

# FORMATION AND ANNEALING OF INTERSTITIAL DEFECTS IN P-TYPE SILICON AND SILICON-GERMANIUM ALLOYS UNDER ELECTRON AND ALPHA-IRRADIATION

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# Energy levels and migration energies of isolated Si self-interstitials\*

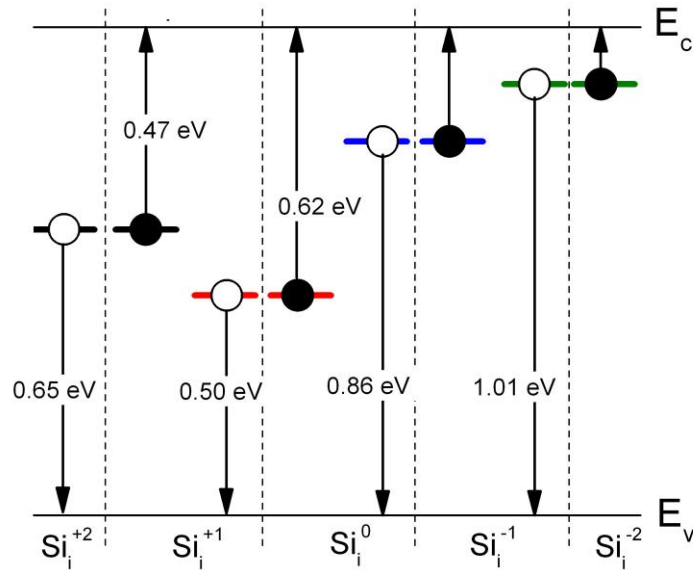


Fig. 1. Activation energies of electron (●) and hole (○) emission by different charge states of isolated Si self-interstitials.

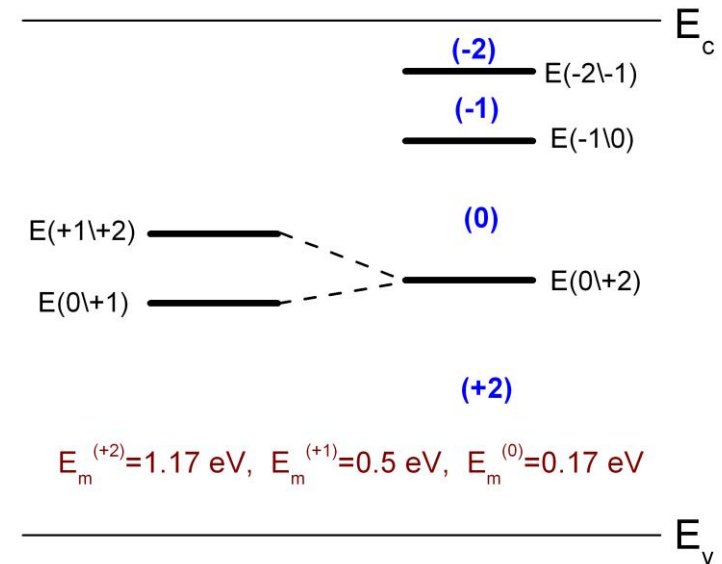


Fig. 2. Occupancy levels and migration energies of isolated Si self-interstitials in different charge states

\*theoretical calculations by N.A. Modine, cited according to S.M Myers, P.J. Cooper, and W.R. Wampler, J. Appl. Phys., **104**, 044507 (2008)

## Other theoretical studies

Theoretical calculations which predicted relatively high migration energy for doubly positively charged self-interstitials were published already in 1984:

*Y. Bar-Yam and J. D. Joannopoulos, Phys. Rev. Lett. 52, 1129 (1984).*

Similar equilibrium characteristics of Si self-interstitials (negative-U ordering of energy levels for positively charged states and their migration energies) were also reported in

*R. Jones, A. Carvalho, J.P. Goss, P.R. Briddon, Mater. Sci. and Eng. B 159-160, 112 (2009).*

## Previous experimental evidences

However due to recombination enhanced migration (REM) it was difficult to obtain experimental evidences of such high energy barriers for  $\text{Si}_i$  migration.

The REM effect takes place especially for electron irradiation. However B. Mukashev with co-workers found that self-interstitials have low mobility in p-type silicon irradiated with protons or alpha-particles at cryogenic temperatures:

- 1. B. N. Mukashev, Kh. A. Abdullin, M.F. Tamendarov and T.B. Tashenov, Phys. Lett. 166A, 40 (1992).*
- 2. Kh A Abdullin, B N Mukashev and Yu V Gorelkinskii, Semicond. Sci. Technol. 11 1696 (1996).*
- 3. B. N. Mukashev, Kh. A. Abdullin and Yu.V. Gorelkinskii, Phys. Stat. Sol. (a) 168, 73 (1998).*
- 4. Bulat N Mukashev, Kh A Abdullin and Yurii V Gorelkinskii, Phys.-Usp. 43 139 (2000).*

However some of their results cannot be interpreted unambiguously and need more detailed investigations.

