INTERPRETATION OF DLTS DATA FOR SILICON DETECTORS IRRADIATED WITH REACTOR NEUTRONS

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DLTS is one of the main methods of defect characterization in semiconductor structures. Its application to point defects is well known and described in many reviews and textbooks. However the procedure of DLTS data treatment is not enough elaborated for structures containing defect clusters.

For the purposes of defect engineering of radiation hard Si detectors is necessary to know as the total content of radiation defects so their local distribution.

This work is an attempt to seek proper ways for answering this questions.

- At present two characteristic features of clustered defects in silicon are well established.
- First, it is temperature dependence of the amplitude for some DLTS peaks and closely related to this feature the inequivalent heights of divacancy peaks [1-4].
- And second, the stretched kinetics for filling of clustered traps [3-5]

- 1. I.V. Antonova, A.V. Vasiliev, V.I. Panov and S.S. Shaimeev, Phys. Tekhn. Poluprov. **22**, 998 (1988).
- 2. I.V. Antonova and S.S. Shaimeev, Phys. Tekhn. Poluprov. **25**, 847 (1991).
- 3. M. Kuhnke Microscopic and Electrical Properties of Clustered Divacancies in n-Type Silicon ROSE/TN/2003-01
- 4. E. V. Monakhov, J. Wong-Leung, A. Yu Kuznetsov, C. Jagadish, and B. G. Svensson, Phys. Rev. **B 65**, 245201 2002.
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Part 1. Numerical simulations

- To calculate temperature dependence of any DLTS peak related to a defect in a cluster it is necessary to calculate the distribution of electrical potential inside and around the cluster and then to determine occupancy number of defect under study.
- To calculate the distribution of electrical potential *(ψ)* for spherical cluster one has to solve boundary value problem:

$$\begin{cases} \dfrac{1}{r^2}\dfrac{d}{dr}\left(r^2\dfrac{d\psi(r)}{dr}\right)=-\dfrac{\rho(r,\psi)}{\varepsilon\varepsilon_0}, \\ \dfrac{d\psi}{dr}\Big|_{r=0}=0, \quad \psi\Big|_{r\to\infty}=0. \end{cases}$$

where charge density *ρ(r)* is, $\rho(r)=e\left(N_d-n(\psi)-N_{VV}(r)\cdot f_{VV}-N_A(r)\cdot f_A\right)$

carrier concentration (n) is related to electrical potential as $n(\psi)=n_0\exp(\frac{e\psi}{k_BT})$

We used two functions to model defect distribution in a cluster

$$N_{VV}(r) = \frac{M}{\sqrt{\pi^3 R_0^3}} \exp\left(-\frac{r^2}{R_0^2}\right)$$

Gaussian distribution

$$N_{VV}(r) = \frac{M}{1+\exp\left(\frac{r-R_0}{\delta}\right)} \frac{3}{4\pi R_0^3 N_F}$$

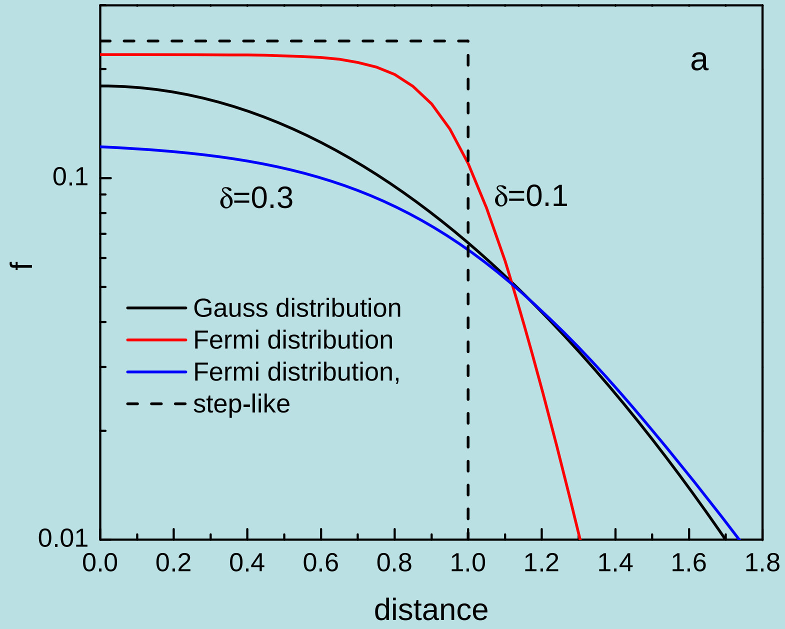
"diffused" Heaviside distribution

$$N_{VV}(r) = \frac{M}{\frac{4}{3}\pi R_0^3} \times H(R_0 - r) = \begin{cases} \frac{M}{\frac{4}{3}\pi R_0^3}, & for\ r<R_0, \\ 0, & for\ r>R_0. \end{cases}$$

where H(x) is the Heaviside function

Normalizing factor is chosen in order to fulfill the following condition:

$$\int_0^\infty 4\pi r^2 N_{VV}(r) dr = M$$



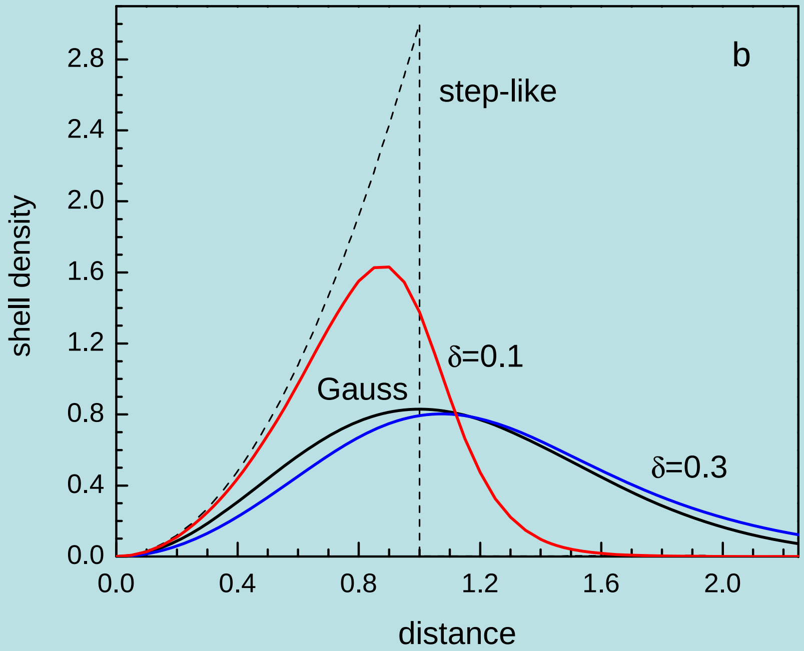


Fig.1. Different distribution functions f(r) used for simulation of band bending around spherical cluster. To analyze the contribution to DLTS signal of defects located at different distances from a cluster center the use of shell density 4πr2 f(r) is more representative (b).

$$n_{sh}(r) = 4\pi r^2 N_{VV}(r)$$

The decrease of DLTS peak amplitude $S_{max}(T)$ with growing temperature amplitude takes place when there is temperature range of incomplete defect occupation in the central region of cluster.

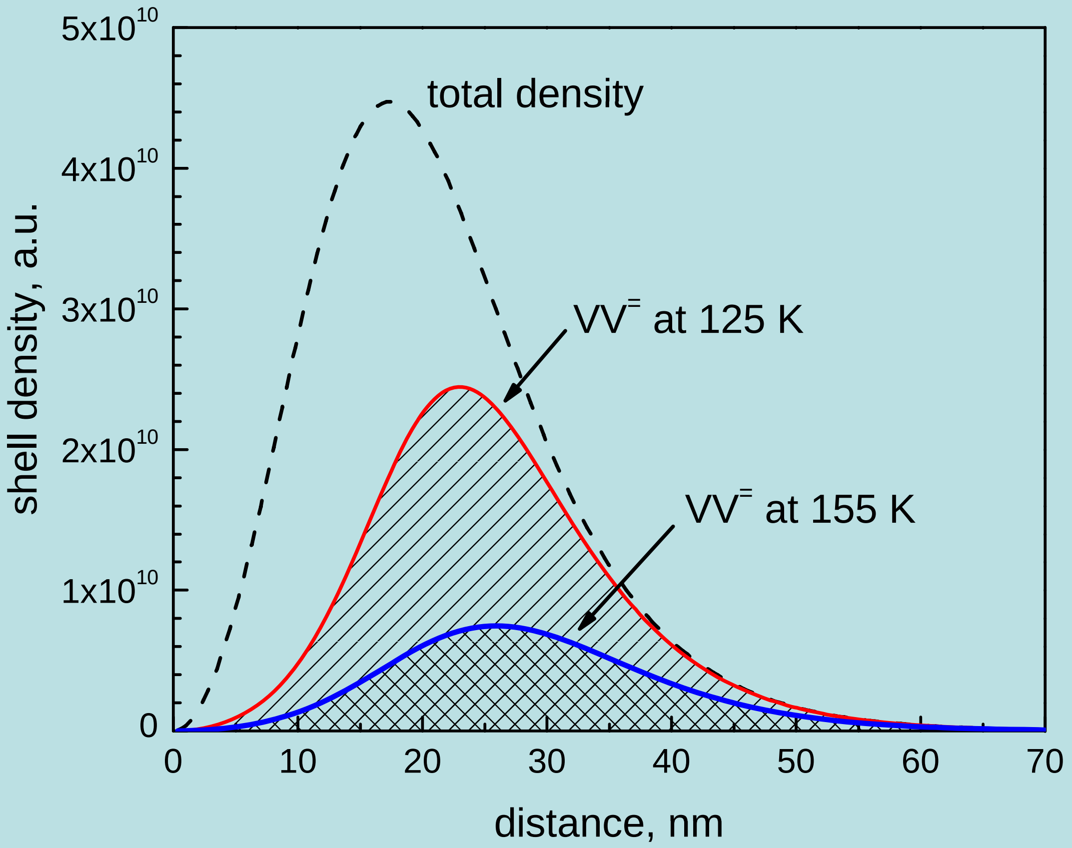


Fig.2. Distribution of doubly negatively charged divacancies inside a cluster at different temperatures.

