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Experimental Comparisons Among Various Models for the Reverse Annealing of the Effective Concentration of Ionized Space Charges (N_{eff}) of Neutron Irradiated Silicon Detectors*

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Abstract

Experimental data of the reverse annealing of the effective concentration of ionized space charges (N_{eff} , also called effective doping or impurity concentration) of neutron irradiated high resistivity silicon detectors has been compared with various models. The models include the compensation model (first order), the cluster model of the first order, the neutral to acceptor model (first order), and the cluster model of the second order. Detectors irradiated to various neutron fluences have been annealed at 80 °C for up to 17 hours to reach the saturation of the first apparent stage of the N_{eff} reverse anneal, which is equivalent of about one year of room temperature (RT) anneal. The anneal time constant, defined as the time at half saturation $\tau_{1/2}$, has been found virtually a constant (~ 140 minutes $\pm 14\%$) for detectors irradiated to fluences ranging from 8.2×10^{12} n/cm² to 3.2×10^{13} n/cm², which is the distinguish characteristic of the first order process. The least square fit of the data to the first order models has shown a time constant of 221.7 minutes with 14% error and that to the second order model has shown a k constant of 7.3×10^{-5} s⁻¹ with 37% error. The best fit, however, is a first order fit with two time constants: a short one (~ 44 minutes $\pm 25\%$) with a small amplitude and a longer one (~ 290 minutes $\pm 12\%$) with almost five times as larger amplitude, suggesting that even for the apparent first stage of the N_{eff} reverse anneal, there may be two stages. There is also evidence that even after the apparent first stage anneal, there is at least another stage which is showing up in higher temperature anneal (150 °C).

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I. Introduction

The studies of neutron radiation induced changes of electrical properties of silicon detectors and the related radiation hardness investigations have been focused in recent years on the increase of the effective concentration of the ionized space charges (N_{eff} , also called effective doping or impurity concentration) during the radiation and during the room temperature (RT) anneal.[1-9] The practical aspect of the problem is that high N_{eff} would make the high resistivity detector impossible to deplete after a radiation of 1.0×10^{14} n/cm² and the RT anneal thereafter (the full depletion voltage $V_d \sim 600$ volts for 300 μ m thick detector). There have been several models in the literature to describe the effect of the N_{eff} reverse annealing: 1) the compensation model, which explains the N_{eff} reverse annealing (a space charge region (SCR) effect) as well as the effect of near intrinsic resistivity in the electrical neutral bulk (ENB), in terms of the compensation by neutron induced deep levels in the ENB and a net acceptor ionized state of space charges during the radiation, and different annealing time constants for acceptor and donor deep levels during the anneal;[6] 2) the transformation of a neutron induced deep level from the electrical neutral to acceptor state model which attributes the N_{eff} reverse annealing as a simple change of the charge state of the deep level;[5,8,10] 3) the cluster model of the first order which describes the N_{eff} reverse annealing as the breaking up of the neutron induced defect clusters into acceptor like single defects;[6] and 4) chemical reaction in the second order[7,9] which suggests, from the results of least square fitting of the data, that the N_{eff} reverse annealing is caused by the recombination of two single neutral defects with about the same concentration into an acceptor like third single defect. One specific reaction of the second order suggested in ref. [6] is the formation of singly charged double vacancies by single vacancies from the breaking up of the defect clusters. We note here that models 1) to 3) are all of the first order and model 4) is of the second order and they all assume one stage of the reverse annealing. However, there are evidences now that the reverse annealing of N_{eff} may be a multi-stages processes [7] and, as we will report in this work,

the kinetic of each stage may be different. The aim of this work though, given the complexity of the problem, is two fold: a) lay out some detailed mathematical modeling of the models mentioned above to find distinguish differences among them or between the first and second order processes; and b) make systematic comparisons between the experimental data and various models and/or the first order and second order processes. The goal of this work is that it would take us a step closer towards the understanding of the real physical processes behind the reverse annealing effect and therefore make it more possible to develop neutron radiation hardened silicon detectors for the new collider experiments.

