Studies on n-type silicon after electron irradiation

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Outline

- Motivation
- Radiation-induced bulk damage
- Results on electron irradiation from 1.5 to 15 MeV
- Conclusions

Starting point:

I. **Joint project between NIMP Bucharest and University of Hamburg –" Electron irradiation of Si-diodes at E = 1 - 15 MeV'** presented by Prof. G. Lindström at the last *WODEAN Workshop in Bucharest, 13/14 May 2010*

II. **"Comprehensive investigation on bulk radiation damage in defect engineered silicon - from point defects to clusters" –** Project Director Ioana Pintilie, 2011

Aim: *Identification of both the structure of the electrically active defects responsible for the electrical properties of irradiated silicon diodes and the possible reactions with different impurities in the material.*

Objectives:

1) **Irradiation with 1.5, 3.5, 6 and 15 MeV electrons – studies performed in Hamburg**

- Electrical characterization (CV/IV) before/after irradiation - V_{dep} and I_{dep} space charge distribution, recombination-generation current also after annealing (isothermal and isochronal)
- Analysis of electrically active defects by means of DLTS and TSC methods before/after irradiation - correlation with results from diode characteristics

2) **Electron induced damage in Si implanted with ^{17}O and ^{13}C – investigations performed in Bucharest**

- Studies for defect identification by Electron Paramagnetic Resonance (EPR, ENDOR) methods - in defect engineered silicon (O enriched, O lean, C rich, C lean)
- Microstructural investigation of the extended and clustered defects by High Resolution-Transmission Electron Microscopy (HRTEM) - Identify the structure of the radiation-induced electrically active defects and establish the role of the impurities in their generation and kinetics.

Earlier studies showed that:

Particle type	Damage created
^{60}Co-γ irradiation (1.1 and 1.3 MeV) $E_{rec.max}$ = 200 eV	only point defects
Reactor neutron irradiation (1 MeV) $E_{rec.max}$ ~ 50 keV	dominant cluster defects
High energy protons (23 GeV)	both point and cluster defects
Threshold for formation of point defects : $E_{rec.}$ ~ 21 eV Threshold for formation of cluster defects : $E_{rec.}$ ~ 1.2 keV	

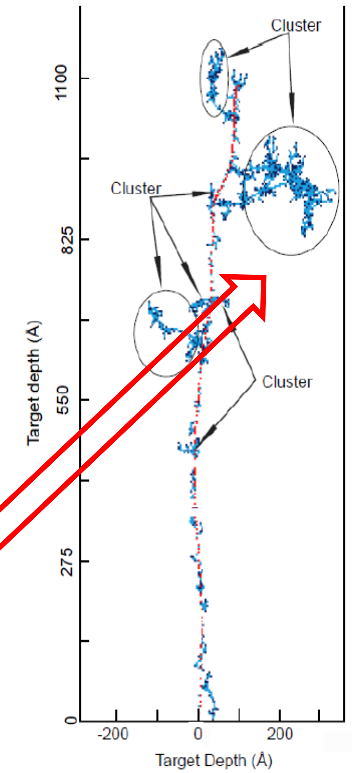
Irradiation with electrons, from low (E_e=1,5 MeV) to higher energies (E_e=15 MeV), in order to study the difference between radiation-induced point and cluster defects

$$T_{max} = \frac{2T_e(T_e + 2m_e c^2)}{M_0 c^2 A}$$

T_{max} = maximal energy transfer
$T_e = E_{e.kin.}$ = electron kinetic energy

A. Akkerman et al. / Radiation Physics and Chemistry 62 (2001) 301–310

$E_{e,kin.}$ = 1 MeV, T_{max} = 154 eV
$E_{e,kin.}$ = 3.5 MeV, T_{max} = 1.2 keV
$E_{e,kin.}$ = 6 MeV, T_{max} = 3.2 keV
$E_{e,kin.}$ = 15 MeV, T_{max} = 18.3 keV
$E_{e,kin.}$ = 30 MeV, T_{max} = 71 keV



