OPEN ACCESS

Operational voltage of silicon heavily irradiated strip detectors utilizing avalanche multiplication effect

To cite this article: E Verbitskaya *et al* 2012 *JINST* **7** C02061

View the [article online](#) for updates and enhancements.

Related content

- [The impact of active base on the bulk current in silicon heavily irradiated detectors](#)
V. Eremin, N. Fadeeva and E. Verbitskaya
- [Modeling of electric field in silicon micro-strip detectors irradiated with neutrons and pions](#)
G. Kramberger, V. Cindro, I. Mandi *et al.*
- [Effects of accelerated long term annealing in highly irradiated n⁺-p strip detector examined by Edge-TCT](#)
M Milovanovi, V Cindro, G Kramberger *et al.*

Recent citations

- [Simulation of Low Gain Avalanche Detector characteristics based on the concept of negative feedback in irradiated silicon detectors with carrier impact ionization](#)
E. Verbitskaya *et al*
- [Restriction on the gain in collected charge due to carrier avalanche multiplication in Si heavily irradiated strip detectors](#)
E. Verbitskaya *et al*

IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

RECEIVED: October 28, 2011

REVISED: December 22, 2011

ACCEPTED: January 19, 2012

PUBLISHED: February 28, 2012

THE 9th INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS,
12–16 SEPTEMBER 2011,
ABERYSTWYTH, U.K.

Operational voltage of silicon heavily irradiated strip detectors utilizing avalanche multiplication effect

E. Verbitskaya,¹ V. Eremin and A. Zabrodskii

*Ioffe Physical-Technical Institute of Russian Academy of Sciences,
194021 St. Petersburg, Russia*

E-mail: elena.verbitskaya@cern.ch

ABSTRACT: Recent results on the collected charge Q_c in heavily irradiated Si strip detectors developed by RD50 collaboration for the high luminosity operation of the LHC (sLHC) showed a significant Q_c enhancement if the detectors were operated at a bias voltage beyond 1000 V. To explain these results, a physical model based on carrier avalanche multiplication in high electric fields near a n^+ -p junction was developed at the Ioffe Physical-Technical Institute. This study represents an extension of the model, whose goal is finding the detector bias voltage and the other operating conditions which lead to such charge enhancement. The electric field distribution and collected charge in heavily irradiated Si strip detectors are calculated at different conditions: bias voltage, temperature, radiation fluence and strip detector geometry. It is demonstrated that: a) the minimum operational voltage, which initiates the avalanche process, depends on the fluence (being 500 V and 1500 V for LHC and sLHC fluence range, respectively); b) in avalanche multiplication mode the electric field near the n^+ -strips is stabilized via potential redistribution inside the detector and formation of a pronounced DP electric field profile and is about 300 kV/cm; and c) the model predicts that the maximum collected charge in detectors irradiated to $(2-5) \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ is larger than in a non-irradiated detector that nicely agrees with the experimental data. Another factor, which gives an enhanced avalanche multiplication at lower bias voltage, is the electric field focusing near the strips which then also leads to an enhancement of Q_c .

KEYWORDS: Radiation-hard detectors; Detector modelling and simulations II (electric fields, charge transport, multiplication and induction, pulse formation, electron emission, etc)

¹Corresponding author.

Contents

1	Introduction	1
2	Model of avalanche multiplication in heavily irradiated Si detectors and calculation procedure	2
3	Results on the calculation of electric field distribution and collected charge	3
3.1	Influence of temperature on $E(x)$ distribution and collected charge	4
3.2	Influence of operational bias voltage and fluence on the $E(x)$ distribution and collected charge	4
3.3	Influence of detector geometry	6
4	Summary	8

1 Introduction

A significant issue of the application of semiconductor detectors in High Energy Physics is their radiation hardness. The maximum equivalent neutron fluence F_{eq} at the current LHC experiments can be as high as $10^{15} \text{ n}_{\text{eq}}\text{cm}^{-2}$ and for most experiments the bias voltage V for the operation of the Si strip detectors is in the range 200–500 V. At the upgraded, very high luminosity collider (sLHC), the fluence will reach $10^{16} \text{ n}_{\text{eq}}\text{cm}^{-2}$ and for efficient detector operation this will require increased applied bias voltages, going to 1000 V or higher. Recent studies on the collected charge Q_c in heavily irradiated Si strip detectors, which are developed by CERN-RD50 collaboration for sLHC, showed a significant Q_c enhancement if the detectors were operated at bias voltages around and beyond 1000 V [1–7]. Our analysis showed that this enhancement arises from carrier avalanche multiplication in the high electric field at the n^+ -p junction. This interpretation was first presented in references [8, 9] and the detailed explanation was given in [10]. This model of enhanced charge collection developed at the Ioffe Physical-Technical Institute (IPTI) is based on the two effects:

- formation of the double peak (DP) electric field profile in the detector bulk due to carrier trapping by radiation induced deep level defects,
- carrier avalanche multiplication as formation of electron-hole pairs due to impact ionization produced by electrons in the space charge region (SCR) near the n^+ strip side.

In Si detectors irradiated by particles (neutrons, protons, pions) the dominant induced defects are acceptors that lead to increased negative charge in the space charge region. The model of charge enhancement considers two sources of holes which influence the effective space charge concentration N_{eff} — those generated in the detector bulk as equilibrium carriers, and the holes arising in the SCR because of avalanche multiplication. The holes are captured by the deep level

radiation induced defects which, because of their high density, lead to reduced negative N_{eff} near the n^+ strips. This acts as a negative feedback mechanism and results in the decrease and stabilization of the electric field near the collecting n^+ strips, as already described in [10]. This predicted self-stabilization of the electric field profile and of the total detector performance leads, both to the enhanced collected charge and to prevention of the detector breakdown at high bias.

The goal of this study is an estimation of the minimal bias voltage that initiates the avalanche process, which has a practical importance for maintaining appropriate power dissipation and engineering of the experimental set-up. Calculations of the collected charge are performed for heavily irradiated n-on-p strip detectors. In the calculations the variable parameters and conditions are:

- radiation fluence in the range of LHC and sLHC;
- bias voltage and temperature T ;
- strip detector geometry.

These calculations allow estimation of the operational conditions at which the carrier avalanche multiplication may develop.

2 Model of avalanche multiplication in heavily irradiated Si detectors and calculation procedure

The value of the collected charge in heavily irradiated Si strip detectors is derived from the competition of two processes:

- the charge reduction arising from the trapping due to the deep level radiation induced defects of non-equilibrium carriers drifting in the detector bulk,
- increase of the charge caused by carrier avalanche multiplication in high electric field at the n^+ -p junction of the collecting strips.

The details of the model and the calculation procedure are described in reference [10]. In the calculations of the electric field profile $E(x)$ inside the detector bulk and collected charge, the following processes were taken into account:

- formation of a steady-state $E(x)$ distribution by considering the generation of equilibrium carriers (bulk generation current), avalanche generated carriers near the n^+ strips, and carrier trapping by the radiation induced deep level defects;
- charge collection in the detector bulk with a calculated $E(x)$ profile.

In heavily irradiated Si detectors the $E(x)$ profile is highly non-uniform and has a DP shape with two maxima near the p^+ and n^+ contacts and a base region *in-between* in which the electric field E_b has a value of order a kV/cm [11, 12]. We used a one-dimensional approach for the detector geometry, which considers the Poisson equation combined with the Shockley-Read-Hall statistics for the occupancy of the deep energy levels. Two effective midgap energy levels that act as traps, were used in the calculations: deep acceptors (DAs) and deep donors (DDs), with

Table 1. Parameters of carrier trapping and avalanche multiplication used in the calculations.

parameter	units	electrons	holes	reference
$\beta_{e,h}$	cm^2s^{-1}	3.2×10^{-16}	3.2×10^{-16}	[2]
$A_{e,h}$	cm^{-1}	$8.026 \cdot 10^5$	$4.8015 \cdot 10^6$	[13]
$B_{e,h}$	V/cm	$1.1989 \cdot 10^6$	$2.1769 \cdot 10^6$	[13]

activation energies of $E_c - 0.53$ eV and $E_v + 0.48$ eV, respectively. The trapping time constants of the electrons and holes, $\tau_{e,h}$, depend on the radiation fluence F :

$$1/\tau_{e,h} = \beta_{e,h} F_{\text{eq}} \quad (2.1)$$

where $\beta_{e,h}$ is the proportionality constant for electrons and holes, respectively. In avalanche multiplication for Si, the ionization rate for electrons α_e is far higher than that for holes, α_h . Therefore, in the estimation of the collected charge, we neglect the contribution of the carriers coming from hole induced ionization, which considerably simplifies the calculation.