II. Mathematical Modeling

As we have mentioned above, there are basically four types of models in the literature describing the effect of N_{eff} reverse annealing. In this section, we will give some mathematical details to each model to find the distinguish differences among them, which would make it easy to be compared with the experimental data in the next section.

1) The compensation model

This model, proposed in ref. [6], is based on the compensation in the ENB by neutron induced deep levels and a net ionized acceptor charge state in the SCR. At high neutron fluences ($\Phi_n > 10^{13} \text{ n/cm}^2$) the ENB is highly compensated resulting in high (near intrinsic) resistivity and the net concentration of ionized space charges (N_{eff}) is also high and increase with Φ_n in the SCR resulting in high depletion voltages. The effect of the N_{eff} reverse annealing is explained by two levels (in addition to other levels) in the SCR, with opposite charge states and about same concentration (~ 0 in net space charge), anneal in different rates, or with different anneal time constants. The reverse anneal is attributed to the fast annealing of the deep donor level (+ space charge) as compared with the deep acceptor level (- space charge), resulting in a net increase of the negative space charge in the given time range.

The initial fast anneal ($\tau_{ann} \sim 10$ days) (the anneal before the reverse anneal) of the N_{eff} at RT is explained by the annealing of a third deep level (acceptor). Following this initial anneal, the reverse anneal start to take place. Let us just consider the reverse anneal component of the N_{eff} , N_{eff}^* . Right after the radiation

$$\begin{cases} N_{eff}^*(t) = N_{t2^+}(t) - N_{t1^-}(t) \\ N_{t1^-}(t) = N_{t1^-}^0 e^{-t/\tau_{t1}} \\ N_{t2^+}(t) = N_{t2^+}^0 e^{-t/\tau_{t2}} \end{cases} \quad (1)$$

where N_{t1^-} and N_{t2^+} are the concentrations of the acceptor level and donor level, respectively; and τ_{t1} and τ_{t2} are corresponding time constants. Assuming that the two deep levels have the same initial concentration: $N_{t1^-}^0 = N_{t2^+}^0 = N_t^0$, we have:

$$\begin{aligned} |N_{eff}^*(t)| &= N_t^0 e^{-t/\tau_{t1}} (1 - e^{-t(\frac{1}{\tau_{t2}} - \frac{1}{\tau_{t1}})}) \\ &\approx N_t^0 (1 - e^{-\frac{t}{\tau_{t2}}}) \quad (\text{since } \tau_{t2} \ll \tau_{t1} \text{ and for } t \ll \tau_{t1}) \end{aligned} \quad (2)$$

Therefore the process is of the first order and the time constant is the same as that of the deep donor level.

2) Neutral to acceptor transformation model

This model was first proposed by the people of the University of Hamburg. [5,8,10] The N_{eff} reverse anneal effect is explained as the creation of negative space charges via the transformation of a neutron induced deep level from electrical neutral state to an acceptor state. One specific reaction of such a transformation was suggested in ref. [6]: the V-V center may change from the V-V⁰ charge state to the V-V⁻ charge state when the Fermi level moving up during the anneal:

The kinetic of this reaction is also of the first order and can be expressed as the following:

$$|N_{eff}^r(t)| = N_{V-V^0}^0 (1 - e^{-\frac{t}{\tau_{V-V^0}}}) \quad (4)$$

where $N_{V-V^0}^0$ is the initial concentration of the V-V⁰ center and τ_{V-V^0} is the corresponding anneal time constant.

3) Cluster model of the first order

This model, first suggested in ref. [6], describes the N_{eff} reverse annealing as the increase of ionized net acceptors in the SCR from the breaking up of the neutron induced defect clusters into a single acceptor level. One possible such level is the V-V⁻ center:

This reaction is again of the first order and can be written as:

$$|N_{eff}^r(t)| = \eta N_C^0 (1 - e^{-\frac{t}{\tau_C}}) \quad (6)$$

where N_C^0 is the initial concentration of the clusters, τ_C the corresponding annealing time constant, and η the number of V-V⁻ centers per cluster breaking.

