Electrically active defects in semiconductors induced by radiation

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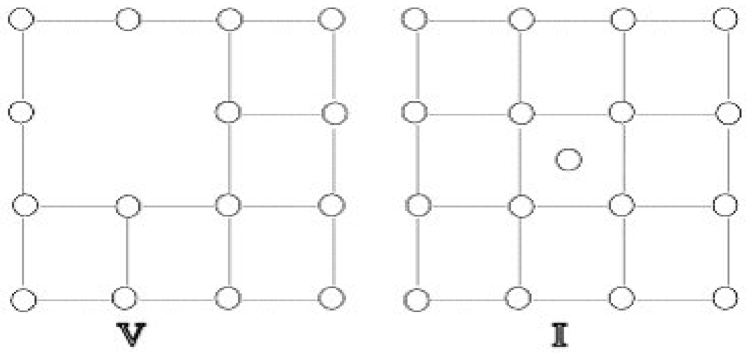
Outline

- Radiation damage
- Capacitance transient techniques
- Experimental results: radiation induced defects in n-type Si and Ge
- Conclusion

Radiation damage

Primary damage is the displacement of a lattice atom to create an interstitial and a vacancy. These can:

- Recombine … no damage
- Migrate to an oxide coated surface where they may result in excess interface charge
- React with impurities in the silicon eg VO or displace atoms eg B_i which are mobile and will react with other impurities or defects … these are likely to have electrical activity
- The intrinsic defects may react with each other eg V_2 to generate electrically active centres or possibly inert defects.

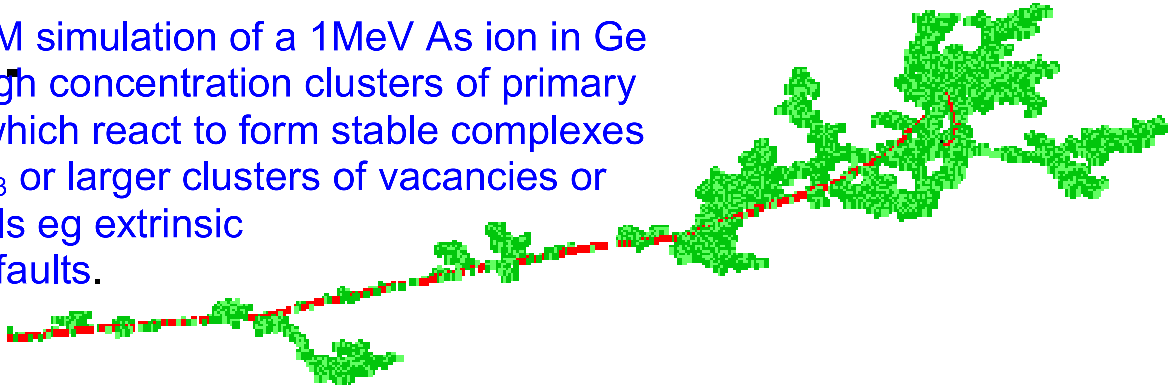


Effects of particle type and flux

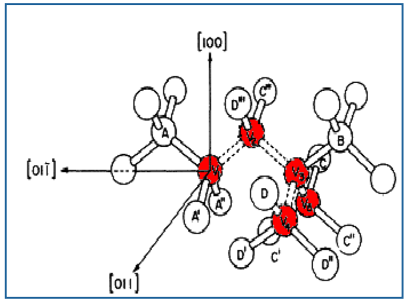
At low levels of irradiation with electrons or gamma rays almost all the lattice damage is in the form of simple point defects which can be studied by many techniques and are relatively well understood in Si.

Damage from energetic particles or heavy ions is much more complex, difficult to study and with many unknowns in terms of electrical activity and reaction energetics.

This SRIM simulation of a 1MeV As ion in Ge shows high concentration clusters of primary defects which react to form stable complexes eg V_2 , V_3 or larger clusters of vacancies or interstitials eg extrinsic stacking faults.



Vacancy cluster in Si



Main theme of our research in the last few years has been implant damage sometimes using fast neutron irradiation (at TRIGA Ljubljana) to help us to understand ion damage.

Factors affecting the defect species created by particle irradiation or implantation

- Type and concentration of impurities
- Nature of surface eg in Si an oxided surface sinks vacancies
- Particle species
- Particle energy
- Particle dose (fluence)
- Particles dose rate (flux)
- Temperature

Fundamentally this is a consequence of local concentrations of intrinsic defects.

Impact of defects on detector performance

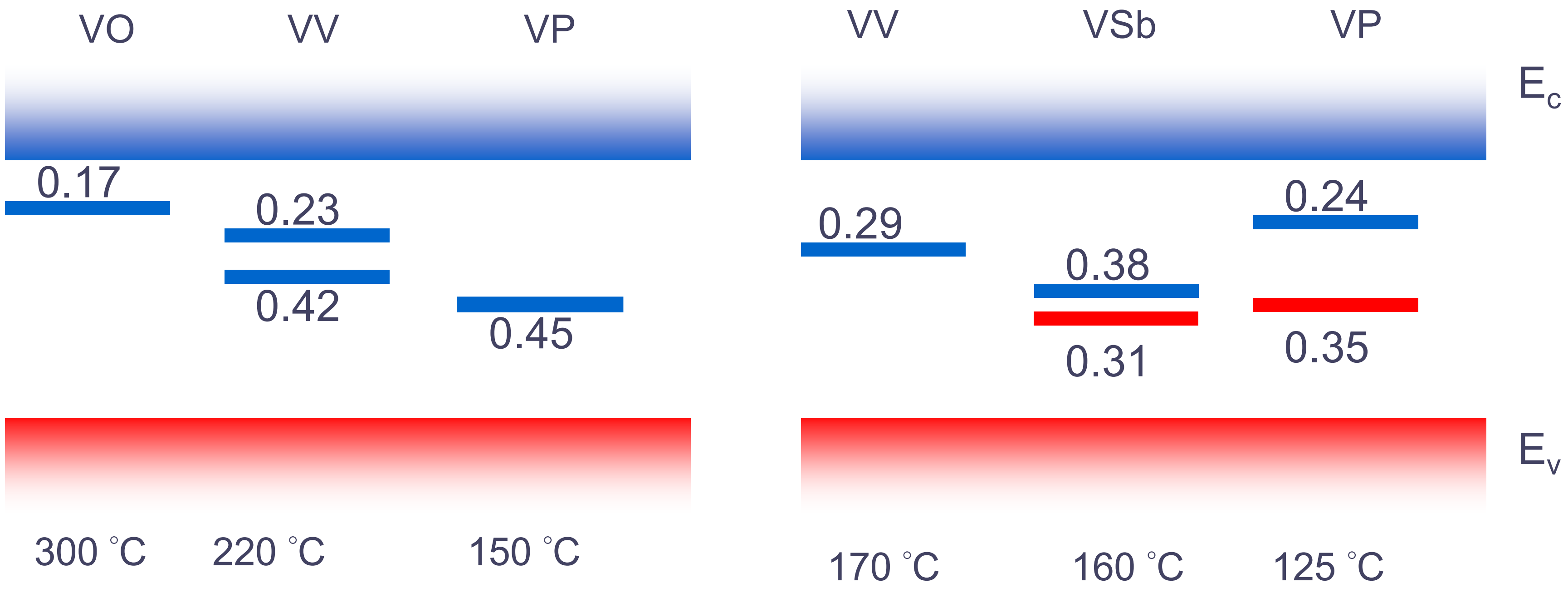
- Creation of donor and or acceptor like defects
- Generation current (reverse bias leakage)
- Recombination in neutral regions
- Carrier trapping

The detector community has made dramatic advances in radiation hardness in the last decade both through device and system design.
Is it possible to engineer defect kinetics to reduce (or eliminate) the above effects?

How can we engineer defect reactions to minimise the impact on electrical properties?

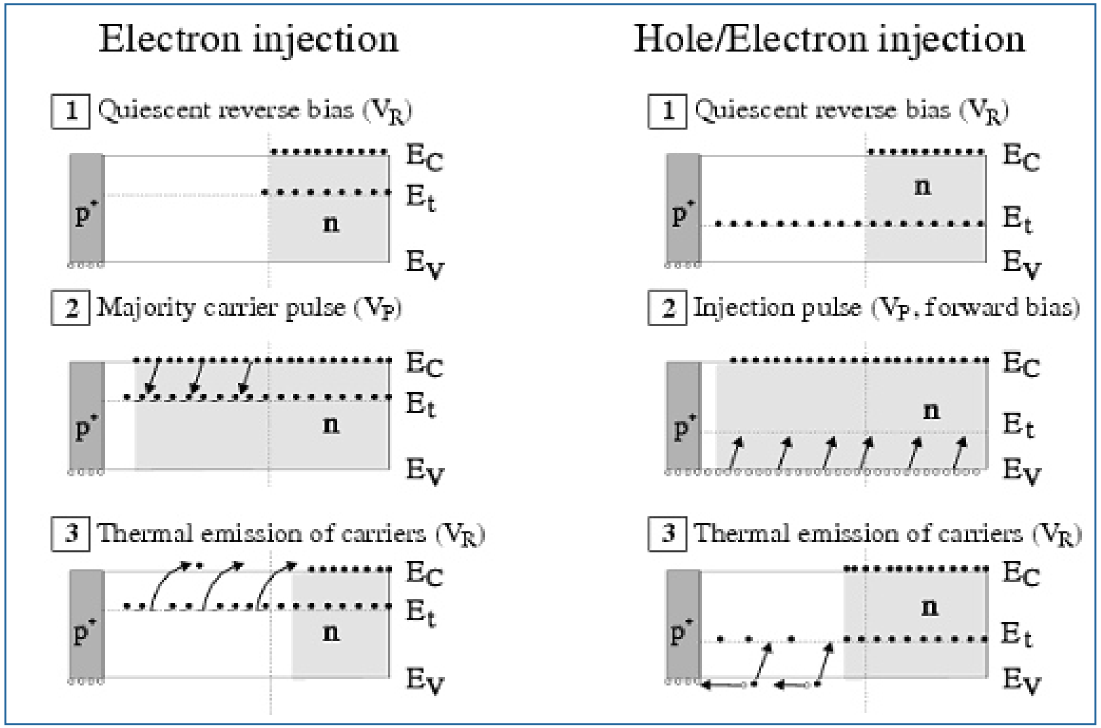
- Understand the reaction pathways for particle irradiations (essentially cluster kinetics)
- Use DLTS and/or Laplace DLTS to study the structure of the defects…

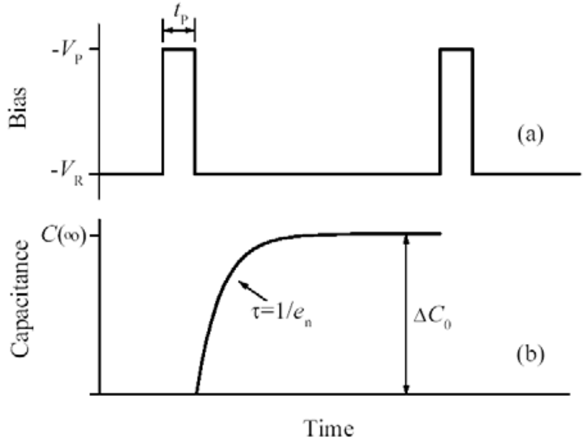
Electrically active defects

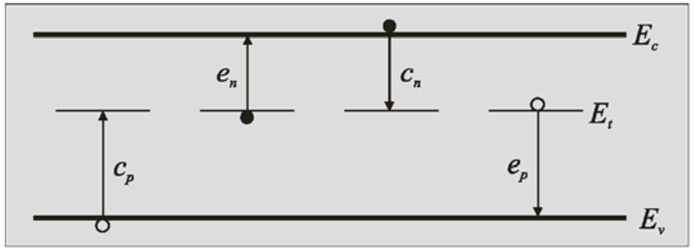


***n*-type Si** **_n_-type Ge**

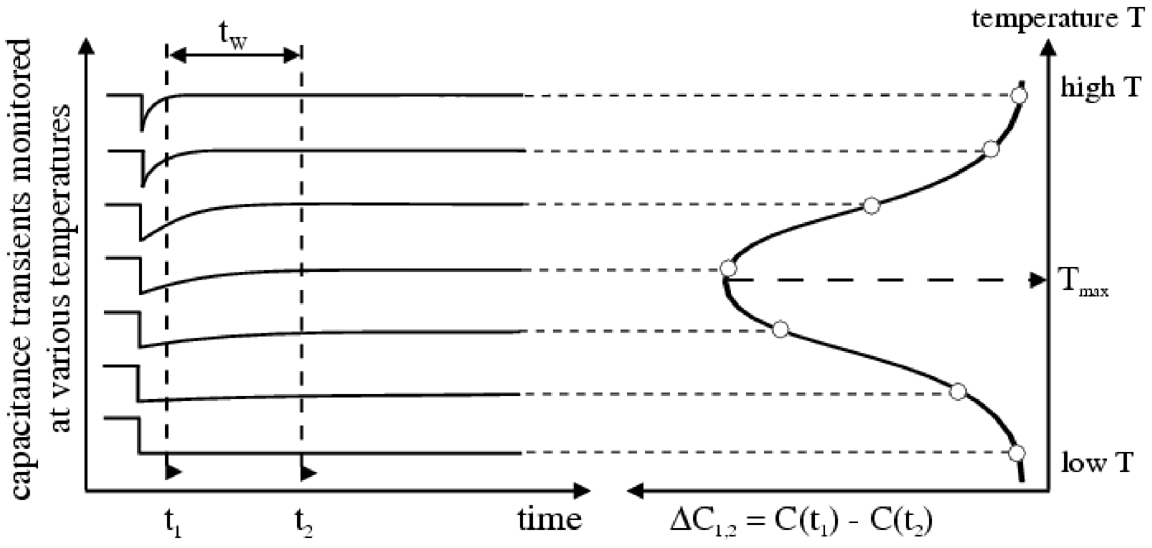
Deep level transient spectroscopy (DLTS)