The major feature of this approach and calculation procedure is that the complex problem of signal generation and charge collection in a heavily irradiated detector is subdivided into the several independent processes specified above. For the calculation of Q_c the weighting field was taken into account, which resulted in the changes of $Q_c(V)$ dependences in comparison with those for pad detectors. The focusing of the current and electric field at the collecting strips was considered by introducing special parameters, which were dependent on the ratio of pitch to strip width. Calculations were carried out for the n-on-p strip detector processed on the wafers of p-type Si with a resistivity of ~ 3 k Ω and thicknesses d of 300 μm and 100 μm . Non-equilibrium carriers were generated by MIPs. For these calculations, a program was developed in MS Excel. The program contained two blocks in which the characteristics were calculated numerically basing on the main analytical equations of semiconductor device physics. Using this program, the following dependences can be derived: the distributions of $N_{\text{eff}}(x)$ and $E(x)$, Q_c vs. V and Q_c vs. F . The main parameters for the calculation are specified in table 1. Here the parameters A and B characterize carrier avalanche multiplication: $A_{e,h}$ are numerical coefficients and the $B_{e,h}$ are the critical electric fields, both for electrons and holes, respectively.

3 Results on the calculation of electric field distribution and collected charge

The experimental dependences of $Q_c(V)$ for detectors irradiated either by 1 MeV neutrons or their equivalent, in the range $(5 \times 10^{14} - 1 \times 10^{16})$ n/cm² presented in reference [2] were used as a starting point for fitting the free parameters in the model — the introduction rates K of trapping centres. Among the experimental curves we chose the $Q_c(V)$ dependence of a detector irradiated to 3×10^{15} n/cm² since the enhancement of the collected charge was maximal and Q_c at $V = 1600$ V and at $T = -20^\circ\text{C}$ was as high as in a non-irradiated detector, i.e. about 24 ke⁻. By fitting the calculated dependence to the experimental one, the introduction rates were estimated as $K_{DA} = 2$ and $K_{DD} = 0.07$. The last value is too low for defects induced by radiation in the silicon bulk. The reason for this is, first, that we consider effective energy levels, which may differ from real defects,

and, second, some features of detector processing, namely, high temperatures, may create sinks that affects defect formation, especially near the contacts. For a correct interpretation of the results on the collected charge, which were calculated with a consideration of the carrier avalanche multiplication, we estimated also the corresponding characteristics disregarding the avalanche effect.

3.1 Influence of temperature on $E(x)$ distribution and collected charge

In figures 1, a, b the $E(x)$ profiles in an n-on-p Si strip detector with a thickness of $300\ \mu\text{m}$, a pitch and strip width of $80\ \mu\text{m}$ and of $20\ \mu\text{m}$, respectively (pitch to strip ratio 80/20), after irradiation to a fluence of $3 \times 10^{15}\ \text{n/cm}^2$, are depicted at room and lower temperatures and operational bias of 1800 V. The coordinate $x = 0$ corresponds to the detector p^+ contact. In the profiles in figure 1, a, which are calculated disregarding avalanche multiplication, the electric field has a single peak shape with high electric field near the n^+ strip while the rest of the bulk represents a base region in which the electric field E_b is significantly lower. All calculations were made setting the E_b value equal to 1 kV/cm. The electric field near the strips is in the range (400–800) kV/cm and decreases with temperature reduction. This change is related to the reduction of the absolute value of the negative N_{eff} ($\text{abs}N_{\text{eff}}$) caused by the changes in the deep level occupancy at lower T due to the increase of carrier detrapping constants. The reduction of $\text{abs}N_{\text{eff}}$ leads to the potential redistribution in the detector bulk and increase of the space charge region (SCR) depth W_n near the n^+ contact. When the $E(x)$ profiles were calculated with consideration of carrier avalanche multiplication, a DP shape is observed (figure 1, b). The maximum electric field near the n^+ contact is significantly lower (close to 300 kV/cm) and stays stable independent of the temperature reduction. At lower T the electric field near the p^+ contact goes down due to the potential redistribution.