4) Cluster model of the second order

The reverse annealing of the N_{eff} was first suggested by Fretwurst et al. of the University of Hamburg as the second order chemical reaction.[5] They have found a better least square fit of the second order process to the experimental data than the traditional first order one. The model is based on the formation of an acceptor level during the anneal by two neutral deep levels with about the same concentrations. Since both the N_{eff} and N_{eff}^r increases with the neutron fluence, it is likely that these two defect levels are vacancy and /or double vacancies defects. The most probable candidate is the single vacancy itself.

But free single vacancies can not exist at RT after radiation^[11], it has to come from other sources. One possible source is again the defect clusters. As proposed in ref. [6], the clusters may break up into, instead of V-V's as suggested in model 3), neutral single vacancies. These vacancies may still not be totally free but constrained in a loose configuration of the broken-up cluster, and we denote them by a symbol V_C (or closely packed single vacancies):

where θ is the number of single vacancies per breaking of cluster.

The total concentration of vacancies from the breaking up of the clusters (with total initial concentration N_C^0) is:

$$N_{V_C}^0 = \theta \cdot N_C^0 \propto \Phi_n \quad (8)$$

which includes the concentration of closely packed V_C 's (N_{V_C}), the vacancies in the formed V-V's ($2 \times N_{V-V^-}$), and the vacancies that eventually go free and disappear (annealed out) (N_V):

$$\theta \cdot N_C^0 = N_{V_C}(t) + 2N_{V-V^-}(t) + N_V(t) \quad (9)$$

The rate equations can be written as the following:

$$\begin{cases} \frac{dN_{V_C}}{dt} = -\kappa N_{V_C}^2 \\ \frac{dN_{V-V^-}}{dt} = \frac{1}{2} \kappa N_{V_C}^2 \\ N_{V-V^-}(t=0) = 0, \quad N_{V_C}(t=0) = N_{V_C}^0 \end{cases} \quad (10)$$

Assuming that $N_V(t)=0$, the solutions of eq. (10) are:

$$\begin{cases} N_{V_c}(t) = \frac{1}{\kappa t + 1 / N_{V_c}^0} \\ N_{V-V^-}(t) = \frac{N_{V_c}^0}{2} - \frac{1}{2(\kappa t + 1 / N_{V_c}^0)} \end{cases} \quad (11)$$

where κ is a constant that characterizes the rate of the process.

The amplitude of the reverse anneal is therefore as the following:

$$|N_{eff}^r(t)| = N_{V-V^-}(t) = N_{eff}^{r,max} - \frac{1}{\kappa' t + 1 / N_{eff}^{r,max}} \quad (12)$$

where $N_{eff}^{r,max} \equiv N_{V_c}^0 / 2$ is the amplitude of the reverse anneal and κ' is the new constant defined as $\kappa' = 2\kappa$

III. Experimental Comparisons

As we have discussed in the previous section, the first three models can be described by a first order process:

$$\begin{cases} |N_{eff}^r(t)| = N_{eff}^{r,max} (1 - e^{-\frac{t}{\tau}}) \\ \tau_{1/2} = -\tau \cdot \ln(0.5) = \text{constant (not dependent on } \Phi_n) \end{cases} \quad (13)$$

While the fourth model can be described by the second order process:

$$\begin{cases} |N_{eff}^r(t)| = N_{eff}^{r,max} - \frac{1}{\kappa' t + 1 / N_{eff}^{r,max}} \\ \tau_{1/2} = \frac{1}{\kappa' N_{eff}^{r,max}} \propto \frac{1}{\Phi_n} \end{cases} \quad (14)$$

It is clear that the major difference between the first order process and the second order one is that the anneal time constant of the first order one is independent of the neutron fluence and that of the second order one decreases with increasing fluence, as is clearly shown in Fig. 1. The approach for the experimental comparisons with the models is therefore centered with the annealing of detectors irradiated with large difference of neutron fluences.

