INTERSTITIAL DEFECT REACTIONS IN P-TYPE SILICON IRRADIATED AT DIFFERENT TEMPERATURES

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Primary damage events during electron irradiation

$$Si_s \begin{cases} Si_i + V & - \text{separated defects} \\ \left(Si_i + V\right)_{close} & - \text{close Frenkel pair} \end{cases}$$

$$Si_s Si_s \rightarrow \begin{cases} 2Si_i + V_2 \\ \left(Si_i + V_2\right)_{close} + Si_i \\ \left(2Si_i + V_2\right)_{close} \end{cases}$$

There are strong experimental evidences on formation of Si_i, V and V_2 defects under electron irradiation

Formation of secondary defects

- In boron doped silicon main reactions are:
  - $V+O_i \rightarrow VO$
  - $Si_i+C_s \rightarrow C_i$
  - $Si_i+B_s \rightarrow B_i$
- The interstitial atoms of carbon and boron are mobile at room temperature and trapped by interstitial oxygen with formation C_iO_i and B_iO_i complexes. These complexes have energy levels at E_v+0.35 and E_c-0.26 eV, respectively.

Properties of isolated Si vacancy

- The vacancy can exist in five different charge states in the silicon band gap: V^{2+}, V^{+}, V^{0}, V^{-}, V^{2-}.

- The vacancy annealed out at 70 K in n-type, 150 K in p-type, and 200 K in high-resistivity material.
- The migration of the vacancy can also be made to occur even at 4.2 K under optical excitation, as well as by the ionization accompanying the electron irradiation.

- The vacancy has energy level $E(+/++)=E_v+0.13$ eV which allows to register it by DLTS.
- V^{2+}, V^{+} and V^{0} states of the vacancy form negative-U system and this property should be taken into account while interpreting DLTS data.

Properties of isolated self-interstitial

- For a long time self-interstitial atoms are considered to have extremely high mobility which results in impossibility to keep them frozen in temperature interval which are usually utilized to study defect reactions (78-600 K).
- However in 1990s several studies by B.N. Mukashev et al. appeared where it was concluded that self-interstitials can exist in proton and alpha-irradiated silicon up to room temperatures and has energy level E_c-0.39 eV.
- Recently theoretical calculations by N.A. Modine* also predict diffusion activation energy of self-interstitial in doubly positive state equal to 1.17 eV (*cited by: S.M. Myers, P.J. Cooper and W.R. Wampler, J. Appl. Phys., **104** (2008) 044507).

Motivation

- There are not enough experimental data on the properties of self-interstitials in silicon.
- It would be desirable to get more reliable information of their possible effects in silicon detectors under irradiation with different particles at different temperatures.
- The first step in such studies would be the examination of self-interstitial behavior in thermal equilibrium

Experimental

- **Samples:**
- The first type of diodes was produced from high resistivity p-type silicon wafers grown by the MCz ($p=3\cdot10^{12}$ cm^{-3}) method and from epitaxial p-Si ($p=1.3\times10^{13}$ cm^{-3}). The diodes were produced by Centro Nacional de Microelectrónica (Barcelona, Spain).
- The second type of diodes with hole concentration 1.0×10^{15} cm^{-3} was produced from epitaxial p-Si in Minsk.
- **Irradiation and annealing:**
- Room temperature (RT) and liquid nitrogen (LNT) 6 MeV electron ($F=4x10^{12}$ - $1x10^{15}$ cm^{-2}) or
  5.15 MeV alpha-particles from surface source ^{239}Pu
  (surface activity $2x10^{8}$ $cm^{-2}s^{-1}$, irradiation time – 4-10 hours).
- Isochronal and isothermal anneals in the range 100-400 K
- **Measurements:**
- DLTS in the temperature range of 78-350 K, measurement frequency was 1 MHz.