The corresponding dependences $Q_c(V)$ at various T are shown in figures 1, c, d. Without multiplication, the collected charge is small (below $5\ \text{ke}^-$), and only slightly increases at lower T due to the increase of W_n . The collected charge calculated, considering avalanche multiplication (figure 1, d) shows a significant increase starting from V of 500 V and is higher at lower temperatures. This effect may be the combination of two factors: $E(x)$ redistribution due to the change in deep level occupancy, and the contribution of avalanche multiplication. For comparison, the experimental data on $Q_c(V)$ from reference [2] are shown, and the agreement with the corresponding calculated curve is quite good.

3.2 Influence of operational bias voltage and fluence on the $E(x)$ distribution and collected charge

Figure 2 shows the impact of the radiation fluence in the range $(1 \times 10^{14} - 1 \times 10^{16})\ \text{cm}^{-2}$ on the $E(x)$ profile and $Q_c(V)$ dependences for a strip detector with the same dimensions as in section 3.1 and operated at three different voltages: 500 V, 1000 V, 1800 V, and $T = 253\ \text{K}$. These dependences are calculated considering avalanche multiplication. At $V = 500\ \text{V}$ (figure 2, a) the electric field is practically uniform at $F = 1 \times 10^{14}\ \text{cm}^{-2}$. With increasing fluence the $E(x)$ profile becomes asymmetric with a maximum near the n^+ contact. Starting from $F = 5 \times 10^{15}\ \text{cm}^{-2}$ the $E(x)$ distribution has a DP shape with high electric field regions near both contacts. The depth W of these regions decreases as the fluence grows and is only $10\ \mu\text{m}$ at $F = 1 \times 10^{16}\ \text{cm}^{-2}$.

At V of 1000 V and 1800 V the DP shape of the $E(x)$ profile is observed starting from $F = 3 \times 10^{15}\ \text{cm}^{-2}$ (figures 2, b, c). The depth of high E near the n^+ contact W_n is maximal at this fluence

Figure 1. $E(x)$ profiles (a, c) and collected charge vs. V dependences (b, d) at various T for n-on-p Si strip detector with a thickness of $300\ \mu\text{m}$ irradiated to a fluence of $3 \times 10^{15}\ \text{n/cm}^2$. The curves in a, c are calculated disregarding avalanche multiplication; b, d — avalanche effect is considered.

(for $E \geq 100\ \text{kV/cm}$ W_n is $(40-50)\ \mu\text{m}$) and decreases down to $20\ \mu\text{m}$ at $F = 1 \times 10^{16}\ \text{cm}^{-2}$. At the same time the electric field near the p^+ contact increases above $100\ \text{kV/cm}$ in the region with a depth W_p , which exceeds $50\ \mu\text{m}$ at $F = 1 \times 10^{16}\ \text{cm}^{-2}$.

By comparing these profiles with the $Q_c(V)$ curves at different F (figure 2, d) it may be seen that the pronounced increase of the collected charge in irradiated detectors occurs at $V = 1200\ \text{V}$ and $500\ \text{V}$ at the fluence of $1 \times 10^{15}\ \text{cm}^{-2}$ and $3 \times 10^{15}\ \text{cm}^{-2}$, respectively. The charge enhancement is maximal in the detector irradiated to $3 \times 10^{15}\ \text{cm}^{-2}$ where Q_c reaches $\sim 24\ \text{ke}^-$ at $V \geq 1500\ \text{V}$ i.e. is as high as in a non-irradiated detector.

Figure 3 shows the dependence of the collected charge on fluence in the detectors operated at different bias voltage and $T = 253\text{K}$. For comparison, the curve $Q_c(F)$ at $V = 1800\ \text{V}$ calculated without avalanche multiplication is shown. The value of the fluence at which multiplication starts depends on the bias voltage, since at constant V the $E(x)$ profile is different in detectors irradiated to various F values. An unexpected feature is that this model of carrier avalanche multiplication predicts Q_c enhancement above $24\ \text{ke}^-$ at $V \geq 1500\ \text{V}$, which is observed in the peak of a pronounced

Figure 2. $E(x)$ profiles in detector irradiated to different fluences and operated at V of 500 V, 1000 V, 1800 V (a-c, respectively), and the corresponding $Q_c(V)$ dependences (d). $T = 253$ K.

“bump” in the $Q_c(F)$ curves. Maximum Q_c of 34 ke^- is expected for a detector irradiated to F of about $2 \times 10^{15} \text{ cm}^{-2}$ at $V = 1800 \text{ V}$ while at $F = 3 \times 10^{15} \text{ cm}^{-2}$ Q_c is close to 25 ke^- as observed in the experiments. At higher F , the collected charge decreases but still stays larger in comparison with the value calculated disregarding carrier avalanche multiplication.