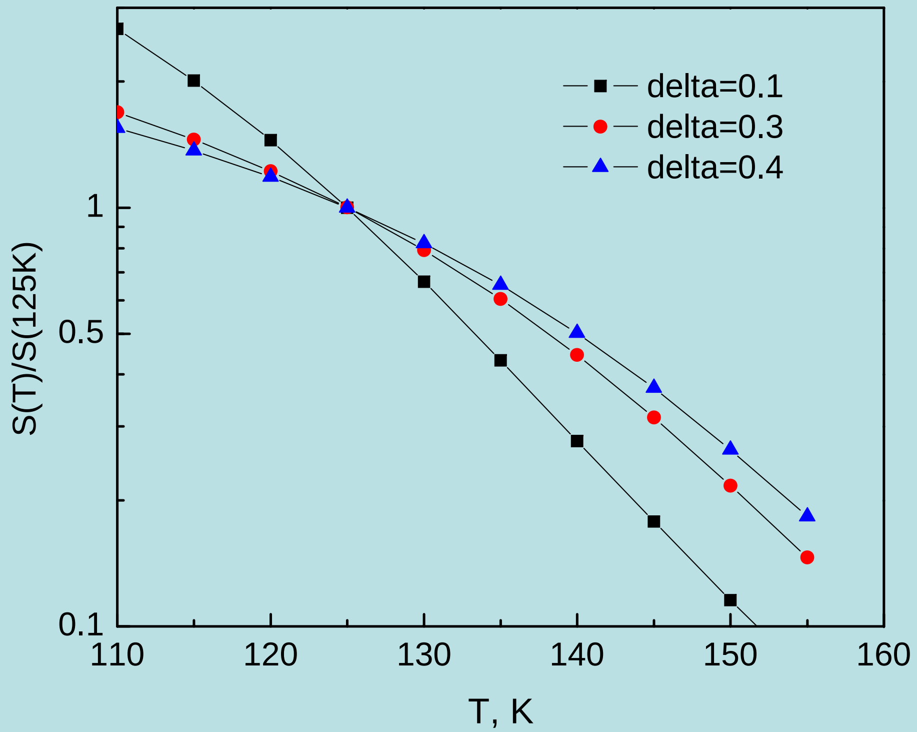
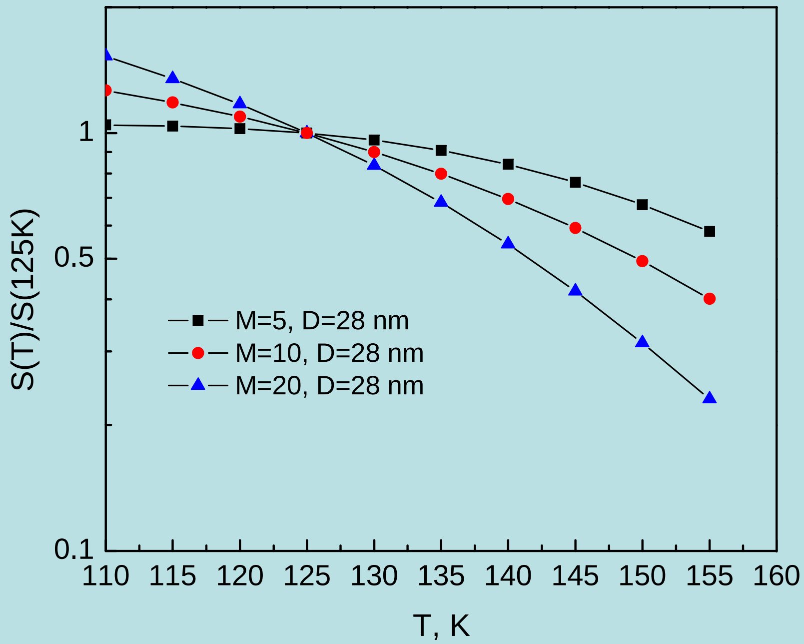


Fig.3. Effect of δ in the “diffused” Heaviside distribution on temperature dependence of VV= peak



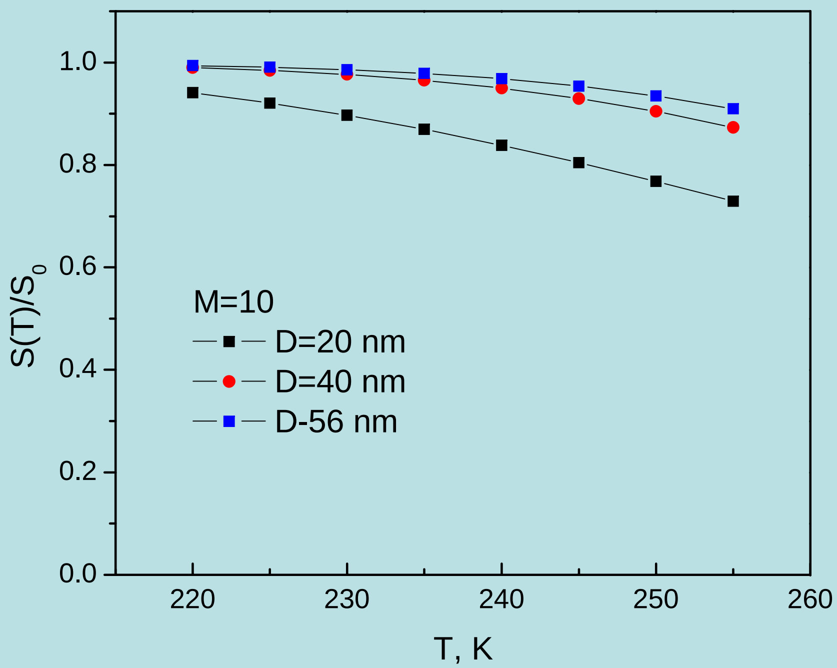
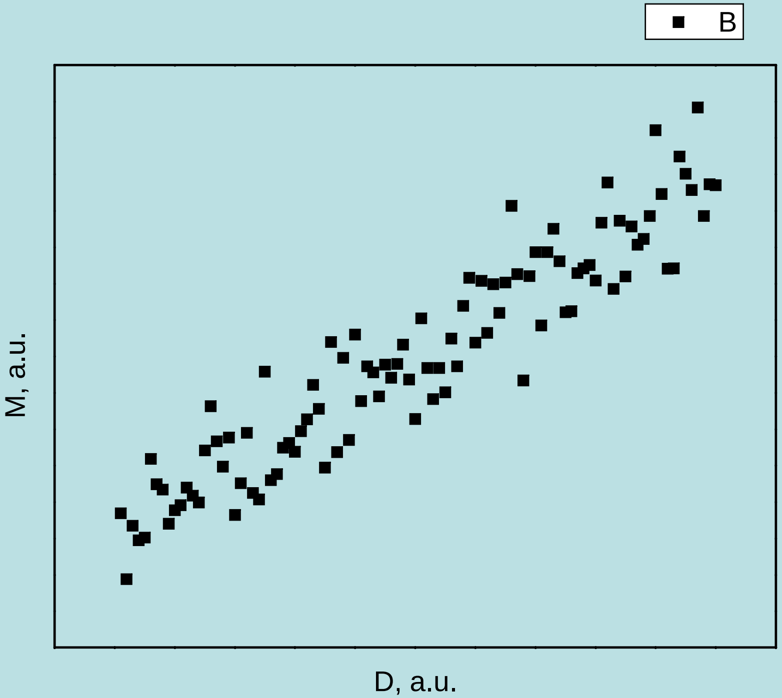


