Radiation effects on the Viking-2 preamplifier–readout chip

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We have studied the radiation sensitivity of the Viking-2 VLSI circuit which has been designed for the readout of silicon strip detectors and manufactured at Mietec in 1.5 μm CMOS technology. Both biased and unbiased chips have been irradiated with a ^{137}Cs γ source up to a total dose of 2 kGy (200 krad) after which all tested chips were still fully functional. We report the characteristic changes of device parameters with dose, including equivalent noise charge for different capacitive loads, and determine transistor threshold shifts and change of mobilities.

1. Introduction

The CMOS Viking-2 VLSI chip belongs to a family of several multichannel frontend circuits which have been developed for the readout of (double-sided) silicon strip detectors in order to approach lowest possible noise at low power consumption [1]. Prototype tests promised also a remarkable radiation hardness of this design [2], and so the Viking-2 chip had been chosen for the readout of the second version of the ARGUS silicon vertex detector [3]. In this e^+e^- collider experiment the readout chips have to withstand a total dose in the order of 1 kGy per year, and we report here results of a systematic study [4], which was performed in order to determine the operating conditions for maintaining optimum performance of the Viking-2 chips also at high radiation doses.

The Viking-2 architecture follows the AMPLEX principle [5]. The 6.15×5.67 mm^2 chip integrates 128 channels each of them consisting of a charge-sensitive preamplifier, a shaper amplifier and a track-and-hold circuit with capacitor Ch as storage device (Fig. 1). The stored charges can be read out sequentially via an analog multiplexer. The amplifiers' feedback resistors Rf and Rs are nonlinear MOS elements controlled externally by bias voltages vfp and vfs. Preamplifier, shaper and buffer operation is maintained by a system of current mirrors which are controlled by externally supplied biasing currents pa_9, sh_13 and ibuf.

For a chip powered with $V_{dd} = +2$ V (13 mA) and $V_{ss} = -4$V (35 mA) the values of bias currents are pa_9 = 210 μA, sh_13 = −50 μA, and ibuf = 100 μA. For unirradiated chips standard bias voltage (SBV) settings of vfp = 100 mV and vfs = 1.25 V have been found to provide lowest system noise at the corresponding 0.9 μs peaking time of the shaped signal.

2. Experimental setup

We have irradiated a total of four Viking-2 chips. Each chip was mounted on a little hybrid interface board inside an aluminum box housing also the main amplifier which was removed during irradiations. In order to simulate the capacitive load of strip detectors four of the readout channels were bonded to capacitors of 12.7, 19.5, 37.5 and 60.5 pF, respectively. Via coupling capacitors of 1.5 pF calibration pulses could be applied to these channels as well as to four floating channels. The digitisation of output signals was done with Sirocco ADCs [7] read out by a CAMAC system. The equivalent noise charge (ENC) has been deduced from the rms value of the common mode corrected pedestal fluctuations observed in 10^3 readout cycles.

The irradiations were performed with the ^{137}Cs γ source of the German Cancer Research Center (DKFZ) at Heidelberg which delivers a dose rate of typically 48 Gy/hour. The radiation doses (quoted in Gy(Si)) were monitored inside the chips' aluminum box (2.5 mm wall thickness) very close to the chip by little alanine dosimeters supplied and evaluated by a commercial company [8]. The measured doses showed excellent agreement with the doses expected from exposure time. We exposed pairs of chips to radiation, the one chip being unbiased with all its connections grounded and the other being supplied with dc power, bias currents and bias voltages. The characteristic parameters of each chip were evaluated after each of the various irradiation steps up to a total dose of 1 kGy (first

