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**STUDY OF NEUTRON-IRRADIATED SILICON COUNTERS
WITH A FAST AMPLIFIER**

RD2 Collaboration

S. Bates, D.J. Munday and M.A. Parker
Cavendish Laboratory, University of Cambridge, Cambridge, UK

F. Anginolfi, A. Chilingarov^{*)}, A. Ciasnovhova, M. Glaser, P. Jarron,
F. Lemeilleur and J.C. Santiard
CERN, Geneva, Switzerland

C. Gössling, B. Lisowski, S. Pilath and A. Rolf
Institut für Physik, Universität Dortmund, Dortmund, Germany

R. Bonino, A.G. Clark, H. Kambara and X. Wu
Dept. Phys. Nucl. et Corpusculaire, Geneva University, Geneva, Switzerland

E. Fretwurst, G. Lindström and T. Schulz
I. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

G.F. Moorhead, G.N. Taylor and S.N. Tovey
School of Physics, University of Melbourne, Parkville, Victoria, Australia

R. Hawkins and A. Weidberg
Department of Nuclear Physics, Oxford University, Oxford, UK

J. Teiger
Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France

Abstract

Silicon detectors have been irradiated with fluences of up to 2.7×10^{13} neutrons per cm^2 , and have subsequently been studied using low-noise preamplifiers with a peaking time of about 15 ns. The detector response to minimum ionizing particles (mip) was found to be close to that of non-irradiated detectors. The short integration time of the preamplifier makes the shot noise caused by the detector dark current tolerable up to at least 15 μA per channel.

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^{*)} On leave from the Budker Institute of Nuclear Physics, Novosibirsk, Russia.

1. INTRODUCTION

Radiation damage to silicon detectors is a major concern in the design of silicon tracking systems planned for the detectors of future colliders such as the Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC). Intensive studies have recently been performed on the different effects of radiation damage in silicon: the increase of the dark current, the change of the impurity concentration resulting in the change of the depletion voltage and n- to p-type conversion, the self-annealing of the above-mentioned defects with relevant temperature dependences, etc. [1–4].

However, the effective drift velocity and collection efficiency for the electrons and holes produced by relativistic particles in a heavily damaged silicon detector has been investigated much less. The reason for this is that such a study needs fast low-noise preamplifiers to suppress the shot noise from the large dark current in heavily irradiated detectors. In a recent study, F. Lemeilleur et al. [2] used the average of many signals from a fast amplifier (rise time < 1 ns) with relatively large noise ($\sim 25\,000$ electrons). In the work presented in this paper we used a moderately fast amplifier but with a noise level allowing the detection of single pulses, therefore obtaining Landau spectra for minimum ionizing particles (mip). Cooling of the detectors to about 0°C was used in several measurements to reduce the dark current, a measure foreseen in the ATLAS [5] Silicon Tracker (SIT) that is now under development [6].

2. DETECTORS

The detectors studied were prototype SIT detectors with a sensitive area of $24 \times 24\text{ mm}^2$ divided into 64 pads of $3 \times 3\text{ mm}^2$ size. The thickness of the detectors was $300\text{ }\mu\text{m}$ with $\pm 5\text{ }\mu\text{m}$ tolerance. All detectors were made of high-resistivity n-type silicon. More detailed information about the detectors is presented in Table 1.

Table 1
Detector characteristics before irradiation

Detector	627-18-4	A348	8986	A353
Producer	MS ^{a)}	IT ^{b)}	IT ^{b)}	IT ^{b)}
Thickness (μm)	297	305	300	304
$U_{\text{depletion}}$ (V)	30	25	20	18
I_{total} at U_{depl} (μA)	20	2.5	0.06	0.01
Irradiation made	no	no	yes	yes

a) MS (Micron Semiconductor)

b) IT (Intertechnique)

Two of the detectors were irradiated using neutrons with a mean energy of 6.2 MeV . The parameters of the irradiations are presented in Table 2. For both detectors the fluence, normalized to that of 1 MeV neutrons (see Ref. [3] for details of the normalization), was more than $1.0 \times 10^{13}\text{ n/cm}^2$. As shown recently [1–4], after such irradiations n- to p-type conversion occurs in the silicon. The depletion voltage and the corresponding total dark current

at the time of the measurements are shown for each detector in Table 3. The interval between the irradiation and the measurement is also shown in this table. During this time the detectors were kept at ambient temperature. Since in all cases this interval is larger than 2.5 months, all the short-term self-annealing processes had taken place before the measurements, and only the long-lasting defects most critical for the normal mode of detector operation at the LHC remain.

