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Study of the inter-strip gap effects on the response of Double Sided Silicon Strip Detectors using proton micro-beams

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Abstract

Double Sided Silicon Strip Detectors (DSSSDs) are segmented silicon detectors widely used for the detection of charged particles. When a charged particle hits the gap between two adjacent strips, a signal, different from the full energy one, can be generated, resulting in an incorrect energy information. With the purpose of studying inter-strip effects on the detector response, an experiment was performed using a proton micro-beam. The response of two DSSSDs, 75 and 998 μm thick, was measured as a function of the proton impact position, beam energy and bias voltage using a low intensity proton micro-beam, of about few hundred particles per second (pps). Results show that the effective width of the inter-strip region, which in turn is related to the efficiency for full energy detection, varies with both detected energy and bias voltage. The experimental results are interpreted within a simplified model.

Keywords: Strip detector, DSSSD, inter-strip gap, proton micro-beam

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1. Introduction

Segmented silicon detectors have been introduced for charged particle detection more than 25 years ago and they have gained a central role in high-energy physics. Nowadays they are in standard use also in low energy nuclear physics experiments, both for structure and dynamics studies, when reaction products have to be detected with good energy and angular resolution in a large solid angle.

The segmented geometry allows accurate measurement of the emission direction, crucial information in experiments aiming to study angular distributions of various processes (e.g. [1–4]), or for the coincident detection of two or more charged reaction products, with the goal to fully characterize the final state of the interaction process (e.g. [5]). Such detectors are also commonly used in unbound state spectroscopy studies using the inverse kinematics thick target scattering method e.g. [6, 7]. They are particularly suitable for experiments with low intensity radioactive ion beams and for measurements of very low cross-section processes with stable beams.

A DSSSD is a silicon detector with both electrodes (front and back side) segmented into strips. If N_f and N_b are the number of strips on the front (junction) and back (ohmic) side respectively, such detector provides information on $N_f \times N_b$ pixels (overlap regions between front and back strips) by using just $N_f + N_b$ electronics channels. Therefore, both sides have several strip-to-strip separation regions, called "inter-strip gaps" in the following. The DSSSD response to a charged particle provides information on its 2-dimensional position of incidence and on the deposited energy. When electron-hole (e-h) pairs created by the ion within the volume of the detector move along the electric-field lines, they induce currents on the electrodes. For particles hitting the central region of the pixel, a signal carrying information on the correct deposited energy in the detector originates only from those two strips that define the considered pixel. On the other hand, it has been observed that ions entering the detector through an inter-strip gap lead to phenomena such as charge-sharing and

31 inverted polarity signals [8–15].

32 Previous studies of the inter-strip effects on the response of segmented Si
33 detectors were performed by using α -particles of low energies [14, 15], 3 MeV
34 protons [15], 59.5 keV γ -rays from an ^{241}Am source [12], laser beams [8, 13] and,
35 more recently, beams of ^7Li and ^{16}O ions of energies between 6 and 50 MeV [11].
36 The study [11], using ^7Li and ^{16}O ion beams, focused on the DSSSD efficiency
37 for full energy detection, defined as the ratio between the number of events
38 measured with the correct full energy and the total number of detected events.
39 It was shown that this efficiency depends on the energy of the detected ion
40 and on the applied bias voltage. In addition, it was found that the measured
41 efficiency is lower than the value extracted by simply considering the geometrical
42 width of the inter-strip gap. This means that the width of the inter-strip region,
43 where the energy of the impinging ions is not correctly measured, is different
44 than the geometrical inter-strip width given in the detector specifications.

45 In principle, the knowledge on the inter-strip width makes possible an *a pri-*
46 *ori* calculation of the DSSSD efficiency for full energy detection of various ions
47 for a range of energies, a crucial information for those experiments where abso-
48 lute cross section measurements are performed. This finding therefore motivated
49 the present study, aiming to perform systematic measurements of the effective
50 width of the inter-strip gap and to improve the understanding of the physical
51 effects occurring there, leading to reduced amplitude signals and corresponding
52 efficiency variations.

53 In this paper, we report results of an experiment performed at the Ruđer
54 Bošković Institute (RBI), in which two DSSSDs with different thickness (75 and
55 998 μm) were characterized by the Ion Beam Induced Charge (IBIC) technique,
56 i.e. by scanning different inter-strip regions with a proton micro-beam and
57 recording the energy pulses along with the spatial coordinates of the impinging
58 proton on the detector surface. Proton beam energies of 800, 1700, 3000 and
59 6000 keV were selected for probing inter-strip effects at different penetration
60 depths (see table 1). Beam currents of the order of few hundred particles per
61 second (pps) have been used in the measurements.

Table 1: Proton beam energies used in measurements with the two DSSSDs and their corresponding range in silicon.

Proton energy(keV)	Proton range in silicon (μm)	DSSSD irradiated (μm)
800	10	75
1700	35	75 & 998
3000	90	75 (punch through)
6000	295	998

62 The paper is organized as follows. Section 2 describes the experimental
63 set-up and methodology. In Section 3, the experimental results are presented
64 separately for each detector. The theoretical model and interpretation of the
65 results is presented in Section 4. Finally, Section 5 summarizes the obtained
66 results.

67 2. Experimental methodology

68 2.1. Micro-beam setup

69 In the last decade, upgrades of the RBI micro-probe facility resulted in
70 the improvement of its focusing system, construction of a versatile spherical
71 scattering chamber, good selection of detectors for different characterization
72 techniques and development of a digital data acquisition system. Since ion
73 beams from either 1 MV or 6 MV tandem accelerators can be injected into the
74 micro-probe beam line, a wide selection of ions can be used for the application
75 of the Ion Beam Induced Charge technique. In the case of the 6 MV Tandem
76 Van de Graaff accelerator used in this work, two negative ion sources, namely

77 Alphasources (used for production of hydrogen and helium ions) and sputtering
78 (used for a wide range of elements such as hydrogen, lithium, carbon, oxygen,
79 silicon, chlorine and others) are available. Ion beam transport and accelerator
80 operation is computer controlled by a custom software based on the Test Point
81 package [16–18].

82 In the present experiment, the ion beam focusing was performed with an
83 Oxford triplet configuration, which is suitable for light ions with $E \cdot m/C^2$
84 of up to 8 MeV A/C² where A is the mass number and C the charge of the
85 accelerated ion. Higher rigidity ions can also be focused, however this is done
86 with a quintuplet configuration or a longer working distance (260 mm) doublet.

87 Application of the IBIC technique for detector testing implies the use of
88 very low micro-beam intensities of few hundreds of pps. This is achieved by
89 significant reduction of both the object and collimator apertures. Owing to the
90 corresponding reduction of beam divergence, the influence of the ion optical sys-
91 tem aberrations was also minimized and a typical micro-beam spatial resolution
92 of less than 1 μm can be easily achieved. The used magnetic scanning system
93 allowed the beam to raster scan over custom square scanning areas over the
94 horizontal (x) and vertical (y) directions with a step of $\sim 5 \mu\text{m}$, and to know,
95 for each recorded event, the beam position inside the scanning area. During the
96 experiment, the scanning areas were centered on the different inter-strip regions
97 to be studied. The size of the scanning area was typically $450 \times 450 \mu\text{m}^2$. The
98 beam scanning and the detector positioning were controlled by means of the
99 SPECTOR software [19].

100 2.2. DSSSDs and signal processing

101 The DSSSDs examined in the present study are model W1, manufactured
102 by Micron Semiconductor Ltd, with declared thickness of 75 and 998 μm . Their
103 area is $50 \times 50 \text{ mm}^2$ and each side is divided into 16 parallel strips 3 mm wide.
104 The junction (front) side is p-type and the ohmic (back) side is n-type. The
105 strips on the front side are perpendicular to the ones on the back side, giving a
106 granularity of $16 \times 16 = 256$ square shaped pixels with an area of $3 \times 3 \text{ mm}^2$.

107 They are built using a standard combination of implantation and pho-
108 tolithography techniques. The front and back side surfaces of a high-purity
109 silicon wafer (n-type) are oxidised to create oxide layers (SiO_2). That are se-
110 lectively removed by photolithography from the areas where active windows
111 (strips) or p-stop layers will be located. The residual SiO_2 spacing between ad-
112 jacent strips (i.e. the inter-strip gap width) is on the front side $100\ \mu\text{m}$ wide and
113 $0.9\ \mu\text{m}$ thick (see figure 1a). The junction is formed by implantation of acceptor
114 ions (p-type), using an accelerator. The back surface of the wafer is implanted
115 with donor ions resulting in strips of n^+ material. To avoid a conducting path
116 between n^+ - n^+ structure, backside strips are isolated by a p-stop implantation
117 $40\ \mu\text{m}$ wide. Hence, the strip separation on the back side is $30\ \mu\text{m}$ SiO_2 , $40\ \mu\text{m}$
118 p-stop and $30\ \mu\text{m}$ SiO_2 , resulting in the total value of $100\ \mu\text{m}$ (see figure 1b).
119 Finally a $0.3\ \mu\text{m}$ thick Aluminum metalization layer, not overlapping with the
120 SiO_2 regions, provides thin ohmic electrical contacts of the strips at both sides.
121 The silicon dead layer, due to the implantation process, has a nominal thickness
122 of $0.5\ \mu\text{m}$ (see figures 1 a and b). The full-depletion voltages declared by the
123 manufacturer for the thick and thin detectors are $180\ \text{V}$ and $3\ \text{V}$, respectively.

