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CHARGE MULTIPLICATION IN SILICON RADIATION
DETECTORS UNDER DENSE IRRADIATION

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ABSTRACT

Charge multiplication at low field has been studied by fission fragments spectroscopy in ion-implanted Si-detectors. Also, various types of Si-detectors were used at CERN to measure a pulsed muon flux of high density, and again multiplication was observed above a flux threshold which depends on the detector design. In the absence of the gold contact no multiplication occurs.

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1. INTRODUCTION

One of the unsolved problems for silicon nuclear radiation detectors in fission fragments spectroscopy is related to the charge multiplication, occurring at bias voltages well below the avalanche breakdown voltage [1,2]. Until now this effect was mainly observed in surface barrier detectors and it depends on the manufacturing procedure [2]. To achieve better understanding of the phenomenon, it seemed particularly interesting to check if the multiplication is limited to surface barrier diodes and to heavy ions. We attempted, therefore, two independent approaches to clarify the underlying mechanism, which we present here: first, the response of ion implanted silicon P-N diodes to fission fragments was investigated as a function of ion-energy, dose and the annealing temperature used in the manufacturing process. Then, surface barriers, as well as ion implanted and diffused junction detectors, were exposed to the dense, pulsed flux of high energy (~ 2 GeV) muons in the CERN PS neutrino beam shielding.

Essentially, we found that multiplication of charge is a general feature for all detector types if a threshold charge density is exceeded, it is dependent on the junction structure, and for implanted diodes it could be suppressed by eliminating the gold contact layer. Finally, we will discuss a model which takes into account these results as well as the previous ones from Walter for surface barrier detectors.

2. RESPONSE OF ION IMPLANTED DETECTORS TO FISSION FRAGMENTS

2.1 Detectors

Boron ions were implanted under non-channeling conditions into $150\ \Omega\text{cm}$, n-type silicon. The implant energy was 15, 40 or 60 keV and the doses were 5×10^{12} , 10^{13} and $5 \times 10^{13}\ \text{B cm}^{-2}$. Implanted slices were annealed for 30 minutes in vacuum at a temperature between 300°C and 700°C .

On the implanted (front) side normally a $300\ \text{\AA}$ gold contact was deposited on top of the implanted layer, on some diodes prior to this a

100 Å thick insulating film of SiO_2 was deposited by evaporation, and on some diodes no evaporations were made at all. Finally, a thick aluminium contact was deposited on the back side.

It should be remembered that this procedure of ion implantation [3] produces a nearly gaussian distribution of dopants with the following characteristics:

- The maximum concentration of acceptors is located at a distance R_p from the surface, which depends on implant energy. The width of the distribution is Δx_1 . The silicon dead layer can be determined experimentally from the pulse height defect and ranges generally from 1000-2000 Å.
- For an implantation dose N_s the highest obtainable dopant concentration is about $N_s / 2.5 \Delta x_1$, when all B-ions are electrically activated. Typically, 10^{14} B cm^{-2} implanted at 15 keV produce a peak of 1.5×10^{19} cm^{-3} active dopants at 530 Å from the surface, after complete activation of the implanted species. Incomplete annealing may reduce this density by a factor 10-100.

2.2 Results

Spectra of fission fragments from ^{252}Cf were recorded as a function of bias voltage. For the evaluation, the pulse amplitudes L and H for light and heavy fragments were determined following the method of Schmitt [4], illustrated in fig. 1. After a non-linear region at low bias voltages, the pulse amplitude tends to saturate; if the voltage is increased the response depends on the presence or absence of the gold layer. For detectors covered with a gold contact, the multiplication effect is always observed. The implant energy plays no role, as is illustrated in fig. 2. At low implanted dose however, the multiplication is stronger than at high dose, for the same energy and annealing temperature (fig. 3). At fixed energy and dose the multiplication diminishes with rising annealing temperatures, which produce more activated dopants and decrease radiation damage defect density. The multiplication phenomenon

increases if the detector operating temperature is lowered, as shown in fig. 4. The multiplication occurs also in the diodes which have a 100 Å thick SiO₂ layer between gold contact and implanted layer.

These results indicate that the multiplication is a decreasing function of the concentration of electrically active Boron atoms, i.e. of the positive charge in the doped interface layer. In table 1 the results are reported as $(\Delta P/\Delta V)/E_f$, the change of pulse amplitude ΔP with the increase of bias voltage ΔV , relative to the fragment energy E_f . (A comparison with Schmitt's parameters [4] is made in table 2).