Experimental approach

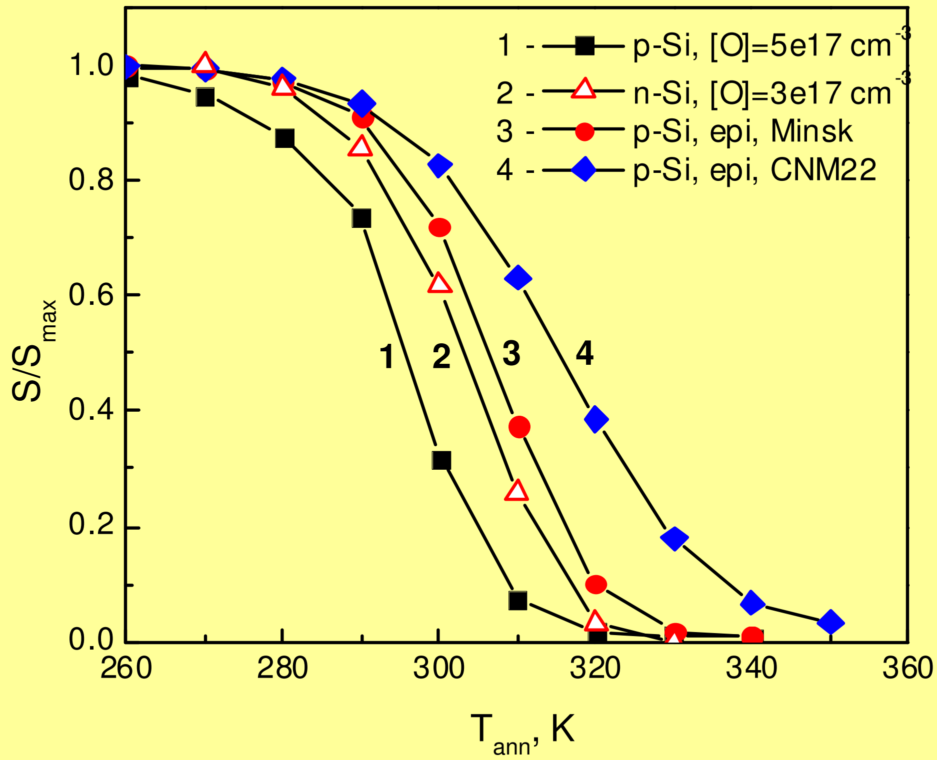
Taking into account the fact that DLTS peak of the self-interstitial in p-Si can be observed only after minority injection and measurement process will influence on it migration rate, we will use indirect method of self interstitial registration be its reaction with substitutional carbon:

$$Si_i + C_s \rightarrow C_i.$$

However, it turn out that in thermal equilibrium the self-interstitial is more stable than interstitial carbon. So to receive the necessary information we have to take account all carbon related centers:

