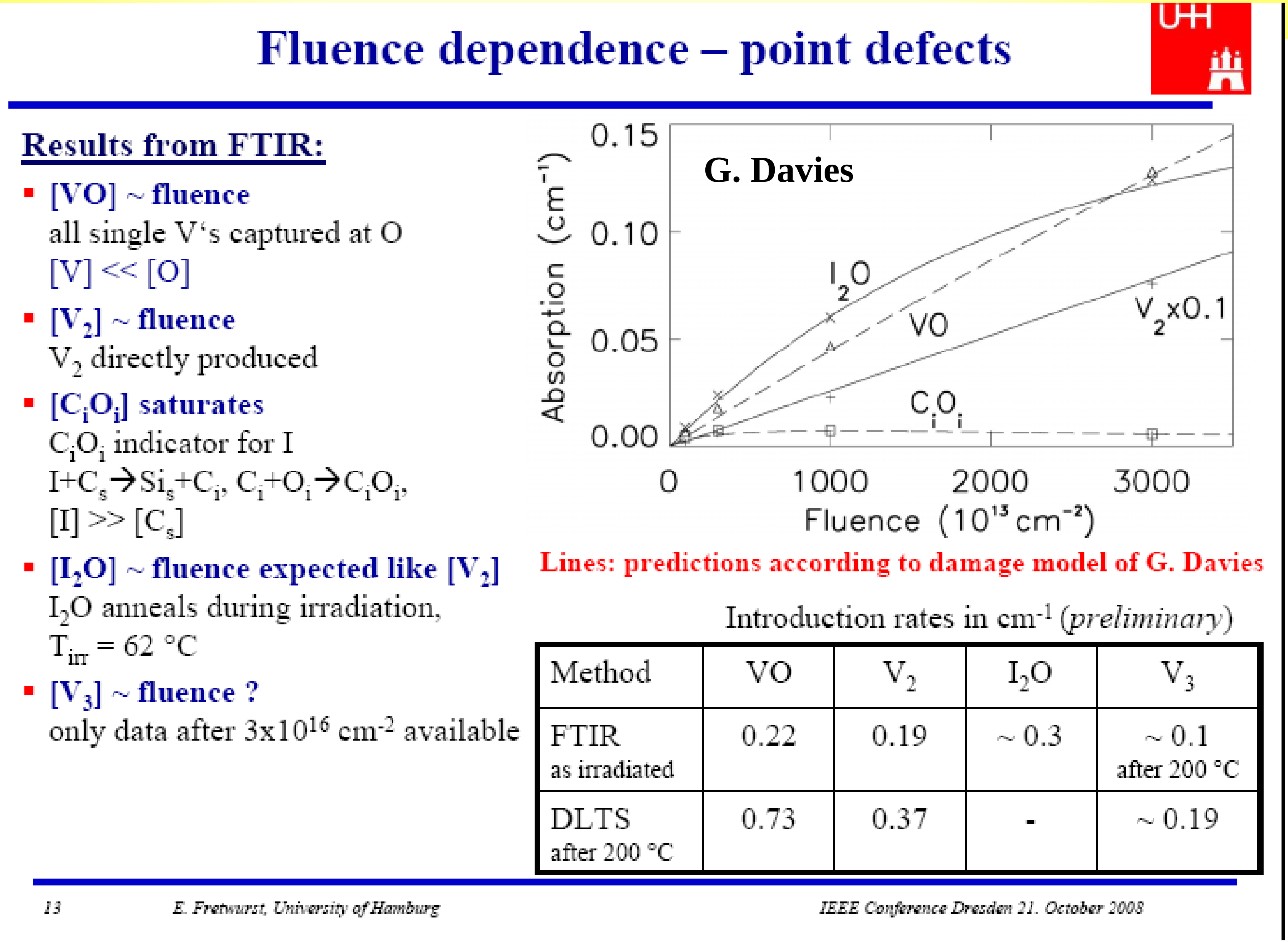
A. Junkes



FTIR: Difference spectra show
formation of V_2O and V_3O in
the range 200 °C – 275 °C
transformation:
$V_2 + O \rightarrow V_2O$
$V_3 + O \rightarrow V_3O$

DLTS: Spectra show
formation of X- and L-center in the same
temperature range ⇒ most likely X=V_2O
L-center = ?
Ratio [L]/[X] ≈ [V_3O]/[V_2O] from FTIR
L increase correlates with E4/E5 decrease

E4/E5 DLTS signals might be attributed to V_3 and L to V_3O



Fluence dependence – point defects

Results from FTIR:

- **[VO] ~ fluence**
  all single V's captured at O
  [V] << [O]
- **[V_2] ~ fluence**
  V_2 directly produced
- **[C_iO_i] saturates**
  C_iO_i indicator for I
  $I + C_s \rightarrow Si_s + C_i$, $C_i + O_i \rightarrow C_iO_i$,
  [I] >> [C_s]
- **[I_2O] ~ fluence expected like [V_2]**
  I_2O anneals during irradiation,
  T_{irr} = 62 °C
- **[V_3] ~ fluence ?**
  only data after $3x10^{16}$ cm^{-2} available

Lines: predictions according to damage model of G. Davies

Introduction rates in cm^{-1} (*preliminary*)

Method	VO	V_2	I_2O	V_3
FTIR as irradiated	0.22	0.19	~ 0.3	~ 0.1 after 200 °C
DLTS after 200 °C	0.73	0.37	-	~ 0.19

RD50

Summary – defects with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\cdot10^{-14}$ cm^2
  - $\sigma p^{I} = 2.3\cdot10^{-14}$ cm^2

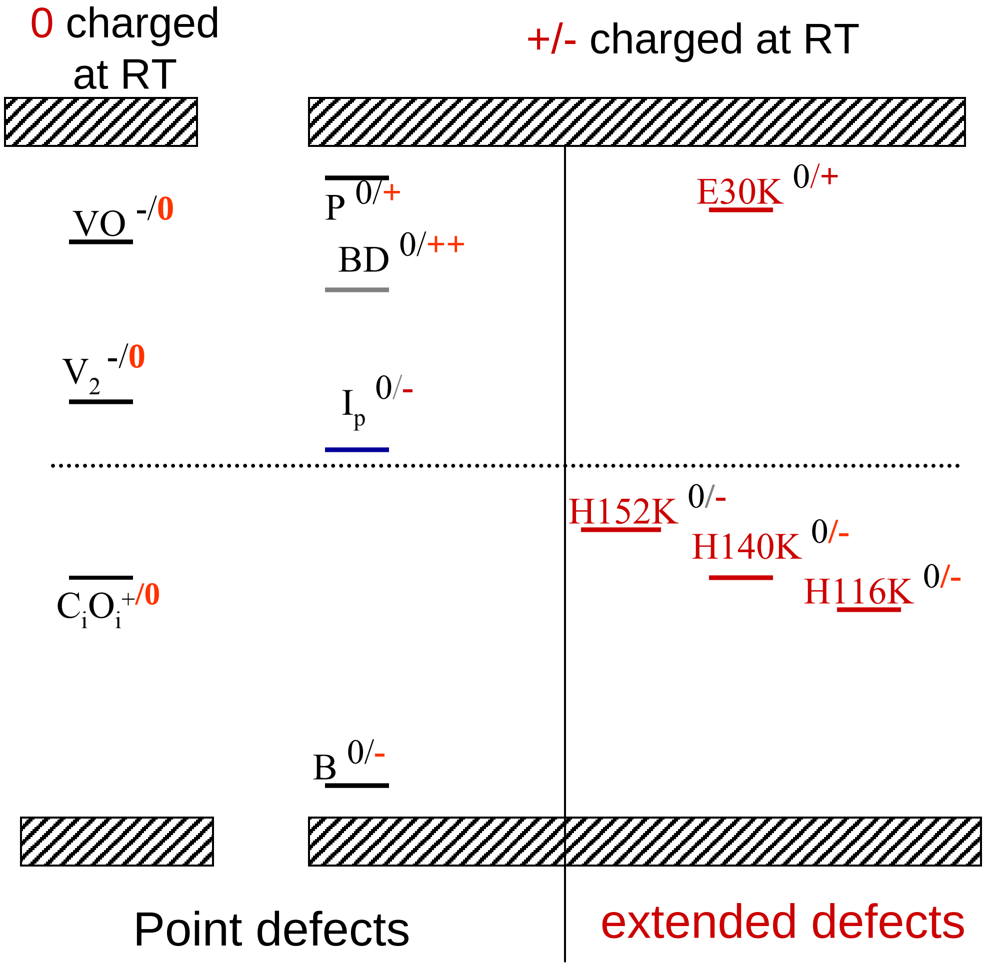
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2