DLTS

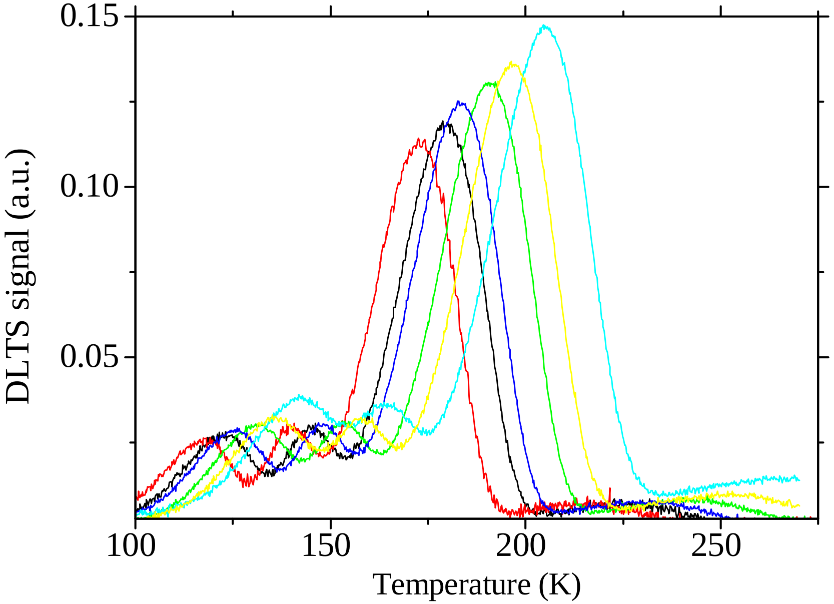


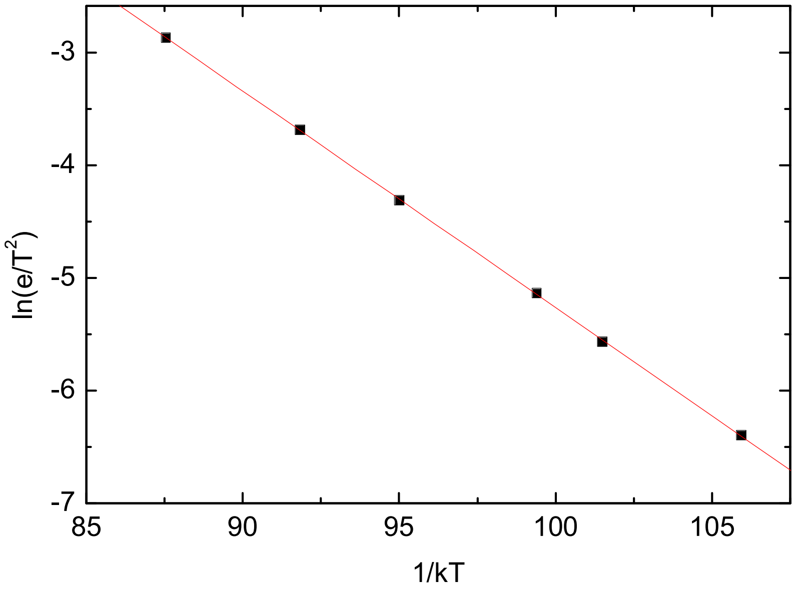
$$\tau_{max} = (t_1 - t_2)\left[\ln\frac{t_1}{t_2}\right]^{-1}$$

At typical doping levels of **10^{14}-10^{16} cm^{-3}** sensitivity of the technique is **10^{9}-10^{11} cm^{-3}**

$$N_t << N_d$$

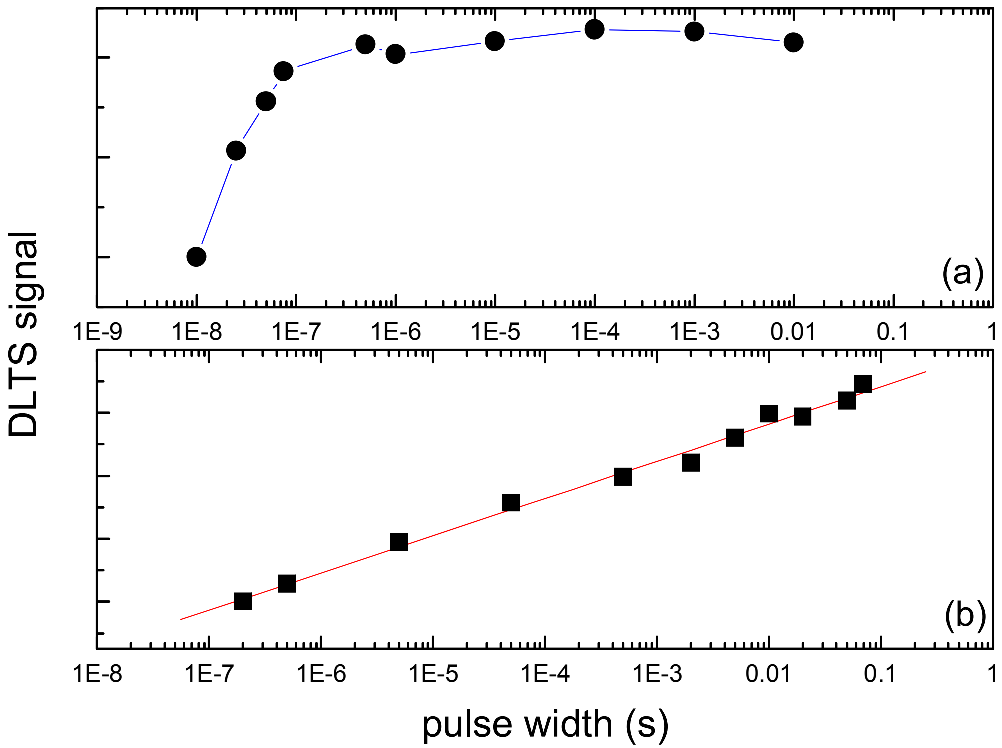
DLTS analysis

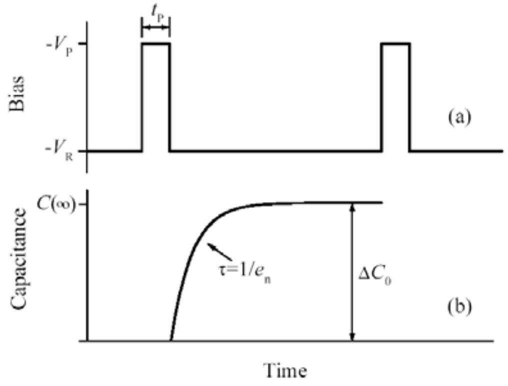




$$e = \kappa\sigma(T)T^2 e^{-\frac{\Delta E}{kT}}$$

DLTS analysis



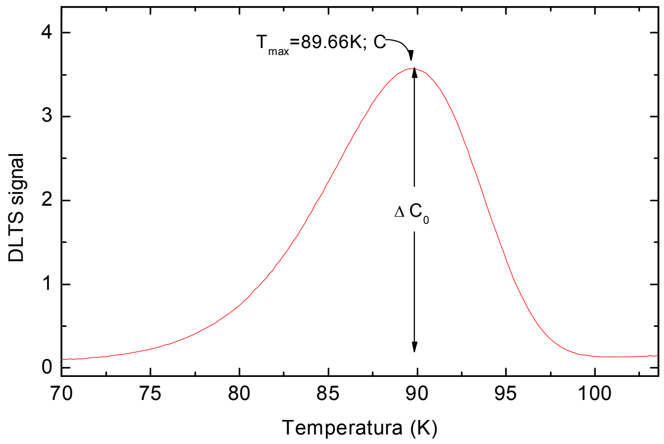


$$\Delta C(t_p) = \Delta C_0 \left[1 - \exp(-c_p t_p) \right]$$

$$n_T(t_p) = \sigma < \upsilon_{th} > n \tau N_T \exp(q\phi_0 / kT) \log(t_p / \tau)$$

[I. Capan et al,Solar Energy Materials and Solar Cells 91 (2007) 931]

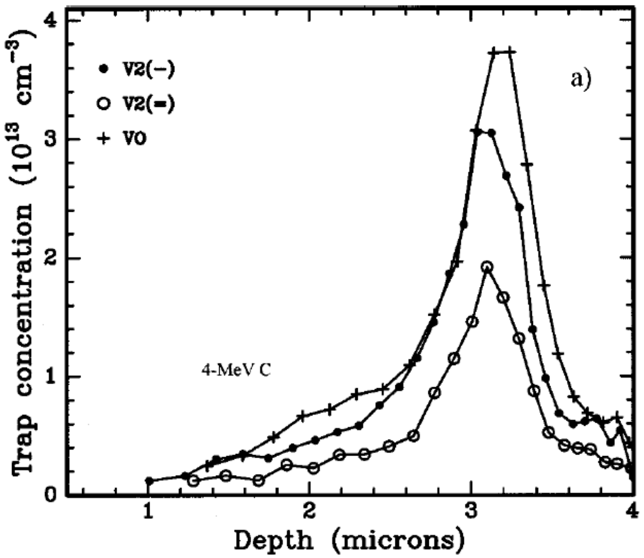
DLTS analysis



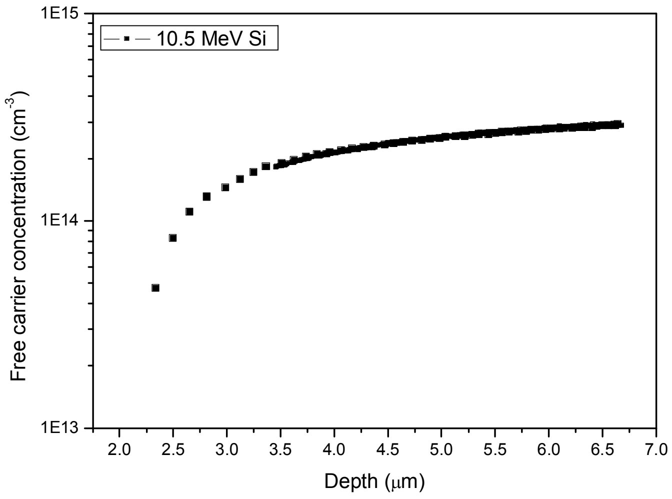
$$N_T = 2 \cdot \frac{\Delta C_0}{C} \cdot N_D$$

$$f(W) = (W_0 - \lambda_0)^2 - (W_1 - \lambda_1)^2 / W_0^2$$

$$N_T = 2 \cdot \frac{\Delta C_0}{C} \cdot N_D \cdot \frac{1}{f(W)}$$

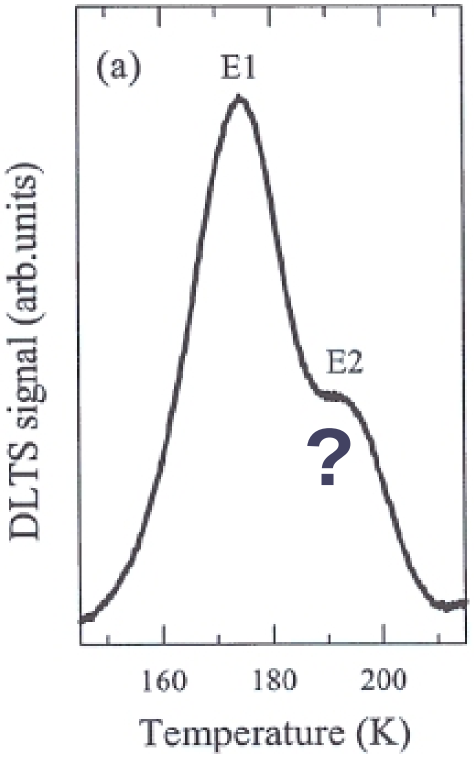


[E. V. Monakhov, Phys Rev B **65** 245201]

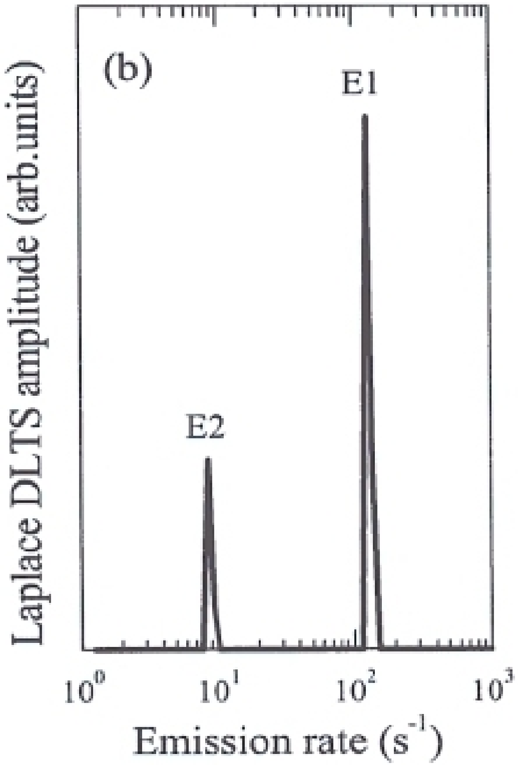


$$W = \frac{\varepsilon_0 \varepsilon_r A}{C} \qquad N^* = \frac{2\varepsilon_0 \varepsilon_r V}{eW^2}$$

The biggest problem → the lack of resolution!