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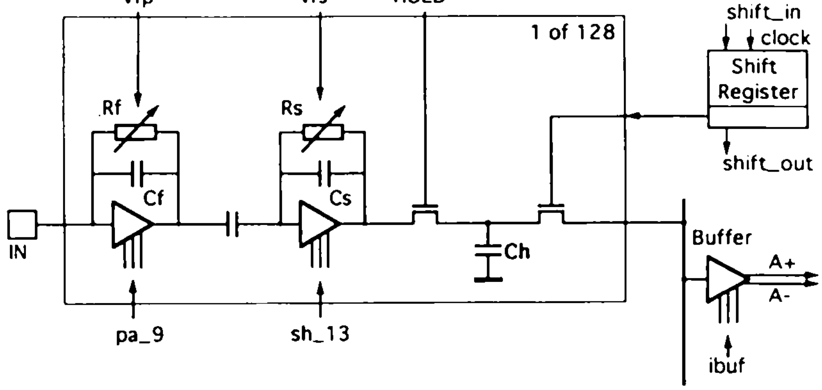

Fig. 1. Functional circuit diagram for one of the 128 channels of the Viking-2 chip.

pair) and 2 kGy (second pair). The time elapsed between first and last irradiations was 37 and 22 days, respectively.

3. Results

All four chips withstood the exposures to total doses of 1 and 2 kGy without loss of functionality. Irradiated prototype test structures remained also functional after a total dose of 4.5 kGy.

3.1. Noise and gain

The most relevant radiation effect is an increase of noise with increasing dose. The ENC exhibits very well the expected linear dependence on load capacitance: for the unirradiated chip, noise offset and slope are 165 e^- and 20.6 e^-/pF, respectively [1]; after exposure of the powered chip to a total dose of 2 kGy, the corresponding values have increased to 567 e^- and 46.7 e^-/pF. As discussed below even smaller noise values, 338 e^- and 40.6 e^-/pF, can be obtained with optimised bias voltage (OBV) settings. Fig. 2 shows ENC data as a function of dose. At fixed load capacitance the ENC increase is not strictly linear with dose, but a global bilinear fit with respect to dose D and load capacitance C_l reproduces the data points quite well. For SBV settings the resulting relation for the system noise (Fig. 2, full symbols, solid lines) is:

$$\mathrm{ENC}/e^- = 169 + 0.232(D/\mathrm{Gy}) + (20.5 + 0.012(D/\mathrm{Gy}))(C_l/\mathrm{pF}).$$

The increase of noise with dose is partly due to a change of peaking time which has been observed to decrease with

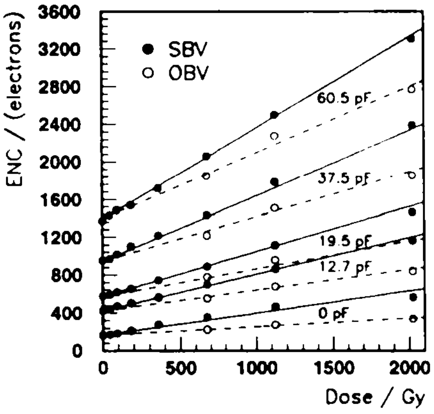

Fig. 2. The equivalent noise charge ENC of a biased chip as function of dose for indicated load capacitances. Solid (open) symbols and full (dashed) lines refer to standard (optimized) bias voltages vfp and vfs.

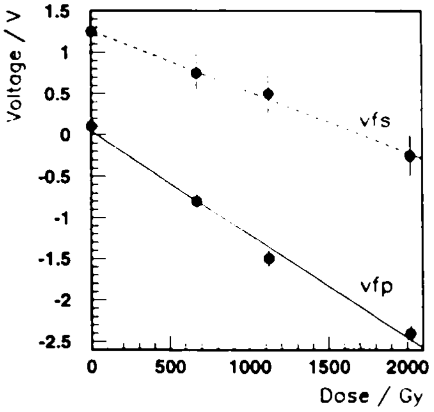

Fig. 3. Optimum settings of control voltages vfp and vfs in dependence of dose.

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[1] See note added in proof.

