ATL-INDET-2000-014
20/05/2000

Bias Dependence and Bistability of Radiation Defects in Silicon

M. Mikuž [1], V. Cindro, G. Kramberger and D. Žontar

Jožef Stefan Institute and Department of Physics,
University of Ljubljana, SI-1000 Ljubljana, Slovenia

Abstract

Influence of bias on effective dopant concentration in neutron and pion irradiated $p^+ - n - n^+$ diodes has been measured. Detailed studies of annealing of the bias-induced damage have revealed three components, with introduction rates from 0.005 to 0.008 cm^{-1} and annealing time constants ranging from 5 to 1000 hours at 20°C. Variation of annealing temperatures yielded activation energies around 1 eV for all the three components. Bistable behavior of radiation damage under bias has been observed and its activation and annealing studied. The bistable damage was associated to the fastest annealing component of bias-induced damage. Using the parameterization obtained, a prediction for ATLAS SCT operation was made. Bias-induced damage is shown to require an additional 80 V to fully deplete detectors at the end of LHC operation

1 Introduction

The radiation environment at experiments at the Large Hadron Collider will be much harsher than anything encountered in the field so far. Especially the inner, silicon tracker parts of both big, omni-purpose experiments ATLAS and CMS will be exposed to fast particle fluences [2] in excess of 10^{14} cm^{-2} and ionizing doses above 100 kGy [1,2]. The latter poses a challenge for electronics and detector design and manufacturing. Fast heavy particles induce bulk damage with three well established macroscopic manifestations [3]: increase of generation current, $n \to p$ type inversion with subsequent increase of depletion voltage and charge trapping. As both of the strip detector communities

[1] Corresponding author, e-mail: Marko.Mikuz@ijs.si

[2] Bulk damage was found to scale with Non-Ionizing Energy Loss (NIEL). NIEL equivalent of 1 MeV neutrons, denoted $\mathrm{n/cm}^2$, is used for all equivalent fluences in this paper.

chose p^+-strips on n-bulk detectors, the combination of fast electronics and trapping demands sufficient over-depletion for these detectors to operate efficiently. Detailed prior knowledge of the full depletion voltage (V_{FD}) changes with irradiation is therefore of uttermost importance for proper design and operation of these detector systems.

A vast amount of data has been accumulated during recent years and considerable insight gained in understanding and even controlling radiation damage in silicon [4]. Considerable less has been, however, done to explore the influence of conditions under which the detectors at the LHC will be irradiated and operated. Fully biasing the detectors during and after irradiation was shown [5] to nearly double V_{FD} near the minimum between annealing and reverse annealing. The annealing of this bias-induced damage was studied in [6] where a first attempt to parameterize the effect was made. This enabled a prediction of the additional bias needed to operate the detectors irradiated and annealed under LHC conditions. Part of the bias-induced damage was found to exhibit a bistable behavior upon bias re-application.

In this paper the study in [6] has been extended with an update of annealing of the bias-induced damage. The emphasis is, however, given to a detailed study of the bistable part of the damage. Predictions for the additional bias for the ATLAS SCT are also provided.

2 Samples and experimental procedure

For the study 14 $p^+ - n - n^+$ pad detectors were used, their size in the range $0.25 - 1$ cm^2, thickness of 300 ± 5 μm, all having guard rings. Substrates were high resistivity standard FZ silicon with initial $V_{FD}^0 < 60$ V resulting from resistivities in excess of 5 kΩcm. Individual sample properties are summarized in Table 1.

Neutron irradiations were performed at the TRIGA research reactor of the Jožef Stefan Institute in Ljubljana. Samples were irradiated in a tube at the outer radius of the reactor core, providing a uniform equivalent neutron flux up to 2×10^{12} n/cm^{2}s, tunable with reactor power down to 2×10^9 n/cm^{2}s. Details on the reactor neutron spectrum and fluence monitoring are given elsewhere [7,8] and on the irradiation procedure in [6]. The systematic error on the equivalent fluence values is estimated to be about 10 %.

Pion irradiation was done at the Paul Scherrer Institut with 200 MeV π^+. Damage factor of these pions amounts to 1.14 [9]. The flux obtained was $\approx 10^9$ π^+cm^{-2}s^{-1} and it took 10 hours to reach the equivalent fluence of 0.47×10^{14} n/cm^2. Details on the irradiation are given in [6].

Table 1
Properties of diodes used: sample label, manufacturer, initial V_{FD}, irradiation temperature, particles, equivalent flux and fluence, and bias during/after irradiation.