New way to study the change from purely point to cluster-dominated effects

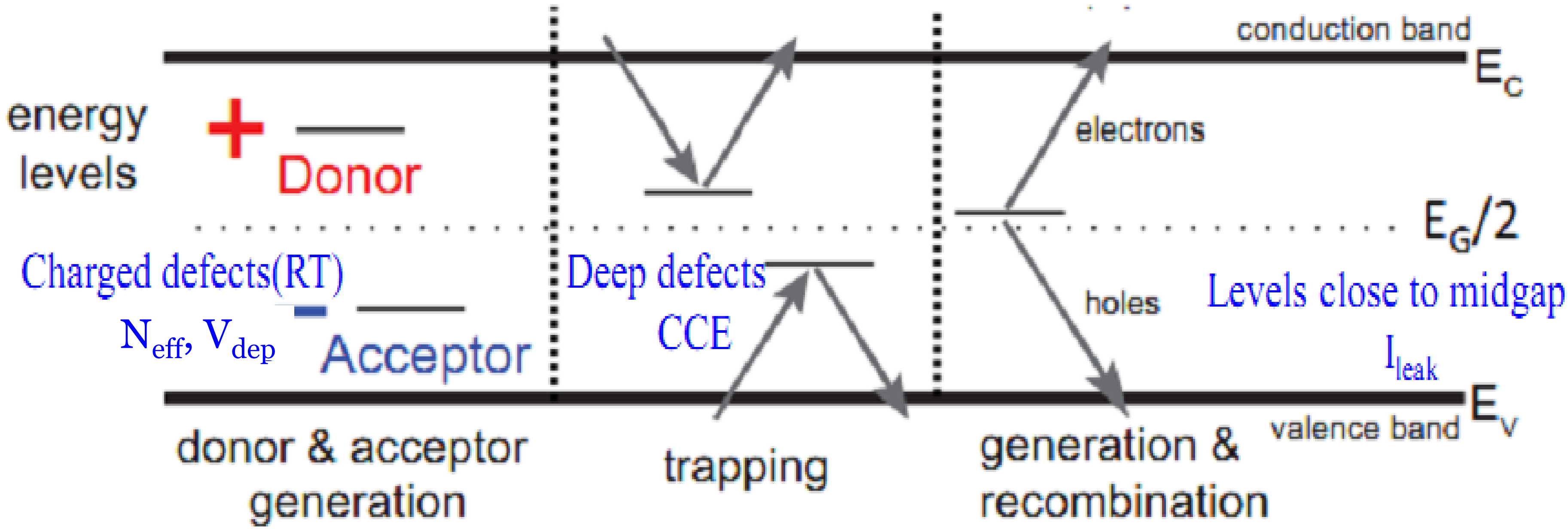
Materials and irradiation

Type	Orientation	d[μm]	N_D[cm^{-3}]	<[O]>[cm^{-3}]	ρ [Ωcm]	Diffusion oxygenated
EPI	<111> <100>	50 100	$6x10^{13}$ $1x10^{13}$	$1x10^{17}$ $2.8x10^{17}$	50 300	- 24 h /1100°C
ST-FZ	<100>	280	$8x10^{11}$	$1x10^{16}$	$5x10^{3}$	-
DO-FZ	<100>	280	$8x10^{11}$	$1.2x10^{17}$	$5x10^{3}$	72 h /1150°C

Electron fluences: $1x10^{12} \rightarrow 1.5x10^{15}$ cm^{-2}, E_e = 1.5 - 15 MeV
(for E_e = 15MeV: Φ_{eq}= $2.7x10^{10} \rightarrow 4.1x10^{13}$)

Hardness factor (k)	
1.5 MeV	$1.88x10^{-3}$
3.5 MeV	$6.50x10^{-3}$
6 MeV	$1.24x10^{-2}$
15MeV	$2.78x10^{-2}$

Radiation induced bulk damage



- Levels shown introduced by irradiation or by initial impurities
- Energy levels in the band gap with impact on electrical sensor properties

Radiation-induced bulk damage

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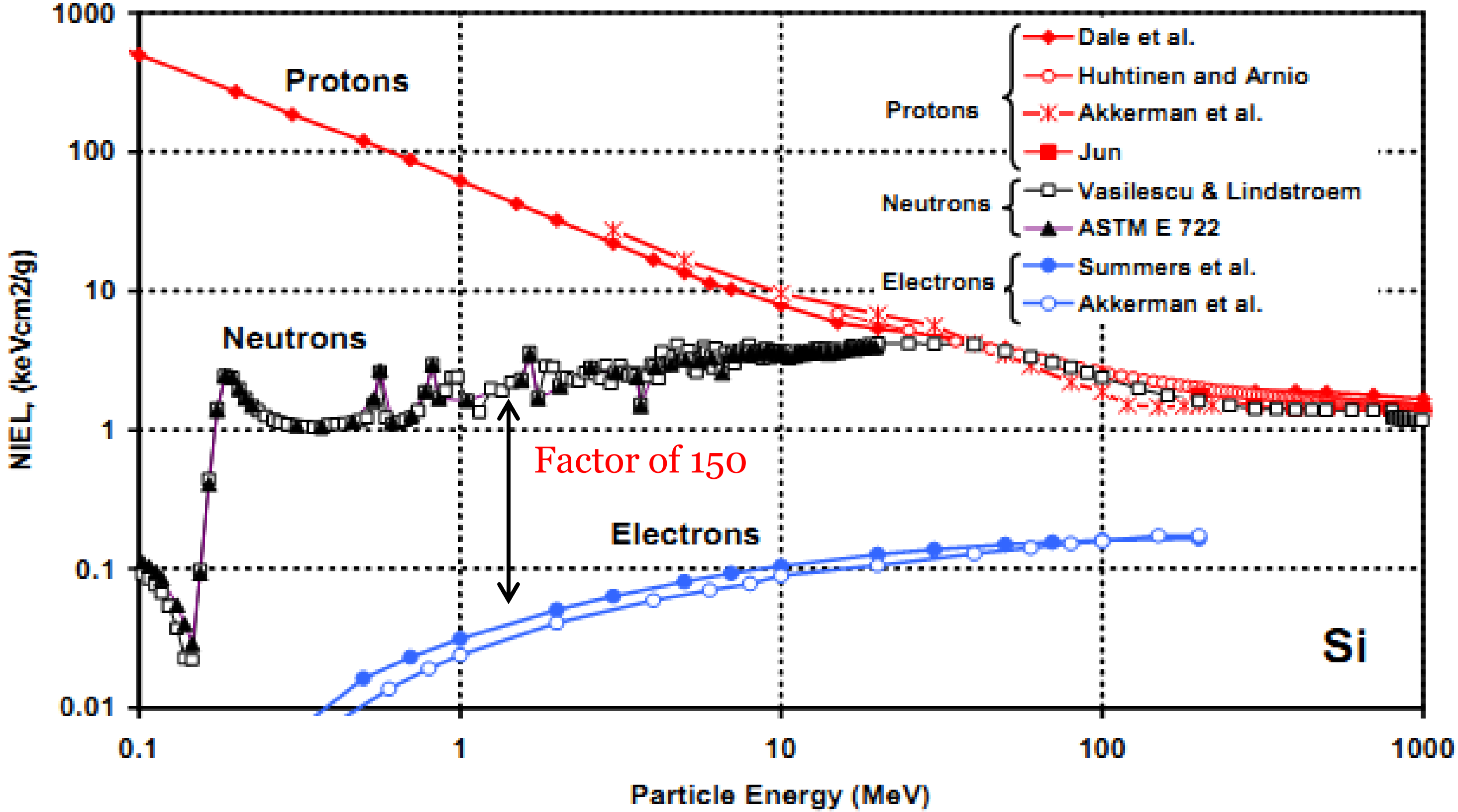
Defects	σ_n [cm^2]	σ_p [cm^2]	E_A [eV]	Assignment/References	Impact on the diodes electrical characteristics at room temperature
E(30K)	2.3 x 10^{-14}		E_C - 0.1	Electron trap with a donor level in the upper half of the Si bandgap /[11]	On the N_{eff} by introducing positive space charge
H(40K)		1.7 x 10^{-15}	E_V + 0.09	Hole trap/[11]	
$VO_i^{-/0}$	1.44 x 10^{-14}		E_C - 0.176	$VO_i^{-/0}$ / [40]	
$C_iC_s^{-/0}$	1.4 x 10^{-14}		E_C - 0.171	$C_iC_s^{A\ -/0}$ / [41, 42]	
$I_p^{+/0}$	1.7 x 10^{-15}		E_V + 0.23	Donor level of V_2O or of a still unkown C related defect/[11 ,30]	
$I_p^{0/-}$	1.7 x 10^{-15}	9 x 10^{-14}	E_C - 0.55	Acceptor level of V_2O or of a still unkown C related defect/[11 ,30]	On the N_{eff} by introducing negative space charge and on LC
$C_i^{+/0}$	1.11 x 10^{-15}	4.28 x 10^{-15}	E_V + 0.284	$C_i^{+/0}$/ [21]	
$V_2^{-/0}$	2.1 x 10^{-15}		E_C - 0.424	$V_2^{-/0}$ /[21]	
E_4	1 x 10^{-15}		E_C - 0.38	$V_3^{=/-}$ / [38]	On LC
E_5	7.8 x 10^{-15}		E_C - 0.46	$V_3^{-/0}$ /[38]	On LC
H(116K)		4 x 10^{-14}	E_V + 0.33	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defect (cluster of vacancies and/or interstitials) /[10,11]	On the N_{eff} by introducing negative space charge
H(140K)		2.5 x 10^{-15}	E_V + 0.36	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defects (clusters of vacancies and/or interstitials)/[10,11]	On the N_{eff} by introducing negative space charge
H(152K)		2.3 x 10^{-14}	E_V + 0.42	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defects (clusters of vacancies and/or interstitials)/[10,11]	On the N_{eff} by introducing negative space charge
H(87K)		0.3 x 10^{-15}	E_V + 0.193	$V_3^{0/+}$ /[37]	
H(98K)		1.2 x 10^{-15}	E_V + 0.234	$V_2O^{0/}$ + $V_3O^{0/+}$ /[37]	