3.3 Influence of detector geometry

In segmented detectors, the distribution of the electric field in the region close to the segmented electrodes should be taken into account. This effect, known as a focusing of the electric field, was analyzed in reference [14] for Si strip detectors designed for the ATLAS Semiconductor Tracker, in which the pitch and strip width are $80 \mu\text{m}$ and $20 \mu\text{m}$, respectively. It was shown that in ATLAS strip detectors, this effect can cause an increase of the electric field near the strips by up to a factor of four. The electric field focusing is obviously combined with the current focusing that has the same gain coefficient. Due to the enhanced electric field at the electron collecting strip n^+ contacts, avalanche multiplication can occur at lower bias voltage.

In figure 4, the $E(x)$ profiles are depicted for detectors with the same pitch of $80 \mu\text{m}$ and different strip width of 20, 10 and $6 \mu\text{m}$. The detectors are irradiated to $F = 3 \times 10^{15} \text{ cm}^{-2}$ and

Figure 3. Dependences of the collected charge on fluence in detectors operated at different bias voltage. $T = 253$ K.

Figure 4. $E(x)$ profiles (a) and $Q_C(F)$ dependences (b) for detectors with the same pitch of $80\ \mu\text{m}$ and different strip width. $V = 1800$ V.

operated at $V = 1800$ V and $T = 253$ K. As the strip width decreases, the reduction of W_n near the n^+ contact occurs, whereas the maximum electric field stays practically the same due to hole trapping. On the other hand, near the p^+ contact the SCR depth W_p becomes larger and the maximum E values rise. Figure 4, b represents the $Q_C(F)$ dependence for the detectors with different strip width at the same conditions. As expected, the increase of the focusing with the strip width reduction results in a rise of the maximum collected charge though the scale of the effect is rather small. The main influence of focusing is a shift of the charge enhancement towards lower fluence.

In heavily irradiated detectors the charge collection length goes down as the fluence rises and at $F \geq 10^{15}\ \text{cm}^{-2}$ its value is only $20\text{--}30\ \mu\text{m}$. Therefore the main part of the detector thickness where the weighting field and external electric field are low gives a low contribution to the charge collected in the space charge regions. The reasonable way to avoid this drawback is to reduce the detector thickness d . This reduction acts as a “compressing” of the electric field lines in a smaller volume.

Figure 5. a) $E(x)$ profiles in a detector with a thickness of $100\ \mu\text{m}$ and irradiated to different fluences, $V = 1000\ \text{V}$; b) $Q_c(F)$ dependences for the same detector operated at various bias voltage. Strip geometry is 80/20; $T = 253\ \text{K}$.

The $E(x)$ profiles at $V = 1000\ \text{V}$ and the $Q_c(F)$ dependence in n-on-p detector with a thickness $d = 100\ \mu\text{m}$ and the strip geometry 80/20 are shown in figure 5. The difference of the $E(x)$ profiles, as compared to those in a $300\ \mu\text{m}$ detector is that in a thinner detector the electric field is close to uniform at $F < 5 \times 10^{15}\ \text{n}_{\text{eq}}\text{cm}^{-2}$ and the DP $E(x)$ shape arises only at higher fluence. The Q_c is maximal at $F = 5 \times 10^{15}\ \text{cm}^{-2}$ that is twofold higher than that for a $300\ \mu\text{m}$ detector

To show the scale of the focusing effect, we compared the dependence of the charge collection efficiency (CCE) on F for detectors with different thickness and operated at $V = 1000\ \text{V}$ (figure 6). From the comparison of figure 6 with the changes of $Q_c(F)$ dependence for the detectors with a different strip width (figure 4, b), it is clear that the reduction of the wafer thickness increases the collected charge more effectively than the electric field focusing at the contact with a smaller width. This demonstrates the influence of a low electric field base region, which damps the avalanche effect in the signal of a $300\ \mu\text{m}$ detector.

4 Summary

Calculations show that enhancement of the collected charge occurs when the electric field at the n^+ contact becomes close to $300\ \text{kV/cm}$ and the $E(x)$ distribution transforms to a DP profile. The electric field near this contact stays stable in the range of $300\text{--}350\ \text{kV/cm}$, whereas without multiplication it would change significantly and reach $800\ \text{kV/cm}$ that is critical for breakdown. The absence of breakdown in the experiments at $V > 1000\ \text{V}$ is a direct confirmation of the detector performance stabilization. Still, we would note that the observed correlation between the DP $E(x)$ profile formation and simultaneous Q_c enhancement needs further study.