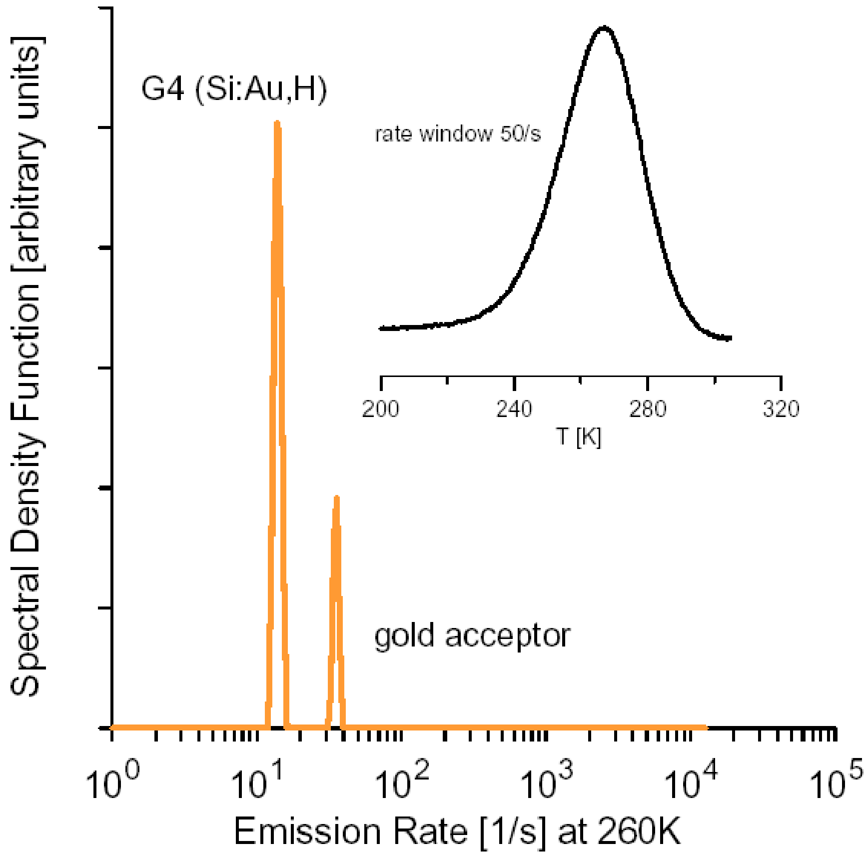


[DLTS]



[Laplace DLTS @ 170K]

Laplace DLTS



$$f(t) = \int_0^\infty F(s)e^{-st}\,ds$$

f(t) → measurements
F(s) → Laplace DLTS signal

Find F(s)!

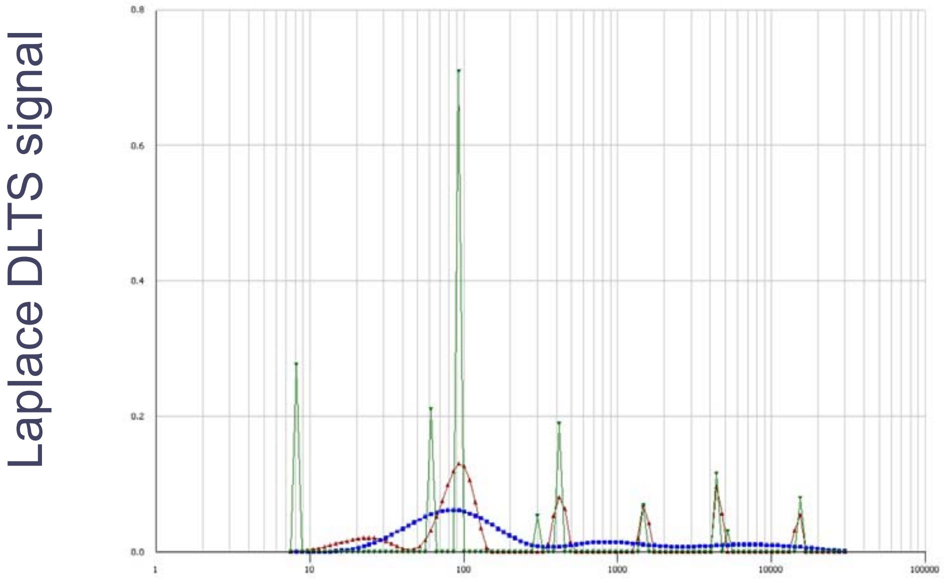
Noise!!!

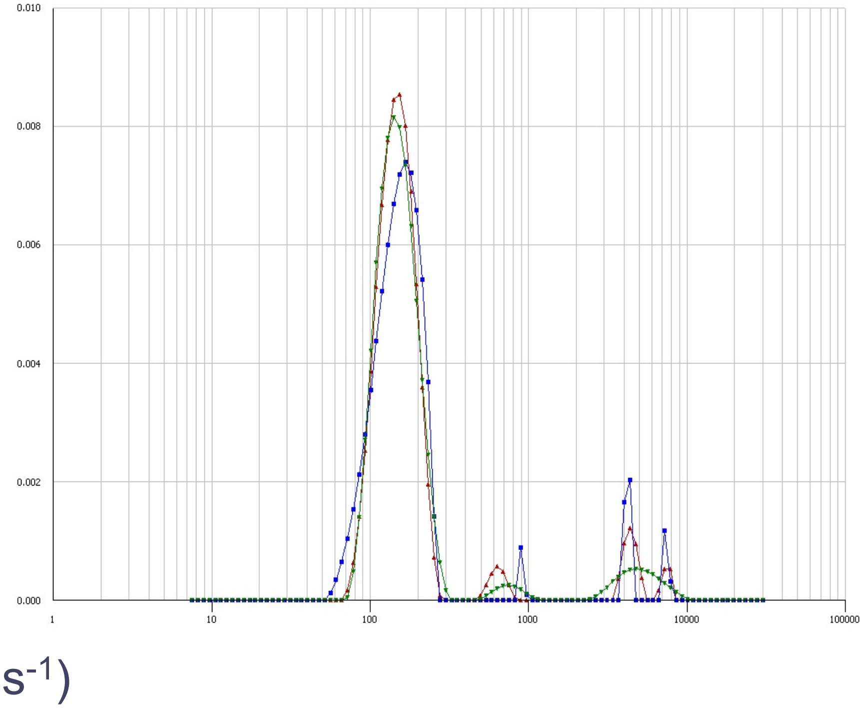
The number of possible solutions is..

[P. Deixler et al, Appl Phys Lett 73 (1998) 3126]

Laplace DLTS

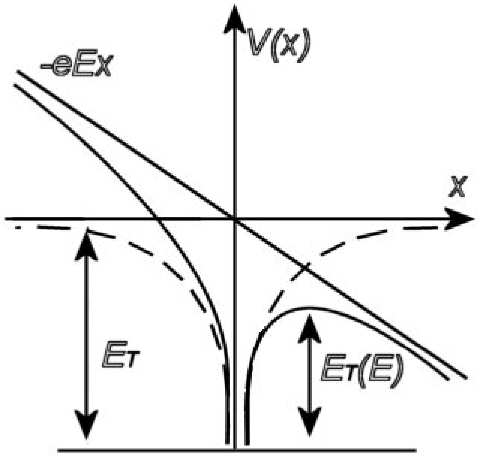
CONTIN [S.W.Provencher, *Computer Physics Communications* **27** (1982) 213]
FTIKREG [J. Weese, *Computer Physics Communications* **69** (1992) 99]
FLOG [developed for Laplace DLTS]





LDLTS –electric-field effects

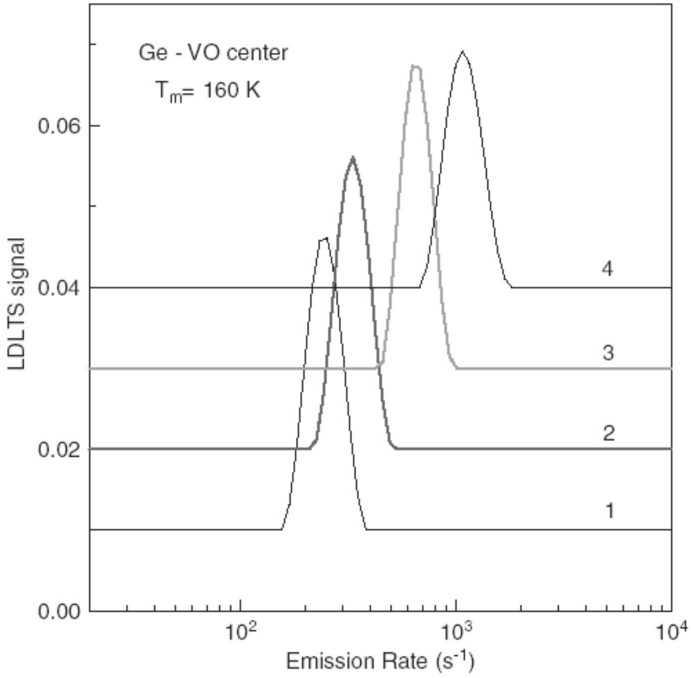
- Electric field
- Laplace DDLTS

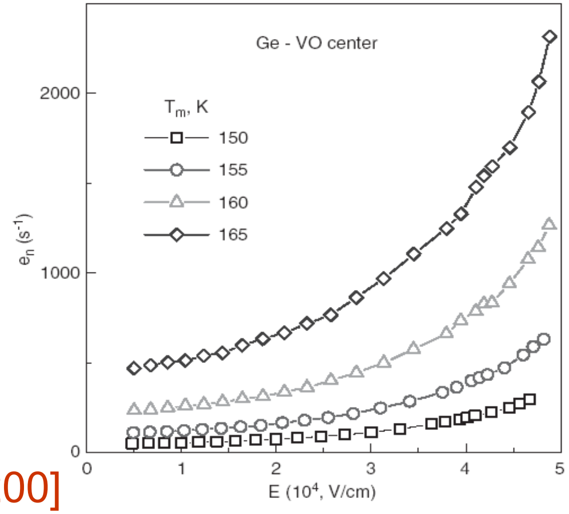


$$e(E)/e(0) = \exp\left(\frac{E^2}{E_{\rm ch}^2}\right)$$

$$E_{\rm ch} = \sqrt{\frac{3m^*h}{2\pi e^2\tau_2^3}},$$

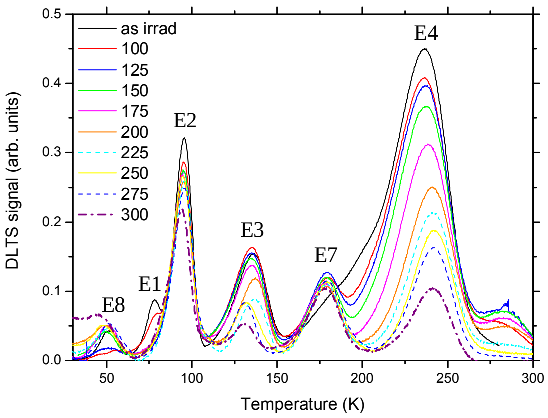
$$\tau_2 = \frac{h}{2\pi k_{\rm B}T} \pm \tau_1$$