LC = Leakage current

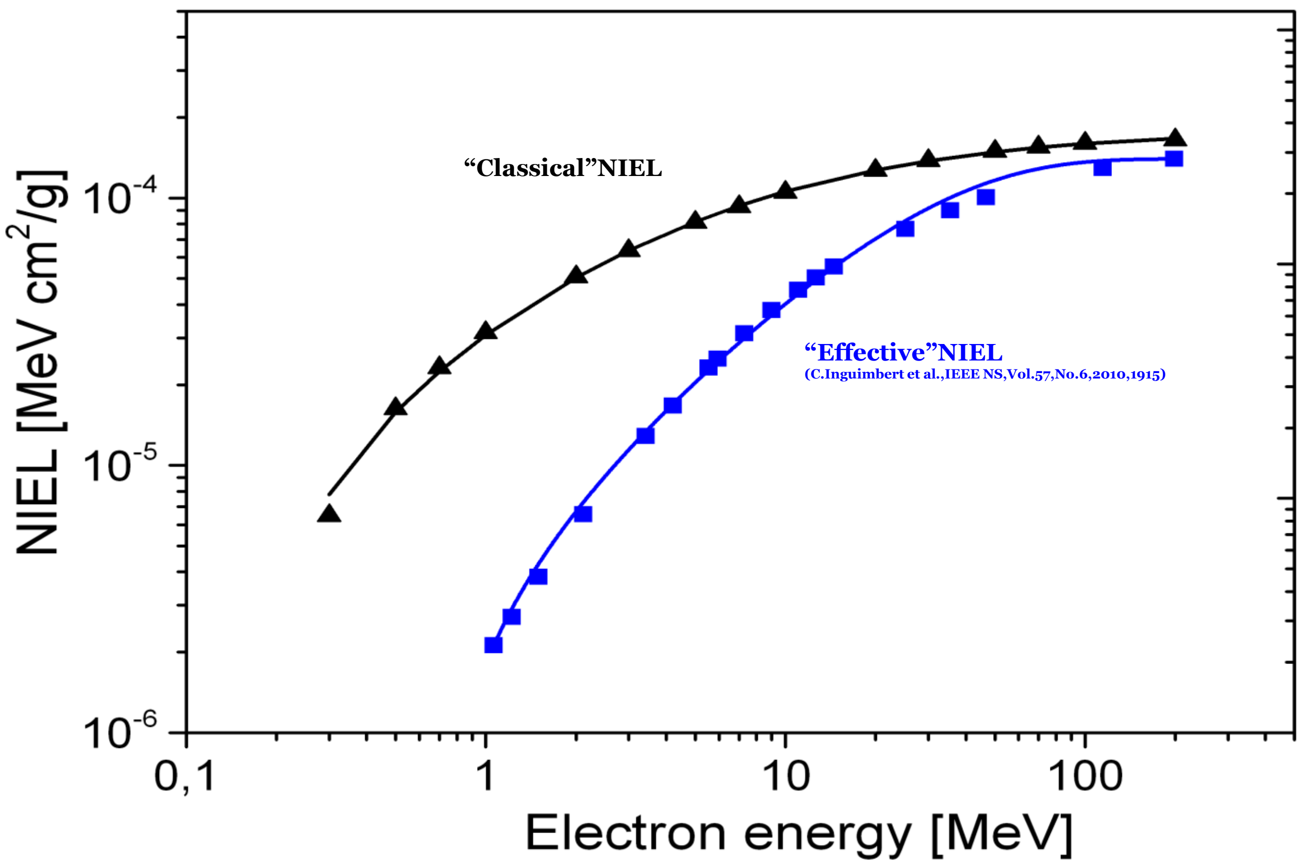
NIEL concept- Reminder



"Classical" NIEL – Non Ionizing Energy Loss is a quantity that describes the rate of energy loss due to atomic displacements as a particle traverses a material

