Point and extended defects in silicon induced by electron irradiation – dependence on the particle energy

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Outline

- Motivation&Goals&Strategy
- Experimental results:
  - electrical characterization
  - HRTEM and EPR investigations
- Summary and Future plans

Motivation: *Bridge the gap between the defect analyses and device performances as a crucial step for further device developments*

Goals: *Identify the chemical structure of the defects causing the change in the detector performance at the operating temperature and find possible ways of improving the radiation hardness of Si sensors*

Strategy: *Irradiation experiments with electrons of different kinetic energies (between 1.5 MeV and 27 MeV), correlated studies of electrical characterization, EPR and HRTEM investigations* *(research started in 2012 with a romanian national funded project PNII-ID-PCE-2011-3 Nr. 72/5.10.2011)*

Electrical properties of the defects – influence on the device performances

In the aprox. n~p~0

Leakage current

$$\Delta LC(T) = q_0 \cdot A \cdot d \cdot N_T \cdot \frac{e_n(T) \cdot e_p(T)}{e_n(T) + e_p(T)}$$

with

$$e_n(T) = v_{th,n}(T) \cdot \sigma_n(T) \cdot N_C \cdot \exp\left(-\frac{E_c - E_t}{k_B \cdot T}\right)$$

$$e_p(T) = v_{th,p}(T) \cdot \sigma_p(T) \cdot N_V \cdot \exp\left(-\frac{E_t - E_V}{k_B \cdot T}\right)$$

(1)

Effective doping concentration

$$\Delta N_{eff}^{acceptor}(T) = -n_t^{acceptor}(T) = -N_t^{acceptor} \cdot \frac{e_p(T)}{e_n(T) + e_p(T)}$$

$$\Delta N_{eff}^{donor}(T) = +p_t^{donor}(T) = +N_t^{donor} \cdot \frac{e_n(T)}{e_n(T) + e_p(T)}$$

(2)

$$N_{eff}(T) = N_d + \sum_i p_{t,i}^{donor}(T) - \sum_j n_{t,j}^{acceptor}(T)$$

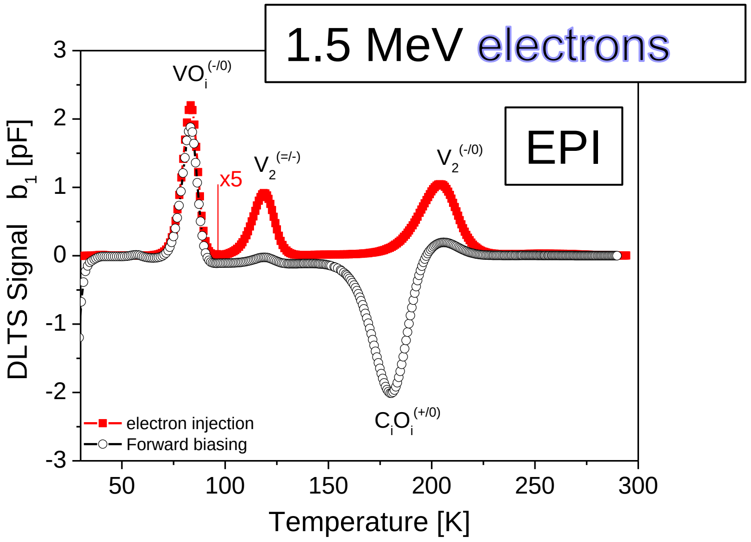
(3)

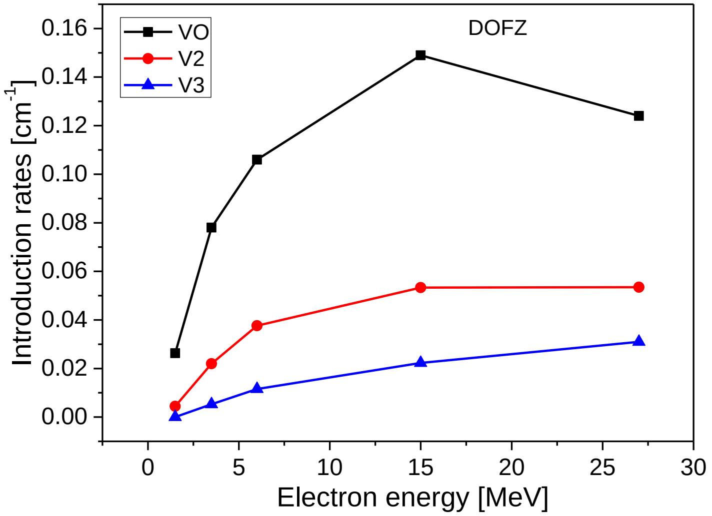
Defects responsible for the device electrical performance