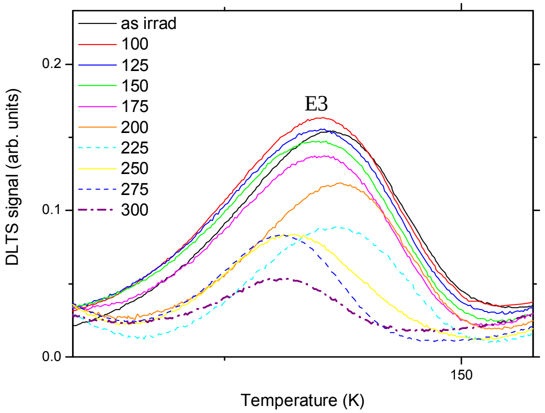




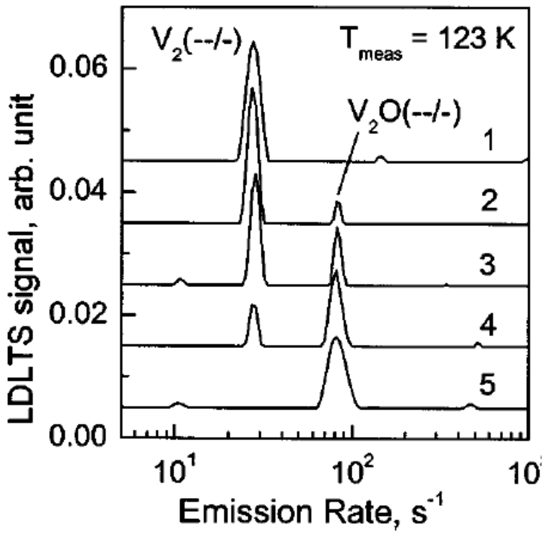
[V.P.Markevich et al, Physica B 376-377 (2006) 200]

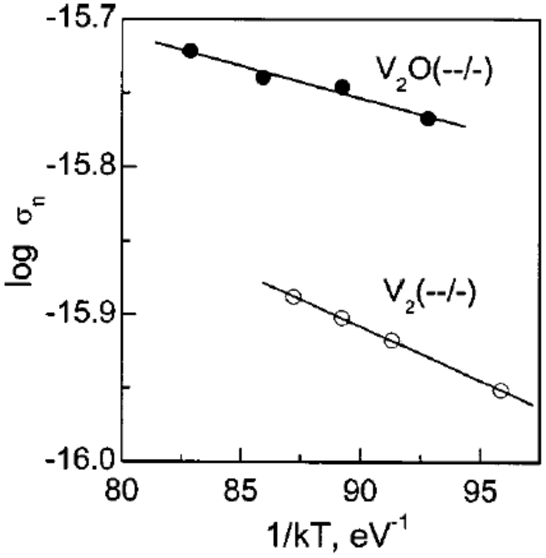
LDTLS – separation of capture rates





$VV+O \rightarrow V_2O$



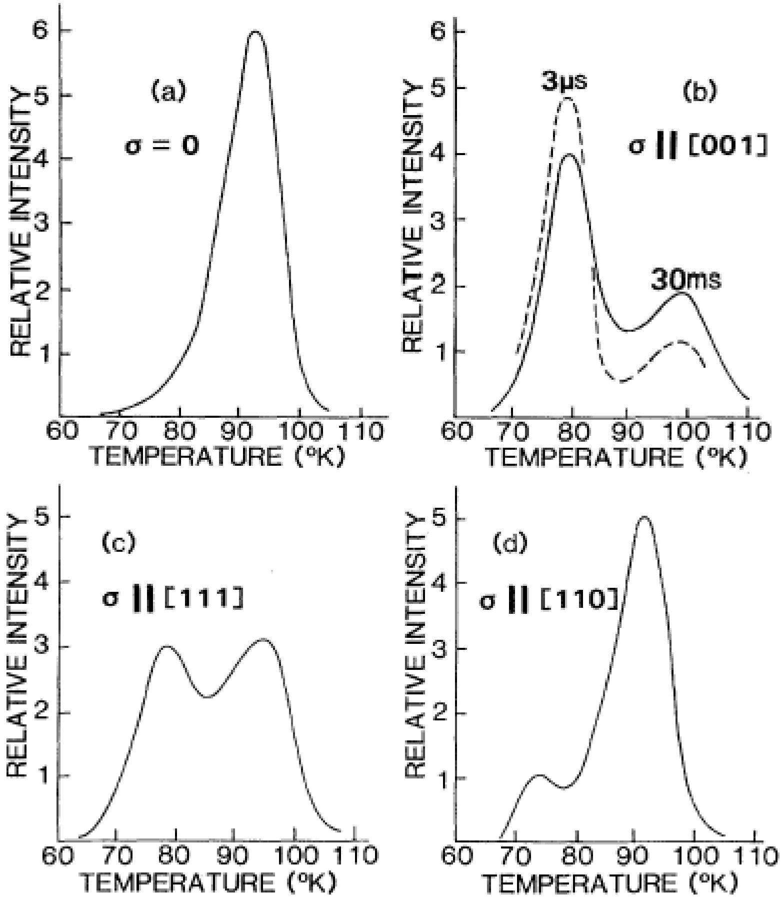


[L.Dobaczewski et al, J. Appl. Phys. 96 (2004) 4689]

$\sigma_n(T)=\sigma_{n0}\exp(-\Delta E_{n\sigma}/kT)$

- The most used techniques are EPR, DLTS...
- +/-

How to get information on structural properties with DLTS?



[Phys. Rev. Lett. 51 (1983) 1286]

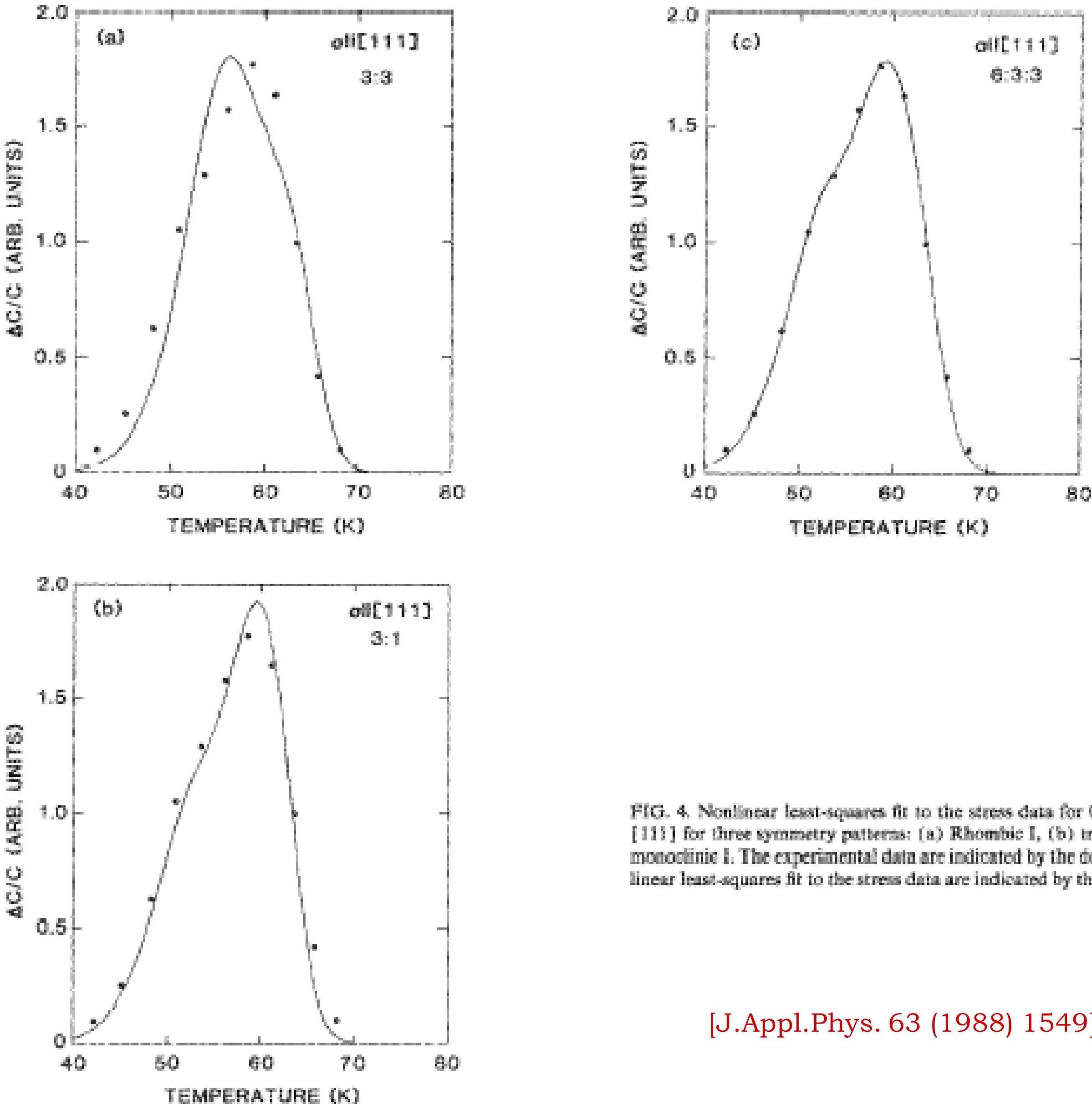
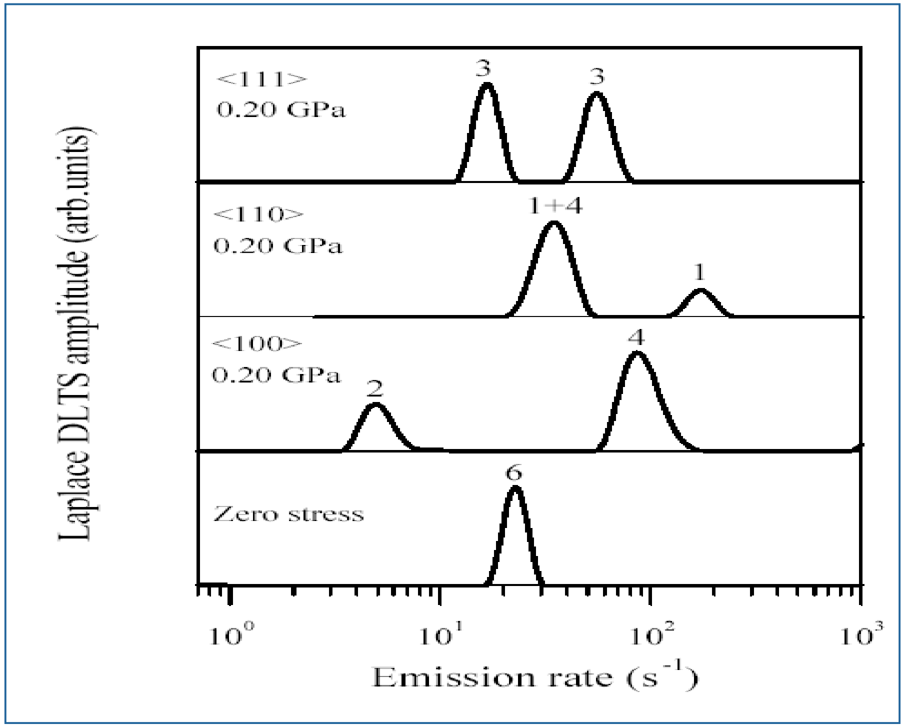


FIG. 4. Nonlinear least-squares fit to the stress data for 0.66 GPa along [111] for three symmetry patterns: (a) Rhombic I, (b) trigonal, and (c) monoclinic I. The experimental data are indicated by the dots and the nonlinear least-squares fit to the stress data are indicated by the solid lines.

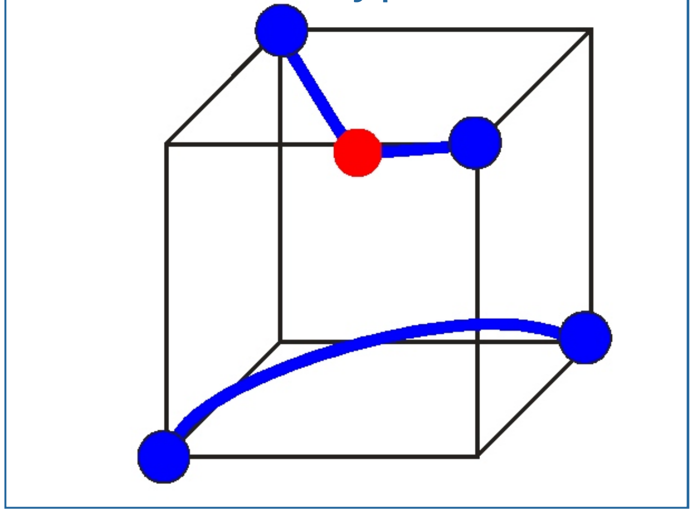
[J.Appl.Phys. 63 (1988) 1549]

Uniaxial stress Laplace DLTS

The symmetry of a defect centre is obtained from the intensity ratio of the split DLTS lines under uniaxial stress applied along the three major crystallographic directions, <100>, <110> and <111>.



