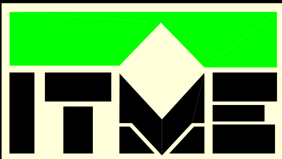
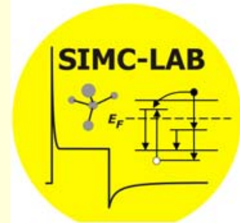


Institute of Electronic Materials Technology



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

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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 $1.7 \times 10^{16} cm^{-2}$ 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 ^{o}C
- Conclusions

Samples

- Epitaxial detectors fabricated by CiS, Erfurt (Germany)

  Process: 261636-13 CiS standard (label - ST)

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

- Active epitaxial layers - ITME Si epi., <100>, *n*-type, 500 Ωcm, 150 μm

- 24 GeV/c proton irradiation, CERN PS source

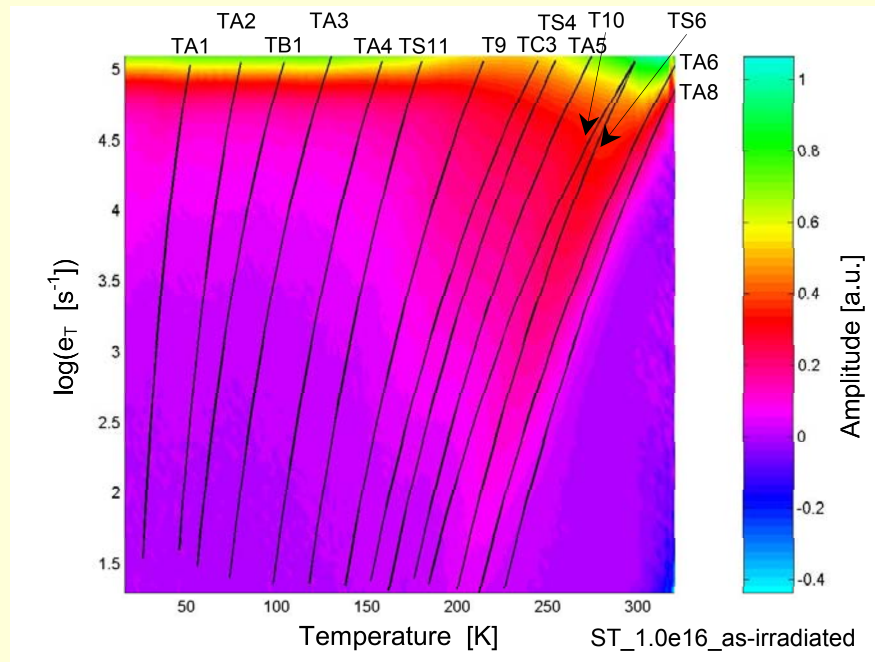
  Fluences: $1.x10^{16}$ and $1.7x10^{16}$ cm^{-2}

Details of HRPITS measurements

- Temperature range: 30 – 300 K, $\Delta T = 2$ 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) → images of correlation spectral fringes for radiation defect centres
  - 2D inverse Laplace transformation algorithm → images of Laplace fringes for radiation defect centres

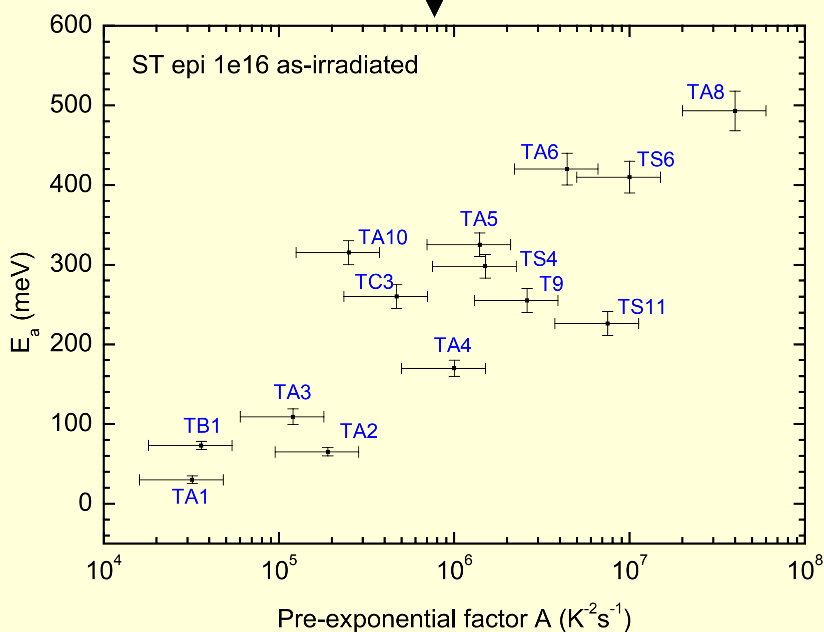
Defect structure of ST Si-epitaxial layer after irradiation with a fluence of $1x10^{16}$ cm^{-2}