Fig.4. Temperature dependencies of DLTS peak amplitude for doubly (a) and singly (b) charged divacancy in clusters. The amplitude for doubly charged divacancy is normalized by the amplitude value at 125 K. The amplitude for singly charged divacancy is normalized by the its total number in cluster. Cluster diameter is indicated in figures



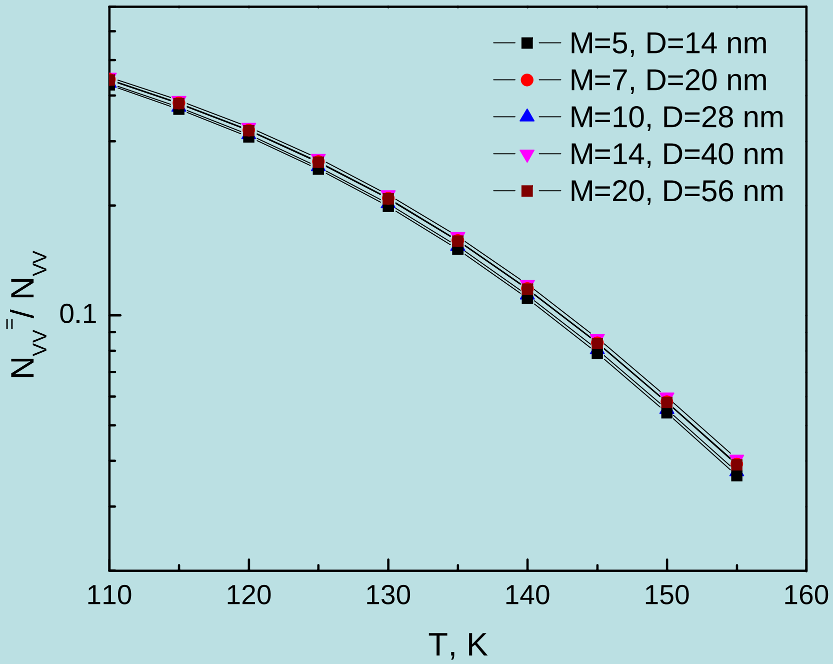


Fig.5. Schematic drawing of M/D_0 correlation for clusters in neutron irradiated Si [Fleming et al., 2007} (left) and normalized temperature dependencies of DLTS peak amplitude for doubly charged divacancy in clusters with constant ratio of M/D_0 (right).

It is expected that $S_{max}(T)$ dependence will be different for silicon diodes with different base doping.

