MEASUREMENTS OF DEGRADATION OF SILICON DETECTORS AND
ELECTRONICS IN VARIOUS RADIATION ENVIRONMENTS

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ABSTRACT

Displacement damage in silicon particle detectors, exposed to a high-energy muon irradiation at the CERN SPS, is observed to be less in p-type than in n-type silicon. X-ray irradiation of various test structures reveals the importance of surface leakage currents. The irradiation of detectors and electronics in the UA2 collider experiment at the SPS indicates a strong, low energy neutron component, which degrades the detectors but hardly influences the CMOS circuits.

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1. INTRODUCTION

Particle physics experiments require ever more sophisticated detectors, which have to survive ever higher radiation doses. One reason is that the interactions of interest often occur amidst a preponderant background of already well-known, "trivial" interactions. Total interaction rates of 10^7 - 10^8 s⁻¹ in future hadron colliders (LHC, SSC) will generate yearly doses of $\sim .1$ MGy (10 Mrad) in the forward regions of the apparatus, where the electronics is often located at present [1]. Silicon particle detectors are attractive for future experiments because of their high speed, their arbitrary granularity, their stable geometry and the simplicity of operation.

The radiation effects in silicon detectors and electronics have to be carefully studied before decisions on large scale application can be taken. It is well known that the practical device lifetime depends on the constituents of the radiation environment and on the properties of the device manufacturing procedure. Users in particle physics have not so far been in a position to impose or even be aware of device manufacturing details. The reliability of detectors and integrated electronic circuits may therefore appear to be fairly unpredictable. Also the composition of the radiation present in an experiment is not too well known and in particular the low energy neutron component can easily be underestimated. Exact dosimetry often presents a practical and organizational problem.

Given the limited amount of data available on radiation damage in high energy particle environments dosimetry should be encouraged whenever possible, and additional test structures used to unravel the factors which influence the degradation of a given device (e.g. surface effects, bulk defects, threshold shift, etc.).

In this paper we present the results of various measurements, both in real experiments and in tests. They illustrate the difficulties mentioned above, of relating observations to device properties.

2. CMOS ELECTRONIC COMPONENTS IN BEAM TESTS

In preparation of the UA2 inner silicon array [2] which uses the Application Specific Integrated Circuit (ASIC) called "AMPLEX" [3], a prototype test chip was irradiated during one week in a 300 GeV π beam. This chip has been manufactured in a 3 μ m n-well CMOS Process^(*). The total dose was 700 Gy (70 krad), as measured

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with thermoluminescent dosimeters (TLD), placed directly on the packaged silicon chips. p-channel and n-channel transistors with $W/L = 11300/3.5$ and active area $200\text{ }\mu\text{m} \times 300\text{ }\mu\text{m}$ were measured, with and without bias during irradiation. The results were obtained using a Hewlett-Packard 4145 B transistor parameter analyzer, and are shown in table 1. The change of gain of an n-channel Operational Transconductance Amplifier (OTA) was measured to be less than 10% and appears to follow the degradation of the transconductance of the input transistor. The dynamic range was slightly decreased due to the threshold shift in the current source.

A neutron irradiation with $4 \times 10^9\text{ n cm}^{-2}$, using a $^{238}\text{Pu Be}$ source (energy up to $\sim 11\text{ MeV}$, peaked $\sim 4\text{ MeV}$) made practically no change to the transistor characteristics. Also no change has been seen during the irradiation in the real UA2 apparatus at the CERN SPS. The estimated dose of ionizing particles during the 1988 physics run has been from 25 Gy to 70 Gy (7 krad), with an accompanying flux of up to $6 \times 10^9\text{ n cm}^{-2}$ in the energy range 3-25 MeV (measured via the activation reaction $^{32}\text{S}(n, p)^{32}\text{P}$). On the contrary, the silicon pad detectors in the same location suffered a factor of 10-30 increase of reverse bias current, as will be further discussed in sect. 5.

