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Rod-like defects in silicon: signatures of distinct RLD structures detected by various measurement methods

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Starting remarks

History

1991~1992 and 2002~2003, IMR Sendai
From 2005, JointLab, Cottbus

Publications

• T. Mchedlidze, V. V. Kveder, J. Jablonski, and K. Sumino, Phys. Rev. B **50**, 1511 (1994).
• T. Mchedlidze and M. Suezawa, Phys. Rev. B **70**, 205203 (2004).
• T. Mchedlidze, S. Binetti, A. Le Donne, S. Pizzini and M. Suezawa, J. Appl. Phys. **98**, 043507 (2005).
• T. Mchedlidze, S. Binetti, A. Le Donne, S. Pizzini and M. Suezawa, Phys. Stat. Sol. (c) **2**, 1807 (2005).

Acknowledgements

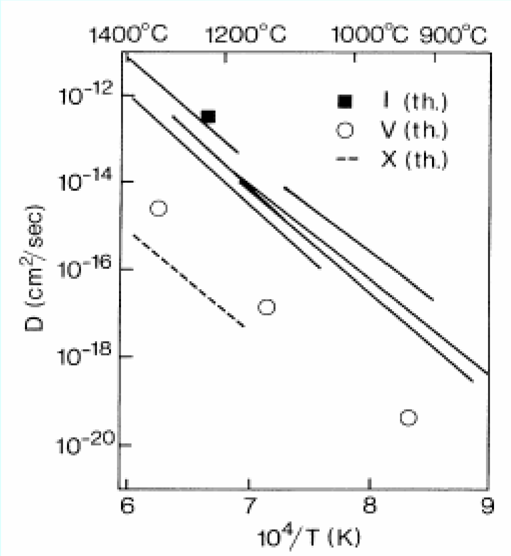
Cordial thanks are due to: Vitaly V. Kveder
Koji Sumino
Masashi Suezawa

Outline

- Reviewing what was known
  - Interstitial agglomerates in Si
  - Transmission electron microscopy
  - Theoretical calculations
  - Photoluminescence and deep level transient spectroscopy
  - Electric-dipole spin resonance
- Experimental
  - Samples, measurement technique
- Signatures of rod-like defects
  - Deep level transient spectroscopy
  - Photoluminescence
- Summary

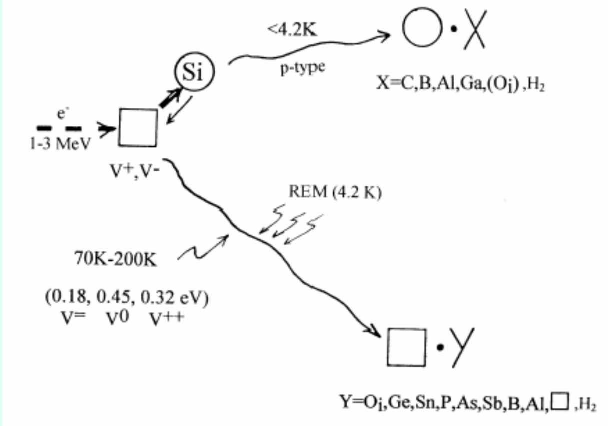
Self-interstitials in Si

Diffusion processes (TED)



P.E. Blochl et al., PRL **70**(1993)2435

Defect reactions



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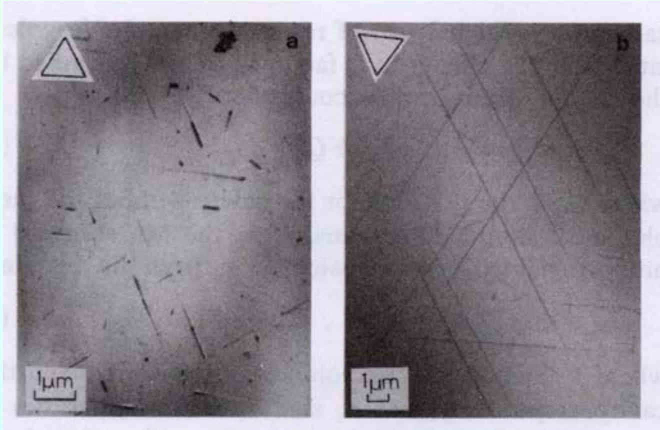
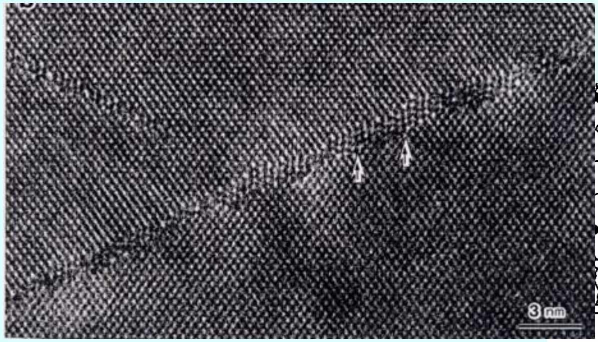
Thermal donors in silicon: oxygen clusters or self-interstitial aggregates?

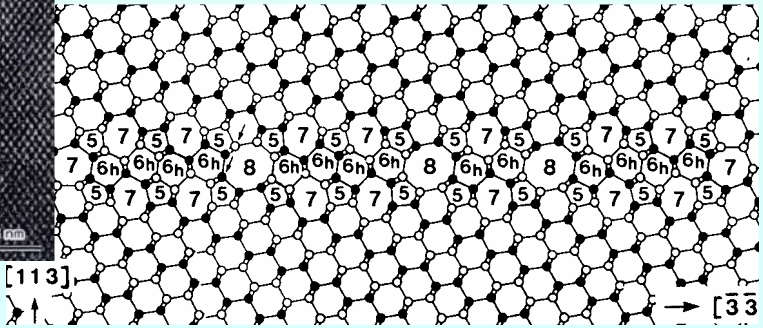
R.C. Newman, J.Phys.C: Sol.St.Phys.18(1985)L967