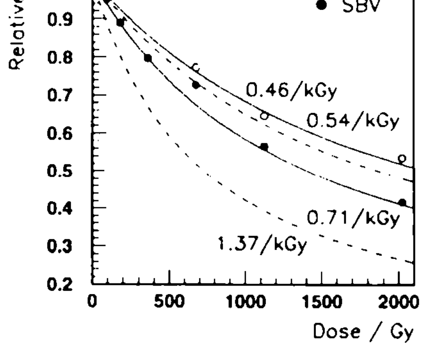

Fig. 4. Relative gain for biased chips as a function of dose D. Curves show functions, $1/(1 + cD)$, with indicated parameters c.

increasing dose monotonically from 0.9 μs (0 Gy) to 0.55 μs (2 kGy). Obviously irradiation changes the characteristics of the MOS elements serving as feedback resistors. By varying vfs with dose as shown in Fig. 3, the peaking time can be restored to 0.9 μs. A similar readjustment of vfp (Fig. 3) leads to a further noise reduction by restoring the value of the preamplifier's feedback resistor to its optimum value (see Fig. 6 of ref. [2]). It is obvious from Fig. 2 (open symbols), that at high radiation doses the ENC values can be considerably reduced by using these optimised bias voltage (OBV) settings. The corresponding expression for the line fit (Fig. 2, dashed lines) reads now:

$$\mathrm{ENC}/\mathrm{e}^- = 166 + 0.089(D/\mathrm{Gy}) + (20.6 + 0.010(D/\mathrm{Gy}))(C_\mathrm{I}/\mathrm{pF}).$$

Choosing $C_\mathrm{I} = 10$ pF and $D = 2$ kGy, for example, the latter expression implies pre- and postirradiation ENC values of 372 e^- and 750 e^-, respectively. The degradation of the unpowered chips has been found to be even smaller.

Fig. 4 shows the change in the overall relative gain of a chip ($C_\mathrm{I} = 0$ pF) powered during irradiations. The loss of gain with dose is significantly smaller with the OBVs of Fig. 3. The curves represent functions of dose D, $1/(1 + cD)$ with parameters c as indicated in the plot. With OBV (SBV) settings, values of $c = 0.535$ (1.37) are expected if the ENC increase would be exclusively due to the loss of gain. This hypothesis indeed approximates the situation met in case of OBV settings.

3.2. Bias current input circuits

The bias voltages of the different Viking-2 amplifier stages are controlled by externally supplied bias currents pa_9, sh_13 and ibuf. Somewhat different from the AMPLEX design (see figs. 3 and 6 of ref. [5]), the Viking-2 biasing current input circuits of preamplifier and shaper are made up of n-channel and p-channel MOSFETs, respectively (Fig. 5). The voltages required for maintaining the nominal bias currents (pa_9 = 210 μA, sh_13 = −50 μA) show strong variations with dose (Fig. 6). Exhibiting a similar flow with dose as does the pa_9 voltage, the ibuf voltage drops from about −2 V at 0 Gy to about −2.2 V at 2 kGy. For the sh_13 voltage a systematic difference is observed which depends on the bias condition of chips during irradiation. Moreover, the sh_13 data show for all the four irradiated chips a very reproducible functional dependence on dose which may be used for monitoring the dose deposited in the chip. The smooth curves shown in fig. 6 result from fits of the expression $V = V_0/(1 + sD^{2/3})$ with $V_0 = 1.93$ (−2.00) V and $s = 4.276$ $(4.283)/\mathrm{kGy}^{2/3}$ for chips being biased (unbiased) during irradiations.

3.3. Threshold voltages and mobilities

The current–voltage (I–V) characteristics of the bias current input circuits pa_9 and sh_13 (Fig. 5) allow the

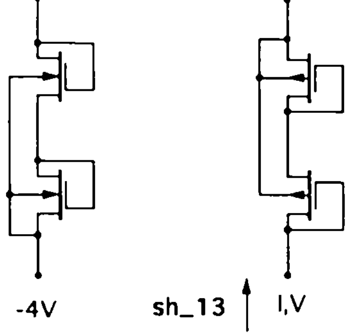

Fig. 5. Biasing current input circuits for preamplier (pa_9) and shaper (sh_13).

