INTERACTION OF RESIDUAL HYDROGEN WITH RADIATION DEFECTS IN SILICON PARTICLE DETECTORS

L.F. Makarenko, F.P. Korshunov**, S.B. Lastovski**, N.M. Kazuchits*, M.S. Rusetsky*,*

*E. Fretwurst***, G. Lindström***, M. Moll****, I. Pintilie*****, N.I. Zamiatin*******

** Belarusian State University, Minsk, Belarus*

***Institute of Solid State and Semiconductor Physics, Minsk, Belarus*

****Hamburg University, Hamburg, Germany*

*****CERN, Geneva, Switzerland*

******National Institute of Materials Physics, Bucharest-Magurele, Romania*

*******Joint Institute for Nuclear Research, Dubna, Russia*

1. Introduction

It is well-known that hydrogen can easily penetrate into silicon crystals at various stages of p-n structures manufacturing. Therefore possibly all silicon particle detectors contain hydrogen which remained in these structures after fabrication. There are some indications on interaction of residual hydrogen with defects in irradiated Si detectors. It is expected that the increase of hydrogen content will lead to the increase of radiation tolerance of devices. It may be due to, first, hydrogen passivation of radiation defects, and, second, acceleration of oxygen diffusion by promoting the formation of oxygen dimer O_2.

Both high mobility and reaction ability of hydrogen result in its redistribution during subsequent technological processes occurring even at rather low temperatures 200-400 °C. Therefore one expects that concentration of hydrogen in various areas of detectors will depend substantially on sequence of technological operations of their manufacturing and now there is not enough information on hydrogen in ready detector structures. It is the aim of this work to get experimental data on hydrogen content and distribution in p^+-n-n^+ structures made of detector grade silicon and influence of hydrogen on elimination of electrically-active radiation defects.

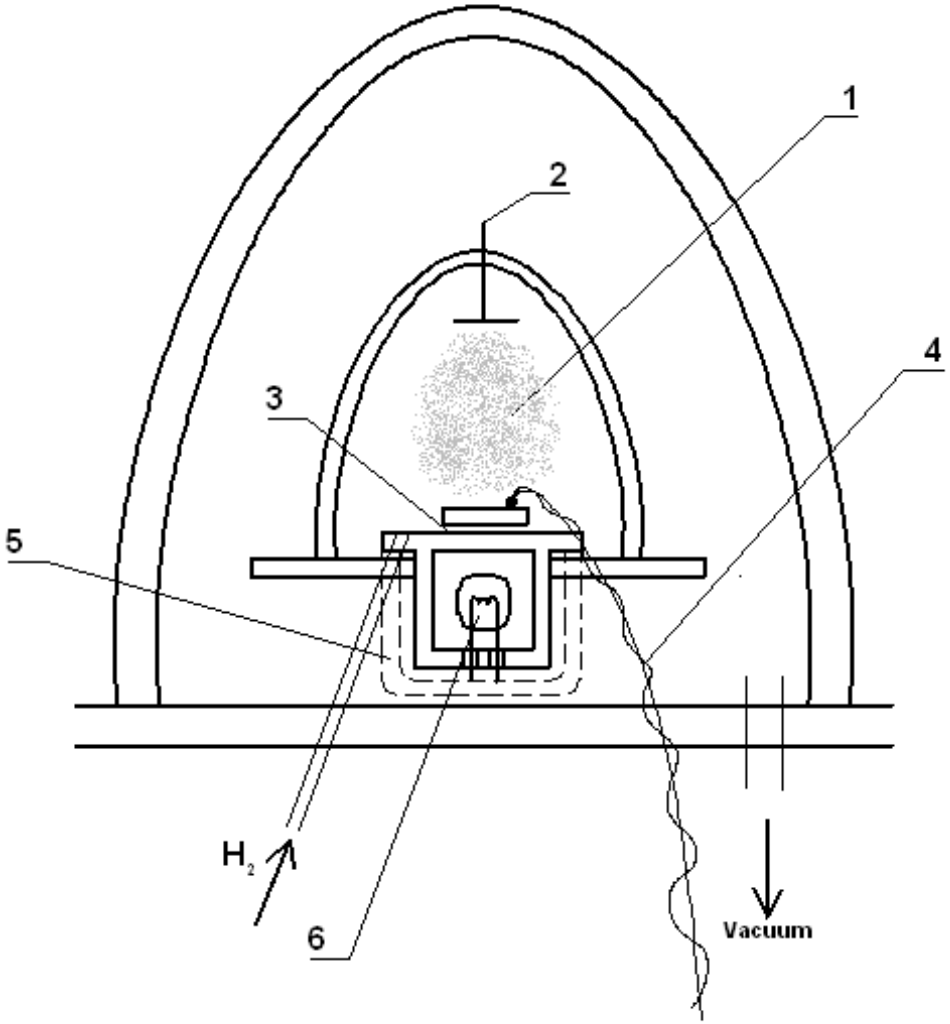
2. Experimental

Detector structures were manufactured from standard n-type Wacker Si by the following producers: 1) CiS Institute for Microsensors, Erfurt, Germany (CA-diodes); 2) ST Microelectronics, Catania, Italy (W336-diodes); 3) ELMA, Zelenograd, Russia (Z-diodes). Simple p^+-n-n^+ structures with a guard rings were employed. The Z diodes were prepared are by the same technology as for the CMS preshower sensors.

Table 1. Parameters of samples used for experiments

Device acronym	Thickness, μm	Starting resistivity, KΩ·cm	Orientation	Rear contact
CA	285	4	<111>	grid
W336	290	2	<111>	grid
Z	330	4	<111>	block

Hydrogenation was performed using treatment in hydrogen plasma at T=300 °C during 0.5-4 hours. Glow discharge plasma of hydrogen was created using a discharge chamber of the standard facility for the ionic etching . The discharge dc voltage was 500 V. The density of the plasma current was 3-5 $\mu A/cm^2$ that corresponded to density of ion current about 2×10^{12} $cm^{-2}\cdot s^{-1}$. Samples were arranged on a surface of a heater located in the discharge chamber. The control of temperature was carried out with the help of the thermocouple which was in contact to a control sample of the same thickness.



1 – H^+ plasma

2 – anode

3 – sample

4 – thermocouple

5 – heat shield

6 – heater in a bulb

Irradiation with electrons (E=3.5 or 6 MeV) was done using accelerators at the Institute of Solid State and Semiconductor Physics (Minsk). The irradiated samples were subjected to 30 min isochronal annealing in the temperature range 50-350 °C with temperature increments of 50 °C.

Defect reactions have been studied using capacitance deep level transient spectroscopy (DLTS) (T_{meas}=77-325 K) and high frequency capacitance-voltage (C-V) measurements at room temperature. The experimental equipment consisted of a capacitance meter, a HF-generator (1 MHz), a DC source and a pulse generator, and personal computers, which controlled the pulse generator and performed the data acquisition. Possible variations of the reverse bias and the rate window are up to 19 V and the rate window 4-19000 s^{-1}, respectively. Normally both the reverse bias and the pulse voltage were 5 V, and the rate window setting was 190 s^{-1}.

