KINETICS OF INTERSTITIAL CARBON ANNEALING AND MONITORING OF OXYGEN DISTRIBUTION IN SILICON PARTICLE DETECTORS

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Interstitial carbon (C_i) reactions play very important role for radiation damage of silicon. They are responsible for the formation of interstitial type defect complexes which are stable at room temperature (RT).

	Vacancy type defects	Interstitial type defects
Low irradiation fluences	$V+O \rightarrow VO$ etc.	$I_{Si} + C_s \rightarrow C_i$ $I_{Si} + B_s \rightarrow Bi$ C_i and B_i are highly mobile at room temperature. $C_i + O_i \rightarrow C_iO_i$ $C_i + C_s \rightarrow C_iC_s$
High irradiation fluences	$V + VO \rightarrow V_2O$ etc.	$I_{Si} + VO \rightarrow O_i$ etc

The description of C_i reactions is based on three assumptions which are valid for low irradiation fluences:

- Substitutional carbon (C_s) atoms are the main traps for silicon intersitials in high resistivity silicon crystals.
- Only isolated carbon atoms in interstitial position created by the Watkins replacement mechanism are the only source of mobile carbon species responsible for the formation of carbon related complexes stable at room temperature.
- Kinetics of their formation at low irradiation fluences is controlled by C_i diffusion coefficient and C_i capture radii by oxygen, substitutional carbon and doping impurities (phosphorous etc.).

- The first assumption is valid when concentration of boron is about two orders of magnitude less of carbon concentration.
- However the last two assumptions have not got unambiguous experimental confirmation.
- The second assumption has been called in question for detector grade silicon in a paper by *B. Schmidt V. Eremin, A. Ivanov, N. Strokan, and E. Verbitskaya Z. Li J. Appl. Phys. 76 (7), 1 October 1994 p. 4072*. It has been found there that in detectors irradiated with α-particles only a part of C_iO_i complex (labeled usually as H2 trap in DLTS studies) forms simultaneously with the disappearance of C_i and there is some delay in the additional growth of H2 trap

The aim of this talk is to suggest an explanation of the delayed appearance C_iO_i .

- Our explanation is based on two assumptions:
- The rate of interstitial carbon annealing is dependent on the distance from diode surface;
- Interstitial carbon and substitutional carbon-interstitial carbon complex have different ratios between minority (c_p) and majority (c_n) carrier capture cross sections.

- *First consider an evidence for the 1st assumption.*

We used high resistivity <100> and <111> n-type FZ Silicon was produced by Wacker Siltronic, Burghausen, Germany and the processing into detector structures was performed by ST Microelectronics, Catania, Italy. Simple p+-n-n+ structures with one guard ring were used. The material resistivity was determined from capacitance-voltage measurements was about 1 kΩ·cm for the first set and about 2 kΩ·cm for the second set.

Irradiation by electrons with an energy of 6 MeV was done using an accelerator at the Institute of Solid State and Semiconductor Physics, Minsk, Belarus. Irradiation fluence was $F=1\cdot10^{12}$ e/cm^2. The irradiated samples were subjected to isothermal annealing in the temperature range of 40-70 °C.

Annealing processes have been studied using capacitance deep level transient spectroscopy (DLTS) (Tmeas=77-325 K). The experimental equipment consisted of a capacitance meter, a 1MHz HF-generator, a DC source, a pulse generator and personal computers, which controlled the pulse generator and performed the data acquisition. If not mentioned otherwise, a rate window setting of 190 s^{-1} was used.