# LOW TEMPERATURE ELECTRON IRRADIATION

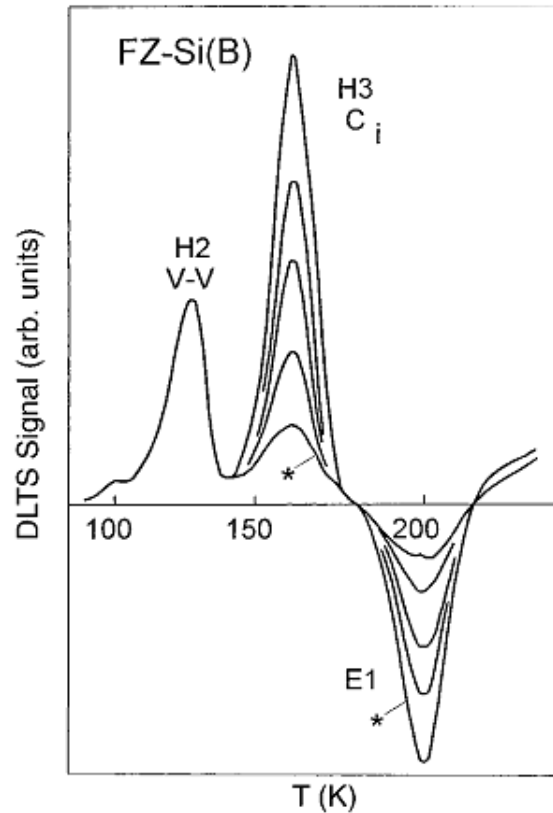


Fig.3. DLTS spectra of the p-FZ-Si(B) sample a-irradiated at about 250 K. The spectra were observed under low level injection conditions. The curve labeled with a star is recorded immediately after irradiation. Before each subsequent DLTS scan a short-term injection at 77 K was performed. [3]

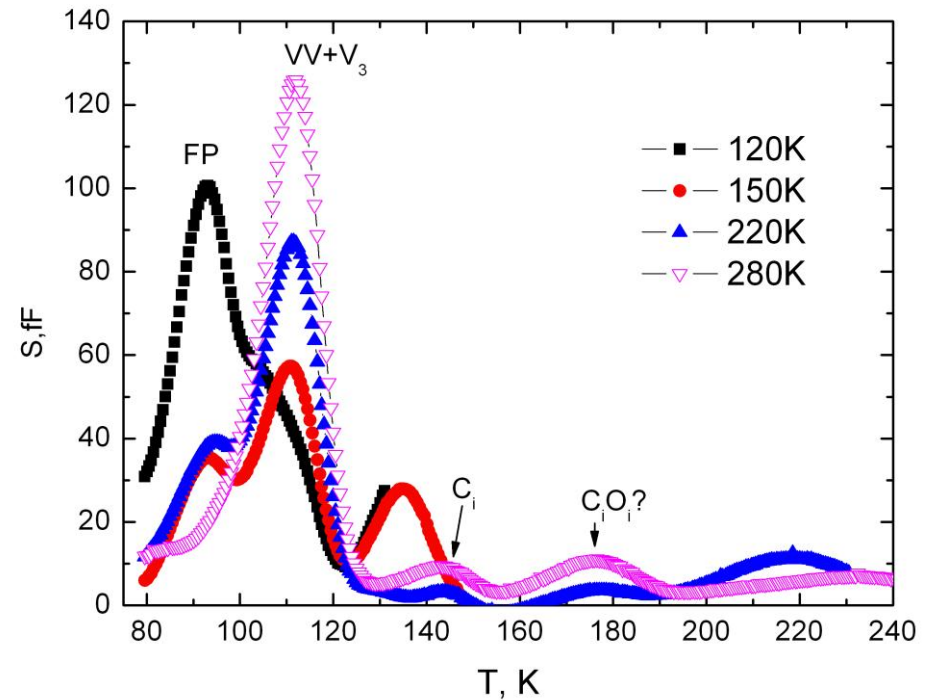


Fig. 4. Evolution of DLTS spectra during annealing of MCz p-Si irradiated at 78 K. Measurements have been performed at rate window:  $w_r=19 \text{ s}^{-1}$  (b). Each annealing step was 15 min long. Annealing temperatures are indicated in the figure.

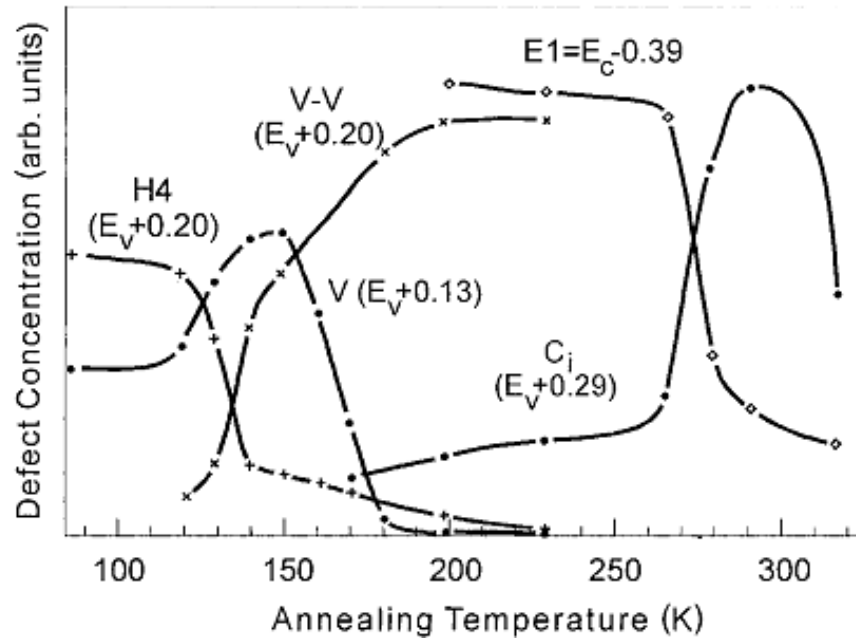


Fig.5. Isochronal (10 min) annealing of a Cz-Si(B) sample bombarded with  $\alpha$ -particles at 77 K [3].

