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NOISE CHARACTERIZATION OF TRANSISTORS IN A 1.2 μm CMOS–SOI TECHNOLOGY UP TO A TOTAL DOSE OF 12 MRAD (SI)

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Abstract

The analog performance of the Thomson HSOI3-HD technology has been measured up to a total dose of 12 Mrad(Si) of ionizing radiation (^{60}Co). The threshold voltage shift is –170 mV for p-channel and –20 mV for n-channel transistors. Transconductance degradation is respectively 4% and 17%. Noise has been measured in the 500 Hz–25 MHz bandwidth. In addition to the 1/f and white noise, a generation-recombination contribution appears in the noise spectrum. This contribution is sensitive to the bias applied to the backgate and body electrodes. The white noise increase after irradiation is 16% for p-channel and 35% for n-channel transistors. The p-channel transistors have very low 1/f noise and are less sensitive to irradiation effects.

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1 INTRODUCTION

The existing rad-hard technologies have been primarily developed for digital ICs. As a consequence, little attention has been devoted so far to their noise characteristics over a wide bandwidth. In particular, the noise of SOI radiation-hardened technologies has never been extensively studied. In this paper, which expands on our previous work [1], we present results on the noise performance of the HSOI3-HD rad-hard technology. This process, industrially developed by Thomson–CSF Semiconducteurs Spécifiques (TCS), is a 1.2 μm CMOS-SOI technology using a SIMOX substrate. The aim of our research is to investigate the analog characteristics and the radiation hardness of the technology in view of complex ICs for signal processing in experiments at the LHC (Large Hadron Collider, CERN, Geneva, Switzerland).

Our study covers irradiation and bias-dependent annealing effects on n- and p-channel transistors. Noise has been studied in the 500 Hz–25 MHz frequency bandwidth. Contributions from 1/f noise and white noise sources have been separately evaluated. In addition, we found that a localized source of free carrier generation can be activated if particular bias conditions are applied to the body and backgate electrodes. Its effect is to introduce a single time constant generation-recombination (G-R) contribution to the noise spectrum.

2 EXPERIMENTAL DETAILS

The HSOI3-HD technology is a polycide gate CMOS-SOI process [2, 3]. The SIMOX substrate is realized by 200 keV O^+ ion implantation at 500–700°C followed by annealing at 1300–1350°C. Isolation between devices is achieved by conventional LOCOS, and a LDD (Lightly Doped Drain) structure is used to lessen impact ionization due to high electric fields. The thicknesses of the gate oxide, silicon body and buried oxide are respectively 23 nm, 150 nm and 380 nm, and the transistors are partially depleted. The minimum line width in this technology is 1.2 μm (size of contacts, vias and interconnections), but the minimum drawn gate length allowed is 1.4 μm.

For this noise study we used large transistors with high transconductance in order to have a low equivalent input voltage noise density. The MOS-SOI n- and p-channel transistors we studied were actually five-terminal devices. We define ‘backgate’ as the substrate electrode (common to the whole chip) and ‘body’ as the silicon film under the gate oxide, accessible separately for every transistor via a lateral contact. The width of the measured transistors was W = 1000 μm, and two different gate lengths were studied: L = 1.4 μm and L = 2 μm.

All measurements presented in this paper refer to one processing batch. A total of 10 chips, containing four transistors each, were used for the prerad measurements. Two of them were irradiated up to a total dose of 12 Mrad(Si). The noise measurements presented in this study were made after an annealing of three months.

Gamma irradiation took place with a calibrated ^{60}Co source at room temperature. It was performed in four steps with pauses at 1.5, 3.5, 7.5 and 12 Mrad(Si). The dose rates were respectively 18, 31, 54 and 54 rad/sec, and five-hour interruptions between each exposure were made for performing static measurements. The uncertainty on the dose was 20%. We have not studied dose rate effects in our work.