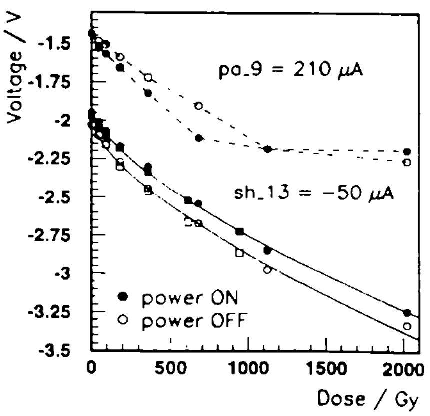

Fig. 6. Dose dependence of the voltages required for maintaining indicated currents in the pa_9 and sh_13 biasing circuits powered "ON" or "OFF" during irradiations. The smooth curves are fits discussed in the text.

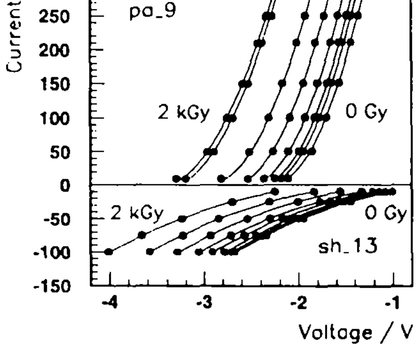

Fig. 7. Current–voltage characteristics of pa_9 and sh_13 biasing current circuits as function of dose. Curves represent parabolic fits. Data sets have measured after the total doses of 0, 45, 90, 180, 359, 674, 1123 and 2021 Gy, respectively.

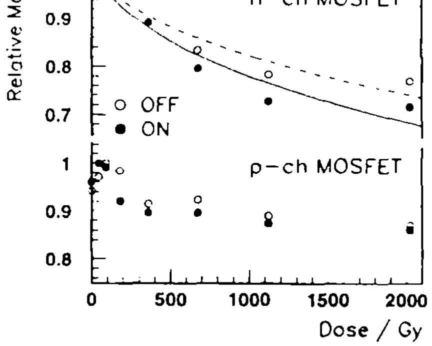

Fig. 9. Relative mobilities as a function of dose in p- and n-channel MOSFETs biased "ON" or "OFF" during irradiations. Full and dashed curves are fits discussed in the text.

determination of the dose dependence of threshold voltages and relative mobilities of n- and p-channel MOSFETs. In the strong inversion transistor model outlined in ref. [9] and accounting for the body effect (ref. [10], p. 77) the following I–V relation can be shown [4] to hold for the pa_9 circuit:

$$I = \text{const.} \times \mu_n\big(V - (V_{ss} + (n+1)V_{th}\big)^2.$$

Curvature and zero of this parabola are determined by electron mobility μ_n and threshold voltage V_{th}, respectively (an equivalent expression holds for the sh_13 circuit). The constant n approximates the effect of fixed charges in the transistor channel; its value ranges usually from 1.3 to 2 and has been determined in the present case by SPICE simulations to be 1.24. Fig. 7 shows the measured I–V characteristics of the pa_9 and sh_13 circuits for a chip biased during irradiations; the data are well reproduced by the parabolic fit curves. Deduced threshold voltages are shown in Fig. 8. The familiar features of threshold voltage shifts [11] are well developed: the different dependence of shifts in n- and p-MOS devices on bias conditions during irradiation, and, in case of n-MOSFETs, reduction of shift at high doses ($\geq$ 1 kGy) due to compensation of oxide-trapped charge by interface states. Relative electron and hole mobilities as function of dose are shown in Fig. 9. The decrease of electron mobilities with dose is much faster than for the hole mobilities. For both biased and unbiased devices the data exhibit at low doses ($\leq$ 0.5 kGy) quite a scatter whose origin is unclear. Nevertheless, the reduction of mobilities with increasing dose appears to be consistently smaller for devices which were exposed with no bias to radiation. Curves have been fitted to the normalized electron mobilities assuming an variation with dose D as $1/(1 + mD^{2/3})$. Such a relationship would be expected if the interface-trap density has the $D^{2/3}$ dependence claimed by various authors [11]. On the other hand, the hole mobilities cannot be fitted well with this ansatz and indicate a smaller power in the order of 0.5.