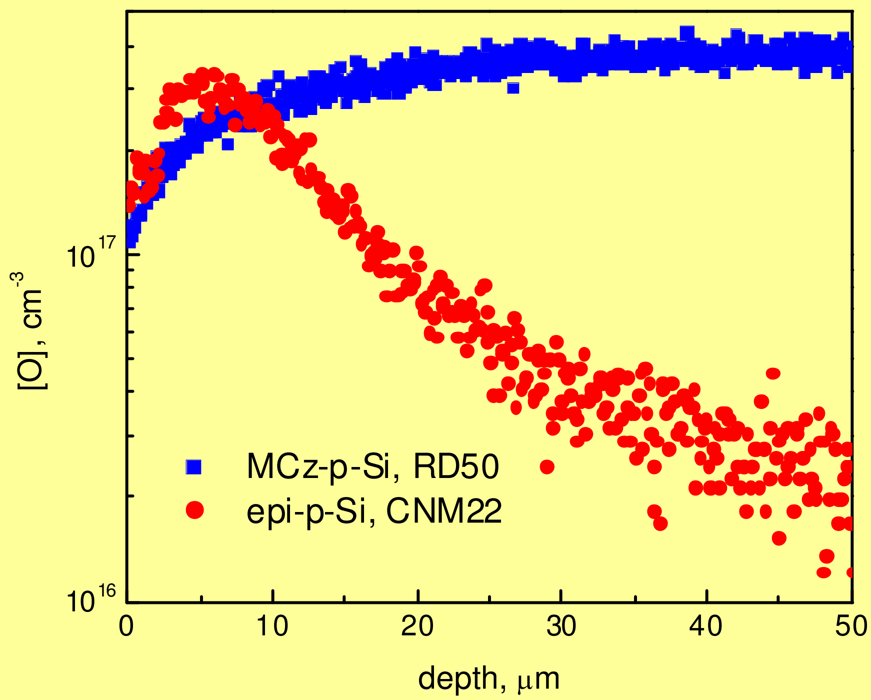
$$C_i,\ C_iO_i^*\ \text{and}\ C_iO_i$$

Rate of C_i annealing



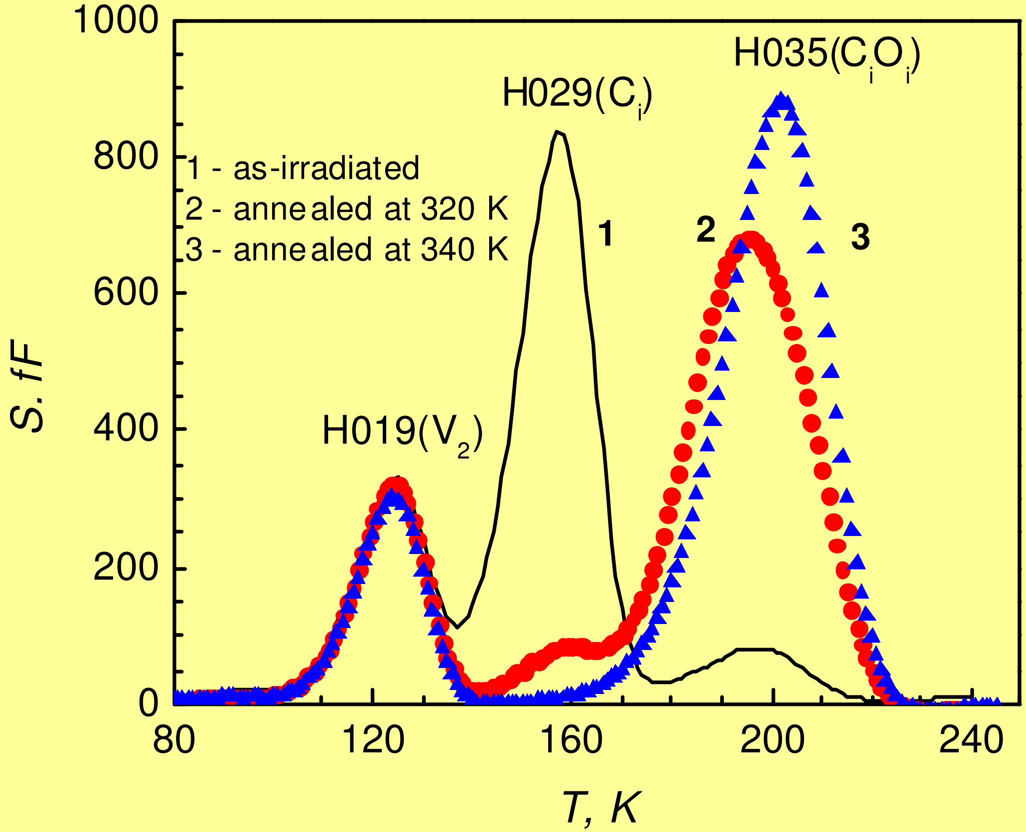
- Fig. 1. Isochronal annealing of C_i in n-Si and in p-Si in electron irradiated diodes made from magnetic Czochralski (curve 1), diffusion oxygenated (curve 2 and 3) and epitaxial (curve 4) silicon diodes. Annealing time was 15 min and temperature step was 10 K.