We have chosen to simulate as much as possible the irradiation effects on the transistors in their operational condition. Therefore both irradiation and annealing occurred in air at room temperature with the devices continuously under bias. The transistors were connected in diode configuration ($V_{ds} = V_{gs} \approx 1.1$ V for n-channel and –1.5 V for p-channel) with a source-drain current of 200 μA. For analog applications in front-end electronics (i.e. charge-sensitive amplifiers), the input transistor gives the major contribution to the overall noise of the circuit. It normally operates with $V_{bg} = V_{ss}$ and V_{source} close to 0 V. To simulate its operational bias we have chosen $V_{body} = V_{source} = 0$ V and a backgate bias of $V_{bg} = –3$ V.

Most noise measurements were performed with the device kept in saturation, with $V_{ds} = 800$ mV, and with a constant source-drain current density of 0.5 μA/μm ($I_{ds} = 500$ μA). The noise measurement chain is depicted in Fig. 1. The drain current noise was amplified and transformed into voltage noise by a low-noise transimpedance amplifier, then further amplified by a voltage gain stage and measured by an HP3588A spectrum analyzer. The reference source of the HP3588A was used to measure the frequency transfer function of the measurement chain, and a PC controlled the whole set-up. In this configuration the noise was expressed as equivalent noise voltage referred to the gate by applying the system transfer function to the measured output noise. The potentials of the backgate and of the body could be adjusted externally in order to investigate their effect on the noise. With this set-up, we could study the noise in the 500 Hz–25 MHz bandwidth.

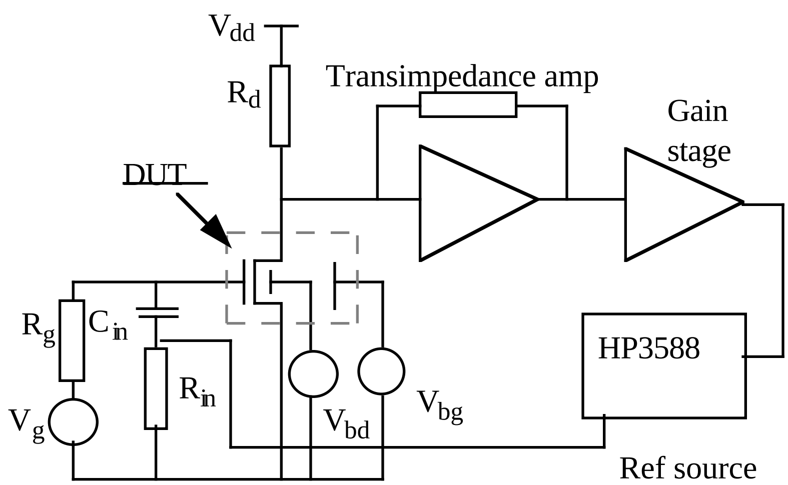

Fig. 1 Noise measurement set-up for transistors in the saturation region. The whole chain is controlled by a PC. The body (V_{bd}) and backgate (V_{bg}) potentials can be changed externally. $R_g = 1$ MΩ, $R_{in} = 50$ Ω, $R_d = 10$ kΩ.

Some additional measurements were done in the linear region of operation. In that case, the transistor was biased with a source-drain voltage $V_{ds} = 20$ mV, and with a load resistor $R_d = 8.3$ kΩ. The noise was amplified by a Brookdeal 5003 Nanovolt Amplifier and measured by the spectrum analyzer.

3 RESULTS AND DISCUSSION

3.1 Static parameters

The evolution of the noise performance with dose and the static transistor parameters may be correlated. Therefore, we again carefully measured these static parameters and found some difference between this processing batch and the previous one [1]. Although our results are based on measurements of about 10 devices in each case, we think that the difference is significant.

In Table 1, we summarize the threshold voltage, transconductance and mobility of n- and p-channel transistors before and after 12 Mrad(Si) exposure and subsequent annealing. The mobility is extracted in the linear region (V_{ds} = 20 mV), while the transconductance refers to saturation, with I_{ds} = 500 μA and V_{ds} = 800 mV.

