Institute of Electronic Materials Technology

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

Characterisation of defect centres in epitaxial silicon irradiated with high proton fluences

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Outline

- Samples – radiation detectors based on epitaxial silicon
- Effect of high proton fluence on detectors electrical characteristics
- Details of HRPITS measurements
- HRPITS images of spectral fringes for radiation defects in standard and oxygenated epitaxial layers – effect on the high proton fluence on the defect structure of as-irradiated material
- 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

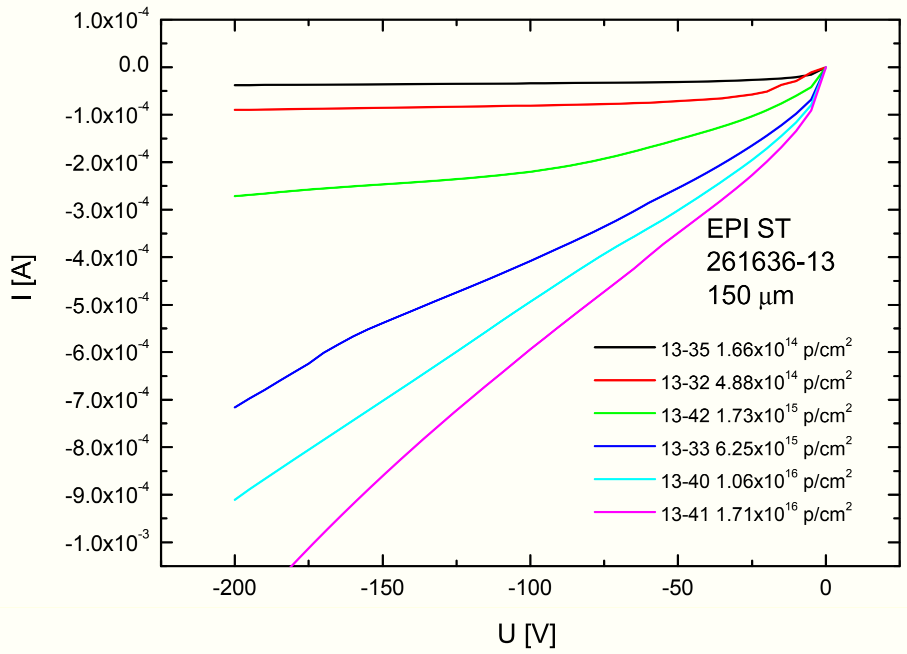
- 24 GeV/c proton irradiation, CERN PS source

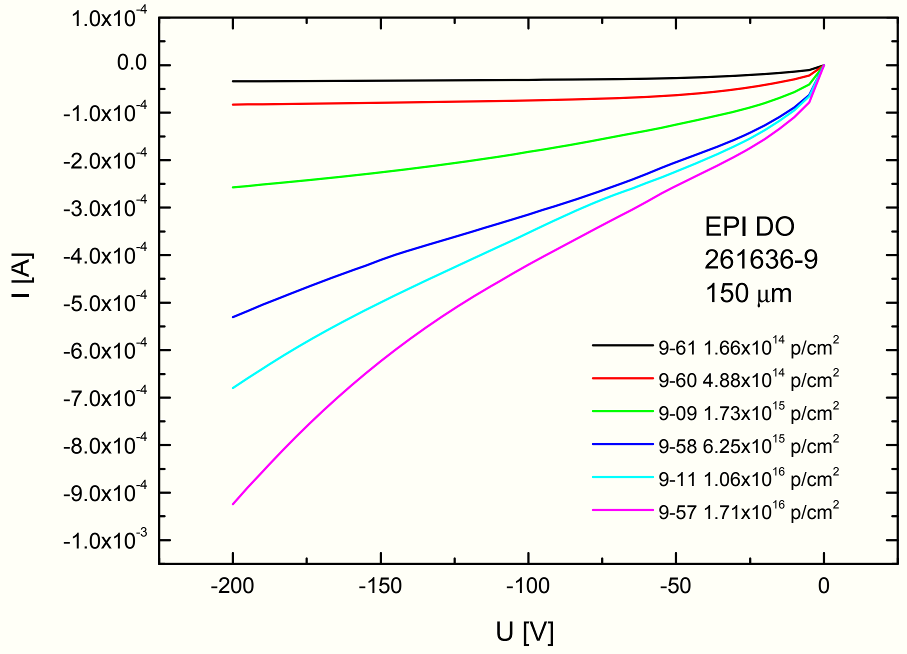
  Fluences: 1.6×10^{14}, 5×10^{14}, 1.6×10^{15}, 5×10^{15}, $1. \times 10^{16}$, and 1.6×10^{16} cm^{-2}