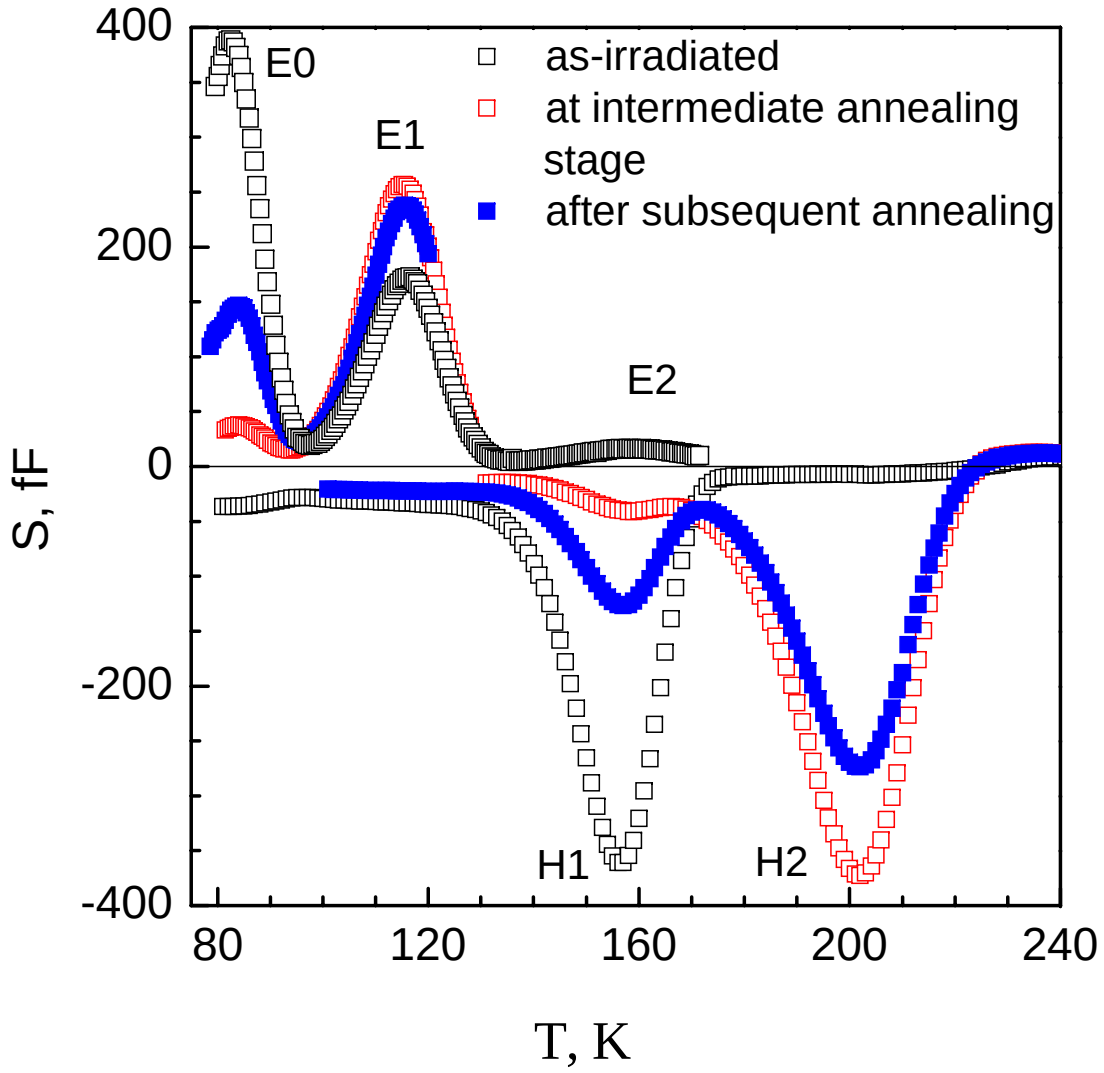

Fig. 1. DLTS spectra obtained immediately after irradiation with 6 MeV electrons and subsequent annealing first at 60° C and, second at 40° C . The crystal orientation is <100>. ρ=2 kΩ·cm.