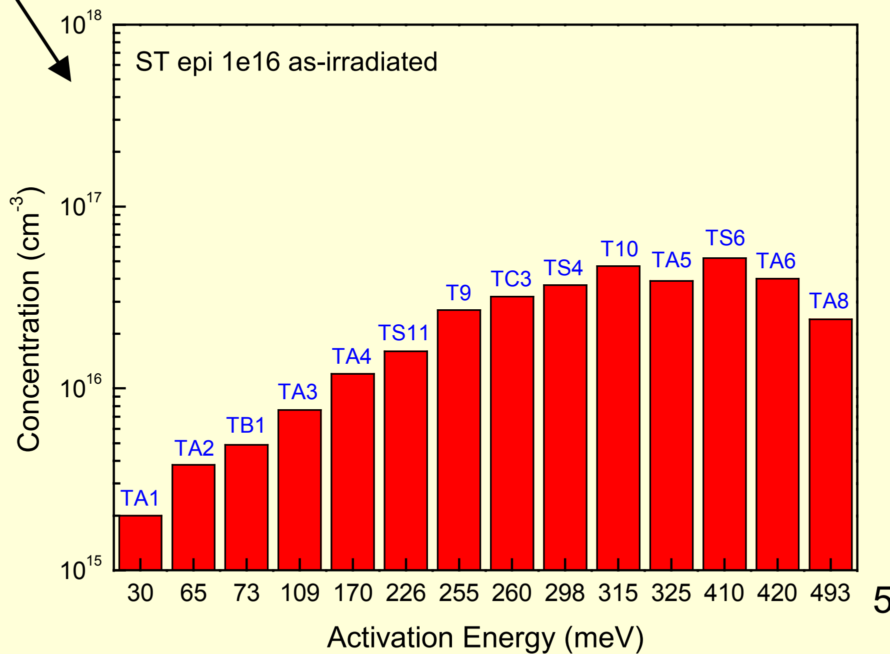
Image of correlation spectral fringes



Concentrations of defect centers

Parameters of defect centers





ST epilayer, as-irradiated, fluence **1x10^{16}** cm^{-2}
Tentative identification of detected defect centers

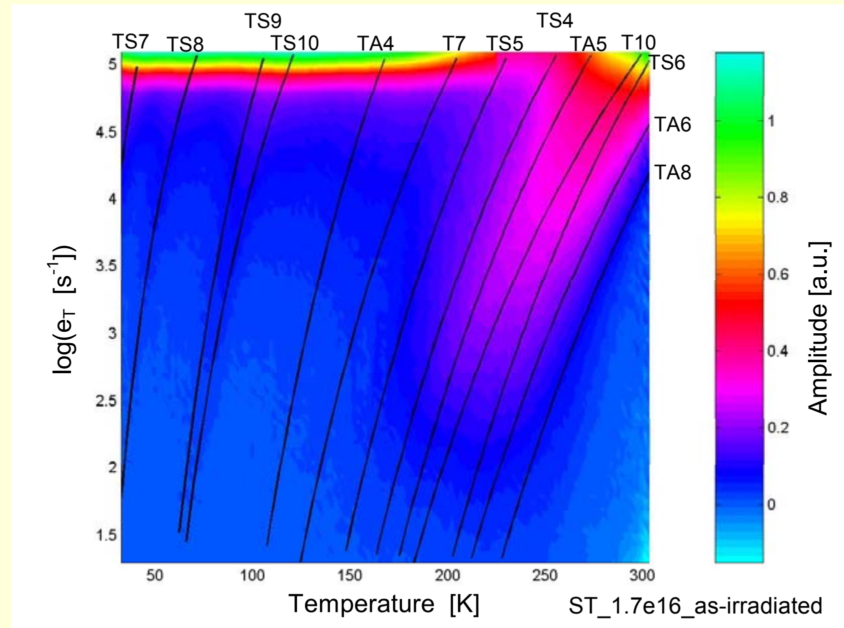
Parameters of defect centers obtained from the HRPITS studies for ST Si epi 150 μm as-irradiated with proton fluence of 1.0x10^{16} cm^{-2}.

Trap label	E_a^* (meV)	A^* (K^{-2}s^{-1})	Concentration (cm^{-3})	Tentative identification
TA1	30±5	3.2x10^4	2.0x10^{15}	shallow donors
TA2	65±5	1.9x10^5	3.8x10^{15}	shallow donors
TB1	73±5	3.6x10^4	4.9x10^{15}	I aggregates (I_3)
TA3	109±5	1.2x10^5	7.6x10^{15}	I aggregates (I_4)
TA4	170±5	1.0x10^6	1.2x10^{16}	VO (-/0)
TS11	226±10	7.5x10^6	1.6x10^{16}	V_2O (2-/-)
T9	255±10	2.6x10^6	2.7x10^{16}	IO_2
TC3	260±10	4.7x10^5	3.2x10^{16}	V_2 (2-/-)
TS4	298±10	1.5x10^6	3.7x10^{16}	V_xO_y complexes (V_3O, V_4O_2 …)
T10	315±10	2.5x10^5	4.7x10^{16}	V_xO_y complexes (V_3O, V_4O_2 …)
TA5	325±10	1.4x10^6	3.9x10^{16}	V_xO_y complexes (V_3O, V_4O_2 …)
TS6	410±15	1.0x10^7	5.2x10^{16}	I_2O
TA6	420±15	4.4x10^6	4.0x10^{16}	V_2 (-/0)
TA8	493±20	4.0x10^7	2.4x10^{16}	complex of O with V aggregates (V_4, V_5)