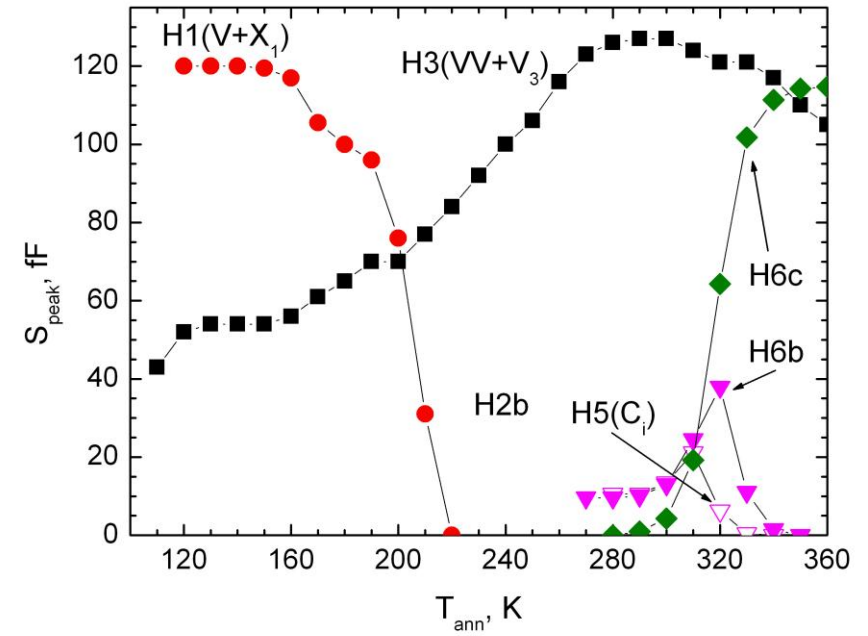


Fig. 6. Evolution of the heights of the main DLTS peaks observed in MCz diodes irradiated at 78 K and annealed at 100-350 K with temperature step 10 K. The annealing duration at each temperature was 15 min.

## Model of Si<sub>i</sub> reactions in boron doped silicon



$$\frac{d[Si_i]}{dt} = -(K_{IB}^*[B_s] + K_{IC}^*[C_s] + K_{IX}^*[X])[Si_i]$$

1

$$f^{(+1)} = \frac{[Si_i^{(+1)}]}{[Si_i]}, \quad f^{(+2)} = \frac{[Si_i^{(+2)}]}{[Si_i]}$$

$$f^{(+2)} \approx 1, \quad f^{(+1)} = \frac{p(+1 \setminus +2)}{p_0}$$

For substitutional boron and carbon one can suppose that:

$$R_{IB}^{(+2)} > R_{IB}^{(+1)} > R_{IB}^{(0)}$$

$$R_{IC}^{(+2)} \approx R_{IC}^{(+1)} \approx R_{IC}^{(0)}$$

$$\begin{cases} K_{IB}^* = 4\pi R_{IB}^{(+1)} D_I^{(+1)} \frac{p(+ \setminus ++)}{p_0} \\ K_{IC}^* = 4\pi R_{IC}^{(+1)} D_I^{(+1)} \frac{p(+ \setminus ++)}{p_0} \\ K_{IX}^* = 4\pi R_{IX}^{(+1)} D_I^{(+1)} \frac{p(+ \setminus ++)}{p_0} \end{cases}$$

Then for Si<sub>i</sub> annealing rate we obtain:

$$1/\tau = D_I^{(+1)} \frac{p(+1 \setminus +2)}{p_0} \propto \frac{1}{p_0} \exp\left(-\frac{E_m^{(+1)} + E_h^{(+2)}}{kT}\right)$$

# Alpha-irradiation geometry and defect distribution in Si diodes

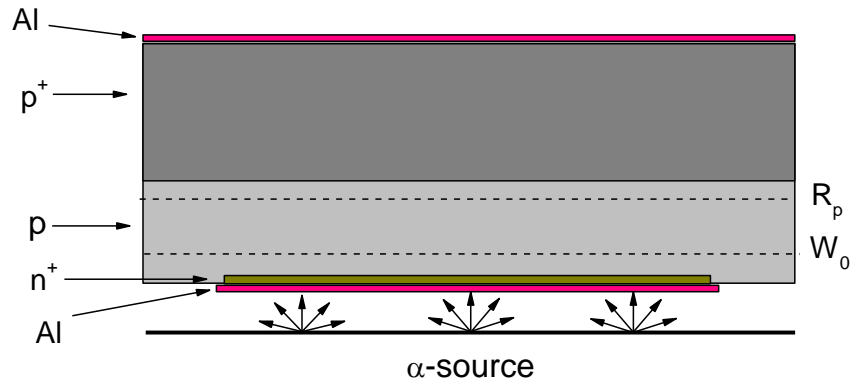


Fig.7. Schematic drawing of irradiation geometry.  $R_p$  is the range of alpha-particles penetrated orthogonally to the surface.

