Results on defects induced by Co^{60}-gamma irradiation in standard and oxygen enriched silicon[†]

I. Pintilie[a)b)*] E. Fretwurst [b)], G. Lindström [b)] and J. Stahl [b)]

[a)] *National Institute of Materials Physics, Bucharest-Magurele, P.O.Box MG-7, Romania*

[b)] *Institute for Experimental Physics, Hamburg University, D-22761, Germany*

Abstract

Radiation induced defects in silicon diodes were investigated after exposure to high doses of Co-60 gamma irradiation, using Deep Level Transient Fourier Spectroscopy and Thermally Stimulated Current methods. The main focus was on differences between standard and oxygen enriched material and the impact of the observed defect generation on the diode properties. Two close to mid gap trapping levels and a bi-stable donor level have been characterized as function of dose. These defects explain the main macroscopic deterioration effects both in standard and oxygen enriched float zone diodes. Radiation damage effects in silicon detectors under severe hadron- and γ–irradiation are surveyed, focusing on bulk effects. Both macroscopic detector properties (reverse current, depletion voltage and charge collection) as also the underlying microscopic defect generation are covered. Basic results are taken from the work done in the CERN-RD48 (ROSE) collaboration updated by results of recent work. Preliminary studies on the use of dimerized float zone and Czochralski silicon as detector material show possible benefits. An essential progress in the understanding of the radiation induced detector deterioration had recently been achieved in gamma irradiation, directly correlating defect analysis data with the macroscopic detector performance.

Keywords: silicon detectors; defect emgineering; point defects defect analysis

[†] Paper presented at 4th Internatl. Conf. On Radiation Effects on Semiconductor Materials, Detectors and Devices, Firenze, Italy, July 10-12, 2002, submitted for publication to Nucl. Instr. and Meth. A

[*] Corresponding author. Tel.: +49-40-8998-4726; Fax: +49-40-8998-2959; e-mail: ioana.pintilie@desy.de , ioana@alpha1.infim.ro

1. Introduction

High resistivity silicon particle detectors will be used extensively in the tracking areas of the CERN Large Hadron Collider (LHC) experiments. Since for this application the detectors are subject to extremely high hadron fluences the radiation tolerance of the bulk material became of prime importance. In all cases high resistivity silicon (ρ > 1 kΩcm) was chosen to allow for low operating voltages.

A lot of investigations on hadron induced damage and the impact on detector performance had been extensively studied by the CERN RD48 (ROSE) collaboration [1-6]. It had especially been proven that the deliberate addition of oxygen ([O]>10^{17} cm^{-3}) in the bulk material is beneficial for the radiation tolerance to charged particle and gamma exposure. The clearest benefit is gained in the case of ^{60}Co gamma irradiation. No change in the initial doping concentration was reported up to a dose of 400 Mrad for high resistivity Diffusion Oxygenated Float Zone (DOFZ) silicon while in the case of Standard Float Zone (STFZ) silicon the type inversion takes place around 250 Mrad [2]. Many radiation induced point defects ($VV^{=/-}$, $VV^{-/0}$, $C_iC_s^{-/0}$, $VO_i^{-/0}$, $C_iO_i^{+/0}$ etc.) were already well characterized by various methods [5-17]. However, these defects cannot explain the irradiation-induced change in the macroscopic parameters of the detector performance (doping concentration and leakage currents) and the improvement of the radiation tolerance for oxygen-enriched silicon. Present defect models attribute the beneficial oxygen effect in gamma irradiated DOFZ silicon to a lower probability of V_2O formation by an enhanced production of VO defects [17-20]. The V_2O defect was identified in Czochralski (CZ) silicon after electron irradiation by Electron Paramagnetic Resonance (EPR) [21] and Photo-EPR measurements [20]. An activation enthalpy of (0.50±0.05) eV from the conduction band was evaluated for the V_2O defect in the neutral charge state [22]. Recently, we have reported on a deep level located at 0.545 eV from the conduction band (E_c) and having electron and hole capture cross sections of $\sigma_n = (1.7\pm0.2)\text{x}10^{-15}$ cm^2 and $\sigma_p = (9\pm1)\text{x}10^{-14}$ cm^2 respectively detected in float-zone silicon after Co^{60}-gamma irradiation with doses up to 42.5 Mrad [23]. This close to midgap trap (the I level in ref.[23]) is strongly generated in STFZ diodes but largely suppressed in DOFZ devices and was suggested to be related to the V_2O complex in the single charge state. According to our results it can explain about 90% of the change in the effective doping concentration (Neff) and 50% of the leakage current (LC) in STFZ silicon. Considering that the I level was also detected in DOFZ material together with the still unexplained difference in the measured and calculated leakage current call for further investigations, especially after higher doses of irradiation. In the following we report on the detection by Deep Level Transient Fourier Spectroscopy (DLTFS) [24] and Thermally Stimulated Current (TSC) [13] methods of other trapping levels induced by gamma irradiation, which together with the mentioned I level can better explain the differences observed between STFZ and DOFZ diodes. The devices investigated in this work are STFZ and DOFZ p^+nn^+ diodes processed by CiS [25] on Wacker silicon with high resistivity (4 kΩcm) and exposed to Co^{60}- gamma irradiation doses of 10 to 300 Mrad. The average oxygen concentration in the DOFZ material is 1.2x10^{17} cm^{-3} while in the STFZ ones it is less than 3x10^{16} cm^{--3} [26].