The model discussed here predicts a non-monotonic $Q_c(F)$ dependence due to competition of two mechanisms: trapping and avalanche multiplication. Indeed, the calculated $Q_c(F)$ dependences show a “bump” in the curves, and at its maximum the collected charge reaches $34\ \text{ke}^-$ ($V = 1800\ \text{V}$) and $15\ \text{ke}^-$ ($V = 1000\ \text{V}$) in the detectors with thicknesses of $300\ \mu\text{m}$ and $100\ \mu\text{m}$, respectively, i.e. by up to a factor of 1.4 and 1.9 higher than that in non-irradiated detectors. The

Figure 6. $CCE(F)$ dependences for detectors with different thickness d . $V = 1000$ V; $T = 253$ K.

first result correlates with recent data on neutron irradiated detectors with a thickness of $320\ \mu\text{m}$ where the increase of the Q_c up to $40\ \text{ke}^-$ was observed after long term annealing [15]. A superior charge enhancement predicted by our calculations for a $100\ \mu\text{m}$ detector is close to the experimental value of 1.85 for proton irradiated detectors with a thickness of $140\ \mu\text{m}$ [5]. This agreement shows that IPTI model gives an adequate description of the experimental results.

For the detector irradiated to $3 \times 10^{15}\ \text{cm}^{-2}$ the DP $E(x)$ profile appears at $V = 500$ V. Therefore a minimal detector operational bias may be 500 V. This is in fact the anticipated maximum bias voltage of Si strip detectors that are installed in the current experiments at LHC, in which the maximum accumulated fluence will be about $(1-2) \times 10^{15}\ \text{n}_{\text{eq}}\text{cm}^{-2}$. However, for sLHC the reduction of the collected charge due to the trapping time constant degradation will compete with avalanche multiplication and, finally, Q_c will go down. For achieving good performance, the signal over noise ratio S/N should be above 8 [4]. As shown in reference [15], the noise of strip detectors with a $320\ \mu\text{m}$ thickness, 6 cm length and a pitch of $75\ \mu\text{m}$ irradiated to a fluence of $(1-5) \times 10^{15}\ \text{n}_{\text{eq}}\text{cm}^{-2}$ and connected to SCT128A readout ASIC is about 1000 ENC. Hence, for this strip length and within this fluence range, the requirement on S/N can be satisfied in the avalanche mode at $V \geq 1500$ V since the collected charge is above $11\ \text{ke}^-$. If F is close to $1 \times 10^{16}\ \text{n}_{\text{eq}}\text{cm}^{-2}$, the S/N ratio may go down. Conversely, with shorter strips and better electronics, an adequate S/N should be achievable at lower voltages.

The rise of the collected charge at lower T is related to the reduction of the $\text{abs}N_{\text{eff}}$ near the n^+ contact. The corresponding extension of the SCR inside the detector bulk is the evidence for the holes influencing the process. However, the Q_c increase is close to saturation below 270 K and in the range of expected T for sLHC (240–250) K becomes insignificant. This behaviour agrees with the experimentally observed small difference between the charges collected in irradiated detectors at -25° and -50°C [7]. Therefore, varying the operating temperature is mainly an option for reducing power dissipation.

The impact of avalanche multiplication on the detector position resolution is related to the electrostatic induction and charge sharing between the strips (disregarding the influence of S/N ratio

on the cluster shape). In heavily irradiated Si detectors the electron drifting from the p^+ contact to the n^+ side induces charge on several strips on the left and the right sides of the electron trajectory. If this electron is trapped far away from the n^+ strip, the charge induced on the neighbouring strips will be conserved, broadening the strip cluster. Thus, only the carriers collected in the region near the strip, where the weighting field is maximal, and which physically reach the strip, will induce charge in a narrow cone at a single strip. In the avalanche mode multiplied electrons, which arise in a very thin layer under the strips, will give additional induced charge on the collecting strip only. However, the main effect of avalanche multiplication on the cluster shape is related to the collection of multiplied holes. The holes will drift first through the region with a maximal weighting field and give an essential increase of the signal on the collecting strip in the case that their number is not significantly reduced by the trapping. Then, the holes, whose number is reduced due to trapping, will drift through the low weighting field region and introduce charge on the strips in the entire cluster. Therefore the cluster shape will have shoulders specific to heavily irradiated detector and an enhanced peak at the fired strip.