Effect on high proton fluence on detectors electrical characteristics

Proton fluence range: $1.66 \times 10^{14} – 1.7 \times 10^{16}$ cm^{-2}

Reverse current



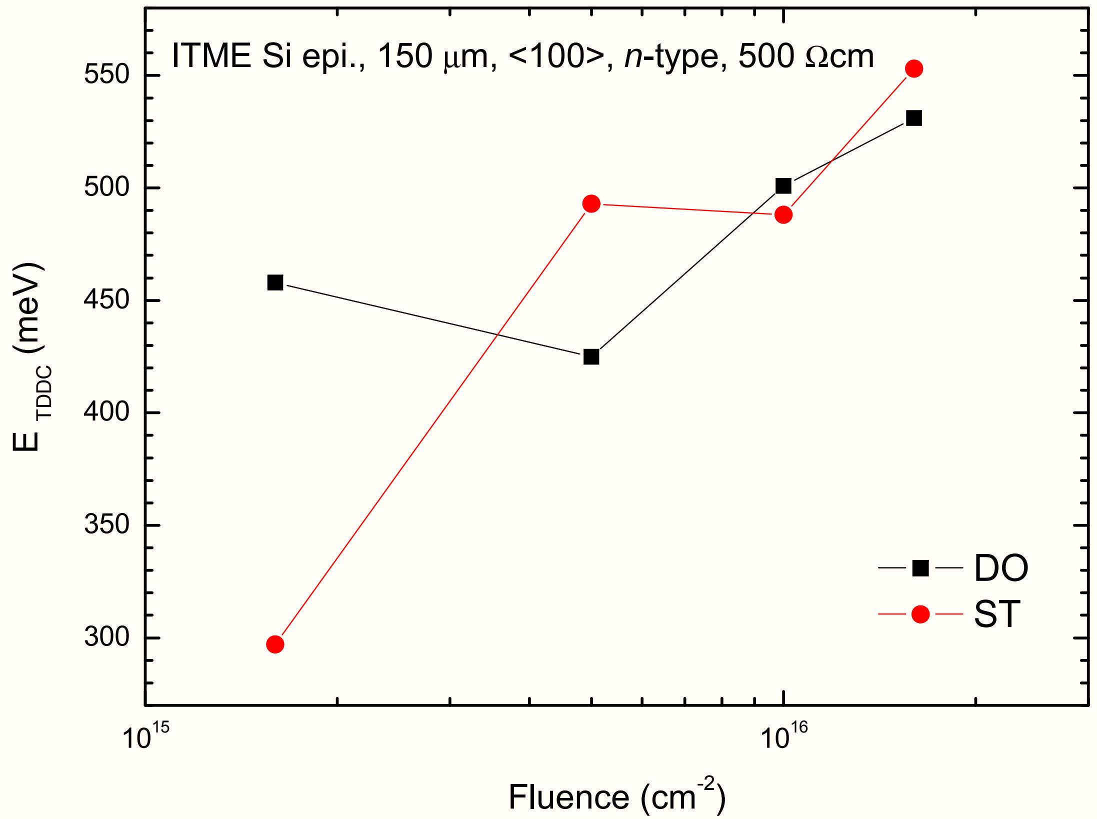


Standard epitaxial layer | **Oxygenated epitaxial layer**

Effect on high proton fluence on detectors electrical characteristics

Proton fluence range: 1.73x10^{15} – 1.7x10^{16} cm^{-2}