2. Experimental results and discussions

2.1. DLTFS results

The DLTFS method was applied for doses up to 42.5 Mrad whereas the higher irradiated samples were investigated by the TSC method. After irradiation all dides were kept at room temperature for at least 4 weeks. DLTFS measurements were performed on both STFZ and DOFZ samples exposed to 10 and 42.5 Mrad irradiation doses. For these high doses the DLTFS spectra can be well analyzed only for temperatures above 240 K where the most abundant irradiation induced point defects (e.g. VO and VV) do not contribute anymore to the recorded capacitive transients. In addition to the mentioned I level (possibly the $V_2O^{-/0}$ complex) another very deep level, labeled as Γ, was detected in these samples as shown in Fig. 1a. An activation enthalpy of ΔH_v =

0.66eV ±1% with respect to the valence band and an effective capture cross-section of σ* = (5±3)x10^{-15} cm^2 were evaluated for the Γ defect from the Arrhenius plot (Fig. 1b). The filling was done using forward bias injection and therefore σ* does not represent the capture cross section for holes only (σ_p) but includes also the electron capture cross section (σ_n). The σ* is given by the following formula [27]:

$$\sigma^* = \sigma_p + \sigma_n \frac{v_{th,n}}{v_{th,p}} \qquad (1)$$

where $v_{th,p}$, $v_{th,n}$ are the thermal velocities of holes and electrons respectively.

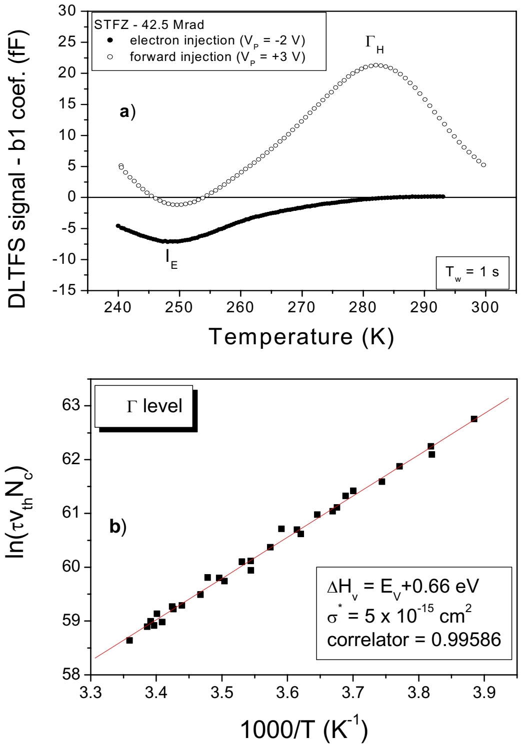

Fig. 1 a) Majority and minority carrier DLTFS spectra recorded on STFZ diode after a gamma dose of 42.5 Mrad. A reverse bias of RB=-16 V was applied during the measurement.b) Arrhenius plot for the Γ level with the evaluation of the activation enthalpy and capture cross section.

The concentration evaluated from DLTFS spectra or by direct analysis of transients after forward injection does not represent the total concentration of defects (N_T) but a quantity given by [27]:

$$p_T^{DLTS}(T) = (N_T - n_T(T)) * \frac{c_p(T)}{c_p(T) + c_n(T)}$$

with

$$n_T(T) = N_T * \frac{c_n(T) * n + e_p}{e_n(T) + e_p(T) + c_n(T) * n + c_p(T) * p} \qquad (2)$$

$$e_{n,p}(T) = c_{n,p}(T) * N_{C,V}(T) * \exp(\pm \frac{E_a(T) - E_{C,V}}{k_b T}$$

where $n_T(T)$ is the steady state occupancy of the Γ level, $c_{n,p}(T) = \sigma_{n,p}(T) * v_{th,n,p}(T)$ are the respective capture coefficients, $N_{C,V}$ are the effective densities of states in the conduction band.