124 In the experiment presented in this paper, the DSSSDs were mounted under
125 vacuum ($\approx 10^{-6}$ mbar) in the nuclear microprobe station in a such way that
126 protons enter the detectors always from the front side. Furthermore, detectors
127 were mounted with the front strips parallel to the vertical direction and the
128 back strips parallel to the horizontal direction. In the following, we will use the
129 names F0 to F15 to indicate the 16 front strips and B0 to B15 to indicate the
130 16 back strips.

131 The electronics was assembled in such a way to allow for the simultane-
132 ous recording of signals of both polarities from all strips. The signals from
133 the strips were processed by MESYTEC MPR 16 pre-amplifiers, SILENA 716
134 programmable amplifiers and SILENA 9418 ADCs. The shaping time of the
135 amplifiers was set to $0.5\ \mu\text{s}$. The acquisition system was triggered by a total OR
136 of the logic signals related to all the 32 strips. Each recorded event consisted
137 of the coordinates (x, y) corresponding to the horizontal and vertical beam

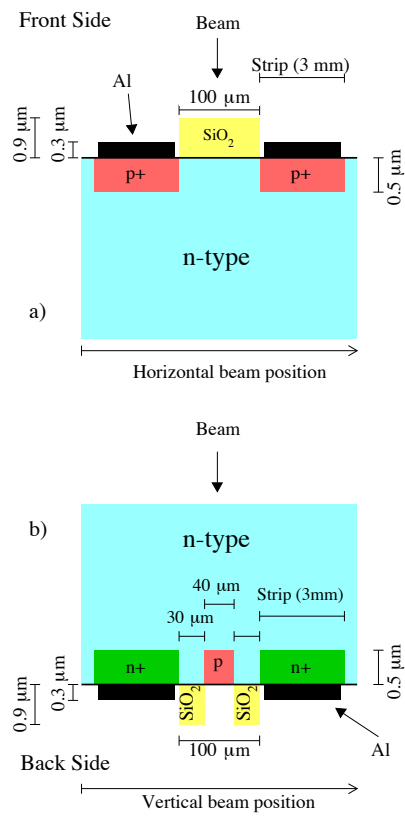


Figure 1: (Colour online) Schematic layout of the inter-strip region of the DSSSD. a) Cross-section of the electrode structure of the front side; b) The same for the back side. The drawing is schematic and not to scale.

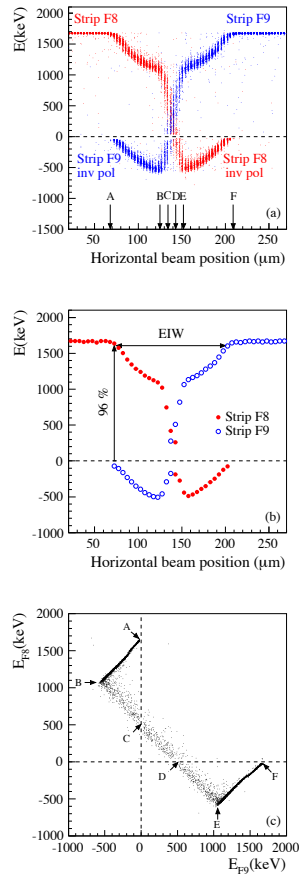


Figure 2: (Colour online) a) Energy signal amplitude profiles for the front strips F8 (red points) and F9 (blue points) of the 998 μm thick DSSSD, over-depleted at 270 V, with the beam scanning area centered on the front inter-strip F8-F9 and for a proton energy of 1700 keV. b) Same as figure 2a but averaged data. The definition of the effective inter-strip width (EIW, see text) is also sketched in the figure. c) Energy correlation F8-F9 for the events of figure 2a. Letters indicating different points in the F8-F9 correlation plot correspond to the ion impact position indicated in figure 2a. See text for further details.

138 position inside the scanning area and 64 energy signals (normal and inverted
139 polarity for each strip) from all the front and back strips.

140 In the experiment, the inter-strip effects were investigated by raster scanning
141 over different inter-strip regions of the front and back side, in order to study
142 the correlation between the energy measured from two adjacent strips and the
143 impact position of the incoming particles. An example of such correlation is
144 shown in figure 2. Here one can see the energy signal amplitudes as a function
145 of the horizontal position (energy signal amplitude profiles in the following) from
146 the front strips F8 and F9 when a proton beam of energy 1700 keV irradiates
147 the 998 μm thick detector operating in over-depletion at 270 V. When the beam
148 hits only strip F8 (i.e. far from the inter-strip region, impact position on the
149 left of point A), complete charge collection and thus full energy detection is
150 achieved. When the beam approaches the left side of the inter-strip gap, the
151 normal polarity F8 signal decreases and, at the same time, inverted polarity
152 signals appear in F9 (region between points A and B) reaching a maximum
153 value at position B. Moving toward the center of the inter-strip, the F9 inverted
154 polarity signals decrease (region between point B and C) and reverts to zero
155 at position C. In the center of the inter-strip gap both strips produce normal
156 polarity pulses (region between points C and D) but with reduced amplitude.
157 In the right half-side of the inter-strip region, the behaviour is symmetrical.
158 The F8 signal reaches zero at point D and inverted polarity signals occur in the
159 region between points D and E, reaching their maximum at point E. Finally,
160 in the region between points E and F the F8 inverted polarity signal amplitude
161 decreases to zero while the normal polarity signal of strip F9 monotonically
162 increases up to the full energy measured, which is reached at point F.

163 Since the effective width of the inter-strip gap is different from the geomet-
164 rical one declared by the manufacturer, our aim was to study how such region,
165 which in turn is related to the DSSSD efficiency for full deposited energy de-
166 tection, depends on the operating conditions, such as detector bias and proton
167 energy. With the aim to compare the results of the various measurements, we
168 transformed the raw data, as the ones in figure 2a into averaged values of posi-

169 tion and energy, as the ones in figure 2b. Data are sorted in steps of $5\ \mu\text{m}$ with
170 an estimated position uncertainty of $\pm 2.5\ \mu\text{m}$. For each position, the mean value
171 of the measured energy and its error were calculated from the recorded data.
172 In this paper we define the effective inter-strip width (EIW) as the difference
173 between the two beam positions where the energy signals from the two adjacent
174 strips drop below 96% of their full amplitude (see figure 2b). The threshold of
175 96% was arbitrarily chosen to enable comparison of all the different shapes of
176 the averaged plots, including those obtained with the thin detector.

177 We recall that, in previous papers, such inter-strip effects for charged particle
178 detection have been studied by observing energy correlations between adjacent
179 strips e.g. [11, 14, 15]. Such a correlation plot for the data of figure 2a is shown
180 in figure 2c, which is similar to the ones observed in e.g. [11, 14, 15]. As shown
181 in figure 2c, the spatially resolved IBIC measurements of charge pulses allowed,
182 for the first time, to clearly associate different points of the F8-F9 correlation
183 plot with the entrance coordinates of the incoming ion.

184 3. Experimental results

185 The response of the two DSSSDs was studied at different bias voltages:
186 under-depleted, fully-depleted and over-depleted. Because of the different be-
187 haviour of the two detectors, the results will be presented separately in the
188 following two sub-sections.