Table 2
Parameters of the irradiations

Detector	8986	A353
Irradiation fluence (n/cm ²)	1.16×10^{13}	2.7×10^{13}
Irradiation duration (h)	1.2	1.8

Table 3
Depletion voltage and corresponding dark current during measurements

Detector	8986	A353
U_{depl} (V)	25	55
Measurement temperature (°C)	23	23
Interval after irradiations (d)	211	79
I_{total} at U_{depl} (μA)	170	250
Measurement temperature (°C)	0	0
Interval after irradiations (d)	222	79
I_{total} at U_{depl} (μA)	35	40

3. EXPERIMENTAL SET-UP

A ⁹⁰Sr β-source was used to study the response of the detectors to minimum ionizing particles. A schematic diagram of the set-up is presented in Fig. 1. The selection of particles crossing the sensitive area of the detector and the minimum electron energy cut were performed by a coincidence between two scintillator counters installed behind the silicon detector. The dimensions of the counters were $11 \times 9 \times 5 \text{ mm}^3$, and $40 \times 40 \times 7 \text{ mm}^3$, respectively. Taking into account the thickness of the silicon detector itself, of the first scintillator, and of the counter wrappings, as well as the threshold for the energy deposited in the second counter, the minimum kinetic energy of the electron which produced a trigger by the scintillator counter coincidence was estimated to be $\approx 1.3 \text{ MeV}$.

Each of the 12 investigated pads of the tested detector were d.c.-coupled to one of the BIPOLTEST preamplifiers described below. All of the other pads were connected to ground. The bias voltage was supplied to the n⁺ common rear electrode of the detector via a limiting resistor of 10 kΩ. The voltage drop at this resistor due to the leakage current of the detector as

well as the ≈ 0.7 V bias of the amplifier input were taken into account to obtain the effective bias voltage at the detector.

The BIPOLTEST preamplifier [7] uses bipolar transistors implemented in the standard p-well 3 μm SACMOS process of Faselec (Zurich). A simplified schematic diagram of the amplifier is shown in Fig. 2. The current gain of the input lateral bipolar transistor T1 is 170 at 200 μA bias. A second stage with unity gain is formed by the n-channel MOS transistor T2. Together T1 and T2 form a current feedback pair, which is followed by the source follower T3, implemented as a vertical bipolar transistor. The lateral bipolar transistor T1 is inherently free of parasitic output capacitance because the base acts as a shield between the collector and the substrate. The problem of a large Miller capacitance complicating high-frequency operation is overcome by applying neutralization via capacitor C_{nf} to the base of T1, which is a current-sensitive input. Very sharp frequency cut-off filtering is applied, and a nearly Gaussian shaping with a peaking time of the output signal of about 15 ns is achieved. The conversion gain is ≈ 0.5 mV/fC, and the power consumption is ≈ 2 mW. The dynamic input resistance is about 100 Ω . In the present set-up, the BIPOLTEST preamplifier was followed by an ELANTEC EL400 operational amplifier that gave a total output signal of about 10 mV amplitude for an injected charge of 21 000 electrons. The output signal was sent directly to a LeCroy 2249A 12-channel integrating ADC.

The response of the preamplifier–amplifier chain to a δ -function charge injection is shown in Fig. 3 for the case of 1.8 pF (a) and 20 pF (b) capacitance connected in parallel to the preamplifier input. The signal amplitudes are normalized to facilitate the comparison of the pulse form.

The ADC gate width was set to 55 ns. The noise dependence as a function of the capacitance connected in parallel to the amplifier input was measured to be:

$$\sigma(\text{ENC}) \approx 2100 + 60 C(\text{pF}) \text{ (electrons)} .$$

For one $3 \times 3 \text{ mm}^2$ element of the fully depleted detector this results in a noise of ≈ 3000 electrons, i.e. an 8:1 signal-to-noise ratio for a mip vertically traversing the 300 μm silicon detector.