The silicon detectors were manufactured from Wacker n-type (111) wafers, with resistivity of 4-6 k Ω -cm, thickness of 300 μ m and 400 μ m, and area of 0.1 cm². The detector were irradiated to neutron fluences ranging from 8.2×10^{12} n/cm² to 3.2×10^{13} n/cm², about a factor of four in difference. High fluences than 3.2×10^{13} n/cm² would make the detectors hard to deplete ($V_d > 500$ volts), and lower fluences than 8.2×10^{12} n/cm² would be too close to the tail of the donor removal effect^[6]. The detectors were annealed at elevated temperatures to reach the saturation's of the first apparent stage of the N_{eff} annealing in reasonable time. The start of the elevated temperature anneal was about one month after the radiation to ensure a complete RT annealing of the initial N_{eff} anneal. The RT reverse annealing may have already started just a little, but should be less than 10% of the total amplitude $N_{eff}^{r, max}$. One or two detectors were used at each fluence and were annealed at a given temperature for various time intervals. C-V measurements were made between each anneal to obtain the detector full depletion voltages.

Fig. 2 shows the C-V characteristics at RT after each annealing time interval for detectors irradiated to various neutron fluences. The annealing temperature was 80 °C and the detectors were annealed for 0 minutes at the start to up to 1,000 minutes at the end. The full depletion voltages are clearly increasing with annealing time and they all start to saturate at $t_{ann} \sim 10$ hours (or 600 minutes). There is no apparent dependence of the annealing time constant, $\tau_{1/2}$, on the neutron fluence. In fact, the time constants obtained from the anneal data shown in Fig. 3 are nearly a constant, as shown in Table I. The

standard deviation from the average value of $\overline{\tau_{1/2}}=8,400$ sec (or 140 minutes) is only 13.6%. This finding, as we have discussed before, would make the second order process unlikely for the first apparent reverse annealing stage, since the $\tau_{1/2}$ would have been different by a factor of nearly four had it been the second order process. In order compare the first order and second order processes directly, the annealing data has been fitted to the first order model in Fig 4a and the second order model in Fig. 4b. There is no apparent difference between the two fittings to the data, although the second order model seems to have better fit in the middle section of the curves (from $t=10,000$ sec to $t=30,000$ sec). However, as we will discuss more in the next paragraph, this middle section may be the boundary of two first order annealing stages. We note here that a parameter N_0 has been used in the fittings shown in Fig. 4 to compensate the initial value of the N_{eff} . The formula are otherwise the same as the those listed in eq(13) and (14) (if N_0 is set to 0, then they are exactly the same).

Further examination of the middle section of the data shown in Fig. 4 has revealed a small step in the section, suggesting two annealing stages in the apparent "first" annealing stage. Fig. 5 shows the fit of the annealing data to a two terms (or two time constants), first order process model. The fitting is obviously the best so far and the misfit in the middle section observed in Fig. 4a disappeared. Since the second order process is unlikely, the apparent "first" annealing stage is therefore probably a two-stage event. We will from now on call them reverse annealing stage one and stage two, respectively.

The fitting parameters for the one-term first order fit are shown in Table II, those for the second order fit in Table III, and those for the two-term first order fit in Table IV. The average time constant for the one-term first order fit is 13,300 sec (or 222 mins) $\pm$ 14.2%, the average κ constant for the second order fit is 7.3×10^{-5} cm³/s $\pm$ 37.4%, and the average time constants for the two-term first order fit are 2,648 sec (or 44 mins) $\pm$ 25% for stage one and 17,400 sec (or 290 mins) $\pm$ 12.3% for stage two. The large error in the time constant for the stage one may be caused by the small amplitude of the annealing stage,

about four times as smaller than the that of the stage two, which makes the precise measurement more difficult. Again, the largest error is associated with the second order fit.