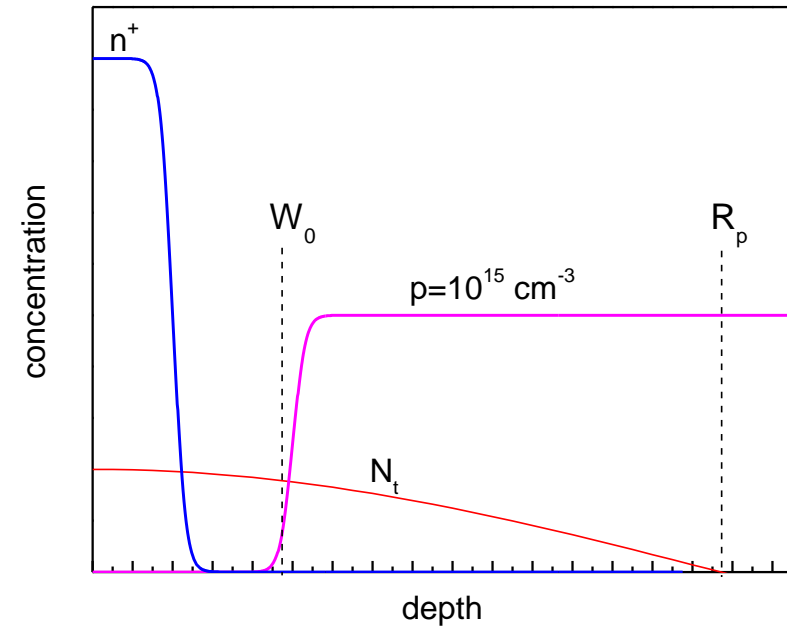


Fig.8. Schematic drawing of carrier and radiation defects ( $N_t$ ) distributions in structures under study.

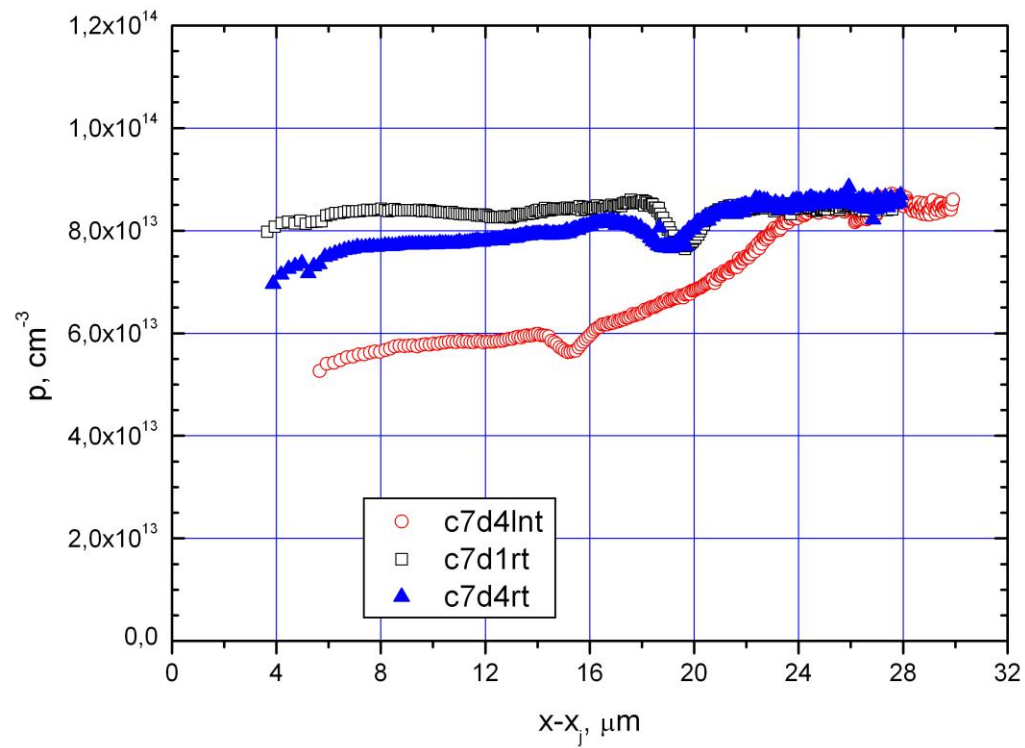


Fig. 9. Charge carrier distribution in epitaxial Si diode after alpha-irradiation. Measurement temperatures were 78 K (red) and 300 K (blue).