Sample	Processing	V_{FD}^0 [V]	T [°C]	Part. type	ϕ_{eq} [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Φ_{eq} [$10^{14}\mathrm{cm}^{-2}$]	V_{bias} [V]
S3A	Micron	32	15	n	$1.9{\cdot}10^9$	0.45	200/0
S3B	Micron	34	15	n	$1.9{\cdot}10^9$	0.45	0/200
UO6B	Sintef	35	20	n	$1.8{\cdot}10^{11}$	1.7	1000/600
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
BAA	Sintef	37	20	n	$4.2{\cdot}10^{11}$	1.0	600
BAB	Sintef	42	20	n	$4.2{\cdot}10^{11}$	1.0	600
BAC	Sintef	44	20	n	$4.2{\cdot}10^{11}$	1.0	600
BAU	Sintef	41	20	n	$4.2{\cdot}10^{11}$	1.0	0
PIB	Sintef	29	22	π^+	$1.25{\cdot}10^9$	0.47	350
PIU	Sintef	27	22	π^+	$1.25{\cdot}10^9$	0.47	0

All the samples were annealed under controlled temperature and bias conditions in a stabilized refrigerator. V_{FD} was measured in regular intervals with the $C-V$ method, its estimate taken from the "kink" in $1/C^2-V$ plot at 10 kHz and 5°C, except for samples of the BA type annealed at 20°C which were measured at their annealing temperature.

3 Annealing of Bias-Induced Damage

As reported in [5,6], the samples irradiated and annealed under bias exhibit about twice higher V_{FD} at the minimum after beneficial annealing than the unbiased ones. Such an increase in V_{FD} would be disastrous for trackers at the LHC. Taking note that out of operation detectors can be left without bias, the key question is what happens to bias-induced additional damage without the presence of electric field. Therefore we have undertaken a long-term annealing study at temperatures typical for operation (-7°C) and maintenance (20°C) of the ATLAS SCT, with an additional point at 5°C. Diodes were irradiated and annealed in pairs with one of them under bias and the other unbiased. First results of this study were reported in [6], here the study is extended by another sample pair (S3A/S3B). Annealing is fitted with $\Delta|N_{eff}|/\Phi_{eq}$ to get introduction rates of components. The time range for BAA, BAB, BAC and BAU is extended to 4000 hours. The fit for annealing at 20°C now contains three exponentials and a constant term wherever data exist for an annealing period longer than 1500 hours.

All sample pairs were annealed near to the minimum in V_{FD} and then the bias on the diode biased until this point was switched off. $|N_{eff}|/\Phi_{eq}$ difference was calculated by subtracting a function, fitting the time behavior of the unbiased sample of the same pair. In this way fluctuations of measurements of the unbiased diode were effectively filtered out. For samples S3B and UO6S a constant plus a 2^{nd} order reverse annealing term $N_Y \cdot [1 - 1/(1 + t/t_{1/2})]$ was used. To fit BAU, the unbiased reference to BAA, BAB and BAC, one exponential decay term was added to account for the still present annealing at the switch-off time of these samples. Since data for the pion irradiated sample PIU exist only up to 500 hours, a linear function fitted the data well enough. The same was true for BA4S due to the lower annealing temperature (5°C). For BA2S, annealed at −7°C, a constant level was adequate.

The annealing of the $|N_{eff}|/\Phi_{eq}$ difference for samples S3B, UO6B, BAA, BAB and BAC was fitted with a constant and three exponential terms

$$\frac{\Delta|N_{eff}|}{\Phi_{eq}}(t) = g_0 + g_1 e^{-t/\tau_1} + g_2 e^{-t/\tau_2} + g_3 e^{-t/\tau_3} \qquad (1)$$

where t is the time from bias disconnection, g's are the introduction rates of the components and τ's the respective decay times. An example of the fit is shown in fig. 1. Absolute errors of individual measurements were adjusted so as to get a normalized chisquare of the fit close to one. As will be shown later, statistical errors on fit parameters anyway represent a minor part of the overall error.

For the pion irradiated sample pair PIB/PIU absence of data above 500 hours after bias disconnection required dropping of the third exponential in the fit. Data for the BA4 pair at 5°C (fig. 2) exist up to 10000 hours. The expected increase of time constants from 20°C is of order ten for an activation energy about 1 eV. Thus the interval seemed to short to fit the longest annealing component. On the other hand, the measured τ_3 of about 1000 hours at 20°C still allows for a considerable influence of this component. As a compromise, the time interval for a two decay component fit was taken at 3500 hours.