Rod-like defects





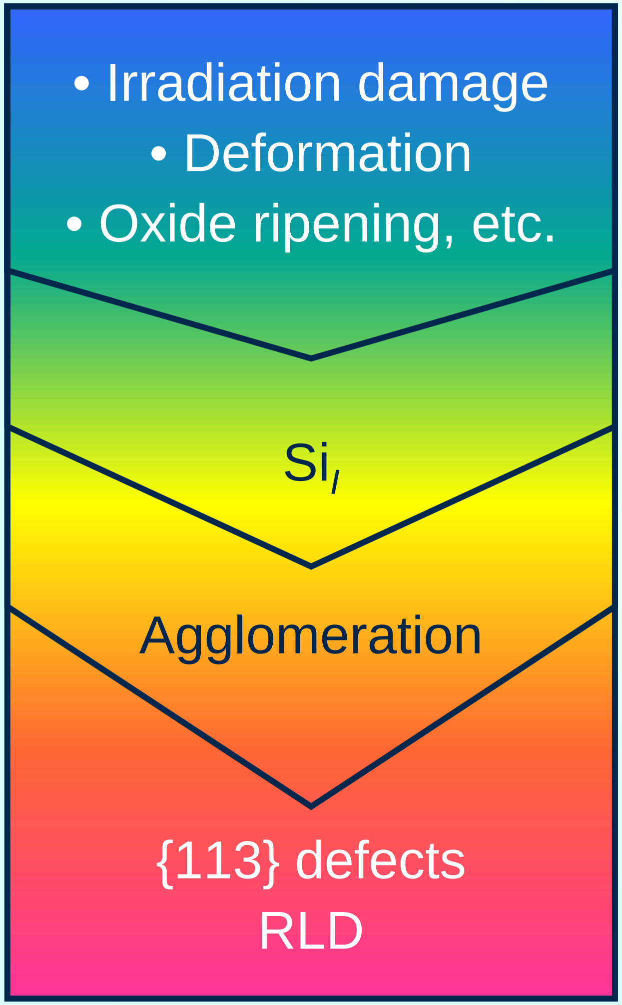
{311} structural defects

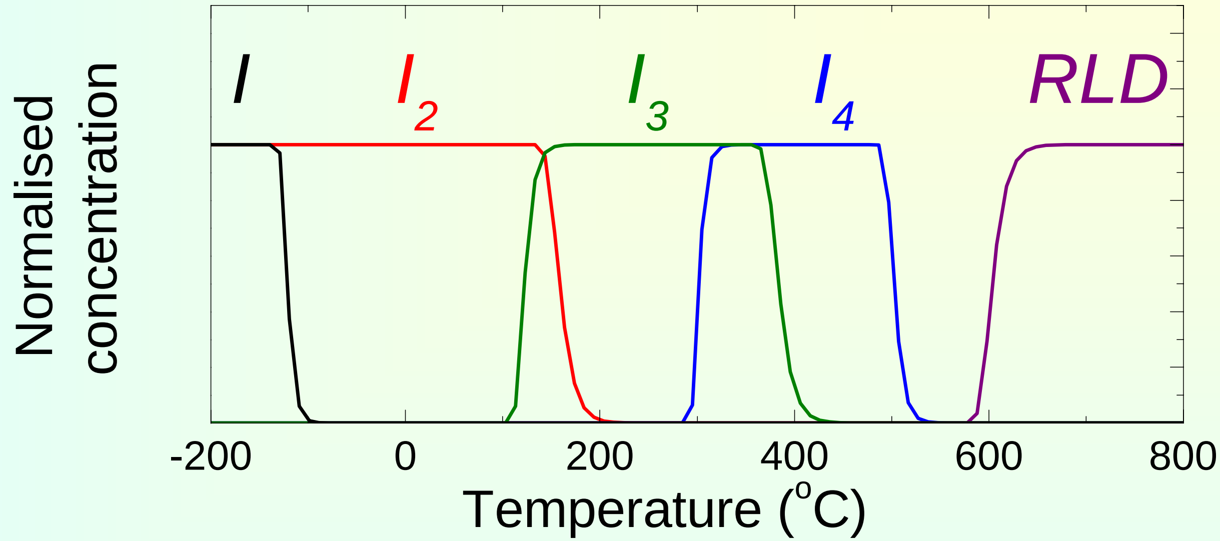


S.Takeda et.al., Phil.Mag.**70**(1994)287

T.Mchedlidze et al., PRB **50**(1994)1511

Formation of self-interstitial agglomerates





? Properties of small clusters

? Formation mechanism:

- ? ripening $(I_n + I \rightarrow I_{n+1})$ or
- ? special role of I_4 and I_8 $(I_n + I_k \rightarrow I_{n+k})$

? Role of impurities (H, O, C, Fe…)

Properties of self-interstitial agglomerates

Theoretical calculations:

- B. J. Coomer, et. al., J.Phys.: Condens. Matter **13**, L1 (2001).
- P. Alippi and L. Colombo, Phys. Rev. B **62**, 1815 (2000).
- J. Kim, et. al., Phys. Rev. Lett., **84**, 503 (2000).
- J. P. Goss, et. al., Appl. Phys. Lett., **85**, 4633 (2004).

Transmission electron microscopy:

- S. Takeda, Jpn. J. Appl. Phys. **30**, L639 (1991);
- M. Kohyama and S. Takeda, Phys. Rev. B **46**, 12 305 (1992).

Electrical and optical investigations:

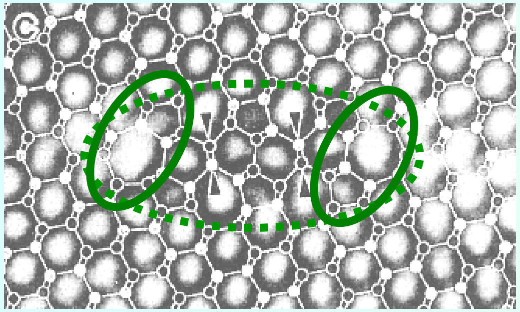
- J. L Benton, S. Libertino, S. Coffa, et. al., Appl. Phys. Lett., 71, 389 (1997); J. Appl. Phys., 82, 120 (1997); J. Appl. Phys., 84, 4749 (1998); Phys. Rev. B, 63, 195206 (2001).
- P. K Giri, Semicond. Sci. and Technol., **20**, 638 (2005).

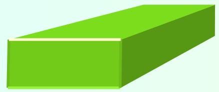
Spin resonance investigations:

- T. Mchedlidze, et. al., Phys. Rev. B **50**, 1511 (1994).
- D. Pierreux and A. Stesmans, Phys. Rev. B **68**, 193208 (2003).
- T. Mchedlidze and M. Suezawa, Phys. Rev. B, **70**, 205203 (2004).
- T. Mchedlidze, et. al., J. Appl. Phys. **98**, 043507 (2005).

RLD – {113} structural defects - TEM

LID





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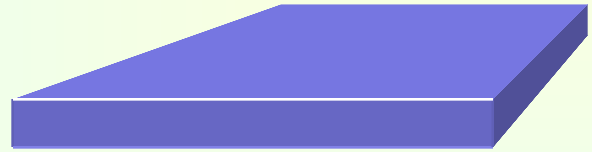
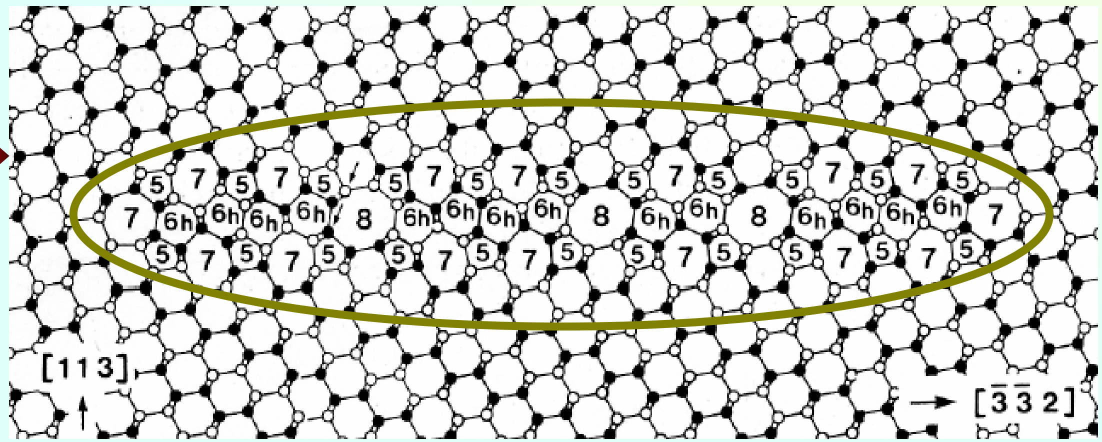
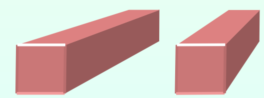
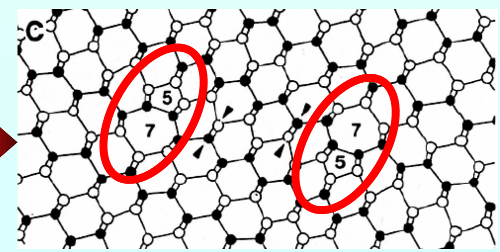






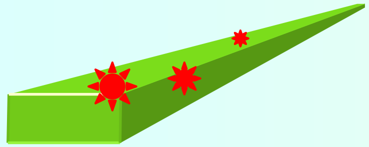
DD

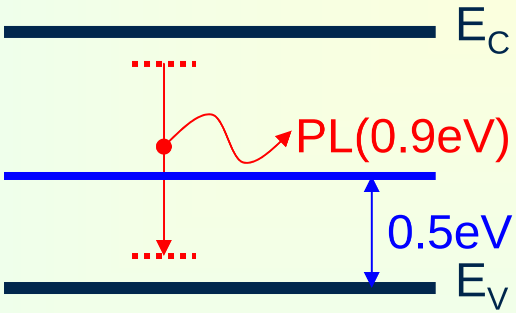


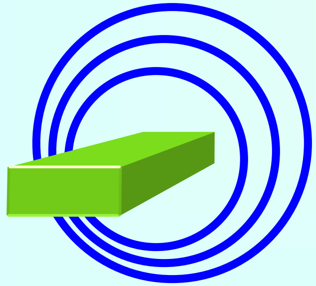
$\otimes$ [1$\bar{1}$0]