C_i: $E(-/0)=E_c - 0.12$ eV (E0),

$E(0/+)=E_v + 0.28$ eV (H1);

C_iO_i: $E(0/+)=E_v + 0.36$ eV (H2);

C_iC_s: $E(-/0)=E_c - 0.17$ eV (E1b),

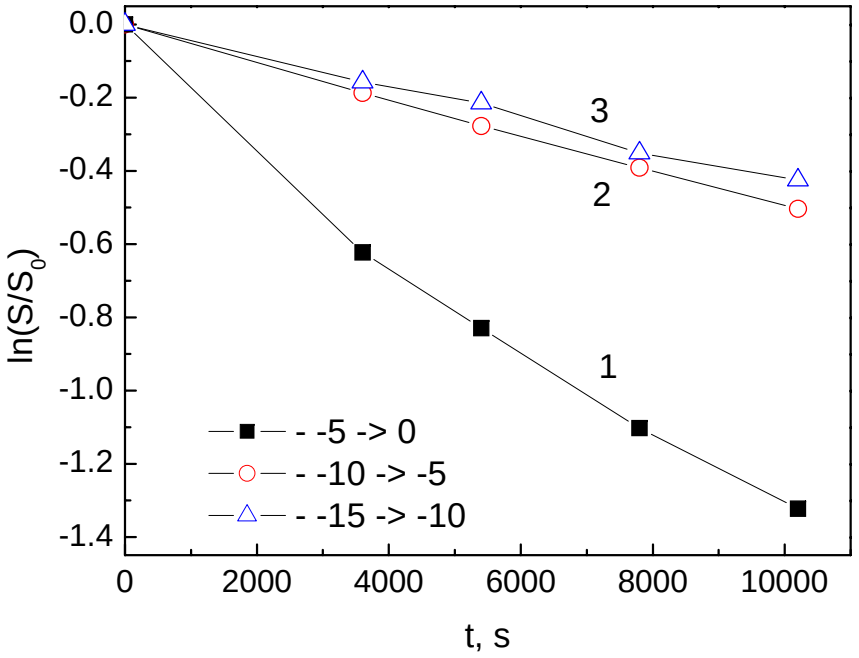

Fig.2. Annealing kinetics of E0 ($C_i^{(-/0)}$) peak in STFZ detector DLTS signal was measured at different bias voltages -5 V and -10 V for <100> diode. Filling pulse amplitude was 5 V. Annealing temperature was 60 °C.

