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Total-Ionizing-Dose Radiation Hardness of PJFETs integrated in a 130 nm SiGe BiCMOS Technology

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Summary: This paper reports on the effects of 10 keV x-rays on the static and noise behaviour of integrated p-channel JFETs and compares these results to measurements on a commercially available discrete NJFET. It is shown that exposure to x-rays affects the DC device parameters and noise spectral density in a way which is substantially different for the two types of devices. After irradiation PJFETs show an increased gate leakage current and an increased noise voltage spectrum over a broad frequency band, whereas NJFETs show only minor degradation of the noise voltage.

Keywords: Radiation hardness,x-ray, TID, JFET, CMOS

Introduction

The silicon junction field-effect transistors (Si-JFET) are attractive in radiative environments as low-noise, high impedance input devices. Junction-gate field-effect transistor (JFET) devices are inherently radiation hard. When JFETs are used as building blocks for sensing and communication electronics (i.e., oscillators, amplifiers, filters, and mixers), inherently radiation-hardened circuits can be achieved.

TID effects in a MOSFET are caused by radiation-induced trapped charge in oxides close to the channel region. A JFET does not employ a dielectric material to modulate channel conductance eliminating the effect of radiation-induced trapped charge. Si-JFETs operate by majority carrier transport through a heavily doped channel. Current flow is remote form the Si surface and the surrounding oxides. Therefore total ionizing dose (TID) effects which degrade the performance of MOS transistors under ionizing radiation are negligible. It has been found that γ-ray irradiation up to doses in the Mrad range causes only minor degradation in JFETs. Pinch-off voltage, transconductance and other channel parameters show only minor changes.

The most significant radiation induced degradation in JFETs is the increase of reverse gate leakage current. The main constraints for JFETs is their limited tolerance to displacement damage (DD). JFET noise properties are known to be degraded by generation of Si bulk lattice defects with low characteristic frequencies which act as trapping-detrapping centres.

In this paper an experimental investigation of the influence of ionizing radiation on PJFETs integrated in IHPs 130 nm BiCMOS technology is presented. For comparison a commercially available discrete NJFET (Texas Instruments JFE150 Ultra-Low-Noise JFET) was tested.

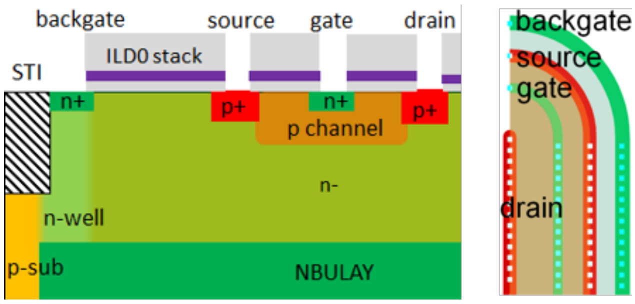

Fig. 1: Cross section and partial top view of the PJFET

Devices were exposed to 10 keV x-rays up to a total dose of about 4 Mrad(Si) and 5.5 Mrad(Si) for PJFET and JFE150, respectively. Electrical parameters such as pinch-off voltage and gate leakage current were monitored during irradiation. The PJFET noise behavior has been measured before and directly after irradiation.

Experimental

JFET Devices

A short channel PJFET (p-channel JFET) with split channel region was modularly integrated in IHPs 130 nm SiGe:C BiCMOS (Silicon Germanium Carbon bipolar complementary metal oxide semiconductor) technology [1]. A cross section and partial top view of the enclosed layout PJFET is shown in Figure 1. The PJFET has gate and channel lengths of 0.31 µm and 3.15 µm, respectively.

Measurement Set-Up

Irradiation was carried out with 10 keV x-rays with a dose rate of 1.5 krad(Si) min^{-1} in a Precision iR160 x-ray irradiator equipped with a man-

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ual probe station. The irradiation dose is increased in steps of 450 krad(Si). During irradiation PJFETs and JFE150 devices were biased at $V_{\mathrm{G}} = 2.5\,\mathrm{V}$ and $V_{\mathrm{G}} = -2.5\,\mathrm{V}$, respectively. All other device terminals were grounded.

In situ on-wafer electrical characterization during irradiation was carried out using a Keithley 4200 semiconductor parameter analyzer.

Measurements of the input referenced noise voltage spectrum (SV_{G}) before and after irradiation were performed using a ProPlus 9812DX Noise Analyzer system. SV_{G} measurements were preformed over a frequency interval of six decades, from 1 Hz to 1 MHz at different drain current values. The PJFET were biased for maximum g_{m} in order to minimize thermal noise. JFE150 were biased for minimum voltage noise.