Acknowledgments

The work was performed within the framework of RD50 collaboration and supported in part by Fundamental Program of Russian Academy of Sciences on collaboration with CERN and Russian Federation President Grant # SS-3008.2012.2.

References

- [1] I. Mandić, V. Cindro, G. Kramberger and M. Mikus, *Measurement of anomalously high charge collection efficiency in n^+p strip detectors irradiated by up to $10^{16} n_{eq}cm^2$* , *Nucl. Instrum. Meth. A* **603** (2009) 263.
- [2] I. Mandić et al., *Observation of full charge collection efficiency in heavily irradiated n^+p strip detectors irradiated up to $3 \times 10^{15} n_{eq}/cm^2$* , *Nucl. Instrum. Meth. A* **612** (2010) 474.
- [3] A. Affolder, P. Allport and G. Casse, *Charge collection efficiencies of planar silicon detectors after reactor neutron and proton doses up to $1.6 \times 10^{16} n_{eq}cm^{-2}$* , *Nucl. Instrum. Meth. A* **612** (2010) 470.
- [4] G. Casse, *Radiation hardness of p-type silicon detectors*, *Nucl. Instrum. Meth. A* **612** (2010) 464.
- [5] G. Casse, A. Affolder, P.P. Allport, H. Brown and M. Wormald, *Enhanced efficiency of segmented silicon detectors of different thicknesses after proton irradiations up to $1 \times 10^{16} n_{eq}cm^2$* , *Nucl. Instrum. Meth. A* **624** (2010) 401.
- [6] M. Mikuž, V. Cindro, G. Kramberger, I. Mandić and M. Zavrtanik, *Study of anomalous charge collection efficiency in heavily irradiated silicon strip detectors*, *Nucl. Instrum. Meth. A* **636** (2011) 550.
- [7] G. Casse, A. Affolder, P.P. Allport, H. Brown, I. McLeod and M. Wormald, *Evidence of enhanced signal response at high bias voltages in planar silicon detectors irradiated up to $2.2 \times 10^{16} n_{eq}cm^{-2}$* , *Nucl. Instrum. Meth. A* **636** (2011) 556.
- [8] V. Eremin, E. Verbitskaya, Z. Li and J. Härkönen, *The avalanche effect in operation of heavily irradiated Si p-i-n detectors*, presented at 14 RD50 collaboration workshop, Freiburg Germany, June 3–5 2009, www.cern.ch/rd50.

- [9] V. Eremin, E. Verbitskaya and A. Zabrodskii, *CCE in irradiated silicon detectors considering the avalanche effect*, presented at *15 RD50 collaboration workshop*, Geneva CERN, November 16–18 2009, www.cern.ch/rd50.
- [10] V. Eremin, E. Verbitskaya, A. Zabrodsky, Z. Li and J. Härkönen, *Avalanche effect in Si heavily irradiated detectors: physical model and perspectives for application*, *Nucl. Instrum. Meth. A* **658** (2011) 145.
- [11] E. Verbitskaya, V. Eremin, Z. Li, J. Härkönen and M. Bruzzi, *Concept of double peak electric field distribution in the development of radiation hard silicon detectors*, *Nucl. Instrum. Meth. A* **583** (2007) 77.
- [12] E. Verbitskaya, V. Eremin, A. Zabrodskii and Z. Li, J. Härkönen, *The impact of neutral base region on the collected charge in heavily irradiated silicon detectors*, *Nucl. Instrum. Meth. A* **624** (2010) 419.
- [13] B.J. Baliga, *Modern Power Devices*, Wiley, New York U.S.A. (1987).
- [14] V. Eremin, E. Verbitskaya, Z. Li, S. Roe and G. Ruggiero, *Double peak electric field distortion in heavily irradiated silicon strip detectors*, *Nucl. Instrum. Meth. A* **535** (2004) 622.
- [15] I. Mandić, V. Cindro, G. Kramberger and M. Mikuž, *Annealing effects in n^+p strip detectors irradiated with high neutron fluences*, *Nucl. Instrum. Meth. A* **529** (2011) 101.