SIMS data on oxygen distribution in structures under study



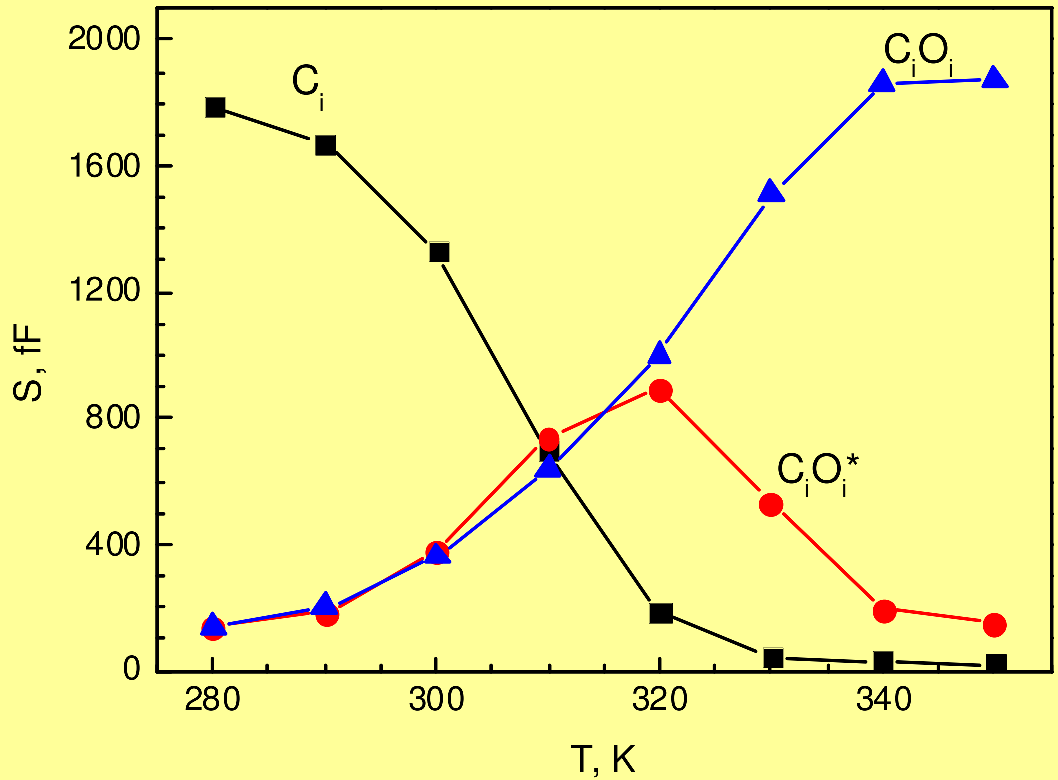
- Fig. 2. Oxygen distribution in MCz and epitaxial diodes used in present experiments. Blue points correspond the 1st curve and red points correspond to the 4th curve in Fig.1 .

Delayed appearance of C_iO_i



- Fig. 3. Development of the DLTS spectra for a p-type Si sample upon isochronal annealing. The spectra were measured immediately after irradiation with 4 MeV electrons ($F= 2x\cdot10^{15}$ cm^{-2}) at about 220 K (1) and after 15 min anneals at 320 K (2) and 340 K (3).

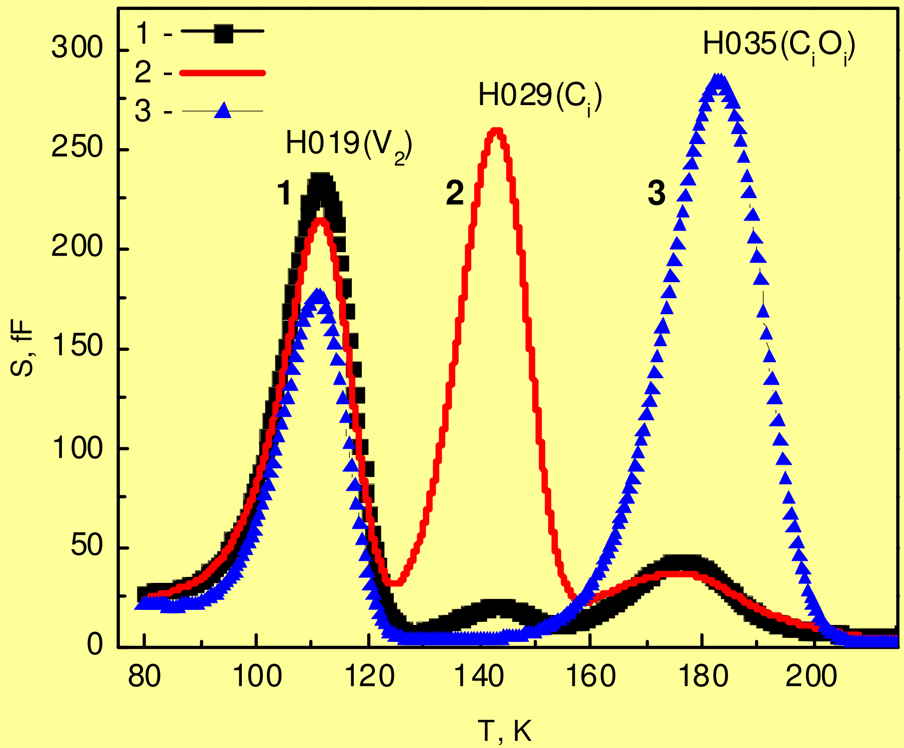
Delayed appearance of C_iO_i



- Fig. 4. Isochronal annealing behavior of the C_i, C_iO_i* and C_iO_i defects for the same sample as in Fig.2.