For detectors without gold surface layer no multiplication effect was observed (fig. 5), but it occurred again after a gold layer (with or without SiO₂ interface layer) was deposited.

3. RESPONSE OF DETECTORS TO DENSE MUON FLUX PULSES

3.1 Experimental conditions

In the CERN 26 GeV neutrino beam Si-detectors have been used to measure the muon flux in the iron shield as function of depth (2.4 m until 11.2 m of Fe) and radial distance from the beam axis (0 cm to 75 cm). Characteristics of detectors, specially used to study multiplication, are reported in table 3. A full ejection of the PS accelerator contains 20 bunches of 10 ns duration and a 100 ns delay between bunches. The charge produced in a detector by the beam is integrated over the complete cycle of 2.1 μ s by a charge-sensitive preamplifier. A peak detector and sample/hold circuit, with a gate from 40 μ s before the pulse, during 4 ms, enable data acquisition on 60 detector channels with a mini-computer and data are written on magnetic tape. The repetition rate is one ejection per 2.4 s and the integrated flux varies from 10³ muons cm⁻² in the end to 5 x 10⁷ cm⁻² in the front of the shield, which corresponds, respectively to 50 and 2.5 x 10⁶ muons cm⁻² in a single bunch. The big dynamic range could be spanned by combinations of feedback-capacitor and detector size. The output signals range then from .1 V to 9.5 V. At the high energies

used, the same particles are able to transverse a stack of several detectors, so that the calibration can be done by comparison with a set of reference detectors, which have been calibrated in absolute scale by counting muon-tracks in a nuclear emulsion, exposed in the beam simultaneously during a few ejections only.

3.2 Results

A linear correspondence is expected between the signals of two detectors when they are placed together in the flux. However, in the highest flux a multiplication effect was observed in some detectors. A typical example is shown in fig. 6, obtained by moving a couple of detectors from a high-flux region to a low-flux region in the shield. All test-detectors showed multiplication above a threshold flux Φ_{th} , which depends on the applied bias voltage. Most runs were done with the beam containing 18 bunches. But we also did a run, diminishing the number of bunches to 13, 8 and 3 per burst, but keeping constant the integrated flux by moving the detectors closer to the beam axis. In the way we could increase the average muon density in time. We observed that the multiplication threshold Φ_{th} becomes correspondingly lower, as is illustrated in fig. 7. This result shows unambiguously that the multiplication effect depends on the ionization density in one single bunch of 10 ns. In table 4 we have reported for several detectors the value Φ_{th} and the ionization density under the different conditions. The latter is around 10^{12} cm^{-3} , amazingly low when compared to the ionization density for fission fragments. The dependence of Φ_{th} on the electric field strength is plotted in fig. 8 for some detectors. Above a certain field Φ_{th} does not decrease any more. The ion-implanted detectors have higher Φ_{th} than the surface barriers. We applied a variety of surface treatments both to surface barrier and implanted detectors, as indicated in table 3. Boiling for 5 or 15 minutes in HNO_3 or dichromate solution, was applied before gold evaporation. We did not find any notable difference between treated and non-treated diodes. However, when the gold contact was completely removed from the implanted detectors no multiplication was observed for the available fluxes, as is shown in fig. 9. Removing a thin aluminium contact layer on the diffused detectors produced nearly no effect.

3.3 Comparison with results from literature

Non-linear effects in the transient response of detectors to a pulsed proton beam of 830 keV at Los Alamos were reported by Hemmendinger et al. [5] but he did not explain the origin of the effects. More recently Lakin used a Si-detector in the pulsed electron beam of SLAC [6]. He did not report any multiplication effect but the signal-current he used was about 20 times lower than our maximum value, as can be seen in table 5 where some parameters for the various experiments are compiled. Canali et al. [7] irradiated surface barrier detectors with short (150 ps) low energy electron pulses to study space charge limited currents (SCLC), whereas Tove et al. used for similar investigations laser light pulses [8]. Although in both these experiments high signal-currents were obtained, no anomaly was reported. An explication could be that no calibrated reference is available in this case. In table 5 we also report estimated values for the case of fission fragments irradiation, supposing a spread of the cloud of generated charges as indicated by Walter [2]. It appears that initial ionization density and total deposited charge differ by several orders of magnitude for the experiments under discussion. But the signal-current, expressed in carriers per cm^2 per sec, around 10^{18} , is about the same in all cases.