Capacitance-voltage measurements are carried out with a digital capacitance bridge. The capacitance has been measured at different reverse bias values by superimposing an ac voltage on the dc voltage. The reverse bias is typically varied in the range V_R = 0-150 V in steps of 0.045-0:135 V. The amplitude and the frequency of the ac voltage were 25 mV and 1 MHz, respectively. The measurements are controlled by home-developed Pascal program with custom made instrument interface.

Table 1. Parameters of dominant peaks

Peak number	T_{max}, K (at e_n=190 s^{-1})	A, $s^{-1}K^{-2}$	σ_A, cm^2	E_A, eV	Peak origin
E1	94	$3.9\ 10^{7}$	$6\ 10^{-15}$	0.174	VO+CiCs
E2	133	$1.9\ 10^{7}$	$3.1\ 10^{-15}$	0.246	$VV^{=}$
E3	~192	$1.3\ 10^{7}$	$2\ 10^{-15}$(?)	0.358(?)	Stable up 100-150 °C
E4a	230	$7.5\ 10^{6}$	$1.1\ 10^{-15}$	0.423	VV^{-}
E5	174	$9.6\ 10^{6}$	$1.5\ 10^{-15}$	0.314	VOH
E6	111	$1.9\ 10^{5}$	$2.9\ 10^{-17}$	0.163	
E7	146	$8.2\ 10^{5}$	$1.2\ 10^{-16}$(?)	0.238(?)	?
E8	198	$5.9\ 10^{6}$	$0.9\ 10^{-15}$	0.356	?
E9	186	$9.1\ 10^{4}$	$1.4\ 10^{-17}$(?)	0.269(?)	
E10	276	$3.8\ 10^{5}$	$6.1\ 10^{-17}$(?)	0.51(?)	

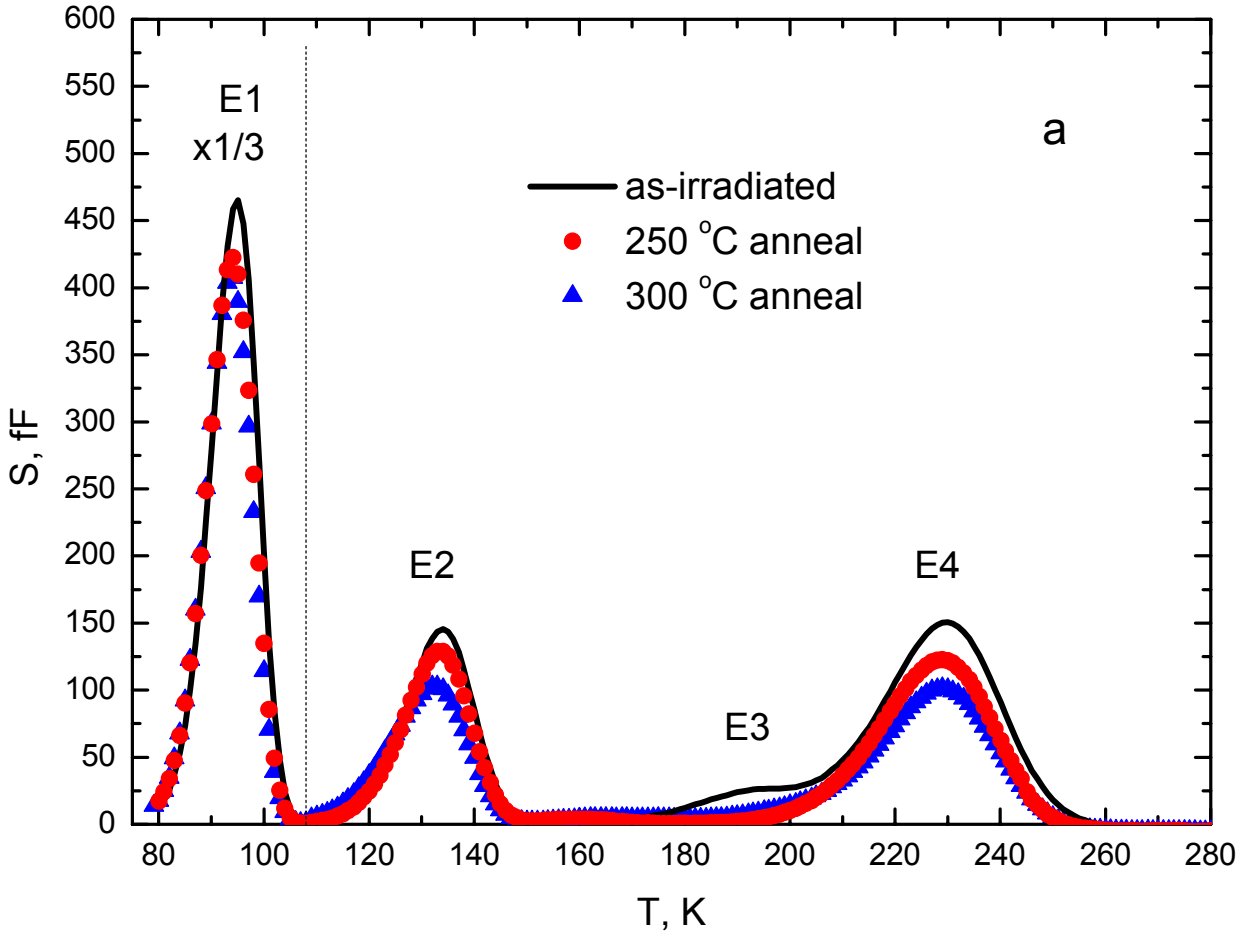


Fig.1a. Development of DLTS spectra for standard FZ diodes (CA-sample) after electron irradiation at room temperature and upon 30-min isochronal annealing with temperature increments of 50 °C. Dose of irradiation was 2×10^{12} cm^{-2} (E_e=3.5 MeV). Measurement settings were
$e_n = 190\ s^{-1}$,
bias $-5 \rightarrow 0$ V, and
pulse duration =10 ms.