189 3.1. Results for the $998\ \mu\text{m}$ thick DSSSD

190 In these measurements proton micro-beams of incident energies 1700 and
191 6000 keV hit the surface of the detector around a front or a back inter-strip
192 region. Results presented in figure 3 concern the measurements with a proton
193 beam of energy 1700 keV and a scanning area centered on the front inter-strip
194 F8-F9 and on the center of strip B7. Bias voltages equal to 0.5, 1.0 and 1.5
195 times the full-depletion one were used. Increasing the bias, the detector response
196 improves both for the front and back side strips, leading to a decrease of both

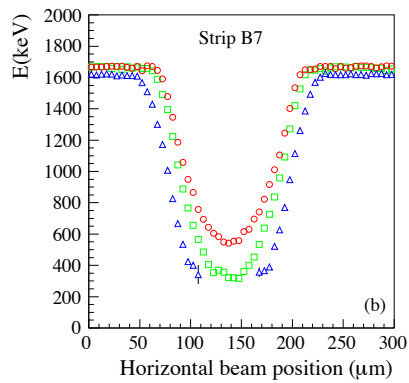
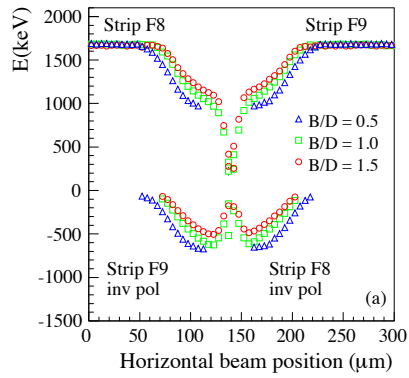


Figure 3: (Colour online) Energy signal amplitude profiles for the 998 μm thick DSSSD with a proton beam energy of 1700 keV and a scanning area centered on the front inter-strip F8-F9 and on strip B7. B/D indicates the ratio between the applied bias and the full depletion voltage. a) Inter-strip behaviour for strips F8 and F9. b) Strip B7 response versus the horizontal beam position.

197 the inverted polarity pulse amplitudes and the EIW. Figure 3b clearly shows
198 that, although the scanning area is centered on strip B7, when the incoming
199 protons cross the front inter-strip region, one has a reduced signal on B7. In
200 such conditions no signals are observed on back strips different than B7 for all the
201 tested B/D values. It is worth noting that, according to the charge conservation
202 principle, the measured back strip signal amplitude equals the sum of the pulses
203 from the two front strips (taking into account their polarities), thus confirming
204 the reliability of the energy calibration [20, 21].

205 Figure 4 presents results of the measurements with a proton beam energy
206 of 1700 keV and a scanning area centered on the back inter-strip B6-B7 and on
207 front strip F9. Contrary to the front inter-strip case, inverted polarity pulses
208 were not observed in all performed measurements as function of detector bias
209 and beam energy. For an over-depleted and fully-depleted detector the EIW is
210 about twice the declared geometrical width of the inter-strip gap, and in under-
211 depleted conditions (blue empty triangles in figure 4a), this area considerably
212 increases. Our results confirm the observation [11] that the sum of the two
213 signals from adjacent back strips provides the correct full energy information
214 for back inter-strip events, if the incoming particle is not crossing the front
215 inter-strip. In all of these measurements the front strip generates the expected
216 full energy signal as it is shown in figure 4b.

217 Figure 5 summarizes the dependence of the measured front and back EIWs,
218 on the bias voltage for different beam energies. The overall behaviour is that
219 both the front and back EIWs decrease by increasing the bias voltage. Black
220 full circles and blue full triangles correspond to proton energies of 1700 keV and
221 6000 keV, respectively, for the same front inter-strip and show that the front
222 EIW for protons at 6000 keV is significantly smaller than the one for protons
223 at 1700 keV. The red empty circles correspond to the results obtained for the
224 back inter-strip at a proton energy of 1700 keV. As one can see on the right
225 Y scale of figure 5, the EIW can be significantly different than the geometrical
226 inter-strip width. At a beam energy of 6000 keV the protons stop inside the
227 detector at depth of 295 μm , quite far from the detector surface, resulting in

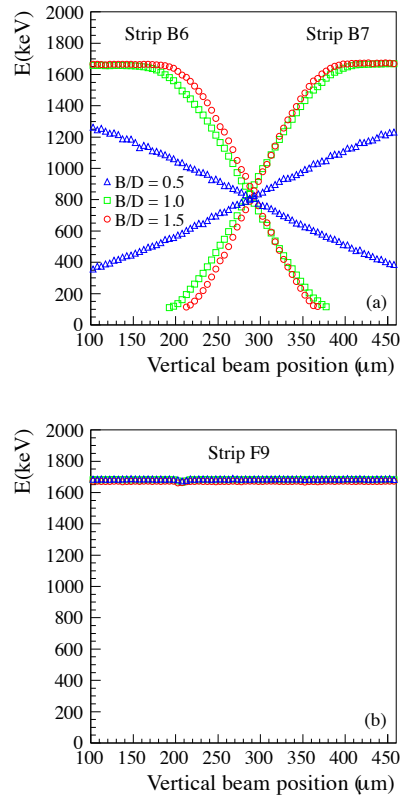


Figure 4: (Colour online) Energy signal amplitude profiles measured with a proton micro-beam of 1700 keV and a scanning area centered on the back inter-strip B6-B7 and on the center of strip F9. B/D is the ratio between the bias and the full depletion voltage. a) Energy response of the back strips versus the vertical beam position. b) F9 strip response versus the vertical beam position.

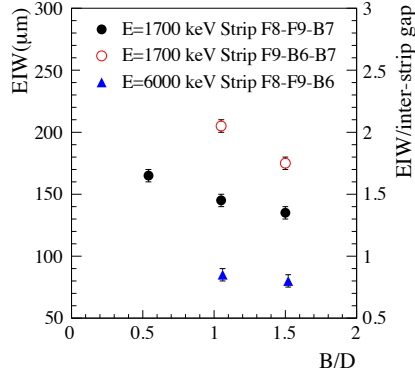


Figure 5: (Colour online) EIW dependence on the ratio between bias voltage and full depletion voltage (B/D). The axis on the right side shows the ratio between the EIW and the declared geometrical width of the inter-strip gap. F8-F9-B7: beam on inter-strip F8-F9 and center of strip B7. F9-B6-B7: beam on inter-strip B6-B7 and center of strip F9. F8-F9-B6: beam on inter-strip F8-F9 and center of strip B6.

228 a reduced effective front inter-strip width. On the contrary, 1700 keV protons
 229 stop at a depth of only $35 \mu\text{m}$, close to the junction side, and an enhanced EIW
 230 is observed.

231 In figure 3b it is shown that for ions passing through the front inter-strip
 232 region, even when a trajectory is passing through the center of a back strip, one
 233 observes a reduced back signal. With the aim to quantify this phenomenon, we
 234 consider the ratio between the minimum energy response (E_{min}) of the back
 235 strip and the full energy response (E_{full}) of the back strip observed when the
 236 beam hits the detector far from the inter-strip gap. The E_{min} value was obtained
 237 as the vertex of the parabola fitting the averaged data, and the corresponding
 238 error was calculated from the parameters obtained from the fit. This procedure
 239 allowed to extract the E_{min} value also for $B/D=0.5$ were, as shown in figure
 240 3b, a few experimental points in the inter-strip center are missing. Figure 6
 241 shows the dependence of $E_{min}/E_{full}(\%)$ on the ratio between bias voltage and
 242 depletion voltage. The plot shows that for low energy protons, stopped close to

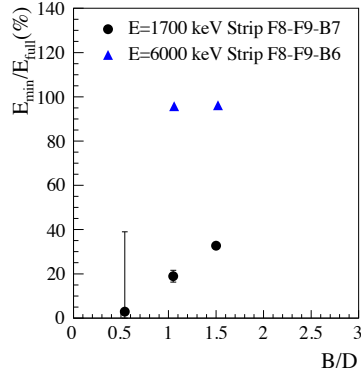


Figure 6: (Colour online) Plot of the ratio $E_{min}/E_{full} (%)$ versus the ratio between bias voltage and full depletion voltage (B/D) for the thick DSSSD. F8-F9-B7: beam on inter-strip F8-F9 and center of strip B7. F8-F9-B6: beam on inter-strip F8-F9 and center of strip B6. See text for details.

243 the detector surface, a small ratio $E_{min}/E_{full} (%)$ is observed.

244 Another measurement was also performed aiming to investigate the detector
 245 response to 1700 keV protons hitting the guard-ring in full depletion working
 246 conditions. Figure 7 shows the energy response of strip F8 (red points) when
 247 the scanning micro-beam moves along the vertical direction towards the guard-
 248 ring (decreasing vertical values). This plot shows that the signal amplitude in
 249 strip 8 gradually decreases when approaching the region between F8 and the
 250 guard-ring. At the same time, when the ions hit the detector volume at the
 251 guard-ring position, an induced signal appears on strips F0 and F15. These are
 252 the two outermost front strips and they are surrounded by the guard-ring. No
 253 induced signals are observed on the other front strips. We interpret this latter
 254 observation as due to the strong capacitive coupling between the outermost
 255 strips and the guard-ring. A similar behaviour is found also for the thin detector.
 256 The guard-rings of both used detectors were floating with no connection to the
 257 detector multipin connector.

