Institute of Electronic Materials Technology

Joint Laboratory for Characterisation
of Defect Centres in Semi-Insulating Materials

High-resolution photoinduced transient spectroscopy of defect centres in epitaxial silicon irradiated with high proton fluences

Paweł Kamiński [1], Roman Kozłowski [1],
Jarosław Żelazko [1], and Eckhart Fretwurst [2]

[1] *Institute of Electronic Materials Technology,*
[2] *Institute of Experimental Physics, Hamburg University*

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Outline

- Samples – pad detectors with active layer of epitaxial silicon irradiated with 24 GeV/c protons; after removing p^+ layer planar ohmic contacts made on the surface of *n*-type epilayer
- Details of HRPITS measurements
- HRPITS images of spectral fringes for radiation defects in standard and oxygenated epitaxial layers – effect of increasing the proton fluence from 1.0×10^{16} to $1.7\times10^{16}cm^{-2}$ on the properties and concentrations of defect centers in the as-irradiated and annealed material
- Changes in the concentrations of selected defect centers with increasing annealing temperature from 80 to 240 ^oC
- Conclusions

Samples

- Epitaxial detectors fabricated by CiS, Erfurt (Germany)

  Process: 261636-13 CiS standard (label – EPI ST 150)

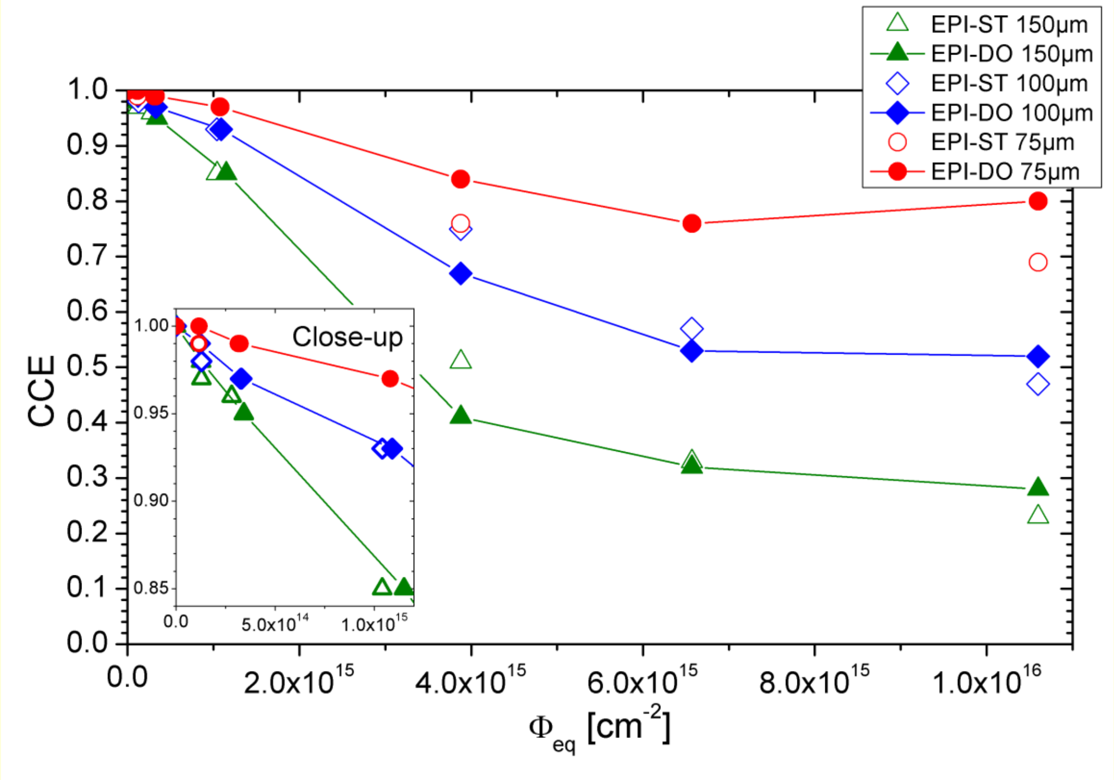
  Process: 261636-9 CiS oxygenated (label – EPI DO 150)

- Epitaxial layers: ITME Si epi., <100>, *n*-type,
  500 Ωcm, ~ 150 μm,
  [O] = 4.5 10^{16} cm^{-3} (EPI ST 150)
  [O] = 1.4 $\times 10^{17}$ cm^{-3} (EPI DO 150)