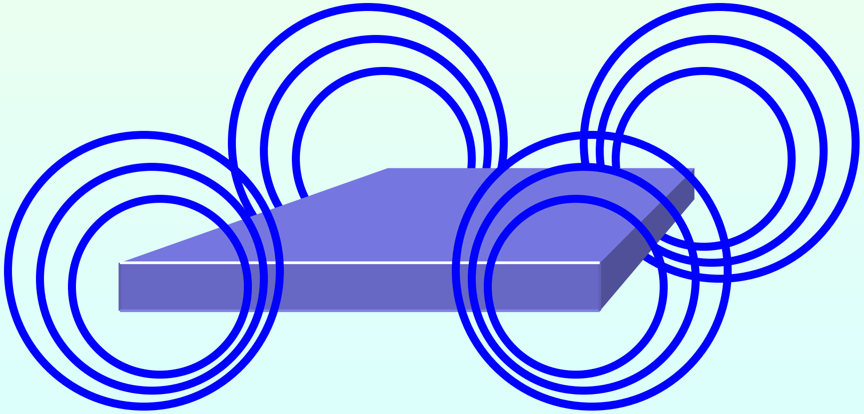
S.Takeda et.al., Phil. Mag. **70** (1994) 287

RLD – {113} structural defects - theory









J. P. Goss, et. al., Appl. Phys. Lett., **85**, 4633 (2004).

RLD – {113} structural defects – DLTS, PL

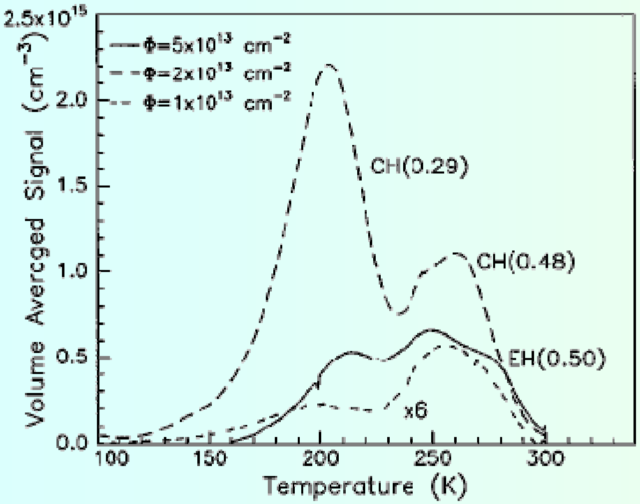


FIG. 5. DLTS spectra after 145 keV Si ion implantation and thermal anneal of 685 °C, 1 h. The concentration of cluster defects increases as the dose is raised from 1×10^{13} to 2×10^{13} Si/cm^2. At a fluence of 5×10^{13} Si/cm^2, the total concentration of cluster defects is dramatically reduced and the extended defect signature, EH(0.50 eV), is observed.

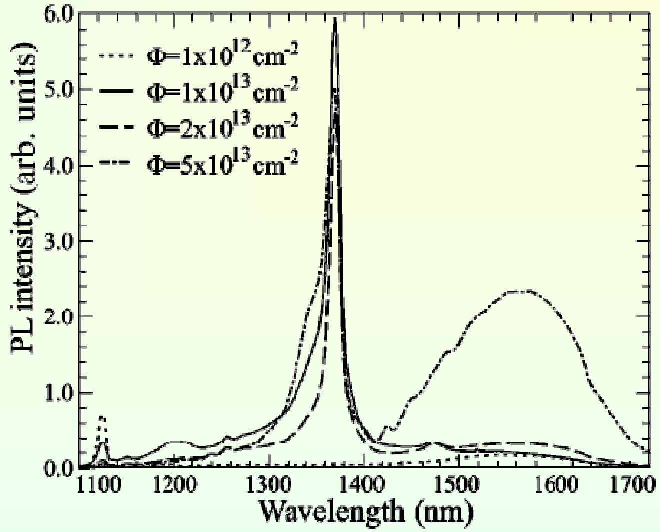
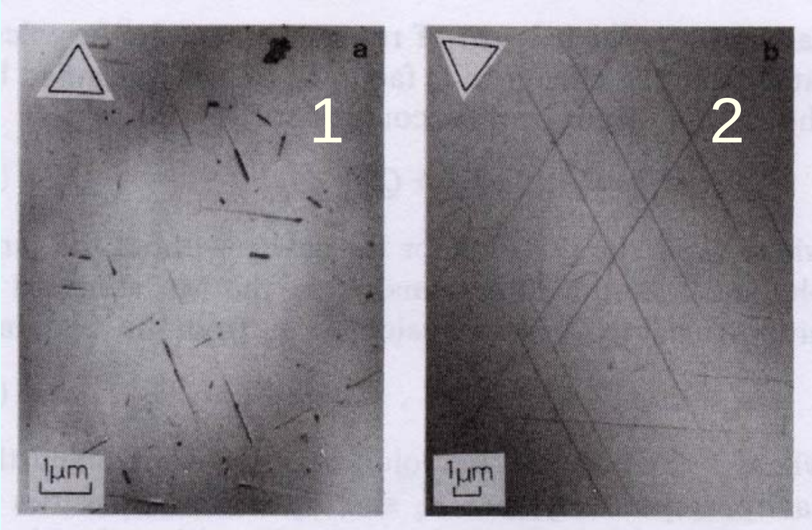


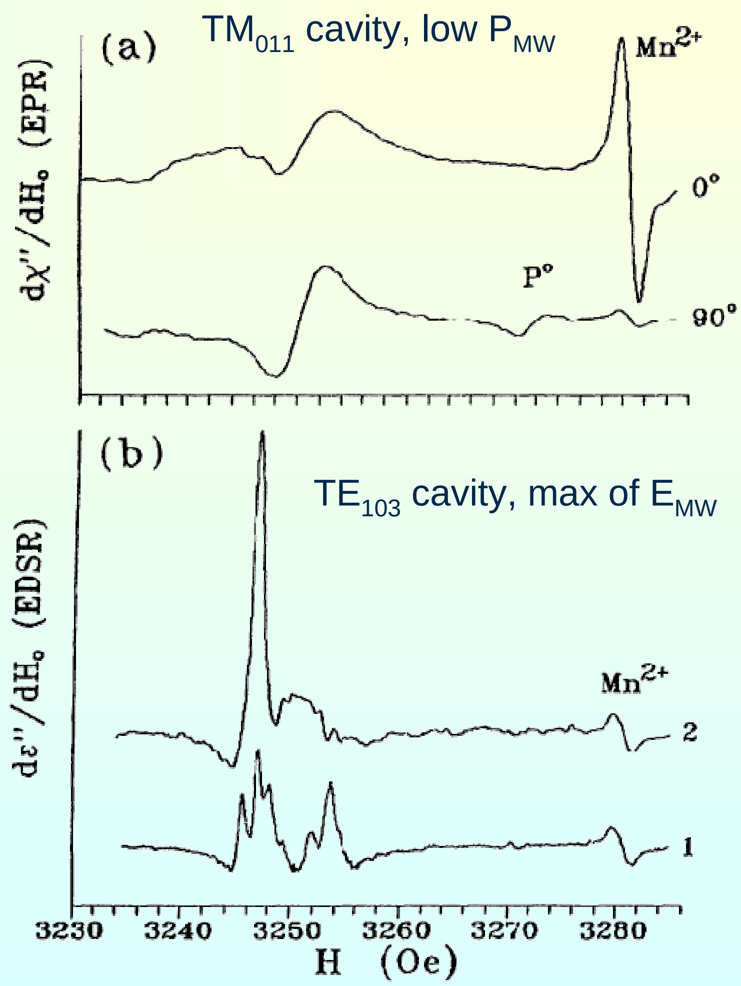
FIG. 18. PL spectra taken at 17 K on *n*-type Si samples implanted with 1.2 MeV Si to doses of 1×10^{12} cm^{-2} (dotted line), 1×10^{13} cm^{-2} (solid line), 2×10^{13} cm^{-2} (dashed line), and 5×10^{13} cm^{-2} (dash-dot-dashed line). The samples have been annealed at 680 °C for 1 h.

- High-dose implantation, >10^{13} Si/cm^2, and annealing at temperatures above 680°C causes the {311} extended defect formation.
- The {311} defect presence is detectable by both electrical (with a signature at E_V+0.5 eV) and optical (with a PL signal at 1376 nm) measurements.

