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Bias-Dependent Radiation Damage in High-Resistivity Silicon Diodes Irradiated with Heavy Charged Particles

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Abstract

High resistivity $p^+ - n - n^+$ planar diodes were irradiated with neutrons to fluences up to 2×10^{14} cm^{-2} 1 MeV neutron NIEL equivalent and with pions to 0.47×10^{14} cm^{-2}. Special care was taken to irradiate samples under strictly controlled conditions (temperature, bias). Influence of bias on the effective dopant concentration as measured with $C-V$ method was studied. Permanently biased diodes exhibit about two times higher $|N_{eff}|$ after beneficial annealing has been completed. Difference between biased and unbiased samples diminishes after switching off the bias with annealing time being temperature dependent. Part of the difference is attributed to a bistable defect since it recovers if the bias is re-applied for a few days at room temperature.

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1 Introduction

Radiation damage in silicon detectors will play an important role in their operation at future high-energy physics experiments. A change of full depletion voltage as well as an increase of leakage current are the two main macroscopic

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effects which may limit the efficiency of detectors. Leakage current may be successfully decreased by cooling the detectors, thus having little influence on noise of detectors with fast readout electronics [1]. Increase of full depletion voltage is of major concern, particularly for detectors with p^+ structure on n bulk material. After effective type inversion of bulk material due to radiation damage these detectors should be over-depleted in order to achieve satisfactory charge collection efficiency [1,2].

Therefore changes of effective dopant concentration after irradiation with heavy particles, electrons and gamma rays have been extensively studied with a particular emphasis on material dependence [3,4]. However it is not straightforward to apply these studies to realistic running conditions of a high energy experiment. Running time of a typical LHC experiment will be about ten years with fluxes from 10^6 to 10^7 /cm^{2}s and accumulated fluences from 10^{14} to 10^{15} /cm^2 1 MeV NIEL equivalent. Detectors will be cooled during operation (for example to about -7°C in the ATLAS experiment) and obviously, they will be biased. Measurements have shown no flux dependence of the long-term radiation damage after irradiation with neutrons in the flux range from 2×10^8 to 5×10^{15} n/cm^{2}s [5]. On the contrary, a large influence of the bias voltage on the effective dopant concentration has been observed [6]. Furthermore, influence of electric field on the formation of defects in neutron, electron and gamma irradiated low-resistivity silicon has been found using DLTS [7]. The results of these studies depend strongly on strict and permanent control of conditions (bias, temperature). Therefore we have extended the study of bias effect with the irradiation of a limited number of diodes in order to estimate its importance for a long term experiment.

2 Irradiations

Irradiations with neutrons were done at the TRIGA nuclear reactor of the "Jožef Stefan" Institute in Ljubljana. Samples were irradiated in the experimental channel positioned in the reactor core. Spectrum of neutrons in the core has a range from thermal to fast (about 10 MeV) neutrons [8]. Neutrons below 100 keV have small non-ionizing energy loss in silicon compared to fast neutrons. Calculations of NIEL using damage functions from [9] and the measured spectrum [8] have shown that they contribute only about 1.5 percent in addition to the NIEL of fast neutrons (above 100 keV). All fluences in this paper are normalized to the 1 MeV neutron equivalent NIEL. Some of the fluences measured with activation analysis and normalized to 1 MeV have been compared to the normalized fluences as determined with the leakage current method as described in reference [10]. The annealing procedure of keeping samples for 2 hours at 60 degrees has been used and the normalized fluence calculated from the measured value of the leakage current. Very good agreement (within few percent) of both methods has been found.

A cooling system using ethylene-glycol as a coolant enabled regulation of the temperature, stable to $\pm 0.5°$C during and after irradiations. For long term studies, regulated standard refrigerators were used to keep the diodes at a fixed temperature.