- 24 GeV/c proton irradiation: CERN PS source

  Fluences: 1.0×10^{16} and 1.7×10^{16} cm^{-2}

Charge collection efficiency

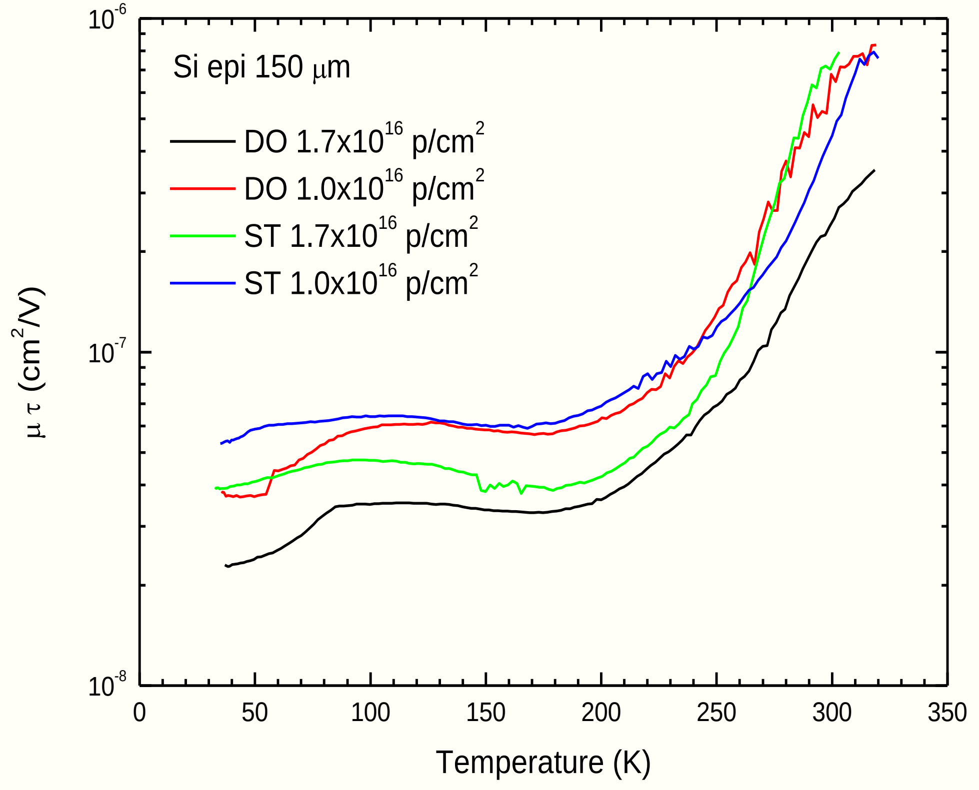


Jörn Lange *et al*. 13th RD50 Workshop, CERN, November 2008

Details of HRPITS measurements

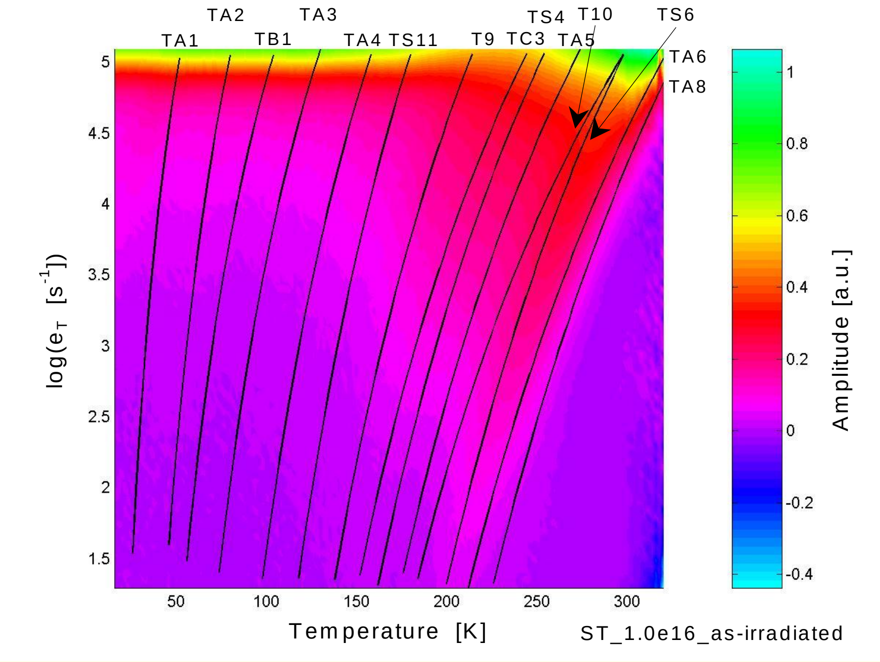
- Temperature range: 30 – 300 K, ΔT = 2 K
- Excitation source: 5 mW, 650 nm laser diode (hν = 1.908 eV)
- Excitation pulse parameters: Period – 250 ms, Width – 50 ms
- Photon flux: 1.3×10^{17} $cm^{-2}s^{-1}$
- BIAS: 20 V
- Gain: 1×10^{6} – 1×10^{7} V/A
- AVG: 250 waveforms
- Analysis of photocurrent relaxation waveforms:
  - 2D correlation procedure (multi-window approach) $\rightarrow$ images of correlation spectral fringes for radiation defect centres
  - 2D inverse Laplace transformation algorithm $\rightarrow$ images of Laplace fringes for radiation defect centres

Temperature dependence of mobility lifetime product



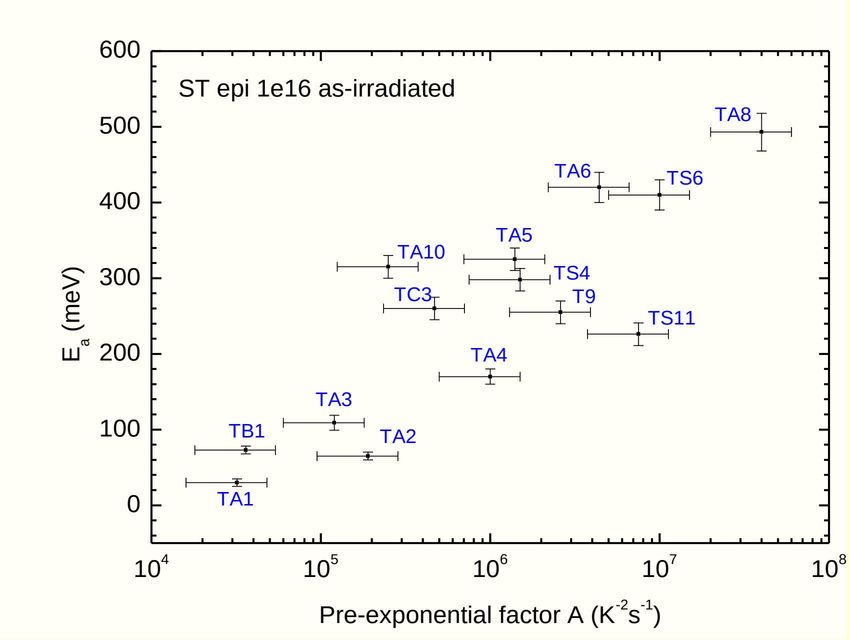
Defect structure of ST Si-epitaxial layer after irradiation with a fluence of $1x10^{16}$ cm^{-2}

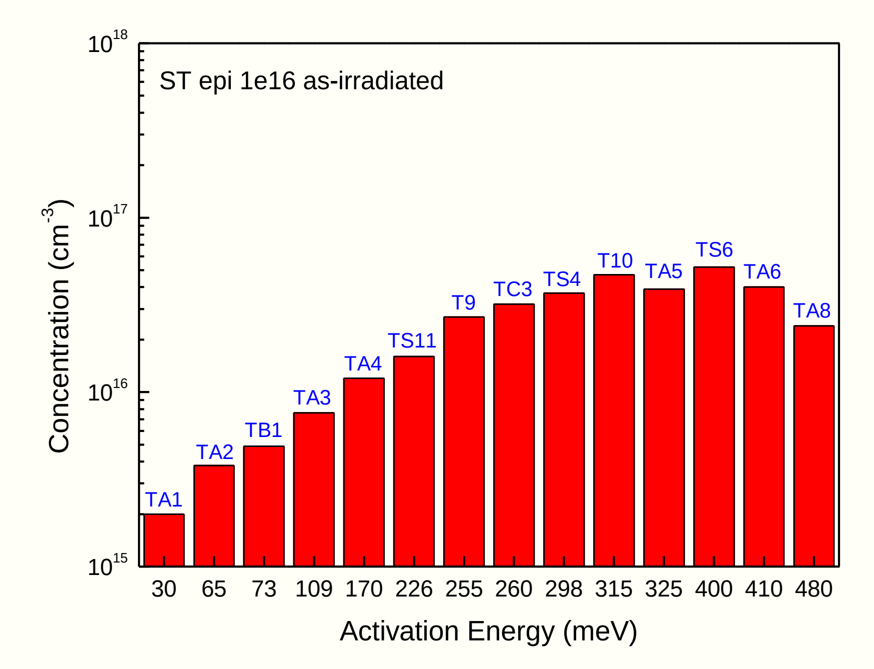
Image of correlation spectral fringes



Concentrations of defect centers

Parameters of defect centers (14 traps)





Parameters of defect centers obtained from the HRPITS studies for ST Si epi 150 μm as-irradiated with a proton fluence of 1.0×10^{16} cm^{-2}.

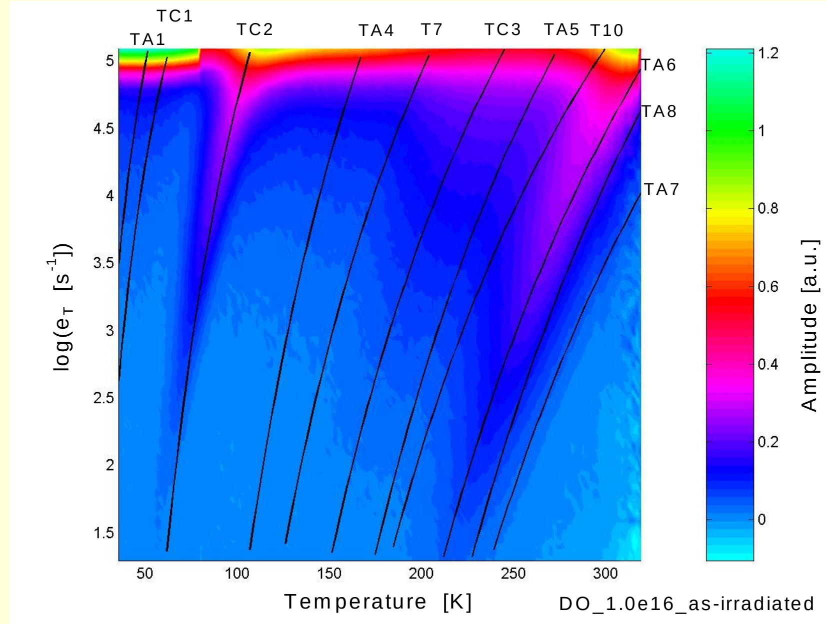
Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TA1	30±5	3.2×10^4	2.0×10^{15}	shallow donors
TA2	65±5	1.9×10^5	3.8×10^{15}	shallow donors
TB1	73±5	3.6×10^4	4.9×10^{15}	I aggregates (I_3)
TA3	109±5	1.2×10^5	7.6×10^{15}	I aggregates (I_4)
TA4	170±5	1.0×10^6	1.2×10^{16}	VO (-/0)
TS11	226±10	7.5×10^6	1.6×10^{16}	V_2O (2-/-)
T9	255±10	2.6×10^6	2.7×10^{16}	IO_2
TC3	260±10	4.7×10^5	3.2×10^{16}	V_2 (2-/-)
TS4	298±10	1.5×10^6	3.7×10^{16}	new, unidentified, vacancy or self-interstitial aggregate ?
T10	315±10	2.5×10^5	4.7×10^{16}	V_3 (2-/-) , (110) planar configuration, C_{2v} symmetry, $E_c - 0.28$ eV [1]
TA5	325±10	1.4×10^6	3.9×10^{16}	new, unidentified, vacancy aggregate V_4 ?
TS6	400±20	1.0×10^7	5.2×10^{16}	new, unidentified, vacancy or self-interstitial aggregate ?
TA6	410±20	4.4×10^6	4.0×10^{16}	V_2 (-/0)
TA8	480±20	4.0×10^7	2.4×10^{16}	V_3 (-/0) , (110) planar configuration, C_{2v} symmetry, $E_c - 0.5$ eV [1]