Table 1

Summary of the static parameters of transistors with W = 1000 μm and L = 1.4 μm before and after irradiation to 12 Mrad and annealing.

	V_{th} [V]	g_m [mS]	μ [cm^2/Vs]
p-channel prerad	–1.31	3.76	200
p-channel 12 Mrad	–1.48	3.63	194
p-channel variation	–0.17	–3.4%	–3%
n-channel prerad	0.85	4.12	357
n-channel 12 Mrad	0.83	3.41	263
n-channel variation	–0.02	–17%	–26%

Both n- and p-channel transistors prove to be radiation hardened as regards static parameters. For the p-channel devices, mobility is less sensitive to irradiation.

The evolution of the threshold voltage shift during irradiation and annealing is shown in Fig. 2. By using the subthreshold current stretchout technique [4], we have separated the contributions of the trapped oxide charge (ΔV_{ot}) and of the interface states (ΔV_{it}).

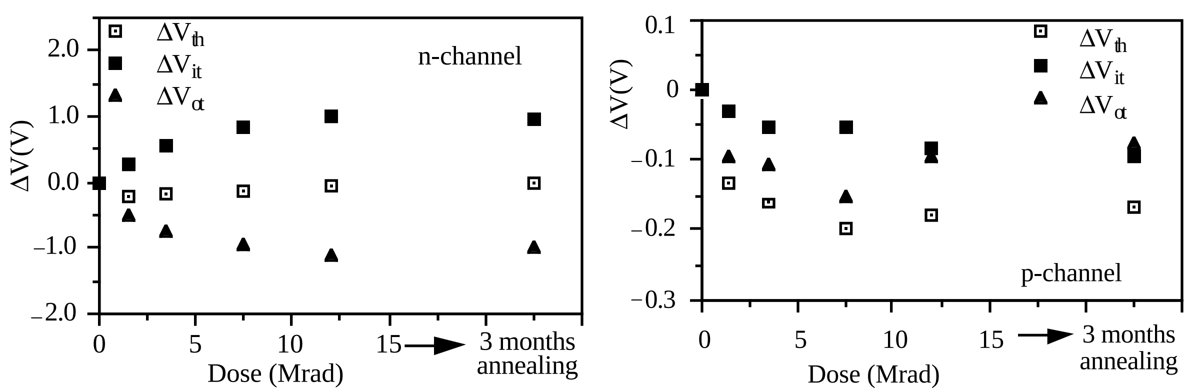

Fig. 2 Threshold voltage shift with irradiation and annealing for n- and p-channel transistors with W = 1000 μm and L = 1.4 μm

The impact of the annealing at room temperature and under bias on the static parameters of the transistors was almost negligible. On the contrary, we observed significant threshold voltage shift with annealing when all terminals were grounded [1]. Therefore, the application of bias even during annealing is important to simulate the realistic behaviour of the transistors.

3.2 Noise

The noise of the n- and p-channel transistors can be described by the superposition of three noise contributions, which can be studied separately. In addition to the usual 1/f and white noise sources, a localized G-R source is active only under particular bias conditions of the body and backgate. In Fig. 3 we show an example in which the different contributions are put in evidence.