Due to its position in the band gap, the Γ level might have a strong influence on the detector performances – the leakage current per unit volume (LC) and the effective doping concentration (N_{eff}). In order to estimate it correctly both capture cross sections (σ_n and σ_p) should be known. Because of the high concentration of $VV^{-/0}$ states a direct investigation of electron emission from the Γ defect is not possible. By direct analysis of transients at different temperatures the $p_T^{DLTS}(T)$ values were determined to be 9.60x10^{9}cm^{-3}, 9.44x10^{9}cm^{-3} and 9.36x10^{9}cm^{-3} at 273 K, 293 K and 298 K respectively. Assuming that there is no temperature dependence of σ_p and σ_n between 273 K and 298 K then eq. 2 results in σ_p/σ_n~100. With such a large difference between the two capture cross sections a good approximation is σ_p = σ* = (5±3)x10^{-15} cm^2 as was evaluated from the Arrhenius plot in fig.1b.

2.2. TSC results

The samples irradiated with higher doses (up to 284 Mrad) were investigated by the TSC method. Also in this case the diodes stayed at room temperature for more than 4 weeks prior to the measurements. The standard experimental procedure consists in cooling down from room temperature (RT) to 20 K under 0 bias, followed by forward injection (1mA) for 30 sec. and then heating up with reverse bias (RB) applied. The heating rate for the TSC experiments was always 0.183 K/s. The filling of traps was done either by forward biasing or using hole injection by 670 nm LED illumination from the rear side of the reverse biased diode.

In Fig. 2 the recorded TSC spectra for STFZ and DOFZ diodes exposed to a dose of 284 Mrad are presented. In DOFZ diodes the generation of I and Γ defects are strongly suppressed, while the VOi center exhibits a larger concentration. This may suggest that the VO_i center plays a major role in the formation of I and Γ defects. In fact, it had been discussed that the V_2O complex results from the reaction $VO_i+V \Rightarrow V_2O$ [17-20]. In addition, there are some features characteristic only for the STFZ or DOFZ material neither reported so far in the literature nor seen in our low dose DLTFS measurements [28].

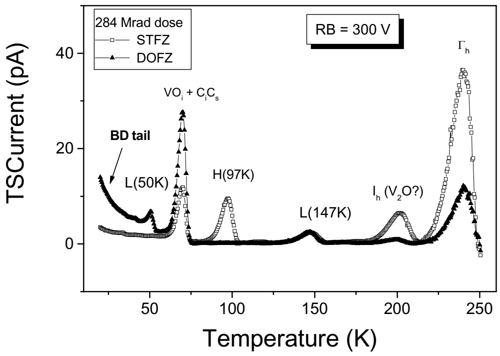

Fig. 2. TSC spectra for STFZ and DOFZ diodes irradiated with 284 Mrad dose recorded after exposure to day light.

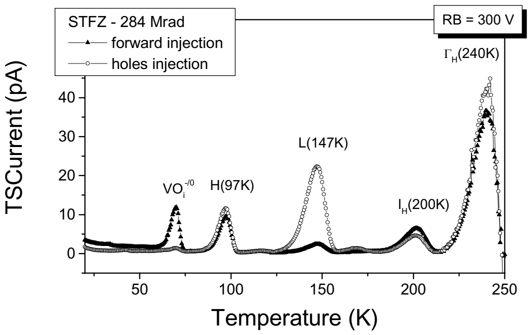

Fig. 3. TSC spectra in STFZ for only hole injection or after forward biasing.

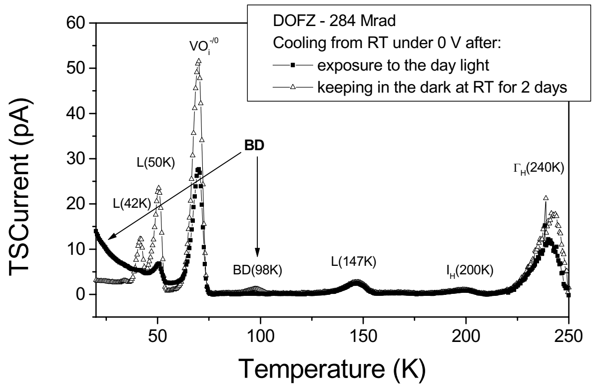

Fig. 4. TSC spectra in DOFZ diodes after forward biasing following different exposures.