* E_a and A - the activation energy and pre-exponential factor in the Arrhenius formula $e_T = AT^2 exp(-E_a/kT)$

[1] – Markevich *et al.* Physical Review B **80,** 235207 (2009)

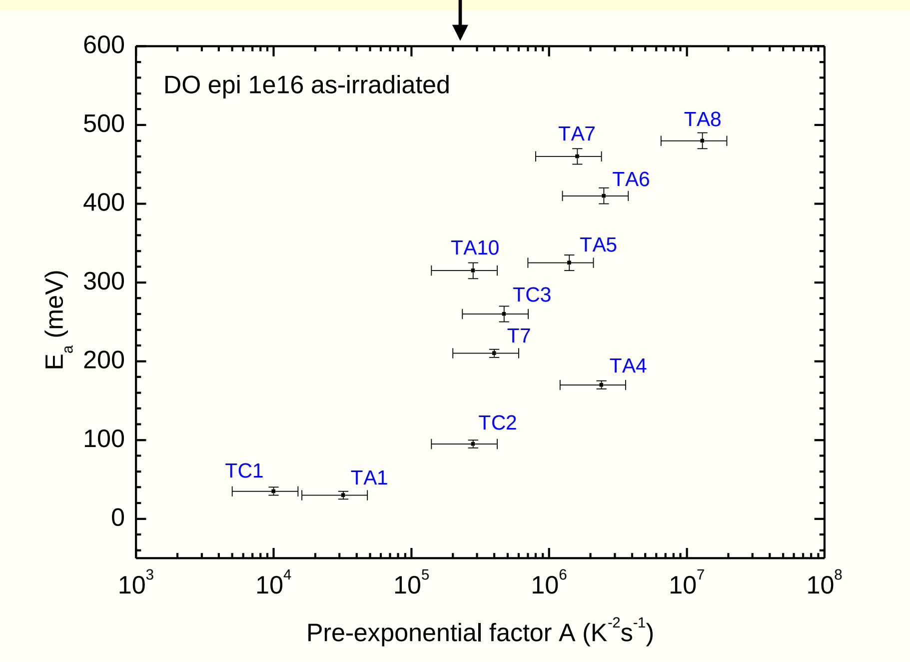
Defect structure of DO Si-epitaxial layer after irradiation with a fluence of $1x10^{16}$ cm^{-2}

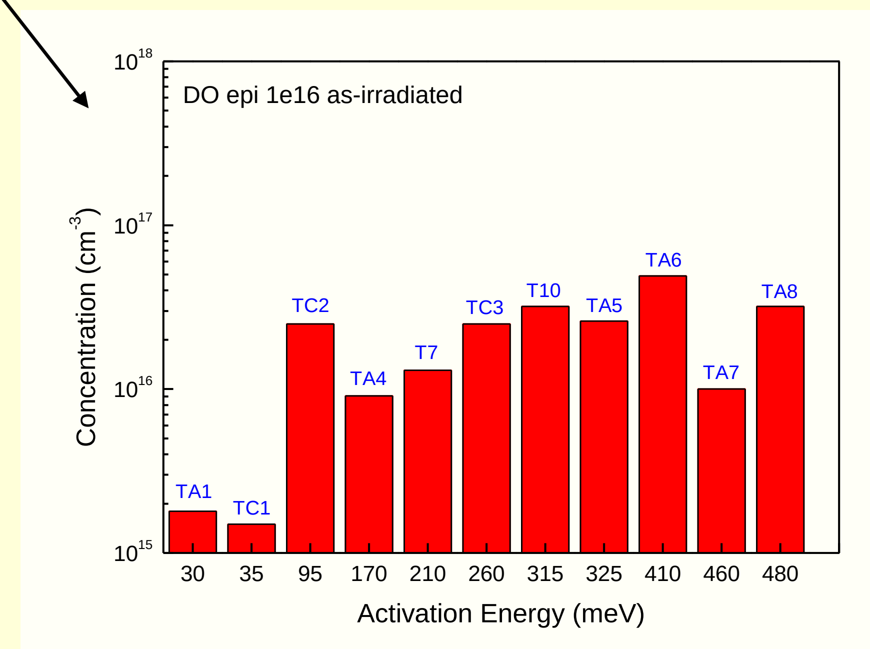
Image of correlation spectral fringes



Concentrations of defect centers

Parameters of defect centers (11 traps)





Parameters of defect centers obtained from the HRPITS studies for DO Si epi 150 μm as-irradiated with a proton fluence of 1.0×10^{16} cm^{-2}.

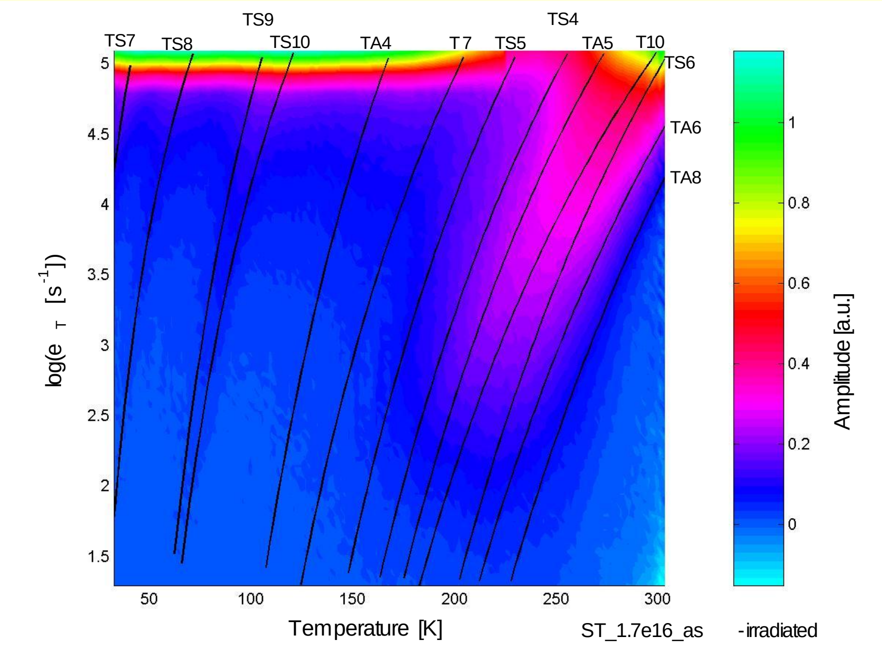
Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TA1	30±5	3.2×10^{4}	1.8×10^{15}	shallow donors
TC1	35±5	1.0×10^{4}	1.5×10^{15}	shallow donors
TC2	95±5	2.8×10^{5}	2.5×10^{16}	V_3 fourfold coordinated D_3 symmetry [1]
TA4	190±5	2.4×10^{6}	9.1×10^{15}	VO (-/0)
T7	210±5	4.0×10^{5}	1.3×10^{16}	V_2 (+/0)
TC3	260±10	4.7×10^{5}	2.5×10^{16}	V_2 (2-/-)
T10	315±10	2.8×10^{5}	3.2×10^{16}	V_3 (2-/-) , (110) planar configuration, C_{2v} symmetry, E_c – 0.28 eV [1]
TA5	325±10	1.4×10^{6}	2.6×10^{16}	new, unidentified, vacancy aggregate V_4 ?
TA6	410±10	2.5×10^{6}	4.9×10^{16}	V_2 (-/0)
TA7	460±10	1.6×10^{6}	1.0×10^{16}	E5, vacancy aggregate V_4 ?
TA8	480±10	1.3×10^{7}	3.2×10^{16}	V_3 (-/0) , (110) planar configuration, C_{2v} symmetry, E_c – 0.5 eV [1]