## Interstitial defect annealing in alpha-irradiated silicon

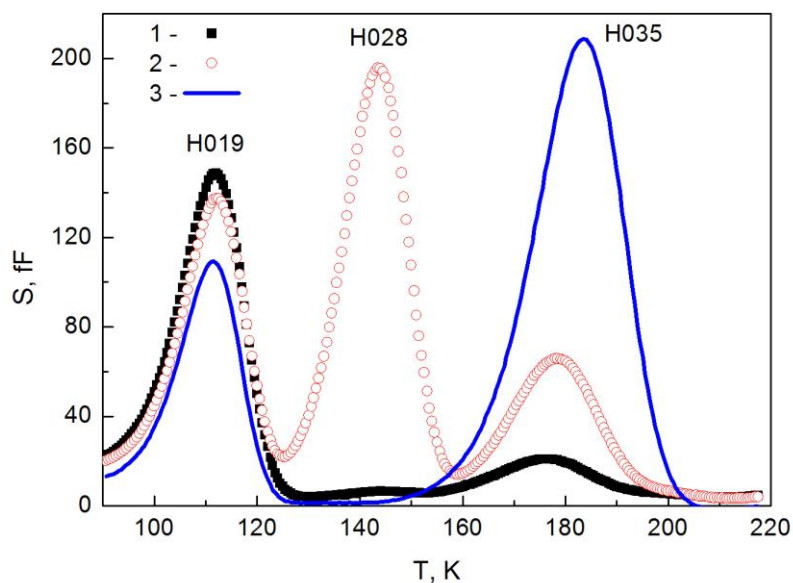


Fig. 10. DLTS spectra for a p-type Si sample irradiated with alpha-particles of Pu-239 source during 400 min at 15-20 °C measured immediately after irradiation (1), after forward injection at 80 K (2) and after subsequent annealing at 373 K for 30 min (3). Measurement settings were: emission rate window  $e_w = 19 \text{ s}^{-1}$ , bias change  $-5 \rightarrow 0 \text{ V}$ , and filling pulse duration  $t_p = 10 \text{ ms}$ .

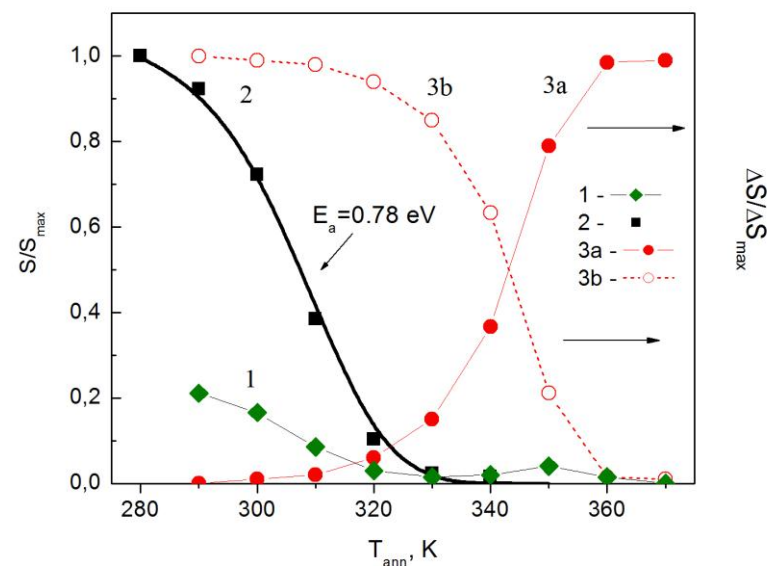


Fig.11. Evolution of concentrations of carbon related centers during isochronal annealing of  $n^+$ -p diodes. Curve 1 represents evolution of H029 peak under thermal annealing. Curve 2 represents evolution of H029 peak under thermal annealing after preliminary current injection performed immediately after irradiation obtained on an identical sample. Curve 3 represents the increase in the total concentration of carbon related centers under thermal annealing.