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

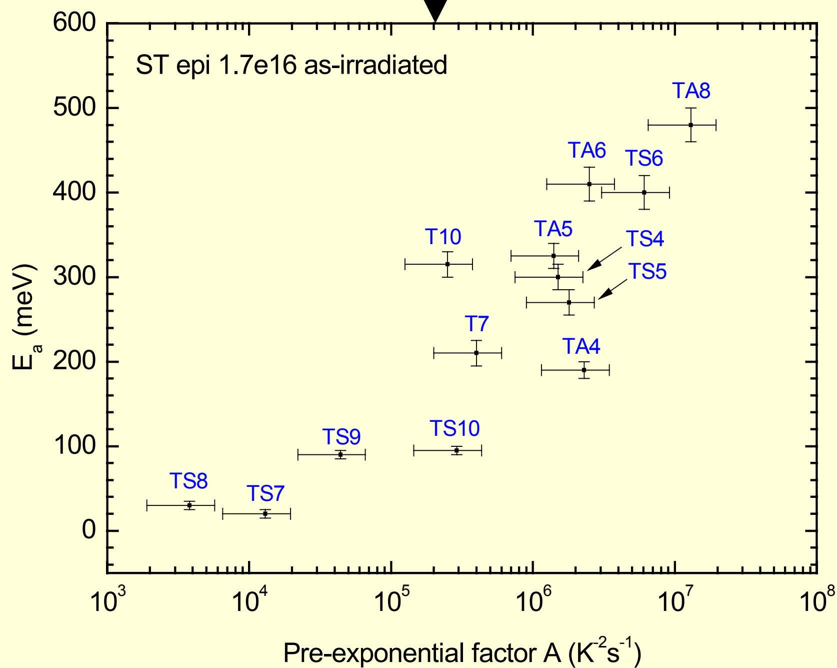
Defect structure of ST Si-epitaxial layer after irradiation with a fluence of 1.7x10^{16} cm^{-2}

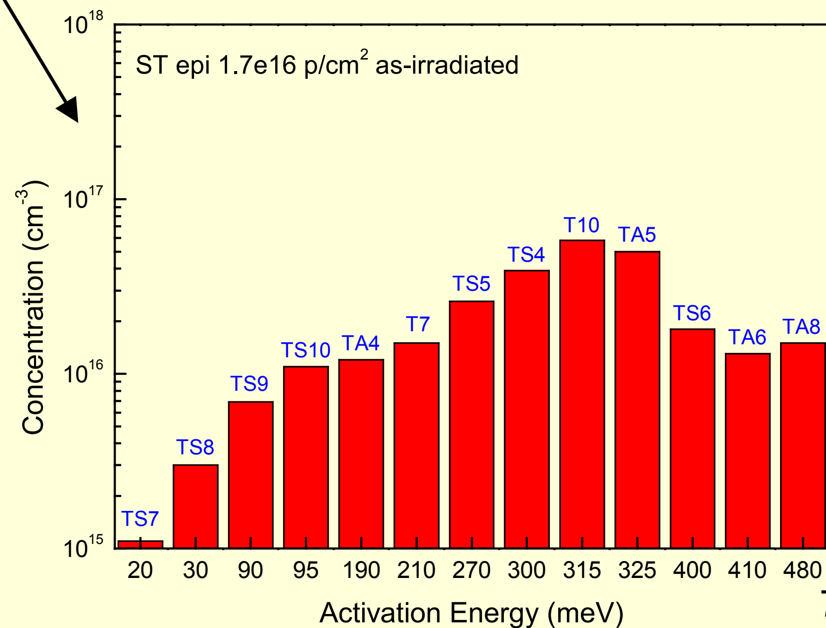
Image of correlation spectral fringes



Concentrations of defect centers

Parameters of defect centers





ST epilayer, as-irradiated, fluence **1.7x10^{16}** cm^{-2}
Tentative identification of detected defect centers