* E_a and A - the activation energy and pre-exponential factor in the Arrhenius formula $e_T = AT^2 exp(-E_a/kT)$

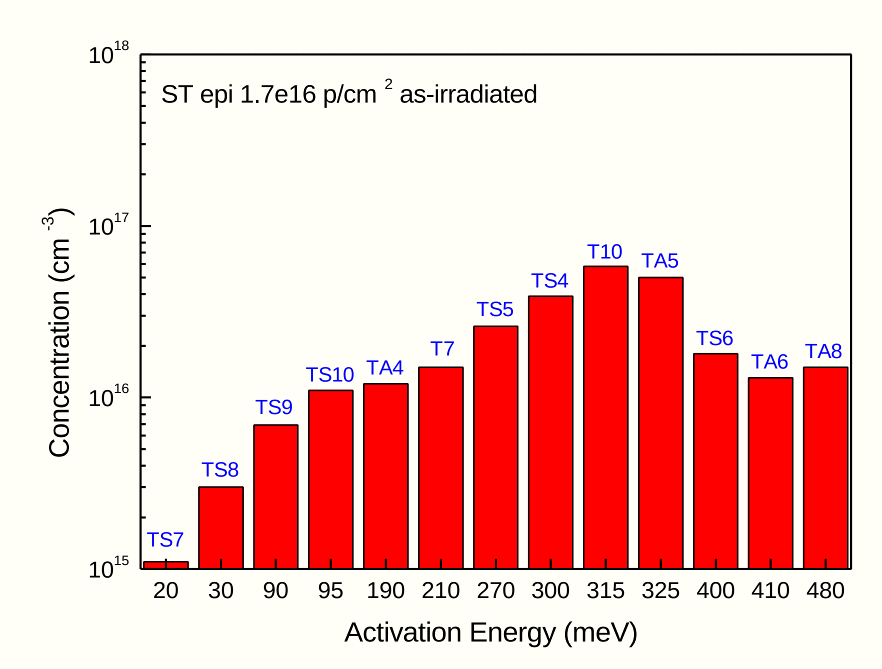
[1] – Markevich *et al.* Physical Review B **80,** 235207 (2009)

Defect structure of ST Si-epitaxial layer after irradiation with a fluence of $1.7x10^{16}$ cm^{-2}

Image of correlation spectral fringes

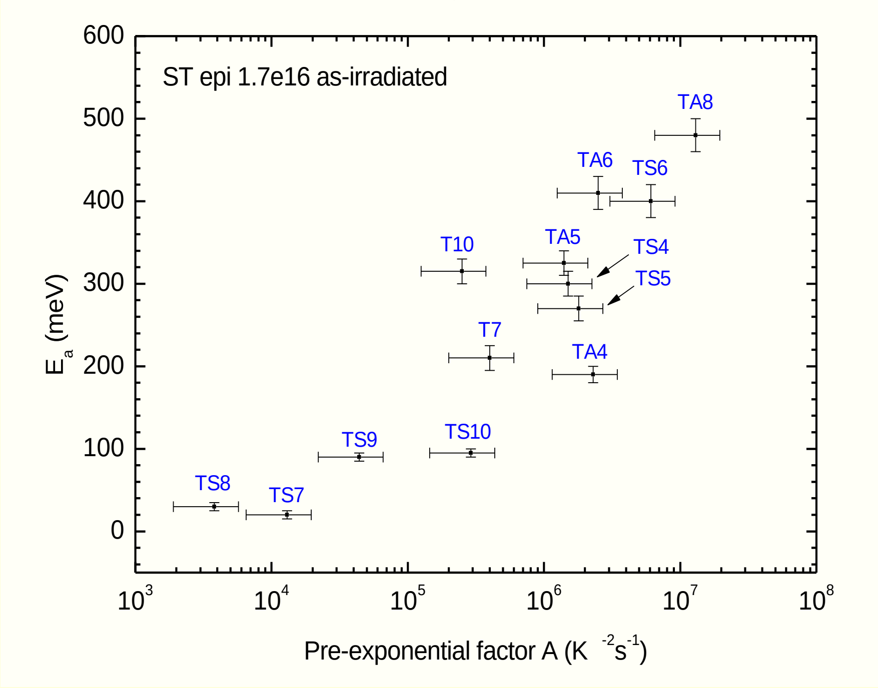


Concentrations of defect centers



Parameters of defect centers

(13 traps)



Parameters of defect centers obtained from the HRPITS studies for ST Si epi 150 μm as-irradiated with a proton fluence of 1.7×10^{16} cm^{-2}.

Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TS7	20±5	1.3×10^{4}	1.1×10^{15}	shallow donors
TS8	30±5	3.8×10^{3}	3.0×10^{15}	shallow donors
TS9	90±5	4.4×10^{4}	6.9×10^{15}	I aggregates (I_3)
TS10	95±5	2.9×10^{5}	1.1×10^{16}	V_3 fourfold coordinated D_3 symmetry [1]
TA4	190±10	2.3×10^{6}	1.2×10^{16}	VO (-/0)
T7	210±10	4.0×10^{5}	1.5×10^{16}	V_2 (+/0)
TS5	270±10	1.8×10^{6}	2.6×10^{16}	IO_2
TS4	300±10	1.5×10^{6}	3.9×10^{16}	new, unidentified, vacancy or self-interstitial aggregate ?
T10	315±10	2.5×10^{5}	5.8×10^{16}	V_3 (2-/-) , (110) planar configuration, C_{2v} symmetry, E_c – 0.28 eV [1]
TA5	325±10	1.4×10^{6}	5.0×10^{16}	new, unidentified, vacancy aggregate V_4?
TS6	400±10	6.1×10^{6}	1.8×10^{16}	new, unidentified, vacancy or self-interstitial aggregate ?
TA6	410±15	2.5×10^{6}	1.3×10^{16}	V_2 (-/0)
TA8	480±10	1.3×10^{7}	1.5×10^{16}	V_3 (-/0) , (110) planar configuration, C_{2v} symmetry, E_c – 0.5 eV [1]

*E_a and A – the activation energy and pre-exponential factor in the Arrhenius formula $e_T=AT^2exp(-E_a/kT)$

[1] – Markevich *et al.* Physical Review B **80,** 235207 (2009)