Annealing of the BA2 pair at −7°C should have prolongated time constants from 20°C by two orders of magnitude, so the influence of the longest annealing

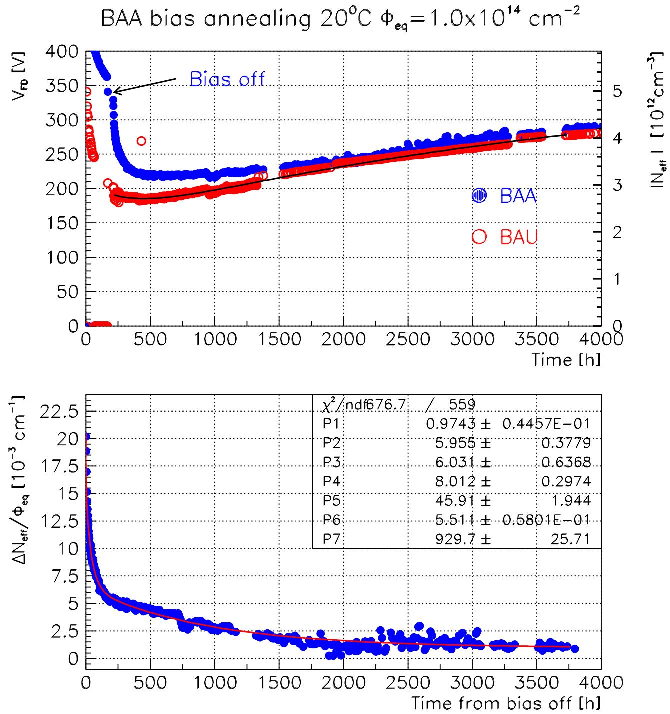

Fig. 1. a) V_{FD} time development for the pair BAA/BAU at 20°C. After 240 hours of annealing, bias on BAA was switched off. The line represents a fit to BAU as described in text. b) Annealing of $\Delta|N_{eff}|/\Phi_{eq}$ after bias disconnection. The line represents a fit according to eq. 1 up to 3750 hours.

component is expected to be moderate even in the complete time interval of 11000 hours. Annealing results are shown in fig. 3.

Table 2
Results of fits to annealing of bias-induced damage. Errors given by the fit are quoted for individual samples. Variance of distributions is quoted as error on the averages.

Sample pair	T_a °C	g_0 $10^{-3}\,\mathrm{cm}^{-1}$	g_1 $10^{-3}\,\mathrm{cm}^{-1}$	τ_1 h	g_2 $10^{-3}\,\mathrm{cm}^{-1}$	τ_2 h	g_3 $10^{-3}\,\mathrm{cm}^{-1}$	τ_3 h
S3B/A	20	-2.0 ± 0.7	3.3 ± 0.6	3.8 ± 1.5	6.8 ± 1.0	99 ± 28	3.3 ± 0.5	1050 ± 710
UO6B/S	20	2.4 ± 1.1	3.0 ± 0.5	3.3 ± 1.3	4.9 ± 0.4	71 ± 18	4.1 ± 0.8	1010 ± 750
PIB/U	20	-1.5 ± 0.1	6.2 ± 0.3	2.8 ± 0.4	7.6 ± 0.2	65 ± 4	-	-
BAA/U	20	1.0 ± 0.1	6.0 ± 0.4	6.0 ± 0.6	8.0 ± 0.3	46 ± 2	5.5 ± 0.1	930 ± 30
BAB/U	20	-0.7 ± 0.1	6.2 ± 0.3	8.6 ± 0.9	8.6 ± 0.2	95 ± 4	4.2 ± 0.1	1380 ± 110
BAC/U	20	3.3 ± 0.1	4.4 ± 0.3	6.7 ± 0.9	8.4 ± 0.2	100 ± 4	3.0 ± 0.1	1060 ± 90
average 20°C		0.4 ± 2.2	4.9 ± 1.5	5.2 ± 2.3	7.4 ± 1.4	79 ± 22	4.0 ± 1.0	1080 ± 170
BA4B/S	5	7.1 ± 0.2	5.6 ± 0.3	31 ± 6	8.4 ± 0.2	760 ± 80	-	-
BA2B/S	-7	4.4 ± 0.2	4.6 ± 0.3	137 ± 23	9.8 ± 0.2	3550 ± 230	-	-
overall average		-	4.9 ± 1.3	-	7.8 ± 1.5	-	-	-