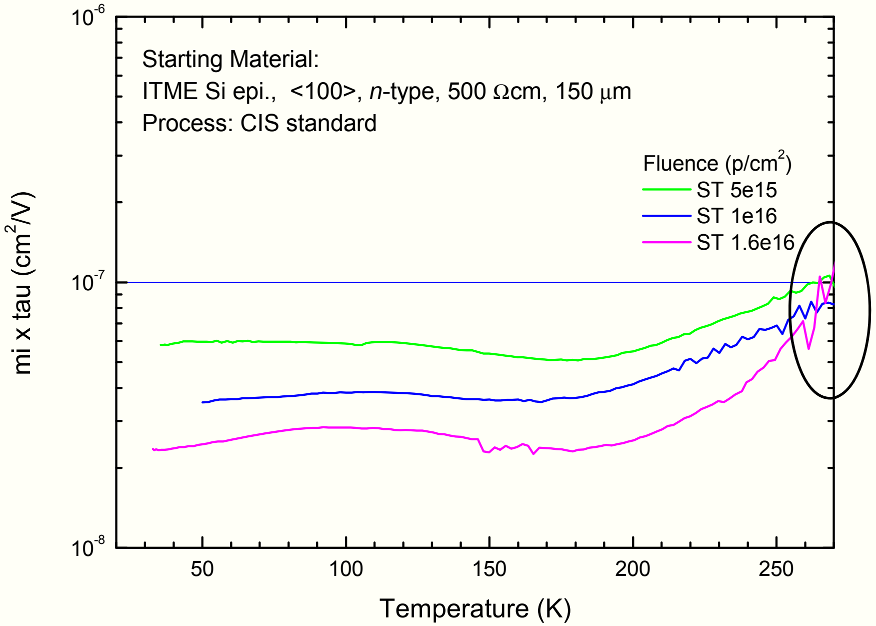
Fermi level position vs proton fluence

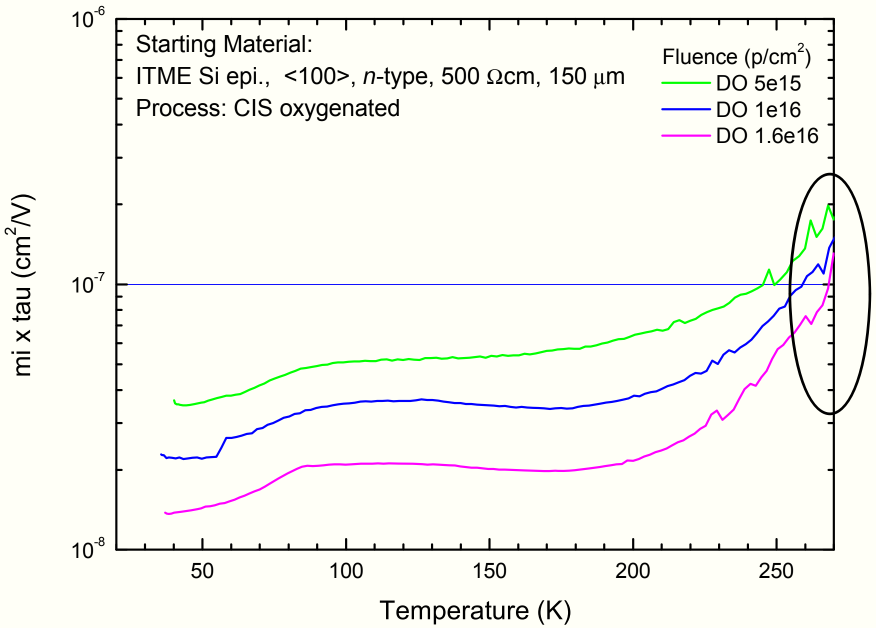


Effect on high proton fluence on detectors electrical characteristics

Proton fluence range: $5x10^{15} – 1.6x10^{16}$ cm^{-2}

Electron mobility lifetime product



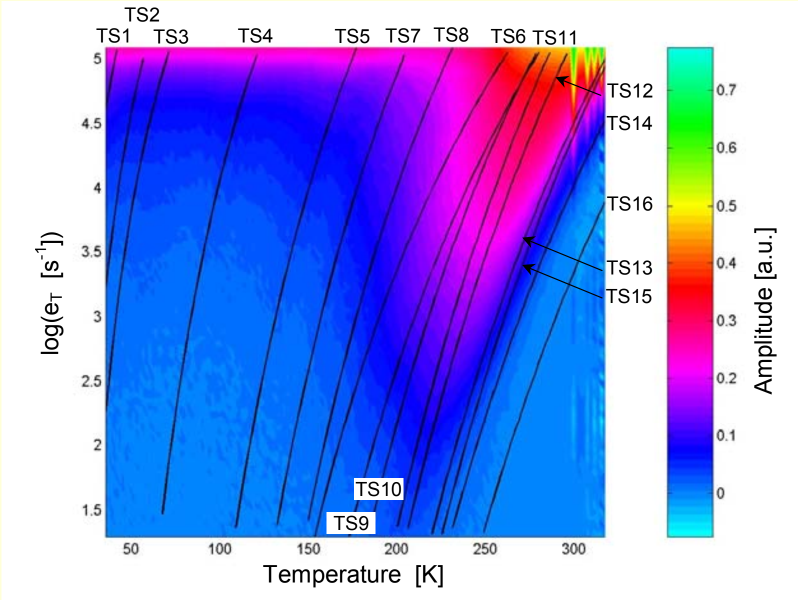


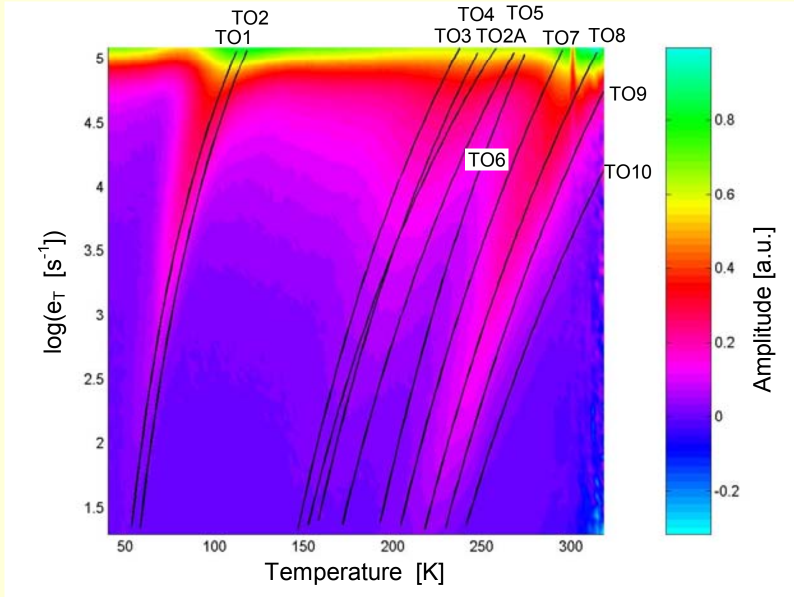
Standard epitaxial layer **Oxygenated epitaxial layer**