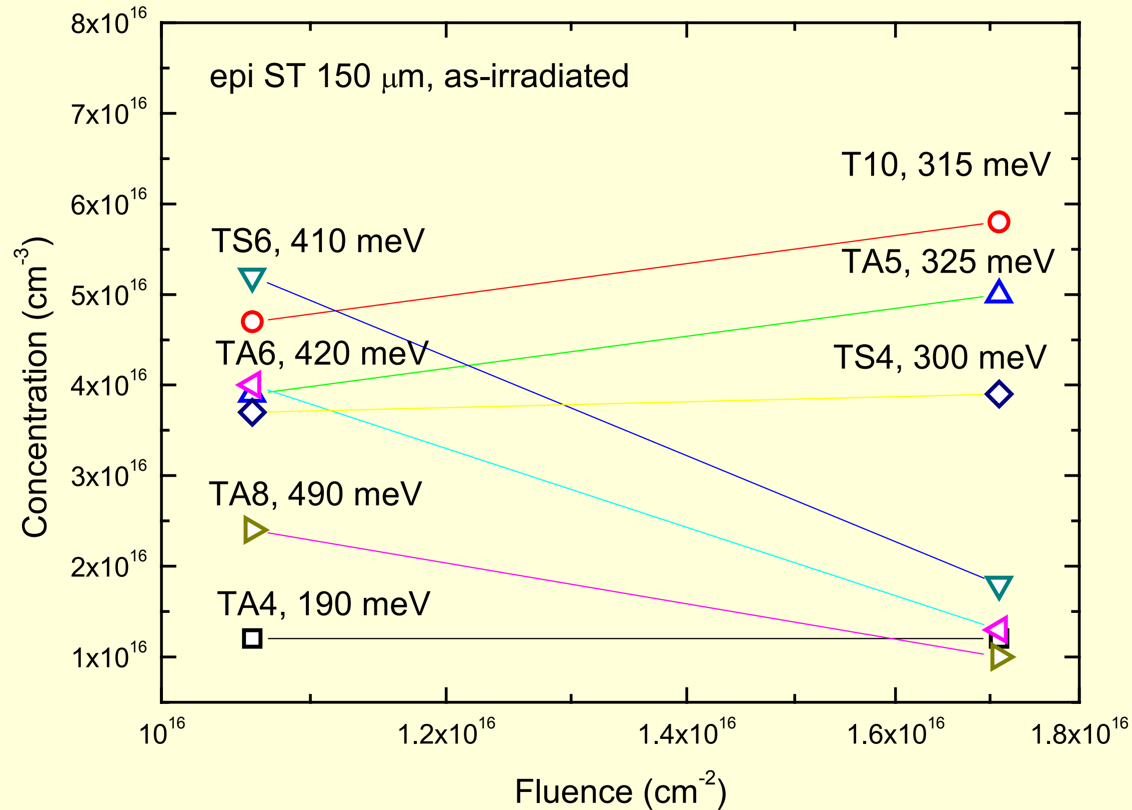
Parameters of defect centers obtained from the HRPITS studies for ST Si epi 150 μm as-irradiated with proton fluence of 1.7x10^{16} cm^{-2}.

Trap label	E_a^* (meV)	A^* (K^{-2}s^{-1})	Concentration (cm^{-3})	Tentative identification
TS7	20±5	1.3x10^4	1.1x10^{15}	shallow donors
TS8	30±5	3.8x10^3	3.0x10^{15}	shallow donors
TS9	90±5	4.4x10^4	6.9x10^{15}	I aggregates (I_3)
TS10	95±5	2.9x10^5	1.1x10^{16}	I aggregates (I_4) in disordered vicinity
TA4	190±10	2.3x10^6	1.2x10^{16}	VO (-/0)
T7	210±10	4.0x10^5	1.5x10^{16}	V_2 (+/0)
TS5	270±10	1.8x10^6	2.6x10^{16}	IO_2
TS4	300±10	1.5x10^6	3.9x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
T10	315±10	2.5x10^5	5.8x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
TA5	325±10	1.4x10^6	5.0x10^{16}	V_xO_y complexes (V_3O, V_4O_2 ...)
TS6	400±10	6.1x10^6	1.8x10^{16}	I_2O
TA6	410±15	2.5x10^6	1.3x10^{16}	V_2 (-/0)
TA8	480±10	1.3x10^7	1.5x10^{16}	complex of O with V aggregates (V_4, V_5)