The results on bias-induced damage annealing are summarized in Table 2. For

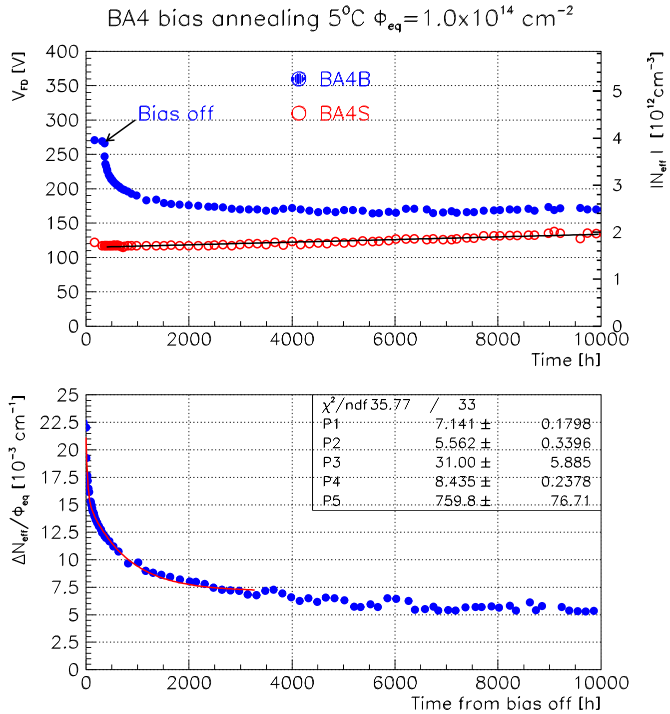

Fig. 2. a) V_{FD} time development for the pair BA4B/BA4S at 5°C. After 400 hours of annealing, bias on BA4B was switched off. The line represents a linear fit to BA4S. b) Annealing of $\Delta|N_{eff}|/\Phi_{eq}$ after bias disconnection. The line represents a fit with two decay terms plus a constant up to 3500 hours.

the average, all results were taken with equal weights, and the variance of parameters taken as the error of the average. In this way the influence of the rather arbitrary error estimate of the individual measurements was avoided. The variance is expected to cover systematic errors such as inadequacy of the model used, fluence fluctuations and sample-to-sample systematic fluctuations. As the constant term at lower annealing temperatures is bound to include also the longest decay term, g_0 was averaged over the samples annealed at 20°C only.

While the systematic errors for the 20°C values are believed to be described by the variance between samples, systematic errors on decay times τ_1 and τ_2 at lower temperatures were estimated by a variation of the fit time interval. At 5°C the fit interval was varied by 1500 hours, so that at the lower limit it still allowed a 95 % decay of the second decay component. Such time interval variation resulted in decay time variations of ±10 hours for τ_1 and ±220 hours for τ_2. At −7°C the complete 11000 hour fit interval is already at the $3\tau_2$ limit, so the interval was decreased by τ_2 to 7500 hours, reducing τ_1 by 45 and τ_2 by 1000 hours. These changes were taken symmetrically as an estimate of systematic errors.