- Final concentration of defects depends only on NIEL (total energy that goes into displacements) and not on the type of initial energy of the particle
- Number of displacement is proportional to PKA energy → nature of damage independent of PKA energy

NIEL predicts the "lifetime" of silicon detectors



"effective" NIEL - based on molecular dynamics (MD) simulation - recombination of displacements in disordered regions is taken into account

NIEL predicts the "lifetime" of silicon detectors

$\alpha = \Delta I / (V \cdot \Phi_e)$

measured at 20°C

E_e[MeV]	α_e[A/cm]	α_{eq}[A/cm]
1.5	2.6×10^{-20}	1.38×10^{-17}
3.5	1.89×10^{-19}	2.91×10^{-17}
6	3.4×10^{-19}	2.74×10^{-17}
15	1.21×10^{-18}	4.35×10^{-17}

"classical" NIEL – hypothesis violated

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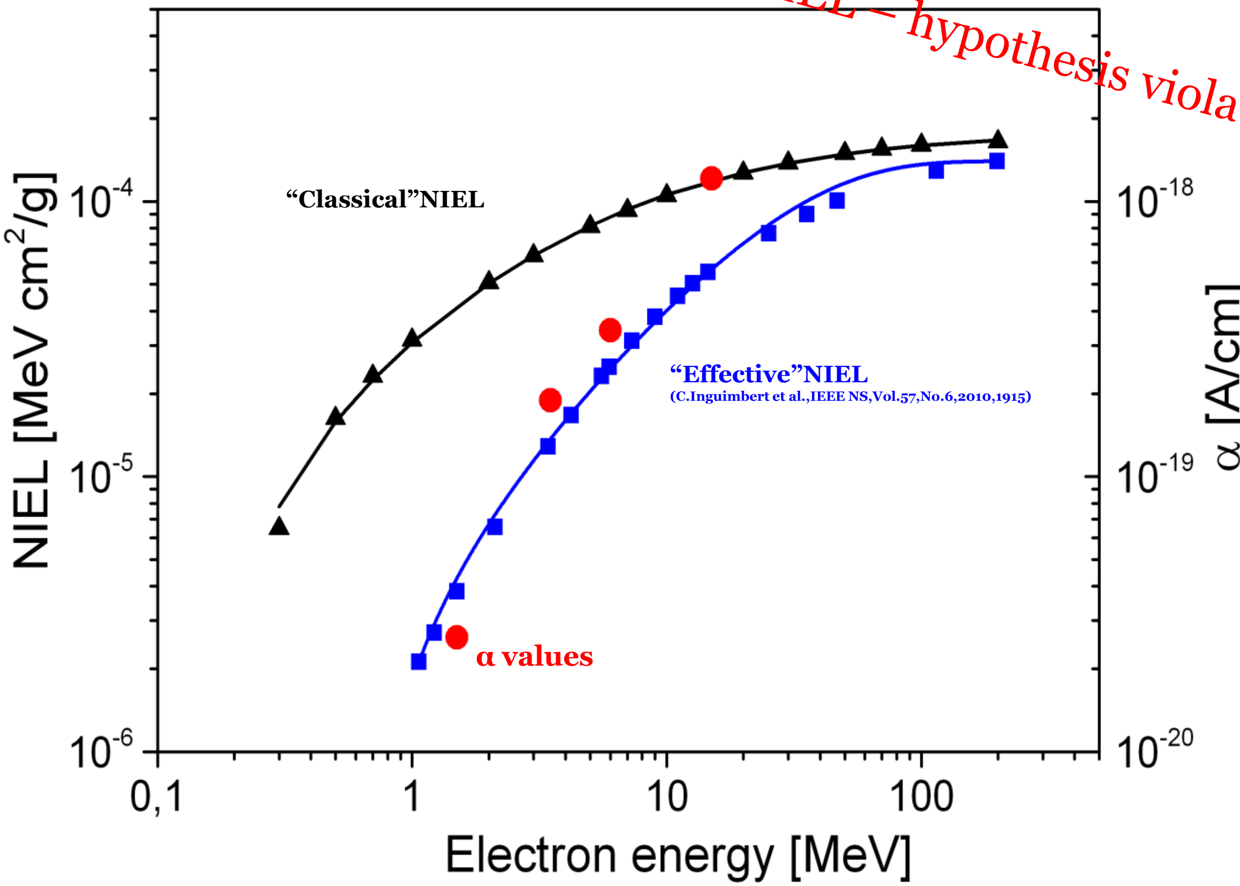
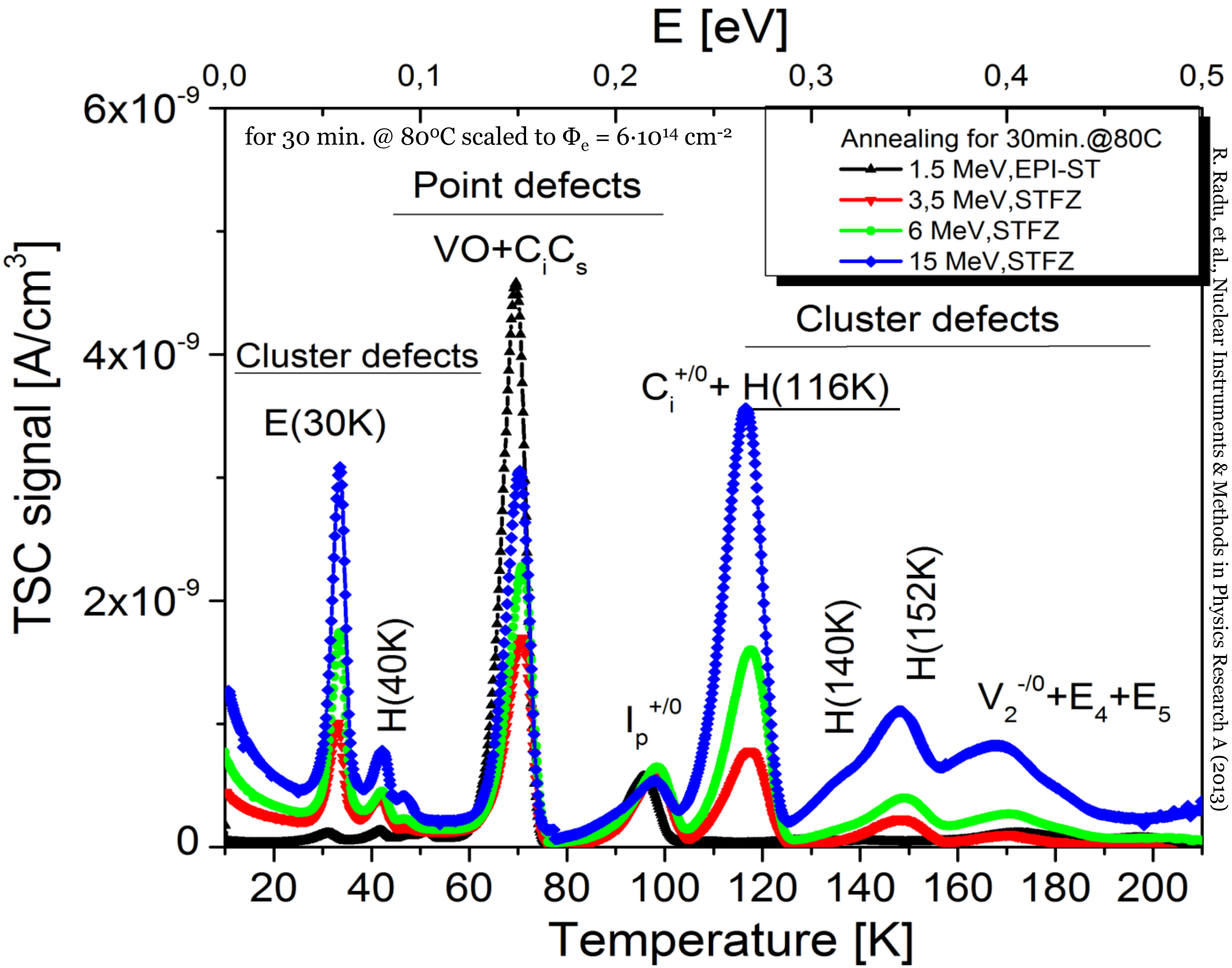