Irradiations with pions were done at the Paul Scherrer Institute in Villigen. The energy of pions was 200 MeV with the damage factor equal to about one [11]. Fluences were determined using the activation foil technique as well as with the leakage current method. Agreement of both methods was within few percent using 1 as the value for the damage factor. The irradiation took ten hours, so the average pion flux was 1.25×10^9 cm^{-2}s^{-1} Samples were irradiated at room temperature (22°C). Since no cooling was available at the irradiation site, the samples were mounted on an Al heat spreader in order to avoid thermal runaway caused by leakage current due to bias on the samples.

An overview of irradiated samples and conditions during and after irradiation is given in Table 1. A series of irradiations was performed with different fluences, samples and temperatures. All diodes used were processed on standard high-resistivity silicon wafers. Different biasing conditions have been used. During and after irradiations, samples have been kept at controlled temperatures.

3 Experimental results

3.1 Effective dopant concentration.

Effective dopant concentrations $|N_{eff}|$ were determined from $C - V$ measurements. Capacitance measurements were done at different frequencies in the range from 100 Hz to 1 MHz. Full depletion voltage (FDV) was determined from the kink in the $1/C^2 - V$ plot. The FDV results were obtained at 10 kHz and 5°C. As the thickness of diodes under investigation was 300$\pm$5 μm, $|N_{eff}|$ is connected to FDV by

$$|N_{eff}| = 1.46 \times 10^{10}\mathrm{cm}^{-3} FDV/\mathrm{V}. \tag{1}$$

The first measurements [6] have shown, the effective dopant concentration after irradiation differs for biased and unbiased samples, while the leakage

Sample	Processing	FDV_0 [V]	T [°C]	Part. type	ϕ_{eq} [$cm^{-2}s^{-1}$]	Φ_{eq} [$10^{14}cm^{-2}$]	V_{bias} [V]
B3	Micron	20	0	n	$1.9{\cdot}10^9$	0.44	200
I3	Micron	24	5	n	$1.9{\cdot}10^9$	0.45	200
D3	Micron	16	15	n	$1.8{\cdot}10^9$	0.47	200
U3A	Micron	17	18	n	$1.8{\cdot}10^9$	0.41	0
U3B	Micron	19	18	n	$1.8{\cdot}10^9$	0.41	0
UO6B	Sintef	35	20	n	$1.8{\cdot}10^{11}$	1.7	$1000/600^{\dagger}$
UO6S	Sintef	35	20	n	$1.8{\cdot}10^{11}$	1.7	0
BA2B	Sintef	44	15	n	$2.1{\cdot}10^{11}$	1.0	500
BA2S	Sintef	44	15	n	$2.1{\cdot}10^{11}$	1.0	0
BA4B	Sintef	40	20	n	$2.1{\cdot}10^{11}$	1.0	600
BA4S	Sintef	36	20	n	$2.1{\cdot}10^{11}$	1.0	0
PIB	Sintef	29	22	π^+	$1.25{\cdot}10^9$	0.47	250
PIU	Sintef	27	22	π^+	$1.25{\cdot}10^9$	0.47	0

Table 1
List of diodes used to study the effect of bias voltage on defect development. FDV_0 is full depletion voltage before irradiation, T is temperature during irradiation, ϕ_{eq} is flux and Φ_{eq} is 1 MeV neutron NIEL equivalent fluence, V_{bias} is voltage applied on the diode during and after irradiation. Thickness of samples was 300±5 μm.

current is independent on biasing condition. We have extended the measurements to the reverse annealing phase in which the increase of effective acceptor concentration dominates. For this purpose the diodes were irradiated with neutrons to Φ_{eq} about 0.45×10^{14} n/cm^{2}s. In order to accelerate the annealing processes samples were heated to 60°C after irradiation. Time evolution of $|N_{eff}|/\Phi_{eq}$ after irradiation with neutrons is shown in Fig. 1. We may notice that the effective dopant concentration for biased and unbiased samples remains different also during the reverse annealing stage.