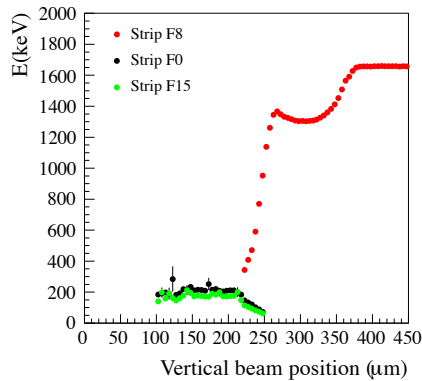


Figure 7: (Colour online) Detector response observed with a proton micro-beam of 1600 keV moving in the vertical direction along strip F8. When ions approach the region between F8 and the guard-ring, the F8 signal decreases and induced signals appear in F0 and F15 (see text for details).

258 3.2. Results for the 75 μm thick DSSSD

259 In these measurements proton micro-beams of incident energies 800, 1700
 260 and 3000 keV hit the front surface of the detector around the front or back
 261 inter-strip regions. In figure 8 are presented results for the DSSSD irradiated
 262 by protons of 1700 keV for three different bias conditions. The scanning area
 263 was centered on the front inter-strip F6-F7 and on the center of back strip
 264 B8. Surprisingly, in this case inverted polarity pulses are recorded only in over-
 265 depleted working conditions (see red empty circles in figure 8).

266 By using the method described in section 2.2, the EIW has been extracted
 267 for different working conditions. Figure 9a shows the front EIW as a function
 268 of B/D up to a B/D value of 2.9 which we do not have for the thick detector
 269 case. As one can see, the front EIW shows a non-monotone trend as function of
 270 the polarization voltage and a region, close to the nominal full-depletion voltage
 271 value, where the EIW value is minimum.

272 Figure 9b presents the results for the back EIW. The trend is similar to the

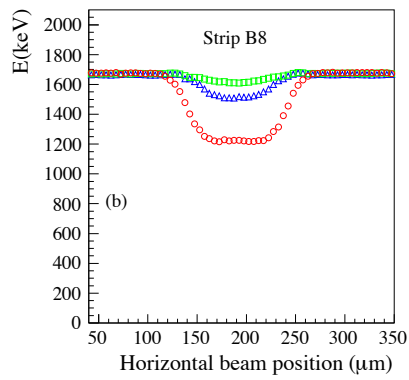
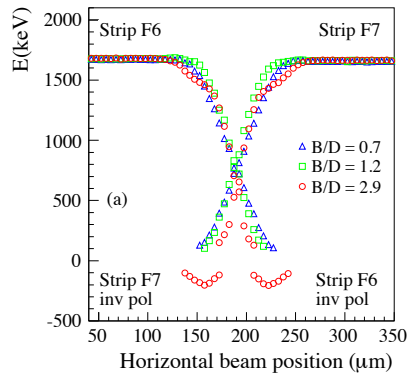


Figure 8: (Colour online) Energy signal amplitude profiles of the 75 μm thick DSSSD for protons of 1700 keV and a scanning area centered on the F6-F7 inter-strip and back strip B8. a) Response of F6 and F7 versus the horizontal beam position for three different bias voltages. b) B8 strip response versus the horizontal beam position. For comparison see figure 3, showing the results of identical measurements for the thick detector.

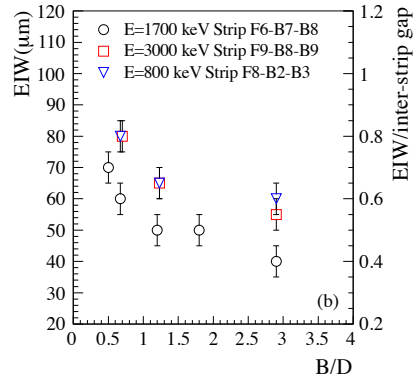
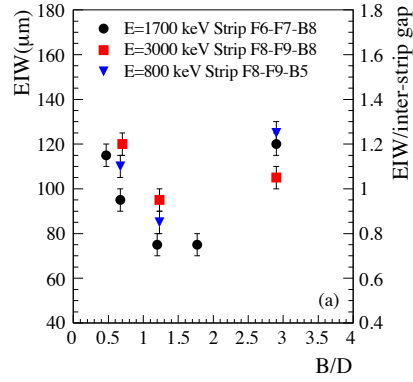


Figure 9: (Colour online) Dependence of the effective inter-strip width on the ratio bias voltage/depletion voltage for the 75 μm thick DSSSD. a) Front inter-strip behaviour. F6-F7-B8: beam on inter-strip F6-F7 and center of strip B8. F8-F9-B8: beam on inter-strip F8-F9 and center of strip B8. F8-F9-B5: beam on inter-strip F8-F9 and center of strip B5. b) Back inter-strip behaviour. F6-B7-B8: beam on inter-strip B7-B8 and center of strip F6. F9-B8-B9: beam on inter-strip B8-B9 and center of strip F9. F8-B2-B3: beam on inter-strip B2-B3 and center of strip F8.

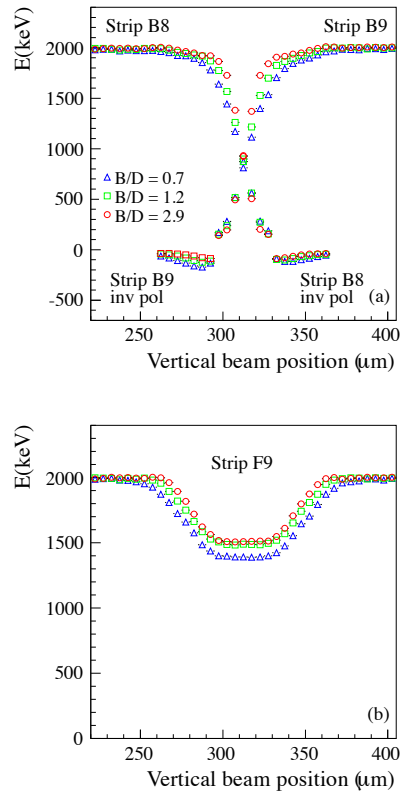


Figure 10: (Colour online) Energy signal amplitude profiles for the 75 μm thick DSSSD with 3000 keV protons, punching through the detector, and a micro-beam scanning area centered on the back inter-strip B8-B9 and on strip F9. a) Behaviour of the B8-B9 back inter-strip. b) strip F9 response as a function of the vertical beam position.

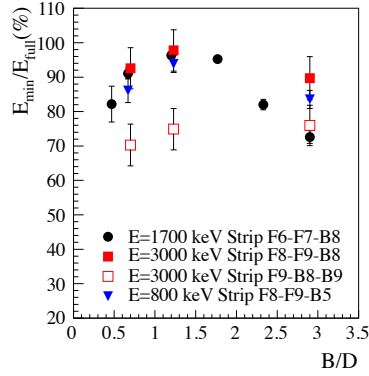


Figure 11: (Colour online) Plot of the ratio $E_{min}/E_{full}(\%)$ versus the ratio bias voltage/depletion voltage for the thin DSSSD. F6-F7-B8: beam on inter-strip F6-F7 and center of strip B8. F8-F9-B8: beam on inter-strip F8-F9 and center of strip B8. F9-B8-B9: beam on inter-strip B8-B9 and center of strip F9. F8-F9-B5: beam on inter-strip F8-F9 and center of strip B5. See text for details.

273 thick detector (red empty circles in figure 5). The back EIW decreases with
 274 increasing bias voltages, but the overall values are smaller than those measured
 275 for the thick detector.

276 The thin detector enables measurements of the detector response for incident
 277 protons punching through the DSSSD, new mode inaccessible in the measure-
 278 ments with the 998 μm thick detector for which protons are stopped in the
 279 DSSSD for all the available beam energies. The observed front inter-strip re-
 280 sponse in the punch-through condition, with protons of 3000 keV, is similar to
 281 that presented in figure 8 for lower beam energies when protons are stopped
 282 inside the DSSSD. On the contrary, the back inter-strip behaviour, shown in
 283 figure 10, is quite different. In fact, inverted polarity signals are observed in
 284 the back strips for all bias conditions, with increasing amplitude for decreasing
 285 bias. Figure 10b clearly shows that even if the micro-beam scanning area covers
 286 the center of strip F9, if the incoming protons are crossing the back inter-strip
 287 region, the considered front strip has a reduced amplitude signal.

288 We report in figure 11 (the analogous of figure 6 for the 998 μm thick detec-
 289 tor), the ratio between the minimum energy response (E_{min}) of the back (front)
 290 strip and the full energy response (E_{full}) of the back (front) strip. Since the
 291 trend of the signal amplitude as function of the position is not parabolic as for
 292 the thick detector, (E_{min}) corresponds to the mean value of the energy projec-
 293 tion relative to the 'flat' region (see e.g. figure 10b). In this case, E_{min}/E_{full}
 294 shows a maximum around the full-depletion voltage value.