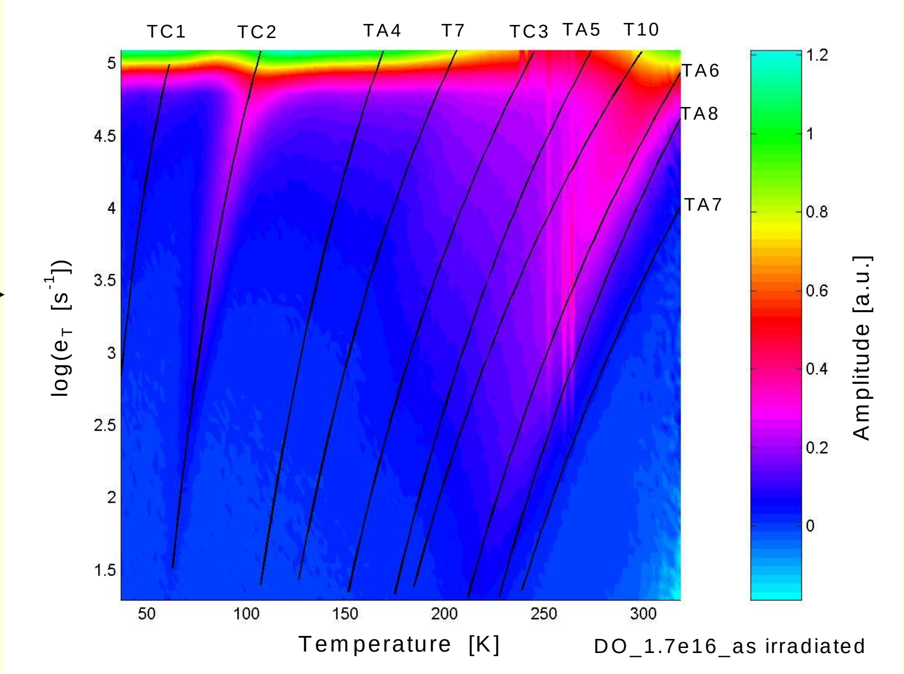
Defect structure of DO Si-epitaxial layer after irradiation with a fluence of 1.7×10^{16} cm^{-2}

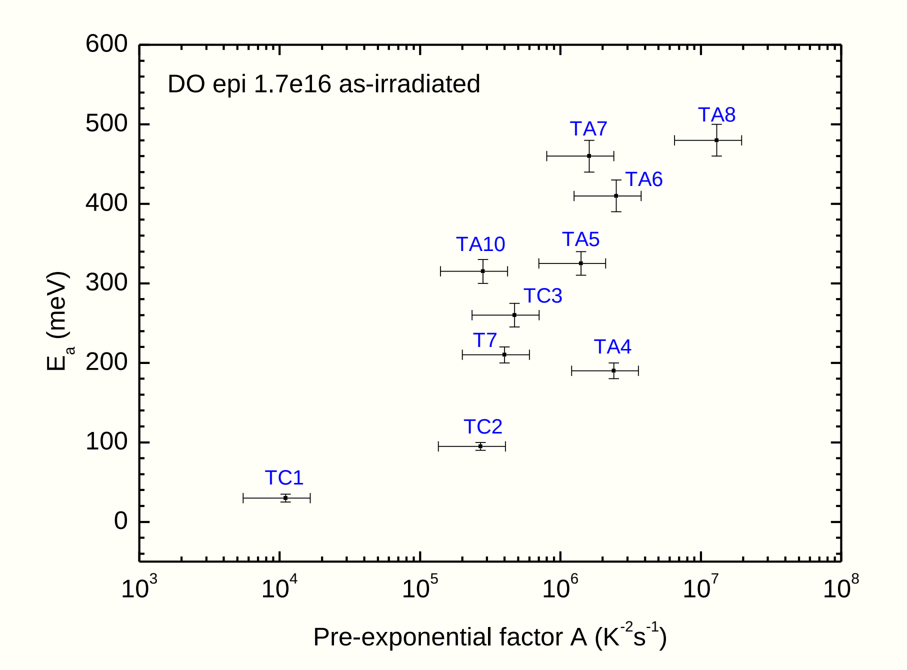
Image of correlation spectral fringes

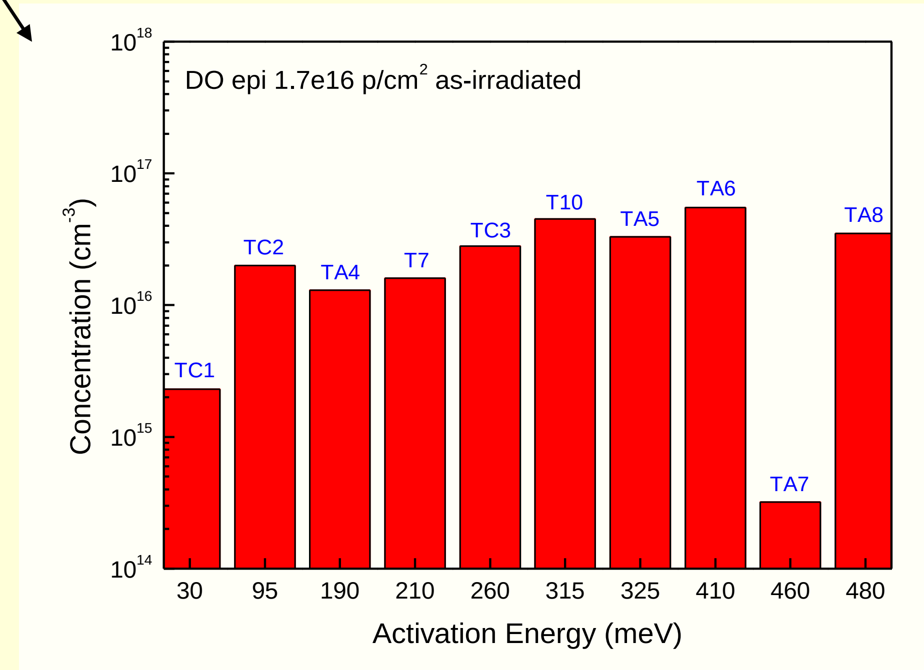
Concentrations of defect centers

Parameters of defect centers

(10 traps)