It is obvious that the reverse annealing amplitude $N_{eff}^{r,max}$ is proportional to the neutron fluence in all three cases. The initial value of the N_{eff} , N_0 , also increases linearly with the neutron fluence when $\Phi_n > 1 \times 10^{13} \text{ n/cm}^2$. At smaller fluences, the value of N_0 is largely affected by the donor removal which is not proportional to Φ_n . [6] The dependence of N_0 and $N_{eff}^{r,max}$ on the neutron fluence can be summarized as the following :

$$\begin{cases} N_0 = 0.03517 \cdot \Phi_n \\ N_{eff}^{r,max} = 0.07331 \cdot \Phi_n \end{cases} \quad (\text{one - term first order fit}) \quad (15)$$

and

$$\begin{cases} N_0 = 0.03272 \cdot \Phi_n \\ N_{eff}^{r,max} = 0.09014 \cdot \Phi_n \end{cases} \quad (\text{second order fit}) \quad (16)$$

and

$$\begin{cases} N_0 = 0.03200 \cdot \Phi_n \\ N_1 = 0.01627 \cdot \Phi_n \\ N_2 = 0.06025 \cdot \Phi_n \\ N_{eff}^{r,max} \equiv N_1 + N_2 = 0.07652 \cdot \Phi_n \end{cases} \quad (\text{two - term first order fit}) \quad (17)$$

The values of N_0 for various models are very close, less than 10% in differences among them. The differences in the values of $N_{eff}^{r,max}$, however, are much larger, over 20%. Based on the previous arguments, eq.(17) is probably the more accurate description of the real process, and the total concentration of the ionized space charges after the reverse annealing stage one and two is:

$$N_{eff}^{1,2} = N_0 + N_{eff}^{r,max} = 0.10852 \cdot \Phi_n \quad (\Phi_n \geq 1 \times 10^{13} \text{ n/cm}^2) \quad (18)$$

It is clear that for high resistivity silicon detectors, a radiation of a fluence larger than $2.5 \times 10^{13} \text{ n/cm}^2$ along with the RT anneal would push N_{eff} value out of the proper window of $|N_{eff}| \leq 2.5 \times 10^{12} \text{ n/cm}^3$ for 300 μm thick detectors ($V_d = 180$ volts). For the 10 year LHC total fluence of $1 \times 10^{14} \text{ n/cm}^2$, the RT temperature operation of the 300 μm thick silicon detectors would then be almost out of question ($V_d = 700$ volts). There have been a few alternatives that would make silicon detectors still applicable to the large collider experiments. One alternative is to operate the detectors at low temperatures, preferable at 0°C , to freeze the reverse annealing of the N_{eff} . This method has been tried in ref.[3,8] with success and been modeled extensively in ref.[6]. The other alternative is to use low resistivity starting silicon materials for silicon detector fabrications, and to give an initial neutron radiation to bring the N_{eff} within the window before the experiment.[6,12] The low resistivity detectors have been found extremely stable at RT for an additional neutron fluence of $1 \times 10^{14} \text{ n/cm}^2$. [12]

IV Discussions

Experimental comparisons among various N_{eff} reverse annealing models have shown that the reactions responsible for the apparent "first" stage anneal are probably of the first order, although there may be two first order annealing stages involved. The key evidence is that the annealing time constant is not neutron fluence dependent at least in range of a few times of 10^{12} n/cm^2 to a few times of 10^{13} n/cm^2 . At higher fluence than $1 \times 10^{14} \text{ n/cm}^2$, however, the defect clusters may be dominant and second order process from the cluster breaking proposed in model 4) may be possible. Also the reverse annealing effect may be a multi-stage effect and each stage may be entirely different in terms of kinetics of the defect formation. So we may attribute the first two stages of the

reverse annealing at modest neutron fluences to the first order processes, we can not rule out the second order process at higher fluences and/or in later annealing stages. In fact, data shown in Fig. 6 demonstrates the exact point we want to make here. After the saturations have been reached at 80 °C, the detectors were then annealed at a higher temperature, 150 °C. Sure enough, one or two additional annealing stages have been discovered, as shown in Fig. 7. It looks like that the amplitude of the third annealing stage is not or not strongly dependent on the neutron fluence and that the annealing time constant is going down with increasing temperature, the distinguish character of the second order process. The fluence dependence of the time constant ($\tau_{1/2}$) of third reverse annealing stage is shown in Table V. The value of $\tau_{1/2}$ are roughly in proportion to $1/\Phi_n$, in agreement with second order process illustrated in eq. (14). We also note from Fig. 8 that the third reverse annealing stage is quickly annealed down (in less than an hour) followed by fourth reverse annealing stage. It is possible that this quick anneal down and the rise of the fourth stage contribute to the behavior of the amplitude of the third reverse annealing stage, which has been found largely independent on the neutron fluence. More detailed results on the multi-stage reverse annealing will be published elsewhere^[13].