Some features of the analog output signals are illustrated in Fig. 4. It shows the output signal produced by mip crossing the detector for two bias voltages. For comparison, the response to the calibration pulse for a 20 pF capacitive load and 21 000 electron-injected charge (that is close to the most probable mip signal in the detector) is also shown in the figure. These pictures were obtained on a digital oscilloscope by averaging 512 signals to suppress the distortion of the pulse by the noise. For the depletion voltage of the detector (25 V) the mip signal is noticeably broader (75 ns at the 10% level) than the calibration signal (55 ns). This is due to the slow collection of the charge carriers (especially of the holes) in the low-electric field of the detector. As can be seen from Fig. 4, the mip signal becomes similar to the calibration signal only at a 60 V bias voltage. At this voltage, the total collection time for the holes is about 30 ns, but 95% of the total charge is collected within less than 20 ns. The formulae used for these estimates are given in the Appendix.

4. MEASUREMENTS AND ANALYSIS

The digitized signals from the twelve detector channels connected to the amplifiers were read out for each event. Runs using a random trigger (from a pulse generator) were used for pedestal measurements. The events were written on to disk for further off-line analysis.

Conversion coefficients (ADC bins per fC) were obtained for all channels (including the preamplifier–amplifier chain and an individual ADC channel) by injection of a known charge via a 1.8 pF calibration capacitor with an 18 pF capacitor (imitating a detector element with all stray capacitances) connected in parallel to the preamplifier input. The overall normalization correction was added during the fit of the final spectra as described below.

The following procedure was used in the off-line analysis. After pedestal subtraction and individual channel normalization by the coefficients obtained as described above, events with large amplitude only in one channel were selected. This selection was made by the requirement that the second largest amplitude was at least two times smaller than the largest amplitude in the event. This led to less than 5% loss of the signal events due to: a) particles hitting the region between two adjoining elements; b) events with more than one track; c) a random coincidence with a large noise fluctuation. Events for which no sensitive elements of the detector were traversed by the charged particle were rejected by the above requirement by a factor of about 5. Only the channel with the largest amplitude was treated as being hit, and only this signal was used in further analysis. By definition each selected event contributed to the spectrum of only one channel.

The spectra were first analysed separately for individual channels. The small trigger counter covered only 8 pads (occupying an area of $12 \times 6 \text{ mm}^2$) of the 12 studied pads. The spectra from these pads were compared and checked for mutual consistency. Good agreement between Landau spectra in individual channels confirmed that the relative electronic calibration was correct within $\pm 2\%$ accuracy. Then the spectra from the 8 pads were superimposed to obtain the final spectrum. When measuring some groups of elements one or two pads known to have electrical connection problems were not included in the superposition.

In the spectra obtained the Landau distribution of the β -particles was well separated from what was left of the noise. Note that the noise peak represents the largest signal of 12 independent Gaussian distributions and is therefore not centred around zero, and its r.m.s. is not equal to that of the noise. For the superimposed spectra a fit by a Landau function was performed.

As an example, two such spectra, one obtained with a non-irradiated detector, and one with a detector irradiated by 2.7×10^{13} neutrons per cm^2 , are shown in Fig. 5, together with an associated Landau fit. The fitting procedure was identical to that described in Ref. [8]. Three parameters were left free in the fit: the total number of events N_0 , the most probable energy deposition E_{mp} (normalized to the nominal detector thickness), and the r.m.s. of Gaussian smearing of the Landau distribution σ , which is a quadratic sum of the electronic noise and the effects of electron binding in the atoms [9]. The Landau distribution parameter

$$\xi = (17.83 \text{ keV/mm}) x/\beta^2 ,$$

where x is the detector thickness and β is the electron velocity, was fixed at the value 5.92 keV, taking into account the interval of the possible kinetic energy of β -particles, and the increase of the particle path in the detector due to multiple scattering. The absolute calibration of the

deposited energy was made using the spectra measured for the non-irradiated counters and the calculated value $E_{\text{mp}} = 270 \text{ eV}/\mu\text{m}$ that includes all the above-mentioned corrections due to the relatively low β^2 . We note that the additional correction to the coefficients obtained earlier by electronic calibration was found to be only a few per cent.

An ADC channel range from 14 to 39 was used for the fit. However, the fit curve is presented for the whole region. The lower cut was made to discriminate against the noise. The upper cut was applied to suppress the difference between the energy loss, described by the Landau distribution, and the energy deposition measured in the given detector. In our case, the latter has a deficit of events in the ‘tail’ owing to the escape of energetic δ -electrons from the detector. In absolute units the ‘fit window’ corresponds to the region of the normalized deposited energy between 170 and 490 $\text{eV}/\mu\text{m}$.