Defects	**$\sigma_{n,p}$ [cm^2]**	**E_A [eV]**	**Assignment/References**	**Impact on electrical characteristics at RT**
E(30K)	σ_n= 2.3 x 10^{-14}	E_C - 0.1	Electron trap with a donor level in the upper half of the Si bandgap /[Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52]	On the N_{eff} by introducing positive space charge - *It makes the difference between proton and neutron irradiations* - *More generated in O rich material*
$BD_A^{0/++}$ $BD_B^{+/++}$	σ_n= 2.3 x 10^{-14} σ_n= 2.7 x 10^{-12}	E_C - 0.225 E_C - 0.15	**Bistable Thermal double donor TDD2** (two configurations A and/or B) - Electron trap with a donor level in the upper half of the Si bandgap/ [Appl. Phys. Lett. 50 (21) (1987) 1500; Nucl. Instr. and Meth. in Phys. Res. A 514 (2003) 18; Nucl. Instr. and Meth. in Phys. Res. A 556 (2006) 197; Nucl. Instr. and Meth. in Phys. Res. A 583 (2007) 58]	On the N_{eff} by introducing positive space charge - *Strongly generated in O rich material*
$I_p^{+/0}$ $I_p^{0/-}$	σ_p= (0.5-9) x10^{-15} σ_n=1.7 x10^{-15} σ_p= 9 x 10^{-14}	E_V + 0.23 E_C - 0.545	Donor level of V_2O or of a still unkown C related defect / [Appl. Phys. Lett. 81 (2002) 165; Appl. Phys. Lett. 83, 3216 (2003); Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52] Acceptor level of V_2O or of a still unkown C related defect/[Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52, Appl. Phys. Lett. 81 (2002) 165]	On the N_{eff} by introducing negative space charge and on LC - *Strongly generated in O lean material*
E_4 E_5	σ_n=1 x 10^{-15} σ_n=7.8 x 10^{-15}	E_C -0.38 E_C -0.46	Acceptor in the upper part of the gap associated with the double charged and single charged states of V_3, respectively (**$V_3^{=/-}$ and $V_3^{-/0}$**) / [J. Appl. Phys. 111 (2012) 023715.]	On LC
H(116K)	σ_p=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) / [Appl. Phys. Lett. 92 (2008) 024101, Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52-68]	On the N_{eff} by introducing negative space charge
H(140K)	σ_p=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)/[Appl. Phys. Lett. 92 (2008) 024101, Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52-68]	On the N_{eff} by introducing negative space charge
H(152K)	σ_p=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)/[Appl. Phys. Lett. 92 (2008) 024101, Nucl. Instr. and Meth. in Phys. Res. A 611 (2009) 52-68]	On the N_{eff} by introducing negative space charge

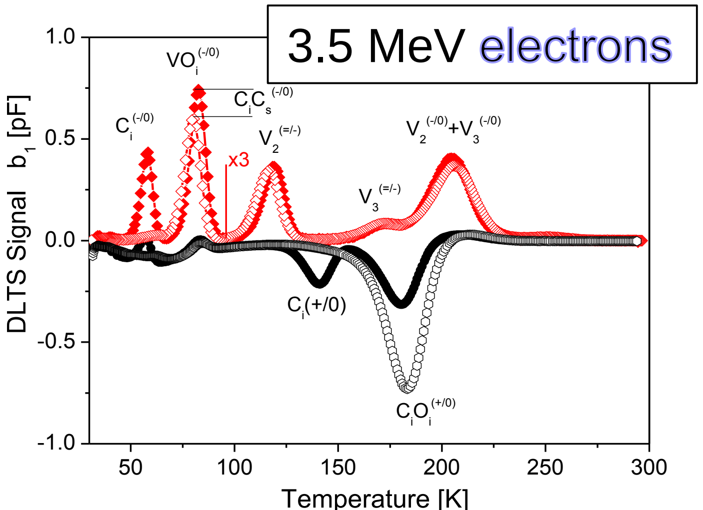
Generation of extended defects (clusters)

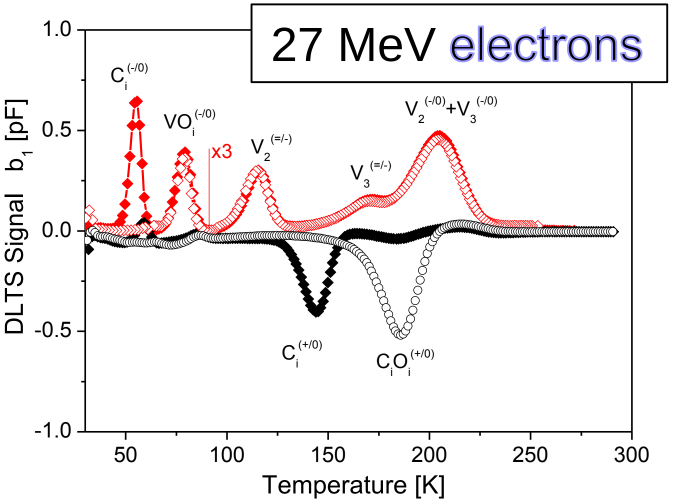
I) <u>low irradiation fluences</u> - DLTS measurements





- <u>Only point defects</u> are detected after irradiation with <u>1.5 MeV electrons</u>





- DOFZ (open symbols)
- STFZ (filled symbols)

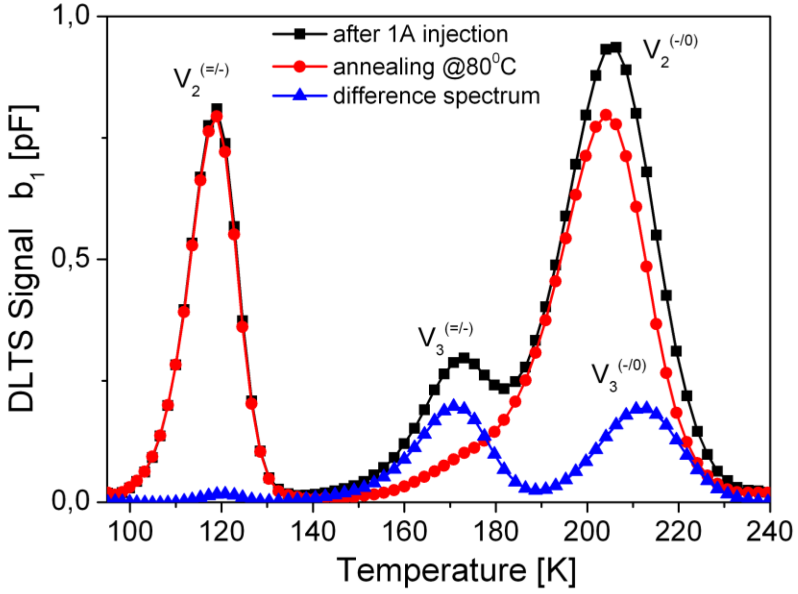
Starting with <u>3.5 MeV electrons</u> - **Generation of V_3**(small cluster)