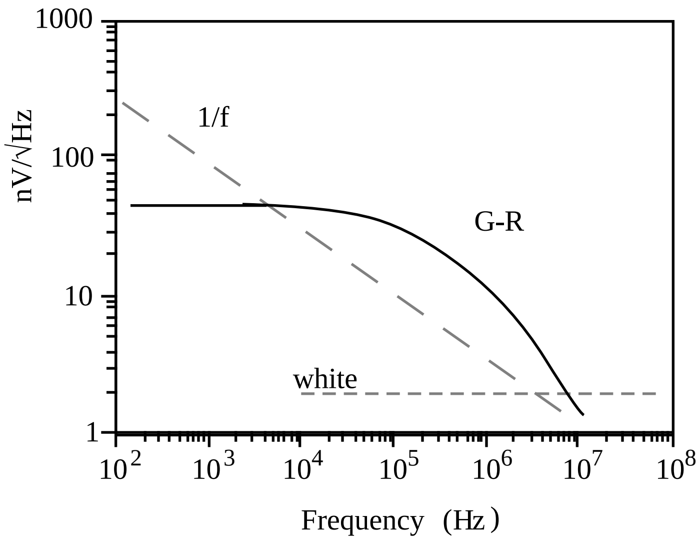

Fig. 3 Qualitative noise spectrum of a transistor in saturation showing the superposition of the three different contributions. The G-R term moves depending on the applied body and backgate bias.

The G-R hump changes in frequency and amplitude depending on the backgate and body potentials. We take advantage of this characteristic and move it to lower frequencies when we want to study the white noise, or to higher frequencies when the 1/f region is of major interest.

3.2.1 G-R noise

Generation-recombination noise in MOS transistors is related to the random emission of carriers at defect centers in the depletion region in the semiconductor bulk. The spectrum which describes the G-R contribution, in the case of a single time constant, can be expressed as equivalent noise voltage at the input [5] and depends on the time constant of the emission process τ_t as

$$S_V^2 \propto \frac{\tau_t}{1+\omega^2\tau_t^2} \,. \tag{1}$$

The time constant τ_t determines the cutoff frequency ($f_{cutoff} = 1/2\pi\tau_t$) where the G-R input referred noise is 3 dB under the value at the plateau.

This contribution is usually negligible in present bulk technologies, where the defect concentration in the depleted region close to the gate oxide is very low. SOI technologies using SIMOX substrate may nevertheless have a relatively high defect concentration in the region of the buried oxide, as shown by a number of studies [6, 7, 8]. Some of these works have revealed the presence of a monoenergetic defect centre. These results are dependent on the particular SIMOX substrate, changing considerably with ion implantation dose temperature and annealing temperature.

We have found a G-R noise component in the noise spectra of both p- and n-channel transistors in the HSOI3-HD technology. Its cutoff frequency and amplitude show a strong dependence on the bias condition. In Fig. 4 the dependence of the cutoff frequency and amplitude on the backgate potential is depicted for an n-channel transistor. These spectra have been obtained by subtracting the 1/f and white noise contributions from the measured noise curve.

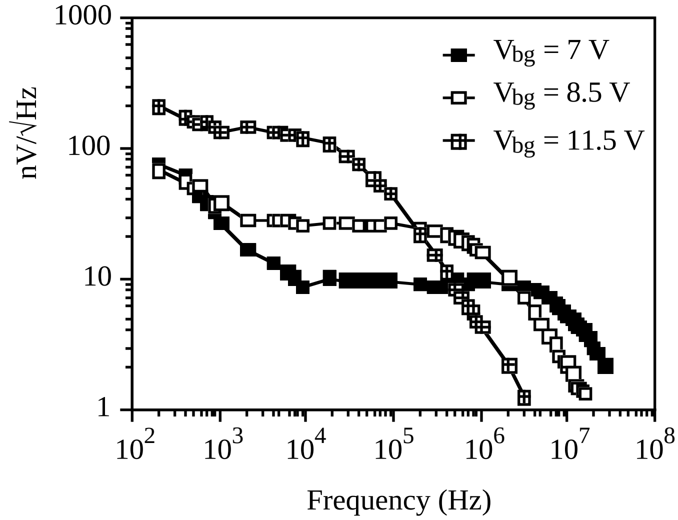

Fig. 4 Input referred noise voltage coming from the G-R contribution for different backgate bias. V_{body} = 0 V. The cutoff frequency of the G-R hump moves more than two decades with the backgate passing from 7 to 11.5 V. The backgate threshold voltage is 26 V, and the transistor size is W = 1000 µm, L = 1.4 µm.