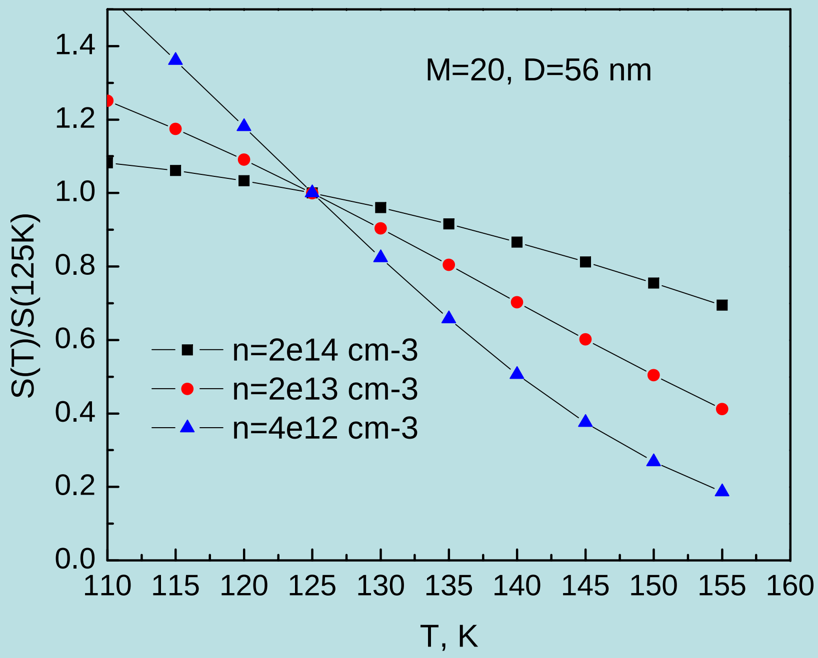
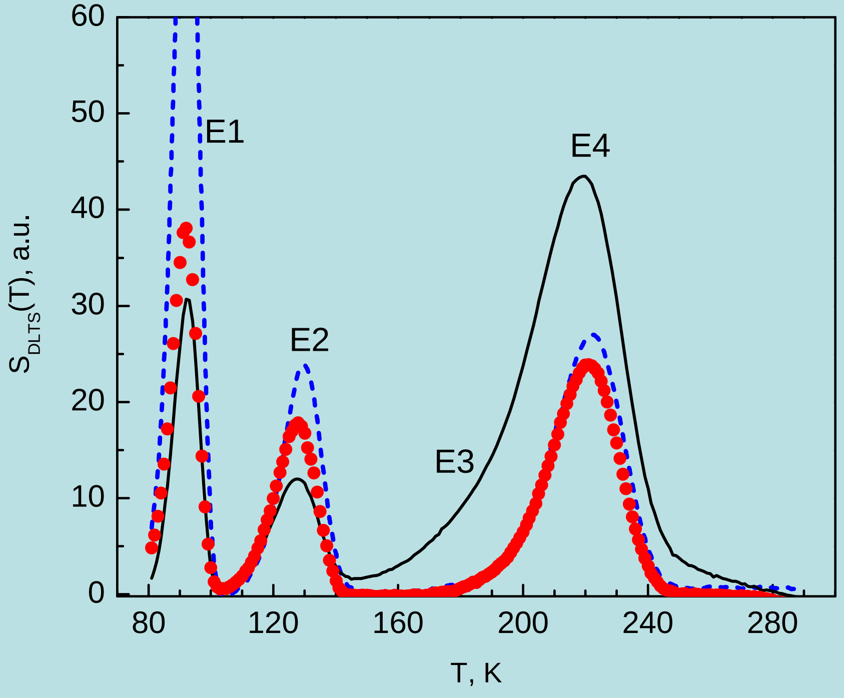


Fig.6. Normalized temperature dependencies of DLTS peak amplitude for doubly charged divacancy in the same clusters located indifferently doped semiconductors.

Part 2. Experimental data

Acronym	Resistivity, carrier concentration	Oxygen content	Processed	Irradiation fluence
EPI-8364	169 Ωcm, $N_d = 2.55\text{x}10^{13}$ cm^{-3}	lean	CiS process	6×10^{11} cm^{-2}
MCZ-8556	1090 Ω·cm, $N_d = 3.96\text{x}10^{12}$ cm^{-3}	rich	CiS process	6×10^{11} cm^{-2}
W-337	2090 Ω·cm, $N_d = 2.6\text{x}10^{12}$ cm^{-3}	lean	STM	3×10^{11} cm^{-2}



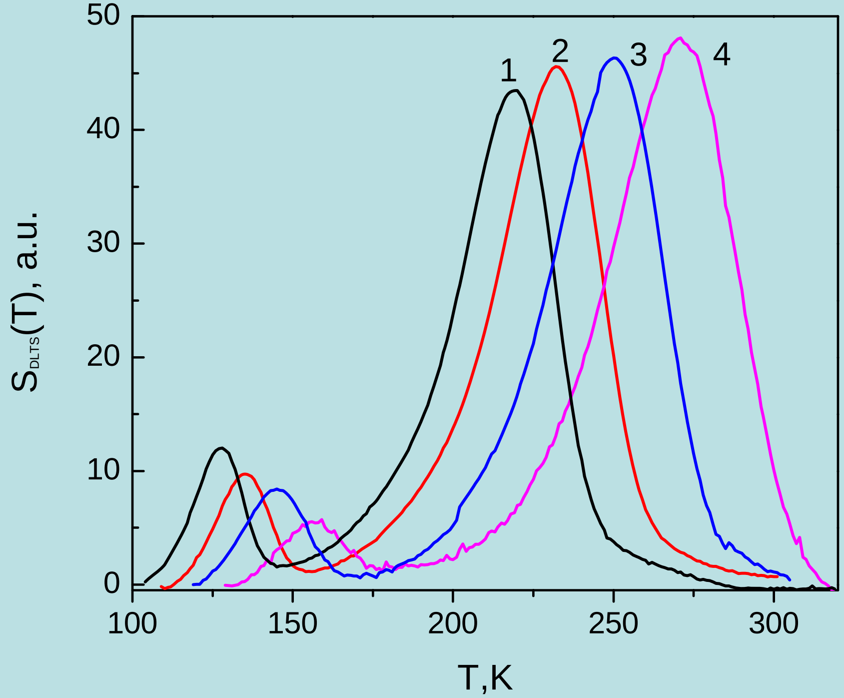
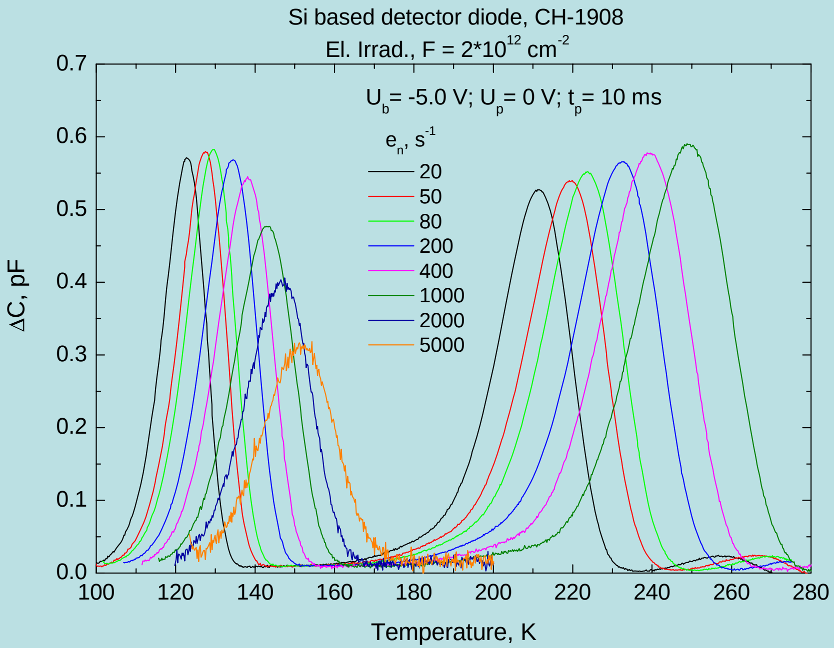