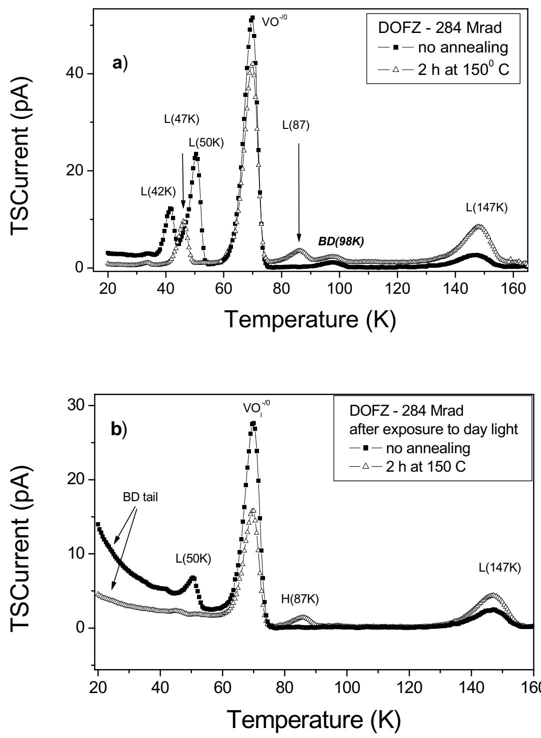

Fig. 5. Annealing at 150 ^{0}C . a) TSC spectra for DOFZ after keeping the diode in the dark at RT for 2 days;.b) TSC spectra for DOFZ after exposure to day light

In the STFZ material a strong peak is observed at 97 K which proved to act as a trapping level for holes (see Fig. 3). In the DOFZ case we see a peak at 50 K overlapping a very low temperature signal labeled “BD tail”. The BD tail disappears after keeping the diode in the dark for 2 days at room temperature (RT). Instead, the L(42K) and BD(98K) levels appear in the TSC spectrum (see Fig. 4). A level with similar trapping parameters like L(50K) was already investigated by DLTS and IR- Absorption methods in oxygen rich Si and was associated with the single negative charge state of the interstitial silicon-oxygen dimer complex ($IO_2^{-/0}$) annealing out completely at 150 ^{0}C [15]. Our experiments revealed that both L(50K) and L(42K) levels anneal out after 150^0 C heat treatment (Fig. 5). Instead of these two levels another peak labeled L(87K) appears in the spectrum. The L(47K) peak is not a result of the annealing. It can already be seen as a shoulder in the L(50K) peak prior to annealing.

It is worth to mention here that no change in the magnitude of the leakage current or Neff was measured after the annealing at 150^0 C. Depending on the experimental TSC procedure (cooling after exposure to day light or after keeping the sample in the dark) a direct correlation between the BD tail and BD(98K) level was observed (see Fig. 5). It is well known that such bi-stability is characteristic for the thermal double donors TDD1 and TDD2 (associated with small size oxygen clusters) [29-31].

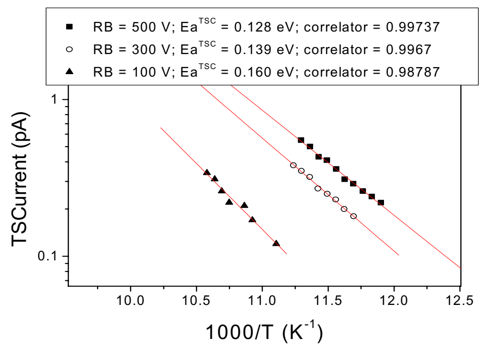

Fig. 6. Change of the activation enthalpy of BD(98K) with different reverse bias applied during TSC measurement.

The donor activity of the BD(98K) level was proven observing the Poole Frenkel effect when different RB-values were applied during the TSC measurements. The change in the activation enthalpy was evaluated from Arrhenius plots of the increasing part of the peak (see Fig. 6) resulting in a zero field activation enthalpy of 0.225 eV for BD(98K) . Thus, contrary to the effect of I and Γ the BD centers will contribute with positive space charge to Neff. These properties of the BD centers (donor activity, bi-stability, zero field activation energy) together with their strong generation in oxygen enriched material suggest a possible identification with the thermal double donors TDD2.