Long-term time dependence of $|N_{eff}|$ is dominanted by reverse annealing. It was fitted using both first order [12]

$$|N_{eff}|(t) = g_C\ \Phi_{eq} + g_Y\ \Phi_{eq}(1 - e^{-k_1^Y t}) \qquad (2)$$

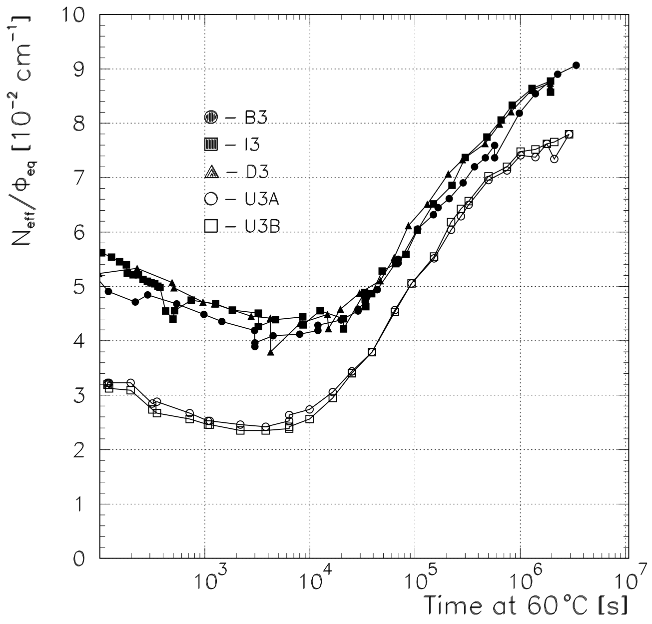

Fig. 1. Comparison of time development of $|N_{eff}|/\Phi_{eq}$ for biased (B3, D3, I3) and unbiased (U3A, U3B) samples.

and second order parameterizations [13] of reverse annealing:

$$|N_{eff}|(t) = g_C \ \Phi_{eq} + g_Y \ \Phi_{eq}(1 - \frac{1}{1 + g_Y \ \Phi_{eq} \ k_2^Y t}) \ . \tag{3}$$

Here g_C is the introduction rate of defects stable in time, g_Y the introduction rate of defect responsible for reverse annealing and $k^Y_{1,2}$ the corresponding reaction constants. Their values obtained from the fit are shown in Table 2. Damage stable in time caused by irradiation in unbiased samples ($g_C = 2.2 \pm 0.4 \times 10^{-2}$ cm^{-1}) agrees with the value obtained by a global survey [14] ($g_C = 1.77 \pm 0.07 \times 10^{-2}$ cm^{-1}) within the experimental error. The stable damage in biased samples however, is nearly about two times higher ($g_C = 4.0 \pm 0.6 \times 10^{-2}$ cm^{-1}). We should stress, that most of our error on g_C is due to the fluence measurement. Systematic uncertainties are common to all our fluence measurements, so they do not enter in relative comparisons between measurements presented in this paper. The amplitude of reverse annealing (g_Y) is approximately equal for biased and unbiased samples, while the reaction constants differ for a factor of about two. However, measurements of these constants are not conclusive, since samples have been only partially biased during the late reverse annealing stage. Voltage on biased samples was fixed at 200 V, resulting in not fully biased samples when effective dopant concentrations exceeded 3×10^{12} cm^{-3}.