VO in n-type CZ:Si



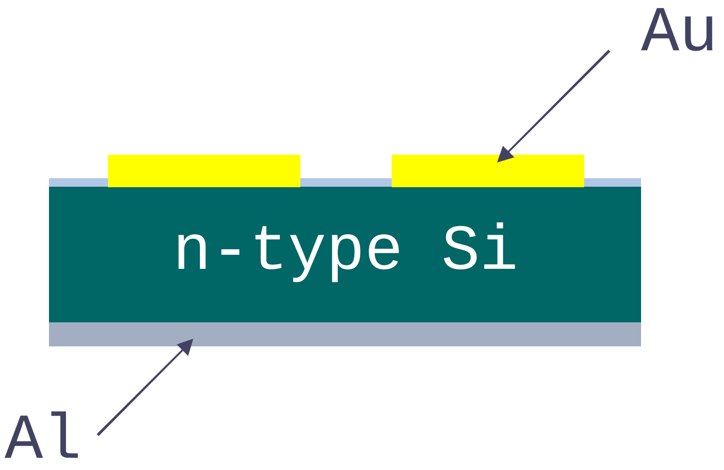
The splitting pattern establishes the orthorhombic-I symmetry of the VO complex.

[O.Andersen PhD thesis]

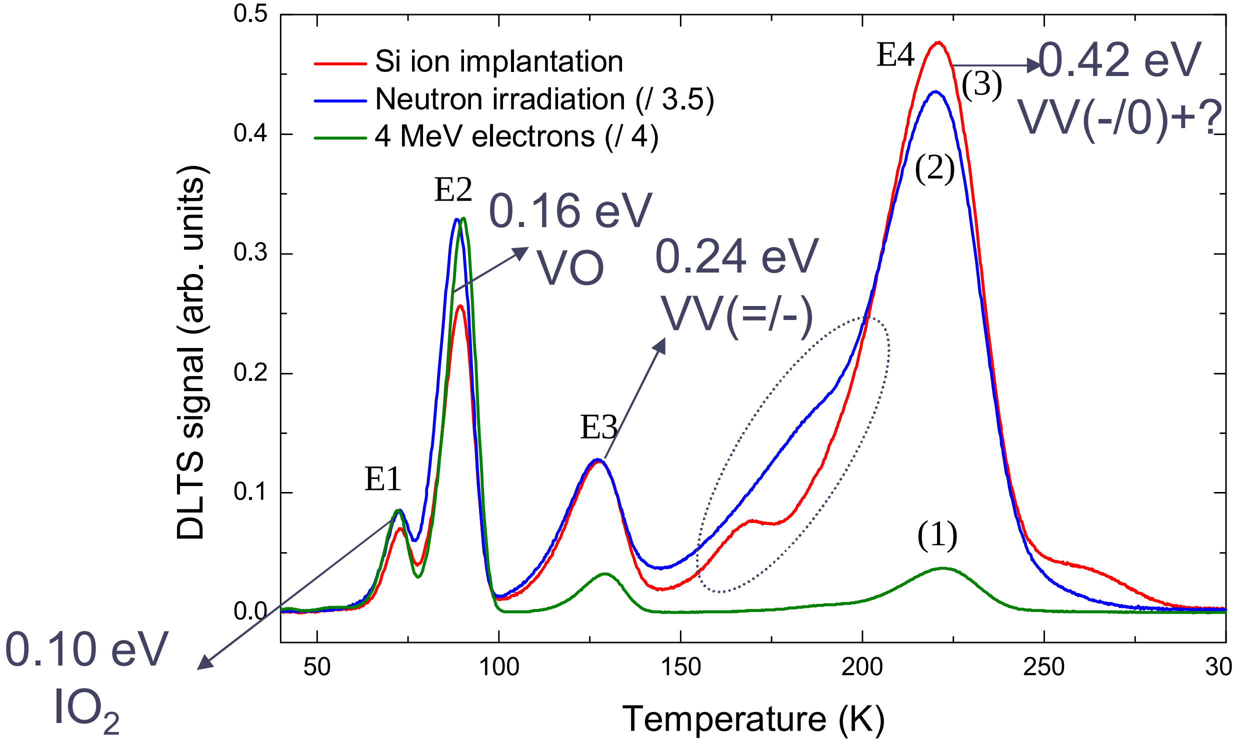
Silicon

- Phosphorus-doped n-type CZ-grown silicon crystal with initial resistivity of (1–2) Ωcm.

- The accumulated doses of fast neutrons were 2×10^{14} cm^{-2} and 2.4×10^{12} cm^{-2} for Si:n1 and Si:n2, respectively.



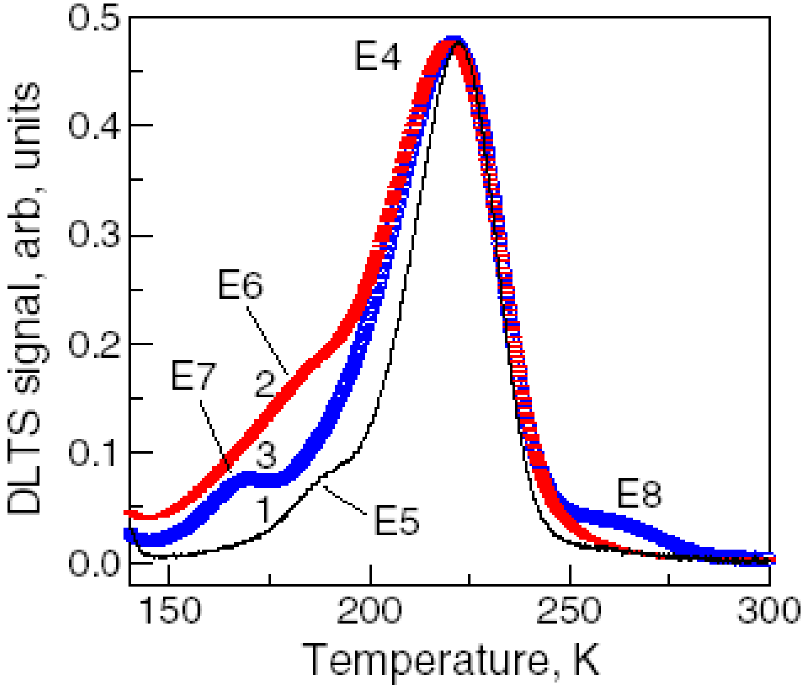
Si:n1 sample after neutron irradiation



(1) 4 MeV electrons (F = 1×10^{15} cm^{-2})
(2) 1 MeV neutrons (F = 2×10^{14} cm^{-2})
(3) 800 keV Si ions (F = 1×10^{9} cm^{-2})

[I. Kovačević et. al., J. Phys.: Condens. Matter 17 (2005) S2229]

Cluster related → E4 = VV(-/0)+?



(1) 4 MeV electrons (F = 1×10^{15} cm^{-2})
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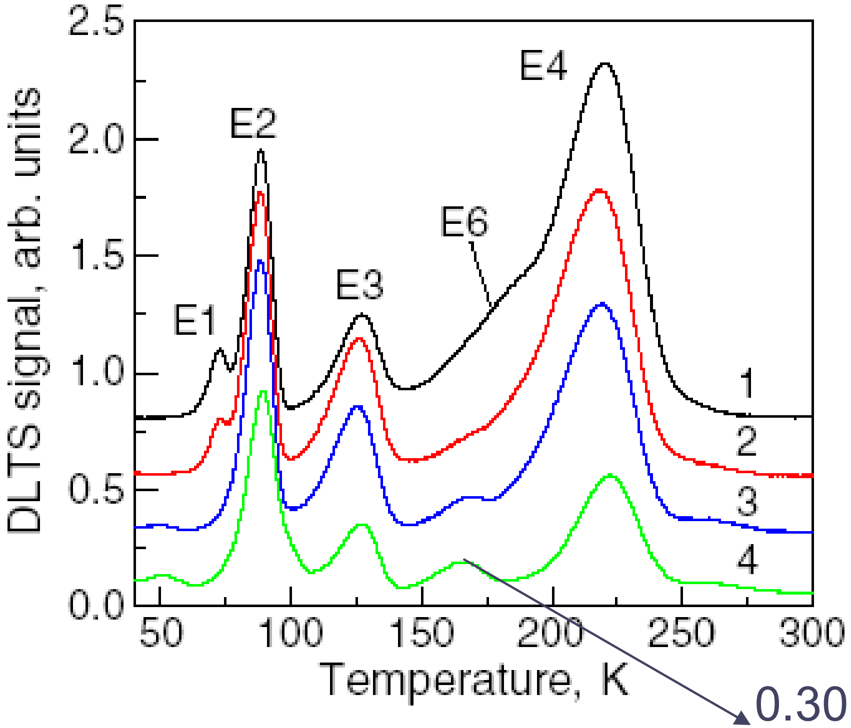
(3) 800 keV Si ions (F = 1×10^{9} cm^{-2})

Si:n1 sample → annealing study



0.30 eV
VOH

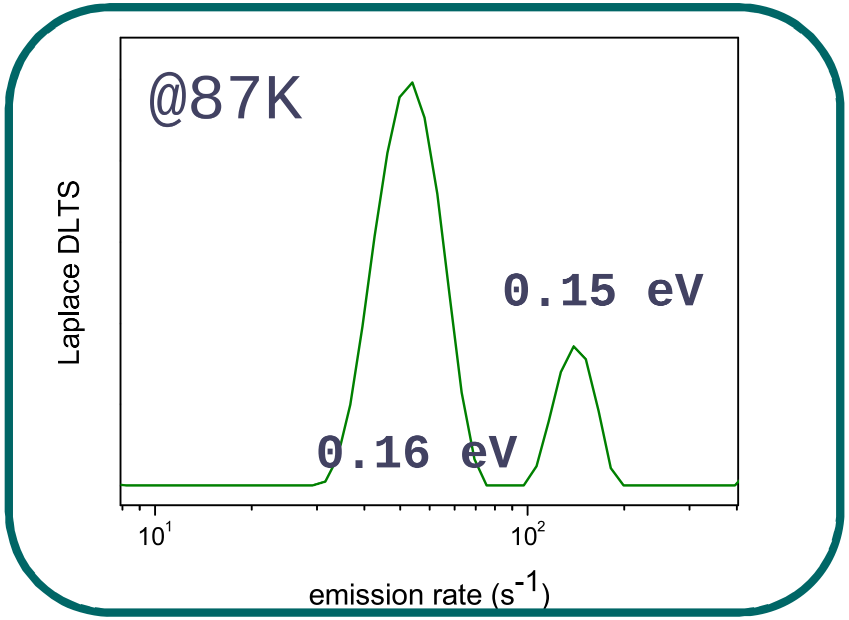
(1) as irradiated
(2) 100 °C
(3) 150 °C
(4) 200 °C

VV(=/-)↑ VV(-/0)↓

[I. Kovačević et. al., J. Phys.: Condens. Matter 17 (2005) S2229]

What we can learn with Laplace?

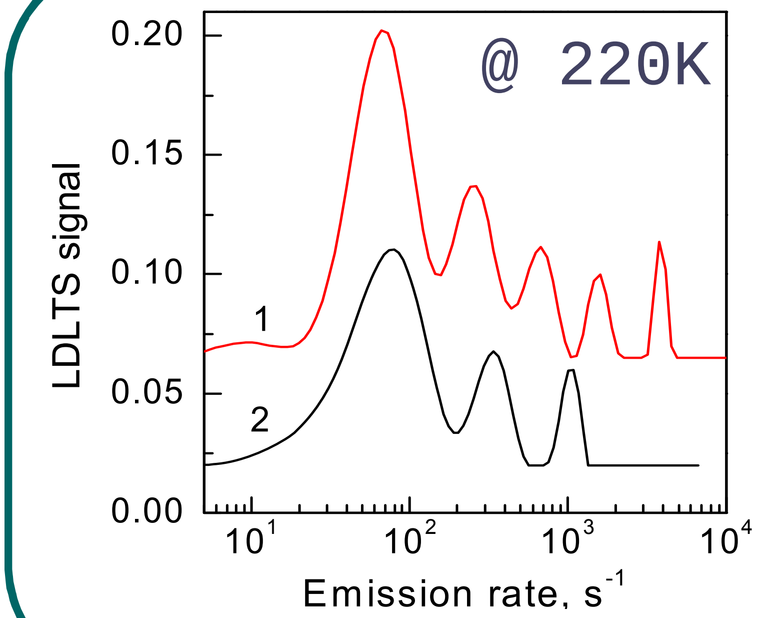
No measurements on as irradiated samples!



Laplace DLTS spectrum for the Si:n1 sample after neutron irradiation and the following annealing at 200 °C.