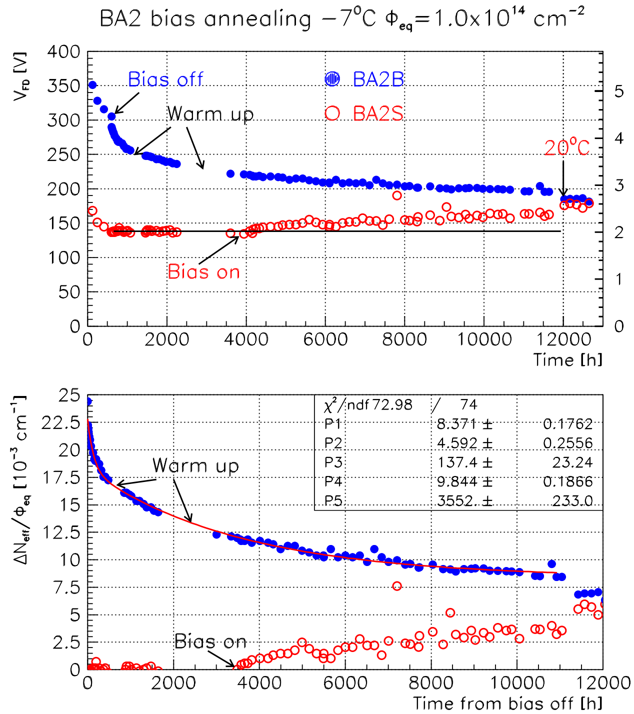

Fig. 3. a) V_{FD} time development for the pair BA2B/BA2S at $-7°$C. After 600 hours of annealing, bias on BA2B was switched off. After 4000 hours of annealing, bias was applied to the previously unbiased sample BA2S. The line represents a constant fit to BA2S up to bias application. Two accidental warm-ups to room temperature were corrected by an appropriate extension of the time scale. After 12000 hours samples were switched to room temperature. b) Annealing of $\Delta|N_{eff}|/\Phi_{eq}$ after bias disconnection. The line represents a fit with two decay terms plus a constant up to 11000 hours.

Systematic errors are clearly dominant and were added in quadrature to the fit errors. The final results on annealing time constants τ_1 and τ_2 are given in Table 3.

Table 3
Results on annealing time constants τ_1 and τ_2 including their overall error estimate at the three temperatures.

T_a °C	τ_1 h	τ_2 h
20	5.2 ± 2.3	79 ± 22
5	31 ± 11	760 ± 230
-7	137 ± 50	3550 ± 1000

The values of τ_1 and τ_2 at the three temperatures were fitted with the Arrhenius relation

$$\tau(T) = \tau_0 \cdot e^{\frac{E_a}{k_B T}} \tag{2}$$

where τ_0 represents the infinite temperature decay time, E_a the activation energy and k_B is the Boltzmann constant. The results of the fit, depicted in fig. 4, are

$$E_a(\tau_1) = 0.81 \pm 0.15 \text{ eV} \quad \text{and} \quad E_a(\tau_2) = 0.95 \pm 0.10 \text{ eV}.$$

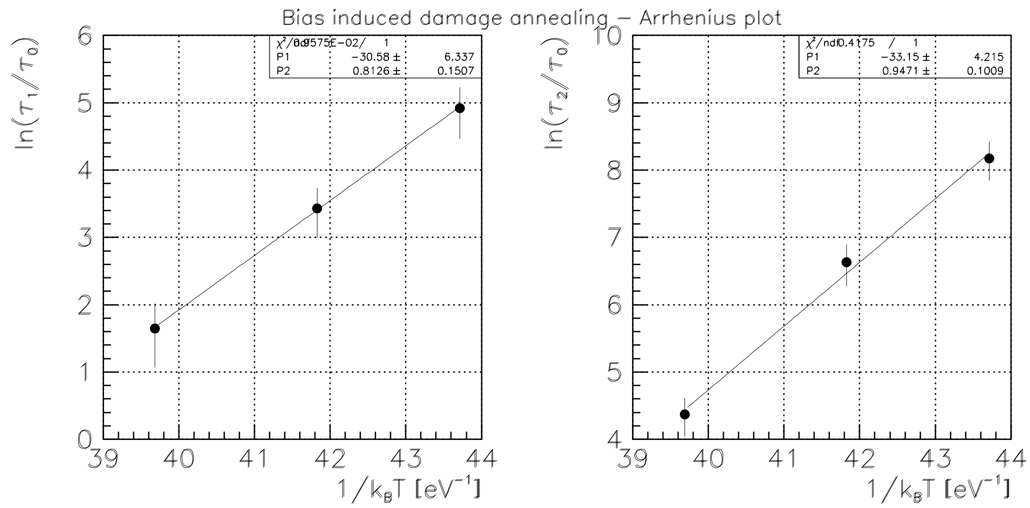

Fig. 4. Arrhenius plot of bias-induced damage annealing decay times τ_1 and τ_2. The lines represent a fit to the Arrhenius relation.

To estimate the activation energy of the longest decay time τ_3 data at 5°C were fitted over the complete 10000 hour annealing interval according to eq. 1. The rather short time interval induced a large correlation between the constant term and the long decay component. The fit was unstable unless the constant was fixed. Fixing it at zero gave values of the parameters

$$g_1 = (5.5 \pm 0.4) \times 10^{-3} \text{ cm}^{-1} \qquad \tau_1 = 31 \pm 6 \text{ h}$$
$$g_2 = (7.6 \pm 0.3) \times 10^{-3} \text{ cm}^{-1} \qquad \tau_2 = 700 \pm 90 \text{ h}$$
$$g_3 = (8.0 \pm 0.3) \times 10^{-3} \text{ cm}^{-1} \qquad \tau_3 = 22500 \pm 2500 \text{ h}$$

consistent with results of the reduced time-interval fit in Table 2. The systematic error on τ_3 was estimated by varying the fixed constant term by 2×10^{-3} cm^{-1}, that being its variance at 20°C. This variation moved the value of τ_3 by 8000 hours, the final results on τ_3 thus reading

$$\tau_3(5°\text{C}) = 22500 \pm 8400 \text{ h} \quad \text{and} \quad \tau_3(20°\text{C}) = 1080 \pm 170 \text{ h}.$$