Sample	g_C [10^{-2}/cm]		g_Y [10^{-2}/cm]		$k^Y(60°C)$	
					[10^{-6}/s]	[10^{-18}cm^3/s]
	1^{st} or.	2^{nd} or.	1^{st} or.	2^{nd} or.	1^{st} or.	2^{nd} or.
I3	4.0	3.9	4.5	5.3	3.8	2.1
D3	4.2	4.1	4.9	5.5	3.3	1.9
B3	4.1	4.0	4.8	5.4	4.5	2.5
average biased	4.1 ± 0.6	4.1 ± 0.6	4.7 ± 0.7	5.4 ± 0.8	3.9 ± 0.4	2.2 ± 0.2
U3A	2.4	2.3	4.8	5.5	8.0	4.6
U3B	2.2	2.1	5.0	5.8	8.4	4.5
average unbiased	2.3 ± 0.4	2.2 ± 0.4	4.9 ± 0.7	5.6 ± 0.9	8.2 ± 0.2	4.6 ± 0.1

Table 2
Results of the fits using first and second order models. In our average values of g_C and g_Y a 15% common systematic error on the dosimetry is included.

In order to measure the bias dependence of damage due to irradiation with pions two samples were irradiated in parallel under the same conditions except for bias, which was 350 V on the biased sample. Irradiation was done at room temperature (about 22°C). Time evolution of $|N_{eff}|$ is shown in Fig. 2. During irradiation (first ten hours) only FDV of the unbiased diode could be measured. Change of effective dopant concentration due to acceptor creation, as well as type inversion can be seen. After irradiation, the FDV of the biased sample was 215 V compared to 130 V of the unbiased sample. Then FDV started to decrease due to annealing of defects. 36 hours after irradiation we put both diodes into a cool box (T approx. -2°C) to suppress annealing of defects during transportation (14 hours). In the laboratory diodes were kept at 5°C, and their FDV was measured at regular intervals. After 20 days, the temperature was increased to 20°C. We may notice (Fig. 3a), that at minimum, FDV of the biased sample is approximately two times higher compared to FDV of the unbiased sample.

3.2 Annealing of bias induced damage

The extent of radiation damage as measured with biased detectors could have a serious influence on the operation scenario of experiments since detectors are bound to be biased during data taking. Since some of the planned exper-

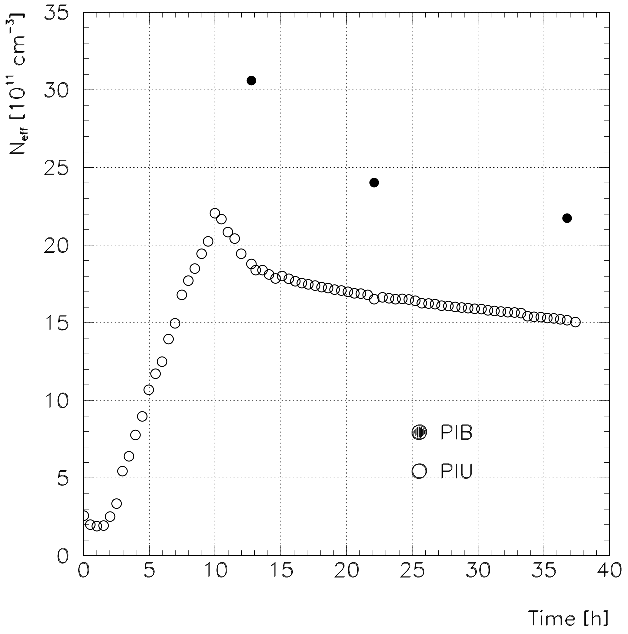

Fig. 2. Time development of $|N_{eff}|$ in biased (PIB) and unbiased (PIU) samples irradiated with pions to 0.47×10^{14} n/cm^2.