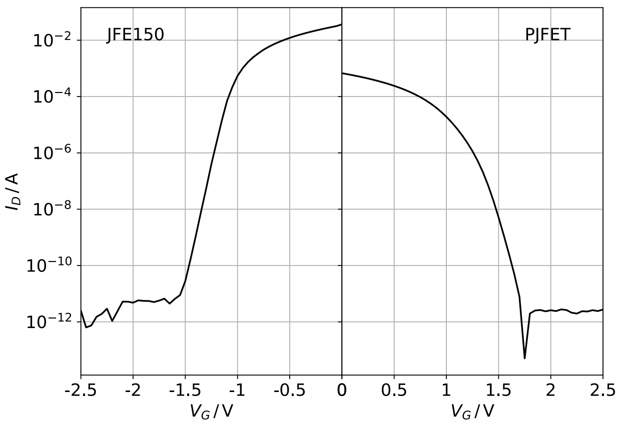

Fig. 2: Transfer characteristic of the investigated JFETs

Results and Discussion

Pre-irradiation Measurements

The most significant parameters for a JFET are the pinch-off voltage and maximum transition frequency. Pinch-off voltage V_{GP} is the gate-channel voltage at which the depletion region extends completely across the channel and the current flow between the source and drain is cut off. The maximum transition frequency f_{T} refers to the operating frequency where current gain goes to unity (zero dB) and above which the JFET can no longer amplify an input signal. The high frequency behavior of the PJET is covered in [2].

Transfer characteristics (drain current I_{D} vs gate voltage V_{G}) of the integrated PJFET and the JFE150 are shown in Figure 2. Pinch-off voltage of the JFE150 is $V_{\mathrm{GP}} = -1.2\,\mathrm{V}$ ($I_{\mathrm{D}} = 1\,\mu\mathrm{A}$) according to [3] and confirmed in the measurement in Figure 2. Using the identical criterion for the PJFET a pinch-off voltage of 1.25 V is extracted.

Figure 3 shows the noise voltage spectra (SV_{G}) of PJFET and JFE150.

It is well known, that JFET noise power spectral density is well fitted by a superposition of defect specific Lorentzian terms added to an $1/f$ noise term and the white noise component. Each Lorentzian term has a constant value up to a characteristic frequency and then decreases with $1/f^2$.

$$SV_{\mathrm{G}}(f) = \frac{A_{\mathrm{W}}(T)}{g_{\mathrm{m}}} + \frac{A_{\mathrm{f}}}{f} + \sum_{i=1}^{N} \frac{A_{\mathrm{L}i}\,\tau_{\mathrm{L}i}}{1 + (2\pi f \tau_{\mathrm{L}i})^2} \quad (1)$$

where f is the frequency and $A_{\mathrm{W}}(T)$ gives the temperature dependence of the white noise component. The parameters A_{f} and A_{L} are constants, and τ_{L} is the time constant of the corresponding Lorentzian term.

For the PJFET Lorentzian terms with a characteristic frequencies dominate from about 1 Hz to 10 kHz. The PJFET is considerable noisier than the JFE150. For the JFE150 device, Eq. (1) can be fitted to the measurement data by a single Lorentzian component with a very small characteristic frequency and a white noise background (see Figure 5). The JFE150 measurements are very similar to the data provided by the manufacturer [3].

The difference in the noise spectra between the device types can be attributed to differences in the number / types of bulk silicon defects due to the different fabrication processes.

Post-irradiation measurements

After irradiation the pinch-off voltages of PJFET and JFE150 show only very small changes. For the PJFET V_{GP} decreases with increasing radiation dose, whereas for JFE150 V_{GP} is essentially unchanged.

In [4] x-ray irradiation was found not to degrade the DC and noise performance of n-channel JFETs, the only relevant effect found after irradiation was an increase of the gate current.

In our experiments the PJFET gate leakage current shows a linear increase with increasing dose (albeit only in the picoampere range; see Figure 4). For JFE150 gate current is unchanged after irradiation.

The gate current increase after irradiation is ascribed to surface carrier generation at the n$^+$-gate / p-substrate junction. Interface state generation between the ILD0 oxide stack and the Si bulk was shown to scale linearly with irradiation dose as demonstrated in measurements on gated diodes [5].

Radiation induced degradation of JFET noise properties has been previously investigated in [4, 6]. Degradation of the low-frequency noise behavior was observed after irradiation with neutrons or ^{60}Co γ-rays and attributed to the creation of lattice defects (DD) in the channel. DD by ^{60}Co γ-rays was explained by secondary electron generation via the Compton Effect.

In our experiments after irradiation with 10 keV x-rays degradation of the low-frequency noise behavior over nearly the whole frequency range is observed for the PJFET. Figure 5 shows the noise-voltage spectrum (SV_{G}) in the frequency