3. The impact of I, Γ and BD defects on the detector performance

The following relations were used to calculate the contribution of the I, Γ and BD centers to LC (α_E) and N_{eff} (n_T):

$$\alpha_E(T) = q_0 * e_n(T) * n_T(T)$$
and
$$n_T(T) = N_T * \frac{c_n(T) * n + e_p}{e_n(T) + e_n(T) + c_n(T) * n + c_n(T) * p} \qquad (3)$$

where q_0 is the free electron charge.

The concentrations of I, Γ and BD centers in STFZ and DOFZ for different dose values are given in Tab. I. The errors are less than 5% in the case of I level and around 20% for the Γ level.

The experimental values of N_{eff} and LC as determined from C-V and I-V measurements as well as the calculated ones are given in Fig. 7. There is a very good agreement between measured and calculated values of Neff for both STFZ and DOFZ diodes. However, the LC cannot be fully described by taken only the I and Γ level into account (especially in the case of DOFZ). Possible reasons for that can be that other deep centers (e.g. $VV^{-/0}$) have not been included.

Table I. Total concentration of I, Γ and BD defects as function of irradiation dose in STFZ and DOFZ silicon

Dose (Mrad)	**I level STFZ** $x10^9$ (cm^{-3})	**I level DOFZ** $x10^{10}$ (cm^{-3})	**Γ level STFZ** $x10^{12}$ (cm^{-3})	**Γ level DOFZ** $x10^{12}$ (cm^{-3})	**BD DOFZ** $x10^{11}$ (cm^{-3})
4	6.08				
10	11.45				
42	62	1.6			
96	120		1.9		
150	276	5	3.2		1.48
190	380	7.5	2.4	1.5	2.04
245	700	11.5	5	2.1	2.96
284	920	16	6	3	3.8

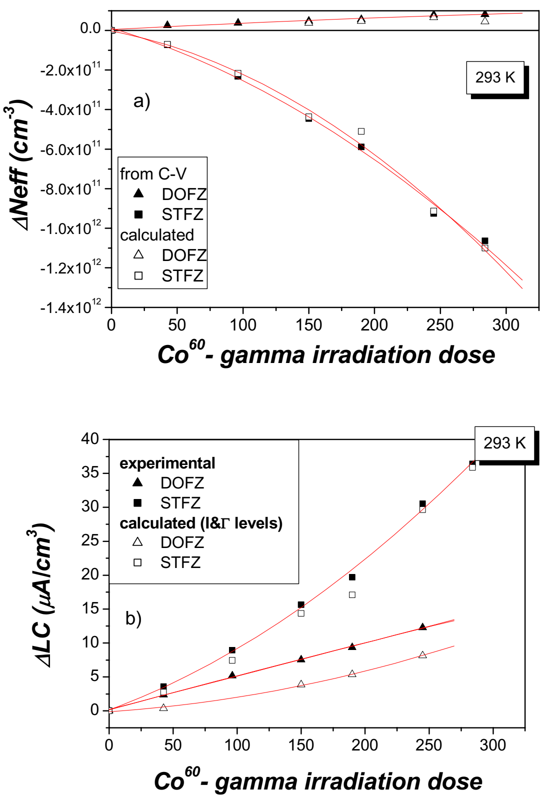

Fig. 7. Experimental and calculated dose dependence of: a) effective doping concentration
b) leakage current per unit volume

4. Conclusions

The DLTFS method applied to gamma irradiated STFZ and DOFZ silicon diodes with doses up to 42 Mrad allowed us to characterize a new close to midgap trapping level (Γ center) in addition to the already reported I defect ($V_2O^{-/0}$?).The trapping parameters of the Γ level are: an activation enthalpy of ΔH_v = 0.66eV ±1% from the valence band and a capture cross-sections of $\sigma_p = 100x\sigma_n = (5\pm3)x10^{-15}$ cm^2. The dependence of the I and Γ concentrations with increasing dose was investigated by the TSC method. It was shown that both defects are largely suppressed in DOFZ diodes. In STFZ the I and Γ level can almost fully explain the change in both the leakage current and the effective doping concentration . In the case of DOFZ diodes the negative space charge due to I and Γ centers is overcompensated by the positive charge introduced by some bi-stable donors (TDD2 ?) leading even to a slight increase of the effective donor concentration.