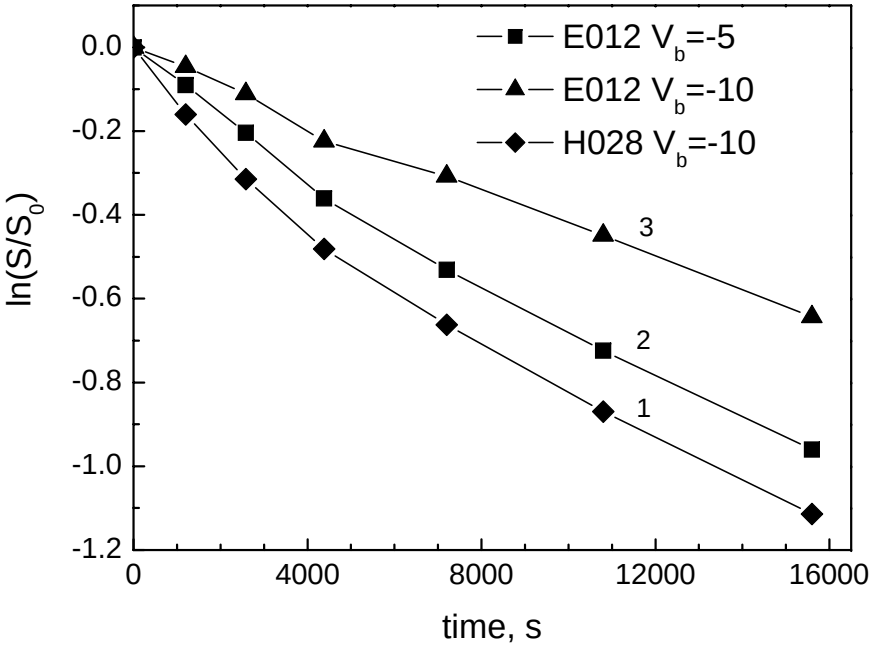

Fig.3. Annealing kinetics of H1 ($C_i^{(0/+)}$) (1,4) and E0 ($C_i^{(-/0)}$) (2,3,5,6,) peaks in STFZ detector DLTS signal was measured at different bias voltages -5 V (2,5) and -10 V (1,3,4,6) for <111> diode. Filling pulse amplitude was 5 V. Annealing temperature was 60 °C.