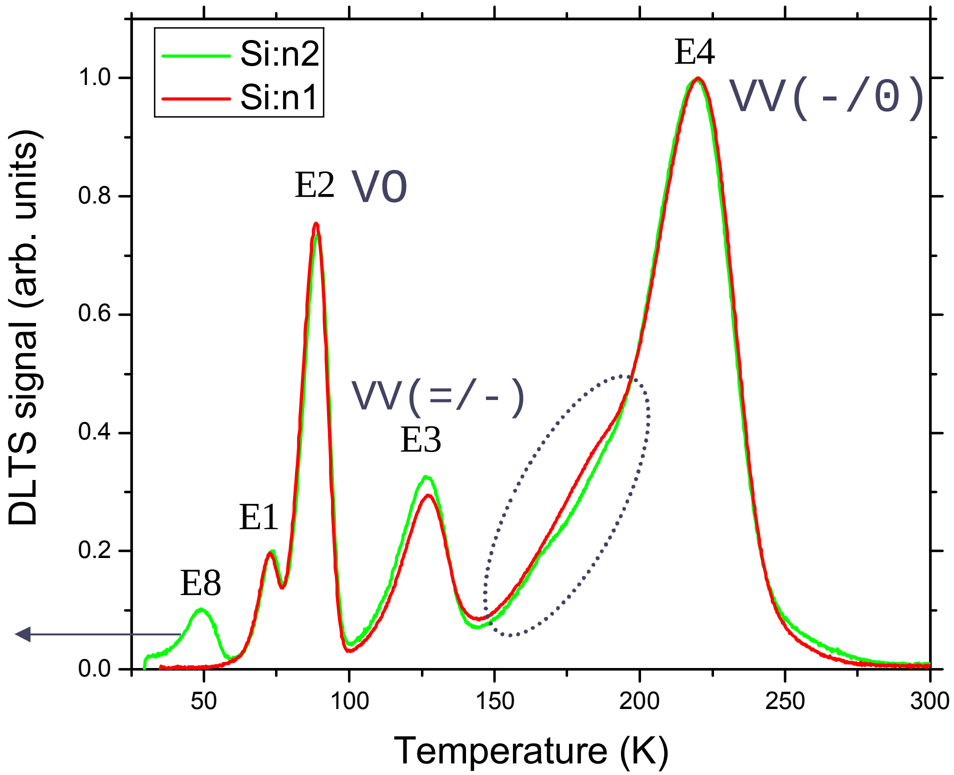
Emission rate with a slightly lower activation energy has been detected in n-type Si implanted with ions heavier than Si ions [J. H. Evans-Freeman et. al., Nucl. Instr. And Meth. In Phys. Res. B 186 (2002) 41].

Laplace DLTS on the E4 peak (cluster related)



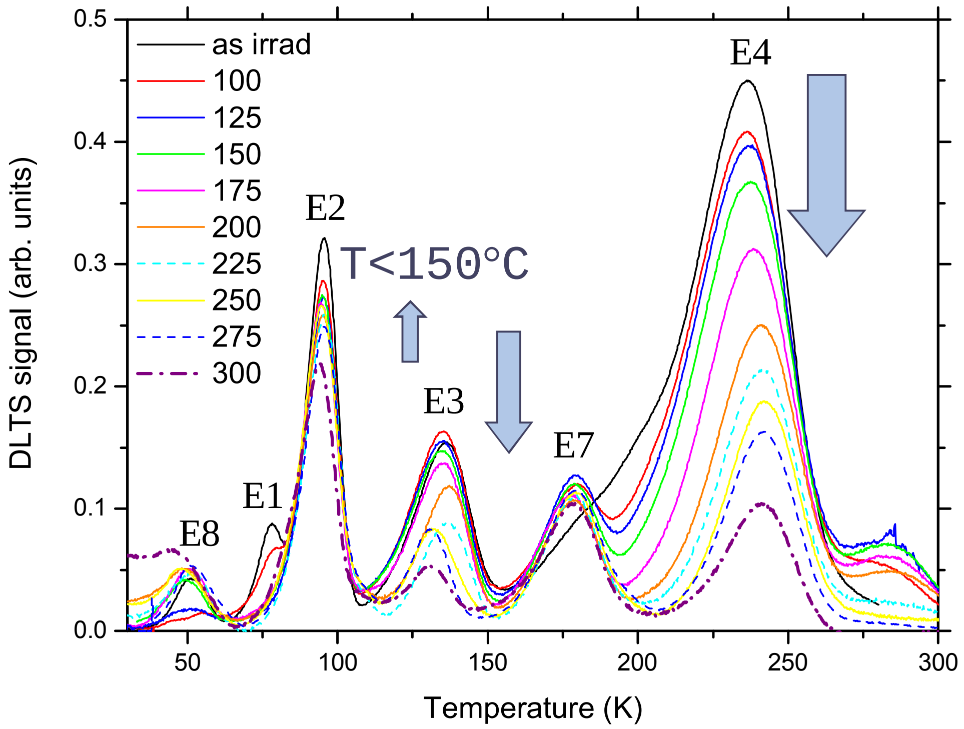
Laplace DLTS spectra for the Si:n1 sample (1) after neutron irradiation and (2) the following annealing at 150 °C for 1 hour.

Same material -- lower dose of irradiation -- less damage



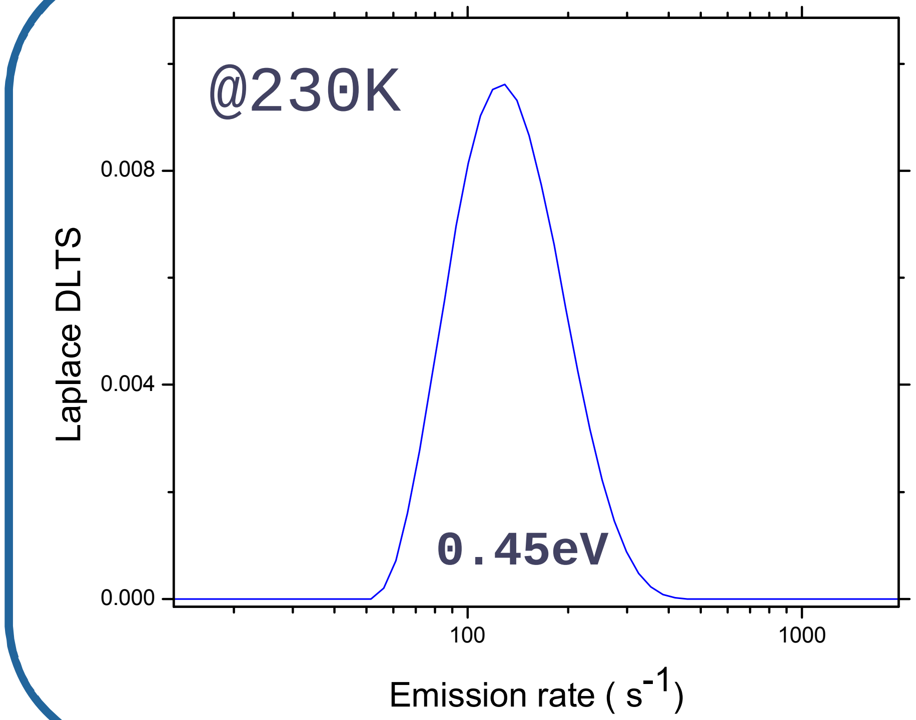
0.10 eV

Si:n2 sample → annealing study



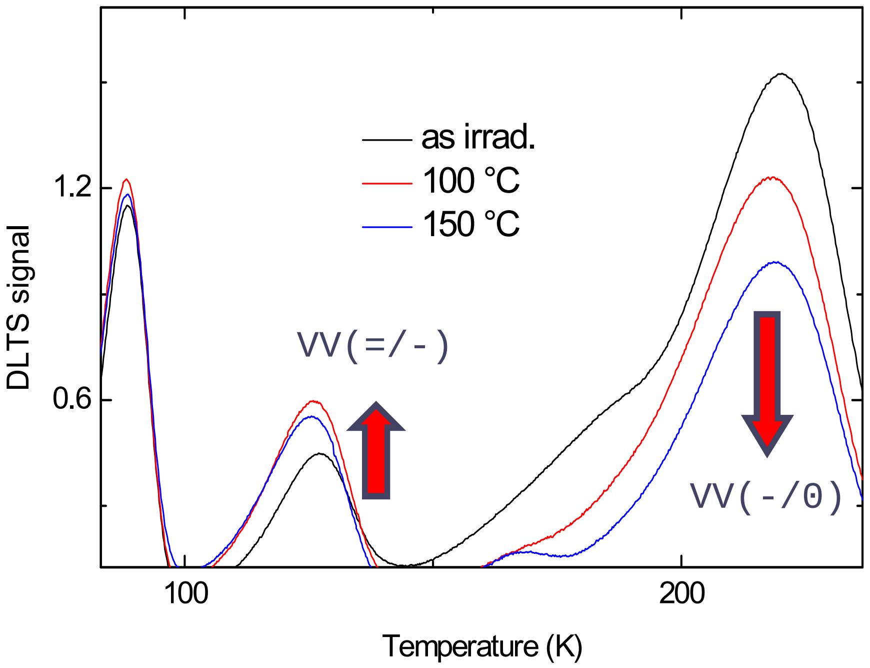
- E8=> ?
- E3=> @ T>200 C → VV + O_i → V_2O
- E7=> VOH

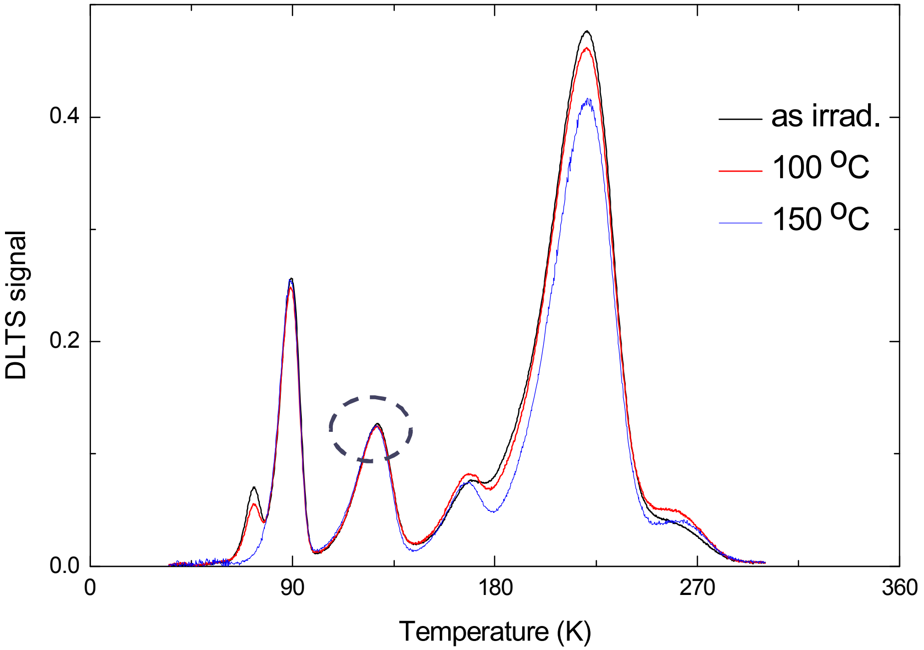
Laplace DLTS on the E4 (Si:n2:300 °C)