## Difference between capture radii for different charge states of $\text{Si}_i$ by boron

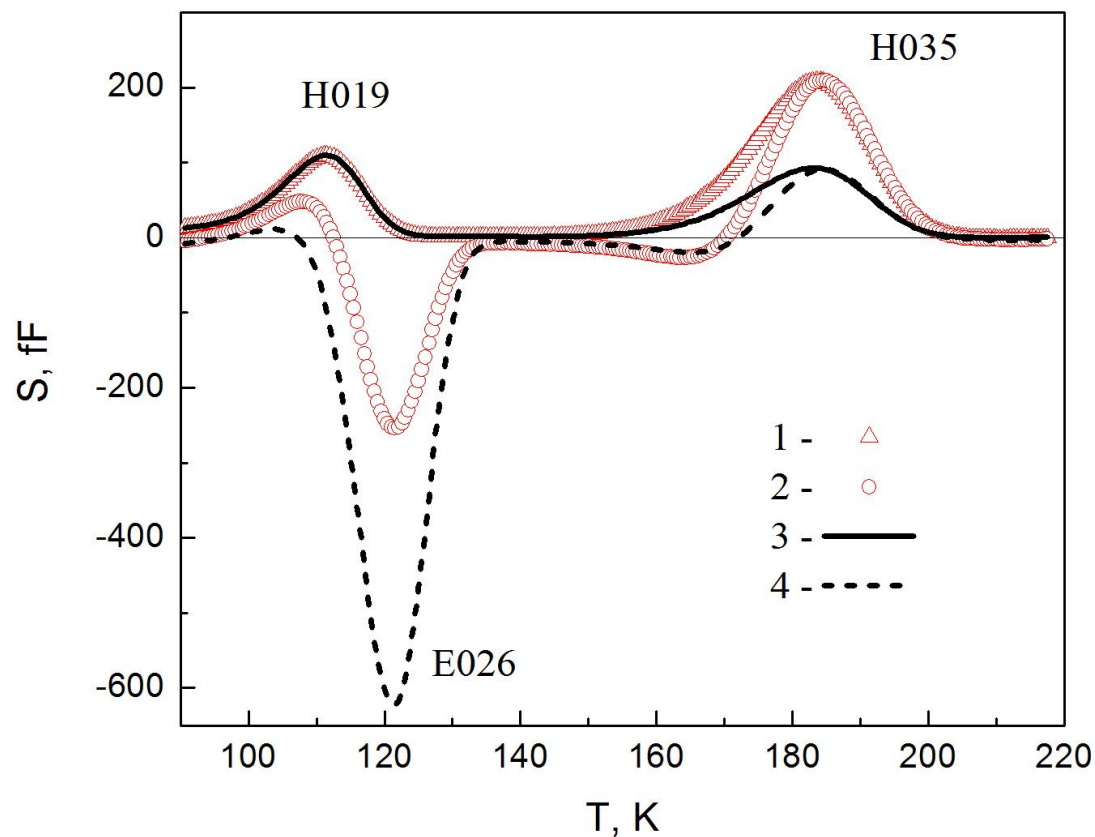


Fig.12. DLTS spectra for the p-type Si samples irradiated with alpha-particles of Pu-239 source during 400 min at 15-20 °C measured after thermal annealing at 373 K with (curves 1 and 2) and without (curves 3 and 4) post-irradiation current injection at 80 K.

Measurement settings were: emission rate window  $e_w = 19 \text{ s}^{-1}$ , bias change  $-5 \rightarrow 0 \text{ V}$  (curves 1 and 3) and  $-5 \rightarrow +2 \text{ V}$  (curves 2 and 4), filling pulse duration  $t_p = 10 \text{ ms}$ .

## Si<sub>i</sub> annealing in samples with different doping

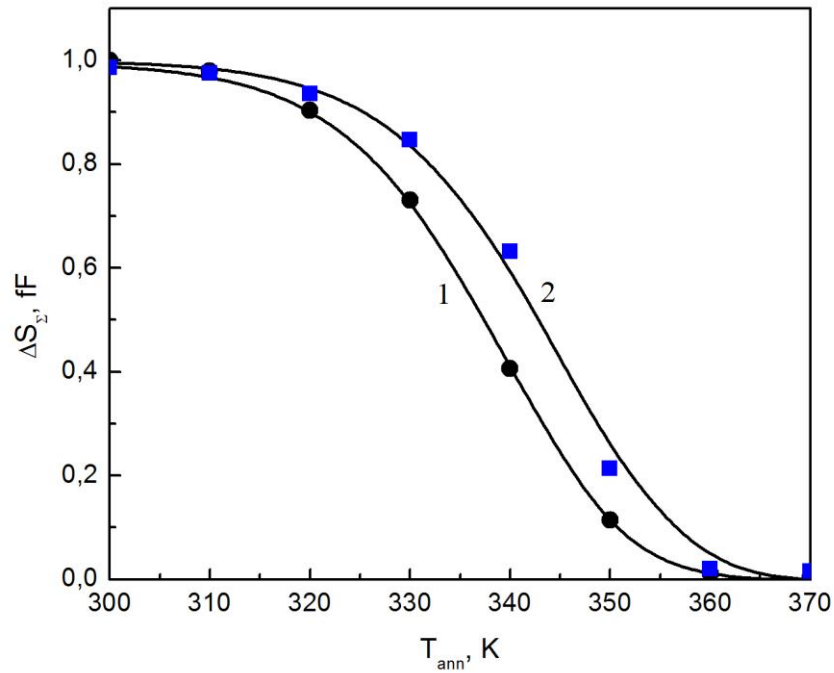


Fig.13. Disappearance of self-interstitials determined by appearance of carbon related centers in  $n^+$ -p diodes irradiated with alpha-particles of Pu-239 source. The hole concentration the diode base is equal to  $8 \times 10^{13} \text{ cm}^{-3}$  (curve 1) and  $1.05 \times 10^{15} \text{ cm}^{-3}$  (curve 2).