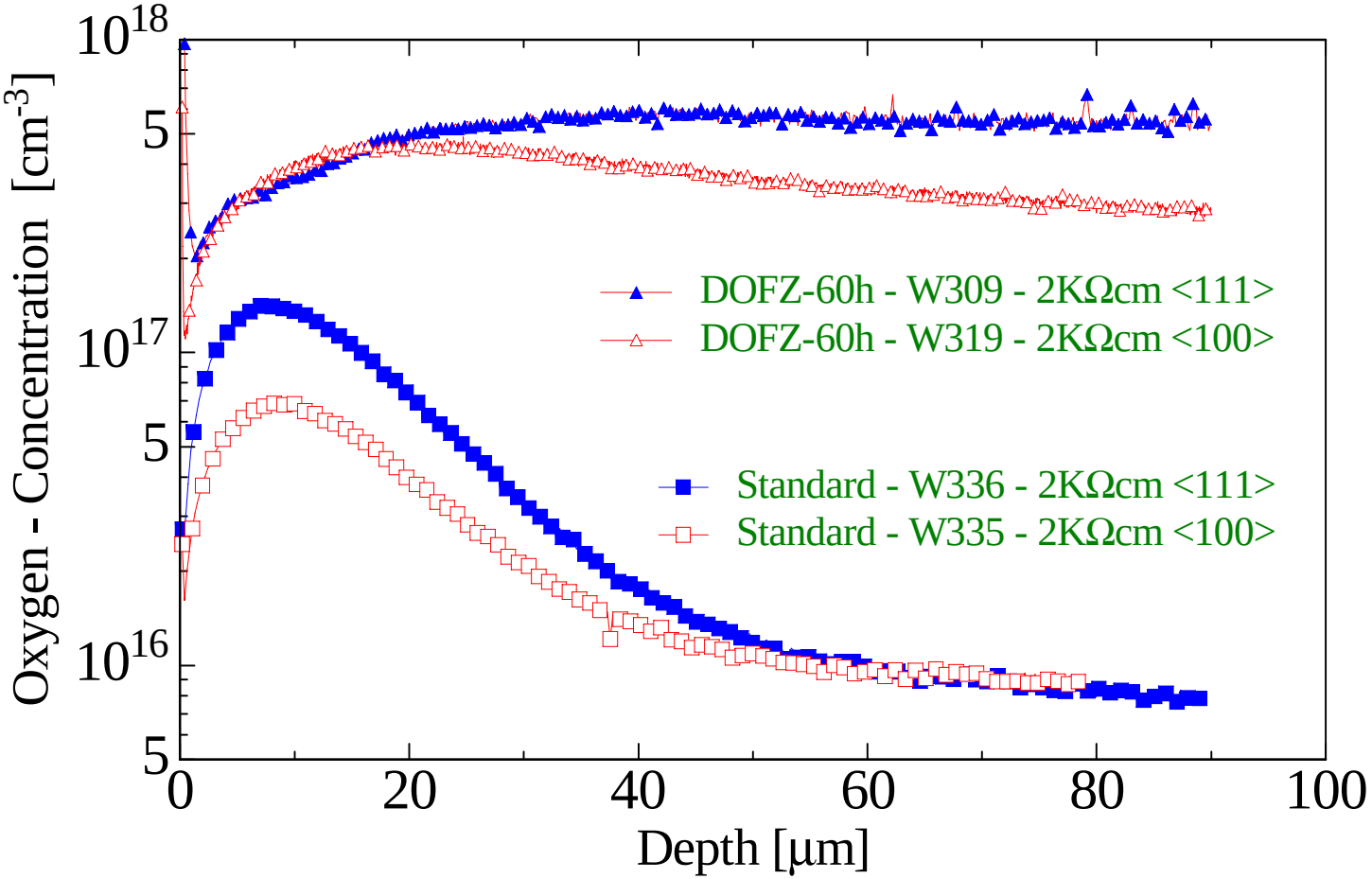

Fig.7. Oxygen profile in Si detectors measured by SIMS.

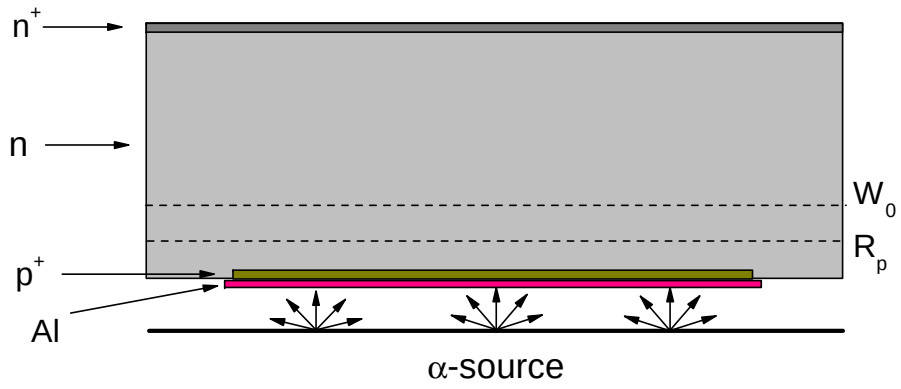

Fig.5. The penetration depth of α-particles with the energy of slightly above 5 MeV into silicon is 20-25 μm which is less than the width of depletion region (about 30 μm for $n=10^{12}$ cm^{-3}).

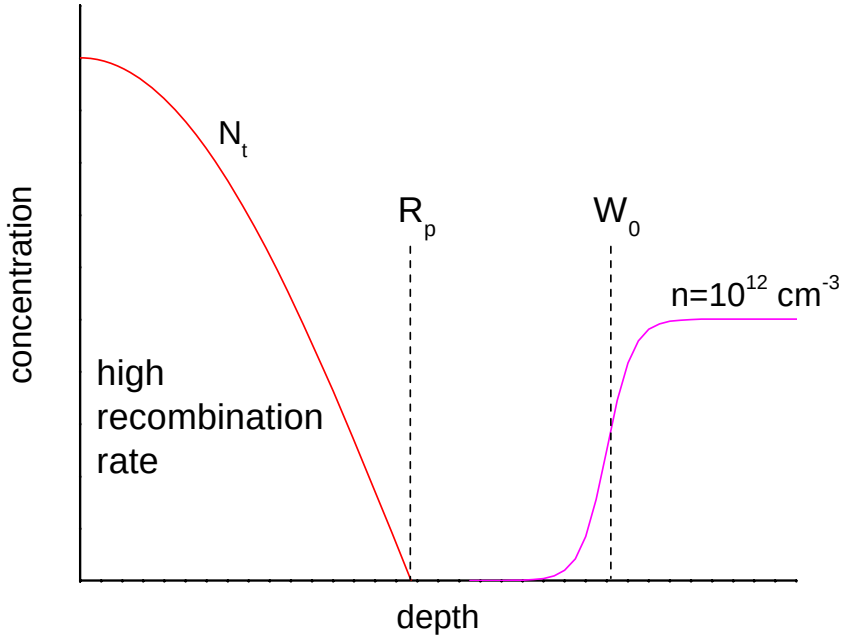

Fig.6. When a surface source of α-particles is used, we have the inhomogeneous depth distribution of radiation damage with a more damaged region near the surface of the structures.