Bistability of V_3 defects

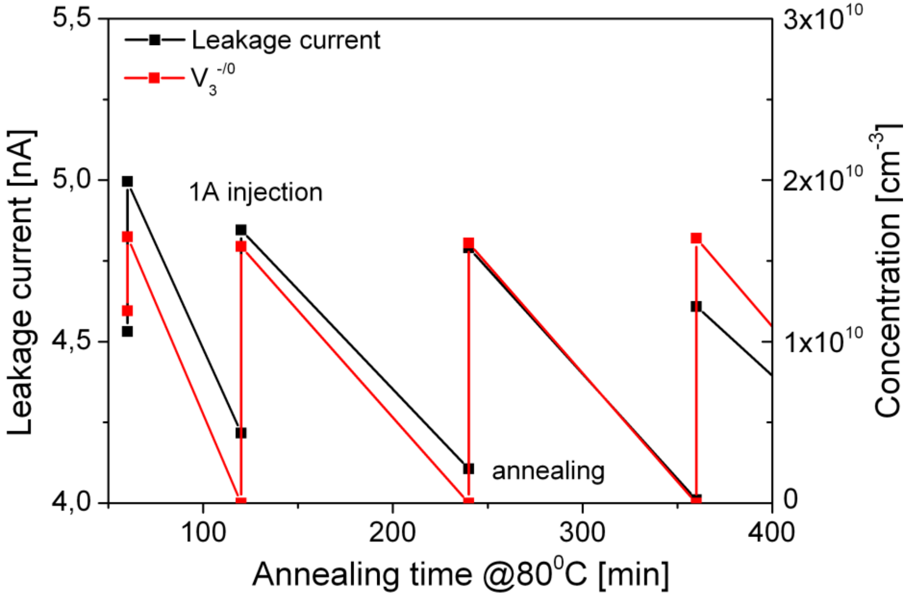
The reversible change from “part of the hexagonal ring” (PHR) configuration - electrically active, to a fourfold coordinated (FFC) configuration (FFC) - electrically inactive

(V. P. Markevich, et al. Phys. Rev. B 80, 235207, 2009; J. Coutinho, et al Phys. Rev. B 86, 174101, 2012)

Recovery of V_3 in PHR configuration after 1A forward injection

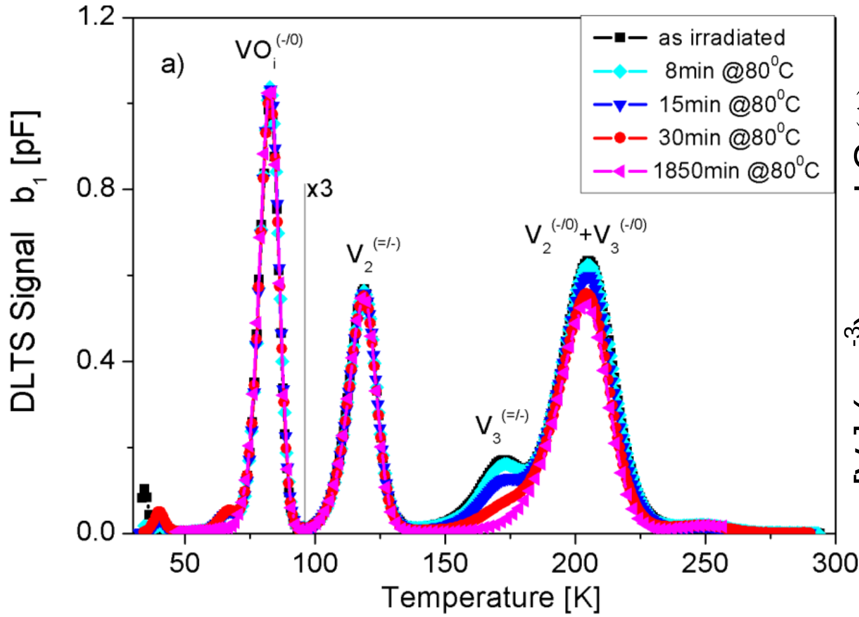


Direct correlation of V_3 in PHR configuration and the leakage current (LC).

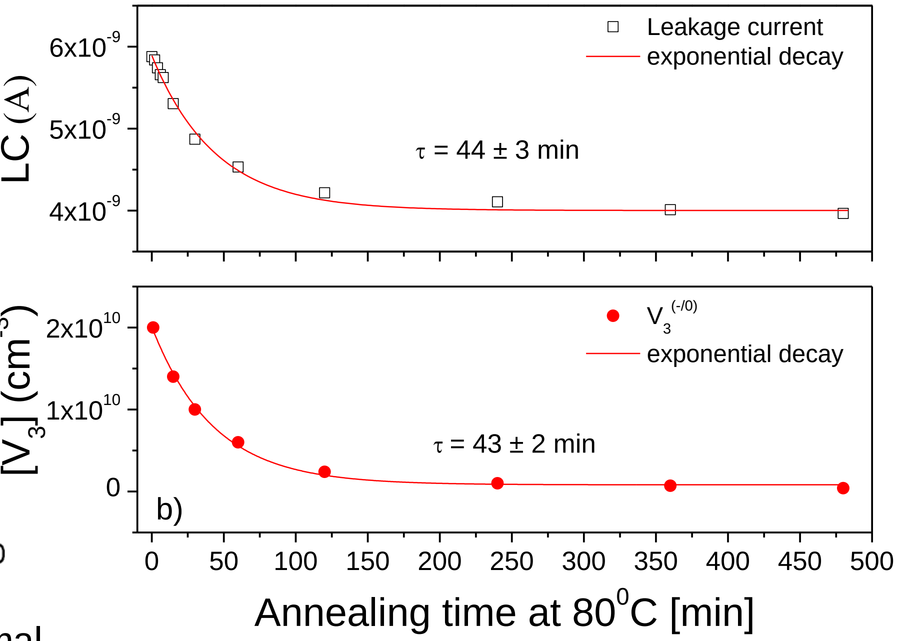


Influence on the leakage current seen previously by:
- R. M. Fleming et al, Appl. Phys. Lett. **90**, 172105, 2007
- I. Pintilie et al, Nucl. Instr. and Meth. in Phys. Res. A **611**, 52-68. 2009
- A. Junkes, et al, Nuclear Instruments and Methods in Physics Research A **612** ,525-529, 2010

Annealing out of V_3 (PHR configuration) and of the LC



(a) DLTS spectra recorded during the isothermal annealing at 80⁰C of a DOFZ diode irradiated with 6 MeV electrons with a fluence of $\Phi = 2.2x10^{12}$ cm^{-2};



(b) Annealing behavior of the V_3 concentration in PHR configuration and of the leakage current measured at 20⁰C.