295 4. Model calculations and interpretation

296 Despite a full numerical modeling of the devices under investigation is beyond
 297 the scope of the present work, a simplified simulation based on the Shockley-
 298 Ramo-Gunn framework is presented in the following subsections in order to
 299 provide a qualitative interpretation of the experimental findings. Since the
 300 whole simulation and interpretation depends on the electrostatic configuration
 301 of the device and on the interpretation of the induced charge pulse signals, such
 302 topics will be discussed first in the general case in subsections 4.1 and 4.2. The
 303 formation of inverted polarity signals will then be discussed in subsection 4.3.
 304 Finally, in the remaining subsections, the previously presented experimental
 305 results will be compared with the results of the simulations.

306 4.1. Interpretation framework

307 In a system at the electrostatic equilibrium with an arbitrary arrangement
 308 of N electrodes, the instantaneous current i_i induced at the i -th electrode by the
 309 motion of a point charge q in the detector volume, can be expressed as [22]:

$$i = -q \vec{v} \cdot \vec{E}_{w,i} \quad (1)$$

310 where \vec{v} is the velocity of the charge carrier and $\vec{E}_{w,i}$ is the weighting field
 311 associated with the i -th read-out electrode considered. The electric field deter-
 312 mines the charge trajectory and velocity. The weighting field, relates the motion
 313 of the charge carriers to the current induced at the read-out electrodes. The

314 weighting field can be expressed in terms of the weighting potential ψ_w :

$$\vec{E}_{w,i} = -\vec{\nabla}(\psi_{w,i}) \quad (2)$$

315 where the weighting potential can be written as the derivative of the electric
316 potential ψ with respect to the voltage applied at the read-out electrode [23, 24]:

$$\psi_{w,i}(\vec{x}) = \frac{\partial \psi(\vec{x})}{\partial V_i} \quad (3)$$

317 The time integration of eq. 1 shows that the total charge induced by q at the
318 i -th read-out electrode is proportional to the difference in weighting potential
319 between its value at the initial position \vec{x}_a , where charge carriers are generated,
320 and at its final position \vec{x}_b [25]:

$$Q_i = q \cdot (\psi_{w,i}(\vec{x}_b) - \psi_{w,i}(\vec{x}_a)) \quad (4)$$

321 It is worth noting that, the position \vec{x}_b can be either the collecting electrode
322 or another position within the detector volume, where trapping or recombina-
323 tion occurred. The signal amplitudes, measured in the present experiment, are
324 proportional to the total induced charge Q in the considered read-out electrode
325 which is obtained by the time integration of the induced current pulse. There-
326 fore, the combination of the charge transport properties of the detector material,
327 the geometry and topology of the electric field and of the weighting potential,
328 define the response of the DSSSDs under investigation for a given incident ion
329 and energy.

330 4.2. Calculation of induced charges

331 A qualitative numerical analysis for the DSSSDs configurations under in-
332 vestigation was implemented performing simplified calculations of the electric
333 field and the weighting field. A 200 μm wide cross section of the devices was
334 simulated both for the front and back inter-strips of the 75 μm and the 998 μm
335 thick detectors. For simplicity, simulations were performed assuming an iso-
336 lated system of three electrodes and neglecting any coupling with the remaining
337 strips.

338 Simulations were performed by means of the commercial finite element method
339 (FEM) solver Comsol Multiphysics 4.3 [26]; using the device specifications given
340 by the manufacturer, maps of the electric potential, weighting potential and
341 electric field stream lines for different values of applied voltage were obtained.
342 Numerical simulations were performed as follows. The electric potential ψ cal-
343 culation was defined by the FEM solution of the Poisson's equation coupled
344 with the carriers stationary drift-diffusion equation:

$$\left. \begin{aligned} -\epsilon \nabla^2 \psi(\vec{x}) &= q [N_D(\vec{x}) - N_A(\vec{x}) - n(\vec{x}) + p(\vec{x})] \\ \nabla \cdot [D_n \nabla n(\vec{x}) + \mu_n \nabla \psi(\vec{x}) n(\vec{x})] &= 0 \\ \nabla \cdot [D_p \nabla p(\vec{x}) - \mu_p \nabla \psi(\vec{x}) p(\vec{x})] &= 0 \end{aligned} \right\} \quad (5)$$

345 where p and n are the hole and electron concentrations, N_D and N_A represent
346 the donor and acceptor concentrations, $D_{n,p}$ and $\mu_{n,p}$ indicate the carriers dif-
347 fusivity and mobility, respectively.

348 In order to describe the static equilibrium, the steady state was considered in
349 the continuity equations by neglecting any transient effect $\partial n/\partial t = \partial p/\partial t = 0$
350 and by setting an infinite recombination time for both charge carriers. Consid-
351 ering Poisson's equation, Dirichlet boundary conditions $\psi(\vec{x}_j) = V_j$ were set
352 at the electrodes, and Neumann conditions were assumed elsewhere. A surface
353 charge density σ was also defined at the oxide interfaces. Considering electron
354 and hole concentrations, Dirichlet boundaries $p(\vec{x}_j) = 0$ and $n(\vec{x}_j) = 0$ were
355 assumed at the front electrodes, and $p = N_A$, $n = N_D$ at the back electrodes.
356 The $p^+ - n$ junction formed by the p-stop at the center of the back inter strip was
357 simulated imposing a Dirichlet boundary condition $n(\vec{x}) = 0$ on the electron
358 continuity equation. Neumann boundary conditions were assumed elsewhere.
359 After the electric field calculation, the weighting potential $\psi_{w,j}$ was then eval-
360 uated according to the prescriptions in eq. 4 and in [23, 24]. Defining, for ease
361 of writing,

$$\frac{\partial \psi}{\partial V_j} = \psi_{w,j} \quad \frac{\partial n}{\partial V_j} = \nu_j \quad \frac{\partial p}{\partial V_j} = \pi_j \quad (6)$$

362 where $j=1,2,3$ is the electrode index, and assuming any other parameter in eq. 5
363 (mobility, diffusivity and dopants concentration) as independent on the applied

364 bias, then the voltage differentiation of eq. 5 provides a new set of differential
 365 equations, written in terms of the weighting field of the read-out electrode:

$$\left. \begin{aligned} -\epsilon \nabla^2 \psi_{w,j}(\vec{x}) &= q \cdot [\pi_j(\vec{x}) - \nu_j(\vec{x})] \\ \nabla \cdot [D_n \nabla \nu_j(\vec{x}) - \mu_n \nabla \psi(\vec{x}) \nu_j(\vec{x}) - \mu_n \nabla \psi_{w,j}(\vec{x}) n(\vec{x})] &= 0 \\ \nabla \cdot [D_p \nabla \pi_j(\vec{x}) + \mu_p \nabla \psi(\vec{x}) \pi_j(\vec{x}) + \mu_p \nabla \psi_{w,j}(\vec{x}) p(\vec{x})] &= 0 \end{aligned} \right\} \quad (7)$$

366 where $i \neq j$ and ψ is the solution of eq. 5. Dirichlet boundary conditions
 367 associated with eq. 7 were defined as

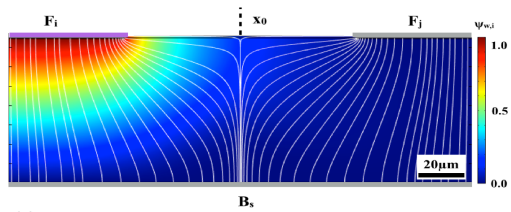
$$\psi_{w,j}(\vec{x}_k) = \delta_{j,k} \quad \nu_j(\vec{x}_k) = 0 \quad \nu_j(\vec{x}_k) = 0 \quad (8)$$

368 where j is the index of the read-out electrode and k is a generic electrode index.
 369 Neumann boundary conditions were assumed elsewhere.

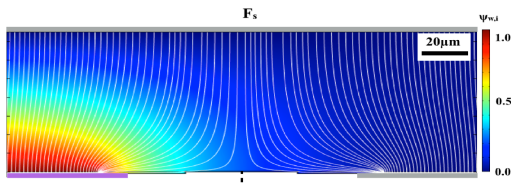
370 In figure 12, the weighting potential maps associated with the read-out elec-
 371 trode (F_i for the front and B_i for the back) are presented for the two DSSSDs
 372 at the nominal full depletion configuration ($B/D=1$), in absence of any surface
 373 charge densities at the oxide interface. The internal electrostatic properties of
 374 the DSSSDs under investigation are similar, from a topological point of view, to
 375 those of other devices or analogous multi-electrode structures previously studied
 376 in references [8–10, 15, 27].