The CMOS process used, not being optimized for radiation hardness, proves to be sufficiently tolerant for a total ionizing dose of about 1 kGy (100 krad). Further measurements, in particular of the digital parts, are necessary.

3. HRSi TEST CHIPS IN IONIZING RADIATION

An experimental $3.7 \times 3.7\text{ mm}^2$ chip with various test structures (fig. 1) has been designed and processed in the ESAT laboratory, the predecessor of the IMEC laboratory in Leuven, Belgium [4]. 60 chips from one wafer with orientation $\langle 111 \rangle$ were mounted in Dual-In-Line (DIL) packages, and the reverse bias currents and flat-band voltages V_{FB} were measured. The V_{FB} varied over the wafer between -2.7 V and -3.8 V in a gradual way. The flat-band shift ΔV_{FB} as a function of dose for ^{60}Co irradiation and for 12.5 keV X-ray radiation from a X-ray tube is shown in fig. 2. The shift is considerable but saturates with dose. The dry oxide is 201 nm thick and grown at 950°C. Compared to the ΔV_{FB} reported in [4] for a similar device with 111 nm thick oxide, the increase in shift grows with nearly the third power of the oxide thickness.

The distribution of the initial leakage currents at 50 V bias for the different 0.25 mm^2 diode structures is shown in fig. 3 (left). The square diode (a) has lower and better defined reverse current than the circular one (b), contrary to the expectation. The guard ring structures (c-h), including even the outer ring diodes, have the best characteristics. The field plate structures (i-l) do not seem to present any better behaviour than the circular diode (b). During the measurements all elements were simultaneously biased. It is supposed that the elements along the edges (b, i-l) are influenced by current generation centres in the edge region of the chip, for which the inner elements (a, c-h) are well-shielded by these edge elements. The average reverse current for the inner elements is $\sim 5 \text{ nA cm}^{-2}$ or 130 nA cm^{-3} , before irradiation.

The effect of different ionizing irradiations (dose 1 krad-1.3 Mrad) on the reverse current is shown in fig. 3 (right). Some diodes hardly increase in current, but a majority does, except for the guard-ring diodes with grounded ring. Therefore it appears that the current increase is due to surface leakage channels which occur stochastically. There is hardly any correlation between the current and the dose received. The radiation used is supposed to cause few displacement defects, and the current evolution for the guard-ring diodes is shown in fig. 4 as a function of dose, both for a ^{60}Co irradiation and a 12.5 keV X-ray irradiation. The current is not stable after irradiation, as indicated. If one applies a conversion factor of $4 \times 10^{13} \text{ m.i.p. cm}^{-2}$ (minimum ionizing particles) for 1 Mrad the damage coefficient $\alpha = 3 \times 10^{-21} \text{ A cm}^{-1}$ is found (see hereafter and sect. 6).

4. CONVENTIONAL SILICON DETECTORS IN GeV MUON FLUX

From 1976 to the present time about 250 silicon surface barrier, diffused and ion-implanted detectors have been used to monitor a pulsed flux of $\sim 200 \text{ GeV}$ muons inside an iron shielding: the Neutrino Flux Monitoring system NFM [5]. The reverse current degradation has been measured as a function of the integrated flux. The intensity per pulse (μs -ms duration every 10-14 s) ranges from 10^3 - 10^8 cm^{-2} , i.e. up to 10 rad (Si), and is fairly homogeneous over an area of several m^2 . Typical degradation is shown in fig. 5 for various detectors. The leakage current $I(V)$ [nA cm^{-3}] after irradiation in flux Φ [particles cm^{-2}] can be characterized by a damage coefficient α [nA cm^{-1}]

$$I(V) = I_0(V) + \alpha \Phi .$$

For detectors built on n-type high resistivity Si the value of α ranges from $1-8 \times 10^{-8} \text{ nA cm}^{-1}$. For the diffused diode detectors on $\sim 2000 \text{ }\Omega\text{cm}$ p-type silicon a much lower value of $1-2 \times 10^{-9} \text{ nA cm}^{-1}$ is found. It would be of interest to study in more detail the performance of p-type detectors, in spite of the manufacturing difficulties related to the surface inversion.