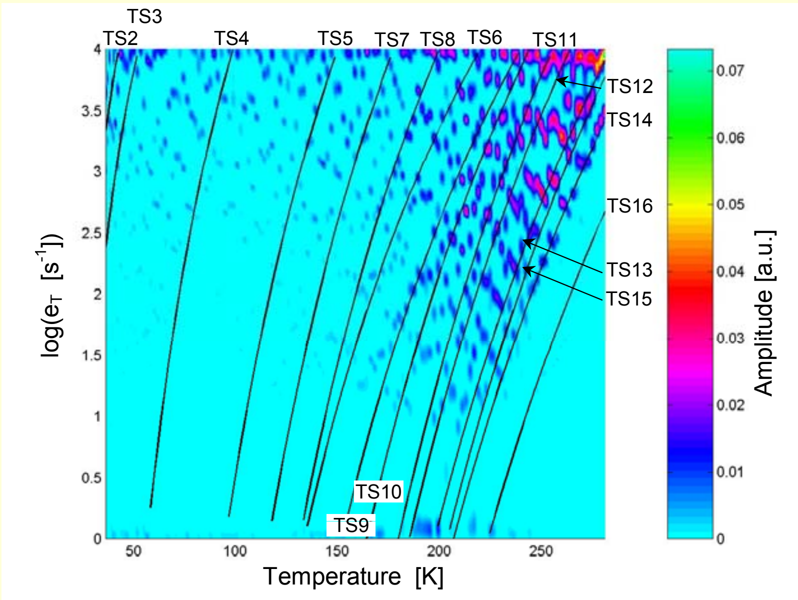
Details of HRPITS measurements

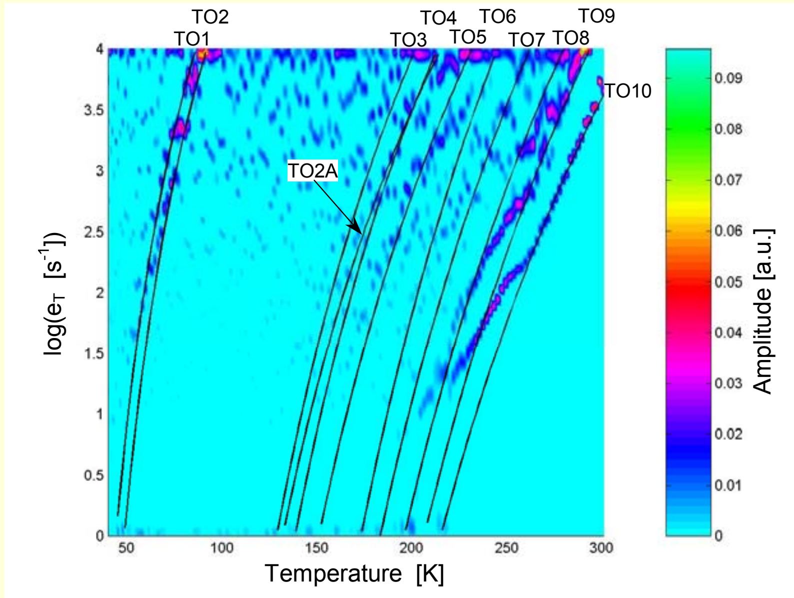
- Temperature range: 30 – 300 K, $\Delta T = 2$ K
- Excitation source: 5 mW, 650 nm laser diode (hν = 1.98 eV)
- Excitation pulse parameters: Period – 250 ms, Width – 50 ms
- Photon flux: $1.3\text{x}10^{17}$ $cm^{-2}s^{-1}$
- BIAS: 20 V
- Gain: $1\text{x}10^{6}$ – $1\text{x}10^{7}$ V/A
- AVG: 250 waveforms
- 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