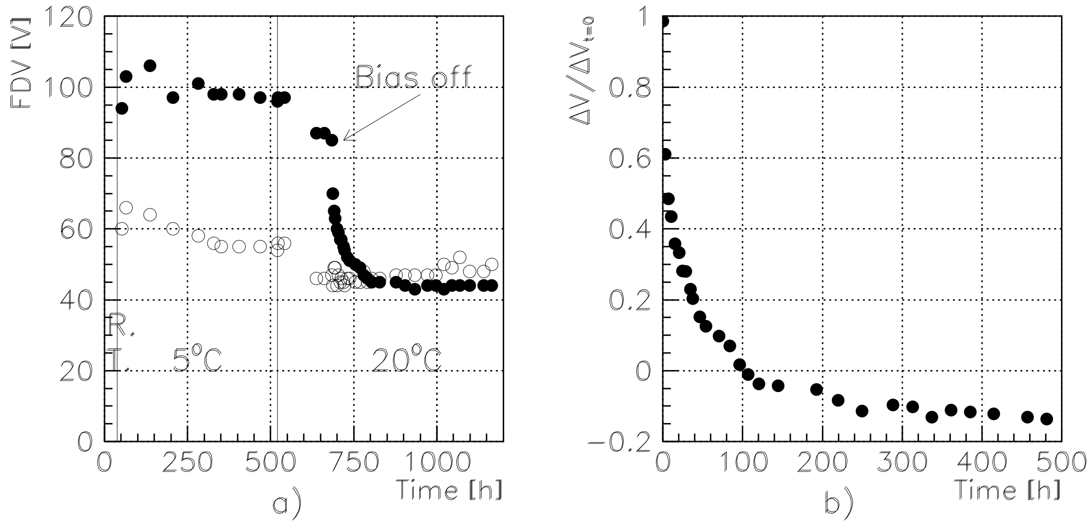

Fig. 3. a) FDV time development of biased (PIB) and unbiased (PIU) samples. After 700 hours bias on PIB was switched off. b) Time evolution of FDV difference between PIB and PIU normalized to the difference at bias disconnection time ($t = 0$). T was 20°C

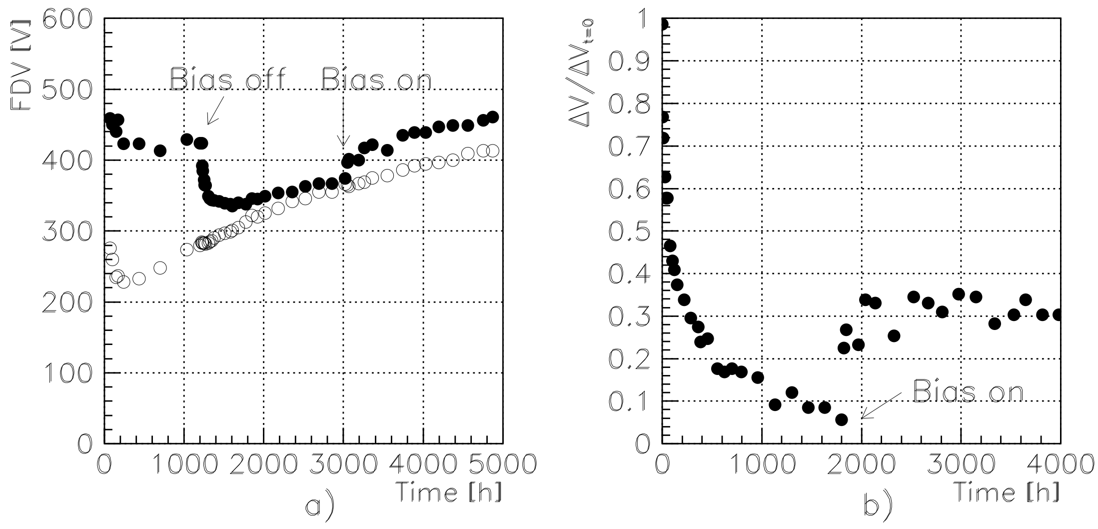

Fig. 4. a) Time development at 20°C of FDV of biased (U06B) and unbiased (U06S) samples irradiated with neutrons. After 1200 hours bias on U06B was switched off and re-applied 1800 hours later. b) Time evolution of FDV difference between U06B and U06S normalized to the difference at bias disconnection time ($t = 0$).

iments will be seriously affected by the increase of full depletion voltage and consequently required operational voltage, an additional unaccounted radiation damage could result in inefficient operation of detectors. However, part of the time detectors could be unbiased (maintenance, shut down of accelerator), therefore we have investigated the evolution of $|N_{eff}|$ after switching off the bias.