The systematic error at 20°C is again believed to be covered by the variance. A fit to the Arrhenius relation, based on the two data points only, yielded a value of $E_a(\tau_3) = 1.4\pm0.2$ eV for the activation energy of the longest annealing time.

4 Bistable Damage

As exhibited in fig. 5 an increase of V_{FD} is observed on irradiated samples upon application of bias (200 V for S3A/S3B). This effect was observed in diodes irradiated under bias as S3B or UO6B after the bias-induced damage had been annealed out, as well as in S3A and BA2S (fig. 3) which were never biased before. Data in fig. 5 also show this damage annealing out in a short time after bias disconnection. Hence this part of damage is bistable upon bias application. To characterize the bistable damage a linear fit to the sample's

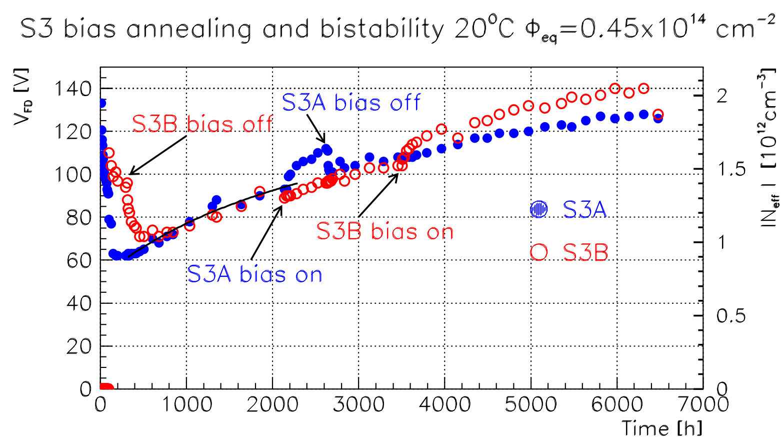

Fig. 5. V_{FD} time development of the S3A/S3B pair. After 400 hours of annealing, voltage on the previously biased sample S3B was switched off and 2200 hours later switched back on. After 2200 hours of annealing bias on the previously unbiased sample S3A was switched on.

own reverse annealing around bias (re)-application was subtracted. Then the difference was fitted by

$$\frac{\Delta|N_{eff}|}{\Phi_{eq}}(t) = g_b \cdot (1 - e^{-\frac{t-t_{on}}{\tau_b}}) \tag{3}$$

with g_b the introduction rate and τ_b the activation time of the bistable damage. The results of the four bistable damage activation fits of S3A, S3B and UO6B at 20°C as well as BA2S at -7°C are shown in fig. 6. The fits are reasonable although there is a hint to a second component with a shorter activation time, especially in the -7°C data.