It should be mentioned that in most cases the detector lifetime in the muon flux was limited by breakdown and noise phenomena which began after an initial period of regular current increase. This breakdown occurred the earlier, the higher the detector resistivity and the higher the detector operating bias voltage. Material type reversal from n-type to p-type and apparent depletion starting from the ohmic side has occasionally been observed. The silicon material characteristics as well as the edge protection play a role in the long-term lifetime, but manufacturers are reluctant or unable to provide detailed information on precise parameters.

5. SILICON PAD DETECTORS IN THE UA2 SPS COLLIDER EXPERIMENT

5.1 Outer Si array during 1987 and 1988

The 1 m^2 area Si detector array [6] built at $\varnothing 30 \text{ cm}$ around the UA2 interaction region suffered a major degradation on 10 December 1987, as seen from the pedestal width measurements illustrated in fig. 6. For $\sim 10 \text{ min.}$ a severe beam loss occurred during a machine development session. At the end of 1987 run the integrated dose of ionizing radiation was found to be 30 Gy (3 krad) and the neutron flux ($3-25 \text{ MeV}$) had been $2.8 \times 10^9 \text{ cm}^{-2}$. The degradation of reverse currents for the pads on one board is shown graphically in fig. 7. The distribution of the current increase ΔI_L for about 1/3 of all detector pads is plotted in fig. 8. The average increase is 105 nA per pad which corresponds to $0.8 \times 10^{-8} \text{ nA cm}^{-3}$ per m.i.p. cm^{-2} , if only related to the 30 Gy of ionizing radiation. If attributed only to the actually measured neutron flux, one finds a damage coefficient of $3.4 \times 10^{-7} \text{ nA cm}^{-3}$ per n cm^{-2} ($3-25 \text{ MeV}$). It appears that the low resistivity pads have a greater spread in current increase than the high resistivity pads. The latter are generally positioned in the central region and may therefore have been more uniformly irradiated than the others, which were either upstream or downstream. From the data in figs 7-8 it cannot be concluded that high resistivity silicon is less affected. However, a low operation voltage seems to be beneficial for detector lifetime, as was already mentioned in sect. 4.

During the 4 months run in 1988 the integrated dose has been measured to be 2-10 Gy, i.e. about 1/10 of the dose in 1987. No further degradation of the outer silicon array has been observed, thanks to the installation of radiation interlocks and a careful attitude of the accelerator operators.

5.2 Inner Si array in 1988

The inner Si array [2] is built directly around the UA2 beam pipe, as illustrated in fig. 9. During the initial beam tuning it was already found to degrade quickly in reverse diode current, as shown in fig. 10. During the first days of the run the damage was quite high whereas the luminosity was low. All boards suffered, but particularly those in the horizontal plane, as can be seen easily in fig. 11. Later during the run, the reverse current grew less rapidly, while the luminosity was high ($10^{-30} \text{ cm}^{-2} \text{ s}^{-1}$). The outward horizontal boards 1 and 12 continued to increase much more than the others, presumably due to beam losses during injections. A large number of TLD and neutron activation monitors was positioned around the interaction region at positions D and D' (fig. 9), but lack of space prevented dosimeters being inserted. A few dosimeters were positioned at the collars of the inner Si detector. The neutron dose below 3 MeV is also not known due to the cut-off of the activation threshold at 2-3 MeV. A certain inhomogeneity in the dose was observed, which seems to be caused by the proton beam halo hitting the edge of the beam pipe at "H" (fig. 9) where the small diameter section begins. The dosimeters and neutron monitors indicate a stronger horizontal, outward component. On the collars of the inner detector the dose varied from 26 Gy (vertical) to 69 Gy (horizontal). In the horizontal upstream position D 167 Gy was measured on the beam pipe and 3 Gy at $\varnothing$ 30 cm. The neutron flux in positions D and D' was less inhomogeneous and varied from $\sim 1 \times 10^9$ at $\varnothing$ 30 cm, to 2×10^9 in the vertical plane and 5×10^9 in the horizontal plane on the (thick) beam pipe. It is suspected that a fairly large flux of ~ 1 MeV neutrons goes undetected, but is the principal cause of the detector degradation. A very precise laboratory measurement of the detector leakage current per individual pad is shown in fig. 12. Again the inhomogeneity of the irradiation is beautifully confirmed, the highest current being at the side where the more intense proton beam enters the apparatus. The 256 pads cover a distance of 56 cm, the pads with number 128 are just around the geometrical centre of the interaction region.