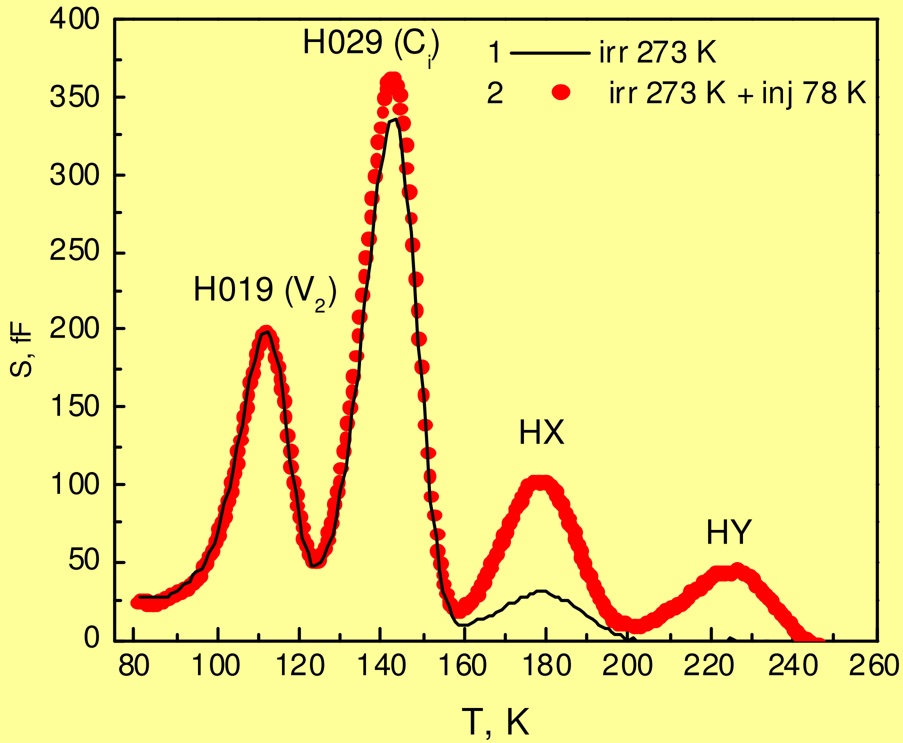
$$C_i + O_i \begin{cases} C_iO_i^* \rightarrow C_iO_i \\ C_iO_i \end{cases}$$