Irradiation vs. implantation

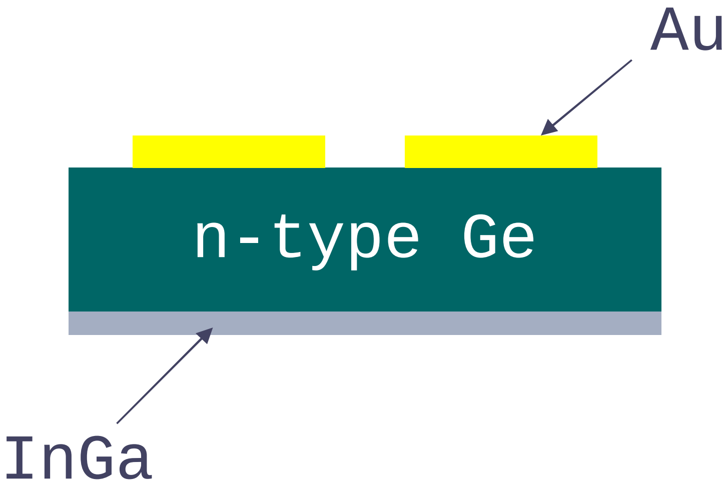
n-type P-doped CZ Si 1-2 Ω-cm



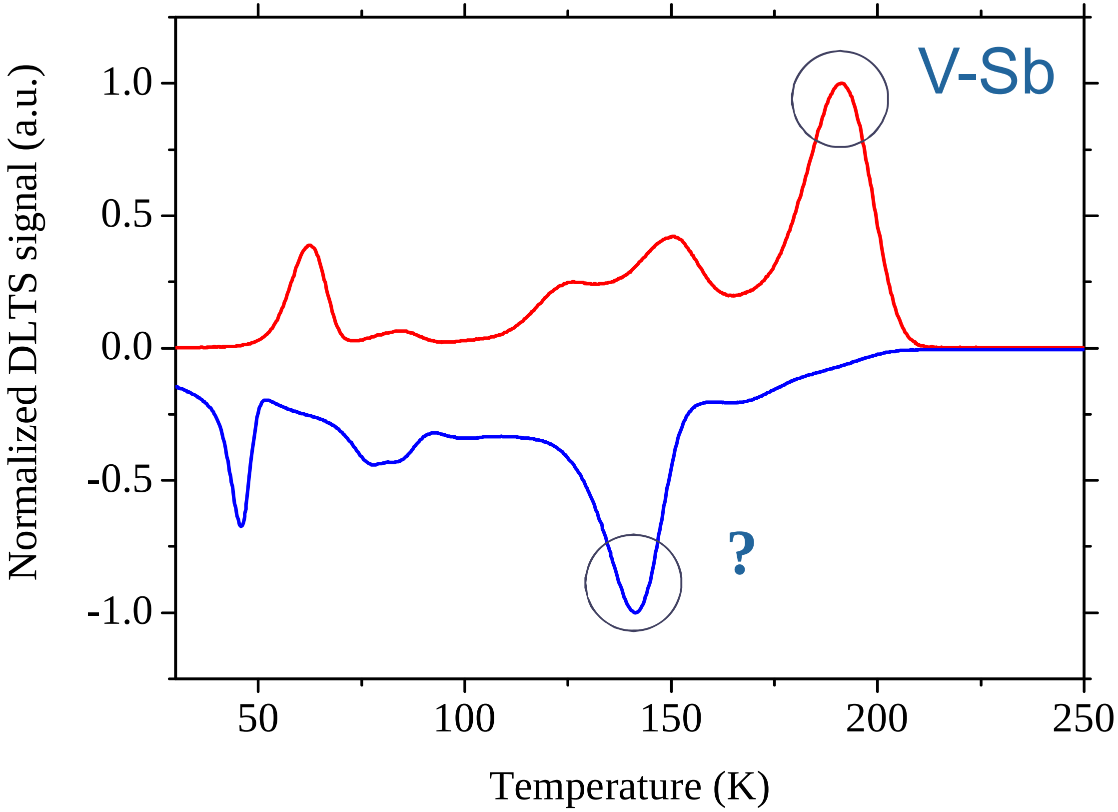


Germanium

- CZ-grown n-type Sb-doped Ge crystal with initial resistivity 2 Ωcm.

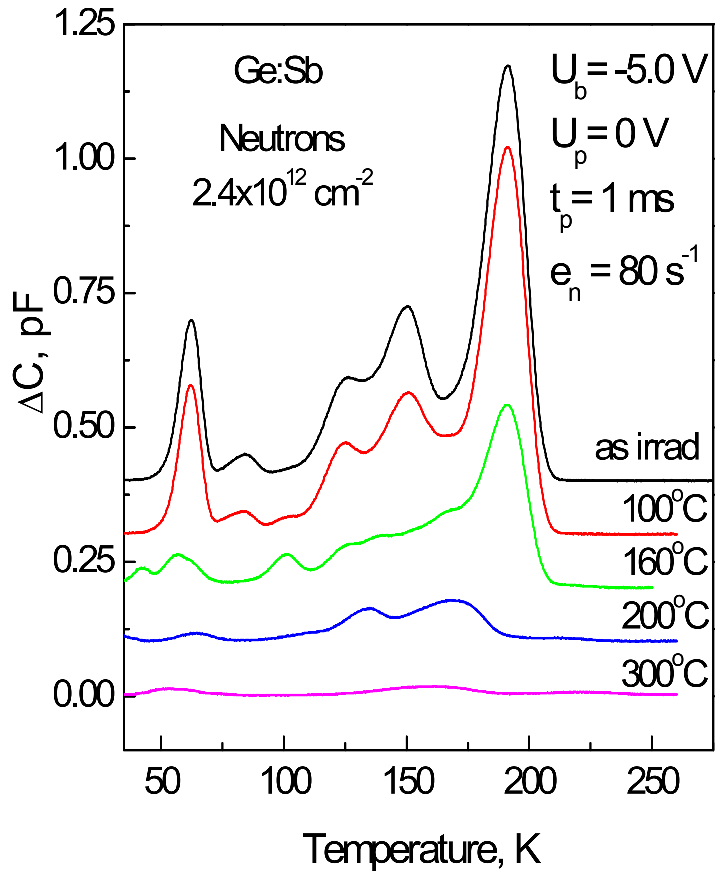


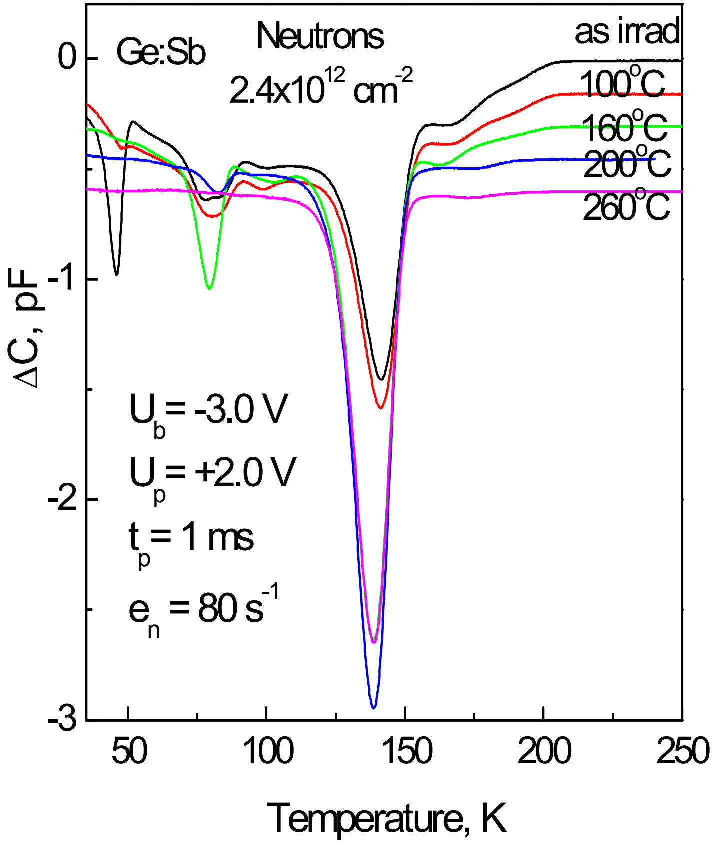
Majority (electron) and minority (hole) carrier traps in nGe



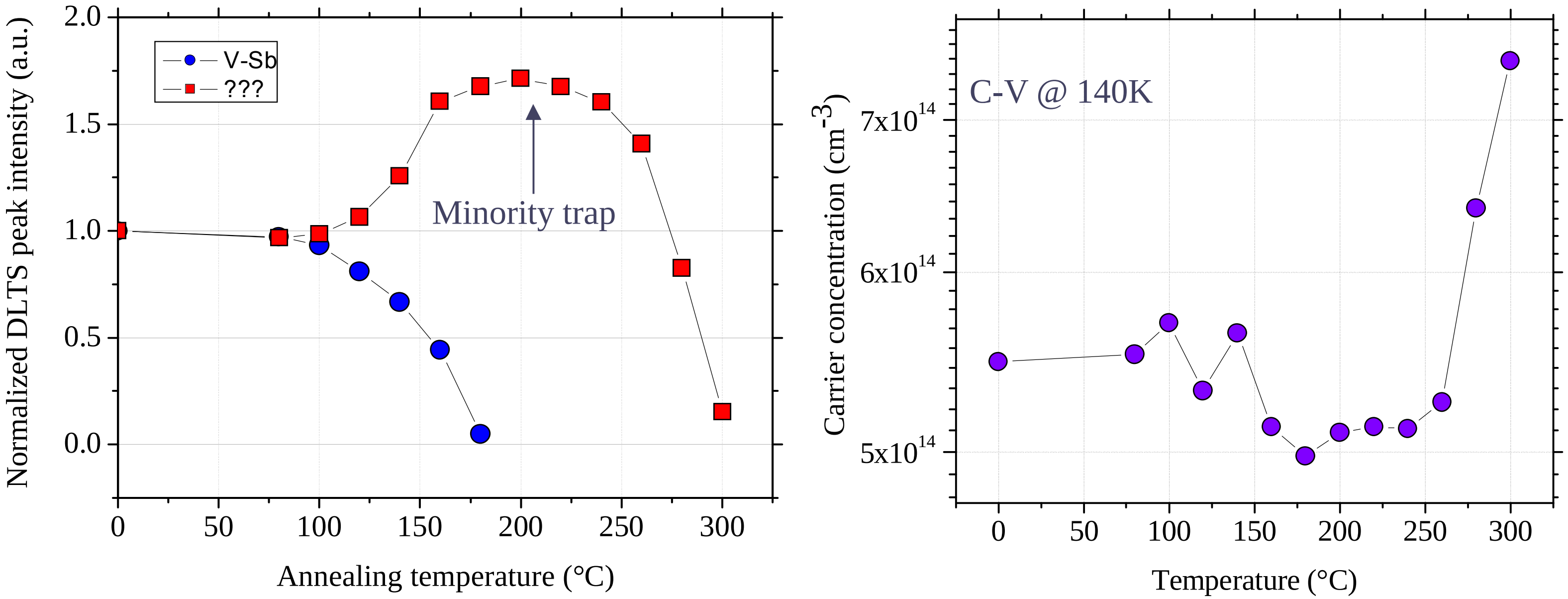
[I. Kovacevic et al,Materials Science in Semiconductor Processing 9 (2006) 606]