HRPITS images – fluence $5x10^{15}$ p/cm^2





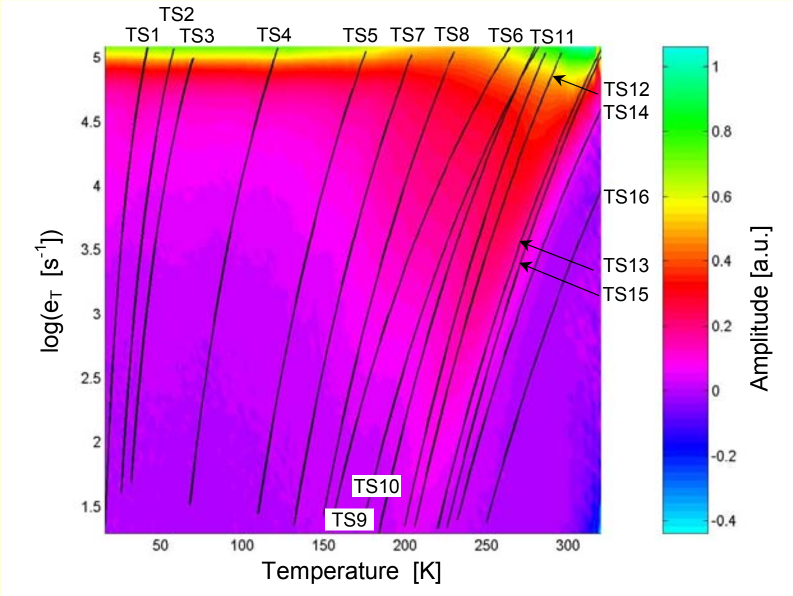


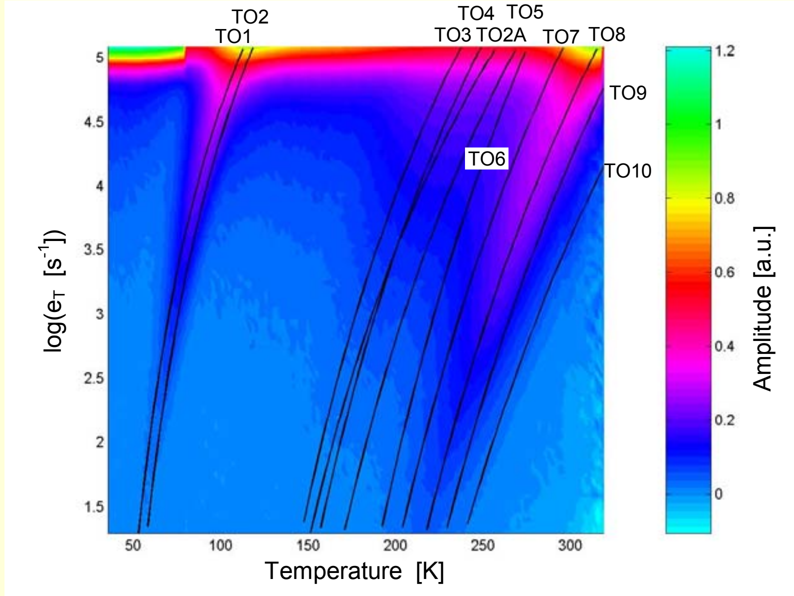


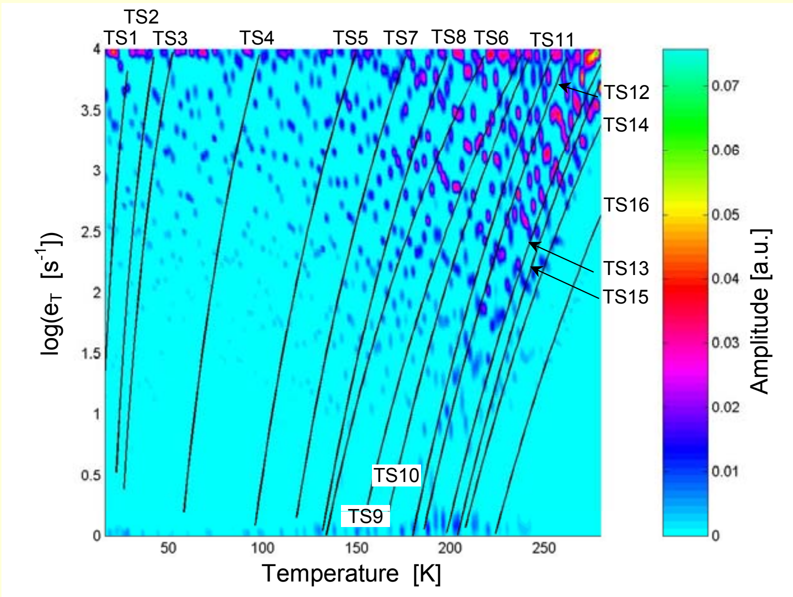
Standard epitaxial layer

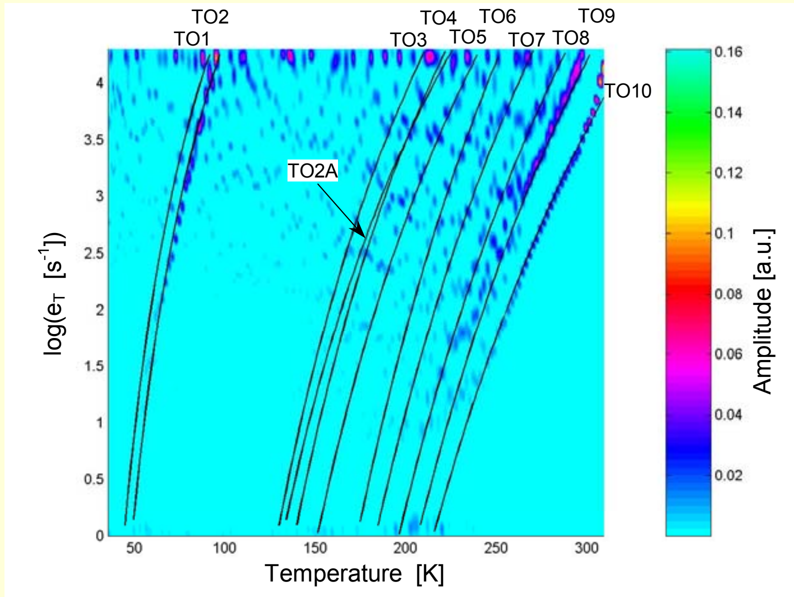
Oxygenated epitaxial layer

HRPITS images – fluence $1x10^{16}$ p/cm^2





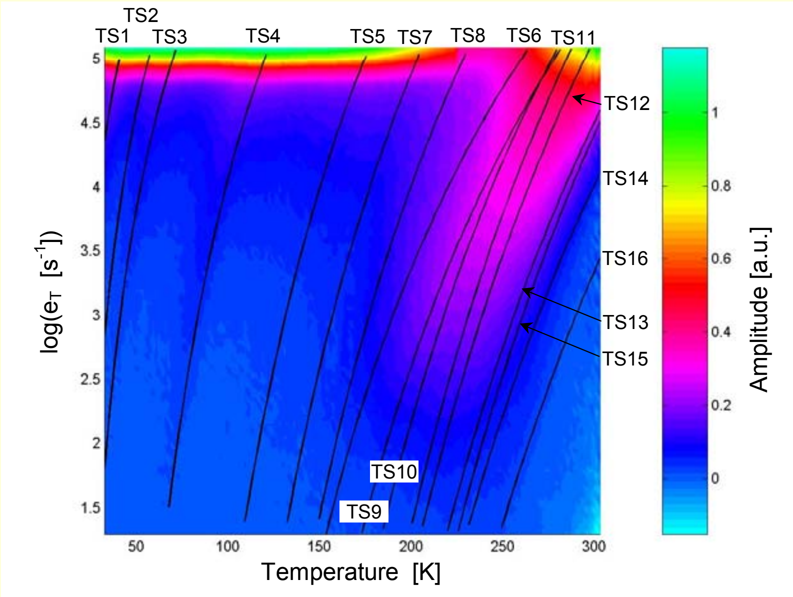


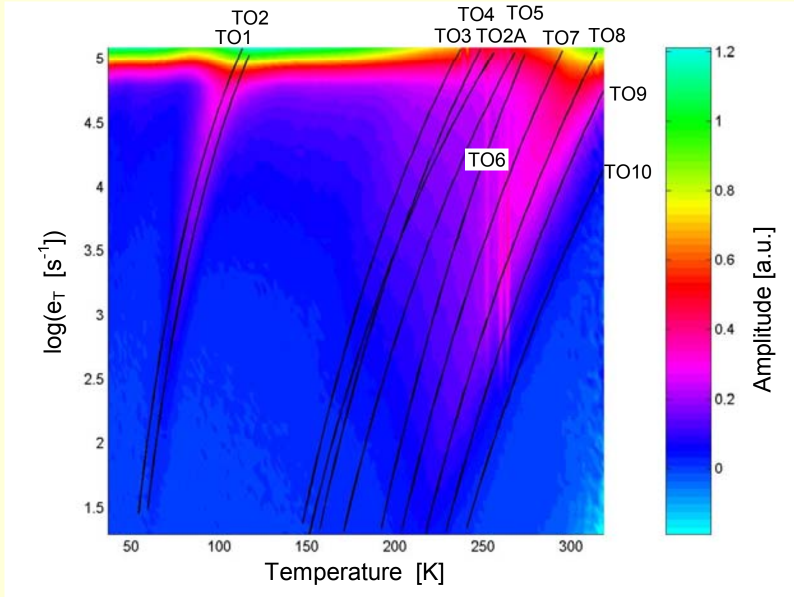


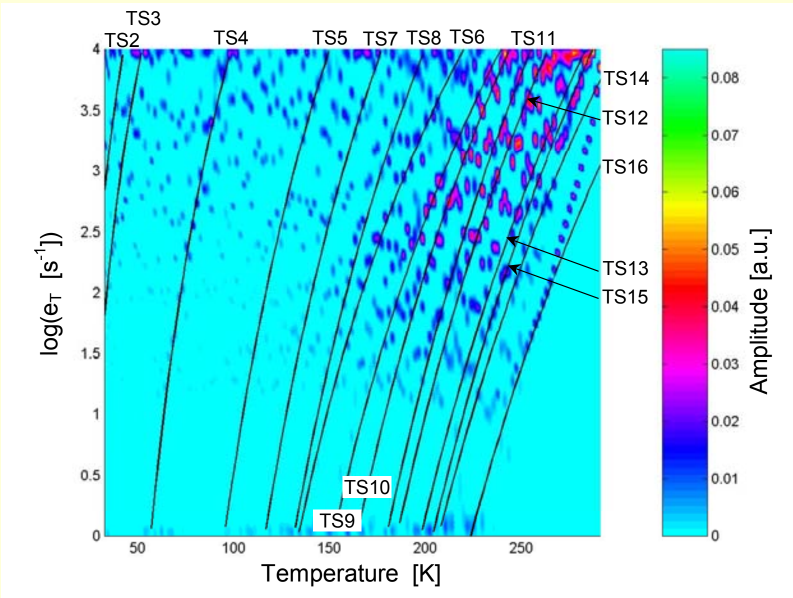
Standard epitaxial layer

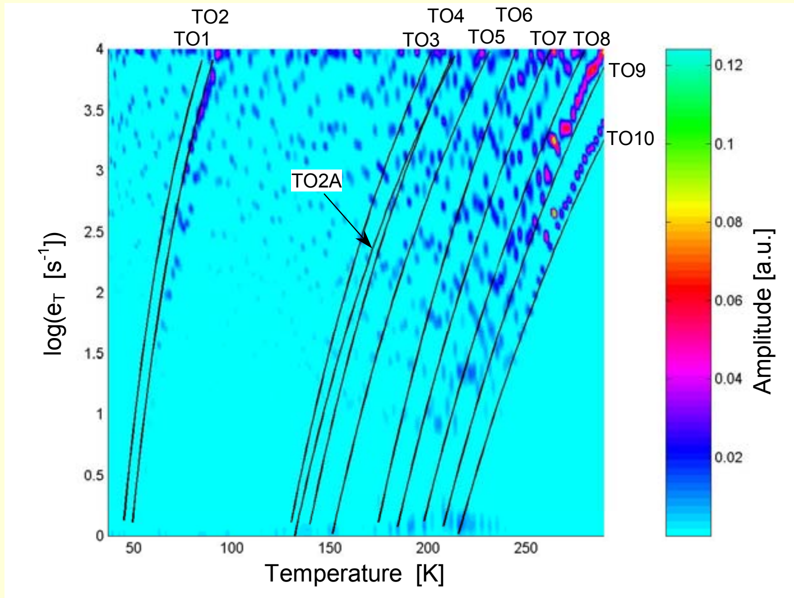
Oxygenated epitaxial layer

HRPITS images – fluence $1.6x10^{16}$ p/cm^2



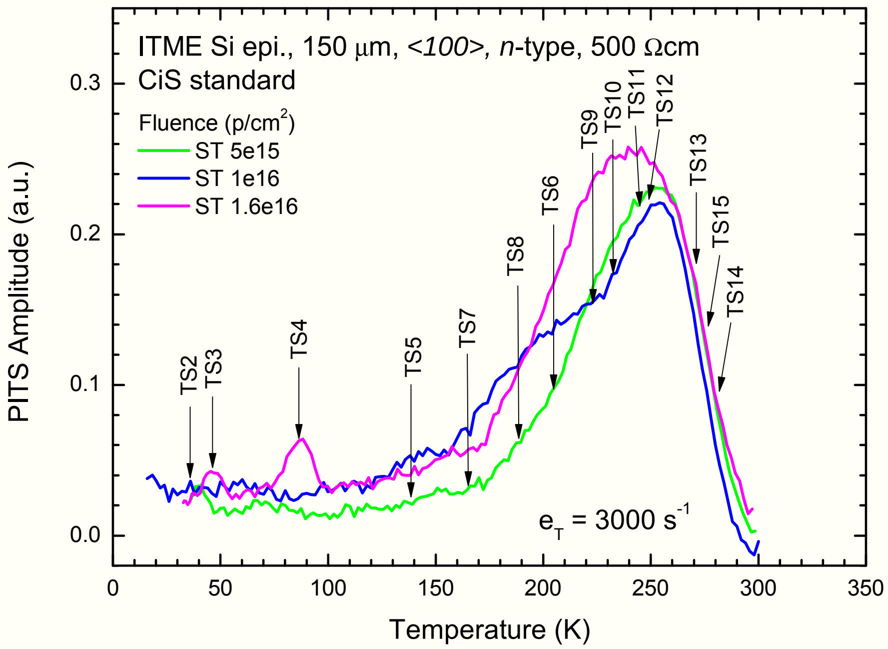


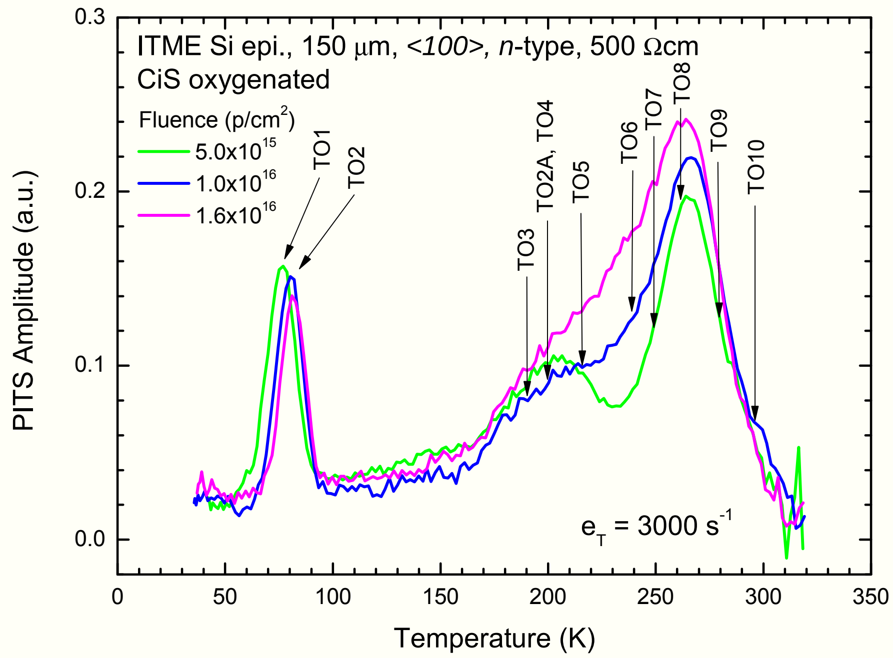




Standard epitaxial layer | **Oxygenated epitaxial layer**

1D-HRPITS spectra for standard and oxygenated epitaxial layers irradiated with proton fluences: $5x10^{15}$, $1x10^{16}$, and $1.6x10^{16}$ cm^{-2}





Standard epitaxial layer

Oxygenated epitaxial layer

Parameters of defect centers obtained from the HRPITS studies for standard and oxygenated epitaxial silicon irradiated with a fluence of 24GeV/c protons ranging from $5x10^{15}$ to $1.6x10^{16}$ cm^{-2}.

Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Remarks/Identification
TS1	15±2	$(4.3±1.0)x10^3$	epi ST, shallow donor, *e*
TS2	25±2	$(5.8±1.0)x10^3$	epi ST, MCz, shallow donor, *e*