## DLTS spectra for SiGe alloys

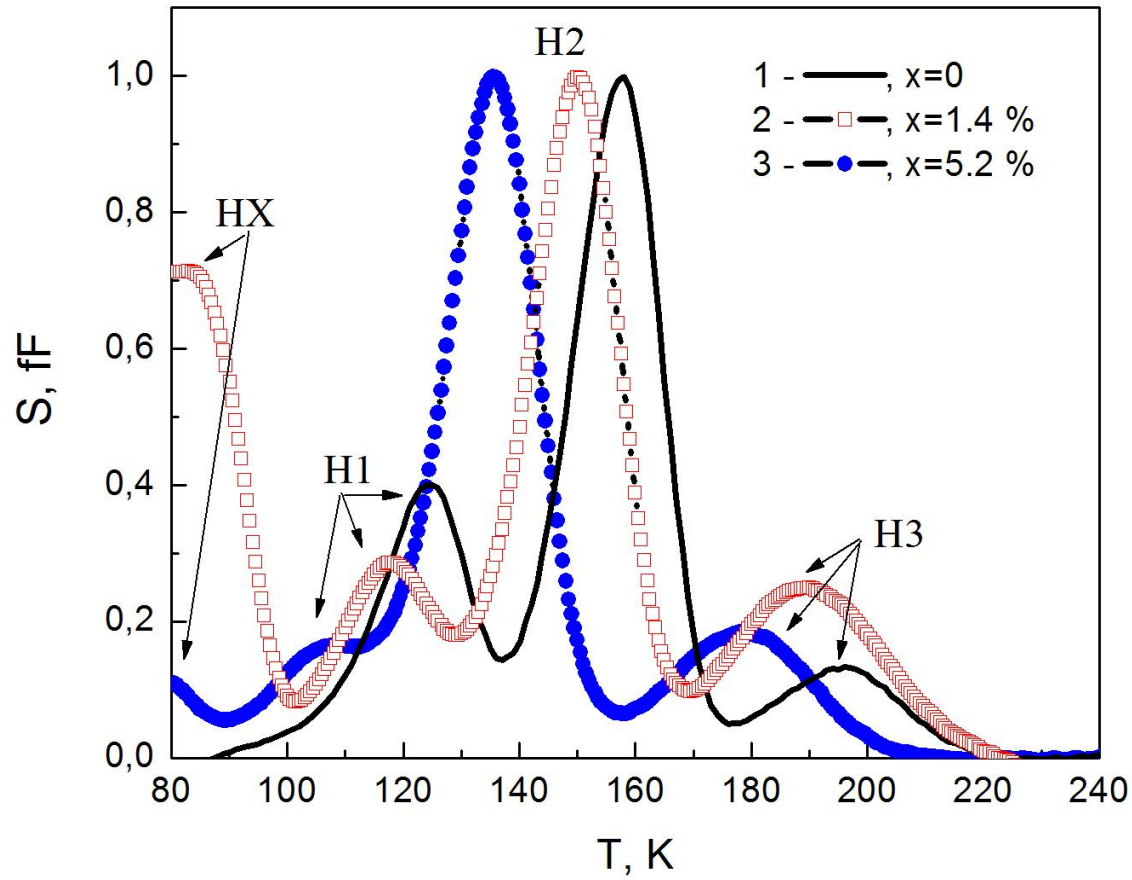


Fig. 14. DLTS spectra for SiGe diodes irradiated with alpha-particles after injecting current pulse at 78K.