J. L Benton, S. Libertino, S. Coffa, et. al.

RLD – {113} structural defects – EDSR





From dependencies of intensity and shape of the EDSR signals on temperature and MW power it was determined that:

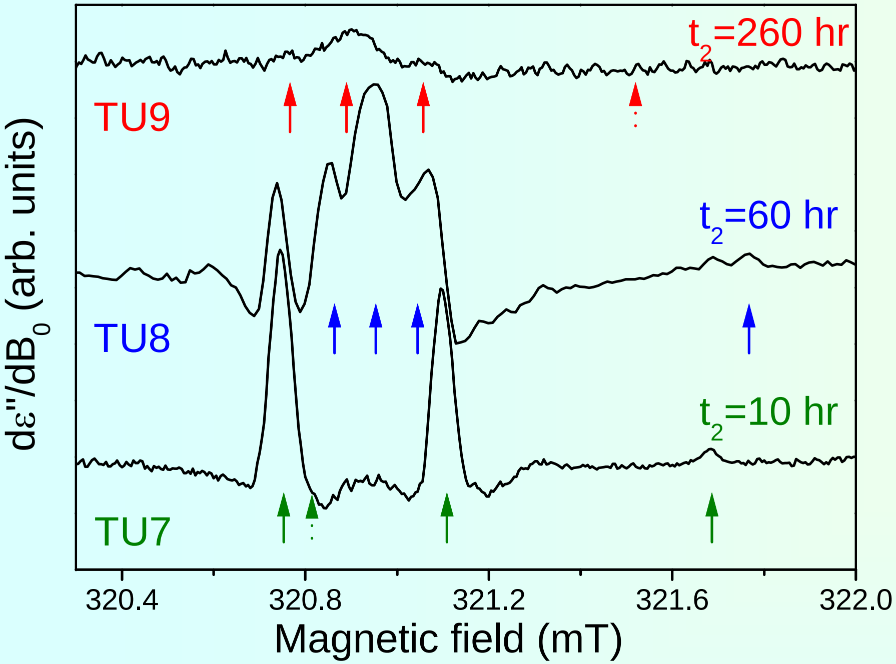
- Relatively deep quasi-one-dimensional energy band is associated with RLDs
- Localization length of electrons along RLDs is of 100 nm order.
- Electron mobility in the band at 10K is more than 500 cm^2/V.

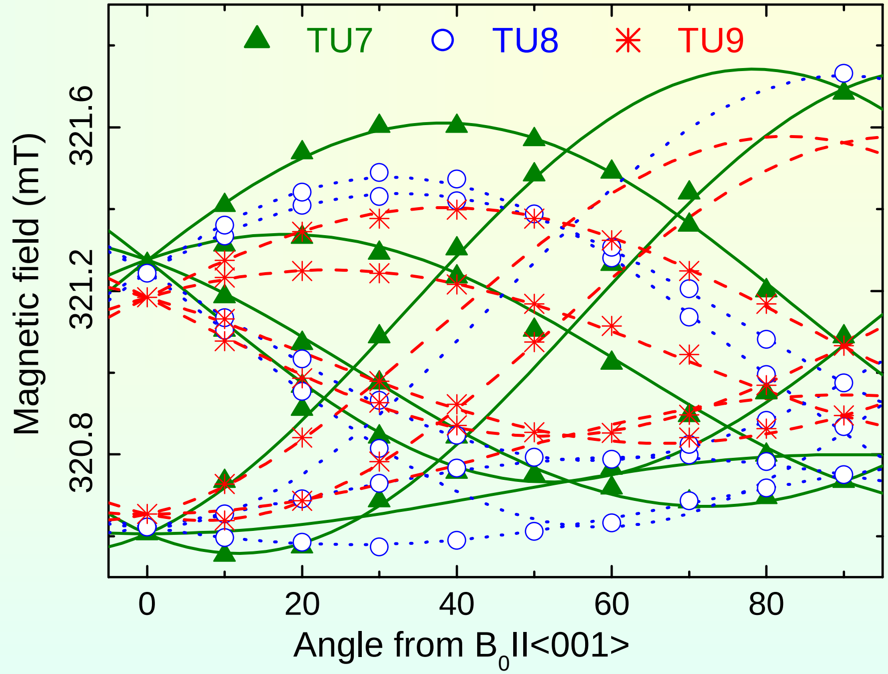
T. Mchedlidze, et. al., Phys. Rev. B **50**, 1511 (1994).

Samples

- Phosphorus-doped Cz-Si crystals.
- Initial resistivity of 0.8 Ωcm.
- Interstitial oxygen concentration of 25×10^{17} cm^{-3}.
- Pre-annealing in evacuated quartz capsules at 450°C for 160 h.
- Subsequent annealing at 650°C for
  - 10 h (sample “S”)
  - 60 h (sample “M”)
  - 260 h (sample “L”)

Identification of EDSR signals from RLDs



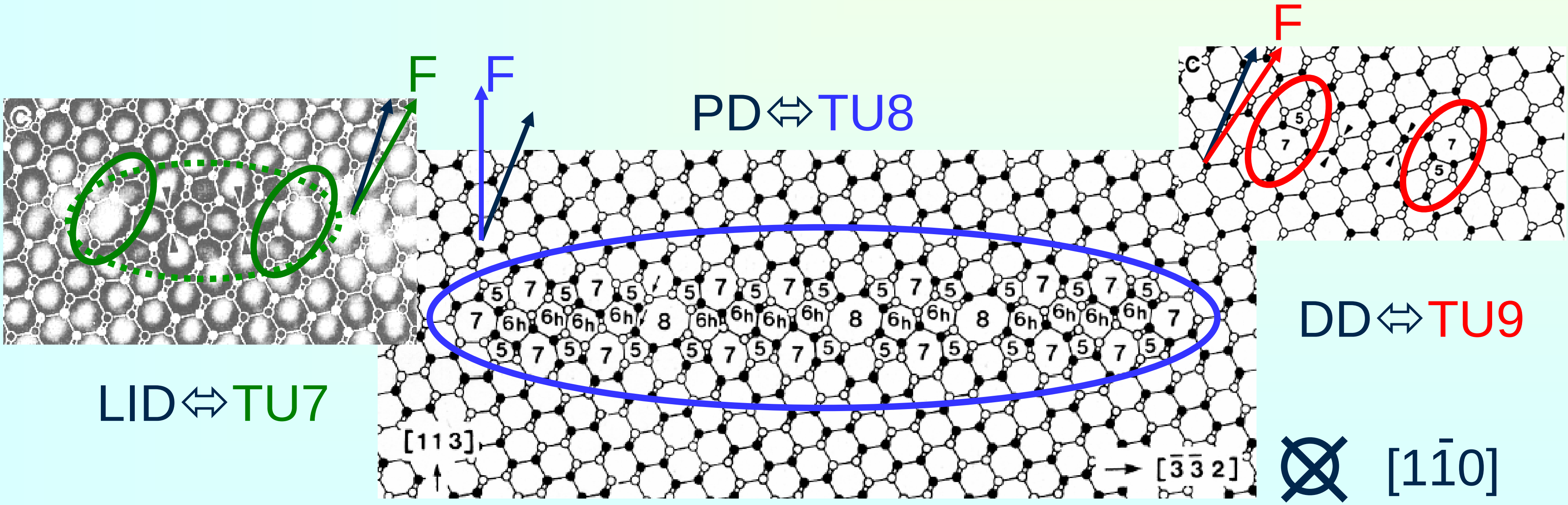


Center	Spin	System	g_1	g_2	g_3	θ	Defect
TU7	½	C_{1V}	2.0005	1.9946	2.0020	12	LID
TU8			1.9947	2.0005	2.0018	27	PD
TU9			1.9996	1.9957	2.0015	9	DD