Appearance of C_i in diodes irradiated with alpha-particles at 273 K



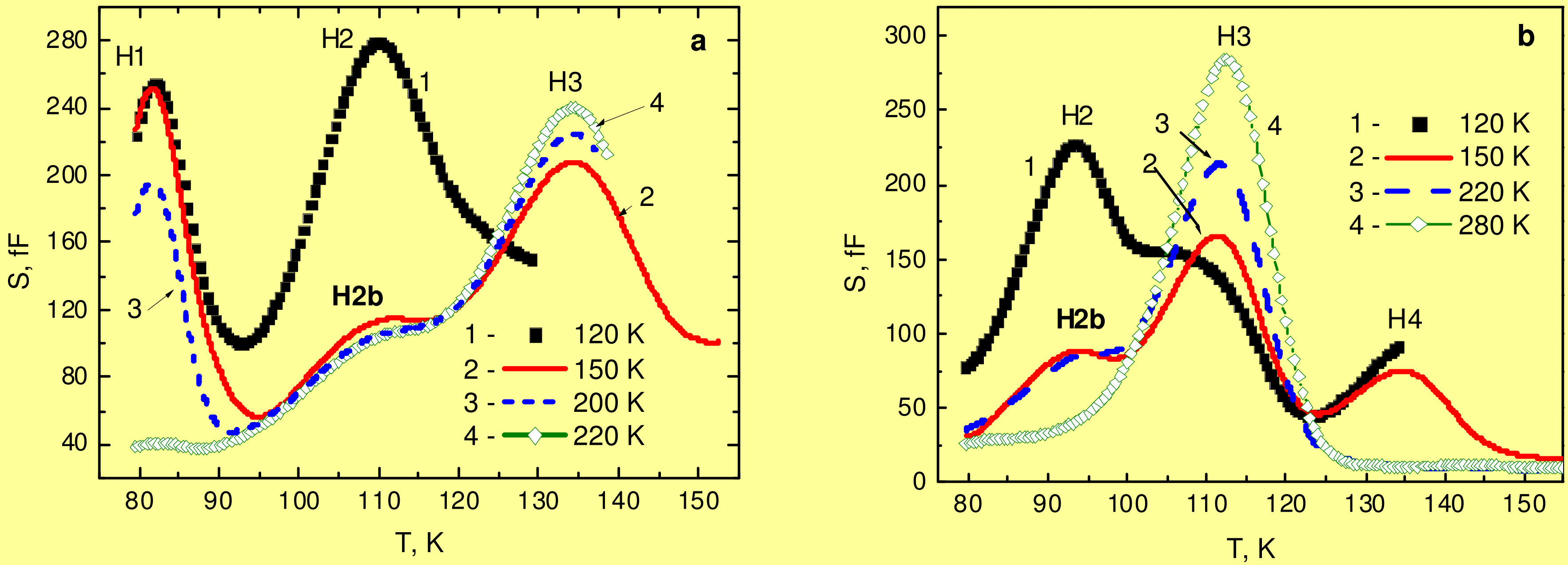
- Fig. 5. DLTS spectra for a p-type Si sample irradiated with alpha-particles of Pu-239 source during 400 min at 15-20 °C measured immediately after irradiation (curve 1), after forward injection at 80 K (curve 2) and after subsequent annealing at 360 K (curve 3).

Appearance of C_i in diodes irradiated with electrons at 273 K



- Fig. 6. DLTS spectra for a p-type Si sample immediately after irradiation at 273 K (1) and after subsequent current injection at 78 K (2). Irradiation fluence was $F=4x\cdot10^{12}$ cm^{-2} at electron beam intensity of $1x\cdot10^{11}$ cm^{-2} s^{-1}.

Appearance of C_i in diodes irradiated with electrons at LNT



- Fig. 7. Evolution of H1-H4 peaks during annealing of epitaxial p-Si irradiated at 78 K. Measurements have been performed at different rate windows: wr=950s^{-1} (a) and wr=19 s^{-1} (b). Each annealing step was 15 min. long. Annealing temperatures are indicated in the figures. H3 peak is related to divacancy (H019). Irradiation fluence was F=2.5x$\cdot 10^{13}$ cm^{-2} at electron beam intensity of 1x$\cdot 10^{11}$ cm^{-2} s^{-1}.