Similar behaviour is also found when changing the body bias. In Fig. 5 we show the cutoff frequency and the noise at the plateau of the G-R component as a function of the body potential applied before irradiation. For both n- and p-channel transistors the amplitude of the plateau increases with the absolute value of the body bias while the cutoff frequency decreases in a complementary way. The product of the spectral density at the plateau times the cutoff frequency is fairly constant, which suggests that a constant number of physical defects is involved in the G-R process.

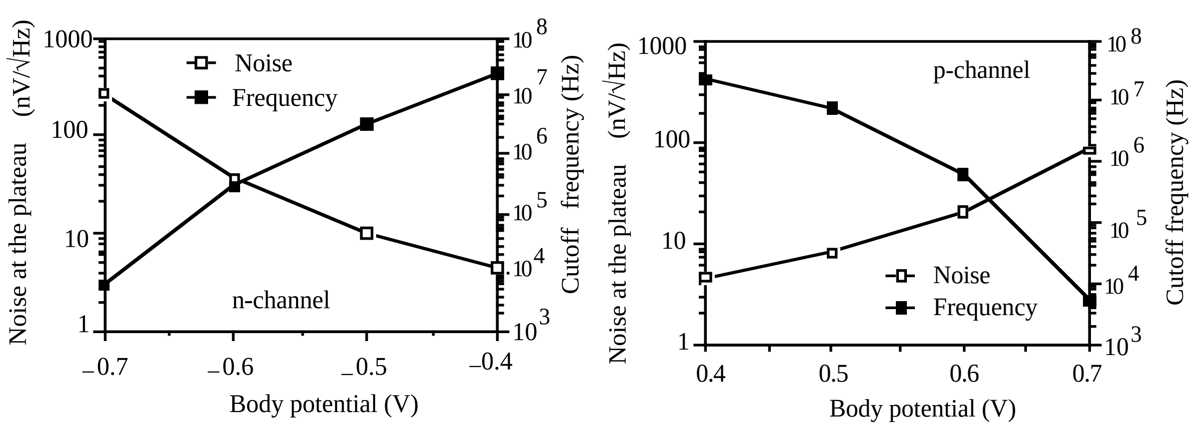

Fig. 5 n- and p-channel transistors with W = 1000 μm and L = 1.4 μm. The noise at the plateau and the cutoff frequency of the G-R component are shown as a function of the body potential applied, with V_{bg} = 0 V. The values have been extracted from unirradiated samples.

Generation-recombination components have been already found in SOS transistors [9], but there the variation of the body potential introduced several terms with different time constants. In our measurements we see only one hump, indicating a single time constant phenomenon. A monoenergetic defect in the depleted silicon close to the buried oxide could be at its origin. The time constant of the generation-recombination is inversely proportional to the majority carrier concentration around the defect. By applying a bias to the body or backgate, we modify this concentration at the interface between the buried oxide and the body — therefore the time constant changes.

If the back interface is at the origin of the G-R noise, we have to understand how this noise source is coupled to the source–drain current where we have measured it. In fact, the front channel is the only conductive path between source and drain in our measurements, the back interface being always far from inversion. To investigate the possible mechanism of transmission, we performed noise measurements in the linear region of operation. In the resulting spectra, the G-R noise was absent for all the backgate or body potentials applied, indicating that the coupling of the noise source to the channel occurs only in the presence of the pinchoff.

We have observed that the G-R component is modified by the irradiation. In identical bias conditions, the cutoff frequency is lower after exposure for n-channel transistors and higher for p-channel. At V_{body} = –0.4 V, for the n-channel the cutoff frequency moves from 24 MHz to 4 kHz. For the p-channel at V_{body} = 0.7 V, it changes from 5 kHz to 900 kHz. This is a consequence of the backgate threshold voltage shift, which is –6 V for the n-channel and –3.4 V for the p-channel transistors. Owing to this shift, the depletion condition of the back interface is different when the same body and backgate bias are applied. Therefore, the time constant of the generation-recombination process is modified.