4. DISCUSSION

The above described experiments made clear that two conditions must be fulfilled for charge multiplication to occur in silicon detectors.

- (a) Some critical rate of carrier generation in the detector must be exceeded. For most of our counters this rate is around 10^{12} cm^{-3} in 10 ns. The threshold is related to the charge density in the interfacial layer, both for surface barrier detectors, where the accumulated surface charge can be modified by surface preparation, as shown by Walter, and for (implanted) p-n diodes where the dose-dependence is revealing.

- (b) A sufficient charge-reservoir must be available in the form of a metal layer or maybe a heavily doped surface. A gold electrode of $40 \mu\text{g cm}^{-2}$ contains about 10^{18} free electrons per cm^2 , the implanted layer not more than 10^{14} cm^{-2} . A diffused layer of $.2 \mu\text{m}$ thickness might contain 10^{16} cm^{-2} .

A simple diagram (fig. 10) depicts the situation in a p-n diode just at the passage of a particle (A) and some time afterwards (B). The collection of minority carriers (holes) towards the interfacial layer enhances the space charge density temporarily and thus the electric field. Our measurements of the ionization threshold for multiplication (table 4) give for e.g. detector 19 a value $1.2 \times 10^{12} \text{ e-h pairs cm}^{-3}$, corresponding to a total charge in the $379 \mu\text{m}$ thick depletion region of $4.5 \times 10^{10} \text{ e-h pairs cm}^{-2}$. The total fixed positive space charge is $2.6 \times 10^{10} \text{ donors cm}^{-2}$, to which corresponds a negative space charge layer with a thickness of only some $\text{\AA}$. When the generated positive charge is collected towards the interface, its density increases and becomes comparable to that on the heavily doped side. The original field strength of 2600 V cm^{-1} would increase to 10^5 V cm^{-1} if the voltage drop were only over a $10 \mu\text{m}$ distance. One might think that the multiplication is then due to an avalanche in this high field region, but the absence of multiplication when the gold contact is removed, contradicts this model. The injected majority carriers (electrons) originate clearly from the metal and their number is proportional to the amount of available free charge. However, the injection probability is very low, apparently less than 10^{-5} . Once the electrons are injected in the space charge region, they survive because the holes are collected before recombination, and an increase in signal is observed. The injection takes place during a short time interval. In fig. 11 we show the current signal, obtained by terminating a $500 \mu\text{m}$ thick totally depleted detector with 50Ω . No change in pulse form could be seen with and without multiplication. Rise time is about 10 ns , the length of the bunch, and charge collection is complete after $\sim 60 \text{ ns}$. The temperature dependence (fig. 4) of the multiplication in implanted diodes gives an indication that carrier transport does not involve tunnelling, which already seems improbable over a distance of

1000 Å. For the case of surface barrier detectors, it is not clear if the oxide layer contains enough impurities to enable conduction by drift and diffusion or if tunnelling is the only possibility. In the literature often different behaviour regarding multiplication in heavy ion spectroscopy is reported for surface barriers and p-n junctions. In the homogeneous flux only some quantitative difference can be seen, but basically they perform in the same way.

A quantitative treatment of steady state majority carrier injection by tunnelling through a thin oxide layer, under influence of radiation induced minority carriers has been given by Green and Shewchun [9] for the case of a metal-insulator-semiconductor (MIS) structure. The frequency response of the multiplication process observed in these devices was treated by the same authors [10]. The injected minority currents they used were some orders of magnitude lower than in the case of multiplying detectors, and they found a very long response time. Still, this device presents some analogies to the case of multiplying detectors.

5. CONCLUSION

Our experiments proved that the charge multiplication effect is not restricted to surface barriers and heavy particles, but that it is a general feature of silicon particle detectors, once the minority carrier charge density per unit time collected at the interface is sufficiently high to initiate majority carrier injection from a suitable charge reservoir, which is the metal contact. Numerical results could be obtained in a pulsed homogeneous flux. Ion implantation provides a better controllable way of studying the influence of the charge at the interface, which in surface barriers depends on the chemistry of surface preparation. The model proposed by Walter emphasizes the tunnelling through the oxide layer. This may be a feature of surface barrier detectors, but certainly is not occurring in p-n junction detectors. A practical implication of our work is clear: for multiplication-free spectrometry ion-implanted or lightly doped diffused detectors without gold contact layers will be most adequate.