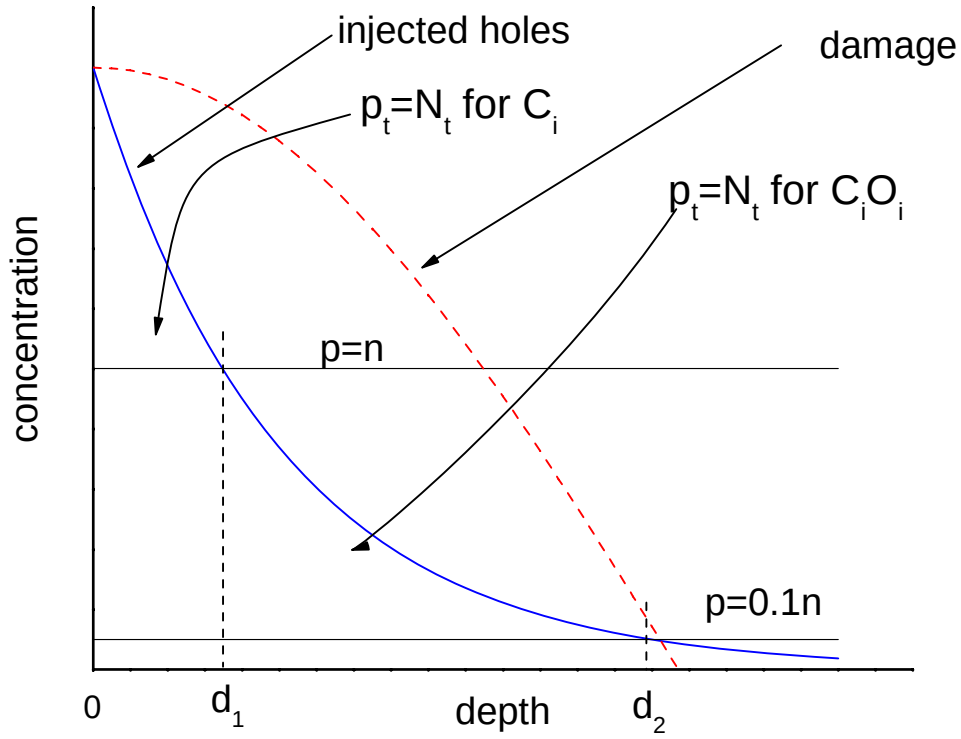

Fig.7. Schematic draw of minority carrier distribution in α-irradiated detector during injection pulse.

H1 trap will be filled by holes at depth less than d_1.

H2 trap will be filled by holes at depth less than d_2.

The damage causes a very strong drop of minority carrier lifetime in the near surface region.

However another explanation of the delayed appearance of C_iO_i complex is also possible. It is related to the formation of C_iO_i precursor ($C_iO_i^*$). The existence of the this complex has been evidenced both by IR measurement. As it has been shown in earlier not all C_i atoms form directly C_iO_i complex. A fraction of C_i is kept in the form C_iO_i* complex which only afterwards transforms to stable CiOi configuration.

Energy level of C_iO_i* is about E_v+0.34 eV which is only about 0.02 eV less than energy level of C_iO_i. However it is enough to distinguish these defects from each other. There are no evidence of the formation of C_iO_i* in n-Si obtained by DLTS. It was observed only p-type diodes. But the data of IR absorption experiments do not allow to exclude possible formation of C_iO_i* in n-type Si also.