→ After electron irradiation the variation seen in the leakage current is entirely related to the change in the concentration of V_3 in PHR configuration

Trapping parameters of $V_3^{-/0}$ (PHR configuration)

Parameters needed to be known for any realistic simulation of the LC, N_{eff} or trapping times:

$E_T = E_c - 0.458$ eV; $\sigma_n = 2.4\text{x}10^{-15}$ cm^2;
$\sigma_p = ?$

$$\Delta LC(T) = q_0 \cdot A \cdot d \cdot N_T \cdot \frac{e_n(T)\cdot e_p(T)}{e_n(T)+e_p(T)}$$

with

$$e_n(T) = v_{th,n}(T)\cdot \sigma_n(T)\cdot N_C \cdot \exp(-\frac{E_c - E_t}{k_B \cdot T})$$

$$e_p(T) = v_{th,p}(T)\cdot \sigma_p(T)\cdot N_V \cdot \exp(-\frac{E_t - E_V}{k_B \cdot T})$$

$$\Delta N_{eff}^{acceptor}(T) = -n_t^{acceptor}(T) = -N_t^{acceptor} \cdot \frac{e_p(T)}{e_n(T)+e_p(T)}$$

By accounting the all variation of LC during annealing at 80C as caused entirely to the change in the concentration of V_3 in PHR configuration the σ_p of V_3 is determined to be **$\sigma_p = 2.5\text{x}10^{-13}$ cm^2**

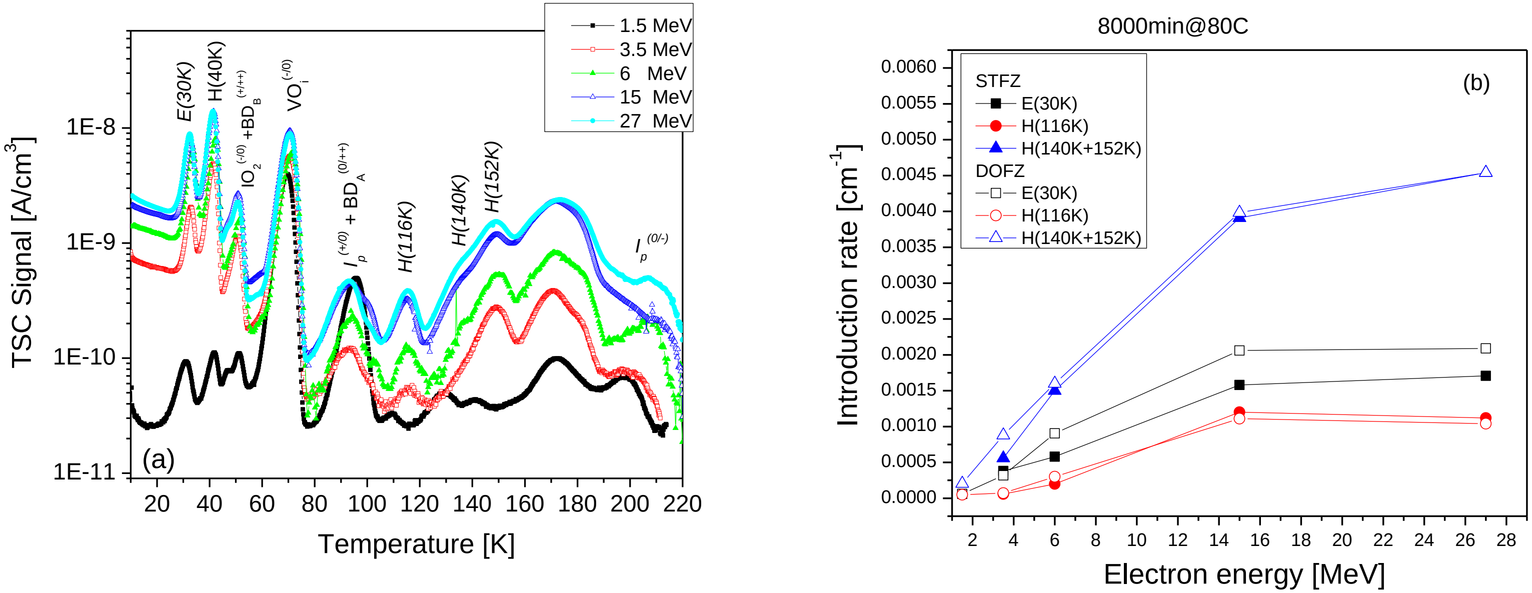
→ The V_3 in single acceptor state is: - **an efficient generation center** (in this case explaining fully the annealing of the LC as well as of about ~30% of the total LC value

→ The V_3 in single acceptor state - **has also some effect on N_{eff} (maximum 1/40 part of [V_3] may be negatively charged at 20^0C)**

Ex: [V_3]=10^{13} cm^{-3} → ΔLC (20^0C) ~ 1μA; ΔN_{eff}(20^0C)~ - $3\text{x}10^{11}$ cm^{-3}

Generation of extended defects (clusters)
II) high irradiation fluences - TSC measurements

E(30K), H(116K), H(140K) and H(152K) defects – seen already after irradiation with 1.5 MeV electrons!