377 To summarize, we consider a sub-system of the DSSSD consisting of three
 378 electrodes for the front inter-strip (figure 12 a and c): two adjacent front strips
 379 biased at negative voltage (F_i, F_j , where F_i is the read-out electrode) and one
 380 grounded back strip B_s . In such a sub-system the electric field stream lines
 381 originating from B_s diverge from the median inter-strip coordinate x_0 , and they
 382 sink either at the left F_i or right F_j front strip. At the front side, the weighting
 383 potential decreases from F_i (where $\psi_{w,i} = 1$) to F_j (where $\psi_{w,i} = 0$), having a
 384 value lower than 0.5 at the median abscissa x_0 . Similarly, the weighting potential
 385 decreases from 1 to 0 along the left edge of the cross section connecting F_i with
 386 the back strip B_s .

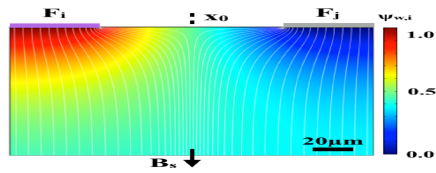
387 A symmetric configuration of the weighting potential is assumed for the
 388 read-out electrode F_j with $\psi_{w,j} = 1$ at F_j and $\psi_{w,j} = 0$ at the F_i and B_s
 389 electrodes.



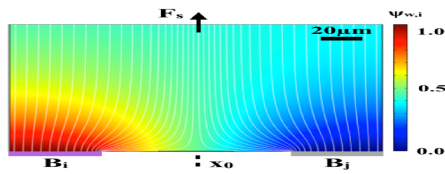
(a)



(b)



(c)



(d)

25
 Figure 12: (Colour online). Simulated weighting potential maps (color scale on the right) and electric stream field lines (in white) at $B/D=1$ assuming zero surface charge at the Si-SiO₂ interface for: a) 75 μm detector, front inter-strip; b) 75 μm detector, back inter-strip; c) 998 μm detector, front inter-strip; d) 998 μm detector, back inter-strip. The read-out electrode, associated with the simulated weighting potential shown, is sketched in purple. The back electrode B_s in c) and the front electrode F_s in d) are out of the figure.

390 For completeness, we remind that the value of the weighting potential asso-
 391 ciated to the back strip B_s at a position \vec{x} inside the detector volume $\psi_{w,s}(\vec{x})$
 392 can be obtained by the charge conservation principle, for which at every position
 393 \vec{x} , the sum of the weighting potentials must be equal to one [21]. Therefore for
 394 our simplified system of three electrodes we have:

$$\psi_{w,s}(\vec{x}) = 1 - \psi_{w,i}(\vec{x}) - \psi_{w,j}(\vec{x}) \quad (9)$$

395 It is worth noting that in a non-isolated system the sum should extend to all the
 396 front and back electrodes of the detector. Similar considerations hold for the
 397 back inter-strip electrostatics (figure 12 b and d), provided that the electric field
 398 stream lines originate from the two back strips B_i, B_j and sink at the front strip
 399 F_s . The evaluated electric field stream lines and weighting potential distribution
 400 show qualitatively the same topological configuration for the 75 μm and 998 μm
 401 thick detectors.

402 4.3. Origin of inverted polarity pulses

403 An interpretation of the induced charge pulse formation is proposed, based
 404 on the results presented in figure 12. The charge induction mechanism is de-
 405 scribed according to eq. 4. Considering the creation of an electron-hole pair
 406 in the front inter-strip gap (e.g., figure 12a and c), the motion of both charge
 407 carriers will induce three concurrent signals on F_i, F_j and B_s . Assuming for
 408 simplicity that the charge carriers are created close to the front surface, the
 409 electron moves towards the back strip, where both j-th and i-th weighting po-
 410 tentials are zero, thus inducing a positive signal on F_i and F_j according to eq.
 411 4; the absolute value of the signal induced on B_s will be given, according to
 412 eq. 9 and eq. 4, by the sum of the signals induced at the front electrodes.
 413 On the other hand, according to the electric field distribution, the hole drifts
 414 towards F_i or F_j depending on its generation position. As an example, an hole
 415 created in the right side of the inter-strip region will move towards strip F_j ;
 416 considering the weighting potential distribution, the hole will therefore induce
 417 a normal (positive) polarity pulse on F_j and an inverted (negative) polarity

418 pulse on F_i according to eq.4 [21]. Thus, if all holes are collected by F_i and
419 all electrons are collected by the back strip B_s , both electron and hole induce
420 positive polarity current signal on strip F_i and the sum of the two contributions
421 will correspond to the full energy amplitude detected. On the other hand, as
422 the signal induced on F_j by the hole collected at F_i has negative polarity, the
423 result is a bipolar induced current at F_j . However, when all the produced charge
424 carriers are collected by F_i and B_s , the time-integration of the induced current
425 signal on F_j gives a total charge equal to zero and the inverted polarity hole
426 signal on F_j cancels out with the electron contribution. However, a non-zero
427 inverted-polarity charge can be induced on the strip F_j if electrons are trapped
428 or recombine along their path, preventing the full collection at the back strip B_s
429 [15, 21]. In the above discussion we understood that, the occurring of anomalous
430 polarity pulses can be always regarded as a consequence of charge losses within
431 the active volume of the device.

432 Particularly, in [8, 9] the occurring of inverted polarity pulses was investi-
433 gated in detail in terms of the presence of a local potential maximum, as well as
434 of radiation-induced damage at the Si-SiO₂ interface. In the model proposed in
435 [21], inverted polarity pulses could occur if the time-integration of the bipolar
436 induced current does not fall to zero, i.e. if the positive contribution due to one
437 carrier species (electrons) is not sufficient to cancel out the inverted polarity
438 current generated by the other one (holes). This is ascribed in the model to a
439 negligible electron lifetime in the device under test in [21] with respect to that
440 of holes.

441 In the present case the good energy resolution and low leakage currents,
442 show that the radiation damage of the detectors if present is at a minor level,
443 both at the oxide interface and in the silicon bulk. Moreover, a large difference
444 in the carriers lifetime, as that proposed in [21], is not suitable to fit the typical
445 charge transport properties of high-purity silicon devices and could be consid-
446 ered only in the case that the manufacturing process would significantly modify
447 the inter-strip detector bulk structure and geometry. A reasonable interpreta-
448 tion of charge losses in the DSSSDs under test is that a significant bending of

449 the electric field lines occurs at the front and back inter-strip silicon-oxide in-
450 terface, due to the build-up of an effective surface charge density, as suggested
451 in [15]. Such an interpretation will be at the basis of the numerical simulations
452 discussed in the following, concerning the interaction of protons, injected from
453 the junction side, on the detectors. Due to the different configuration of front
454 and back inter-strip, the discussion is subdivided into two separate subsections.

455 4.4. Front inter-strip simulation

456 The simple model we implemented to investigate the effects of a charge build-
457 up at the Si-SiO₂ interface of the front inter-strip, is based on considering an
458 effective positive surface charge density σ over the whole SiO₂ layer. The surface
459 charge density was assumed to be constant on the whole interface. The device
460 modelling consisted of performing a parametric sweep over the charge density
461 value up to $\sigma = e \times 10^{10} \text{ cm}^{-2}$, where e is the elementary charge, in order to
462 obtain a reasonable agreement with the experimental data. The amplitude of the
463 signals at the different considered electrodes, proportional to the induced charge
464 at the considered electrode, was obtained taking into account the ionization
465 profiles of the incoming protons evaluated by means of the Monte Carlo code
466 SRIM [28]. In the following, results are discussed separately for the two devices
467 under test.

468 4.4.1. Results for the 998 μm detector

469 A qualitative agreement with the experimental data was obtained assuming a
470 positive charge density at the front Si-SiO₂ interface of $\sigma = e \times 5 \times 10^9 \text{ cm}^{-2}$. The
471 relevant weighting potential and electric field stream lines of the 998 μm detector
472 at B/D=1.0 are shown in figure 13 a. Assuming this value for σ , the applied
473 voltage is not sufficient to prevent a bending of the electric field lines. Thus,
474 the positive surface charge appears as a sink for the electrons generated within
475 the first 20 μm in depth. Despite the significant simplifications assumed in the
476 model, the signal amplitude profiles shown in figure 13 b evidence a qualitatively
477 good description of the experimental profiles in figure 3 a. Particularly, the

478 maximum value of inverted polarity pulse decreases from $B/D=0.5$, where it
479 reaches $\approx 30\%$ of the deposited energy, to $\approx 15\%$ at $B/D=1.5$, in agreement
480 with the experimental findings. Such a behaviour could be explained considering
481 that the increase in the electric field strength, associated with the increase of the
482 applied voltage, contributes to weaken the field stream lines bending towards the
483 Si-SiO₂ interface, thus promoting the electron collection at the back electrode.