Acknowledgements

Many thanks are due to Z. Li and E. Verbitskaja for help in the gamma irradiations at Brookhaven National Laboratory. This work has been performed in the frame of the CiS-SRD project under contract 642/06/00. Financial support of the German Ministry for Education and Research BMBF and of the Romanian Ministry for Education and Research under contract WTZ-ROM 00/01 and of the German Research Foundation DFG under contract FR1547/1-1 is gratefully acknowledged.

References

1. A. Ruzin et al., IEEE Trans. Nucl. Sci. **46** (5) (1999) 1310
2. Z. Li, B. Dezillie, M. Bruzzi, W. Chen, V. Eremin, E. Verbitskaya, P. Weilhammer, Nucl. Instr. and Meth. A **461** (2001) 126.
3. G. Lindström et al. (ROSE collaboration), Nucl. Instr. and Meth. A **465** (2001) 60
4. G. Lindström et al. (ROSE collaboration), Nucl. Instr. and Meth. A **466** (2001) 308
5. V. Eremin, E. Verbitskaya, Z. li,), Nucl. Instr. and Meth. A **476**, 3, (2002) 556

6. V. Eremin, A. Ivanov, E. Verbitskaya, Z. Li, S. U. pandey, Nucl. Instr. and Meth. A **426,** 1**,** (1999) 834
7. L. C. Kimerling, in Radiation Effects in Semiconductors 1976, edited by N. B. Urli and J. W. Corbett (Conference Series No. 31, The Institute of Physics, Bristol, 1977), p. 221
8. O. O. Awadelkarim, H. Weman, B. G. Svensson and J. L. Lindström, J. Appl. Phys. **60** (6) (1986) 1974
9. A. Hallen, N. Keskitalo, F. Masszi and V. Nagl, J. Appl. Phys. **79** (8) (1996) 3906
10. M. Moll et al., Nucl. Instr. and Meth. A **388** (1997) 335
11. E. Fretwurst et al., Nucl. Instr. and Meth. A 388 (1997) 356
12. S. J. Watts and M. Ahmed, CERN/LEB **98-11**, (1998) 432
13. I. Pintilie et al., APL 78 (2001) 550
14. C.daVia and S. Watts, Nucl. Instr. and Meth. B 186 (2002) 111
15. J. L. Lindström et al., Physica B 308-310 (2001) 284
16. M. Vujicic, V. Borjanovic and B. Pivac, Mat. Sci. and Eng. **B 71** (2000) 92
17. G. Davies, E. C. Lighttowlers, R. C. Newman and A. S. Oates, Semic. Sci. Technol. **2** (1987) 524
18. B. MacEvoy, G. Hall and K. Gill, Nucl. Instr. and Meth. A **374** (1996) 12
19. K. Gill, G. Hall and B. MacEvoy, J. Appl. Phys. **82** (1997) 126
20. B. MacEvoy and G. Hall, Mater. Sci. in Semicon. Process. **3** (2000) 243
21. Y. H. Lee and J. Corbett, Phys. Rev. **B 13** (6) (1976) 2653
22. Y. H. Lee, T. D. Bilash and J. Corbett, Radiat. Eff. **29** (1976) 7
23. I. Pintilie, E. Fretwurst, G. Lindstroem and J. Stahl, Appl. Phys. Lett. 81, No 1 (2002) 165
24. S. Weiss and R. Kassing, Solid-State Electronics, **31** , No 12, (1988), 1733.
25. CiS Institut für Mikrosensorik gGmbH, Erfurt, Germany
26. A. Barcz et al., SIMS XIII conference, Nov. 2001, Nara (Japan), to be published in Applied Surface Science
27. D. V. Lang in Thermally Stimulated Relaxation in Solids, editor P. Bräunlich, (Springer-Verlag Berlin 1979) Chapt. 3, pp. 93-128
28. J. Stahl, E. Fretwurst, G. Lindstroem and I. Pintilie, Deep defect levels in standard and oxygen enriched silicon detectors before and after ^{60}Co-γ- irradiation, 9th European Symposium on Semiconductor Detectors, Schloss Elmau, June 23 - 27, 2002, to be publ. in Nucl. Instr. and Meth. A
29. P. Wagner and J. Hage, J. Appl. Phys. A 49, (1989)123
30. YA. I. Latushko et al., Phys. Stat. Sol. (a) 93, (1986) K181
31. A. Chantre, Appl. Phys. Lett. **50** (21) (1987) 1500