5.3 Annealing of inner Si array detectors

Because the detector contacts are provided by pressure only [2], it is easy to dismount the detector chips and anneal them. The result is shown in fig. 13 and the current after annealing at 250°C is only 15% of that immediately after irradiation.

6. CONCLUSION

The increase of reverse diode current can be characterized by a damage coefficient α , as defined in sect. 4. The values of α found in the various measurements are summarized in table 2.

A comparison is made with some data reported by E. Fretwurst et al. [7]. In particular for the "inner Si" data of UA2 the dosimetry is uncertain. The different roles of neutrons and ionizing particles in creating the damage will continue to make interpretation of damage coefficients somewhat arbitrary.

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TABLE CAPTIONS

TABLE 1 Degradation of MOS transistors, W/L = 11300/3.5, 70 Gy.

TABLE 2 Summary of "damage coefficients".

TABLE 1

	p-channel		n-channel	
	Biased	Unbiased	Biased	Unbiased
Threshold ΔV_T (mV)	-300	-500	-230	-180
Mobility change $\Delta\mu/\mu$ %	-11	-25	-37	-37
Transconductance $\Delta g_m/g_m$ %	-10	-18	-30	-30
Interface state density $\text{cm}^{-2} \text{eV}^{-1}$	$2 \times 10^{11} \rightarrow 4 \times 10^{11}$		$8 \times 10^{10} \rightarrow 6 \times 10^{11}$	
Substrate current on 200 $\mu\text{m} \times 300 \mu\text{m}$	$< 10^{-14} \text{ A} \rightarrow 3 \times 10^{-10} \text{ A}$			

TABLE 2

Experiment	Irradiated device	Irradiation	Coefficient
CERN/ IMEC	Test structures	^{60}Co	$3 \times 10^{-12} \text{ nA cm}^{-1}$
NFM	Prototype diodes	^{60}Co	$\sim 10^{-10} \text{ nA cm}^{-1}$ 15×10^{-8} $.6 \times 10^{-8}$ 3.4×10^{-8} 9×10^{-8} $.18 \times 10^{-8}$
	Diodes bulk n-type	Reactor neutrons	
	Diodes bulk p-type	GeV muons+shower beam	
UA2	Outer Si array	Ionization Neutrons	$.8 \times 10^{-8}$ $34 \times 10^{-8} \text{ nA cm}^{-1}$
UA2	Inner Si array	Ionization Neutrons	5.6×10^{-8} 200×10^{-8}
Univ. of Hamburg [7]	Surface barrier detectors	14 MeV n	17×10^{-8}
		25 MeV p	27×10^{-8}