By applying a different body bias we can get pre- and post-irradiation spectra with the same G-R noise cutoff frequency, and observe that the amplitude and shape of the hump remain unchanged. This suggests no significant variation in the defect density responsible for this noise.

3.2.2 White noise

The origin of the white noise in MOS transistors can be traced to the random thermal motion of carriers in the channel. In strong inversion and in saturation, the drain current noise can be referred to the input as a noise voltage spectral density with the expression

$$S_V^2 = 4kT\frac{2}{3} \times \frac{\Gamma}{g_m}, \tag{2}$$

where k is the Boltzmann constant, T the device temperature and g_m the transconductance. The factor Γ is technology- and device-dependent and has no direct physical meaning, but takes into account several effects. First, it includes the factor 1 + δ (where δ depends on the body effect coefficient, the surface potential and the body-to-source bias) resulting from the different depletion condition close to the source and drain diffusions [10]. Furthermore, it corrects the formula for the reduced mobility at high fields and for the increased carrier temperature. The carriers in the channel not necessarily being in thermal equilibrium with the lattice, T used in (2) could be different from the device temperature. The Γ factor also includes in the simple formulation (2) the white noise contributions coming from the polysilicon gate resistance and the body access resistance. To be more precise, these two additional noise sources should be separately evaluated [11].

In Table 2, we report the results of the white noise measurements before and after irradiation. The measured thermal noise is given together with the corresponding g_m and the extracted Γ. The body potential during measurement was –0.7 V for the n-channel and 0.9 V for the p-channel transistors. This bias was applied to move the G-R hump at low frequencies so that the thermal noise was clearly visible in the bandwidth of our measurement set-up. The backgate potential was in every case 0 V.

Table 2

White noise, transconductance and Γ factor for n- and p-channel transistors before and after irradiation and annealing. V_{body} = –0.7 V for the n-channel and 0.9 V for the p-channel transistors. V_{bg} = 0 V in all cases.

	n-channel L = 1.4 µm	n-channel L = 2 µm	p-channel L = 1.4 µm	p-channel L = 2 µm
S_v prerad (nV/√Hz)	1.98	2.02	2.16	2.21
S_v 12 Mrad (nV/√Hz)	2.73	2.66	2.50	2.57
ΔS_v	+38%	+32%	+16%	+16%
g_m prerad (mS)	4.58	4.22	4.52	3.90
g_m 12 Mrad (mS)	4.00	3.55	4.20	3.60
Δg_m	–13%	–16%	–7%	–8%
Γ prerad	1.63	1.57	1.92	1.72
Γ 12 Mrad	2.70	2.27	2.37	2.15
ΔΓ	+66%	+45%	+23%	+25%

The pre-irradiation Γ is about 10% higher for p-channel transistors. This difference could be due to the contribution of the body access resistance, which we know to be higher before irradiation for the p-channel transistors.

After irradiation the situation is reversed. The n-channel transistors reveal a more significant increase in the thermal noise, and they are finally ‘noisier’ than the p-channel ones by 5 to 10%. This result is not only justified by a more pronounced reduction of the transconductance, but also by a sharper increase in the Γ factor. This suggests a higher sensitivity to irradiation for one or more of the parameters contained in Γ. It could be the body access resistance or come from high field effects on the mobility and temperature of the carriers. This last effect is surely important, as shown by the higher increase in Γ for the n-channel transistor with minimum gate length.

3.2.3 1/f noise

According to the McWorther model [12], the 1/f noise in MOS transistors is due to random trapping and detrapping of the mobile carriers in the traps located at the Si–SiO_2 interface and within the gate oxide. It is therefore a direct indication of the quality of the interface, and is very sensitive to trapping states created by irradiation. The noise voltage spectral density referred to the input can be expressed as [13]

$$S_V^2 = \frac{K_f}{C_{ox}^2 WL} \times \frac{1}{f^\alpha}, \qquad (3)$$

where C_{ox} is the gate capacitance per unit area, K_f is a technology-dependent constant and α is a parameter close to 1.