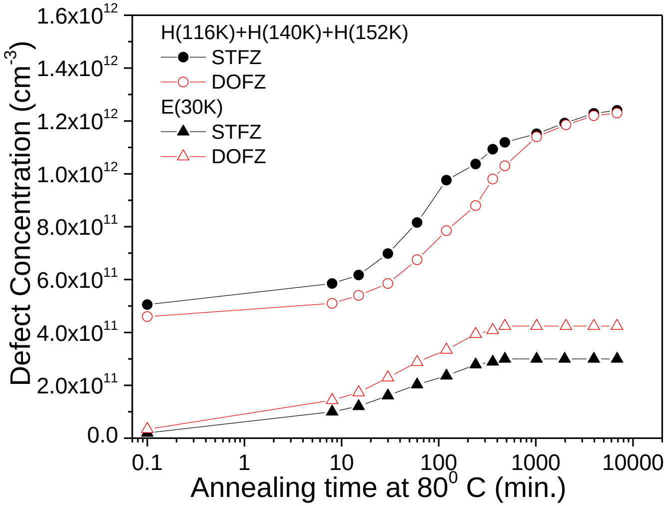


a) TSC spectra after irradiation with different electron energies measured on DOFZ material after annealing for 8 min at 80 ^{0}C;

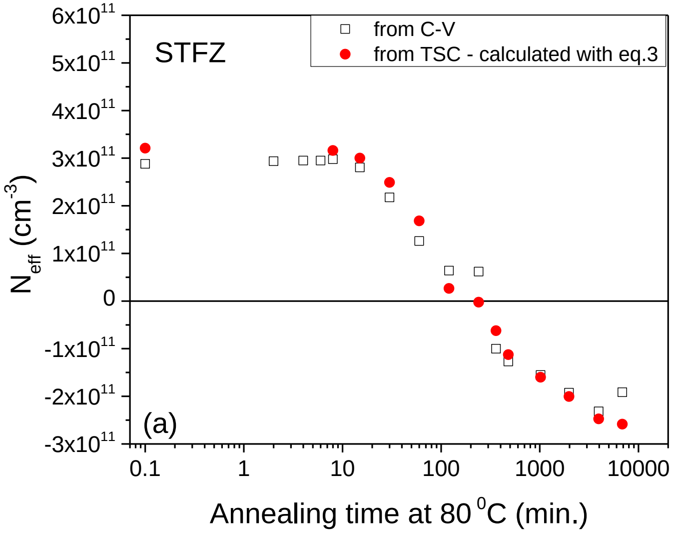
b) The maximum introduction rates of extended defects E(30K), H(116K), H(140K) and H(152K) as function of electrons energy (10% errors)

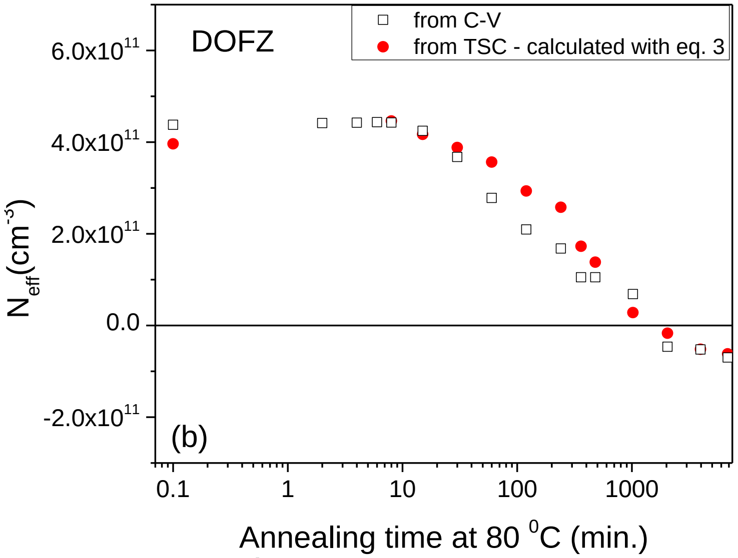
Impact of E(30K), H(116K), H(140K) and H(152K) defects on the electrical performance of the device

annealing-in of H(116K), H(140K) and H(152K) defects in diodes irradiated with 15 MeV electrons

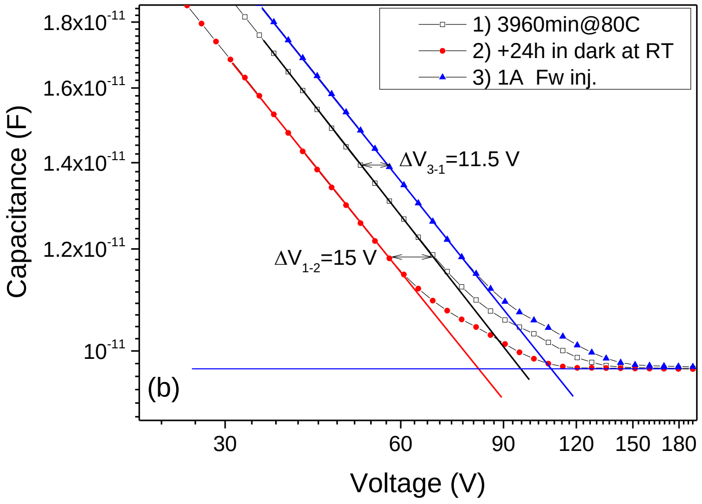


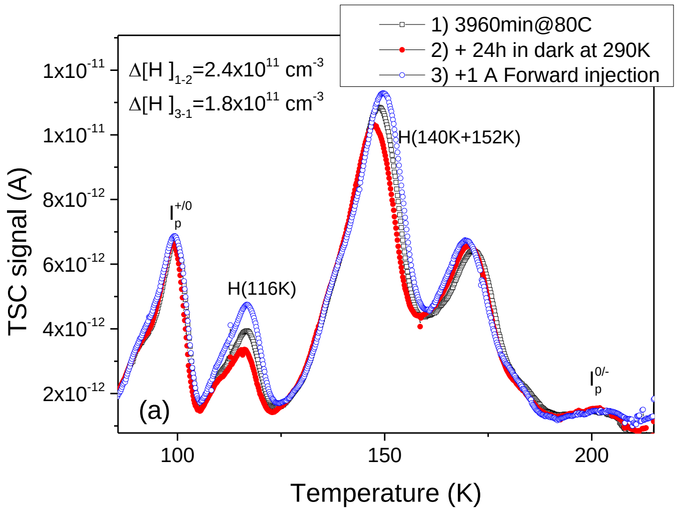
- **Account in their full concentration to N_{eff}** (E(30K) with positive charge and H defect with negative charge)
- **No contribution to the leakage current is seen during the annealing (as expected for coulombic centers)** → ex. for the deepest level H(152K) (E_t=E_v+0.42 eV; σ_p=2.3x10^{-14} cm^2) this means that $\sigma_n < \sigma_p$
- **A delay of annealing in of H defects is observed in O rich materials**