V Conclusion

Based on the experimental comparisons for detector irradiated to modest neutron fluences ($\Phi_n \sim$ a few times of 10^{13} n/cm²) among various models describing the N_{eff} reverse annealing effect, it has been demonstrated that the "first" apparent reverse annealing stage is probably consist of two first order annealing stages: reverse annealing stage one and two. A third reverse annealing stage has been discovered after higher temperature (150 °C) anneal. The third stage is probably a second order process because its annealing time constant is proportional inversely to Φ_n , which is the distinguishably different from that of the first order process that is independent of Φ_n . There may exist a fourth reverse annealing stage whose properties are unknown at this point. It has been

established that the N_{eff} reverse annealing effect is a multi-stage event and that each stage may be caused different interaction between the various defect levels and or defect clusters induced by neutron radiation, and may be modeled by one of the four models discussed in this paper. At higher fluences ($\Phi_n > 10^{14}$ n/cm²), the dominant defect may be defect clusters and the N_{eff} reverse annealing may be dominated by the second order process of the formation of singly charged double vacancies by closely packed single vacancies supplied by the breaking up of the clusters. However, the detector full depletion voltage may not be obtained directly by the conventional $C-V$ method due to high leakage current. Other methods, such as the transient current and charge technique (TCT/TChT)[14], would have to be used to get the accurate information on the effective concentration of ionized space charges (N_{eff}).

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Table I The neutron fluence dependence of the reverse annealing time constant $\tau_{1/2}$ of the apparent "first" stage. The anneal Temperature =80 °C

$$\overline{\tau_{1/2}} = 8,400 \text{ sec (or 140 minutes)} \pm 13.6\%$$

Φ_n (n/cm ²)	8.2×10 ¹²	8.2×10 ¹²	1.36×10 ¹³	1.64×10 ¹³	3.2×10 ¹³
$\tau_{1/2}$ (sec)	8000	8000	10000	9000	7000

Table II The fitting parameters of the one-term first order fit. The fitting formula used here is $N_{eff}(t) = N_0 + N_{eff}^{r,max}(1 - e^{-t/\tau})$ and the anneal temperature =80 °C

Detector #	Φ_n (10 ¹² n/cm ²)	N_0 (10 ¹² /cm ³)	$N_{eff}^{r,max}$ (10 ¹² /cm ³)	τ (sec)
439-112	8.2	0.0910	0.5920	14201
439-123	8.2	0.0870	0.5960	14182
439-98	13.6	0.4260	0.9880	14729
439-99	16.4	0.5370	1.1790	13367
348-114	32.0	1.1610	2.3610	10019
Φ_n dependence	—	$0.03517 \Phi_n$	$0.07331 \Phi_n$	—
Average	—	—	—	13300±14.2%

Table III The fitting parameters of the second order fit. The fitting formula used here is

$$N_{eff}(t) = N_{eff}^{r,max} + N_0 - 1/[\kappa t + 1/N_{eff}^{r,max}] \text{ and the anneal temperature } = 80^\circ \text{C}$$

Detector #	Φ_n (10^{12} n/cm ²)	N_0 (10^{12} /cm ³)	$N_{eff}^{r,max}$ (10^{12} /cm ³)	κ (10^{-5} cm ³ /s)
439-112	8.2	0.0728	0.7525	10.2
439-123	8.2	0.0690	0.7566	10.2
439-98	13.6	0.3914	1.2557	6.1
439-99	16.4	0.4985	1.4870	5.7
348-114	32.0	1.0892	2.8596	4.3
Φ_n dependence	—	$0.03272 \Phi_n$	$0.09014 \Phi_n$	—
Average	—	—	—	$4.3 \pm 37.4\%$