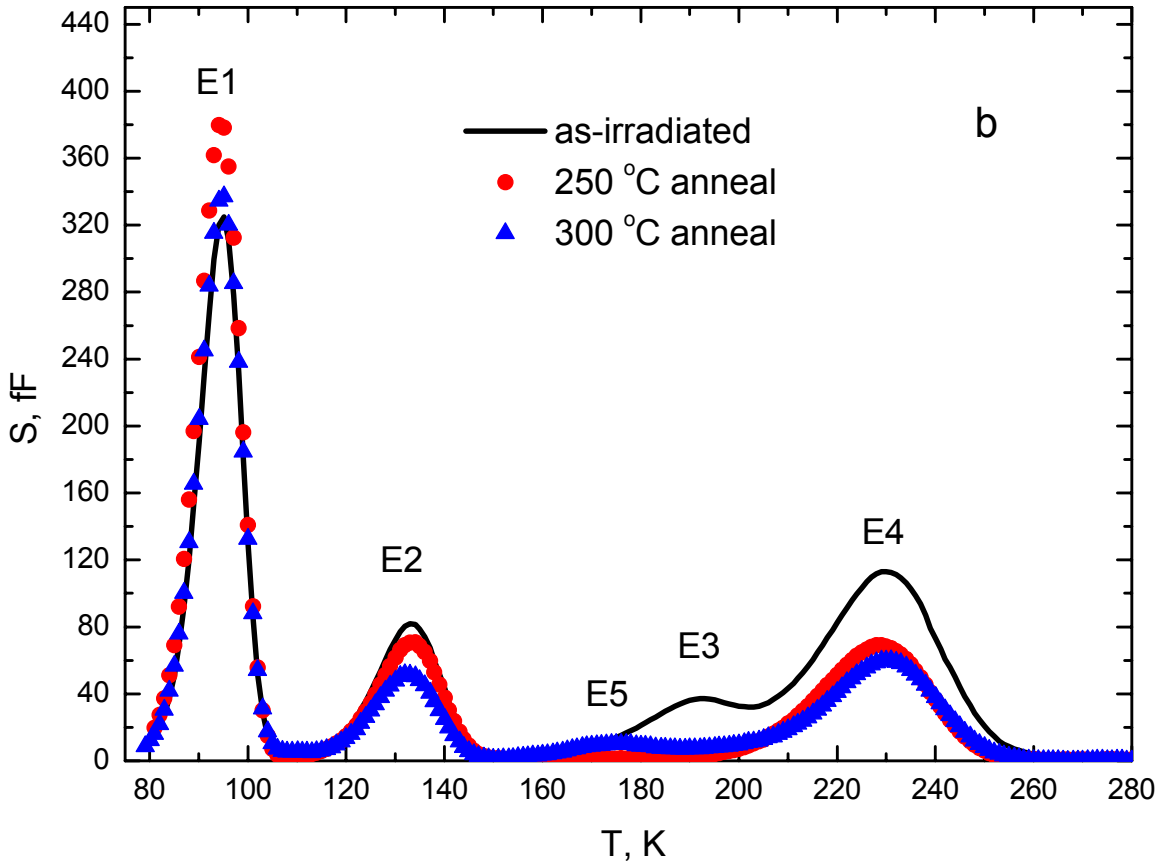


Fig.1b. Development of DLTS spectra for standard FZ diodes (W-sample) after electron irradiation at room temperature and upon 30-min isochronal annealing with temperature increments of 50 °C. Dose of irradiation was 2×10^{12} cm^{-2} (E_e=6 MeV). Measurement settings were
$e_n = 190\ s^{-1}$,
bias $-5 \rightarrow 0$ V, and
pulse duration =10 ms

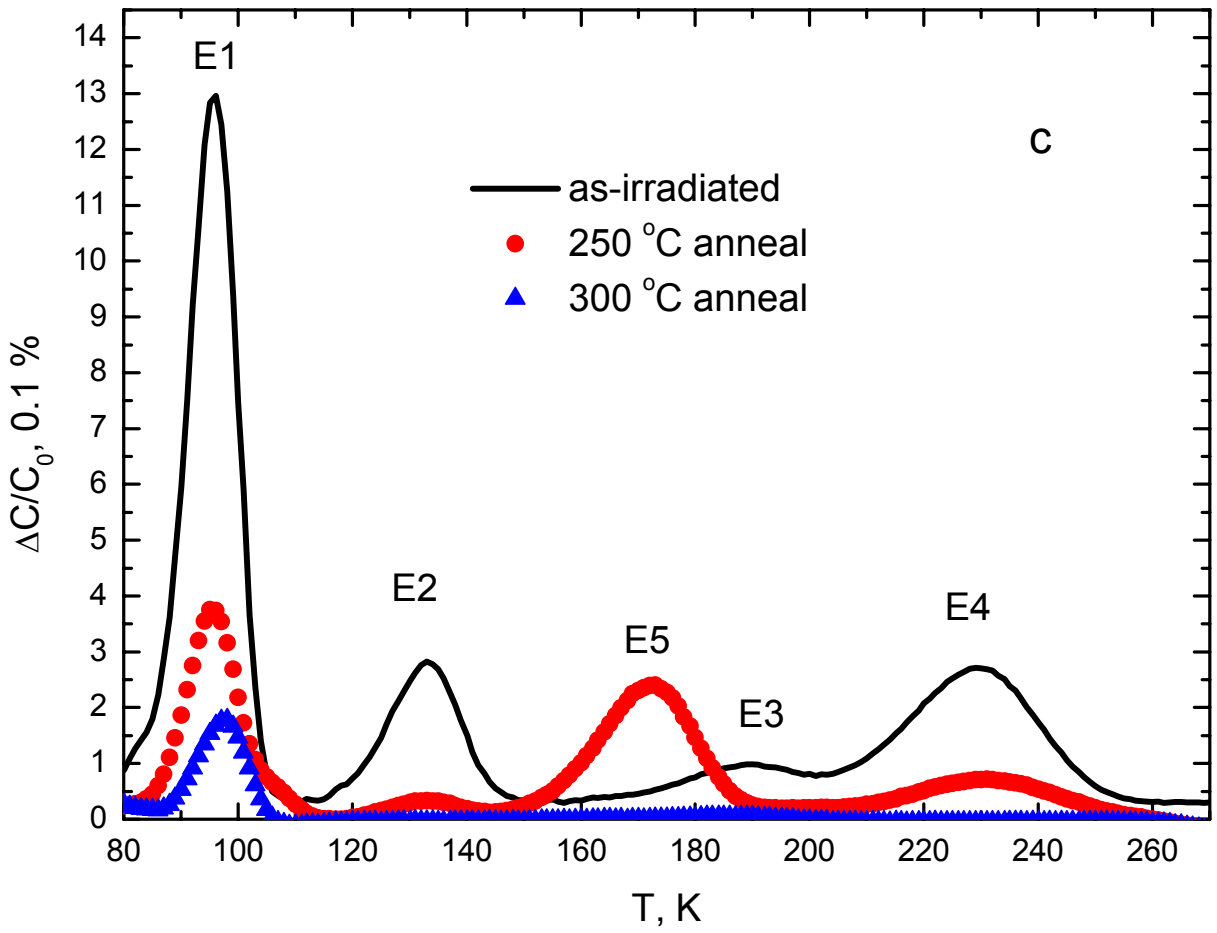


Fig.1c. Development of DLTS spectra for standard FZ diodes (ZA-sample) after electron irradiation at room temperature and upon 30-min isochronal annealing with temperature increments of 50 °C. Dose of irradiation was 1×10^{12} cm^{-2} (E_e=6 MeV). Measurement settings were