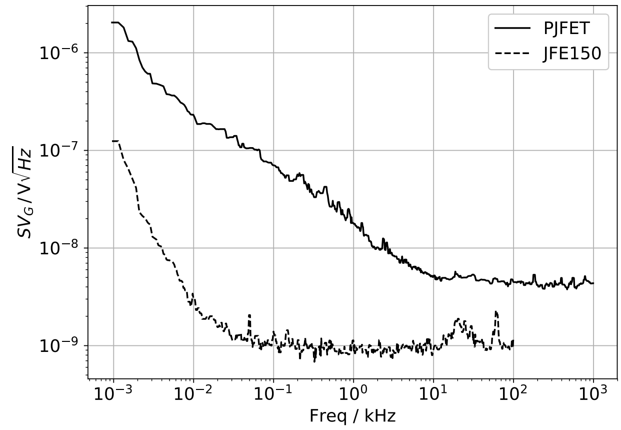

Fig. 3: Input referred noise

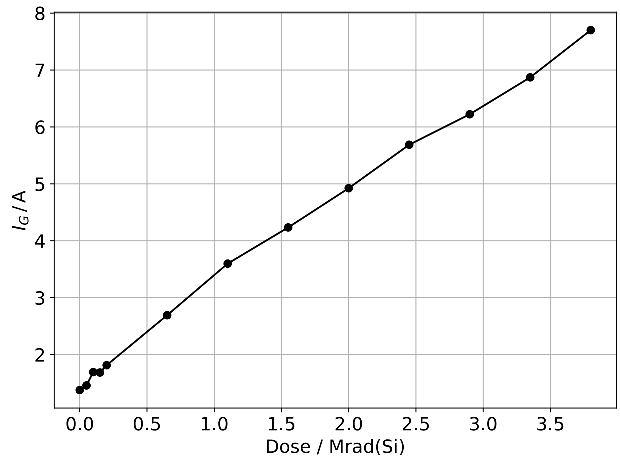

Fig. 4: PJFET gate current as function of dose

range from 1 Hz to 1 MHz, for a PJFET device biased at a drain-to-source voltage $V_{\mathrm{D}} = -2\,\mathrm{V}$ and $V_{\mathrm{G}} = 0\,\mathrm{V}$. White noise contributions are unchanged after irradiation.

For the JFE150 white noise is also unchanged after irradiation, but an increase of the noise voltage between 10 Hz and 1 kHz is found. The best fit of SV_{G} after irradiation is achieved with a single Lorentzian term with a characteristic frequency of about 150 Hz. The observed SV_{G} increase with one characteristic frequency in the region of a few hundred Hertz points to generation of a single type of charge trapping/releasing defect during irradiation.

The root cause for the observed changes in the noise voltage spectrum after x-ray irradiation is currently unclear. X-ray absorption at low photon energies is dominated by the photo-effect. The 10 keV x-rays used in this work are by far not energetic enough to generate an appreciable number of Compton electrons of sufficient energy to generate Si lattice defects.

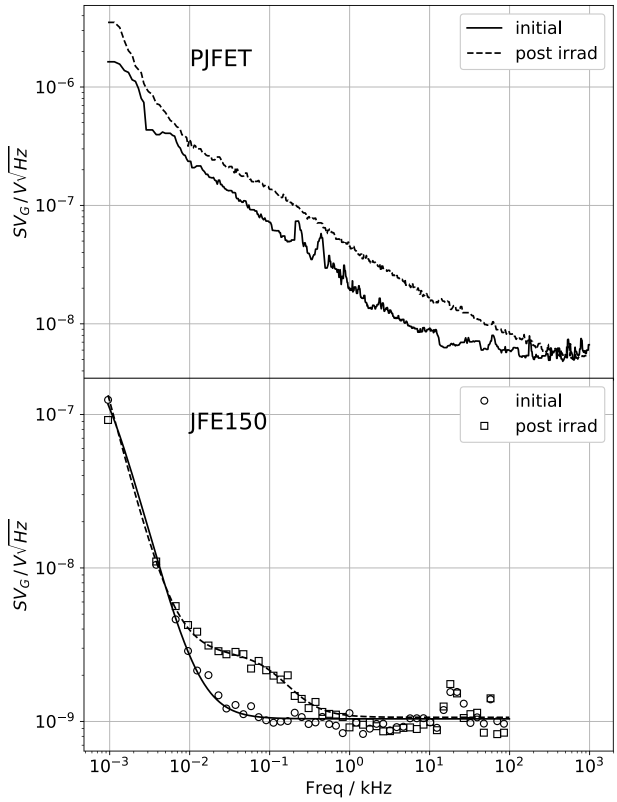

Fig. 5: Input referred noise voltage before and after irradiation. Lines in the bottom Figure for the JFET are fitted using Eq. (1).

Conclusions

Irradiation of an integrated p-channel JFET and a commercially available discrete NJFET with 10 keV x-ray was conducted. The devices were exposed to total doses of 4 Mrad(Si) for the PJFET and 5.5 Mrad(Si) for the commercial NJFET. The integrated p-channel JFET shows an increase of gate current proportional to irradiation dose. No change in gate current was observed for the JFE150 NJFET.

The integrated PJFET exhibits increased noise over a wide frequency range after irradiation. The JFE150 NJFET only shows higher noise level in the frequency range from 10 Hz to 1 kHz after irradiation. This change in noise was fitted with a single Lorentzian term that has a characteristic frequency of about 150 Hz.

Author Contribution

F.K. and J.S. were responsible for experiments and analysis of the results. R.S. was responsible for preparation of the PJFETs devices.

Competing Interests

The authors declare that they have no conflict of interest.

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