Using (3) to fit the experimental points, we have extracted the coefficients K_f and α. In Table 3 a summary of the results for both channels before and after irradiation and annealing is given.

Table 3

Extracted 1/f coefficients before and after irradiation and annealing.

	α prerad	α 12 Mrad	K_f(fC^2/µm^2) prerad	K_f(fC^2/µm^2) 12 Mrad
n-channel L = 1.4 µm	0.88	0.94	2.53×10^{-9}	8.33×10^{-9}
n-channel L = 2 µm	0.88	0.92	5.38×10^{-9}	9.13×10^{-9}
p-channel L = 1.4 µm	0.88	0.92	4.7×10^{-10}	1.35×10^{-9}
p-channel L = 2 µm	0.90	0.96	7.2×10^{-10}	2.22×10^{-9}

The coefficient α is less than one for both p- and n-channel transistors, and increases in all cases after irradiation by about 5%. This indicates a creation of slow trapping states as a consequence of the gamma exposure.

The extracted K_f show a big difference between n- and p-channel transistors. The 1/f noise is in fact much lower in p-channel devices. Owing to the doping implant made to adjust the threshold voltage, the p-channel transistor is a buried channel device. It is therefore less sensitive to the Si–SiO_2 interface trap density.

K_f is proportional to the interface trap states density through some coefficients [13, 14]. The increase in K_f can be compared with the static characterization, in particular with the interface states and oxide trapped charge evolution (Fig. 2). Both the 1/f noise and the static parameter measurements agree that the n-channel transistor interface is more damaged by irradiation. The bias condition during exposure strongly affects this result. The positive voltage applied to the gate of the n-channel transistor forces the positive species generated by the radiation to move towards the interface. This species is mainly responible for defect formation [15].

4 CONSIDERATIONS FOR ANALOG APPLICATIONS

The static parameter study has revealed that the HSOI3-HD technology is adequate to stand a 12 Mrad(Si) ionizing dose with very small changes in its static characteristics. The p-channel transistors have shown themselves to be particulary radiation hardened, having a decrease of mobility and transconductance of about 4% after irradiation and annealing.

In considering the noise behaviour, we should focus our attention on the range of frequencies of interest for our applications. In the LHC experiments, shaping filters will be used to treat the signal coming from the detectors to maximize the signal-over-noise ratio. These shaping techniques determine the frequencies of interest for the noise.

For ICs to be used in the part of the experiments where radiation hardness is required, a low frequency limit ≥1 MHz is foreseen, sometimes even >5 MHz. At these frequencies, transistor noise should come only from the thermal contribution to get the maximum signal-over-noise ratio. The corner noise frequency f_{cn}, which is the frequency where the 1/f and white noise contributions are equal, is generally used as the relevant parameter. It is bias dependent, and thus meaningful only when given together with the current level.

The 1/f noise is of some concern in the studied technology. The n-channel transistors of minimum gate length, which have the highest flicker noise after irradiation, present an f_{cn} of about 800 kHz (I_{ds} = 500 μA). This means the 1/f contribution is still present, though not dominant, as far as 2 MHz, where it gives one third of the total noise. The p-channel transistors, with $f_{cn} \approx$ 180 kHz at 500 μA after exposure, could be used even at lower frequencies without being affected by the 1/f component.

The G-R component can considerably increase the noise in the frequency region of interest. Great care should be taken with the body bias of the transistors where low noise is required. The backgate electrode is common to the whole chip, so the body contact is the only means to control the cutoff frequency of the G-R hump. To reduce the high frequency noise, this contribution has to be moved to a low frequency. This can be obtained by applying a body bias. In Fig. 6 we show the noise spectra for n- and p-channel transistors with an applied body potential of, respectively, –0.9 V and 1.1 V. For the n-channel, the applied bias is sufficient to make the hump disappear at low frequency. For the p-channel, the G-R contribution is moved below 1 MHz, but is still visible in the depicted spectra, where it completely covers the 1/f noise.