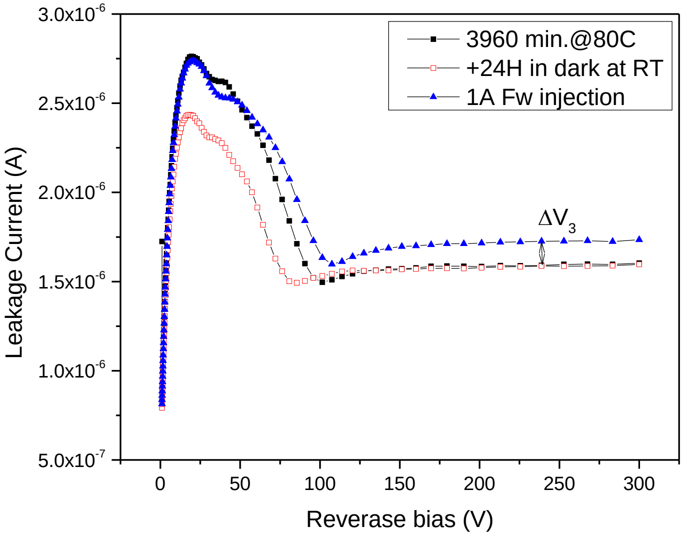




Bistability of the H(116K), H(140K) and H(152K) defects and the corresponding change in the depletion voltage and LC of a STFZ diode irradiated with 27 MeV electrons and annealed for 3960min. at 80^0C







- The change in the concentration of H defects affects only the Depletion Voltage (so, only Neff)
- A change in the LC seen only after 1A Fw injection – when V_3 in PHR configuration is activated (according to the introduction rate only 15% of V_3 is activated in the present case)

Cluster-related defects in Si irradiated with high energy electrons observed by HRTEM

Studied samples:

1. STFZ Si irradiated at RT with electrons: energy 15 MeV, fluency $1x10^{16}$ cm^{-2} .
2. DOFZ Si irradiated at RT with electrons: energy 27 MeV, fluency $2x10^{16}$ cm^{-2}.

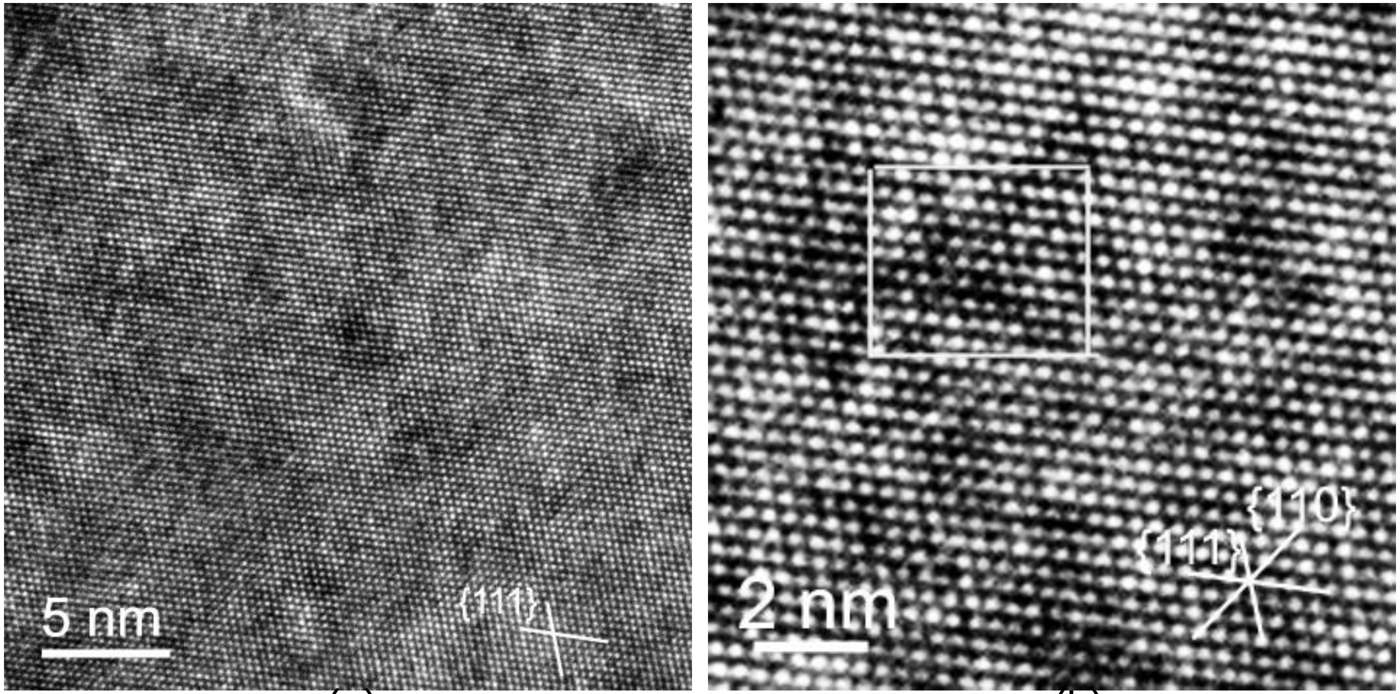
Instrument:

High resolution analytical JEOL ARM 200F operating at 200 kV, with a resolution in the HRTEM mode of 0.19 nm.
HRTEM imaging was performed with the Si specimens oriented along the [110] zone axis.