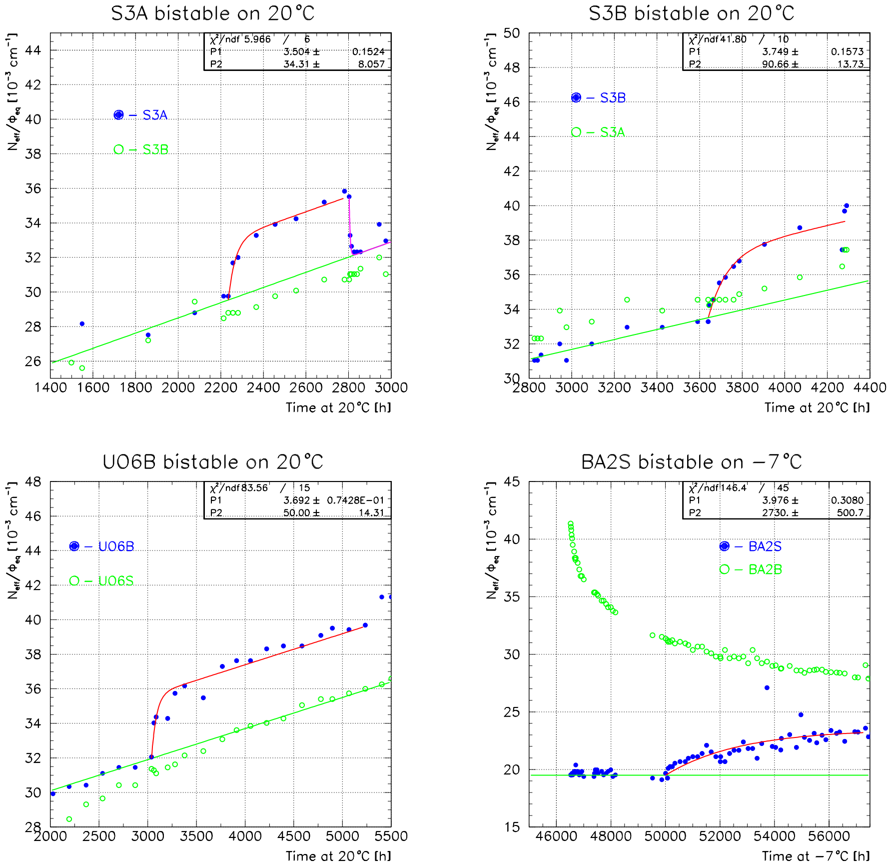

Fig. 6. Activation of bistable damage in S3A, S3B and UO6B at 20°C and in BA2S at −7°C. Lines represent results of fits according to eq. 3 and the weakly printed straight lines the subtracted linear fits to reverse annealing. The other diode in the sample pair is depicted in open circles.

Annealing of the bistable damage was followed on S3A only. A fit to

$$\frac{\Delta |N_{eff}|}{\Phi_{eq}}(t) = g_b \cdot e^{-\frac{t-t_{off}}{\tau_a}} \tag{4}$$

is depicted in fig. 7.

The fitted parameter values of bistable damage activation and annealing are summarized in Table 4. We notice that the value of g_b of S3B and UO6B agrees well with the values of g_1 for the same diodes in Table 2. Agreement is also found between g_1 of BA2B and g_b of BA2S. Finally the annealing time τ_a coincides well with τ_1. Therefore we conclude that the bistable defect under bias is the same as the fast annealing component of the bias-induced damage.

From measurements of activation time τ_a at 20°C and −7°C, Arrhenius relation yields $E_a(\tau_b) = 0.96 \pm 0.15$ eV as the corresponding activation energy.

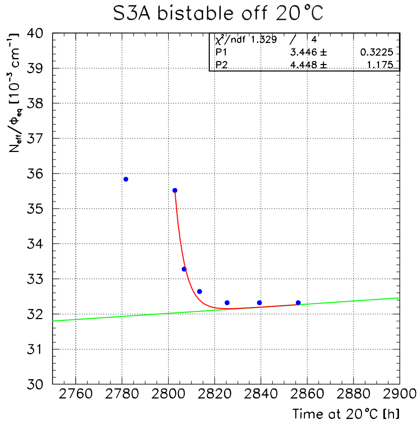

Fig. 7. Annealing of the bistable damage in S3A at 20°C. After 2800 hours of annealing, of which the last 700 h were under bias, the voltage on the sample was switched off. The line represents the result of the fit according to eq. 4 and the weakly printed straight line the subtracted linear fit to reverse annealing.

Table 4
Results on bistable damage activation and annealing parameters.

Sample	T °C	g_b 10^{-3} cm^{-1}	τ_b h	g_b 10^{-3} cm^{-1}	τ_a h
S3A	20	3.5 ± 0.2	34 ± 8	3.4 ± 0.03	4.4 ± 1.2
S3B	20	3.7 ± 0.2	91 ± 14	-	-
UO6B	20	3.7 ± 0.1	50 ± 14	-	-
average 20°C		3.6 ± 0.1	58 ± 30	-	-
BA2B/BA2S	-7	4.0 ± 0.3	2730 ± 500	-	-

This result should be taken with some reservation as there are τ_a measurements at two temperatures only and there is a hint that more than one defect might be responsible for the bistable damage.

5 Predictions for ATLAS SCT

As a benchmark study for the extent of bias-related additional radiation damage the example of the ATLAS SCT was taken. At inner radii detectors will receive an equivalent fluence of $2. \times 10^{12}$ cm^{-2} per low-luminosity and $2. \times 10^{13}$ cm^{-2} per high-luminosity year. The standard LHC scenario of 3 low and 7 high-luminosity years was considered. When comparing with conventional damage projections, one should care, that damage estimates sometimes include a safety factor of 1.5, which was not applied in this estimate.