$e_n = 190\ s^{-1}$,

bias $-5 \rightarrow 0$ V, and

pulse duration =10 ms

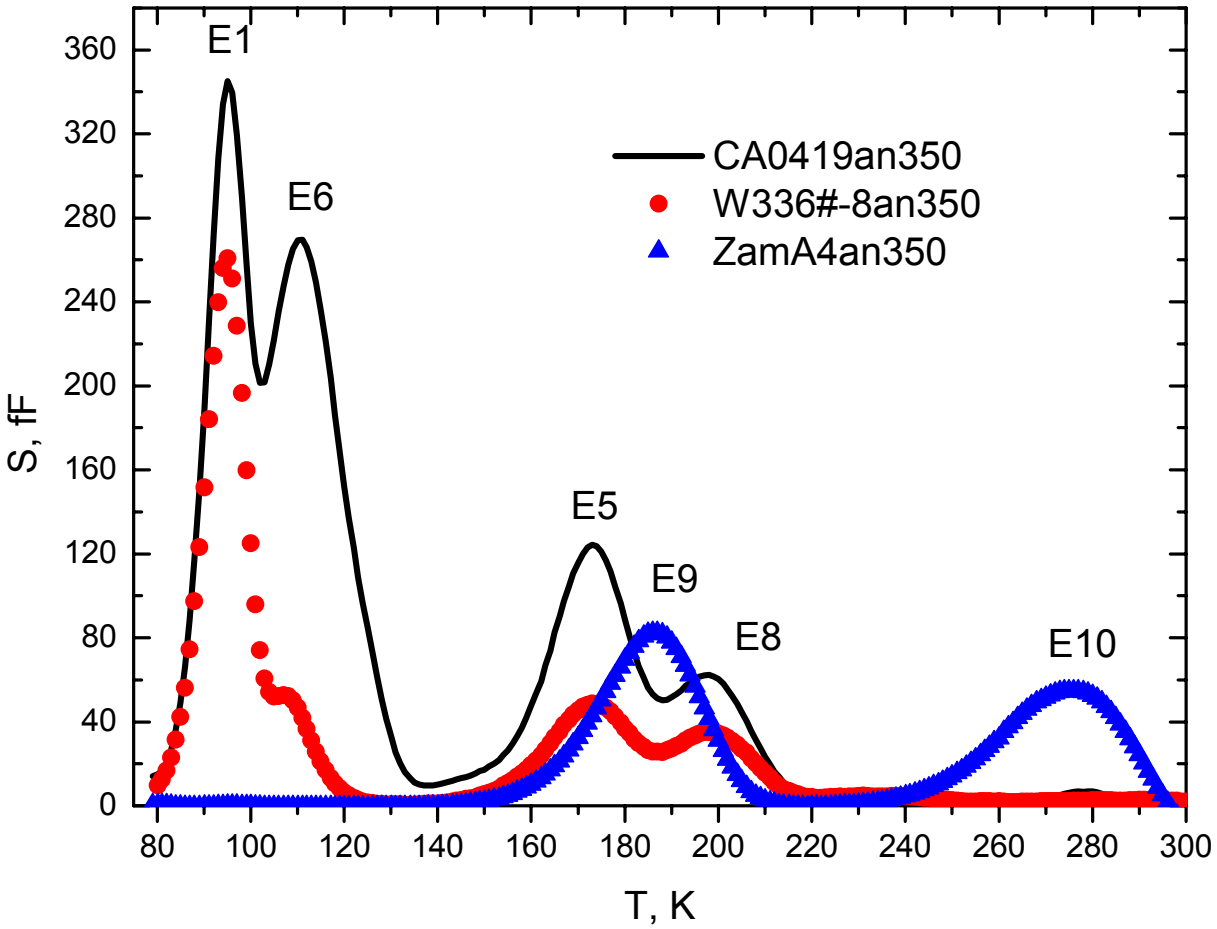


Fig. 2. DLTS spectra for different diodes made of standard FZ silicon after isochronal annealing at temperature 350 °C during 30 min. Measurement settings were $e_n = 190\ s^{-1}$, bias $-5 \rightarrow 0$ V, and pulse duration (t_p) - 10 ms

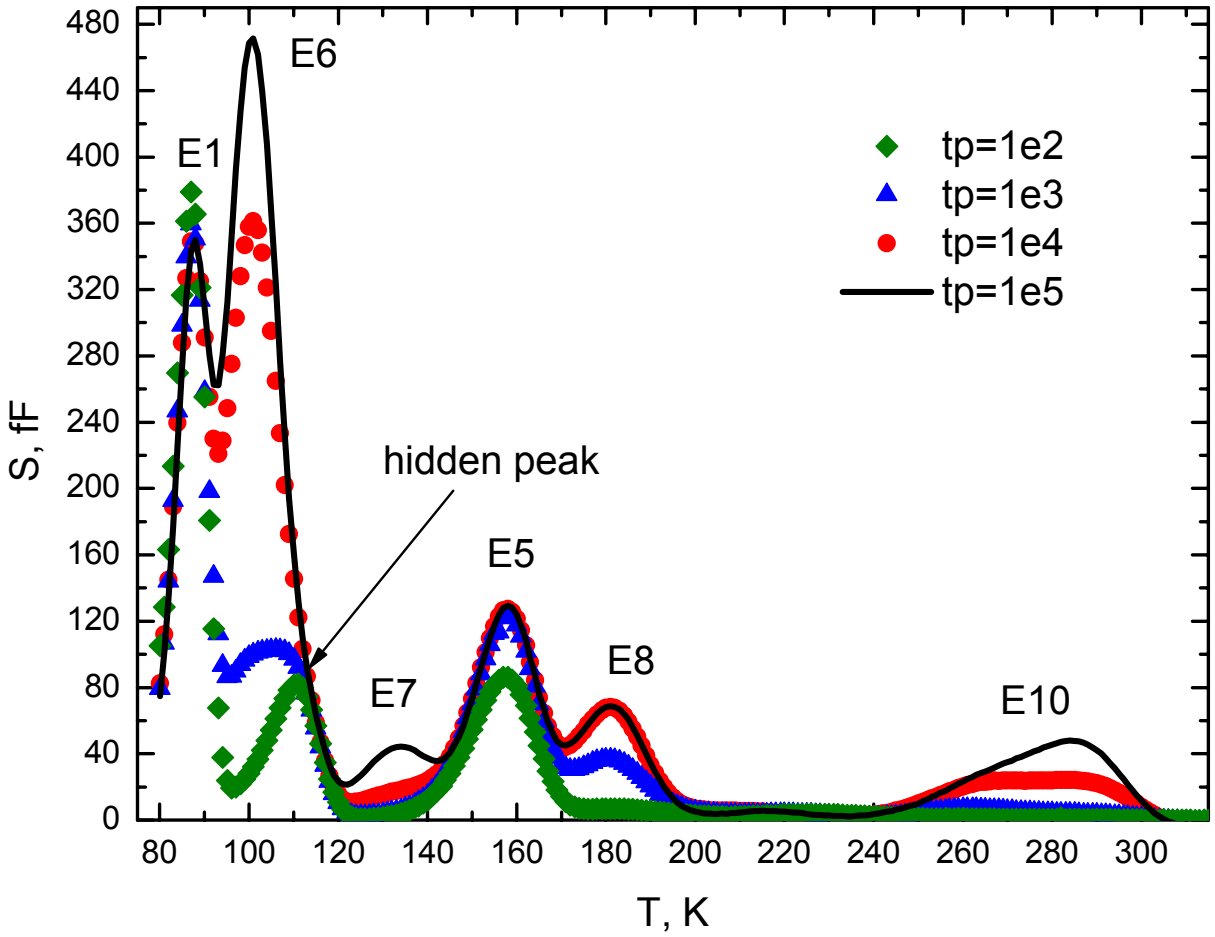


Fig.3. DLTS spectra for standard FZ diode (CA-sample) after isochronal annealing at temperature 350 °C. Measurement settings were e_n = 19 s^{-1}, bias –5 → 0 V, and pulse duration (tp): 0.1 ms, 1 ms, 10 ms, 100 ms.