Fig.7. Comparison of DLTS spectra for epitaxial Si detectors irradiated with neutrons (solid line) and electrons (dashed line). Measurements have been performed at rate window of 95 s^{-1}. Points show DLTS spectra of neutron irradiated diode after 30 min. annealing at 200 ℃.

Fig.8. Divacancy related peaks (E2 or E024 and E4 or E042) in epitaxial Si detectors irradiated with neutrons measured at different rate windows: 1 – 95 s^{-1}; 2 – 380 s^{-1}; 3—1900 s^{-1}; 4 – 9500 s^{-1}.

However the E024 divacancy peak is temperature dependent even electron irradiated samples (see talks at *8th RD50 workshop, Prague, 2006).*



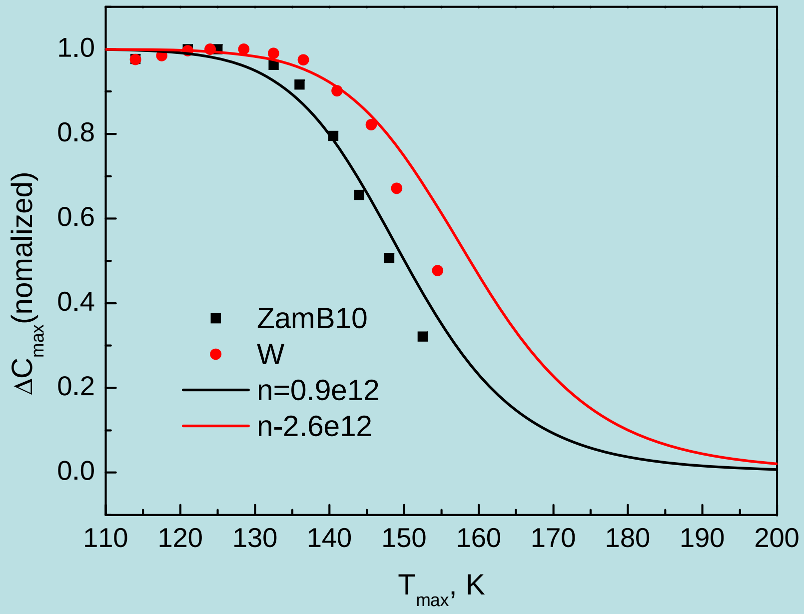


Fig. 9. DLTS spectra for Si detectors (ρ= 4 kΩ·cm) irradiated with electrons (E= 3.5 MeV) measured with different rate windows for E024 and E042 peaks of divacancy. Rate windows are shown in the figure. (8th RD50 workshop, Prague, 2006).

Fig. 10. Dependence of DLTS signal amplitude on temperature of DLTS peak appearance for detectors with different doping. ((8th RD50 workshop, Prague, 2006).

Therefore to study cluster effects on DLTS spectra Si diodes with higher doping are preferable.

Comparison with other works

Antonova et al., 1988-1991:

An approximate analytical expression have been obtained to describe $S_{max}(T)$ dependence for a single clustered defect.

It have been found that the deeper peak (E042) of VV falls with temperature and the shallower one (E024) increases (contrary to our observations)

Fleming et al., 2007:

The step-like distribution have been used in this work to interpret experimental data.

The shallower divacancy peak have been observed to fall with temperature. However its decrease was smaller then ours. This is consistent to our simulation results (Fig.6).

Kuhnke, 2003:

A numerical simulation have been performed for spherical cluster containing purely divacancies with Gaussian distribution. Simulation results are close to ours.