TS3	35±5	$(3.8±1.0)x10^3$	epi ST, MCz, shallow donor or self-interstitial related
TO1	65±3	$(5.5±1.5)x10^3$	epi DO, self-interstitials (I_2, I_3, I_4)
TO2	71±3	$(9.0±3.0)x10^3$	epi DO, self-interstitials (I_2, I_3, I_4)
TS4	90±5	$(5.0±1.0)x10^4$	epi ST, MCz, self-interstitials (I_2, I_3, I_4)
TS5	180±10	$(1.2±0.5)x10^6$	epi ST, MCz, $VO^{-/0}$, *e*
TS6, TO2A	242±10	$(8.4±1.5)x10^4$	epi ST, DO, MCz, $V_2^{2-/-}$, *e*
TS7, TO3	250±10	$(1.2±0.7)x10^6$	epi ST, epi DO
TS8, TO4	280±10	$(1.7±1.0)x10^6$	epi ST, epi DO
TS9, TO5	305±10	$(6.4±4.0)x10^5$	epi ST, epi DO, MCz, IO_i ?
TS10	360±10	$(4.0±2.0)x10^6$	epi ST, MCz, $C_iO_i^{+/0}$, *h*
TS11, TO7	450±10	$(7.4±3.0)x10^7$	epi ST, epi DO, MCz, $V_2^{-/0}$, *e*
TS12, TO6	445±10	$(1.0±0.3)x10^8$	epi ST, epi DO, MCz, $V_2O^{-/0}$, *e*
TS13, TO8	480±10	$(5.0±2.0)x10^7$	epi ST, epi DO, MCz, complex involving V_4 or V_5
TS14, TO10	495±10	$(1.5±0.5)x10^7$	epi ST, epi DO, vacancy aggregate (V_3, V_4, V_5)
TS15, TO9	515±10	$(9.2±4.0)x10^7$	epi ST, epi DO, vacancy aggregate (V_3, V_4, V_5)
TS16	540±20	$(2.9±0.7)x10^7$	epi ST, MCz, vacancy aggregate (V_3, V_4, V_5)

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

Conclusions (1)

- Irradiation with high proton fluences, ranging from $5x10^{15}$ to $1.6x10^{16}$ cm^{-2}, results in dramatic degradation of the electrical properties of epitaxial silicon. The mobility lifetime product at 270 K drops to $1x10^{-7}$ cm^2/V. The detector leakage current at 200 V goes up to ~3 mA. Oxygenation process results in a small increase of the mobility lifetime product and a noticeable decrease in the detector leakage current (to ~1 mA).

- The defect levels in the irradiated epitaxial layers have been scanned by the High-Resolution Photoinduced Transient Spectroscopy (HRPITS). To extract the parameters of radiation defect centres from the photocurrent relaxation waveforms, the images of the correlation and Laplace spectral fringes, depicting the temperature dependences of the emission rate of charge carriers for detected defect centres, were created. The spectral fringes for the standard and oxygenated epilayers have been compared.

- In the standard epitaxial layers, 16 radiation defect centres with activation energies ranging from 15 to 540 meV have been revealed. In the oxygenated layers, 11 defect centres with activation energies ranging from 65 to 515 meV have been found.

Conclusions (2)

- The electrical properties degradation of the both standard and oxygenated epilayers is mainly due to the formation of 5 deep-level radiation centres with activation energies of 445, 450, 480, 495, and 515 meV. The former two are identified with V_2O and V_2, respectively. The latter three seem to be related to aggregates of vacancies (V_3, V_4, V_5).