5. RESULTS AND DISCUSSION

The value of the most probable energy deposition E_{mp} obtained by the fit as a function of U_{bias} is shown in Fig. 6 for two non-irradiated and two irradiated detectors. The depletion voltages for the detectors are given in Tables 1 and 3. It can be seen that in all cases some overdepletion is necessary to enable complete charge collection within the chosen integration time, as discussed in Section 2 (Fig. 4). For measurements of charge-collection efficiency we used the value of the E_{mp} at the plateau of the voltage dependence in order to be sure that all ‘ballistic deficit’ effects due to the charge collection time are irrelevant.

The measurements presented in Fig. 6a were made at room temperature. The maximum bias voltage for detector 8986 was limited by the dark current which increased with U_{bias} even above the depletion voltage. At $U_{\text{bias}} = 60 \text{ V}$ the dark current was about $14 \mu\text{A}$ per pad (depending on the ambient temperature during the measurements). For larger currents the preamplifiers began to saturate. It is not clear from Fig. 6a whether the E_{mp} had reached the plateau for the detector 8986. However, lowering the temperature allows an increase of the bias voltage and an understanding of where the plateau begins for this detector.

The results of the measurements at 0°C are shown in Fig. 6b. Only one of two non-irradiated detectors was used in these measurements. Within the statistical errors, which in these figures are inside the symbol sizes, there is no essential difference in the results obtained at room temperature ($22^\circ\text{--}24^\circ\text{C}$) and at 0°C , except for E_{mp} saturation at lower voltages when the detectors (and the front-end electronics) were cooled. On the one hand, this is due to the measured ($\approx 13\%$) decrease at 0°C of the FWHM of the amplifier response to a δ -function charge injection (see Fig. 3) when the electronics are cooled down. On the other hand, we can expect that the collection time in the detector becomes shorter at lower temperatures. Comparing Figs. 6 a) and b), we can see that E_{mp} for the detector 8986 does not reach full saturation at the highest bias voltage point (60 V) at room temperature measurements.

At both temperatures there is a 5–6% deficiency in the irradiated detector signal at the plateau compared with the non-irradiated detectors. This observation agrees with the results of Lemeilleur et al. [2]. In all other respects the signal spectra from the irradiated detectors are identical to those of the non-irradiated ones. The standard Landau curve fits all the spectra satisfactorily.

The electronic noise was measured as the r.m.s. of the pedestal distributions in special runs with the trigger from a pulse generator. In these runs the detector was illuminated by the

radioactive source as for the runs with the trigger from the scintillator counter coincidence. For non-irradiated detectors, the noise did not depend on the bias voltage, showing only a slight increase at low voltages caused by the increase of the capacitive load at the preamplifier input when the detector was not fully depleted. These results are shown in Fig. 7 for the measurements made at room temperature. They represent the values averaged over the same pads that were used for the measurements of E_{mp} .

Subtracting quadratically the electronic noise from the Gaussian smearing σ of the Landau distribution found in the fit permits a measurement of the smearing r.m.s. due to the atomic binding effects. These results are presented in Fig. 8. Only the data for the non-irradiated detectors, at a bias voltage high enough to provide full charge collection, were used. All measured values coincide within the errors. Their weighted average 5.83 ± 0.24 keV agrees well with the value 5.7 ± 0.5 keV measured by Hancock et al. [8] for 30 GeV pions.

For the irradiated detector the electronic noise increased with bias voltage due to the increase of the dark current. The values of σ^2 are plotted in Fig. 9 as a function of the total dark current of the detector. They are fit well by a straight line as should be so for the statistical sum of the electronic and the shot noises. The slope agrees with expectations for the 55 ns gate width, and the assumption of a uniform current distribution over all detector pads. The difference in the observed slopes is most likely due to the deviations from exact current uniformity. At the last point in Fig. 9 the average current per element was 15 μ A. This is significantly larger than the maximum current per detector element expected after ten years of SIT operation at the LHC, assuming an operation temperature of 0°C [10].