## Annealing of $C_i$ in SiGe alloy

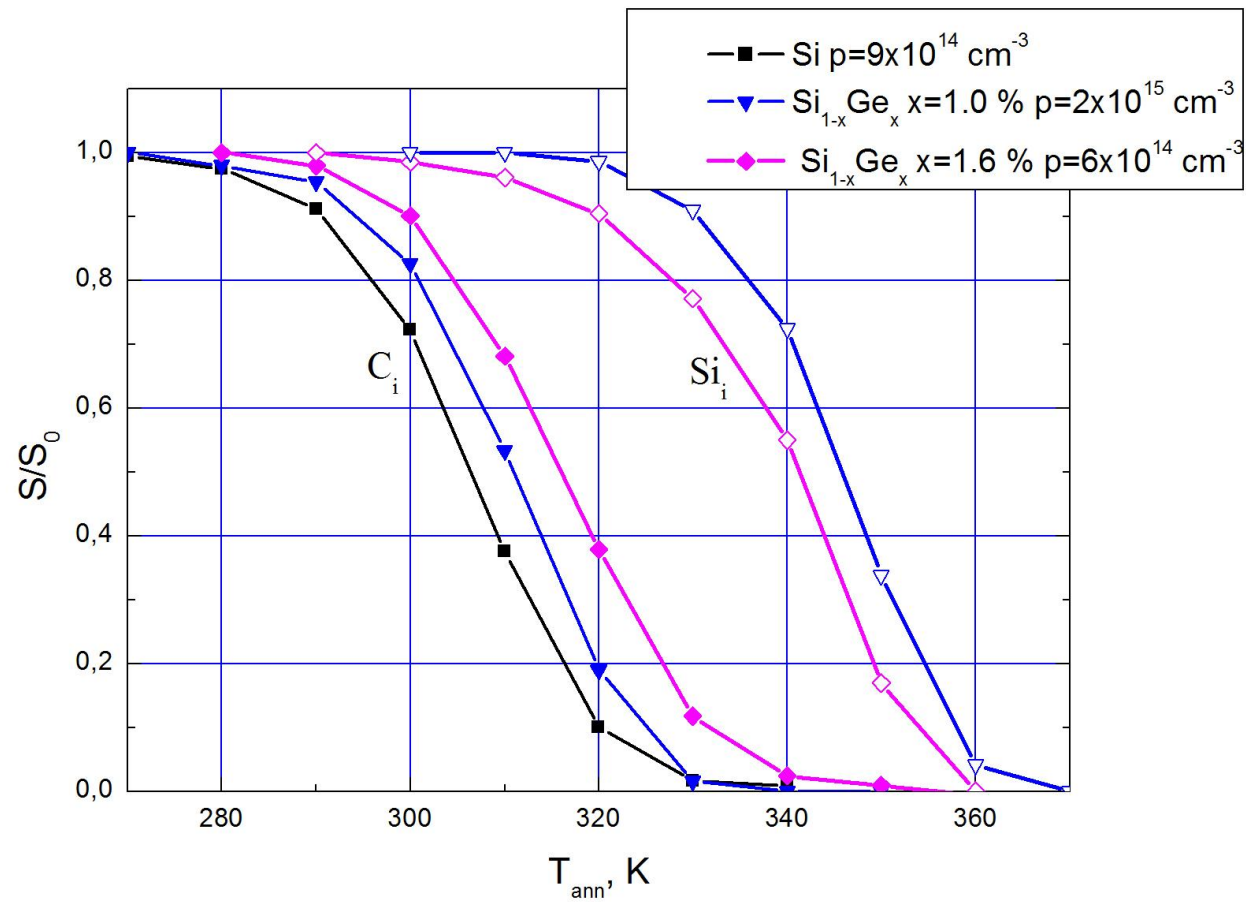
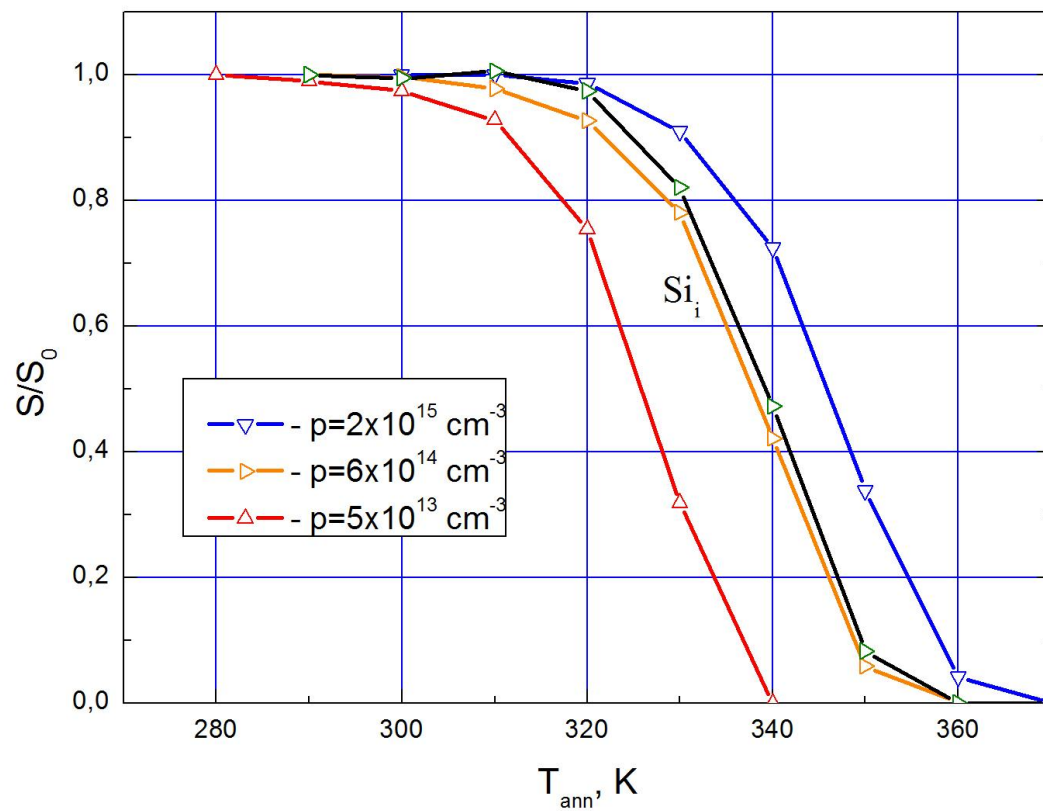


Fig. 15. Isochronal annealing of interstitial carbon in SiGe diodes irradiated with alpha-particles.

## Annealing of $\text{Si}_i$ in SiGe diodes with different base doping

Fig. 16. Disappearance of Si interstitial atom in  $\text{Si}_{1-x}\text{Ge}_x$  alloys with  $x=1.0-1.6\%$



# CONCLUSIONS

We have found that the single silicon self-interstitial atoms can be kept essentially immobile in p-type materials upon irradiation with alpha-particles at room temperature or low intensity electron irradiation at liquid nitrogen temperature. This conclusion is based on observations of the formation of interstitial carbon related defects due to an interaction of self-interstitial ( $\text{Si}_i$ ) with substitutional carbon ( $\text{C}_s$ ) (Watkins replacement mechanism) in the course of isochronal annealing of irradiated samples. We also have found that the relative probabilities of  $\text{Si}_i$  reaction with carbon and boron can be controlled with electronic excitation.

Activation energies of interstitial atom migration (both  $\text{Si}_i$  and  $\text{C}_i$ ) do not depend essentially on germanium content in  $\text{Si}_x\text{Ge}_{1-x}$  alloys ( $x < 2\%$ ).

To explain the observed experimental evidences a model of self-interstitial reactions in p-type silicon is suggested. This model predicts the dependence of the rate for  $\text{Si}_i$  annealing on Fermi level position. The prediction is confirmed experimentally.