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

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}

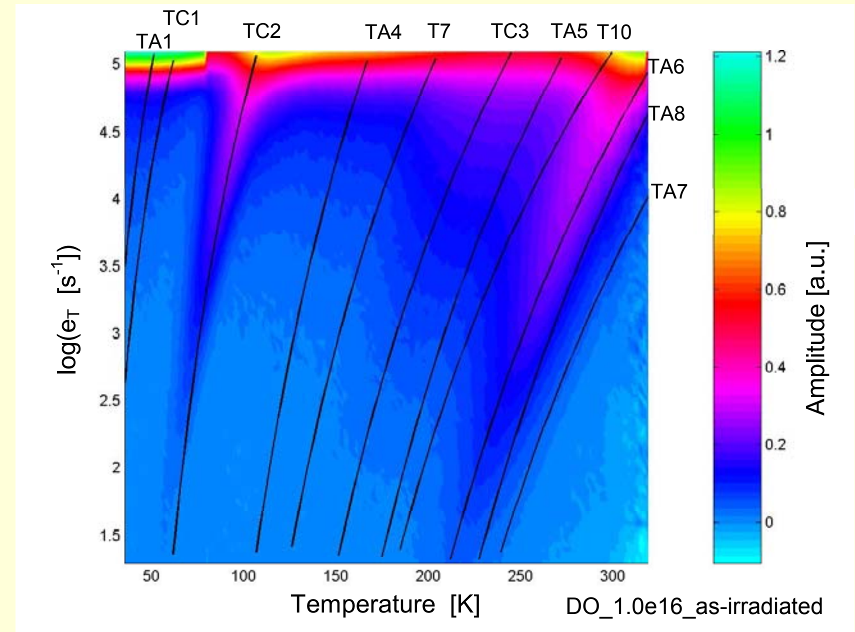


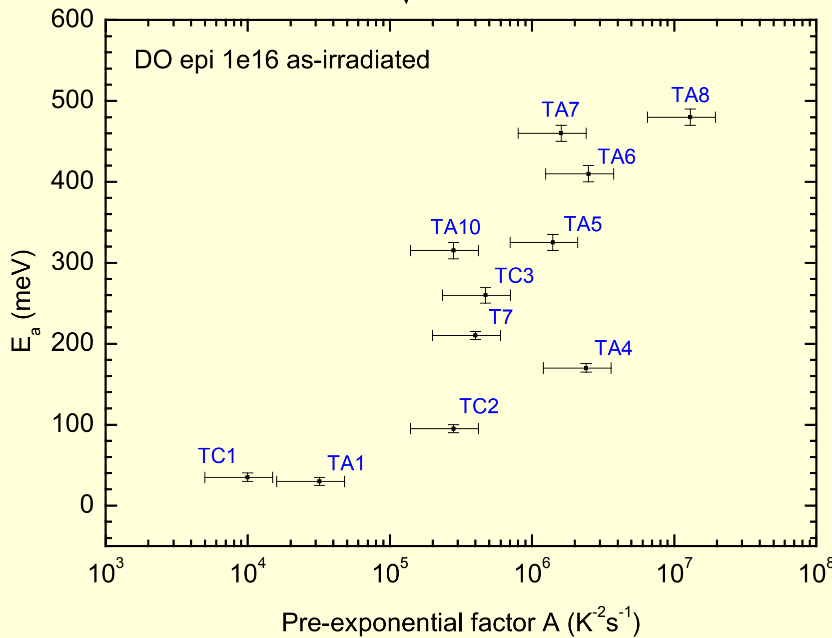
Defect structure of DO Si-epitaxial layer after irradiation with a fluence of 1×10^{16} cm^{-2}

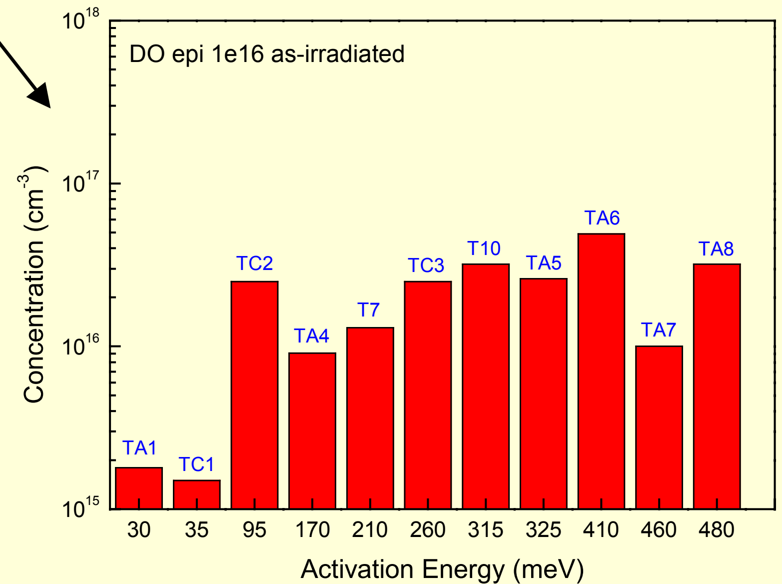
Image of correlation spectral fringes

Concentrations of defect centers

Parameters of defect centers







DO epilayer, as-irradiated, fluence **$1x10^{16}$** cm^{-2}
Tentative identification of detected defect centers

Parameters of defect centers obtained from the HRPITS studies for DO Si epi 150 μm as-irradiated with proton fluence of $1.0x10^{16}$ cm^{-2}.

Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TA1	30±5	$3.2x10^4$	$1.8x10^{15}$	shallow donors
TC1	35±5	$1.0x10^4$	$1.5x10^{15}$	shallow donors
TC2	95±5	$2.8x10^5$	$2.5x10^{16}$	I aggregates (I_3)
TA4	190±5	$2.4x10^6$	$9.1x10^{15}$	VO (-/0)
T7	210±5	$4.0x10^5$	$1.3x10^{16}$	V_2 (+/0)
TC3	260±10	$4.7x10^5$	$2.5x10^{16}$	V_2 (2-/-)
T10	315±10	$2.8x10^5$	$3.2x10^{16}$	V_xO_y complexes (V_3O, V_4O_2 ...)
TA5	325±10	$1.4x10^6$	$2.6x10^{16}$	V_xO_y complexes (V_3O, V_4O_2 ...)
TA6	410±10	$2.5x10^6$	$4.9x10^{16}$	V_2 (-/0)
TA7	460±10	$1.6x10^6$	$1.0x10^{16}$	V_4, V_5
TA8	480±10	$1.3x10^7$	$3.2x10^{16}$	complex of O with V aggregates (V_4, V_5)