- In the oxygenated epilayers, a high concentration of the shallow centres with activation energies of 65 and 71 meV have been observed. These centres are likely to be related to self-interstitial agglomerates.

- Further studies are aimed at determination of the quantitative changes in the defect centres concentrations induced by different proton fluences and oxygenation process. The studies of the epilayers defect structure evolution induced by annealing are also envisaged.

Acknowledgement

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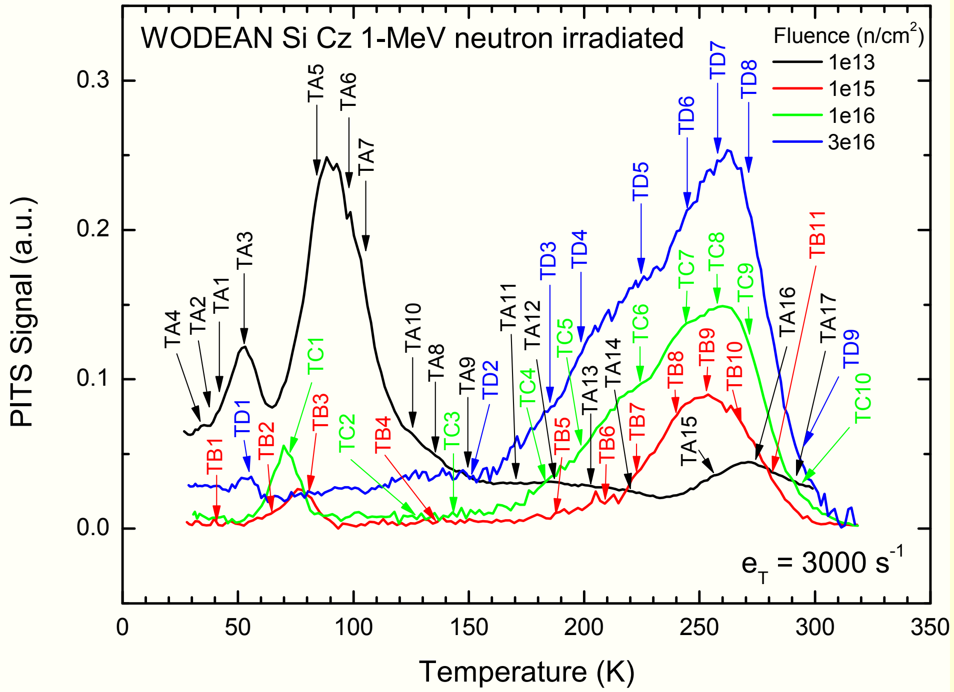
- This work was carried out within the framework of the RD 50 project with financial support of the Polish Ministry of Science and Higher Education under grant No. CERN/15/2007.

1D-HRPITS spectra for MCz-Si irradiated with 1-MeV neutron fluences ranging from $1x10^{13}$ to $3x10^{16}$ cm^{-2}



Trap label	E_a^* (meV)	A^* ($K^{-2}s^{-1}$)	Tentative identification
TA1, TB1	19±2	$(2.9\pm0.5)x10^2$	shallow donor, *e*
TA2	24±2	$(5.2\pm0.5)x10^3$	shallow donor, *e*
TA3	25±2	$(2.7\pm0.5)x10^2$	shallow donor, *e*
TA4	27±2	$(3.7\pm0.5)x10^4$	shallow donor, *e*
TD1	38±2	$(4.2\pm0.5)x10^3$	related to self-interstitials (I)
TB2, TC1	49±2	$(2.3\pm1.0)x10^3$	aggregate of self-interstitials (I_2)
TA5, TB3	67±2	$(6.2\pm0.5)x10^3$	aggregate of self-interstitials (I_3)
TA6	89±2	$(1.4\pm0.5)x10^4$	aggregate of self-interstitials (I_4)
TA7	92±2	$(6.4\pm0.5)x10^3$	C_iC_s $(A)^{+/0}$, *h*
TA8, TB4, TC2, TD2	153±3	$(4.3\pm2.0)x10^4$	TX3, self-interstitial-oxygen dimer complex ($IO_{i2}^{-/0}$), *e*
TA9	166±3	$(5.3\pm1.0)x10^4$	C_iC_s $(A)^{-/0}$, *e*
TA10, TC3	175±5	$(1.9\pm0.5)x10^6$	$VO^{-/0}$, *e*
TA11,	204±10	$(1.4\pm0.5)x10^5$	$V_2^{+/0}$, *h*
TA12, TB5, TC4, TD3	222±10	$(1.0\pm0.3)x10^5$	$V_2^{2-/-}$, *e*
TA13, TB6, TC5, TD4	274±10	$(5.0\pm1.0)x10^5$	$C_i^{+/0}$, *h*
TA14, TB7	301±10	$(4.8\pm1.0)x10^5$	IO_i ?
TB8, TC6, TD5	350±10	$(2.6\pm0.5)x10^6$	$C_iO_i^{+/0}$, *h*
TB9, TC7, TD6	430±10	$(2.8\pm0.5)x10^7$	$V_2O^{-/0}$, *e*
TA15, TB10, TC8, TD7	440±10	$(8.8\pm1.0)x10^6$	$V_2^{-/0}$, *e*
TC9, TD8	463±10	$(5.7\pm1.0)x10^6$	complex involving V_4 or V_5, *e*
TA16, TB11, TC10, TD9	550±10	$(1.3\pm1.0)x10^8$	I centre, aggregate of vacancies (V_3), *e*
TA17	556±20	$(2.7\pm1.0)x10^7$	aggregate of vacancies (V_5) ?
TA18	563±20	$(8.7\pm2.0)x10^8$	aggregate of vacancies (V_6) ?