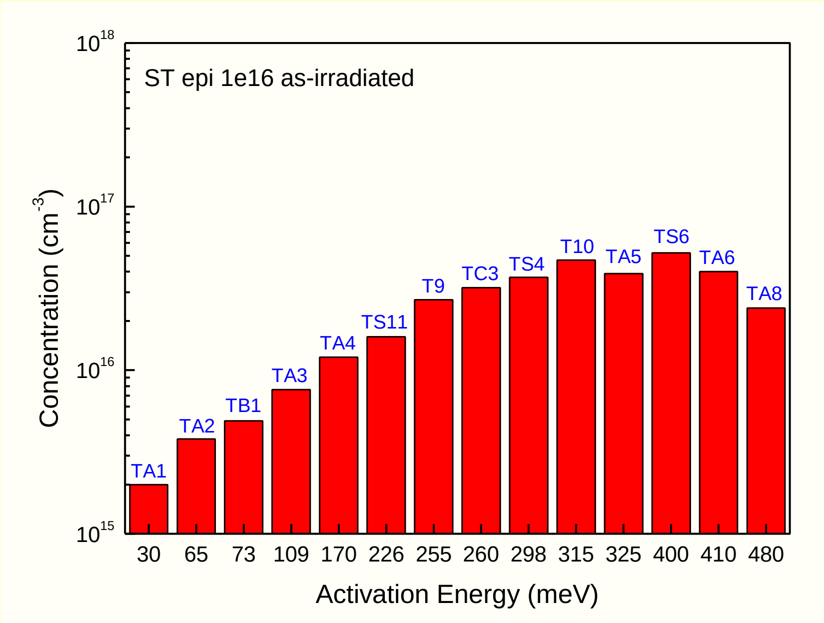


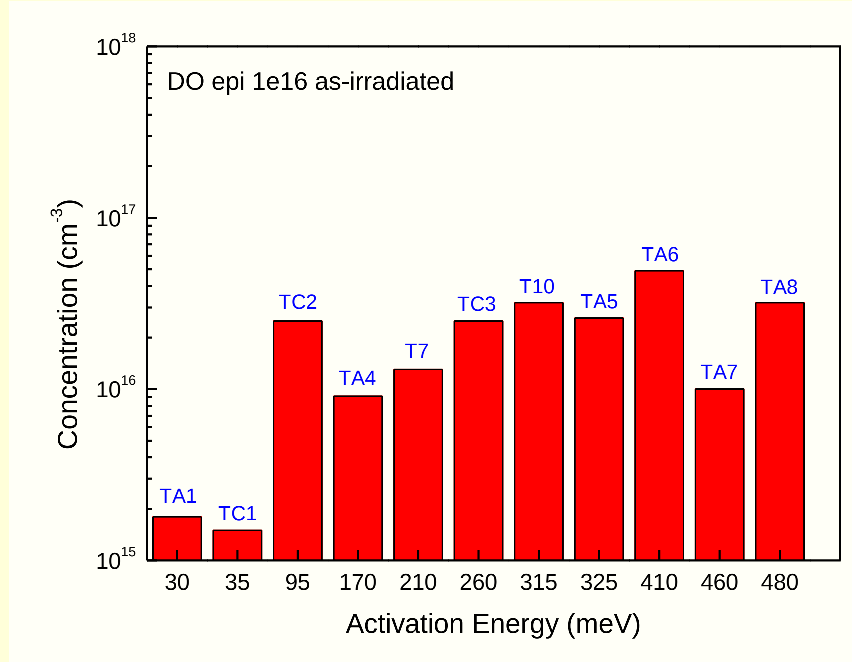
Parameters of defect centers obtained from the HRPITS studies for DO Si epi 150 µm as-irradiated with a proton fluence of 1.7×10^{16} cm^{-2}.

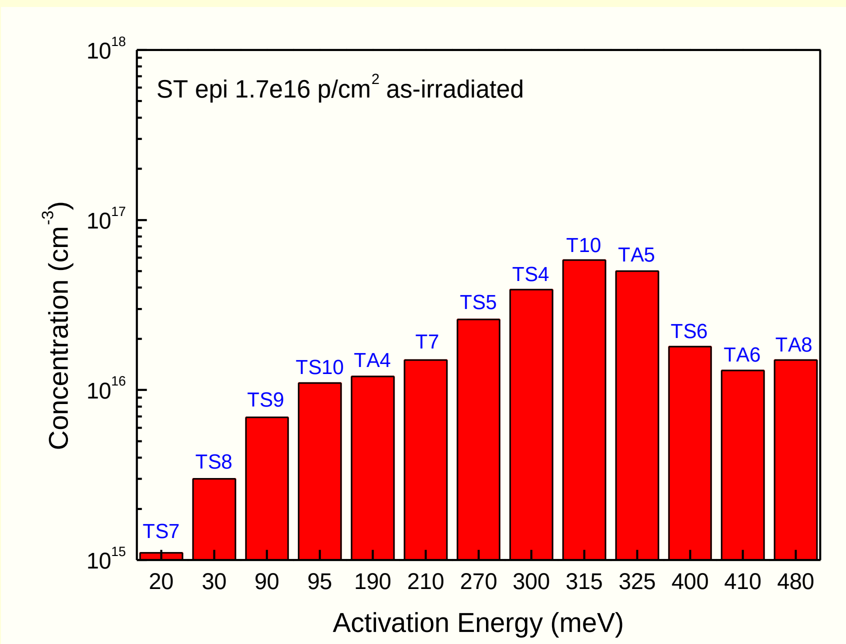
Trap label	E_a^* (meV)	A^* (K^{-2}s^{-1})	Concentration (cm^{-3})	Tentative identification
TC1	30±5	1.1×10^4	2.3×10^{15}	shallow donors – STD (H)
TC2	95±5	2.7×10^5	2.0×10^{16}	V_3 fourfold coordinated D_3 symmetry [1]
TA4	190±5	2.4×10^6	1.3×10^{16}	VO (-/0)
T7	210±5	4.0×10^5	1.6×10^{16}	V_2 (+/0)
TC3	260±10	4.7×10^5	2.8×10^{16}	V_2 (2-/-)
T10	315±10	2.8×10^5	4.5×10^{16}	V_3 (2-/-) , (110) planar configuration, C_{2v} symmetry, E_c – 0.28 eV [1]
TA5	325±10	1.4×10^6	3.3×10^{16}	new, unidentified, vacancy aggregate V_4 ?
TA6	410±10	2.5×10^6	5.5×10^{16}	V_2 (-/0)
TA7	460±10	1.6×10^6	3.2×10^{14}	E5, vacancy aggregate V_4?
TA8	480±10	1.3×10^7	3.5×10^{16}	V_3 (-/0) , (110) planar configuration, C_{2v} symmetry, E_c – 0.5 eV [1]

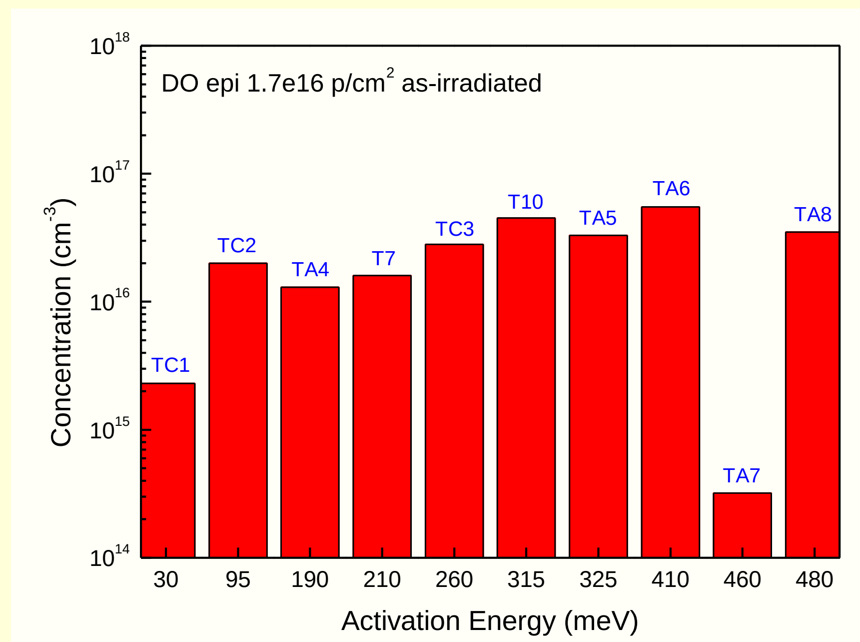
* E_a and A - the activation energy and pre-exponential factor in the Arrhenius formula $e_T=AT^2 exp(-E_a/kT)$

[1] – Markevich *et al*. Physical Review B **80,** 235207 (2009)


ST epi 1e16 as-irradiated
Concentration (cm^{-3})
10^{15} 10^{16} 10^{17} 10^{18}
TA1 TA2 TB1 TA3 TA4 TS11 T9 TC3 TS4 T10 TA5 TS6 TA6 TA8
30 65 73 109 170 226 255 260 298 315 325 400 410 480
Activation Energy (meV)