6. CONCLUSIONS

The study of the response to mip of silicon detectors irradiated by neutrons with fluences (normalized to that of 1 MeV neutrons) up to $\approx 3 \times 10^{13}$ n/cm² demonstrates that these detectors remain fully functional. The large dark current resulting from the irradiation may be effectively suppressed by the use of a fast preamplifier. We were able to maintain a good signal-to-noise ratio up to ≈ 15 μ A per element. With the exception of a 5–6% drop in the signal value within about 20 ns collection time, there is no other deterioration in the detector performance after the irradiation. The amplitude distribution is described well by the standard Landau distribution. Cooling to about 0°C permits a reduction of the dark current, thereby allowing an increased operating voltage without any change in the detection efficiency. To assure a fast collection time, an operating voltage significantly above the depletion voltage is sometimes required. These results confirm the possibility of satisfactory operation of silicon detectors in the ATLAS Outer Silicon Tracker during at least 10 years at LHC design luminosity.

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APPENDIX

PULSE FORMATION IN A PLANAR DIODE

A point-like charge q being displaced by a distance Δx from one electrode of a fully depleted semiconductor diode with a thickness w to another electrode induces on either electrode the charge

$$\Delta Q_i = q \Delta x / w , \quad (1)$$

in accordance with the Ramo theorem [11]. This expression is the same as for an empty flat capacitor. As has been stressed by G. Cavalleri et al. [12] the space charge in the depleted bulk of semiconductor detectors does not affect the above relation. The current induced on to the electrodes depends on the velocity of the charge movement

$$I = \Delta Q_i / \Delta t = q v_q / w . \quad (2)$$

Therefore, in contrast to the induced charge, the current depends on the space charge in the semiconductor bulk through the dependence of the drift velocity v_q on the electric field.

In an ideal semiconductor the electric field changes linearly with coordinate x perpendicular to the electrodes of the diode. For velocities noticeably lower than the saturation velocity (8×10^6 cm/s in silicon at 300 K) the well-known expression

$$v_q = \mu E , \quad (3)$$

relates the drift velocity and the electric field. In silicon the mobility μ for holes is ≈ 2.5 times smaller than for electrons. Therefore the collection of holes usually defines the total duration of the current pulse in the detector.

Using expressions (2) and (3) it is easy to obtain the time dependence of the induced current for the point-like charge created at point x inside a semiconductor diode. These formulae may be found for example in Refs. [13,14]. To obtain the signal induced by the collection of the initial ionization uniformly distributed from one diode electrode to another, it is necessary to integrate the incremental contributions from charges Δq created at the different small intervals Δx along the projectile track. Such a calculation gives the following result for the time dependence of the induced charge on time [13]:

$$Q_{e,h}(t) = (Q_0/8) \{ (\alpha + 1)^2 [1 - \exp(-t/\tau_{e,h})] - (\alpha - 1)^2 [\exp(t/\tau_{e,h}) - 1] \} , \quad (4)$$

where Q_0 is the total electron or hole charge deposited along the semiconductor thickness w , α denotes the ratio of the applied bias voltage V (together with the 'built-in' voltage V_0) to the depletion voltage of the detector V_d ,

$$\alpha = (V + V_0)/V_d , \quad (5)$$

and $\tau_{e,h}$ is the so-called 'transit time' for electrons and holes, respectively

$$\tau_{e,h} = w^2 / (2 V_d \mu_{e,h}) . \quad (6)$$

The expression (4) is only valid for a totally depleted detector, i.e. for $\alpha \geq 1$, and should be applied independently to the signals produced by the movement of electrons and holes.

The full collection time for both types of charge carriers is

$$T_{e,h} = \tau_{e,h} \ln [(\alpha + 1) / (\alpha - 1)] , \quad (7)$$

and diverges logarithmically when $\alpha = 1$. This is due to the fact that in this idealized model the electric field is equal to zero near one of the electrodes. In practice, in such a case the carriers from this area are collected by the diffusion process. As may be seen from Eqs. (4) and (7) each type of the carriers contributes half of the total charge signal

$$Q_e(T_e) = Q_h(T_h) = Q_0/2 . \quad (8)$$

Differentiation of expression (4) gives the corresponding current

$$I_{e,h}(t) = (Q_0/8 \tau_{e,h}) [(\alpha + 1)^2 \exp(-t/\tau_{e,h}) - (\alpha - 1)^2 \exp(t/\tau_{e,h})] , \quad (9)$$

valid for $0 \leq t \leq T_{e,h}$ respectively. Note that $dI/dt < 0$ for any t in the above-mentioned interval. This means that even when the charges move with an increasing velocity (in the direction of the field increase) the decrease of the amount of charge that is still moving is more significant than the increase of its velocity.