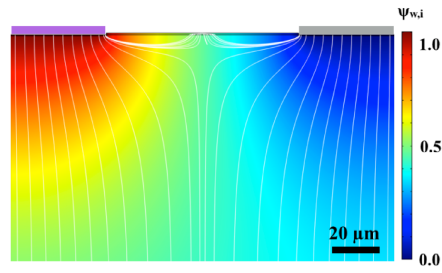
484 The simulated signal amplitude profile at the back electrode, for protons
485 hitting the front inter-strip and the centre of the considered back strip, is shown
486 in figure 14. As one can see, simulation results in figure 14 qualitatively repro-
487 duces the trend of the experimental data shown in figure 3 b, supporting once
488 more the interpretation proposed above.

489 *4.4.2. Results for the 75 μm detector*

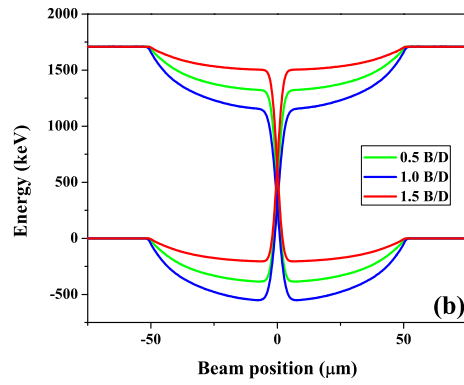
490 Unlike the case of the 998 μm detector, inverted polarity pulses were clearly
491 measured in the 75 μm detector only in the over-depletion configuration with
492 $B/D=2.9$. The simulated signal amplitude profiles are shown in figure 15 a for
493 B/D values of 0.7, 1.2, 2.9. Simulations were implemented performing a sweep
494 over the σ parameter at the Si-SiO₂ interface. The σ value corresponding to
495 each B/D was chosen in order to obtain the best reproduction of the measured
496 EIWs shown in figure 9 a and the obtained σ values are reported as a function
497 of B/D in figure 15 b. The corresponding simulated EIWs, to be compared
498 with the experimental values of figure 9a, are shown in figure 16. As one can
499 see, in order to reproduce the data at $B/D=2.9$ (a B/D value which we do not
500 have for the thick detector) we had to assume a value of the charge density
501 σ considerably larger than for the other B/D values where the σ value is almost
502 constant.

503 The field distribution in the case of $B/D=2.9$, simulated at the corresponding
504 charge density shown in figure 15 b, is reported in figure 17.

505 In summary, the presence of inverted polarity pulses appears to be connected
506 with the increase of positive surface charge at the front Si-SiO₂ interface for
507 increasing applied voltage, in agreement with the interpretation of [15].



(a)



(b)

Figure 13: (Colour online) Simulated weighting potential map and electric field stream lines (in white) at $B/D=1$ for the front inter-strip of the $998 \mu\text{m}$ detector, where a uniform surface charge density $\sigma = e \times 5 \times 10^9 \text{cm}^{-2}$ was assumed. The read-out electrode, associated with the simulated weighting potential shown, is sketched in purple. b) Simulated energy signal amplitudes for 1700keV protons as function of position along the front inter-strip assuming $\sigma = e \times 5 \times 10^9 \text{cm}^{-2}$. Beam position 0 corresponds to the center of the inter-strip.

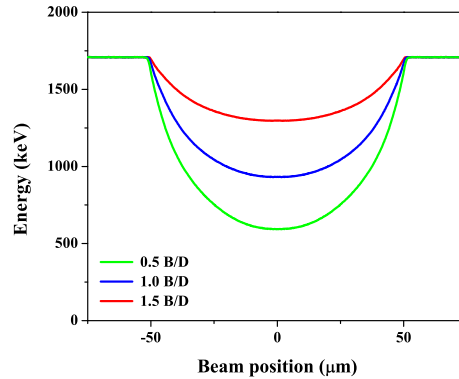


Figure 14: (Colour online) Signal amplitude profile of the back electrode of the 998 μm detector for front inter-strip events, simulated at different B/D assuming $\sigma = e \times 5 \times 10^9 \text{cm}^{-2}$ for 1700 keV protons. Beam position 0 corresponds to the center of the inter-strip.

508 *4.5. Back inter-strip simulation*

509 The same interpretation framework proposed for the front inter-strip, was
510 assumed to hold for the qualitative analysis of the experimental results con-
511 cerning the back inter-strip of the DSSSDs, provided that the role of holes and
512 electrons is exchanged. For consistency with the interpretation of the front
513 inter-strip results, we assume charge build-up in the two silicon-oxide interface
514 layers in the back inter-strip, causing a local field reversal and acting as a sink
515 for the electric field lines, thus preventing hole from collection at the front elec-
516 trode. The simulations were performed implementing a parametric sweep of
517 the σ values in the same range as that of the front inter-strip analysis. The
518 p-stop at the center of the back inter strip, which is not connected to an external
519 circuitry, was simulated by imposing a Dirichlet boundary condition on the
520 electron continuity equation. Also in this case the analysis of the experimental
521 data is subdivided into two separate subsections for the 998 μm and the 75 μm
522 detectors.

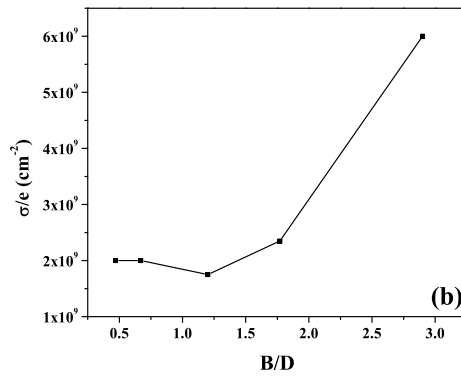
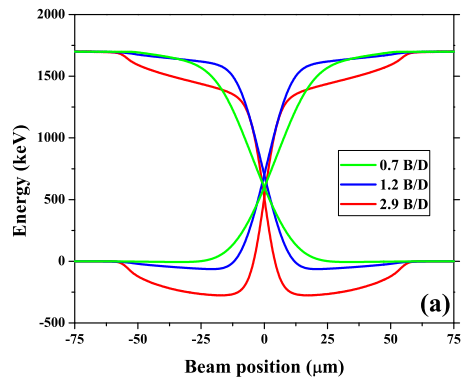


Figure 15: (Colour online) a) Simulated energy signal amplitudes for 1700 keV protons as function of position along the front inter-strip for the 75 μm detector at different B/D values. Beam position 0 corresponds to the center of the inter-strip. b) Best fitting values of σ/e as a function of B/D. See text for details.

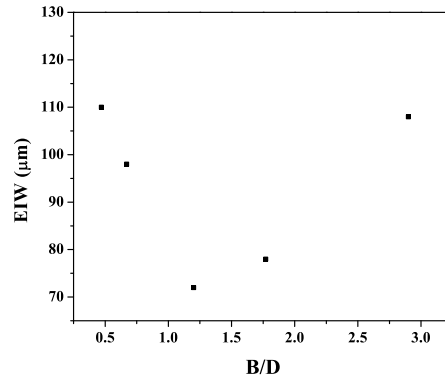


Figure 16: Simulated EIW values as function of B/D for the front inter-strip of the 75 μm detector.

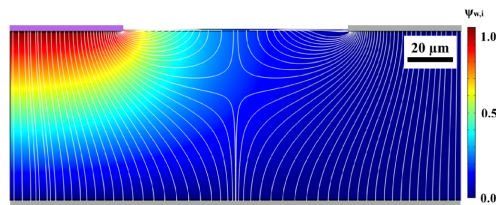


Figure 17: (Colour online) Simulated weighting potential maps (color scale on the right) and electric field stream lines (in white) for the 75 μm detector, considering $B/D=2.9$ and $\sigma = e \times 6 \times 10^9 \text{cm}^{-2}$. The read-out electrode, associated with the simulated weighting potential shown, is sketched in purple.

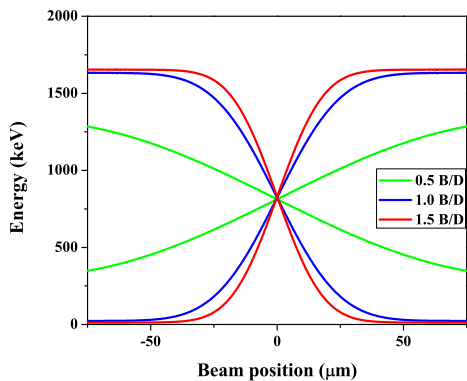


Figure 18: (Colour online) Simulated energy signal amplitudes for 1700 keV protons as function of position along the back inter-strip of the 998 μm detector for different B/D values assuming $\sigma = 0$. Beam position 0 corresponds to the center of the inter-strip.