Samples irradiated with neutrons were annealed at 20°C to the minimum of FDV, then bias was switched off. For comparison one unbiased diode was irradiated in parallel with each sample, stored and measured under same conditions except for the bias. Time evolution of FDV after switching off the bias at three different temperatures (-7, 5 and 20°C) is shown in Figs. 4, 5 and 6. Clearly, after switching off the bias, the difference decreases with time, and the time evolution is strongly temperature dependent. Due to power-cuts, the samples at -7 and 5°C experienced accidental warm-up to room temperature. The time scale at warm-up times was extended to obtain a continuous function for time development.

Annealing of bias-induced damage after switching off the bias was also followed for the sample irradiated with pions. Time evolution is shown in Fig. 3. Annealing was faster compared to the annealing at 20°C (Fig. 4) of the sample irradiated with neutrons.

At least four exponentials were needed to fit the time behavior. Their sharing

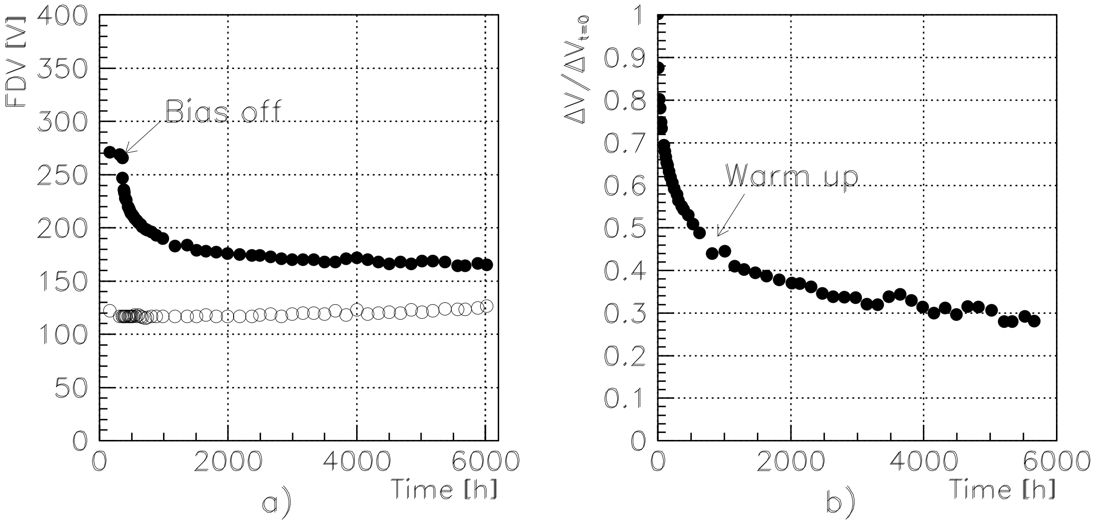

Fig. 5. a) Time development at 5°C of FDV of biased (BA4B) and unbiased (BA4S) samples irradiated with neutrons. b) Time evolution of FDV difference between BA4B and BA4S normalized to the difference at bias disconnection time ($t = 0$).