Table IV The fitting parameters of the two-term first order fit. The fitting formula used

$$\text{here is } N_{eff}(t) = N_0 + N_1(1 - e^{-t/\tau_1}) + N_2(1 - e^{-t/\tau_2}) \text{ and the anneal}$$

temperature = 80 °C

Detector #	Φ_n (10^{12} n/cm ²)	N_0 (10^{12} /cm ³)	N_1 (10^{12} /cm ³)	N_2 (10^{12} /cm ³)	τ_1 (sec)	τ_2 (sec)
439-112	8.2	0.07060	0.1200	0.5161	3395	18792
439-123	8.2	0.06720	0.0822	0.5478	2461	16932
439-98	13.6	0.3669	0.2038	0.8907	2038	19695
439-99	16.4	0.4972	0.2398	1.0190	3321	17427
348-114	32.0	1.0700	0.5585	1.9778	2025	14087
Φ_n dependence	—	$0.03200 \Phi_n$	$0.01627 \Phi_n$	$0.06025 \Phi_n$	—	—
Average	—	—	—	—	$2648 \pm 25\%$	$17390 \pm 12.3\%$

Table V Dependence of the time annealing time constant of the third reverse annealing stage on the neutron fluence. Annealing temperature = 150 °C

$\Phi_n (10^{12} \text{ n/cm}^2)$	8.2	1.36	3.2
$\tau_{1/2} (\text{min})$	20	10	<5

Figure Captions

- Fig. 1 Simulated reverse annealing of various saturation values: a) first order process and b) second order process.
- Fig. 2 C - V characteristics after various time periods of anneal at 80 °C for detectors irradiated to: a) 8.2×10^{12} n/cm²; b) 1.36×10^{13} n/cm²; c) 1.64×10^{13} n/cm²; and d) 3.2×10^{13} n/cm².
- Fig. 3 N_{eff} reverse annealing at 80 °C as a function of anneal time for detectors irradiated to various neutron fluences.
- Fig. 4 Fitting of the data of the N_{eff} reverse annealing at 80 °C to a) an one-term first order model and b) a second order model.
- Fig. 5 Fitting of the data of the N_{eff} reverse annealing at 80 °C to a) an two-term first order model.
- Fig. 6 C - V characteristics after the saturation of 80 °C anneal and additional anneal at 150 °C for detectors irradiated to: a) 8.2×10^{12} n/cm² and b) 1.64×10^{13} n/cm².
- Fig. 7 N_{eff} reverse annealing at 80 °C and at 150 °C as a function of anneal time for detectors irradiated to various neutron fluences.

Simulated Neff Reverse Anneal, 1st order
 $\tau = 1.0E4$ sec

a)

Simulated Neff Reverse Anneal, 2nd order
 $k = 4.3E-17$ cm3/sec

b)

a)

b)

d)

**Elevated Temp. Anneal(80 C)
#348 and #439, 4-6 k, 0.1 cm²**

Elevated Temp. Anneal(80 C)
#348 and #439, 4-6 k, 0.1 cm²

Fluence (n/cm ²)
+ 8.2E12
△ 8.2E12
○ 1.36E13
+ 1.64E13
▲ 3.2E13

a)

Elevated Temp. Anneal(80 C)
#348 and #439, 4-6 k, 0.1 cm²

Fluence (n/cm ²)
+ 8.2E12
△ 8.2E12
○ 1.36E12
+ 1.64E13
▲ 3.2E13

b)

Elevated Temp. Anneal(80 C)
 #348 and #439, 4-6 k, 0.1 cm²

Fluence (n/cm ²)	
+ 8.2E12	
△ 8.2E12	
○ 1.36E13	
+ 1.64E13	
▲ 3.2E13	

Elevated Temp. Anneal(80 C and 150 C)

#439-123, 4-6k, 300 μ m, 0.1 cm²

a)

Elevated Temp. Anneal(80 C and 150 C)

#439-99, 4-6k, 300 μ m, 0.1 cm²

b)

Elevated Temp. Anneal(80 C & 150 C)

#348 and #439, 4-6 k, 0.1 cm²

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