Appearance of C_i in diodes irradiated with electrons at LNT

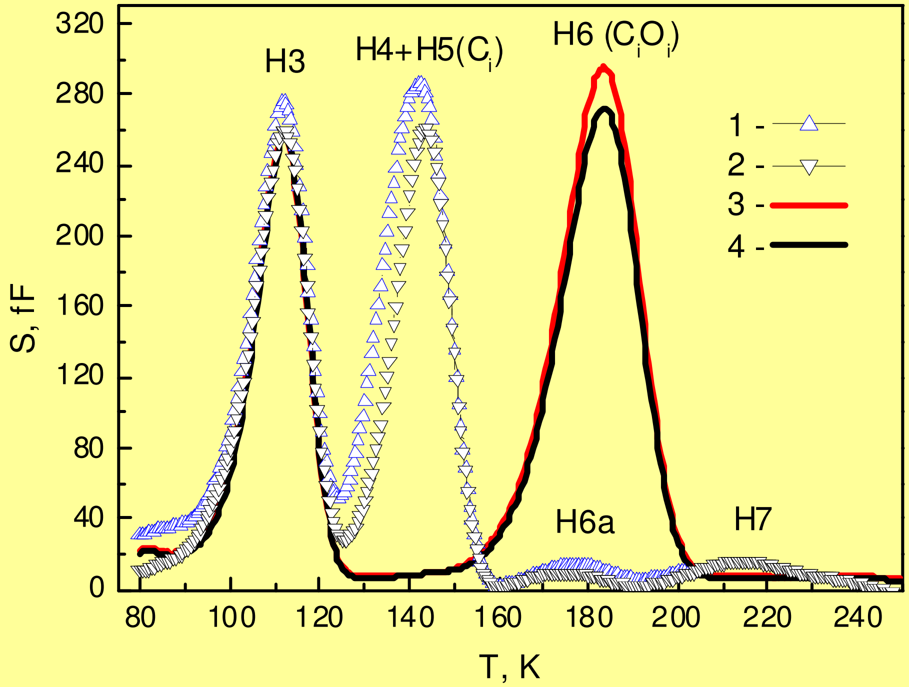
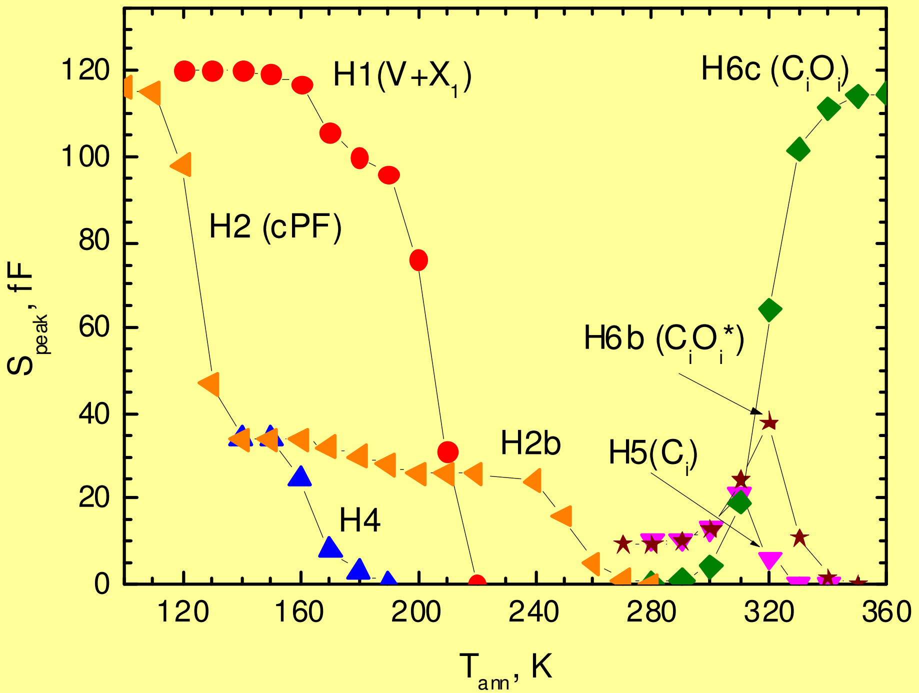


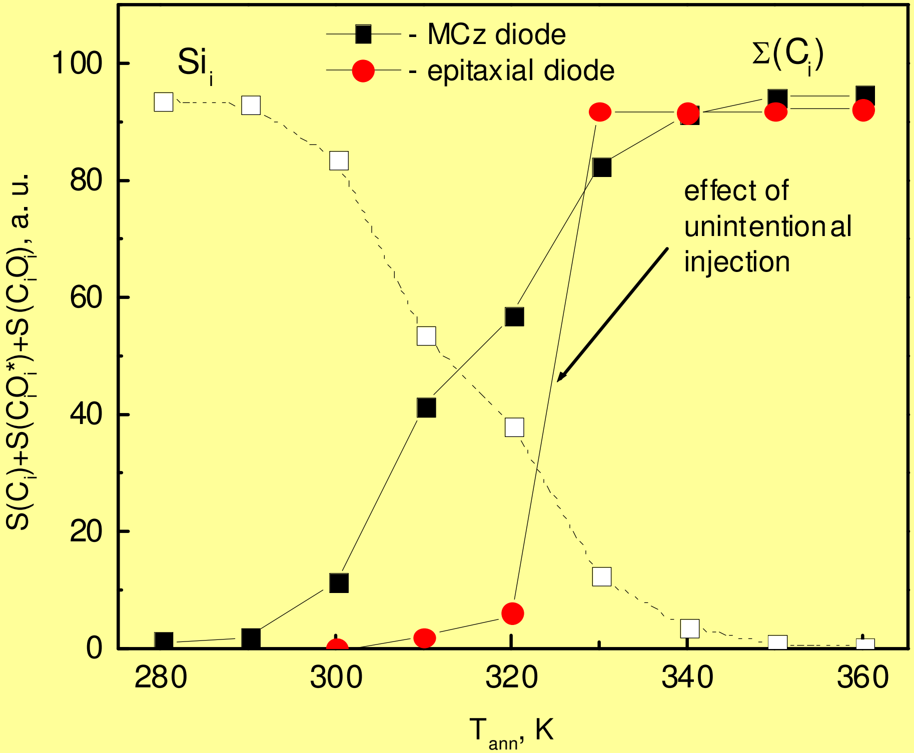
Fig. 8. Comparison of DLTS spectra measured after irradiation and forward current injection at 78 K (1) and after subsequent annealing steps at 200 (2) and 360 K (3) of the same epitaxial diode. The solid line (4) represents spectrum for another diode which underwent only a sequence of thermal annealing steps up to 360 K.