I.Pintilie, NSS, 21 October 2008, Dresden

RD50

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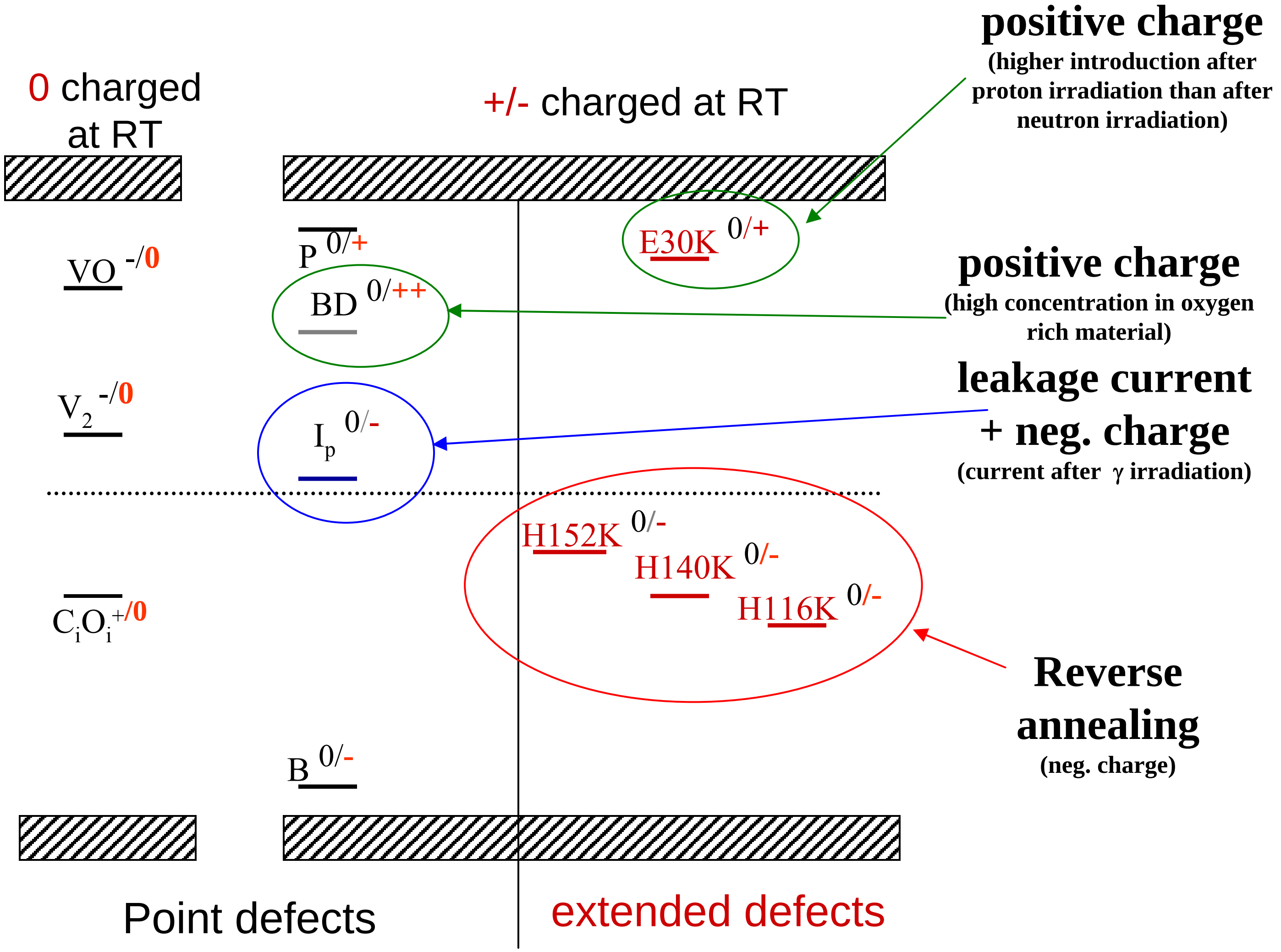

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

leakage current + neg. charge
(current after γ irradiation)

Reverse annealing
(neg. charge)

I.Pintilie, NSS, 21 October 2008, Dresden

Conclusions

The study of radiation induced microscopic damage has been carried out by RD50 since the collaboration started. Since 2006 the WODEAN project has given a significant contribution about the study of the most relevant parameter changes in irradiated silicon detectors. Defects have been studied by different techniques in a coordinated way in an extremely wide fluence range (10^{11}-10^{16} ncm^{-2}).

Some conclusions (WODEAN Project on Neutron irradiation) are:

-small damage events (point defects) and disordered regions (clusters)

-Electron damage model of G. Davies can be applied to small damage events in neutron damage;

-Clusters: some information can be deduced from DLTS;

-Proposed assignment for E4/E5-and L-center: E4/E5: different charge states of V_3 and L = V_3O (comparison with FTIR);

-Bistability of E4/E5 correlates with dark current;

-Deep acceptors H(116K)…H(152K) responsible for reverse annealing of N_{eff}

Program in next future:

- **Modelling and understanding role of clusters**
- **Extend studies to p-type silicon detectors**
- **Extend search on defects responsible for trapping**