Identification of EDSR signals from RLDs

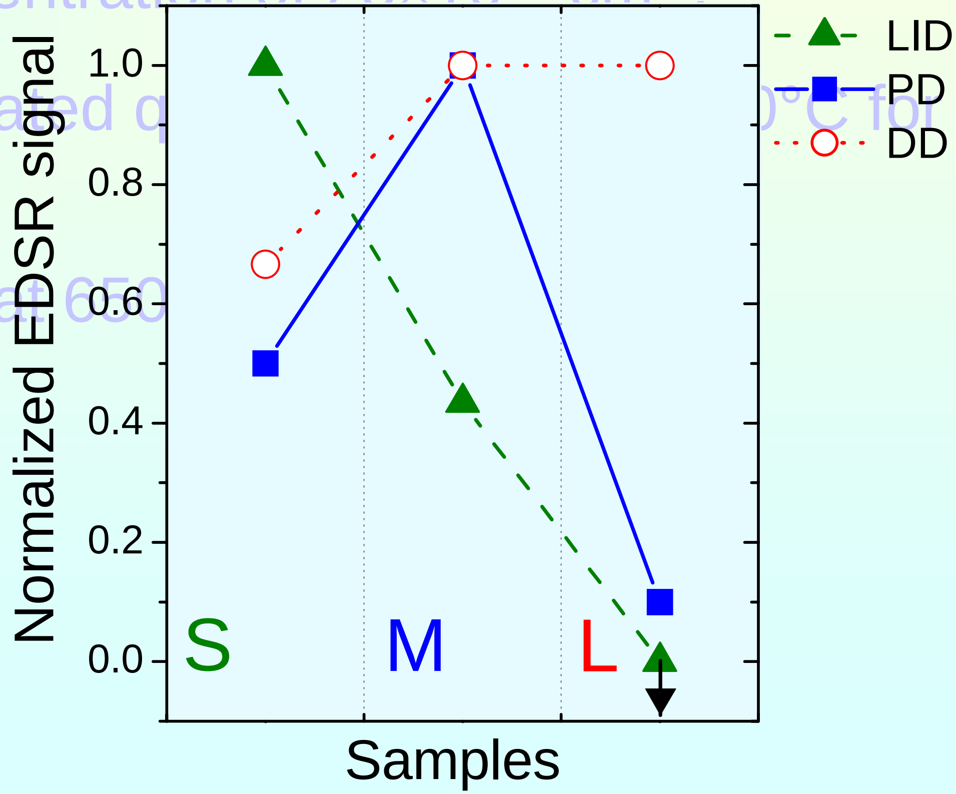
• Summetry of the TU7-TU9 centers fits that expected for the RLD structures. Moreover, the directions for the main axes of g tensors closely fits those expected for the RLD structures, i.e., ~[113] for PDs and ~[115] for LIDs and DDs.

• Formation kinetics for the EDSR signals and related RLD structures also well correlates.



Samples pre-characterized by EDSR

- Phosphorus-doped Cz-Si crystals.
- Initial resistivity of 0.8 Ωcm.
- Interstitial oxygen concentration of 25×10^{17} cm^{-3}.
- Pre-annealing in evacuated q… 0°C for 160 h.
- Subsequent annealing at 650…
  - 10 h (sample “S”)
  - 60 h (sample “M”)
  - 260 h (sample “L”)



Experimental

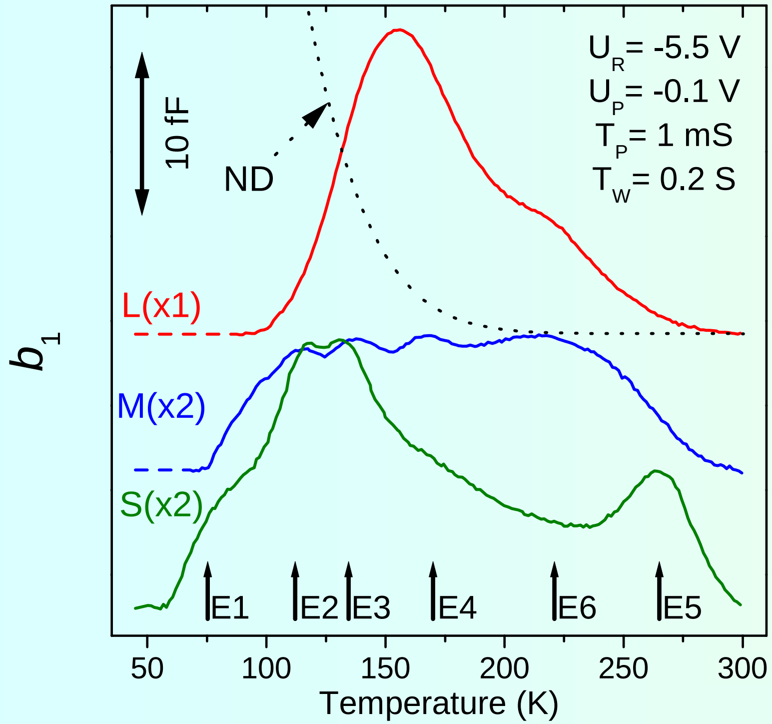
DLTS measurements:

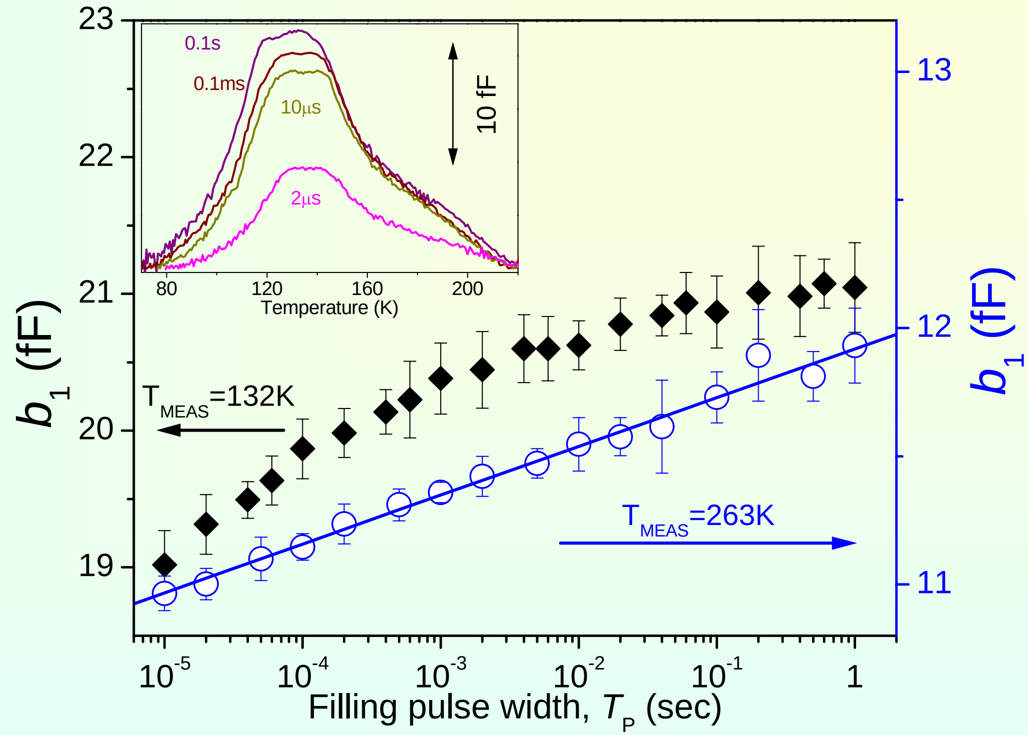
- Au Schottky contacts, ∅ 0.7 mm.
- Ohmic contacts: GaIn alloy.
- Transient Fourier spectroscopy DL-8000 system (Accent). T_{MEAS}: 20 ÷ 300 K.
- Representative DLTS spectra change of b_1 Furrier coefficient with temperature (T_{MEAS}) and/or with sampling period (T_W).

PL measurements:

- Excitation with Ar-ion laser:
  - λ = 454 nm
  - Power density: 10 ÷ 1000 W/cm^2
- T_{MEAS}: 5 ÷ 300 K.
- PL system: monochromator→ N_2 cooled Ge-detector + laser-beam chopper and a lock-in system.
- Detection range 0.7-1.5 eV.