The standard ATLAS yearly temperature and biasing scenario was applied implying 100 days operation under bias at -7°C. Then the bias is switched off first for 100 days still at -7°C, followed by a 2 plus 14 days maintenance at 20 and 17°C, respectively. The remaining 150 days are spent again unbiased at the operational temperature of $-7°C$.

The bias-induced damage parameters were taken from Table 2. The constant term g_0 was discarded, but therefore the longest annealing component introduction rate was increased to 6×10^{-3} cm^{-1}. The annealing times were scaled with the respective activation energies according to eq. 2. In accordance with findings of the previous section, the bistable damage introduction rate was set equal to that of the bias-induced component with the shortest annealing time g_1 (4.9×10^{-3} cm^{-1}). Defects available for activation were the ones created by irradiation in previous years and annealed out in the idle period. The activation time under bias at $-7°C$ is 100 days, so about 60 % of this damage are re-activated. According to the single measurement at 20°C, complete annealing of the bistable part could be assumed during each year's high temperature period.

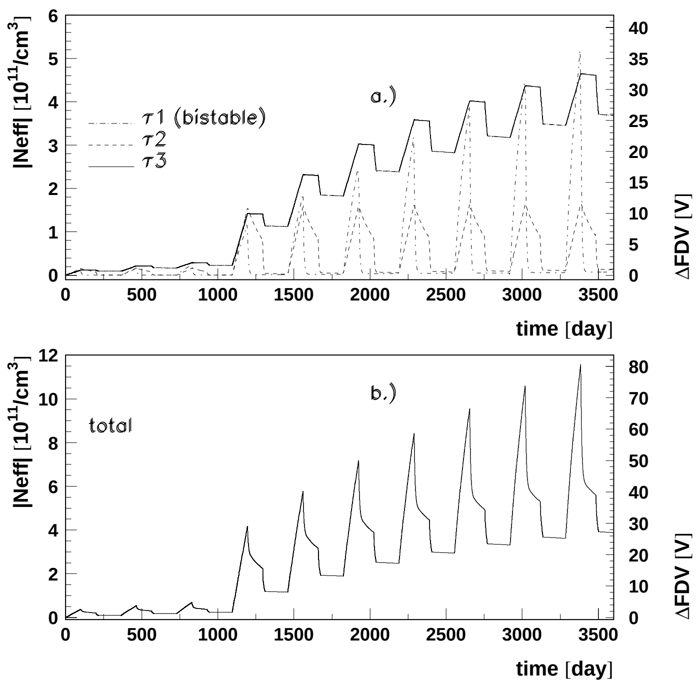

Fig. 8. Prediction of the influence of bias-related damage to ATLAS SCT detectors in 10 years of LHC operation: a) each of the components considered separately and b) the total of the bias-related damage. For fluences and temperature scenarios applied see text.

The prediction for additional acceptor density and additional voltage needed to fully deplete ATLAS SCT detectors resulting from bias-induced damage is shown in fig. 8. Additional damage, corresponding to additional 25 V of bias, is created during irradiation in each high-luminosity year. The relatively short time constants τ_2 and τ_2 allow for a complete annealing of the respective damage during idle time. The longest annealing component exhibits a saturation leading to an additional 30 V at end of operation, where re-activation of previous years' bistable damage contributes another 30 V. All added up, additional 80 V are predicted to be needed to fully deplete ATLAS SCT detectors at end of operation. This is about half the expected contribution from the introduction of stable acceptors by irradiation.

6 Conclusions

Influence of the electric field on radiation damage in silicon now seems to be an established phenomenon. Several defects present in detectors irradiated and annealed under bias have been identified and their annealing studied at temperatures, representative for operation and maintenance of LHC detectors. Activation energies of annealing components were deduced from data. Part of the damage was found to be bistable under bias. Activation of this bistable part was observed even on samples not biased previously. Time constants for bistable damage activation and annealing were extracted. Bistability could be associated with the annealing component of the bias-induced damage with the shortest time constant.

Bias-related effects add an additional burden to be surmounted by detectors at the LHC. Measurements reported in this paper have enabled a parameterization of creation and annealing of the bias-induced and bistable damage. A prediction for ATLAS SCT, based on parameters obtained this way, estimates the additional voltage needed to fully bias detectors to 80 V at end of LHC operation.

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