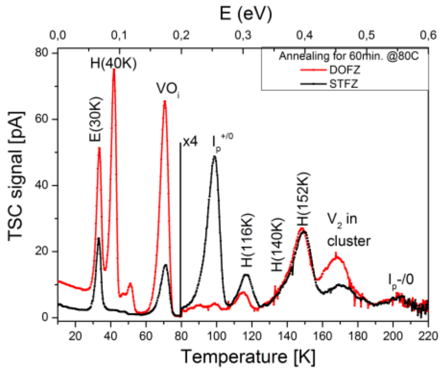
- α for electrons compared with "effective" and "classical" NIEL
- "effective" NIEL describes the energy dependence of α much better

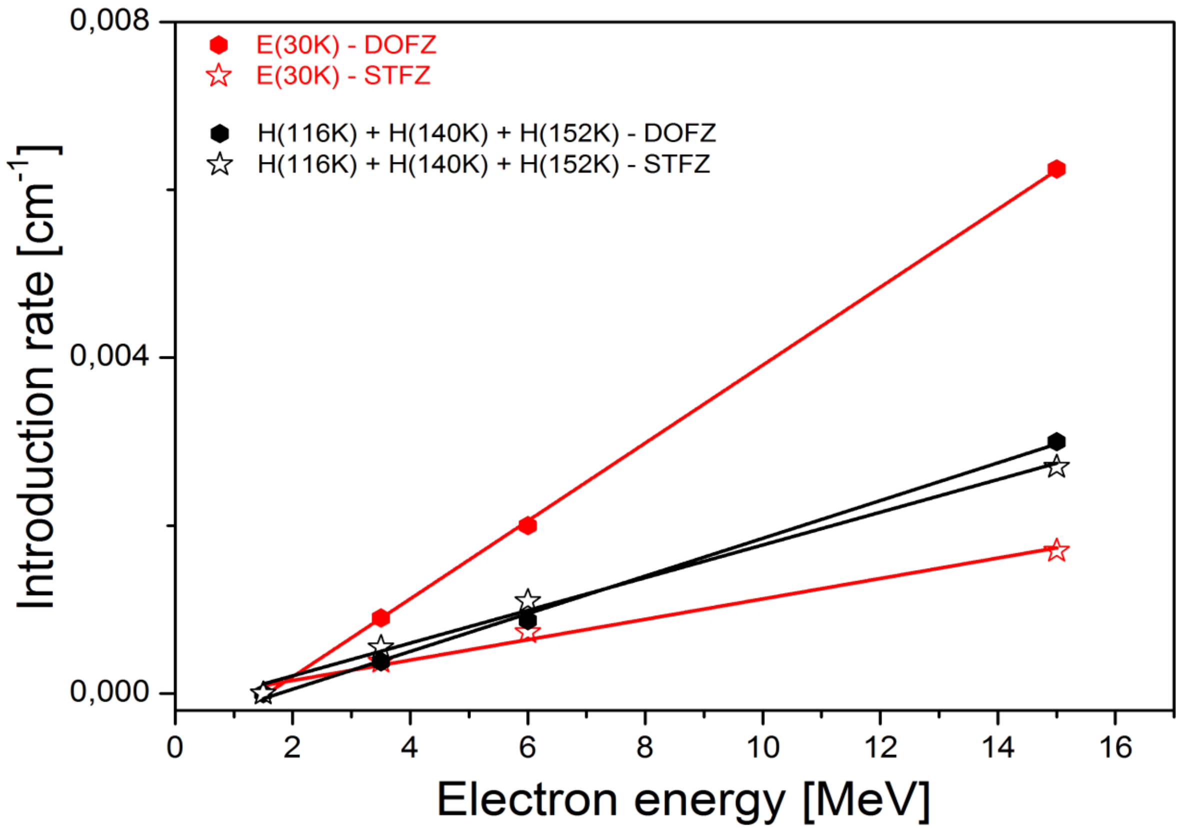
Energy dependance of defects, E_e = 1.5 to 15 Mev