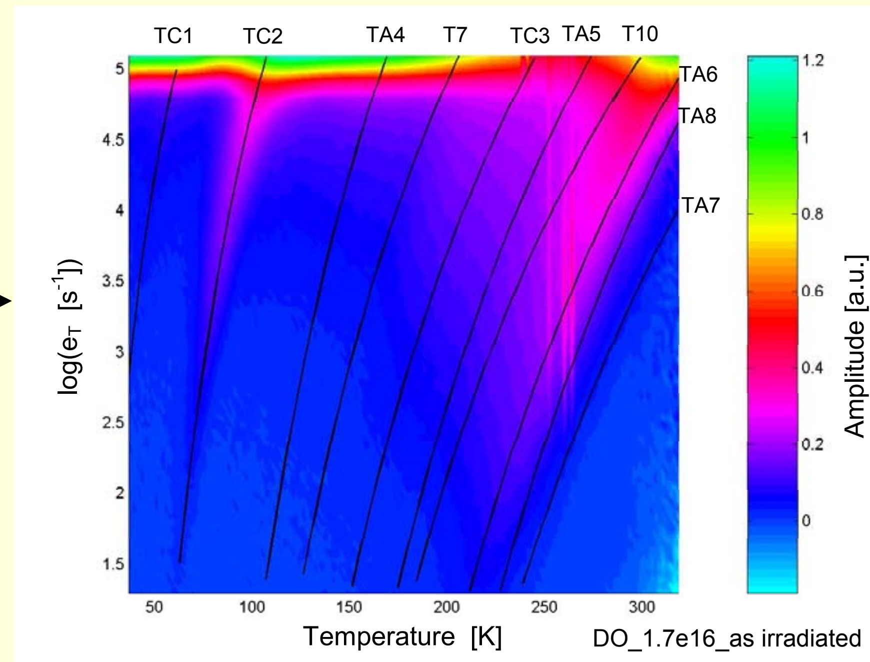
* E_a and A - the activation energy and pre-exponential factor in the Arrhenius formula $e_T=AT^2exp(-E_a/kT)$

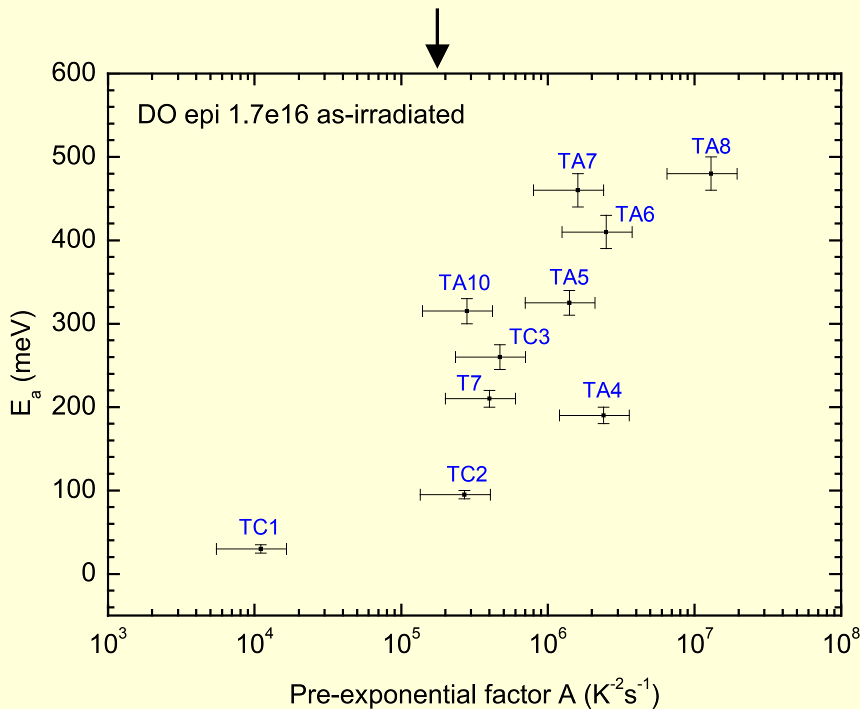
Defect structure of DO Si-epitaxial layer after irradiation with a fluence of 1.7×10^{16} cm^{-2}