Appearance of C_i in diodes irradiated with electrons at LNT



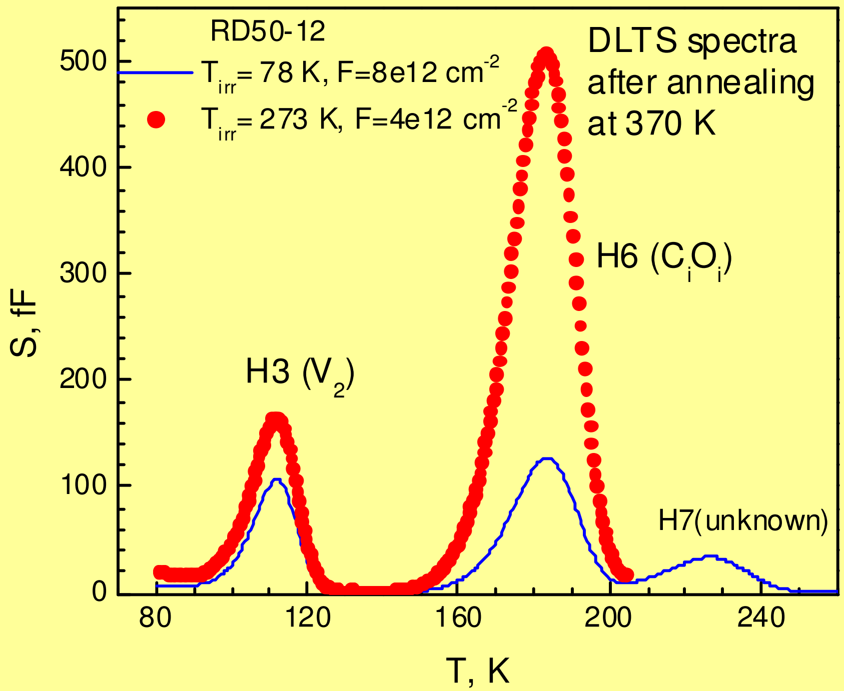
- Fig. 9. Evolution of the heights of the main DLTS peaks observed in MCz diode irradiated at 78 K and annealed at 100-350 K with temperature step 10 K. The annealing duration at each temperature was 15 min.

Disappearance of Si_i in diodes irradiated with electrons at LNT



- Fig. 10. Growth of the total concentration of carbon related defects during isochronal annealing for MCz and epitaxial diodes irradiated at 78 K. The growth is a result of Si_i disappearance.

Comparison of defect introduction rates in diodes irradiated at different temperatures



- Fig. 11. DLTS spectra of MCz diodes irradiated at 78 and 273 K after 30 min. annealing at 370 K. Irradiation dozes are indicated in the figure. Doze rate was $1x{\cdot}10^{11}$ cm^{-2} s^{-1}.

Conclusions

- It has been shown that silicon self-interstitials can be kept alive in p-Si even after irradiation at near room temperatures when the ratio of electron-hole generation rate to Frenkel pair generation rate is relatively low.
- Silicon self-interstitials have low mobility at room temperature in p-Si at thermal equilibrium conditions but quickly disappear after direct current injection at liquid nitrogen temperature.