Increasing electron energy → increase of local density of vacancies and interstitials → cluster defects

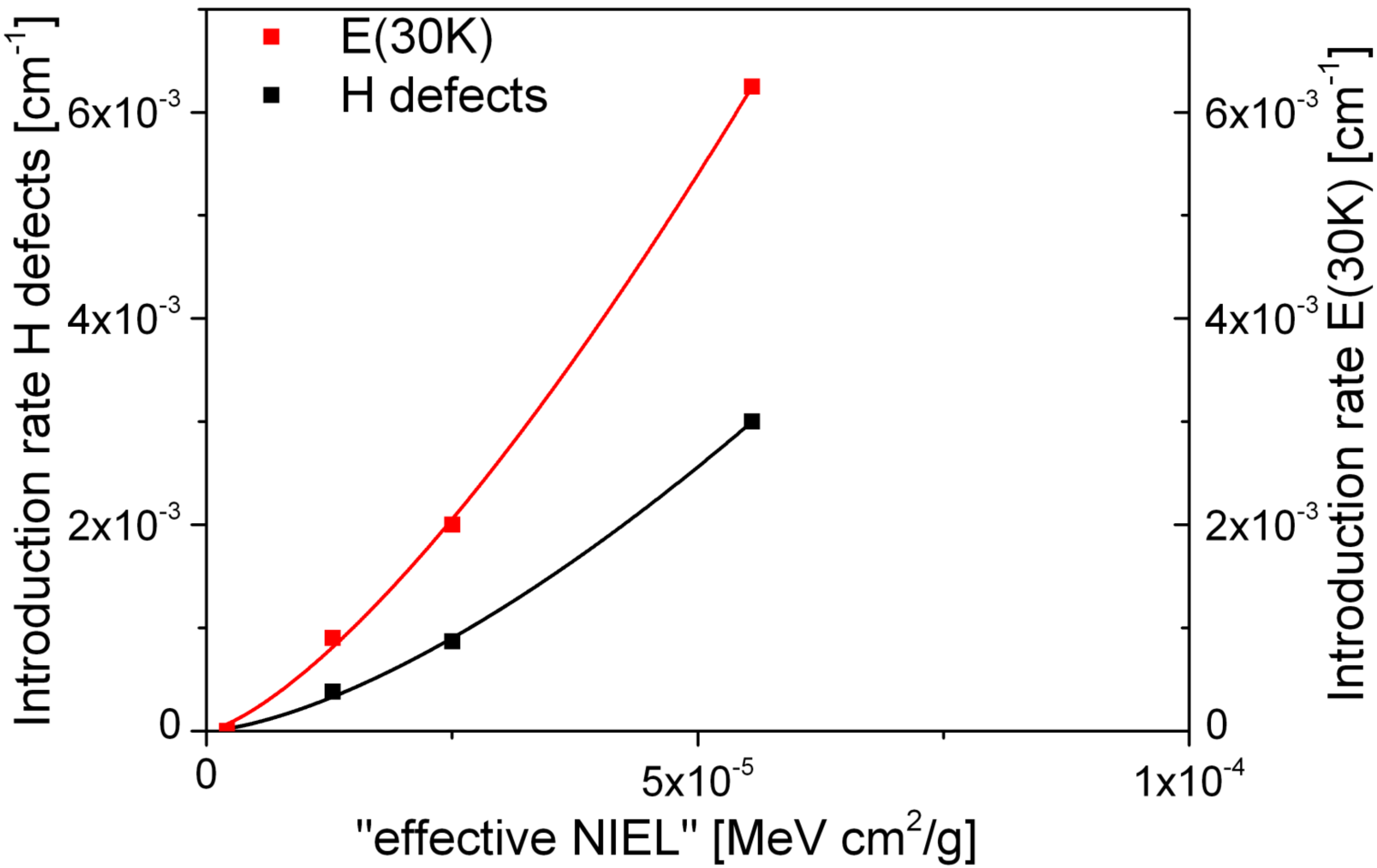
Energy dependence of introduction rates for E(30K) and H-defects