Annealing study





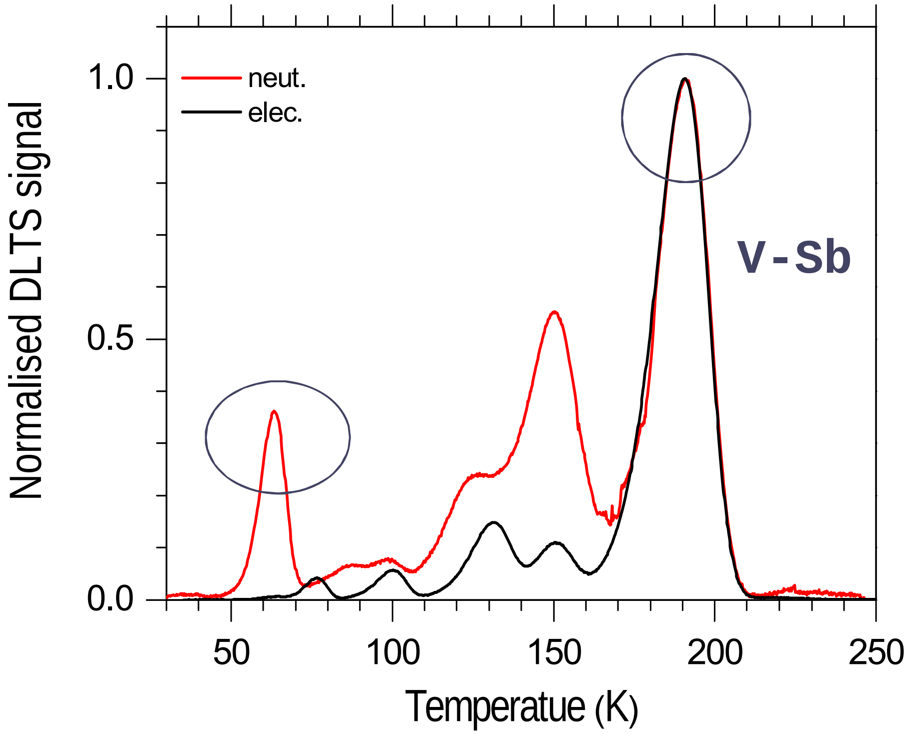
Annealing study + C-V



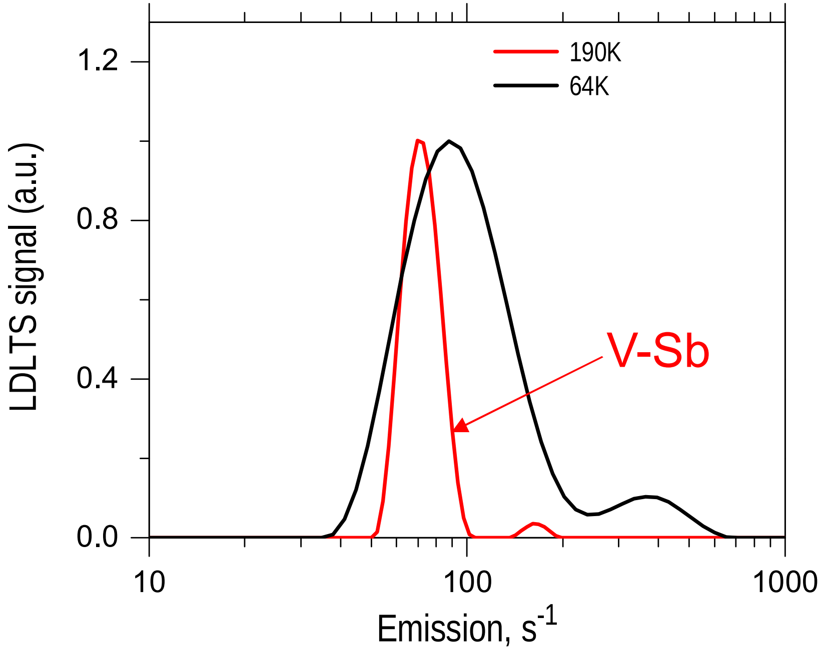
V-Sb + Sb → VSb_2

Uniaxial stress LDLTS measurements

- CZ *n*-type (100) Ge:Sb 5Ωcm
- Dose: **$5 \cdot 10^{11}$ cm^{-2}**

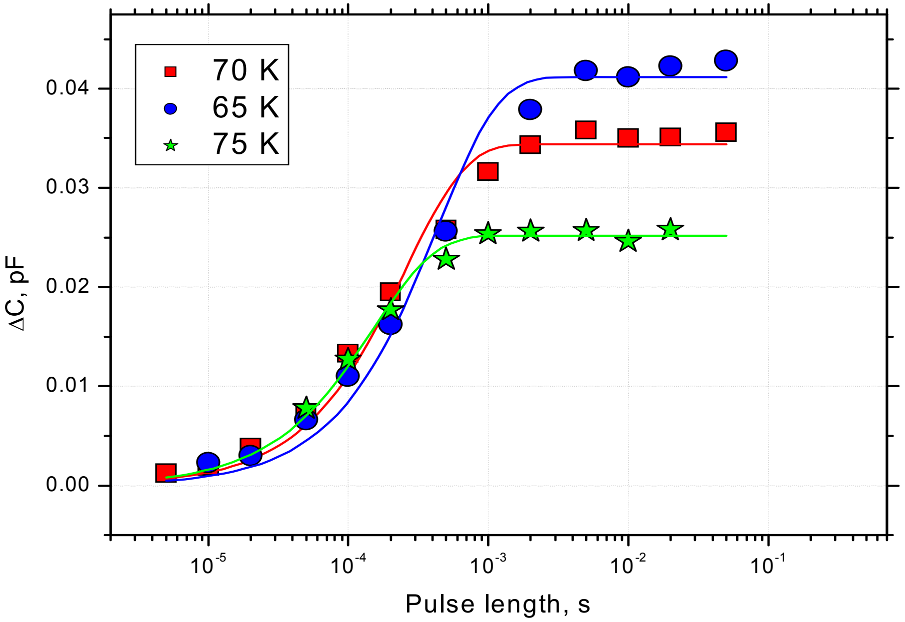


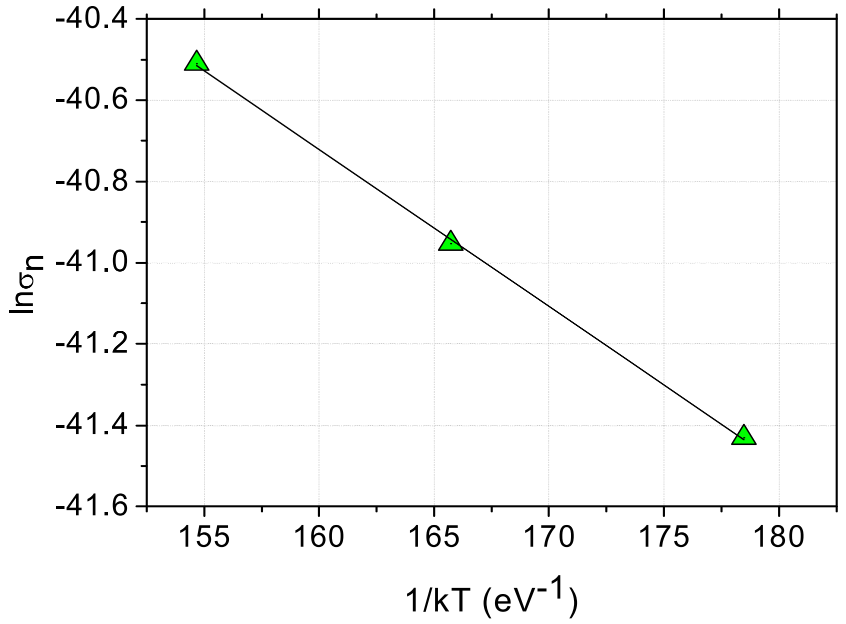
Point-like defects and clusters as seen by Laplace DLTS



[A. R. Peaker et al, Solid State Phenomena 131-133 (2008) 125]

Vacancy clusters – 0.10 eV





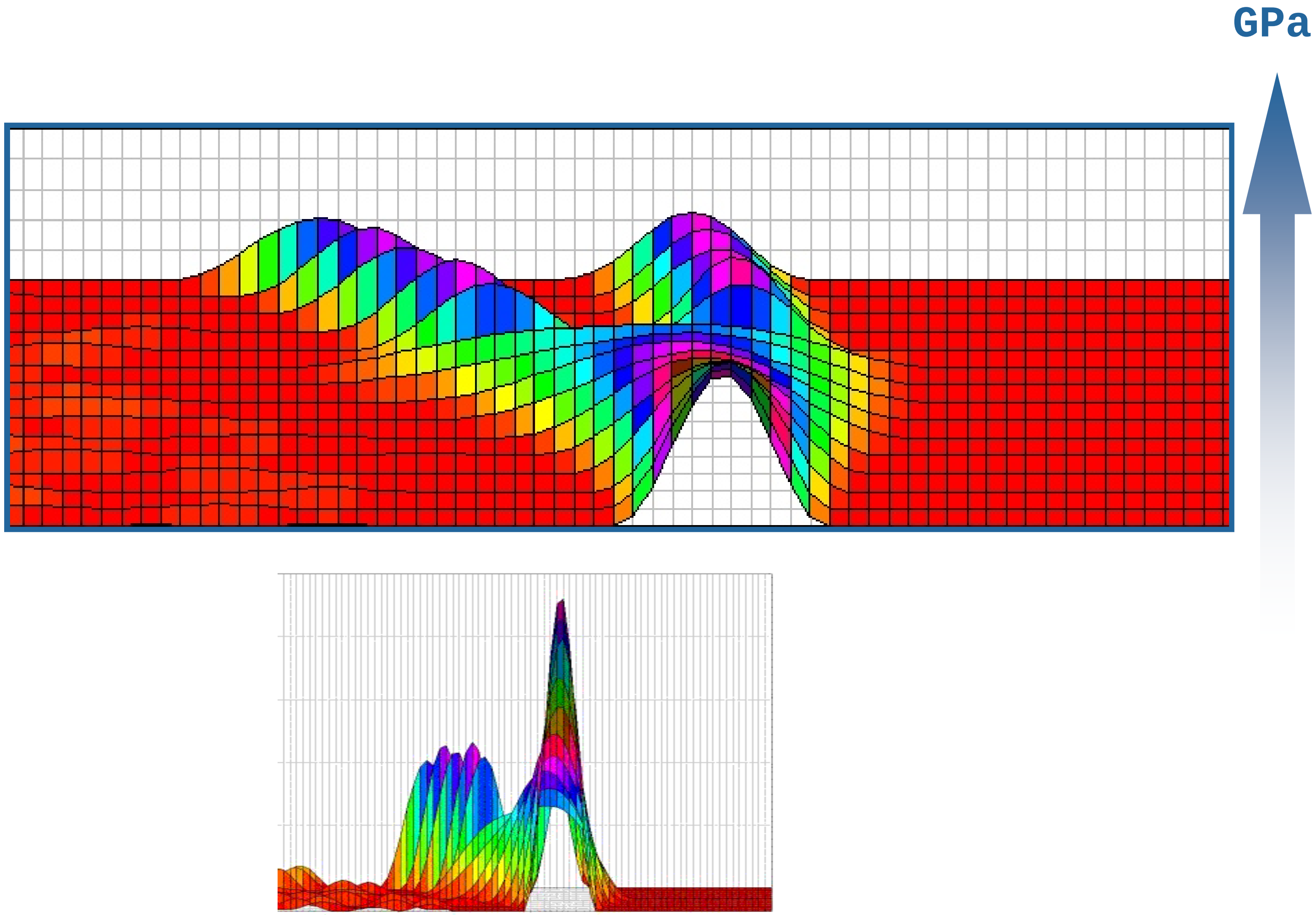
$\sigma_n(T)=\sigma_{n0}\exp(-\Delta E_{n\sigma}/kT)$

$\Delta E_{n\sigma}$ =0.04 eV; σ_{n0} =1 × 10^{-17} cm^2

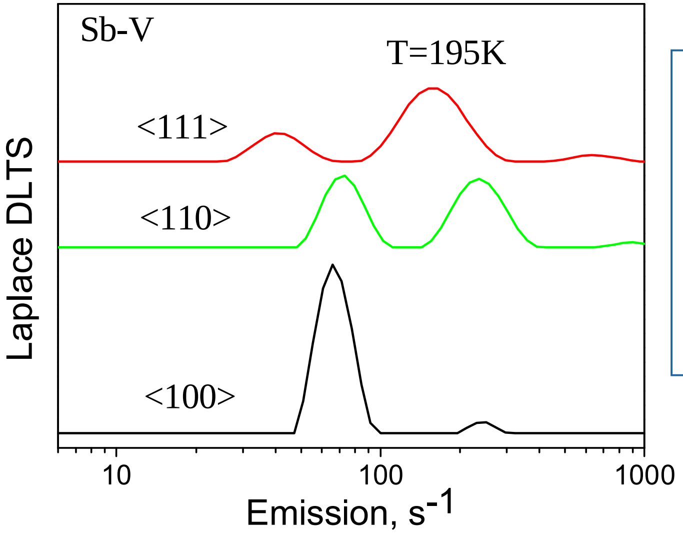
Akceptor-like defekt → **Vacancy clusters**!!!

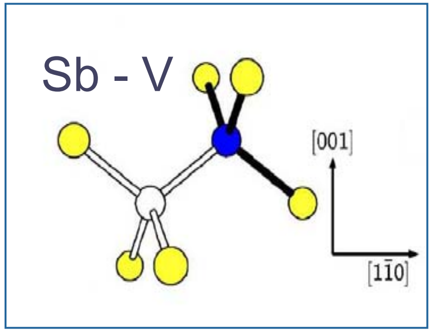
[I. Capan et al, Vacuum 84 (2010) 32]

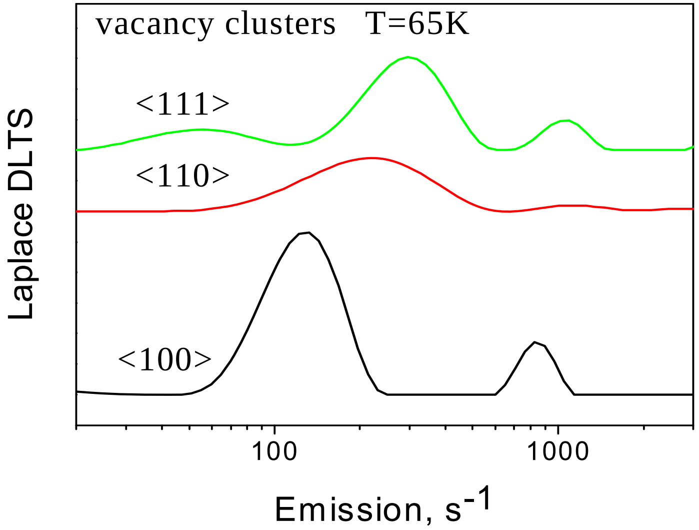
V-SB → <110>



	<100>	<110>	<111>
C_{3v} – *trigonal*	NS	1:1	1:3
C_{1h} - *monoclinic*	1:2	1:2:2:1	1:2:1







- Sb-V pair → C_{3v}
- Vacancy clusters → C_{1h} ???

Summary and conclusions

- A first attempt to study neutron-irradiation induced defects by means of high-resolution Laplace DLTS in Si and Ge.

- Annealing study of n-type Si irradiated with fast neutrons clearly shows that the concentration of the double negative charge state of the divacancy increases with annealing temperature as vacancies and/or divacancies are released from cluster related defect, the E4 defect.

- The annealing behaviour of the H trap consists of “negative” and “positive” annealing stages, some of which are related to transformations of simpler radiation-induced defects to more complex structures. These changes are related to the capture of mobile Sb-V and V-V pair by Sb atoms with the creation of Sb_2-V complexes.

- Trigonal symmetry for V-Sb.