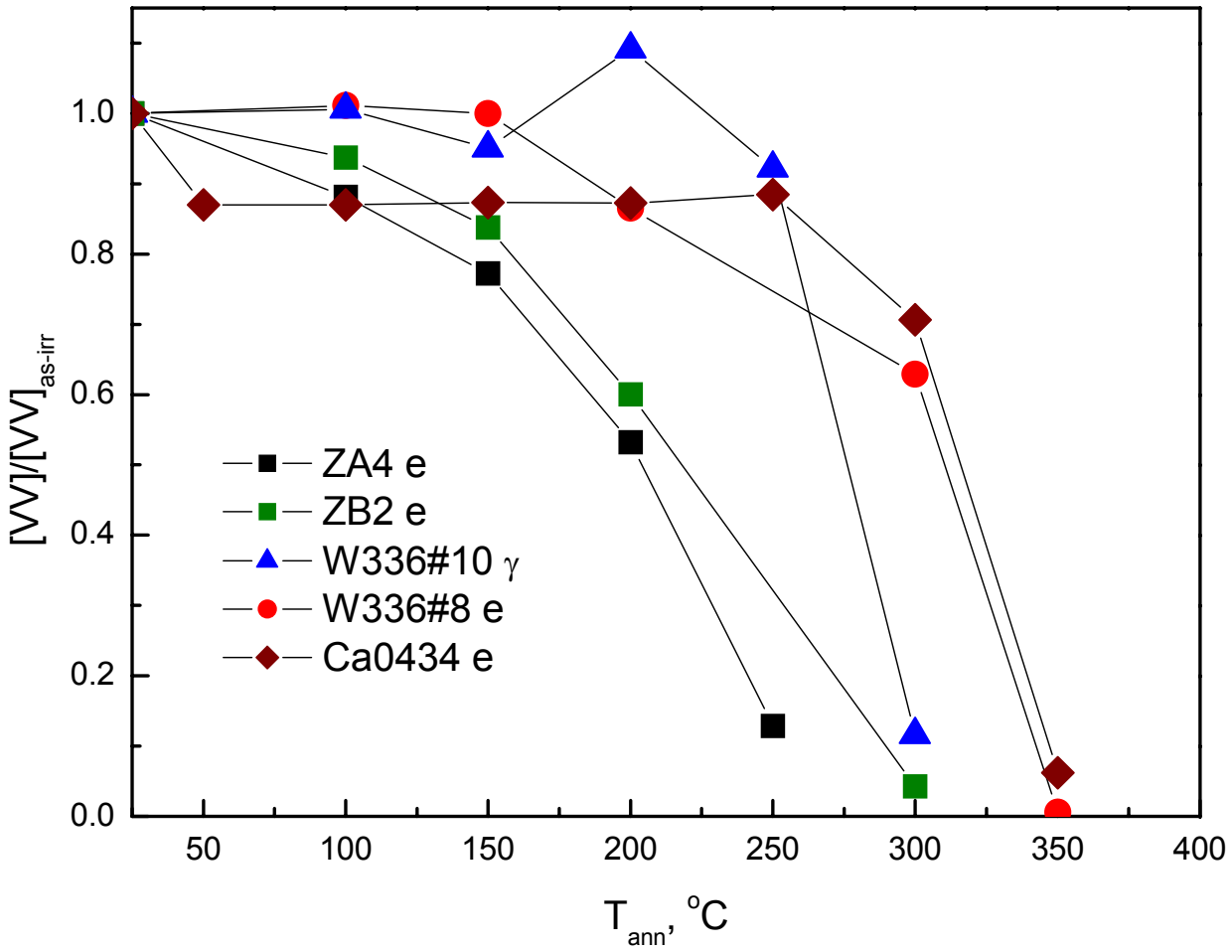


Fig.4. Annealing behavior of divacancy (trap E2) in different diodes irradiated with electrons or gamma-rays (W336 diodes).