Solving Eq. (4) as a function of t gives the time needed for the collection of a given part of the maximum signal $k = Q_{e,h} / (Q_0/2)$,

$$t_{e,h}(k) = \tau_{e,h} \ln \left\{ [\alpha^2 + 1 - 2k - 2\sqrt{\alpha^2 + k^2 - k(\alpha^2 + 1)}] / (\alpha - 1)^2 \right\} . \quad (10)$$

Normalized to the total collection time this expression becomes an almost universal function of k depending only weakly on α . For example for $\alpha > 1.1$, 90% of the charge is collected within about 0.6 of the total collection time.

Another question of practical interest is the bias voltage required to provide the collection of a given amount of charge within a specified time. Regarding only those cases when k is close to 1 it is reasonable to assume that all of the electrons are collected so that the charge deficiency is only due to the incomplete collection of holes. With this assumption it is easy to solve Eq. (4) (for the case of holes) as a function of α , and obtain the required bias voltage

$$V + V_0 = V_d [1 + C - 2\sqrt{C(1 - k_h)}] / (1 - C) , \quad (11)$$

where $C = \exp(-t/\tau_h)$ and $k_h = Q_h / (Q_0/2)$. This expression is valid for

$$1 - C \leq k_h \leq 1 , \quad (12)$$

because when $k_h \leq 1 - C$, the depletion voltage is already sufficient to provide the necessary charge collection within the specified time [as is easy to see from expression (4) with $\alpha = 1$]. Note that the effects discussed do not concern the trapping of the charge carriers and are only due to the finite duration of the induced-current pulse. As an illustration, the bias voltage needed for the collection of 95% of the total charge (90% of the holes) in 300 μm silicon is shown in Fig. 10 as a function of the depletion voltage for 4 values of integration time. It can be seen from these curves that a considerable overdepletion is necessary to ensure fast charge collection when the depletion voltage is low. Therefore, in the LHC and SSC experiments, a voltage only slightly exceeding V_d cannot always be regarded as a suitable operation voltage. However, the magnitude of the required overdepletion decreases as the depletion voltage increases, owing to radiation damage.

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Fig. 1 Schematic layout of the experimental set-up

Fig. 2 BIPOLTEST schematic diagram

Fig. 3 The output signal for calibration pulses with 1.8 pF (a) and 20 pF (b) capacitance in parallel to the input. The amplitudes are normalized. The horizontal scale is 10 ns per division.

Fig. 4 The calibration signal (a) (20 pF input capacitive load and 21 000 electron-injected charge), and the average signal from mip for bias voltages 25 V (b) and 60 V (c), applied to the detector irradiated by 1.0×10^{13} neutrons per cm^2 . The pictures were obtained using a digital oscilloscope by averaging 512 signals in each measurement. The vertical scale is 2 mV per division, the horizontal scale is 20 ns per division.

a)

b)

Fig. 5 The Landau distribution for the non-irradiated detector (a), and the detector irradiated by 2.7×10^{13} neutrons per cm^2 (b). The bias voltage is 70 V for plot (a) and 80 V for plot (b). The values of the χ^2/n_{df} for the Landau fit are 19.7/23 and 20.9/23 for (a) and (b), respectively. The measurements were made at 0°C . See text for further details. Vertical axis represents the number of events, and horizontal axis is the energy deposited in the detector in relative units.

Fig. 6 The most probable energy deposition compared with the bias voltage: (a) at room temperature, (b) at 0°C. Open symbols refer to the non-irradiated detectors, and shaded symbols to the irradiated detectors. The statistical errors are within the symbol's size.

Fig. 7 The r.m.s. of the pedestal distribution representing the equivalent noise charge (ENC) in units of electron charge, measured as a function of the bias voltage for non-irradiated detectors at room temperature.

Fig. 8 The r.m.s. of the Gaussian smearing of the Landau distribution due to the effects of electron binding in silicon atoms found from the fit after the subtraction of the electronic noise. Only the measurements with non-irradiated detectors at high bias voltages were used for extracting this value.

Fig. 9 The dispersion of the electronic noise as a function of the total dark current of the detector.

Fig. 10 The bias voltage needed for collection, within a specified time, of 95% of the charge deposited uniformly in a $300 \mu m$ silicon planar diode, as a function of the depletion voltage of the diode.