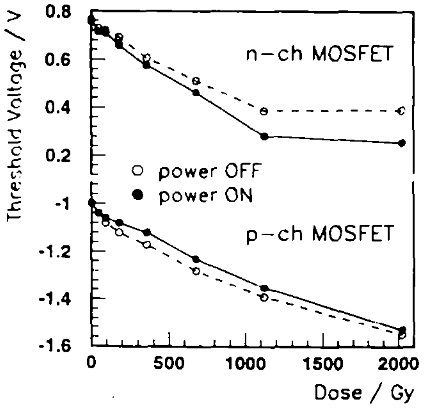

Fig. 8. Threshold voltages as a function of dose for p- and n-channel MOSFETs biased "ON" or "OFF" during irradiations.

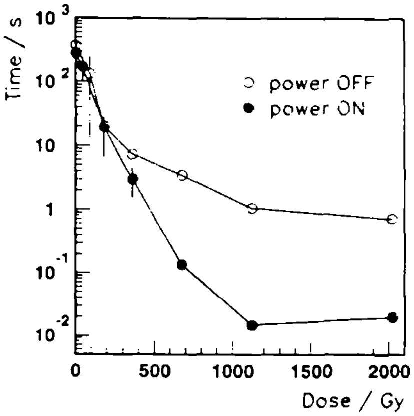

Fig. 10. Signal decay time $t_{1/2}$ for chips which were powered (unpowered) during irradiations.

dose of 2 kGy. At $C_l = 0$ pF, the ENC had increased by 25% to 414 e^- with OBVs of vfs = +0.3 V and vfp = −1.3 V. The threshold voltage of the p-channel MOSFETs showed small change (≤ 40 mV), while for the n-MOSFETs it had shifted from 0.26 V by 0.39 V to 0.65 V. Mobilities remained practically unchanged. By examining the ENC as a function of peaking time T_p we identified an increase of the T_p-independent noise contribution i.e. increased flicker noise [2]. This effect as well as the threshold voltage shifts imply an increase of interface state density during annealing.

3.4. *Further effects*

By variation of the time span between hold signal and the begin of the readout cycle we measured the decay time of signals stored on the hold capacitors Ch. Fig. 10 shows the time $t_{1/2}$ after which the signal has decayed to half of its height as a function of dose. For chips powered during irradiation $t_{1/2}$ is about 15 ms at the total dose of 2 kGy; unpowered chips show a much smaller effect. At low dose (≤ 0.2 kGy) the signal droop is up to times very close to $t_{1/2}$ essentially zero and becomes than suddenly very large; at higher total doses it shows roughly an exponential decay. The very strong decrease of $t_{1/2}$ with dose might be understood assuming discharge of the storage capacitor Ch via the hold transistor (see Fig. 1) since subthreshold currents of n-channel MOSFETs are known to show a similar spectular increase with dose [11].

Radiation effects on the digital chip circuitry have been studied by measuring the minimum (maximum) high (low) shift-in level at the input of the shift register (Fig. 1). By extrapolating the observed shifts of transition voltages, typically −0.4 V/kGy, the functionality of the digital section seems to be unaffected even at doses approaching 10 kGy.

4. Conclusions

The performance of the Viking-2 chip has shown very gentle degradation under irradiations up to total doses of 2 kGy. Radiation-induced threshold shifts are compensated by biasing the circuits with constant currents rather than fixed voltages. The ultimately fatal dose for the Viking-2 chip has not been reached in our study and is presumably well above 4 kGy. The most relevant radiation effect is an increase of noise, which depends on the absorbed dose D and load capacitance C_l. We also have shown how to adjust bias voltages with dose in order to obtain optimum ENC values; this procedure leads, for example, to ENC = 750 e^- at $D = 2$ kGy and $C_l = 10$ pF. If chips are not biased during exposure to radiation, degradation is even smaller. The measured changes of threshold voltages and relative mobility with dose are most important device parameters required to model the radiation damage to the Viking-2 chip within SPICE.

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Note added in proof

In a different setup a noise slope of 14.4 e^-/pF with a constant term of 125 e^- has been measured with a shaping time of 1.5 μs [O. Toker et al., Nucl. Instr. and Meth. A 340 (1994) 572]. The difference is likely due to different external common mode pick-up in the two measurements.

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