Results: DLTS

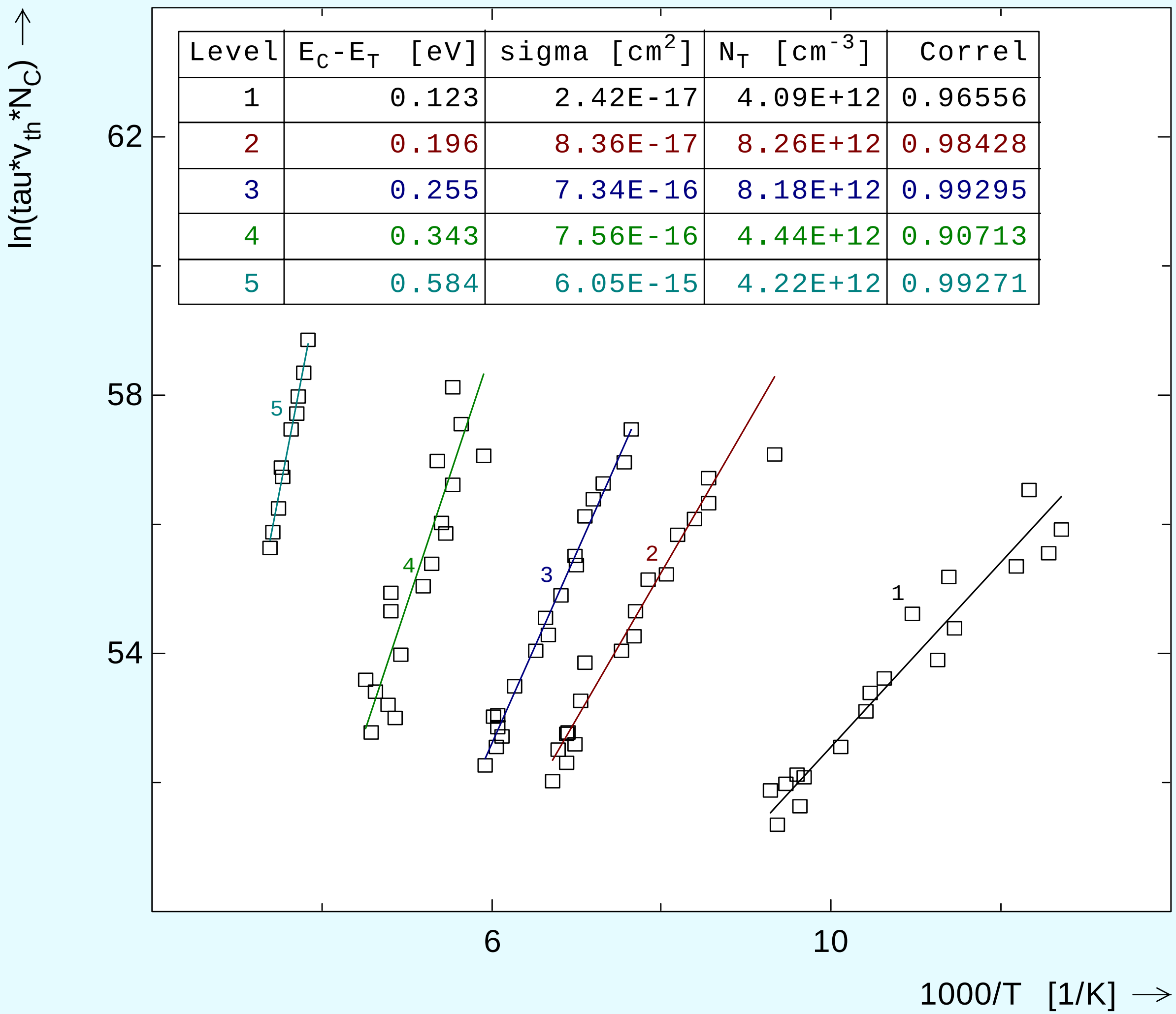




Character of defect states:

- E_2 & E_3 are extended defects with band-like states;
- $E_{5\ are}$ extended defects with localized states. E_4 & E_6 are extended defects;
- E_1 character of defects states couldn't be determined.

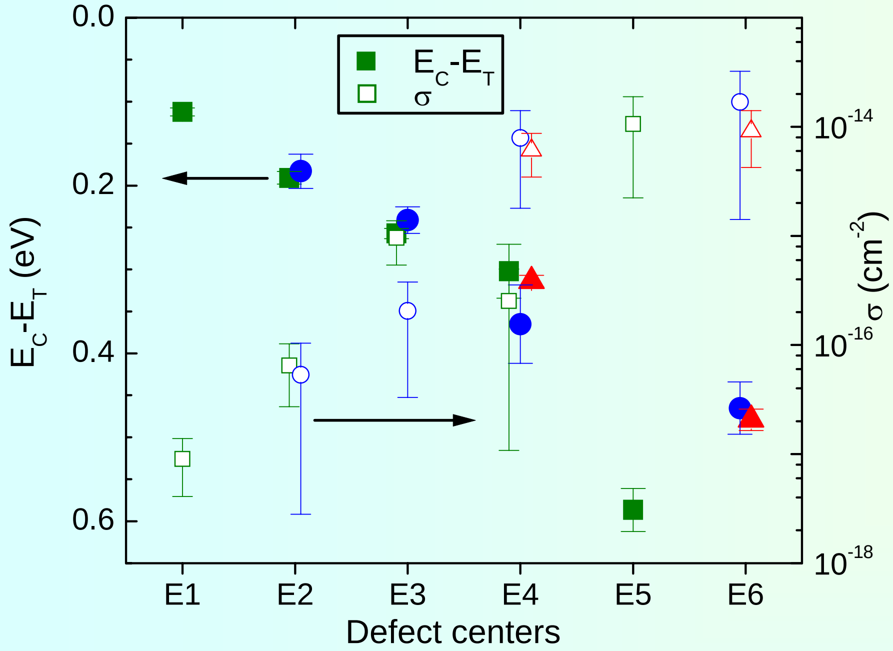
Results: DLTS: Arrhenius plot (example)

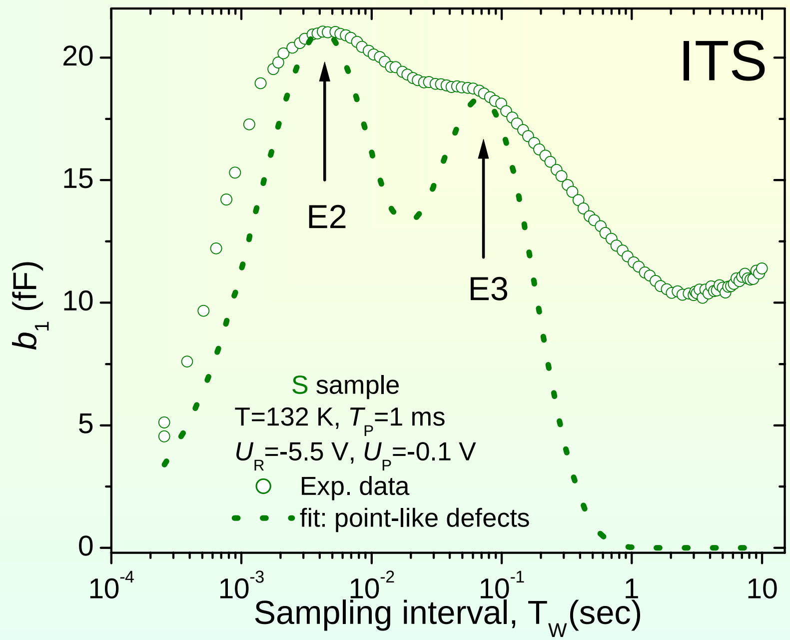


Level	E_C-E_T [eV]	sigma [cm^2]	N_T [cm^{-3}]	Correl
1	0.123	2.42E-17	4.09E+12	0.96556
2	0.196	8.36E-17	8.26E+12	0.98428
3	0.255	7.34E-16	8.18E+12	0.99295
4	0.343	7.56E-16	4.44E+12	0.90713
5	0.584	6.05E-15	4.22E+12	0.99271

Name = @A_001.ATA
Comm = Rodlikes in ch5 new soft
ID = CH5
rcID = 0000
Date = 08/15/2006
Type = n-Si
Area = 3.95E-03 cm^2
N_S = 4.32E+14 cm^{-3}
T_W = 2.05 ms
t_P = 1.00 ms
U_R = -5.50 V
U_P = -0.10 V

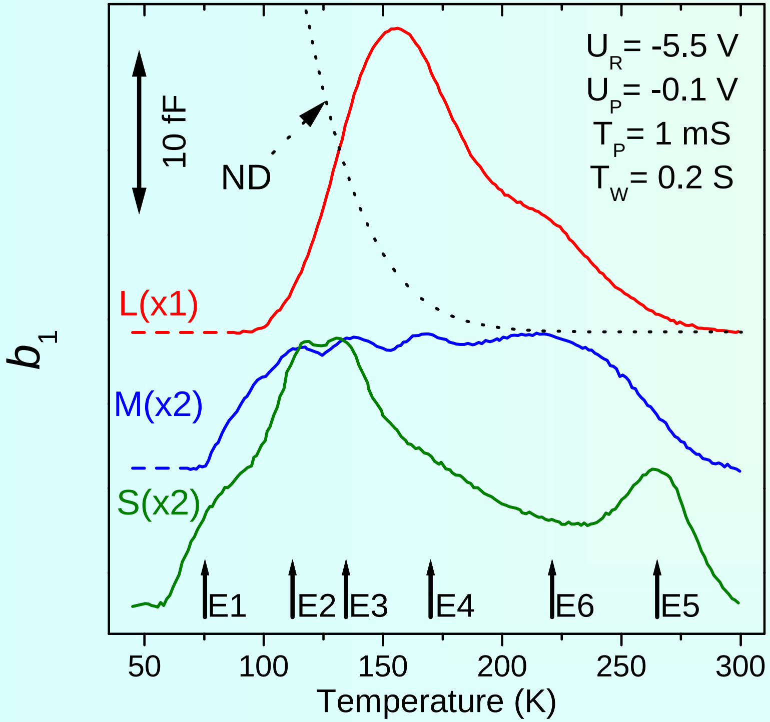
Results: DLTS





- Scatter of E_C-E_T and σ parameters is related to extended character of states.
- Estimations of trap density is not valid; E_C-E_T and σ are only rough estimates.
- From Isothermal Transient Spectrum detected at 132K and from fitting of this spectrum with point-like defect model: $N(E_2) = N(E_3)$.