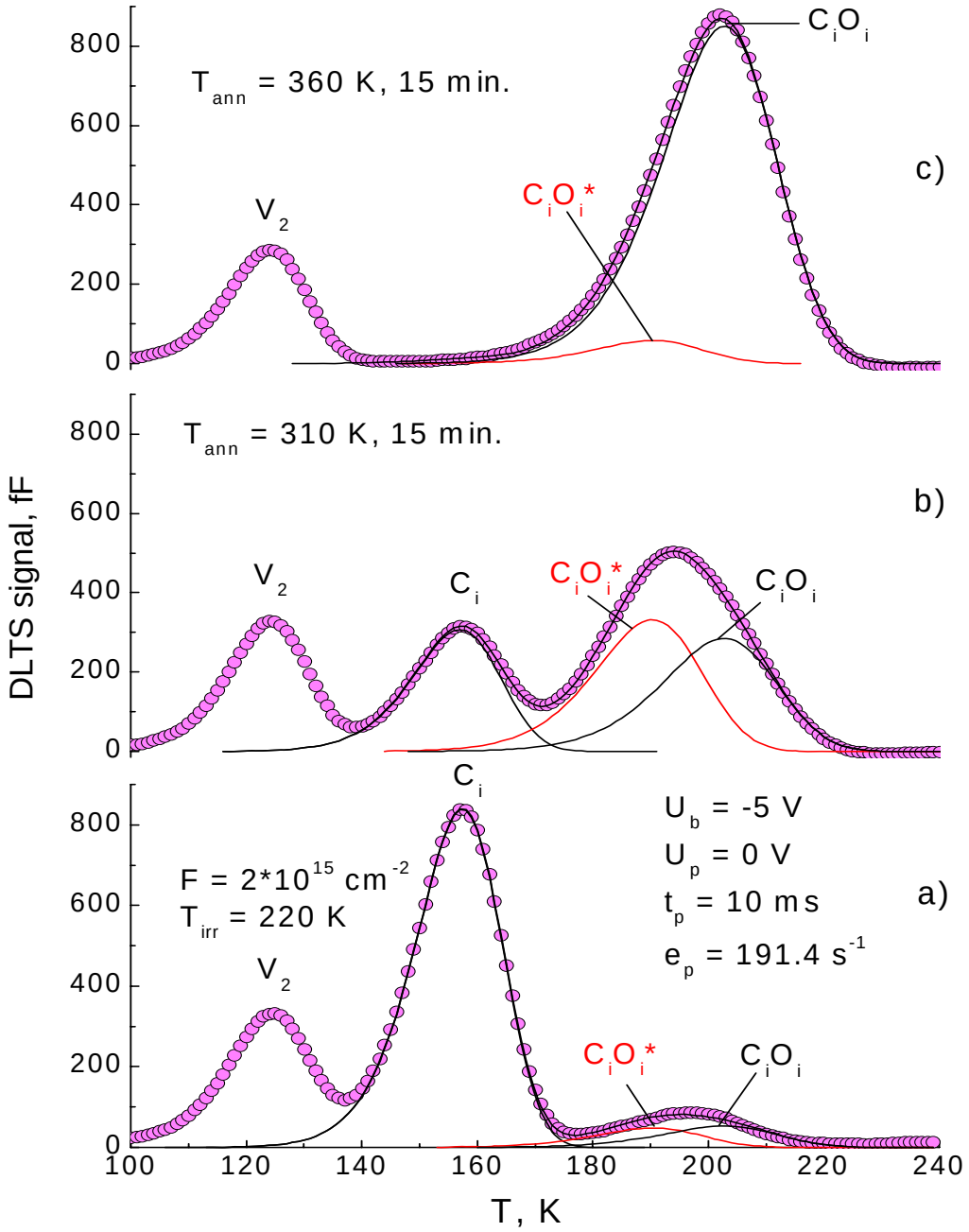

Fig. 8. Evolution of the DLTS spectra for a p-type Si (ρ=18 Ohm·cm) upon isochronal annealing. The spectra were measured after irradiation with 3.5 MeV electrons for a dose of $2 \cdot 10^{15}$ cm^{-2} at about 220 K (a), after 15 min anneals at 310 K (b) and 360 K (c). The solid lines are fitting curves obtained by a least-square procedure.