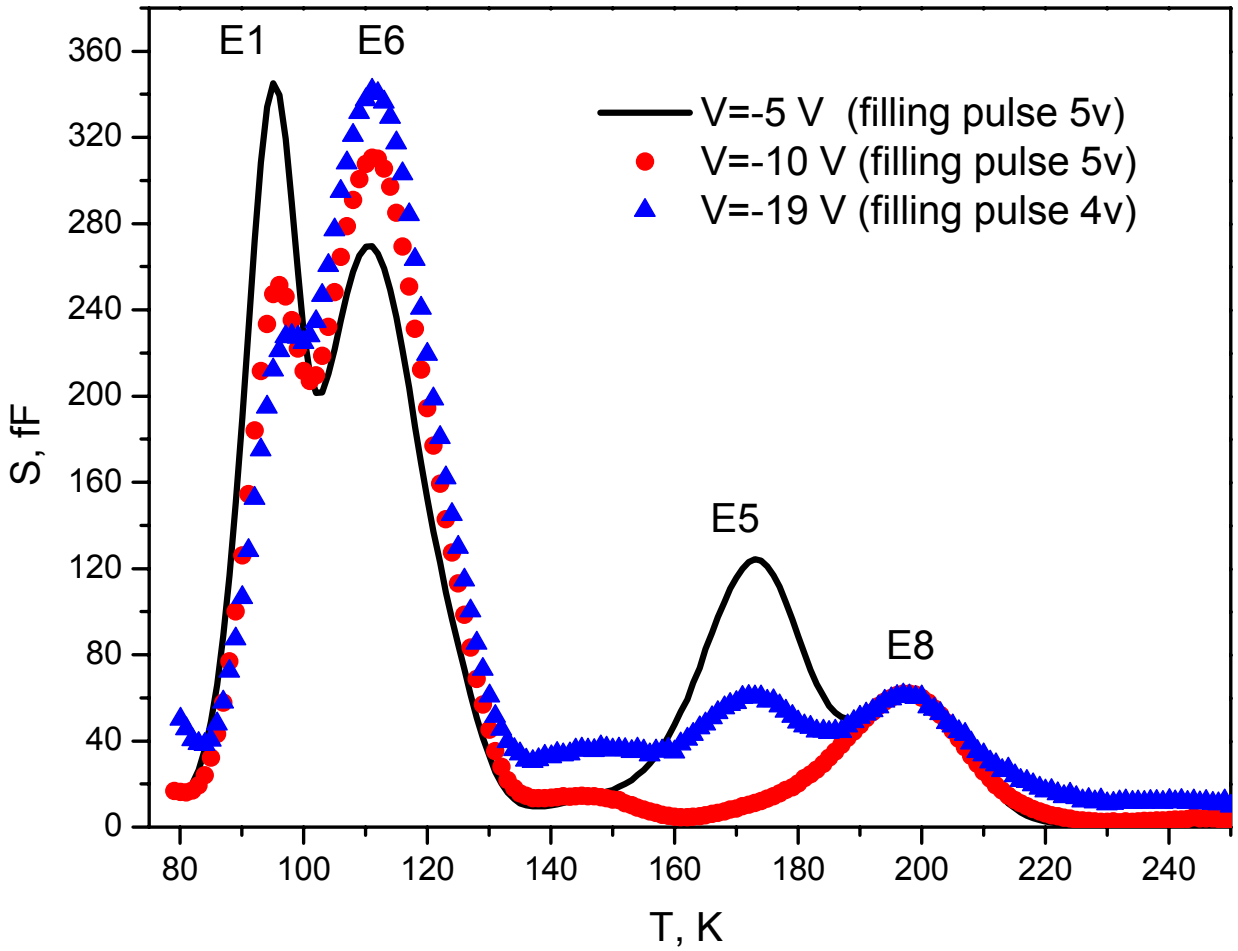


Fig.5. DLTS spectra for standard FZ diode (CA-sample) after irradiation with 3.5 MeV electrons at room temperature and upon 30-min annealing at 350 °C.. Dose of irradiation was 3×10^{12} cm^{-2}. Measurement settings were: rate window of 190 s^{-1}, pulse duration of 10 ms, bias: a) -5 → 0 V, b) −10→ −5 V and c) −19→ −15 V. The peak amplitudes are normalized assuming constant concentration of E8 trap.

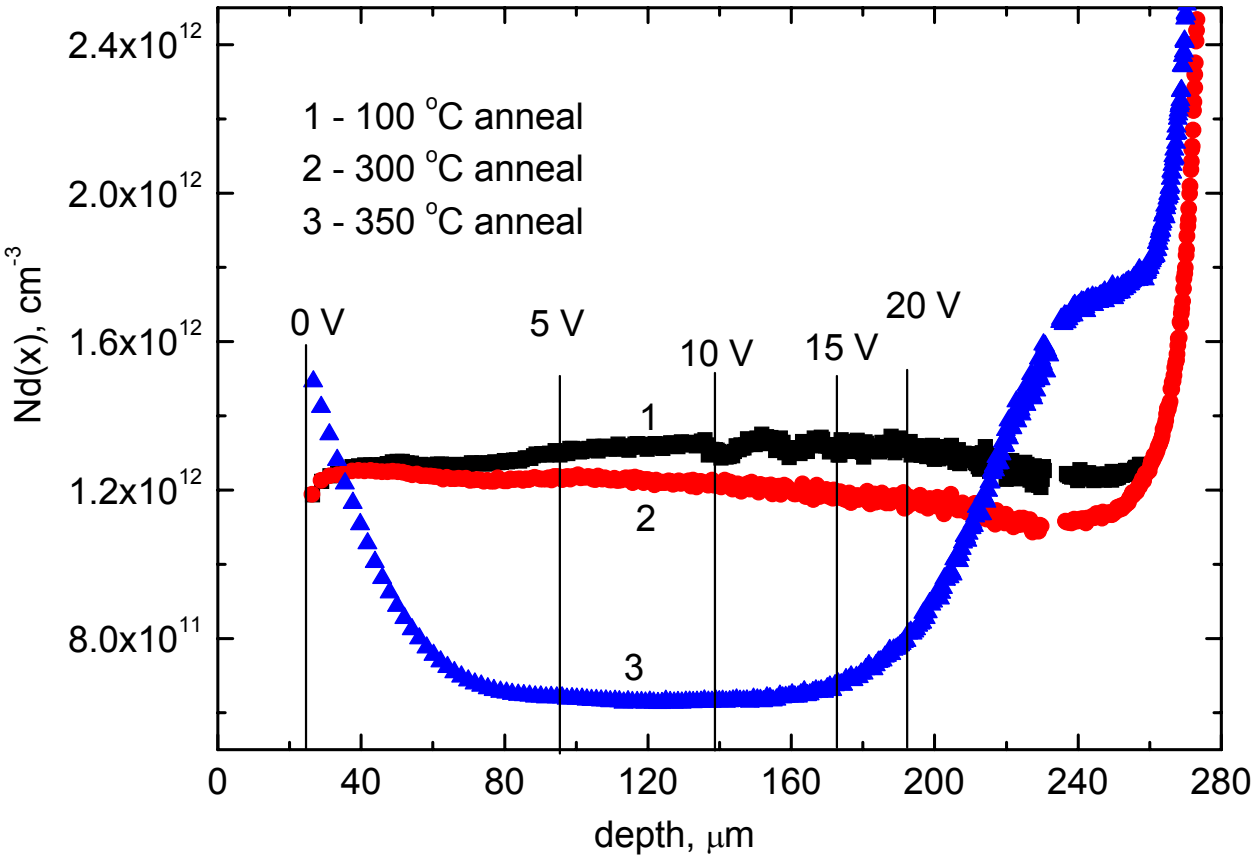


Fig 6. Carrier depth profile for a CA sample determined from C-V characteristics.

Vertical lines mark inverse voltage which is necessary to obtain corresponded width of depletion region.