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TABLE 1

MULTIPLICATION IN ION-IMPLANTED DETECTORS

$$\text{Slope } \left(\frac{\Delta P}{\Delta V} \right) / E_f \times 10^{-2}$$

		light fragments	heavy fragments
Dose	5×10^{12}	1.01	1.175
	10^{13}	.798	.97
	5×10^{13}	.48	.55
Temperature of annealing	400 °C	.72	1.032
	500 °C	.66	.705
	600 °C	.48	.55
	700 °C	.375	.505

TABLE 2

COMPARISON WITH SCHMITT's PARAMETERS [3]

Parameter	Schmitt	Our result
N_L/N_V	> 2.85	2.7
N_H/N_V	~ 2.2	2.1
N_L/N_H	~ 1.30	1.28
$\frac{\Delta L}{L-H}$	< 0.38	.34
$\frac{\Delta H}{L-H}$	$\lesssim 0.45$	.43
$\frac{H-HS}{L-H}$	< 0.70	.705
$\frac{LS-L}{L-H}$	$\lesssim 0.49$	.495
$\frac{LS-HS}{L-H}$	$\lesssim 2.18$	2.21

TABLE 3

DETECTOR CHARACTERISTICS AND THRESHOLD FLUX

Detector		Type	Treatment	Area mm ²	Thickness μm	Total Depletion V _D volt	Resistivity k Ω cm	Actual voltage volt	Threshold flux Φ _{th} x 10 ⁶
2	Surface barriers	SB	H15	28.2	243	5	47.	100	9.
3		SB	H15	28.2	222	20	14.5	70	8.7
4		SB	-	28.2	232	15	16.	50	10.1
5		SB	-	28.2	270	50	4.7	60	8.1
6		SB	-	28.2	226	30	6.3	60	11.7
7		SB	H5	28.2	199	50	9.5	50	8.7
8		SB	H5	28.2	341	50	7.7	100	6
9		SB	H5	28.2	255	30	7.6	50	12.9
10		SB	B10	28.2	288	50	4.2	100	6.
11		SB	B10	28.2	364	50	2.7	90	8.8
12b		SB	B10	28.2	301	30	4.2	75	> 9
13		Ion-implanted	I15	-	28.2	281	50	4.7	100
14	I15		-	28.2	299	30	8.5	60	20.2
15	I15		H15	28.2	284	50	5.8	80	13.
16b	I15		H15	28.2	277	50	7.6	100	14.
17	I15		B	28.2	281	20	100.	60	20.
18	I15		B	28.2	207	20	10.	80	16.
19	I60		-	28.2	379	70	7.7	100	12.2
20	I60		-	28.2	410	70	18.	120	15.
21	I60		H15	28.2	268	30	7.3	50	> 19
22	I60		H15	28.2	257	30	32.	150	12.4
23	I60		B10	28.2	274	20	27.	75	16.
24b	I60		B10	28.2	238	50	6.6	100	16.4
290	Commercial	SBP	-	50	98	10	2.5	25	13.
299		SBP	-	50	97	8	2.5	60	12.
300		SBP	-	25	100	12	2.5	10	> 35
400		SBO	-	327	219	90	2.7	60	1.5
293	Diffused	DS28	-	50	300			60	10.
296		DS35	-	50	300			120	5.6

Legenda:

Type

SB surface barrier
 I15 ion-implanted 15 keV B ions
 I60 ion-implanted 60 keV B ions
 dose 10¹⁴ cm⁻², area 28.2 mm²
 gold contact 12.6 mm², annealed
 at 400 °C.
 DS diffused junction p-type.

Treatment

H5, 15 boiling HNO₃, 5 resp. 15 min.
 B 10 bichromate treatment 10 min.
 Resistivity is deduced from C-V
 measurement.