Specimen preparation for HRTEM:

- sawing strips from the Si irradiated wafer;
- gluing the strips face to face with a glue which cured at room temperature;
- mechanical thinning followed by ion milling.

The 15 MeV irradiated STFZ Si specimen



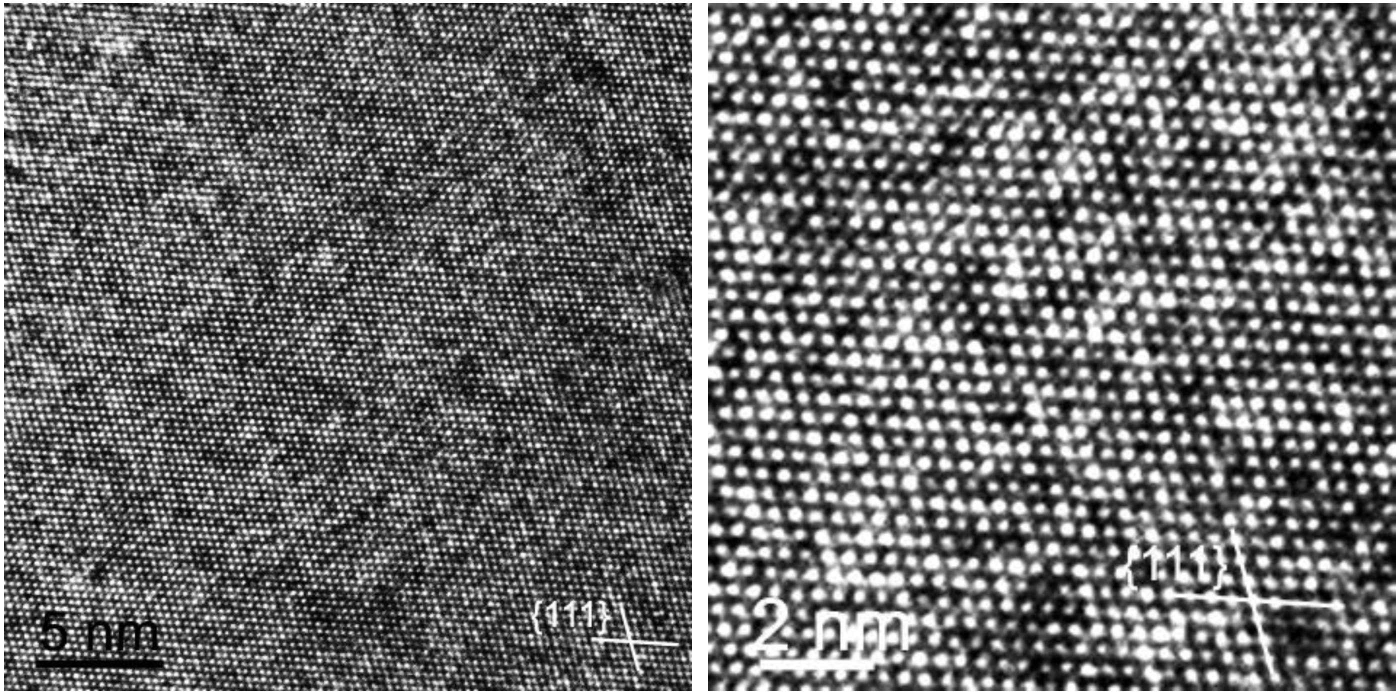
(a) (b)

HRTEM images of the as irradiated specimen. Clusters of point defects (vacancies and interstitials) are revealed by their darker contrast. Some aggregate in the {111} or {110} planes, as revealed at higher magnification (b)-boxed.

The contrast at the {111} defect in the HRTEM image can be interpreted as resulting from a Frank vacancy loop formed by accumulating vacancies in the {111} plane. The defect is further stabilized by a partial filling with interstitials [L. Fedina et al Phil. Mag. A 77, 423 (1998)].

The contrast at the {110} defect can be interpreted as agglomeration of self-interstitials [S.Takeda, T. Kamino PRB 51, 2148 (1995)].

The 27 MeV irradiated DOFZ Si specimen

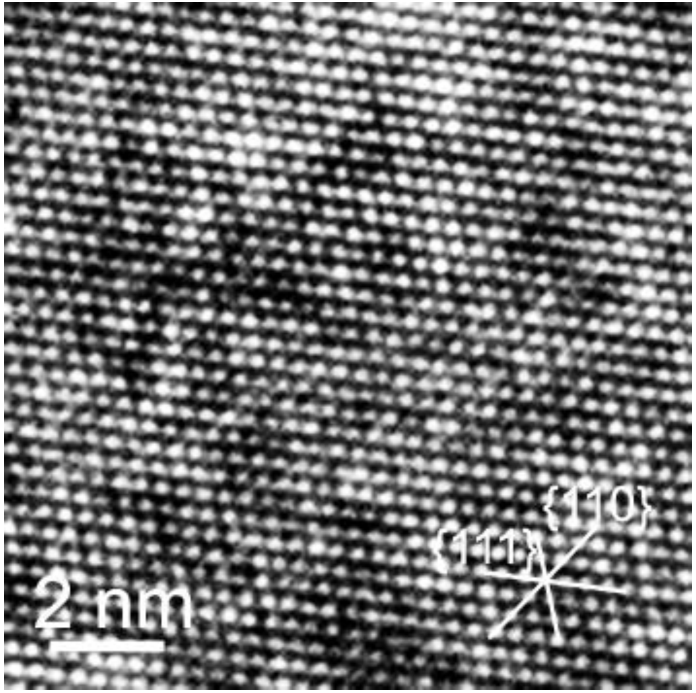


(a) (b)

HRTEM images of the as irradiated specimen. A high density of clusters of point defects (vacancies and interstitials) appears, revealed, as previously, by their darker contrast. Some clusters are grouped along the principal crystallographic directions (a), or agglomerate forming darker patches with sizes of 2-3 nm (b).