Results: DLTS



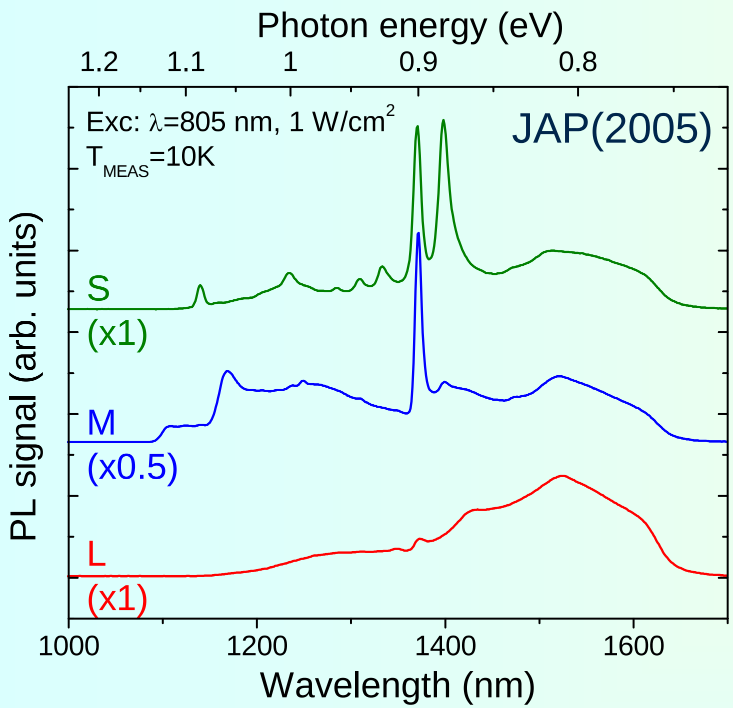
<u>Attribution by change in signal intensity:</u>

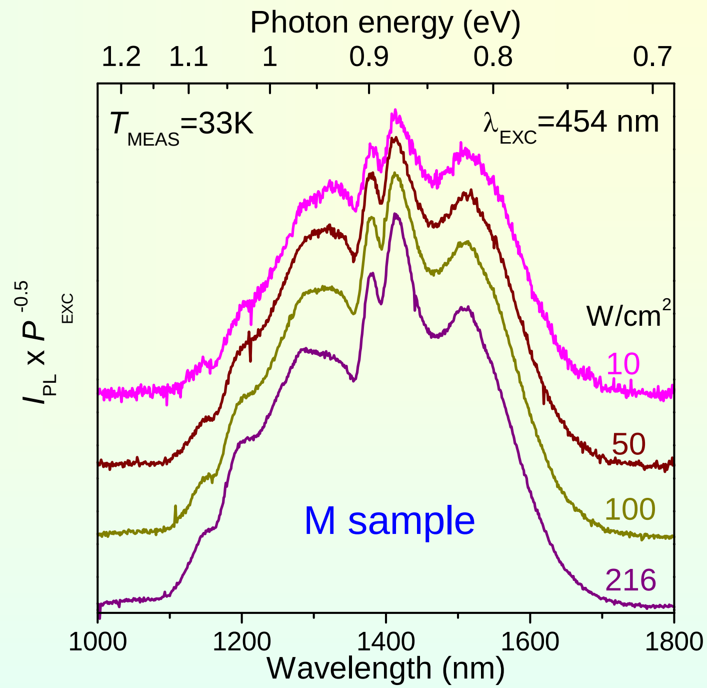
- E_2(~0.2 eV) & E_3(~0.25 eV) – LID
- E_5(~0.59 eV) – LID (?)
- E_4(~0.35 eV) – DD
- E_6(~0.48 eV) – PD
- E_1(~0.11 eV) – ??

<u>Attribution by character of states:</u>

- E_2, E_3 – LID, localized along defects
- E_5 – LID, defects in structure or non-RLD
- E_4 – DD, localized and band-like states
- E_6 – PD, localized and band-like states
- E_1 – non-RLD (?)

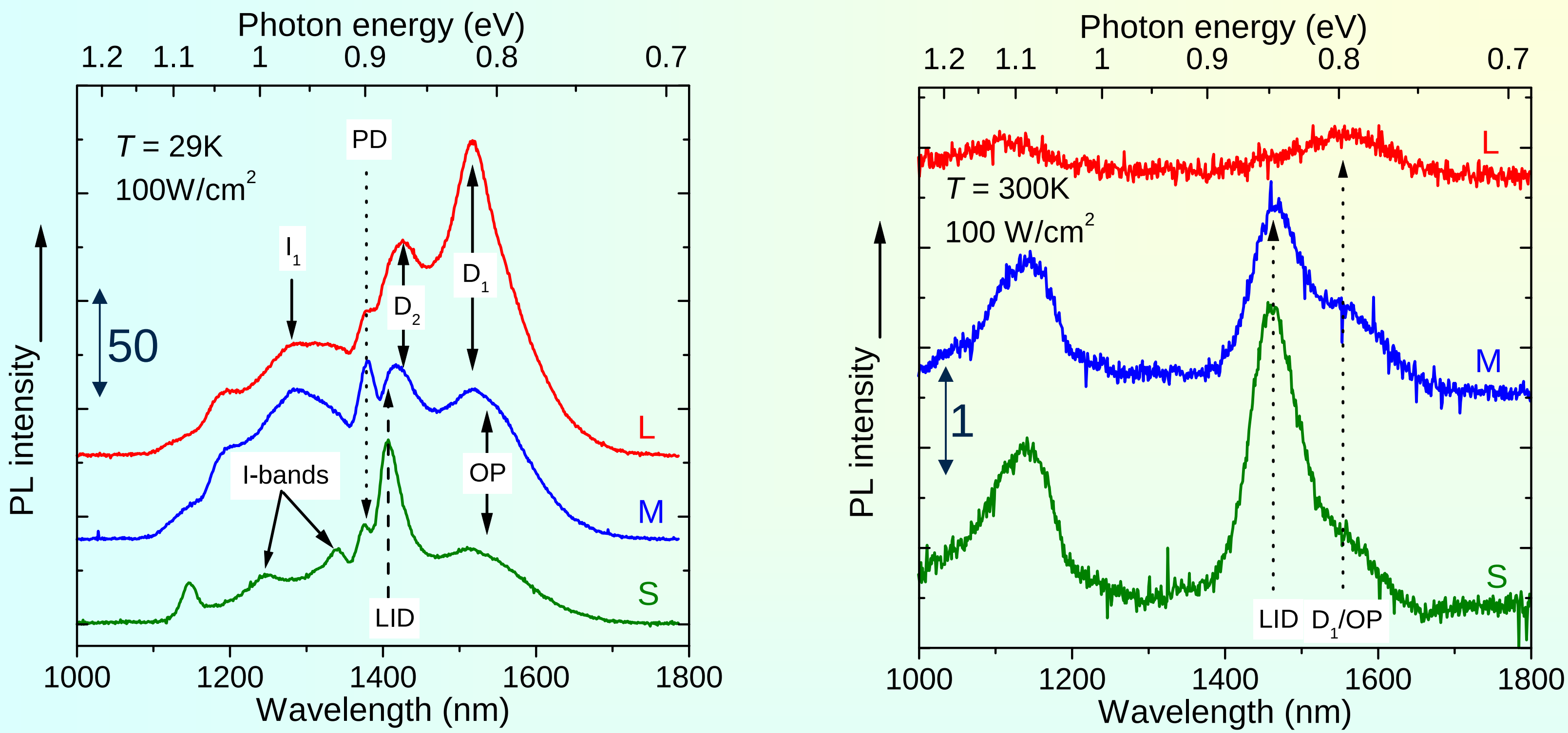
Results: PL





- Small power density was used previously to achieve maximal resolution.
- To excite possibly large number of transitions and suppress influence of variation in recombination cross-sections, possibly high power density should be used for excitation.
- Excess power density may cause loss of resolution and local heating.