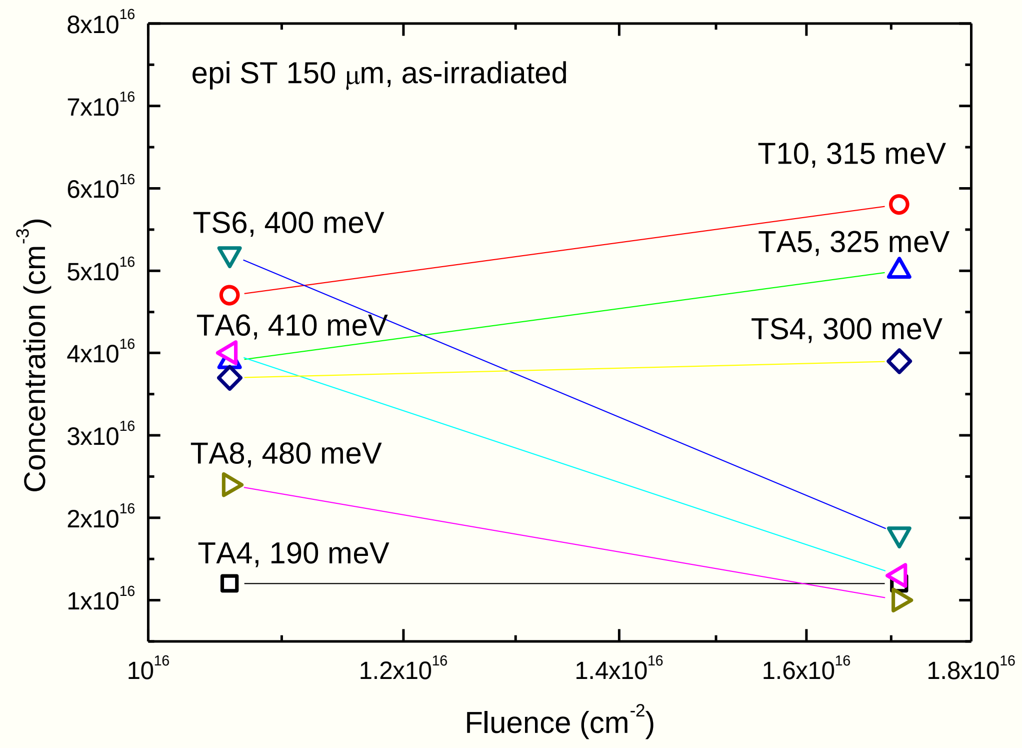

DO epi 1e16 as-irradiated
Concentration (cm^{-3})
10^{15} 10^{16} 10^{17} 10^{18}
TA1 TC1 TC2 TA4 T7 TC3 T10 TA5 TA6 TA7 TA8
30 35 95 170 210 260 315 325 410 460 480
Activation Energy (meV)


ST epi 1.7e16 p/cm^2 as-irradiated
Concentration (cm^{-3})
10^{15} 10^{16} 10^{17} 10^{18}
TS7 TS8 TS9 TS10 TA4 T7 TS5 TS4 T10 TA5 TS6 TA6 TA8
20 30 90 95 190 210 270 300 315 325 400 410 480
Activation Energy (meV)


DO epi 1.7e16 p/cm^2 as-irradiated
Concentration (cm^{-3})
10^{14} 10^{15} 10^{16} 10^{17} 10^{18}
TC1 TC2 TA4 T7 TC3 T10 TA5 TA6 TA7 TA8
30 95 190 210 260 315 325 410 460 480
Activation Energy (meV)

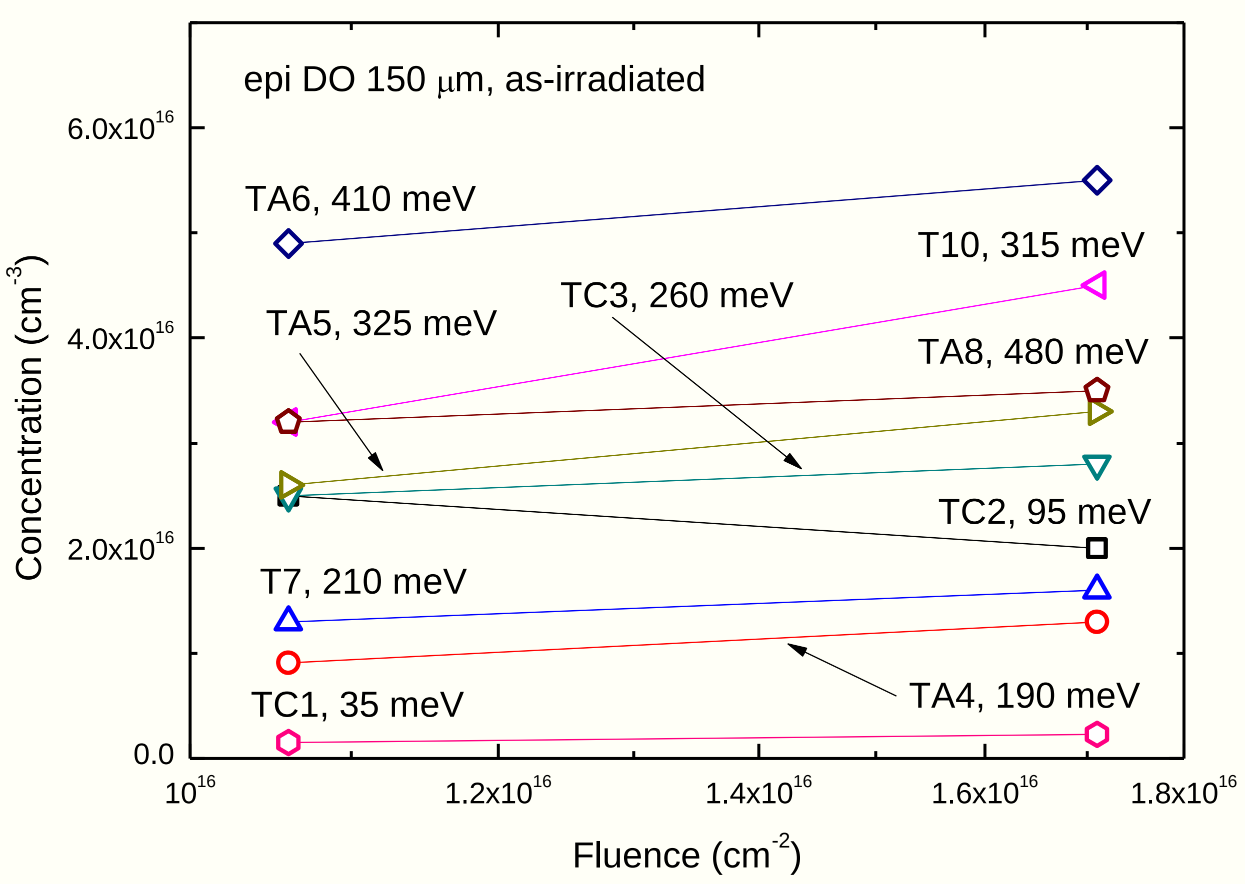
ST epilayer, as-irradiated

Changes in the radiation defect centers concentrations with increasing the proton fluence from **1.0x10^{16}** to **1.7x10^{16}** cm^{-2}