TABLE 4

THRESHOLD FLUX AND IONIZATION DENSITY

Detector	N_d cm^{-3}	18 bunches Φ_{th} cm^{-2}	ionization cm^{-3} per bunch	13 bunches Φ_{th}	ionization per bunch	8 bunches Φ_{th}	ionization per bunch	3 bunches Φ_{th}	ionization per bunch
6	8.3×10^{11}	11.7×10^6	7.2×10^{11}	8.03×10^6	6.8×10^{11}	6.09×10^6	8.4×10^{11}	2.72×10^6	10×10^{11}
17	5×10^{10}	$21. \times 10^6$	1.3×10^{12}	16.5×10^6	1.4×10^6	11.4×10^6	1.6×10^{12}	5.9×10^6	2.2×10^{12}
19	7×10^{11}	17.7×10^6	1.1×10^{12}	13.2×10^6	1.1×10^{12}	10×10^6	1.4×10^{12}	5.2×10^6	1.9×10^{12}

TABLE 5

Si-DETECTORS IN PULSED BEAMS

Experiment	CERN	Los Alamos [6]	SLAC [7]	Canali et al. [8]	Tove [9]	fission fragment [2]
Particles, energy	μ^+ , μ^- 1-15 GeV	p^+ 830 keV	e^- 19-22 GeV	e^- 30 keV	$h\nu$ 6143 Å	100 MeV
pulse duration	10 ns	1 μ s-1 ms	1.6 μ s	150 ps	1 ns	5 ns
penetration depth	all	15 μ m	all	7 μ m	2 μ m	25 μ m
spot size	homogeneous	50 mm ²	4 mm ²	3 mm ²	7.1 mm ²	7×10^{-6} - 1.3×10^{-1} mm ²
number of particles normalized cm ⁻²	$< 2.5 \times 10^6$	3.6×10^6 (1 μ s)- 1.3×10^{10} (1 ms)	2.5×10^3 - 2.5×10^7	$< 3.3 \times 10^5$	$< 2.1 \times 10^{-7}$ J cm ⁻²	(initial) (spread out) 1
energy deposited per pulse eV, normalized cm ⁻²	$< 10^{11}$ in 100 μ m	3×10^{12} - 1.1×10^{16} in 15 μ m	$< 9 \times 10^{11}$ in 100 μ m	10^{10} in 7 μ m	1.3×10^{12} in 2 μ m	1.4×10^{15} - 7.7×10^{10} in 25 μ m
ionization per pulse e-h pairs cm ⁻³	$< 2.8 \times 10^{12}$	5.5×10^{14} - 2×10^{18}	$< 2.5 \times 10^{13}$	3.9×10^{12}	1.8×10^{15}	1.5×10^{17} - 8.5×10^{12}
e-h pairs cm ⁻³ sec ⁻¹	$< 2.8 \times 10^{20}$	$< 2 \times 10^{21}$	$< 1.6 \times 10^{19}$	2.6×10^{22}	$< 1.8 \times 10^{24}$	3×10^{25} - 1.7×10^{21}
e-h pairs cm ⁻² sec ⁻¹ in actual thickness (signal-current density)	2.8×10^{18}	3×10^{18}	1.6×10^{17}	1.8×10^{19}	3.6×10^{20}	4.2×10^{18}

FIGURE CAPTIONS

- Fig. 1 Typical pulse height spectrum for ^{252}Cf fission fragments. Schmitt's spectrum parameters are indicated.
- Fig. 2 Effect of the ion-energy for B-implanted detectors on the charge multiplication for ^{252}Cf light fragments.
- Fig. 3 Effect of the total implanted dose on the charge multiplication for ^{252}Cf light and heavy fragments.
- Fig. 4 Tail on ^{252}Cf spectrum at various detector operating temperatures.
- Fig. 5 Shift of pulse amplitude for ^{252}Cf after gold contact layer was deposited. Before, no multiplication is seen.
- Fig. 6 Signal of detector 6 as function of muon flux, measured by a reference detector. Multiplication starts at $\Phi_{\text{th}} = 12 \times 10^6$ for applied bias voltage 60V.
- Fig. 7 Threshold flux Φ_{th} becomes lower if ionization density is increased, by measuring some intergrated flux in shorter time.
- Fig. 8 Φ_{th} as function of electric field in some detectors.
- Fig. 9 Removing gold layer eliminates multiplication.
- Fig. 10 Schematic picture of detector and space charge just at (A) and sometime after (B) passage of radiation.
- Fig. 11 Single bunches of muons, recorded as current signal in 50Ω termination of $500 \mu\text{m}$ thick detector.

fig. 1

fig. 2

fig. 3

fig. 4

fig. 5

fig. 6

fig. 7

fig. 8

fig. 9

SPACE CHARGE DISTRIBUTION

fig.10

fig.11