523 *4.5.1. Results for the 998 μm detector*

524 The reference electrostatic configuration for the unperturbed device under
525 test (i.e. $\sigma=0$) is depicted in figure 12 d. Recalling that the penetration depth of
526 1700 keV protons is about 35 μm , we can assume that the hole motion towards
527 the front electrode is not affected by local modifications of the electric field lines
528 at the back side. For this reason, the detection of charge losses and inverted
529 polarity pulses is not expected in the present configuration. A parametric sweep
530 over σ confirmed such an analysis, showing an insensitivity of the energy signal
531 amplitude profiles in the $\sigma = \pm e \times 5 \times 10^9 \text{cm}^{-2}$ range. The simulated energy
532 signal amplitude profiles, when the beam scans the back inter-strip region, are
533 shown for different B/D in figure 18. In agreement with the lack of inverted
534 polarity signals, the absence of charge losses is confirmed by the fact that sum-
535 ming the signals of two adjacent back strips one reproduces the amplitude of
536 the full signal. The decrease of the EIW for increasing voltage is in qualitative
537 agreement with the experimental findings shown in figure 4 a. When charge

538 carrier generation occurs at several hundreds of micrometers above the back
539 electrodes, the electron cloud size increases during the drift inside the detector
540 bulk, contributing to the charge sharing between two adjacent back strips. Such
541 an effect is more pronounced at low bias voltages, i.e. at 0.5 B/D. This phe-
542 nomenon was shown in previous works on silicon and other detector materials
543 (see e.g. [29, 30]). By increasing the bias voltage of the DSSSD, the strength of
544 the electric field rises, leading to a reduction of the lateral diffusion of the charge
545 carriers. The experimental decrease of the EIW for increasing voltage for the
546 998 μm detector, is in qualitative agreement with the present interpretation.

547 *4.5.2. Results for the 75 μm detector*

548 For protons of 1700 keV, the back inter-strip energy signal amplitude profiles
549 are qualitatively the same as the ones of the 998 μm device, and are compatible
550 with the previous discussion. In this case, the electron cloud travels on a shorter
551 path than in the thicker detector; thus its lateral diffusion is less pronounced.
552 Correspondingly, in agreement with the experimental findings, the simulated
553 back EIW is smaller than the one of the 998 μm detector, as one can see com-
554 paring figures 18 and 19. Also in this case, a relative insensitivity to a surface
555 charge density on the back side was observed, in the $\sigma = \pm e \times 5 \times 10^9 \text{cm}^{-2}$
556 range, for the energy signal amplitude profiles associated with 1700 keV protons,
557 so that the unperturbed electric field distribution in figure 12 b is adequate to
558 describe the present case. On the other hand, the inverted polarity pulses exper-
559 imentally observed with a 3000 keV proton probe, having a penetration depth
560 larger than the detector thickness, can be explained by assuming that a nega-
561 tive surface charge density is present at the back Si-SiO₂ interface. Simulated
562 energy signal amplitude profiles at 3000 keV for different B/D values, shown in
563 figure 20 a, were evaluated setting a constant negative surface charge density
564 $\sigma = e \times 5 \times 10^9 \text{cm}^{-2}$ on the two back SiO₂ layers. The bending of the electric
565 field stream lines associated with such a configuration, depicted in figure 20 b,
566 is effective in causing the holes, generated within 20 μm above the back side, to
567 drift towards the charged oxide interface.

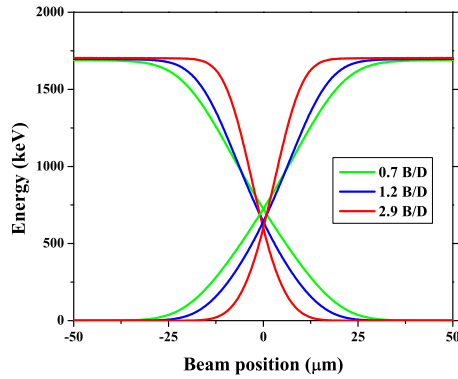


Figure 19: (Colour online) Energy signal amplitude profiles for the 75 μm detector back inter-strip, with 1700 keV protons and for different B/D values. Beam position 0 corresponds to the center of the inter-strip.

568 The qualitative agreement of the simulation predictions with the experimen-
 569 tal data shown in figure 10 a, appears to support the present tentative inter-
 570 pretation for the charge signal formation mechanism in the back inter-strip. An
 571 interesting feature of both experimental findings and simulation results is that,
 572 differently from the results for the front inter-strip of the thin detector, the
 573 absolute value of the inverted-polarity signals decreases at increasing voltage.
 574 Such a behaviour is compatible with the assumption, which was implemented
 575 in the simulations, that the negative surface charge density is almost constant
 576 in the voltage range under investigation.

577 5. Summary and conclusion

578 A systematic study of the response of two DSSSDs of different thickness (75
 579 and 998 μm) was performed by scanning the front and back inter-strip regions
 580 using proton micro-beams of different energies and for different detector bias
 581 voltages. Correlations between the position of the incoming ion and the signal

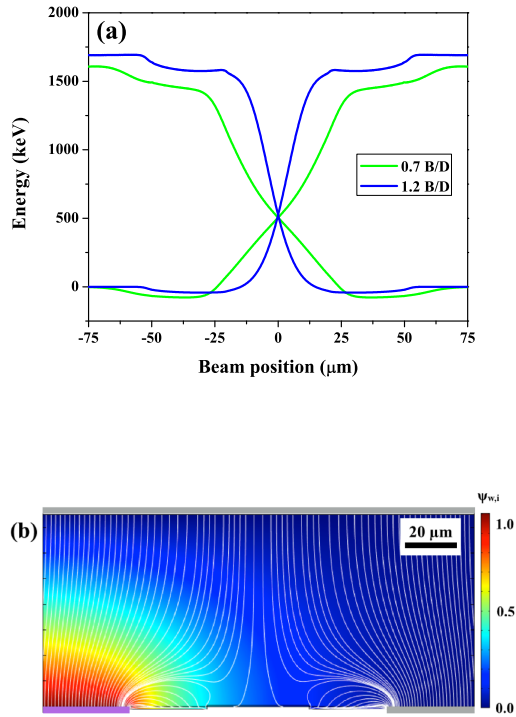


Figure 20: (Colour online) a) Energy signal amplitude profiles for the back inter-strip of the 75 μm detector with 3000 keV protons. Simulations were performed at different B/D assuming $\sigma = e \times 5 \times 10^9 \text{cm}^{-2}$. Beam position 0 corresponds to the center of the inter-strip. b) Corresponding simulated weighting potential maps (color scale on the right) and electric field stream lines (in white). The read-out electrode, associated with the simulated weighting potential shown, is sketched in purple.

582 amplitude from the individual strips were studied using proton micro-beams
583 of well defined size and trajectory. This allowed us to perform a systematic
584 study of the behaviour of the effective inter-strip width, which is correlated to
585 the DSSSD efficiency for full deposited energy detection, as a function of the
586 operating conditions of each detector.

587 For the thick DSSSD the protons were always stopped inside the detector
588 at all the available proton energies. In these conditions, signals of reduced am-
589 plitude are observed for the front inter-strip events, including inverted polarity
590 ones. For back inter-strip events charge sharing between the two adjacent strips
591 was observed, in absence of opposite polarity signals. The obtained results show
592 that both front and back EIW can be much larger than the nominal width of
593 the inter-strip gap and depend on the energy of the detected particles and on
594 the polarization voltage.

595 The thin detector has been characterized both with protons stopping inside
596 the DSSSD and in punch-through conditions. For protons punching through the
597 detector, inverted polarity signals were clearly observed in the back inter-strip
598 events for the first time.

599 The experimental observations were compared with the results of simplified
600 simulations based on the Shockley-Ramo-Gunn framework. It was shown that
601 assuming the build up of positive charge at the oxide interface in the front inter-
602 strip and of negative charge at the oxide interface in the back inter-strip, one
603 can obtain a satisfactory qualitative reproduction of all the observed inter-strip
604 effects. A more complete analysis of the device, including additional details
605 such as plasma effects, non uniformity of the surface charge density at the oxide
606 interface or its dependence on the polarization voltage, might provide additional
607 information but is beyond the scope of the present work.

608 In conclusion, the obtained results show that the front and back effective
609 inter-strip widths, which are related to the DSSSD efficiency for full deposited
610 energy detection, depend on the detector thickness and on the operating con-
611 ditions. In addition, in [?]] it has been shown that for detectors operated
612 in atmosphere the inter-strip effects have a time dependence after biasing and,

613 for detectors in dry atmosphere, steady state conditions can take days to be
614 reached. Therefore, for detectors operating in high vacuum, as in the present
615 case, a time dependence of the efficiency for full energy detection over the first
616 days of measurement cannot be excluded. In summary, for those experiments
617 aiming at accurately measuring quantities dependent on the efficiency for full
618 energy detection, especially if two or more DSSSD are used in coincidence, a
619 complete characterization of the used DSSSDs is required.

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