As shown in Fig. 6, the noise is determined only by the thermal contribution at frequency > 1 MHz for the p-channel transistor and > 3 MHz for the n-channel when an adequate body bias is applied.

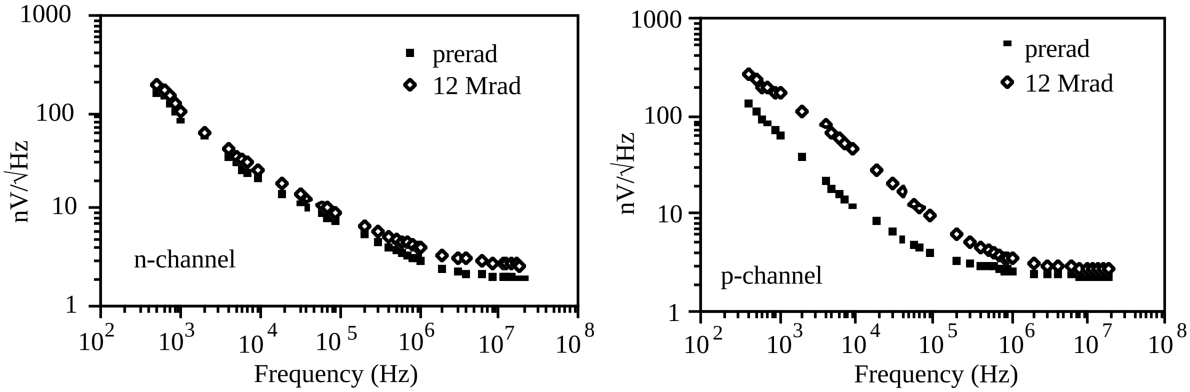

Fig. 6 Noise before and after irradiation and annealing for n- and p-channel transistors with W = 1000 μm and L = 1.4 μm. The body bias applied during measurement was –0.9 V for the n-channel and 1.1 V for the p-channel. V_{bg} = 0 V. The 1/f noise of the p-channel is covered by the G-R hump.

5 CONCLUSIONS

Static characteristics of n- and p-channel transistors in the HSOI3-HD technology have been measured before and after irradiation and annealing up to 12 Mrad(Si) from a ^{60}Co source. For n-channel transistors the threshold voltage shift is –20 mV, the transconductance degradation is 17% and the mobility variation is –26%. For the p-channel, we have found ΔV_t = –170 mV and a degradation in both mobility and transconductance of less than 5%.

Noise has been studied in the 500 Hz–25 MHz bandwidth. The spectra reveal the contribution of three noise sources. In addition to the 1/f and thermal noise, which have been fully characterized, a G-R contribution has been found. The noise source responsible for it is located spatially close to the back interface, and can be coupled to the front channel under certain bias conditions. The cutoff frequency of this G-R noise can be changed over a wide range by acting on the body and substrate bias. For the n-channel, a body bias of –0.9 V is sufficient to move the whole G-R contribution below 1 MHz when V_{bg} = 0 V, whilst a 1.1 V bias is necessary for the p-channel.

The p-channel transistors have lower 1/f noise and are less sensitive to irradiation in the whole explored bandwidth. Their increase in the white noise after 12 Mrad(Si) is about 16% against 35% for the n-channel.

In comparison with bulk radiation-hardened technologies in similar studies [16, 17], the HSOI3-HD technology performance seems better for both 1/f and thermal noise. In particular, the radiation hardness of the noise characteristics is very good. In addition, SOI technology has low sensitivity to single-event phenomena [18]. Therefore, the studied technology is a good candidate for mixed analog–digital applications in harsh environments.

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