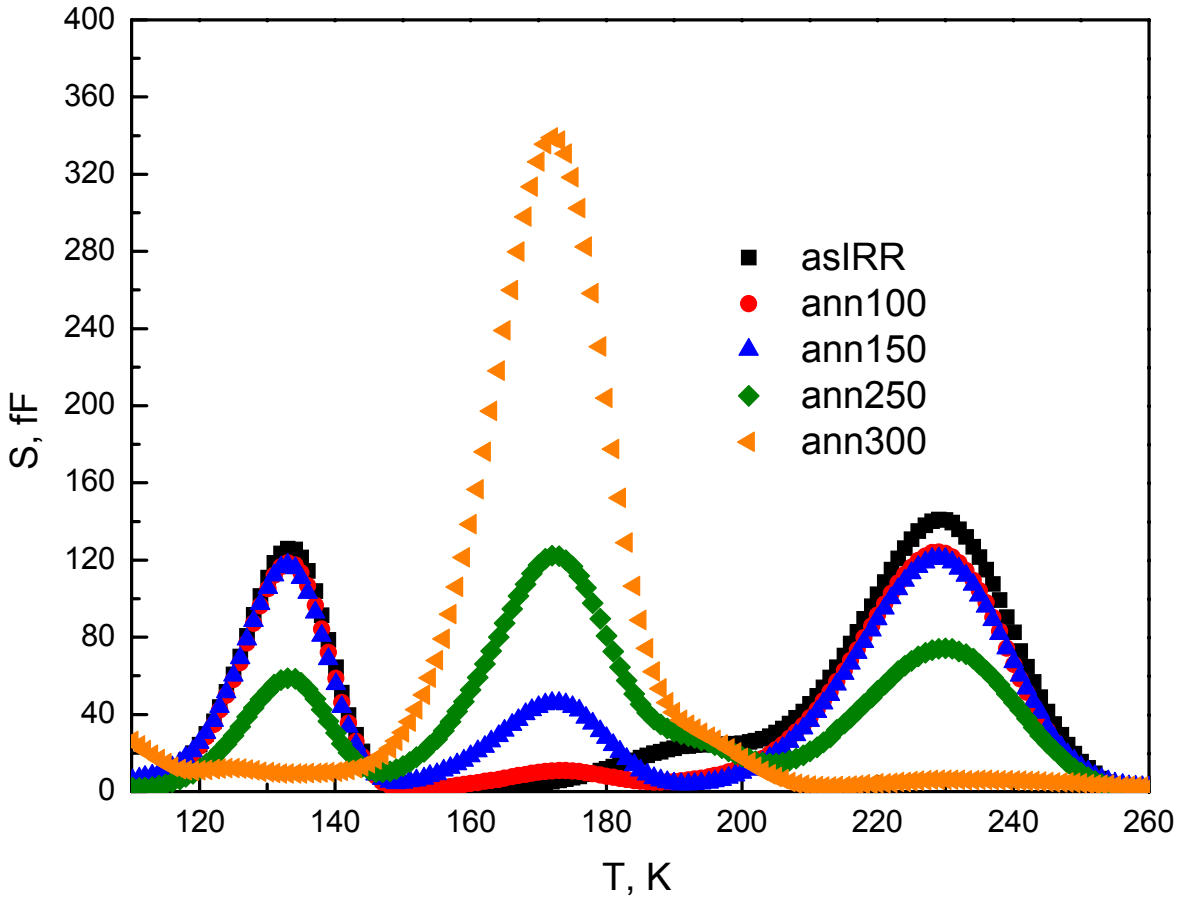


Fig. 7. Development of DLTS spectra for hydrogenated standard FZ diode(CA-sample) after irradiation with 3.5 MeV electrons at room temperature and upon 30-min isochronal annealing with temperature increments of 50 °C. Dose of irradiation was 3×10^{12} cm^{-2}. Measurement settings were e_n = 190 s^{-1}, bias –5 → -0 V, and pulse duration 10 ms.

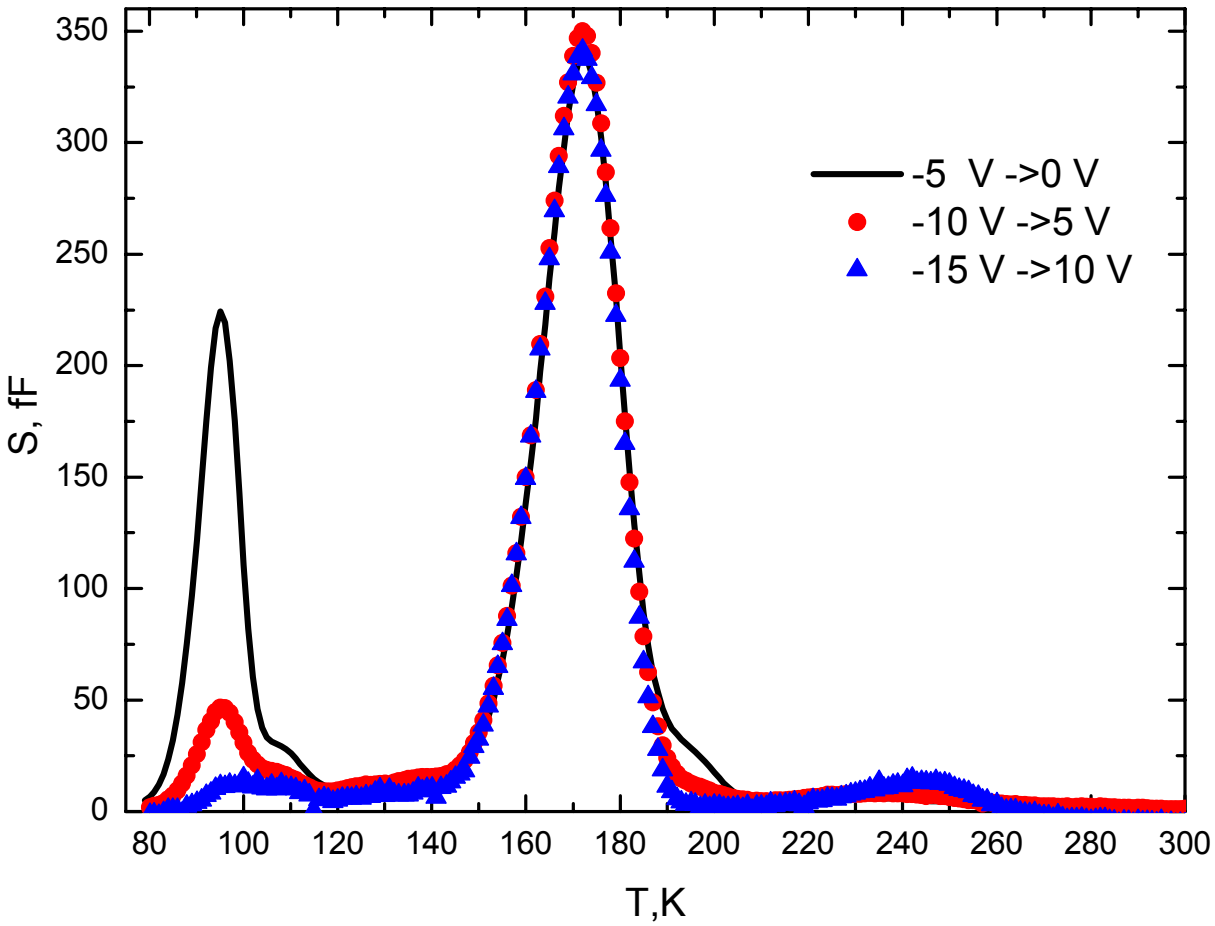


Fig.8. DLTS spectra for hydrogenated standard FZ diode(CA-sample) after irradiation with 3.5 MeV electrons at room temperature and upon 30-min annealing at 300 °C. Dose of irradiation was 3×10^{12} cm^{-2}. Measurement settings were e_n = 190 s^{-1}, pulse duration 10 ms bias: a) -5 → 0 V, b) −10→ −5 V, b) −15→ −10 V. All spectra normalized the E5 peak (VOH) amplitude.