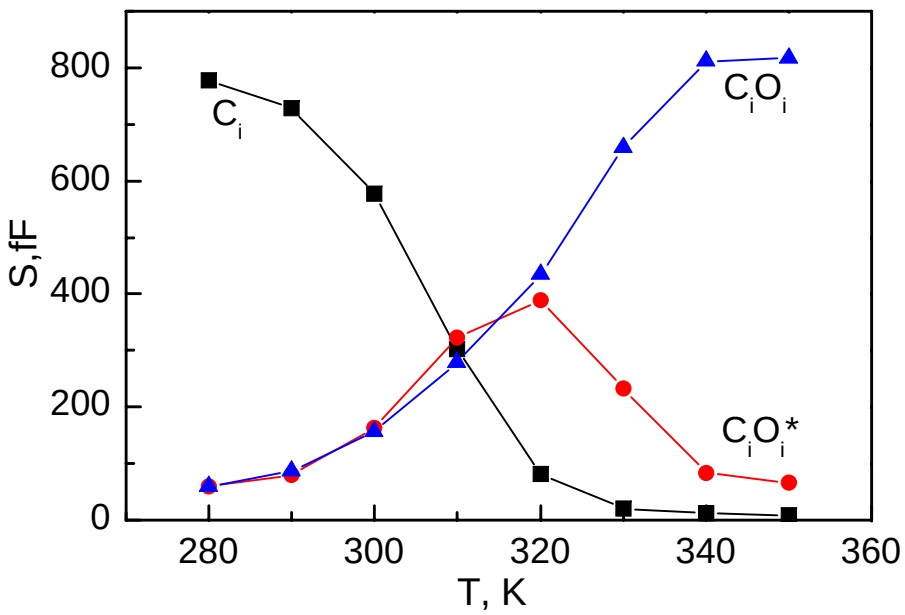

Fig. 9. Isochronal annealing behavior of the C_i, C_iO_i* and C_iO_i defects.

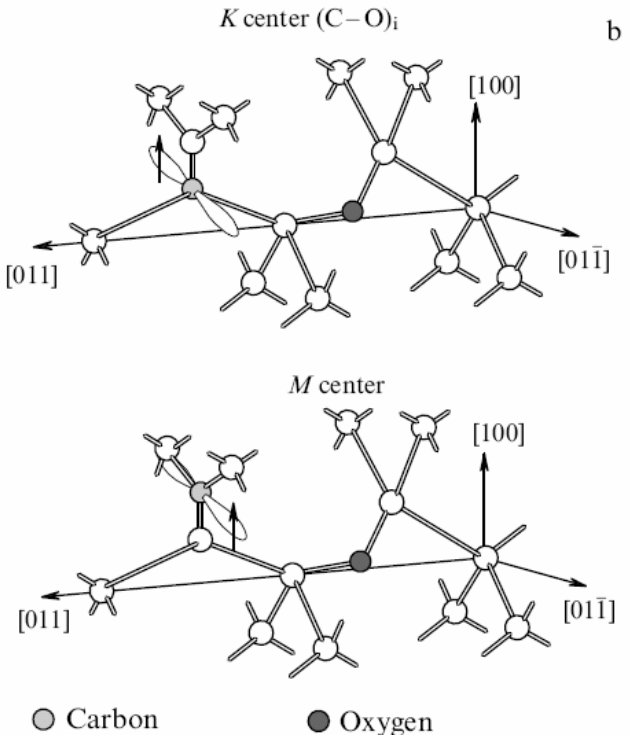

Fig. 10. Models of K center [Trombetta, Watkins 1987] and M-center [Mukashev et al., 2000].

Conclusions

- It has been shown that the rate of interstitial carbon annealing in detectors made of high resistivity silicon depends on the distance from the diode surface. This is first of all caused by inhomogeneous depth distribution of oxygen in fully processed detectors.

- This fact can strongly influence on the interpretation of experimental data obtained with the DLTS method.

- Interstitial carbon reactions can be used to monitor background impurity content and their depth distribution in fully processed detector structures