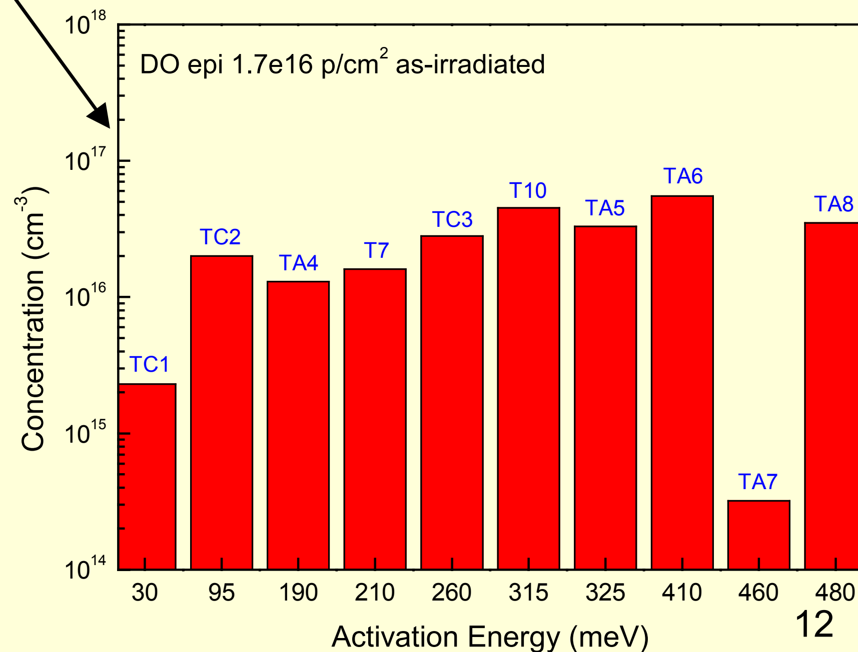
Image of correlation spectral fringes

Concentrations of defect centers

Parameters of defect centers







DO epilayer, as-irradiated, fluence **$1.7x10^{16}$** cm^{-2}
Tentative identification of detected defect centers

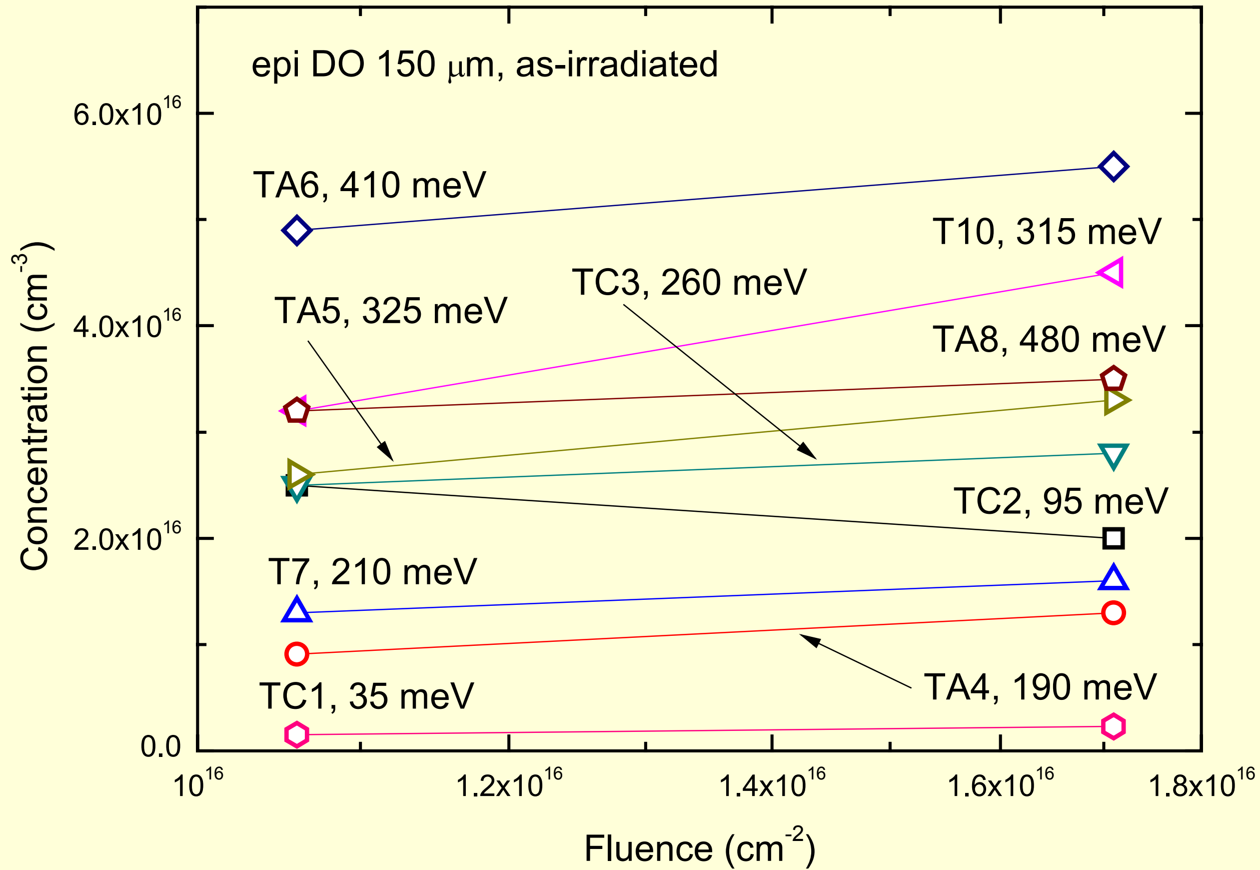
Parameters of defect centers obtained from the HRPITS studies for DO Si epi 150 μm as-irradiated with proton fluence of $1.7x10^{16}$ cm^{-2}.

Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Concentration (cm^{-3})	Tentative identification
TC1	30±5	$1.1x10^4$	$2.3x10^{15}$	shallow donors – STD (H)
TC2	95±5	$2.7x10^5$	$2.0x10^{16}$	I aggregates (I_3)
TA4	190±5	$2.4x10^6$	$1.3x10^{16}$	VO (-/0)
T7	210±5	$4.0x10^5$	$1.6x10^{16}$	V_2 (+/0)
TC3	260±10	$4.7x10^5$	$2.8x10^{16}$	V_2 (2-/-)
T10	315±10	$2.8x10^5$	$4.5x10^{16}$	V_xO_y complexes (V_3O, V_4O_2 …)
TA5	325±10	$1.4x10^6$	$3.3x10^{16}$	V_xO_y complexes (V_3O, V_4O_2 …)
TA6	410±10	$2.5x10^6$	$5.5x10^{16}$	V_2 (-/0)
TA7	460±10	$1.6x10^6$	$3.2x10^{14}$	V_4, V_5
TA8	480±10	$1.3x10^7$	$3.5x10^{16}$	complex of O with V aggregates (V_4, V_5)

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

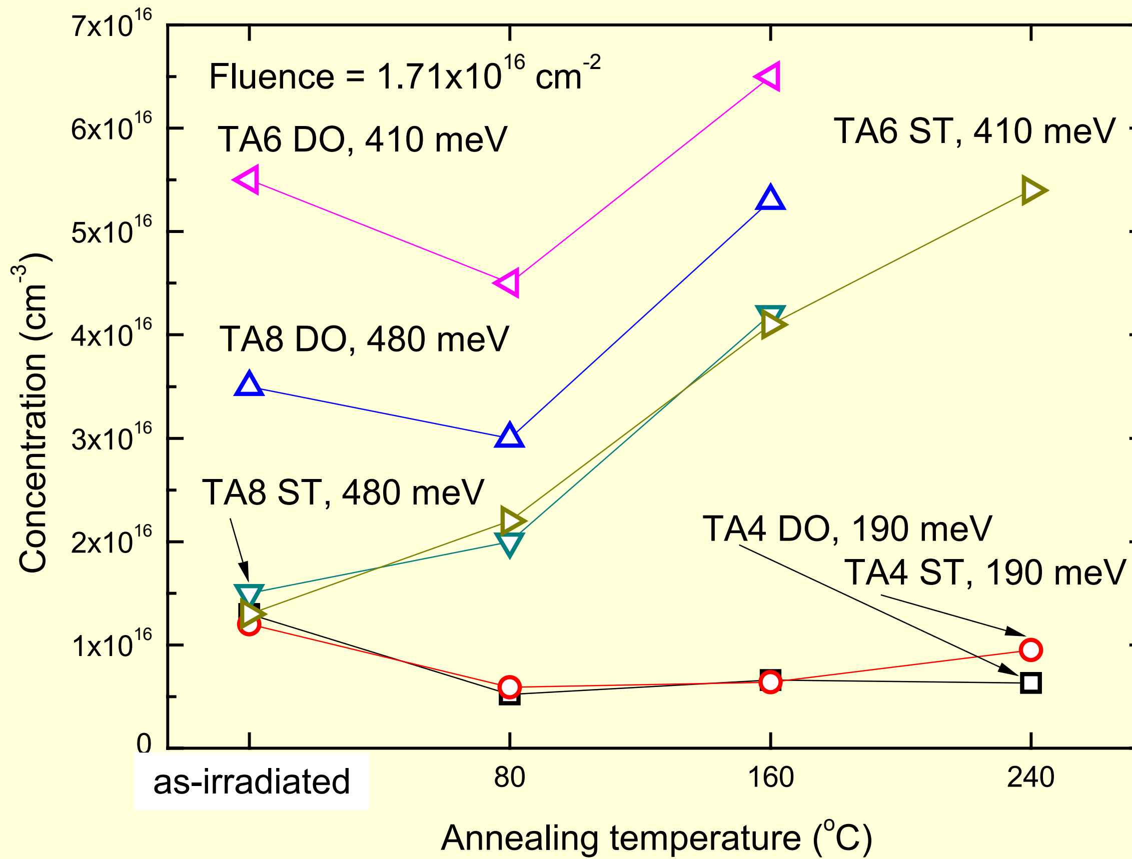
DO epilayers, as-irradiated

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 410 meV. This center, the concentration of which was 5.2×10^{16} cm^{-3}, is presumably related to I_2O complex. The concentrations of the other radiation centers with activation energies 255, 260, 300, 315, 325, 420, 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 V_xO_y complex. The concentrations of the 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 420 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 420 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

- We would like to thank Michael Moll for performing the proton irradiations.
- 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. CERN/15/2007.