FIGURE CAPTIONS

- Fig. 1 Layout of the test chip. This figure represents the aluminium contact pattern. The square bonding pads and contact lines are on top of the ~ 200 nm thick oxide. The guard rings around the square and circle at the left are simply metal plates on top of the oxide (field plates), whereas the rings around the square and circle in the middle cover guard ring diodes of the same type as the diodes themselves. The area of each of the 6 large diodes is $.25 \text{ mm}^2$.
- Fig. 2 Flat-band voltage shift ΔV_{FB} (V) as a function of irradiation dose in krad (Si), measured with TLD. Curve (a) represents a sample irradiated with 12.5 keV X-rays; curves (b) and (c) are samples irradiated in a ^{60}Co source. In all cases the reverse bias was 50 V.
- Top Lower range 0–100 krad.
Bottom Range up to 1.3 Mrad.
- Fig. 3 (Left) Histogram of the current distribution for 50 V reverse bias of various diode elements on 60 identical chips. The geometry of the elements is pictured in the middle.
- (Right) Histogram of the currents after irradiation with 12.5 keV X-rays (crosses), or ^{60}Co source (open squares) or in 10 keV synchrotron radiation (filled squares), with various doses, varying from 1 krad to 1.3 Mrad. The samples which are represented at the right, beyond the scale, are the ones that increased in current. The others hardly changed and sometimes even improved in reverse currents.
- Fig. 4 Evolution of normalized leakage current of guard-ring diodes as a function of irradiation dose (krad) in a ^{60}Co source or a X-ray generator (12.5 keV). The current in the X-ray irradiated sample kept increasing for a while after the irradiation, but finally decreased again. The ^{60}Co irradiated sample started decreasing immediately.

FIGURE CAPTIONS (Cont'd)

- Fig. 5 Typical examples of normalized reverse leakage current ($\mu\text{A cm}^{-3}$) as a function of muon flux (cm^{-2}):
 (a) is a surface barrier detector,
 (b) is an ion-implanted detector, among the best of all n-type detectors,
 (c-d) are typical p-type detectors with diffused junction.
 The reverse current damage coefficients are given in each plot.
- Fig. 6 Evolution with time of the average pedestal width expressed in ADC channels during the 1987 run.
- Fig. 7 The values of reverse diode leakage current in all pads and guard rings of a UA2 outer detector board. The bottom of each vertical line represents the initial current, and the top the current measured after the run, so that the length of the line indicates the degradation. Nearly all pads remain in the acceptable region.
- Fig. 8 Distribution of the current increase ΔI_L for pads with (a) low resistivity ($V_{\text{bias}} > 50 \text{ V}$) and for pads with (b) high resistivity ($V_{\text{bias}} \leq 50 \text{ V}$). The difference between the two distributions could be explained by gradients in the radiation and by the difference in operation voltage of the detectors.
- Fig. 9 Schematic layout (not to scale) of the beam pipe and the inner and outer Si arrays. The position of the dosimeters D and D' are indicated.
- Fig. 10 Increase of leakage current for several complete boards. The upper curve (a) is the average of the most irradiated outward horizontal boards 1 and 12. The middle one (b) is the average of the inward horizontal boards 6 and 7. The lowest curve (c) is the average of all the other boards. The temperature of the boards is around 30°C . The scale for the curve (d) indicating the integrated luminosity is at the right.

FIGURE CAPTIONS (Cont'd)

- Fig. 11 Increase of leakage current in the 12 boards, for successive periods. The inner white area represents the initial values of the current. The black increase was obtained during the first day of accelerator setting-up (13 September 1988). The next current values, at the radii of the outer white sectors, were measured on 3 October 1988, after 3 weeks of operation. The light shaded values were the leakage currents after 7 weeks (20 November 1988) and the outer values those at the end of the run, on 20 December 1988. For board 11 no measurements could be made and only the final value is given.
- Fig. 12 Measured leakage currents for all individual pads of detectors S-4 (board position 1), S-17 (board position 12) and S-16 (board position 11). The average initial currents were ~ 5 nA for all pads.
- Fig. 13 Annealing curves for 4 individual pads of a badly irradiated Si detector. The current is measured at room temperature each time after 30' anneal in nitrogen gas, at the indicated temperature.

Fig. 1

Fig. 2

CURRENT DISTRIBUTION

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

BEAM PIPE UA2 EXPERIMENT

(Not to scale)

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13