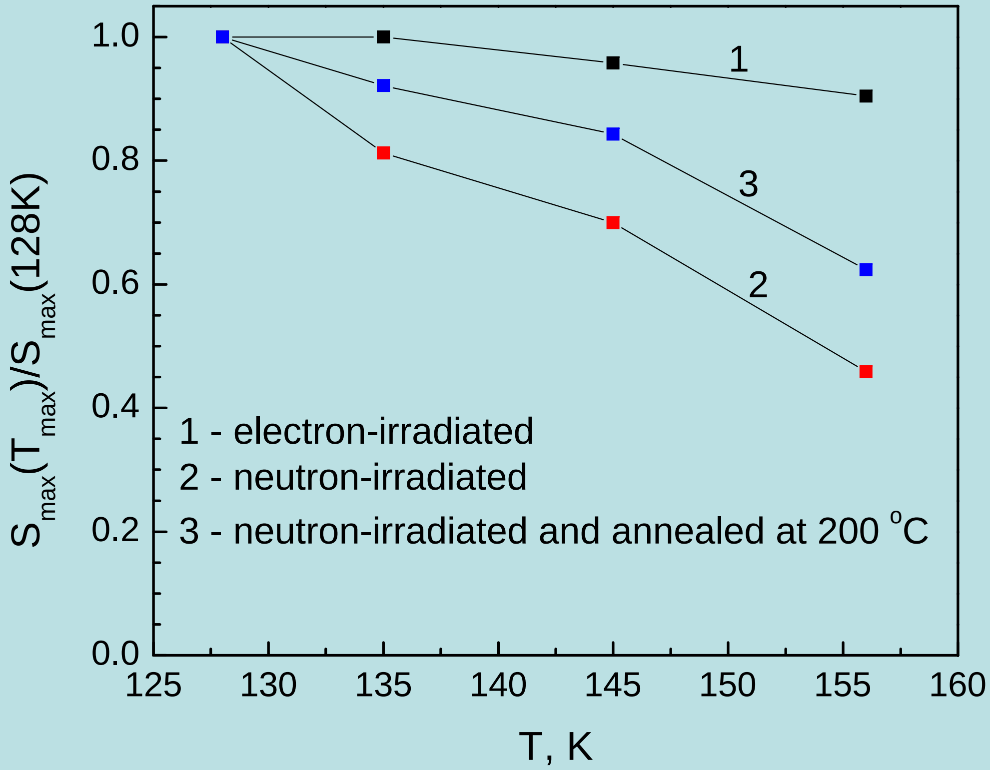


Fig.11. Amplitudes of the E2 trap measured at different temperatures (Tmax) for epitaxial Si detectors irradiated with electrons (1) neutrons (2, 3). The 3rd curve have been obtained after annealing at 200 ℃.

The different S_{max}(T) dependences in as-irradiated and annealed diodes are the consequence of a decrease of cluster charge.

Contrary to oxygen lean (STFZ or epitaxial) diodes, DLTS peak of E1 peak (Ec-0.17 eV) is also temperature dependent. It is an evidence of clustered V-O complexes in oxygen rich material.

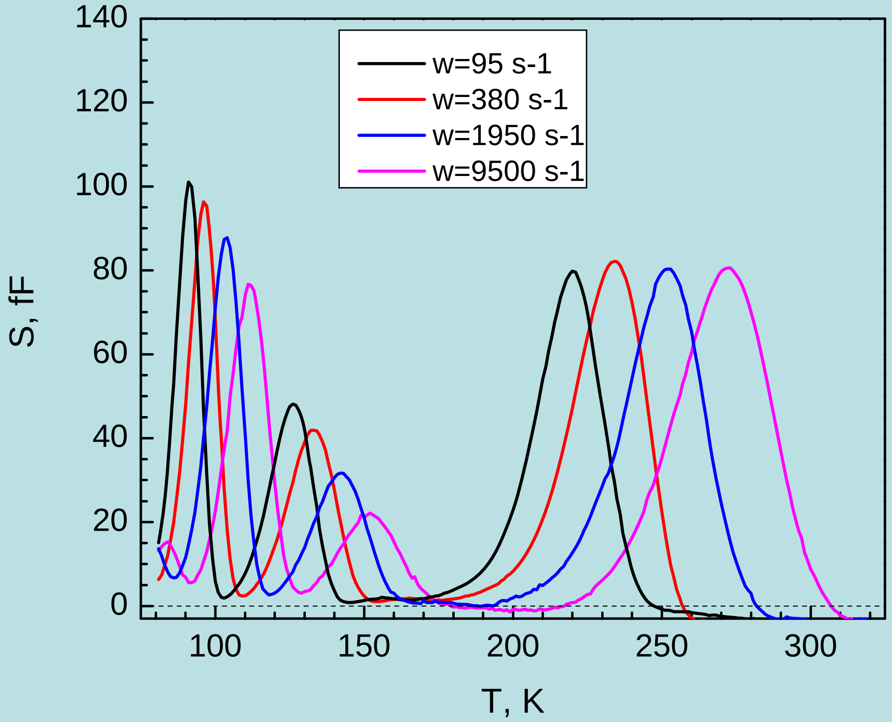


Fig.12. DLTS data for MCZ Si detector irradiated with neutrons measured at different rate windows: 1 – 95 s^{-1}; 2 – 380 s^{-1}; 3—1900 s^{-1}; 4 – 9500 s^{-1}.

A new effect related to defect bistability was found in neutron irradiated Si transistors (see R. M. Fleming, C. H. Seager, D. V. Lang, E. Bielejec, and J. M. Campbell Appl. Phys. Lett. 90, 172105 (2007)). The found that current injection at 300 K can change number of defects visible in DLTS spectra.