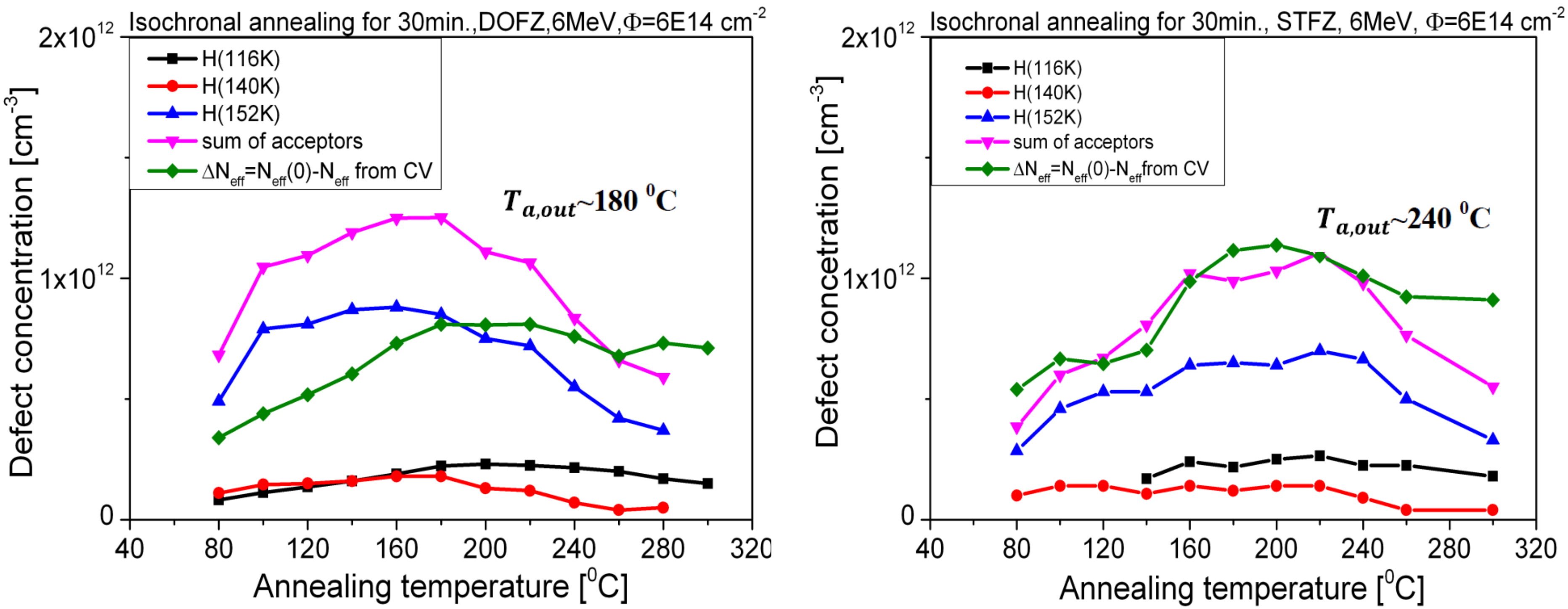


- Introduction rates for H defects for DOFZ & STFZ are similar → **no** [O] dependent
- Introduction rate for E (30K) is **3 times** larger in DOFZ material → [O] dependent
- Chemical structure of these defects unknown → **next step: isochronal annealing to get an overview of defect kinetics**

Introduction rates for E(30K) and H-defects vs. NIEL



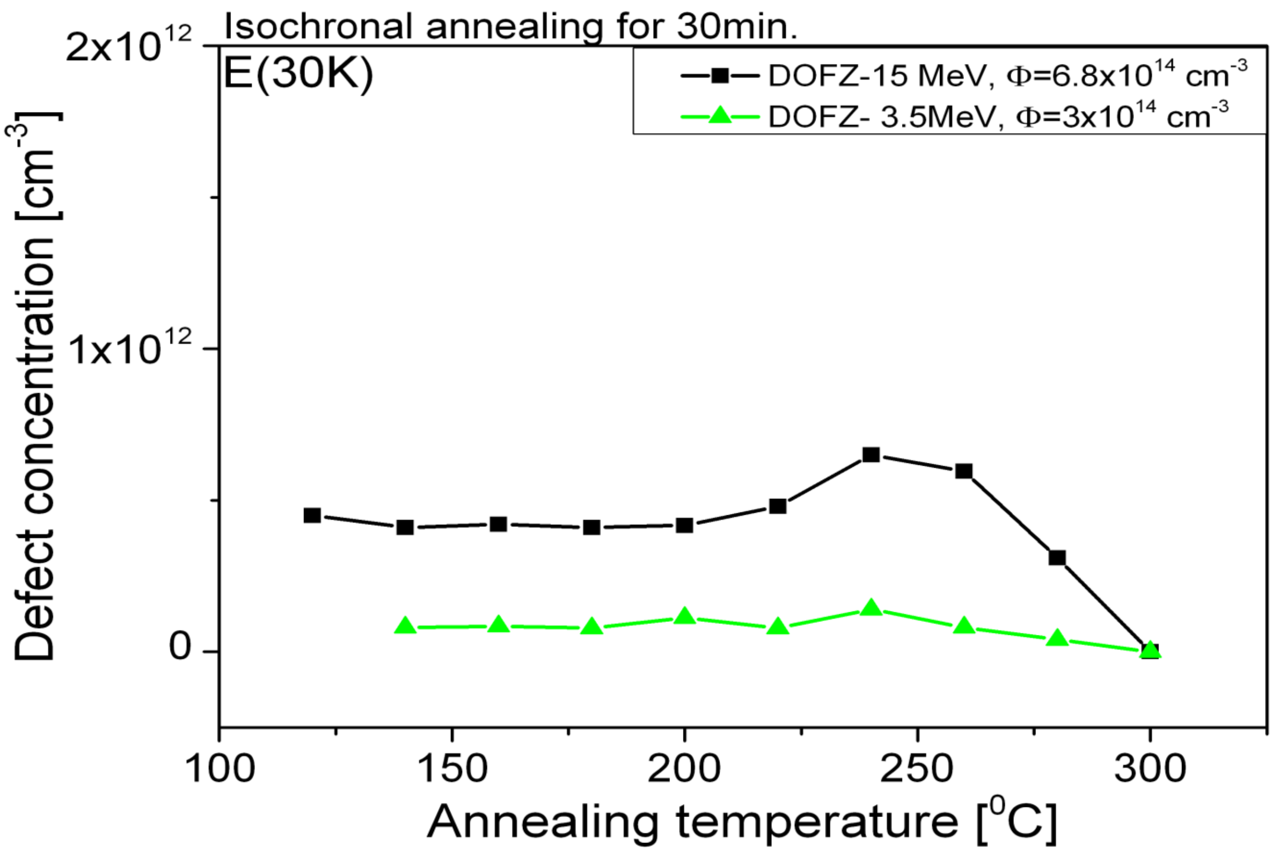
Introduction rates for E(30K) and H defects versus "effective" NIEL follows a power law function



What is the origin of H defects?