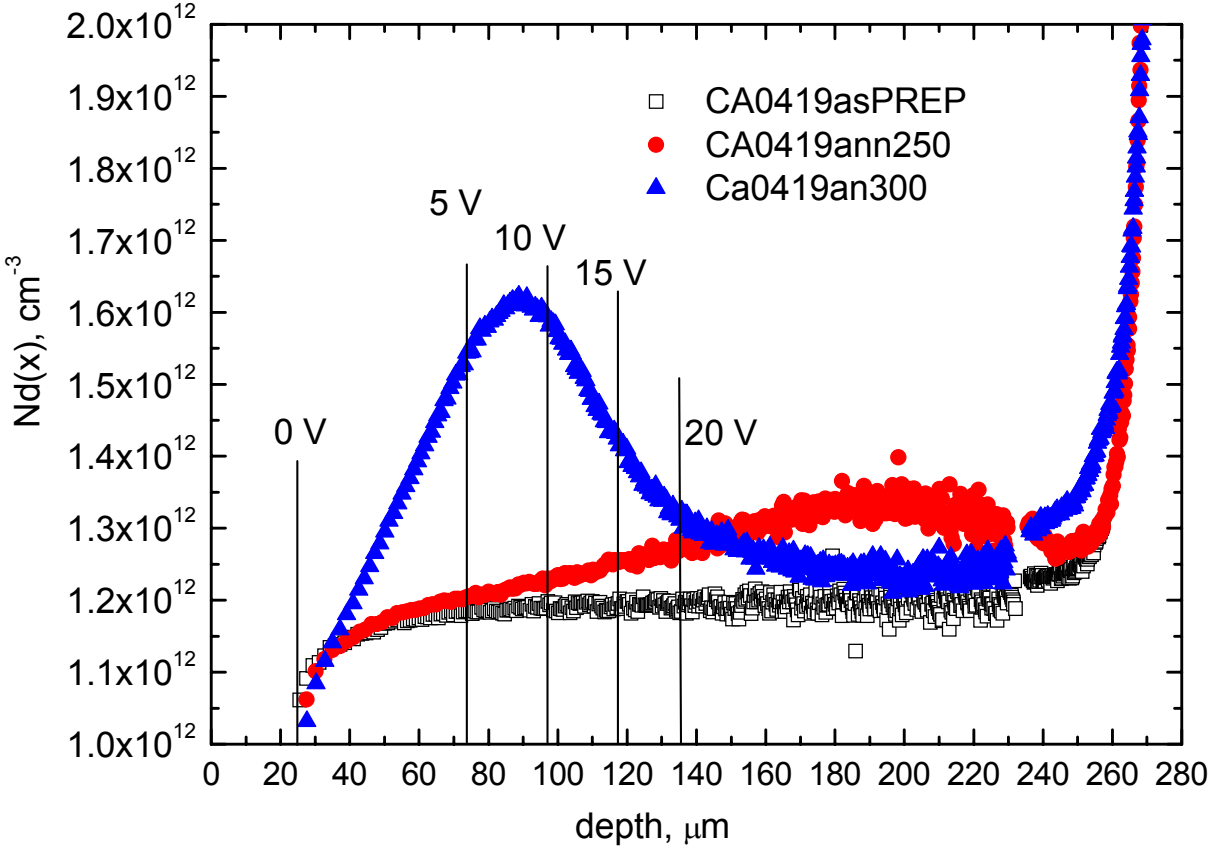


Fig.9. Carrier depth profile for a CA sample determined from C-V characteristics. Vertical lines mark inverse voltage which is necessary to obtain indicated width of depletion region.

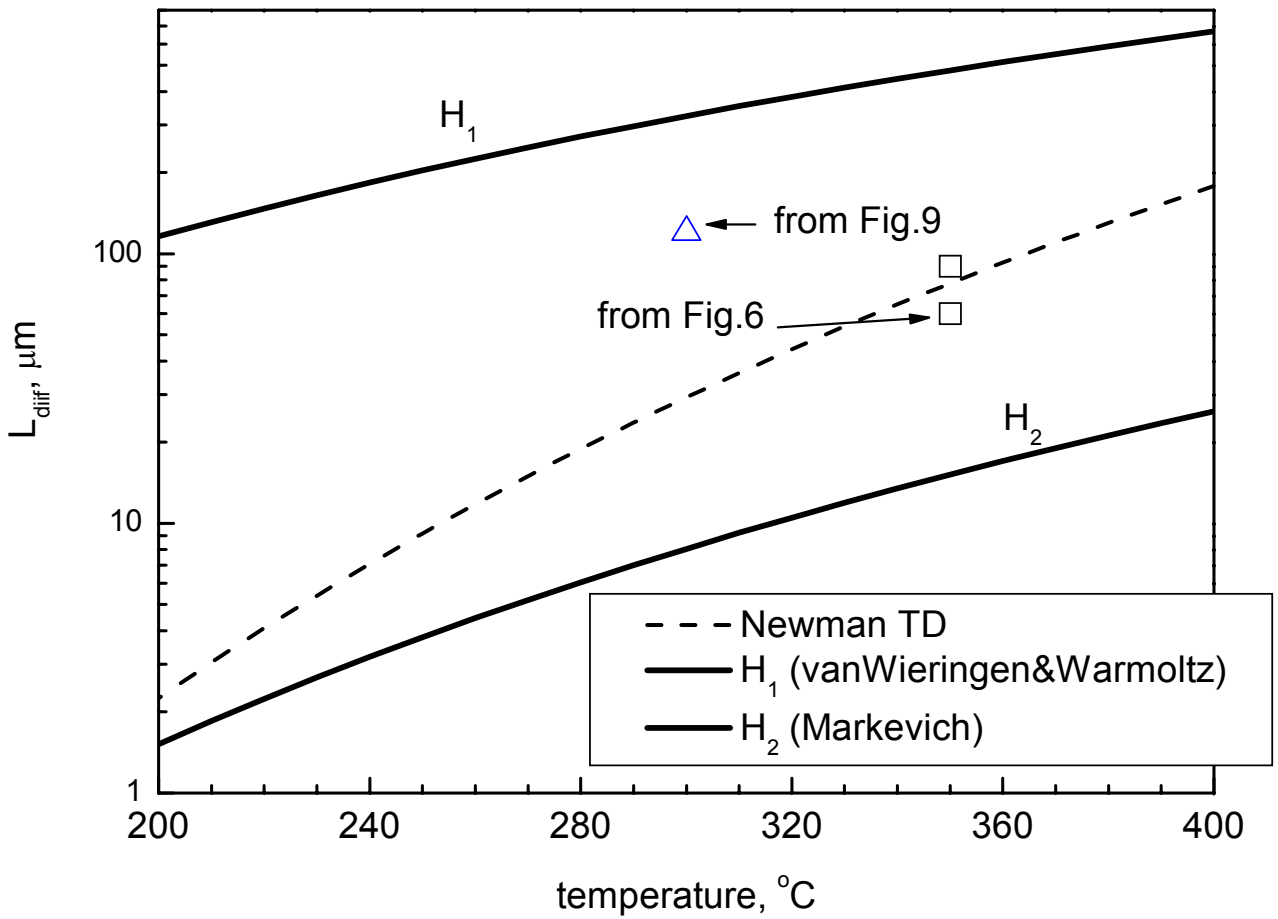


Fig.10. Diffusion length for different hydrogen forms (monoatomic H and H dimer) in silicon calculated for 30 min time period. Points shows our estimations from the depth of donor formation in nonhydrogenated (Fig.6) and hydrogenated (Fig.9) samples.

Conclusions

Hydrogen may exist in different regions of silicon particle detector.
When it is present in the base region of a diode then it interacts with radiation defects already at temperatures of 100-150 °C.

When hydrogen is present at Si-SiO_2 boundary or in strongly doped regions then its activation temperature is in the range of 250-350 °C. At these temperatures hydrogen can penetrate in the base region at the depth of 50-100 μm during 30 min and its penetration depth depends on the form of diffusing hydrogen particles (H or H_2)

It is a procedure of diode processing that influence on hydrogen distribution in silicon detectors of particles.