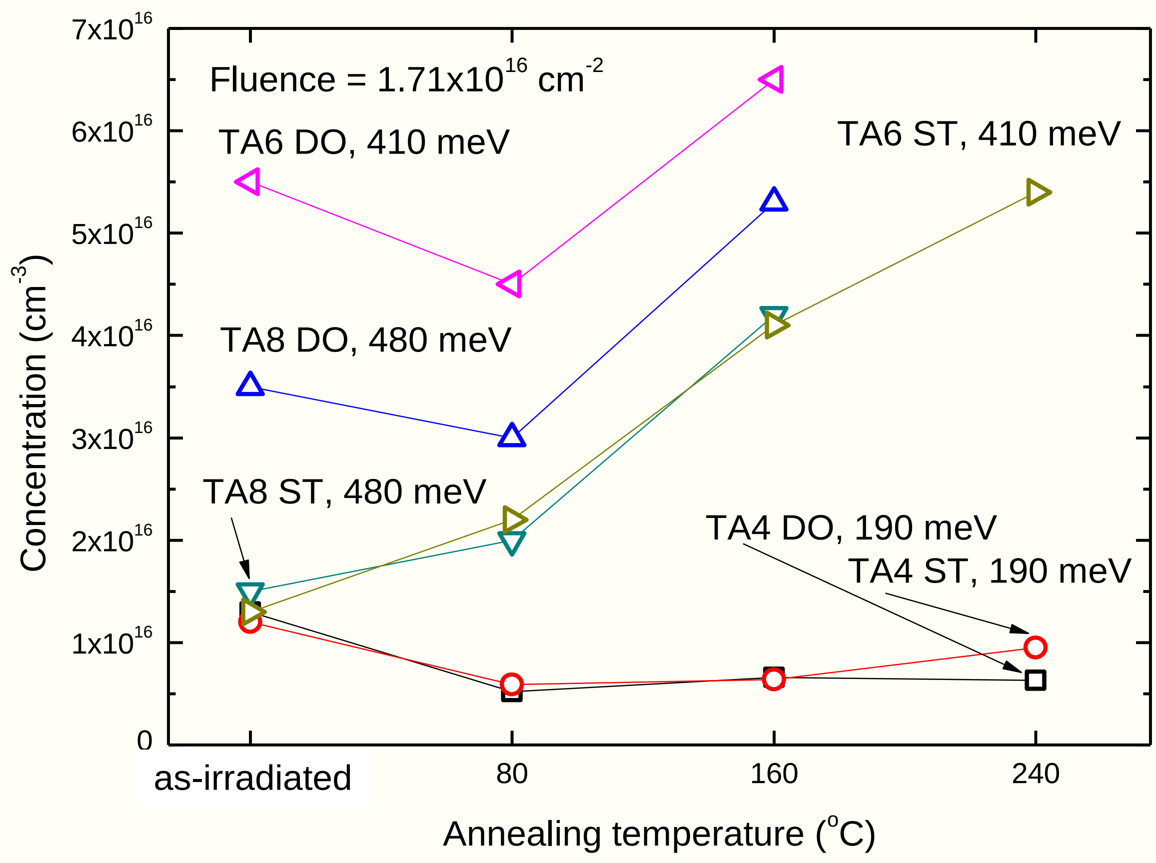
DO epilayers, as-irradiated

Changes in the radiation defect centers concentrations with increasing the proton fluence from **1.0×10^{16}** to **1.7×10^{16}** cm^{-2}



ST and DO epilayers

Changes in the concentrations of radiation defect centers with increasing the annealing temperature



Conclusions (1)

- High-resolution photoinduced transient spectroscopy (HRPITS) has been used to imaging defect structure of *n*-type epitaxial layers being the active layers of pad detectors irradiated with 24 GeV/c protons. The effect of increasing fluence from 1.0×10^{16} cm^{-2} to 1.7×10^{16} cm^{-2} on parameters and concentrations of radiation defect centers has been studied.

- In standard epitaxial layers irradiated with the lower proton fluence, the activation energy of the predominant defect center was found to be 400 meV. This center, the concentration of which was **5.2×10^{16} cm^{-3}**, is presumably related to a vacancy aggregate . The concentrations of other radiation centers with activation energies 255, 260, 300, 315, 325, 410, and 480 eV ranged from 2.4×10^{16} to 4.7×10^{16} cm^{-3}.

- In standard epitaxial layers irradiated with the higher proton fluence, the activation energy of the predominant defect center was found to be 315 meV. This center, whose concentration was **5.8×10^{16} cm^{-3}**, is tentatively assigned to a trivacancy. The concentrations of other radiation centers with activation energies 270, 300, and 325 eV, ranged from 2.6×10^{16} to 5.0×10^{16} cm^{-3}.

Conclusions (2)

- In oxygenated epitaxial layers with the lower proton fluence, the activation energy of the predominant defect center was found to be 410 meV. This center, the concentration of which was **4.9x10^{16} cm^{-3}**, is presumably related to a divacancy $V_2^{-/0}$. The concentrations of the other radiation centers with activation energies 260, 315, 325, and 480 eV, ranged from 2.5x10^{16} to 3.2x10^{16} cm^{-3}.

- In oxygenated epitaxial layers with the higher proton fluence, the activation energy of the predominant defect center was found to be 410 meV. This center, the concentration of which was **5.5x10^{16} cm^{-3}**, is presumably related to a divacancy $V_2^{-/0}$. The concentrations of the other radiation centers with activation energies 260, 315, 325, and 480 eV, ranged from 2.8x10^{16} to 4.5x10^{16} cm^{-3}.

- It was found that after 1-h annealing at 240 ^{o}C the activation energy of the predominant defect center is 575 meV. In the standard epitaxial layers irradiated with proton fluences 1.0x10^{16} cm^{-3} and 1.7x10^{16} cm^{-2} the concentrations of this center after the annealing were **9.2x10^{16}** and **8.0x10^{16} cm^{-3}**, respectively.

- In the oxygenated epitaxial layers irradiated with proton fluences 1.0x10^{16} cm^{-3} and 1.7x10^{16} cm^{-2}, the concentrations of the predominant 575-meV center after the annealing were **5.4x10^{16}** and **7.0x10^{16} cm^{-3}**, respectively.

Acknowledgement

- This work was carried out within the framework of the RD 50 project with financial support of the Polish Ministry of Science and Higher Education under grant No. DPN/N185/CERN/2009.

Model of Photocurrent Relaxation Waveforms

$$\boldsymbol{i_m(t, T) = I_m(\lambda, T)\,\exp(-e_{Tm}t);}$$

$$I_m(\lambda, T) = n_{tom}(T)\, e_{Tm}(T)\, \mu_T(T)\, \tau_T(T)\, C(\lambda, T) qE$$

$$i(t, T) = \sum_{m=1}^{M} I_k(\lambda, T)\,\exp(-e_{Tm}t);$$

$$\boldsymbol{e_{Tm} = A_m T^2 \exp(-E_{am} / k_B T)}$$

$$A_{mn} = \gamma_n \sigma_{mn}\,;\, A_{mp} = \gamma_p \sigma_{mp}$$

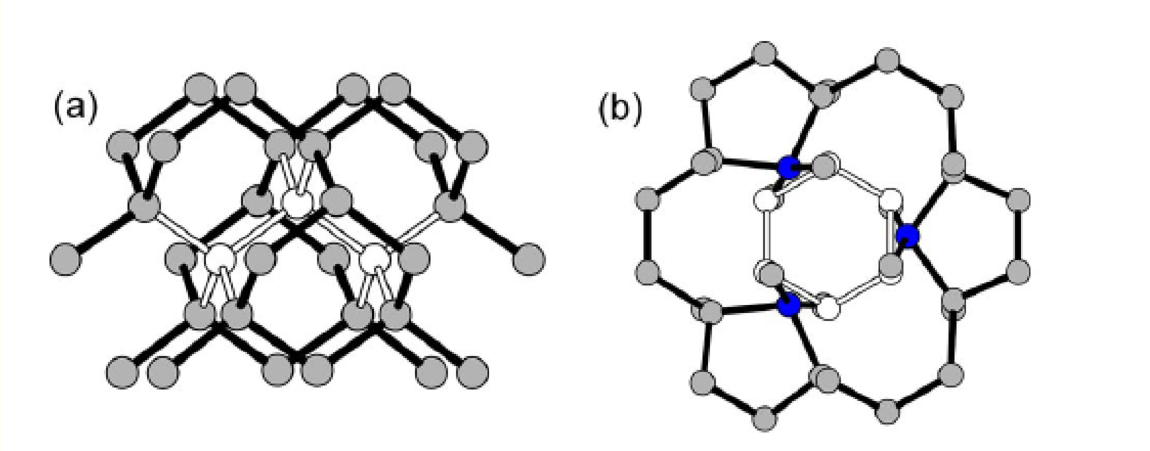
For Si: $\gamma_n = 1.07 \times 10^{21}$ cm^{-2}K^{-2}s^{-1} ; $\gamma_p = 2.64 \times 10^{21}$ cm^{-2}K^{-2}s^{-1}

$$N_T = \frac{U_{cal}}{qBe_T lE}$$

$$B = \exp(-t_1 e_T) - \exp(-t_2 e_T)$$

$t_1 = 1{,}23/e_T$; $t_2 = 3t_1$

$$U_{cal} = \frac{S(T)\,\alpha(T)\,I_0}{\mu\tau}$$



Atomic structures of V_3 (C_{2v}) - (a) and V_3 (D_3) – (b)

MARKEVICH *et al*. PHYSICAL REVIEW B **80**, 235207, (2009)