- After irradiation – small concentration, than start to increase
- **Puzzle:** If the introduction rates for H defects is not [O] dependent why the annealing in/out temperature is different for the two materials?
- Is there a relation between H defects and higher order vacancies V_n (n>3)?

Annealing of E(30K) defect



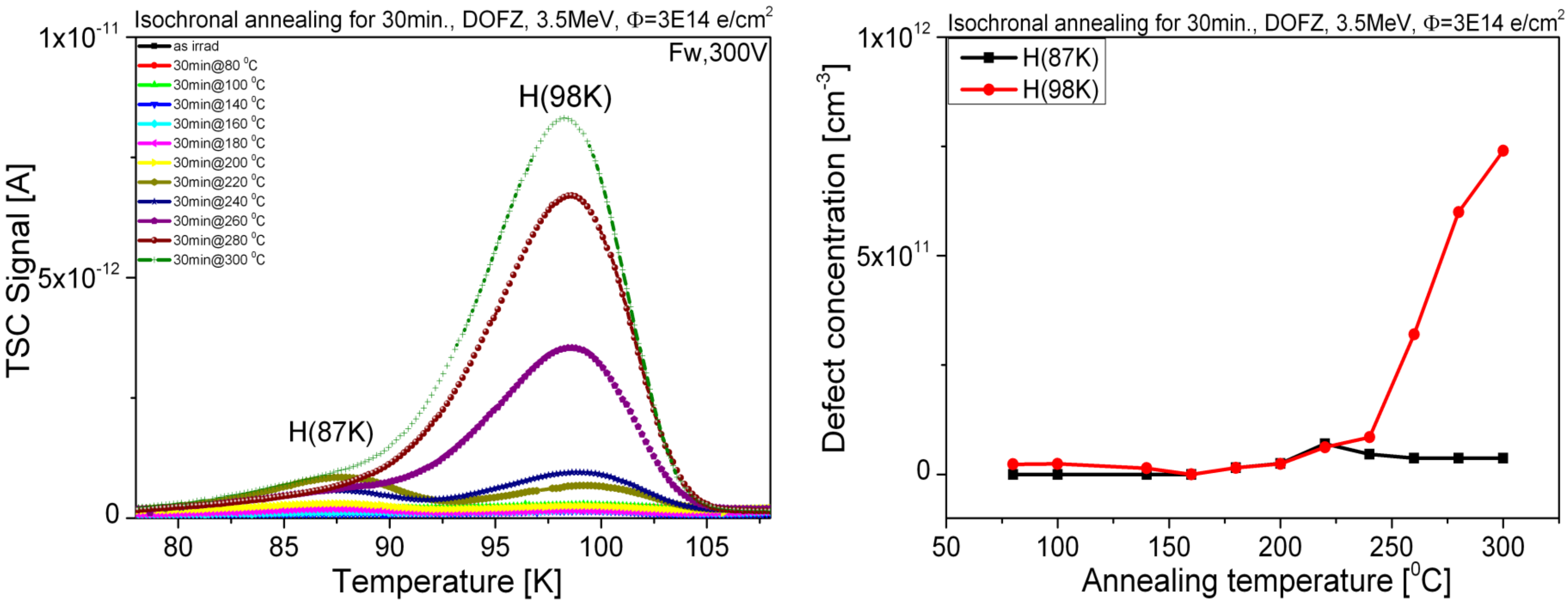
Unknown kinetic mechanism

What is the origin of E(30) defect?

- The E (30K) defect, a shallow donor, increases the positive space charge
- The E(30K) maximum concentration ~240°C and anneals out at 300°C

Next step: isothermal annealing at high temperature to identify its formation kinetics

Material dependence – new defects



V_2 and V_3 become mobile at T > 200°C, they are trapped by oxygen

Two donor levels have been detected in TSC only after injection of holes

1) Hole trap (87K): $V_2^{+/0}$ - stable up to 220 °C

$V_3^{+/0}$ - changed to the ffc. – configuration

2) Hole trap (98K): overlap of $V_2O + V_3O$ donor levels

→ consistent with *V.P.Markevich et al: Phys.Status Solidi A 208,No3, 568-571,2011*

Next step: isothermal annealing at high temperature to identify their formation kinetics

Summary and Outlook

Energy dependence of current related damage parameter α:

– α proportional "Effective" NIEL; "Classical" NIEL scaling violated

Energy dependence of cluster-related defects E(30K) and H-defects :

– Increasing electron energy → introduction rates increase (linear with E_e, power law with "effective" NIEL)
– Rates for H-defects → no [O] dependence
– Rate for E (30K) → [O] dependence

Isochronal annealing (80°C → 300°C)

– Concentration of the H defects increase with T_{an} up to ~ 180°C for DOFZ and ~ 240°C for STFZ materials followed by a decrease at higher T_{an}
– Annealing of E(30K) shows a maximum at ~ 240°C for DOFZ

Next steps:

– Isothermal annealing at high temperatures (already started)
– Aim: get more information of defect kinetics of H-defects and E(30K) (activation energies for the formation and decay, frequency factors) – for comparison with results from other methods like EPR → identify defect structures

Thank you for your attention!

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