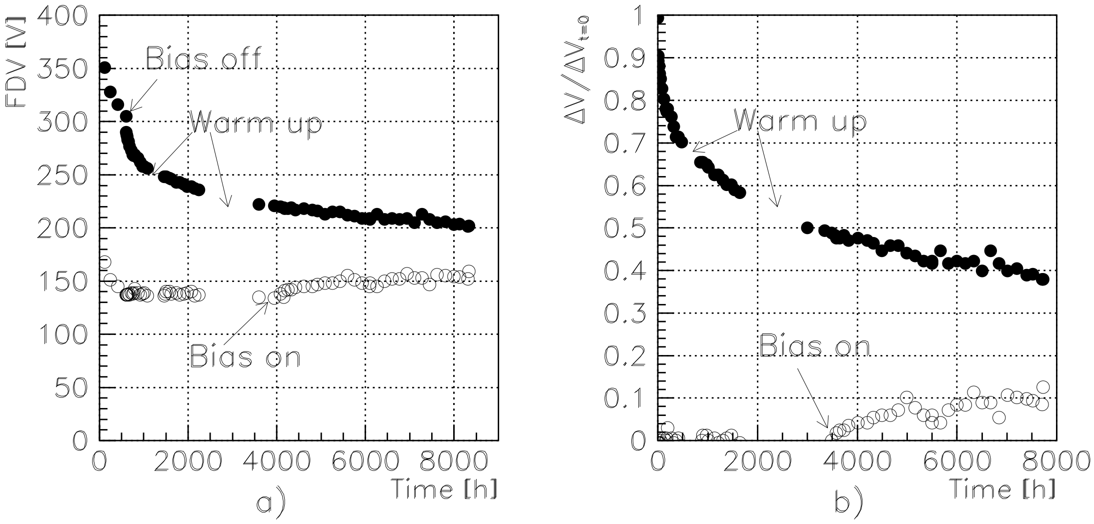

Fig. 6. a) Time development at −7°C of FDV of biased (BA2B) and unbiased (BA2S) samples irradiated with neutrons. After 4000 hours bias was applied to the previously unbiased sample. b) Time evolution of FDV difference between BA2B (full circles) or BA2S (open circles) and BA2S at bias disconnection time ($t = 0$) normalized to the BA2B-BA2S difference at $t = 0$.

was found to be temperature dependent so it was not possible to unambiguously determine the parameters of the processes responsible for annealing of the bias dependent damage.

Nevertheless, times at which 50 % of the difference annealed out were found to be about 3000 h, 500 h and 50 h for neutron-irradiated samples at -7, 5 and 20°C, respectively. For the pion-irradiated sample the half-time was 15 h only. Annealing of 90 % of the initial difference could only be reached for samples at 20°C after 200 h (PIB, pion irradiation) or 1500 h (U06B, neutrons). After 5000 h (over half a year) of annealing, 40 % of the difference still persisted at -7°C while 30 % were left over at 5°C.

3.3 Bistability of defects

It is known that some of the defects created by irradiation are bistable - their properties depend on the applied electric field. A bistable defect created during reverse annealing at elevated temperature (larger than 60°C) was found by the Hamburg group [15]. Our measurements show part of defects exhibiting a bistable behavior already in the very early stage of reverse annealing and at room temperature or even below that (Figs. 4, 6). Bistability of defects was found also on the samples not biased previously (Fig. 6). The amount of bistable defects varies from sample to sample, their contribution to $|N_{eff}|$ is from 10 to 30 percent.

4 Conclusions

A large surplus of effective dopant concentration was measured on samples irradiated and stored under bias. Samples irradiated under bias exhibit about two times larger stable damage creation rate g_C as unbiased ones. Measurement of annealing of the bias-induced damage at different temperatures have shown a strong temperature dependence. So for example, the bias-induced damage in neutron-irradiated samples decreased to half of the initial value after 50 hours at 20°C, while 500 hours were needed at 5°C and 3000 hours at -7°C. At 20°C the relative difference decreased below the 10 % margin after 1500 hours, while at 5°C and -7°C 30-40 % of the difference persisted even for annealing times exceeding half a year. Annealing time measured after irradiation with pions was significantly shorter, the half value was reached already after 15 hours and the 90 % point after 200 hours. The irradiated samples were not, however, from the same production batch, so part of the difference in annealing times could be due to different processing. In addition, irradiation conditions (temperature, flux) were not exactly the same for irradiations with neutrons and pions, so it is to early to conclude on the reason for the different annealing rates.

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