Results: PL

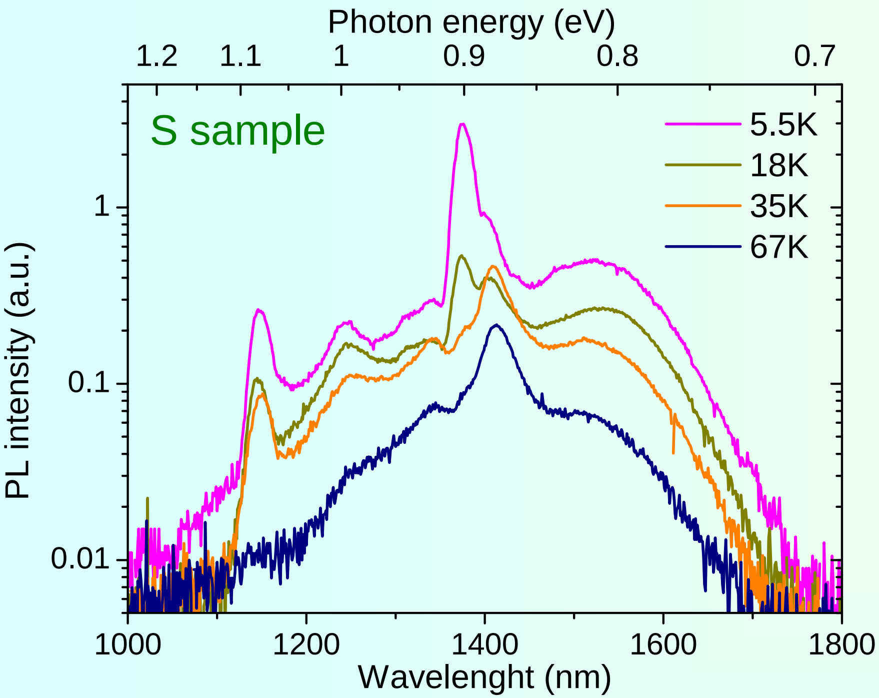


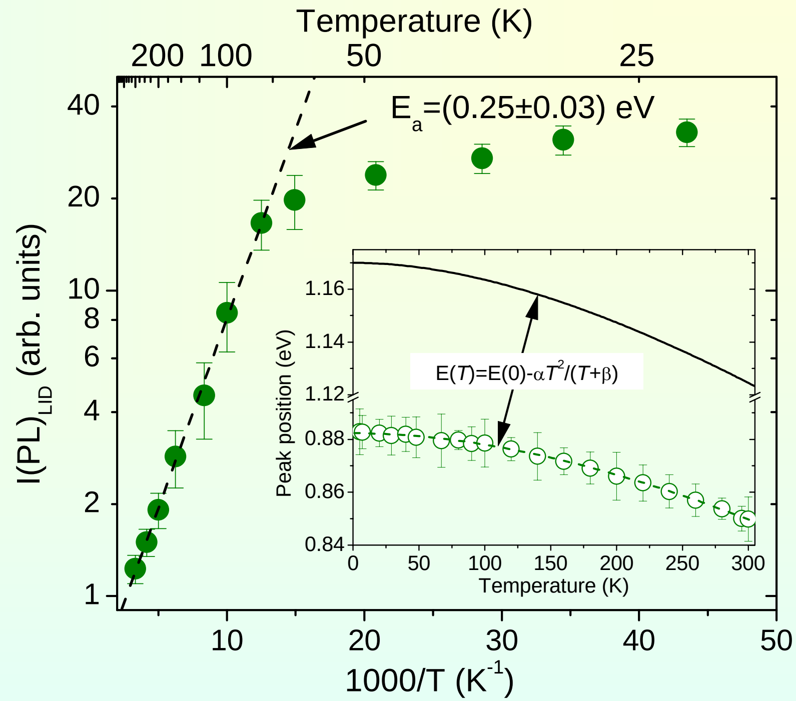
• For all T_{MEAS} the PL spectra for S, M and L samples differed significantly.

• Assignment of PL peaks was done according to EDSR results for samples and using published data for PL peaks.

• Temperature behavior of peaks was complex.

Results: PL



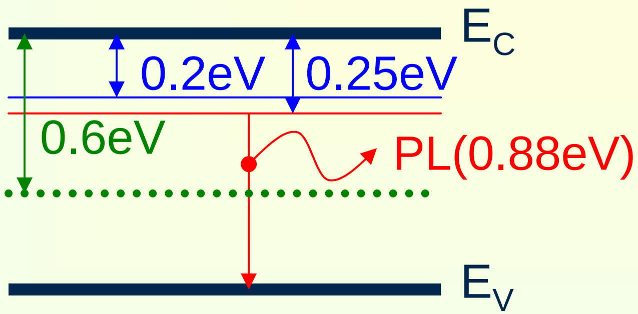


- Quenching of the LID peak intensity was observed from $T_{MEAS} \geq 70$ K. Activation energy of this process, $E_a \approx E_C - E_{LID}$(PL) ≈0.25eV

$E(T) = E(0)-\alpha T^2/(T+\beta)$	$E_T(0)$ (eV)	α (10^{-3} eV/K)	β (K)
Si band gap	1.17	4.7	636
LID	0.88	4.7	999

Summary

Line-interstitial defects:



- Appear at early stages of RLD formation
- They have extended band-like states

Optical signatures:

PL: PL peak at 1405nm (0.88eV) at He temperatures. Peak persists up to room temperature, energy of the PL peak is shifted to ~1458nm (0.85eV). This peak corresponds to band-edge transition and could be observed even at room temperature.

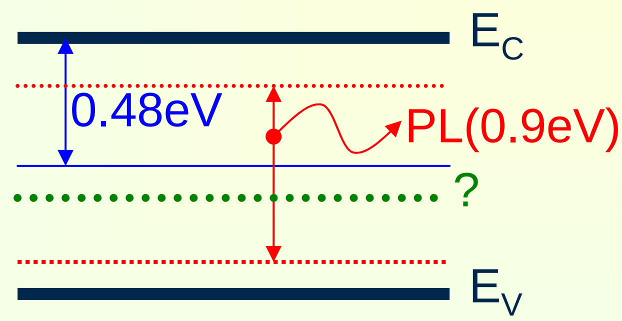
Electrical signatures:

DLTS: Pair of energy bands with similar density of states are positioned at ~0.2eV and ~0.25eV from the conduction band.

Possibly LID has also deep extended localized states located at ~0.6eV from conduction band. This states may be related to irregular parts of LIDs.

Summary

Plane defects:



- Appear at intermediate stages of RLD formation
- They have extended band-like states

Optical signatures:

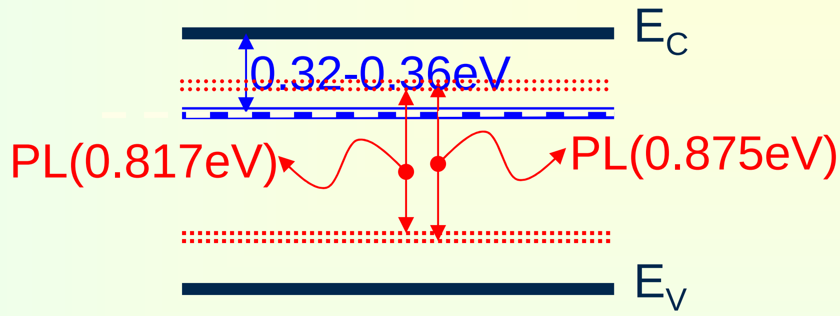
PL: Strong PL peak at 1372nm (0.9eV). At room temperature energy of PL peak is shifted to ~1458nm (0.85eV). Origin of this emission is unclear. The peak has strong temperature dependence: the intensity decreases more than 20 times when the T_{MEAS} changes from 5 to 35 K.

Electrical signatures:

DLTS: Energy band is positioned at ~0.48eV from the conduction band.

Possibly PD has also deep extended localized states. This states may be related to irregular parts of PDs.

Summary



Dislocation dipoles:

- Appear after dissociation of plane defects
- Extended localized (mostly) and band-like states

Optical signatures:

PL: PL peaks positioned at 1426nm (D_2, 0.875eV) and 1515nm (D_1, 0.817eV). Origins of this emissions are unclear.

Electrical signatures:

DLTS: The energy level (levels) for these defects are positioned at 0.32 – 0.36 eV below the conduction band.