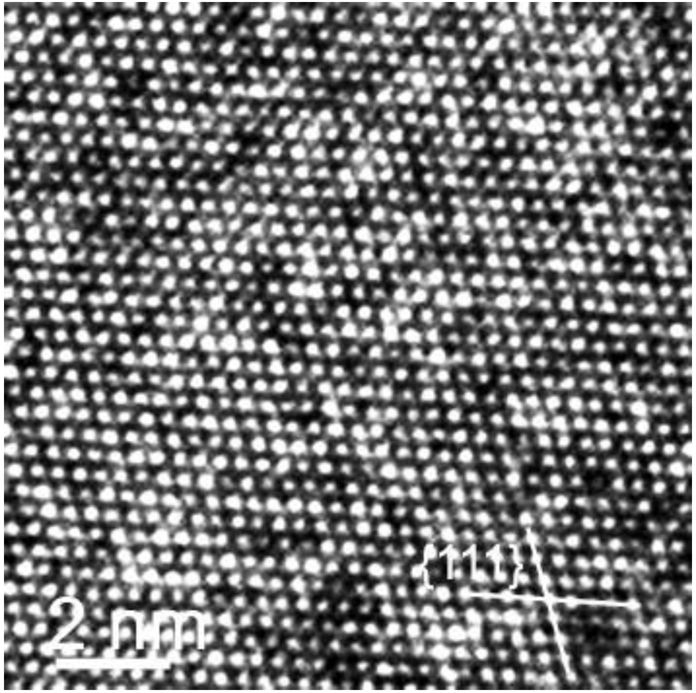
Effects of high energy electron irradiation on FZ Si samples with and without diffused oxygen.

STFZ Si, as irradiated



15 MeV; 1x10^{16} cm^{-2}

DOFZ Si, as irradiated

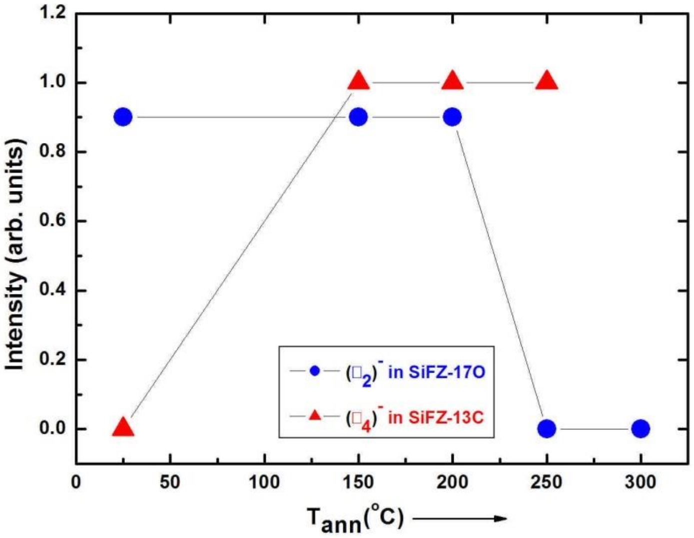


27 MeV; 2x10^{16} cm^{-2}

Although the energy and fluency for the DOFZ Si sample were higher than for the STFZ Si sample, no significant differences appeared in the density of the clusters of defects introduced by the high energy electron irradiation, as revealed by HRTEM. One concludes that it might exist a saturation effect in the rate of introducing the clusters of defects at high energies and that these defects are not related to the presence of oxygen in the specimen.

EPR investigations

Center	Host	*g*	T_{meas} (K)	Production	Annealing (^{0}C) / IR bleaching
DB	SiFZ-17O SiFZ-13C	2.0060	300-10	As received.	No photoeffect.
GGA2	SiFZ-13C	2.0028	< 50	As received	T_{ann} = 150 ^{o}C No photoeffect.
P_0	SiFZ-13C	1.9999	100	As received. Strong μW saturation	No photoeffect.
P_o	SiFZ-17O	1.9999	100	After T_{ann}=150^{o}C	No photoeffect.
G7 / $[(v_{Si})_2]$-	SiFZ-17O SiFZ-13C*	$g_{\|\|}$ =2.0115 $g_{\_\|}$=2.0080	<150	637nm photoinduced at T < 150K (*) After T_{ann}=150^{o}C	T_{ann} = 250 ^{o}C
A3 / $[(v_{Si})_4]$-	SiFZ-13C	$g_{\|\|}$ =2.0028 $g_{\_\|}$=2.0103		637nm photoinduced (T < 150K) after T_{ann}=150^{o}C	T_{ann} = 300 ^{o}C



Summary and future plans

1. After low irradiation fluences, small clusters of vacancies (V_3) are observed for electrons energies ≥ 3.5 MeV
2. All the electrical parameters of V_3 are determined → significant influence on LC and Neff
3. After high irradiation fluences other clusters of vacancies or interstitials are observed already after irradiation with 1.5 MeV!
4. Common feature of vacancies clusters (V_3-V_6) is their bistability (in this respect the H defects may be associated with V_4-V_6)
5. The HRTEM studies revealed that the high energy electron irradiation introduces in FZ Si clusters of point defects (vacancies and interstitials) not related to the presence of oxygen in the samples. The density of the introduced defect clusters, as observed in the HRTEM images, does not apparently differ, although the two samples were irradiated at different electron energies and fluencies. It might exist an effect of saturation in the rate of introducing the clusters of defects at high energies.
6. V_4 was identified by EPR after thermal annealing and it is a good candidate for being associated with one of the H defects. Still a lot of work to do on evaluation of EPR spectra on samples irradiated with 27 MeV electrons
7. Future plans: EPR and HRTEM investigations on samples irradiated with low energy electrons

Thank You !