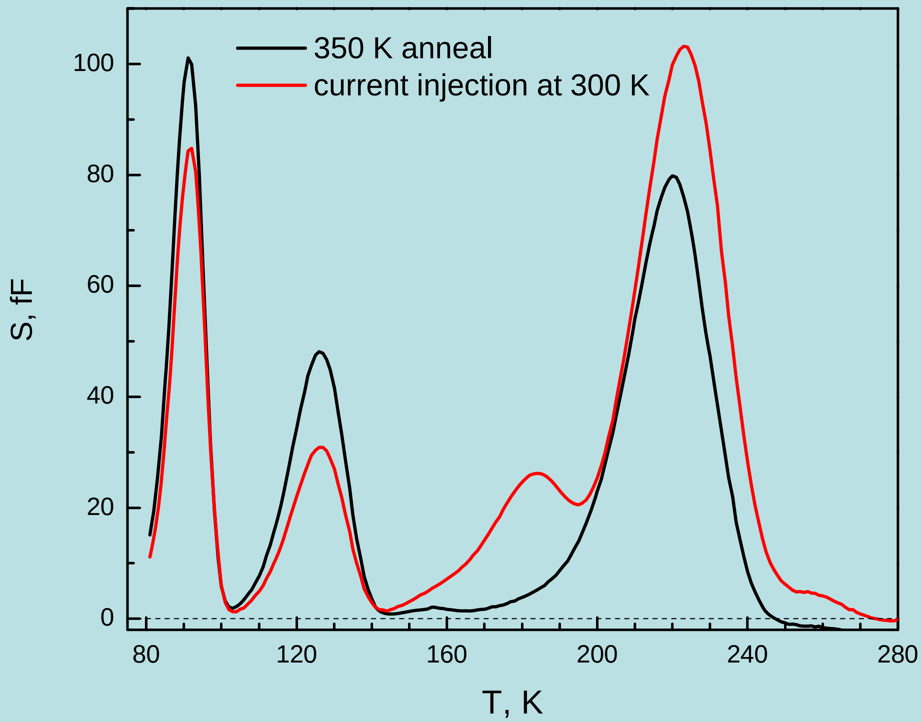


Fig.13. DLTS data for MCZ Si detector irradiated with neutrons and annealed at 200 °C. Measurements were performed after current injection at 300 K and after subsequent annealing at 350 K. Rate window was 95 s^{-1}.

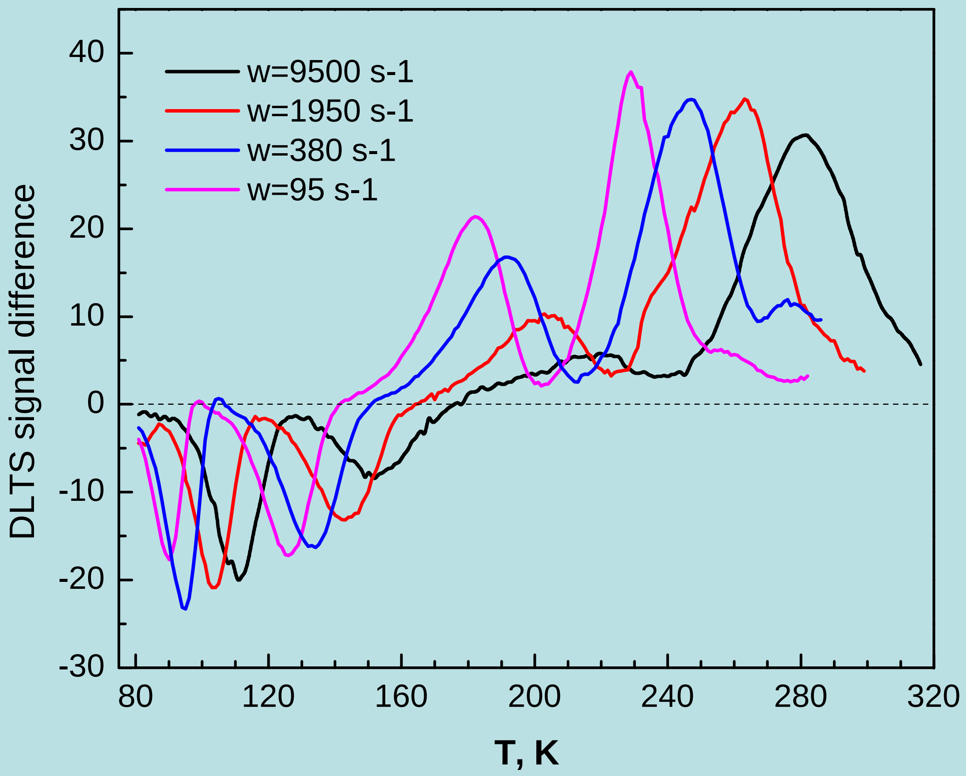


Fig.14. Difference between DPTS spectra for MCZ Si after current injection at 300 K and after subsequent annealing at 350 K. Measurements were performed at different rate windows: 1 – 95 s^{-1}; 2 – 380 s^{-1}; 3—1900 s^{-1}; 4 – 9500 s^{-1}.

CONCLUSIONS

Temperature dependence of DLTS peak amplitude helps to extract useful information on local distribution of defects in clusters. Though it does not allow to obtain unambiguously both the values of cluster size (D_0) and number of defects in a single cluster (M), this dependence may be used for comparative evaluation of different defect clusters.

It has been found that in detectors made on MCZ silicon not only divacancies but also vacancy-oxygen complexes are distributed in the form of clusters.

It has been shown that bistable defects in neutron irradiated and annealed silicon detectors behave similar to divacancies. It suggest that they have two energy levels in the gap.

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