JFET preamplifiers for low noise applications in calorimetry and radiation spectroscopy

P.F. Manfredi, V. Re, V. Speziali

Dipartimento di Elettronica, Università di Pavia, Via Abbiategrosso 209, 27100 Pavia, Italy, and INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy

A monolithic process based on epitaxial channel N-JFETs has been employed in the realisation of calorimetry front-end systems with outstanding noise performances on a broad temperature range. The same process is presently being extended to applications in high resolution radiation spectrometry with detector capacitances in the 10 pF range.

1. INTRODUCTION

A process based on a buried-layer approach has been developed in order to integrate N-channel JFETs on a silicon substrate [1, 2]. The JFETs belonging to this process were proven to feature outstanding noise characteristics. The spectral power density $S_{\text{Th}}$ of their channel thermal noise follows quite closely the theoretical dependence on the transconductance $g_{\text{m}}$.

$$S_{\text{Th}} = 4kT \frac{2}{3} g_{\text{m}}$$

where $k$ is the Boltzmann's constant and $T$ the absolute temperature. The noise behaviour in the low-frequency range was found to be adequately approximated by a spectral density $S_{\text{ff}}$ sum of a $1/f$ and a Lorentzian term:

$$S_{\text{ff}} = \frac{A_f f}{1 + (2\pi)^2 f^2 \tau^2_{L}} + \frac{A_L}{f}$$

For a device of input capacitance $C_i$, the intrinsic coefficients of $1/f$ noise, $H_f = A_f C_i$, and Lorentzian noise, $H_L = A_L C_i$, were found to attain very low values, respectively $10^{-28}$ Joule and $3 \cdot 10^{-28}$ Watt.

As a first application of the buried-layer N-JFET process, calorimetry preamplifiers were developed to match detector capacitances in the 100-1000 pF range. The input device of these preamplifiers has a gate width $W = 11000 \mu\text{m}$ and an active gate length $L = 5 \mu\text{m}$. These preamplifiers have been employed as building elements of a front-end system in a liquid Kr test calorimeter [3]. The first part of the paper is devoted to their noise characterisation.

The second part discusses the possibility of extending the N-JFET monolithic process to spectrometry applications with detector capacitances in the 10 pF range. Preliminary noise results obtained with a JFET realised in the same process with a size suitable for matching such capacitance values are given.

2. PREAMPLIFIERS FOR CALORIMETRY APPLICATIONS

Figure 1 shows the schematic diagram of the charge-sensitive preamplifier for calorimetry applications. It consists of an input cascode ($J_1, J_2$), of a bootstrapped active load ($J_3, J_4, J_7$) on the drain of $J_2$ and an output buffer ($J_9$).

The transistors on the signal path ($J_1, J_2, J_7, J_9$), for which a large transition frequency is a fundamental requirement, are devices of
shorter channel length (L = 5 μm). All the other JFETs in the circuit are, instead, required to feature a large drain-to-source impedance. They are, therefore, realised with a longer gate (L = 10 μm). The resistors and capacitors shown in the diagram, including the feedback elements, are off-the-chip components.

The current in the input branch is the $I_{DSS}$ of J4 and its design value is 2 mA. Considerations of noise and gain-bandwidth product may require that the standing current in J1 be increased beyond this value. This is obtained by injecting into J1 the additional current provided by $R_{BL}$.

The calorimetry preamplifier is available in two versions that differ for the resistivity of the epitaxial layer which constitutes the JFET channel material. The version of lower channel resistivity (L type, $\rho = 0.5 \, \Omega \cdot \text{cm}$) is intended for calorimetry applications from room temperature down to liquid Krypton (120 K). The one of higher channel resistivity (H type, $\rho = 1.6 \, \Omega \cdot \text{cm}$) suits better the operating conditions of liquid Argon calorimetry (90 K).

The noise features of two preamplifiers that have identical architectures but differ for the resistivity of the JFET channel region is given in figure 2. These results were obtained with an external capacitance $C_D$ simulating the detector of 480 pF. The signal at the preamplifier output was shaped by a bipolar $(RC)^2-(CR)^2$ filter [4] with 50 ns peaking time.

![Diagram](image.png)

Figure 1. Schematic diagram of the charge-sensitive preamplifier for calorimetry applications.

![Graph](image.png)

Figure 2. Equivalent noise charge as a function of temperature for two preamplifiers employing JFETs of different channel resistivity: a) channel resistivity $\rho = 0.5 \, \Omega \cdot \text{cm}$; b) channel resistivity $\rho = 1.6 \, \Omega \cdot \text{cm}$.

2. PREAMPLIFIERS FOR SPECTROMETRY APPLICATIONS

The excellent noise characteristics of the JFETs obtained with the buried layer approach suggest that the process may be employed for preamplifiers oriented to high resolution spectrometry.

In moving from preamplifiers for calorimetry applications, where the input device is designed to match capacitances of hundreds of pF, to preamplifiers where the input device is much smaller, a significant
difficulty is encountered. It has to do with the contribution to the total noise brought about by devices other than the input one. This can be understood with reference to the circuit diagram of figure 1, which can be considered an architecture of general validity in the NJFET monolithic process, regardless of the size of the input device. In the circuit of figure 1 the spectral power density of the input-referred noise voltage can be written by considering the high frequency terms only as:

\[
S_w = \frac{2}{3} \frac{T}{g_m} \left( 1 + \frac{g_{m3}}{g_{m1}} + \frac{3}{2g_m R_{BL}} \right)
\]

where \(g_{m1}\) and \(g_{m3}\) are the transconductances of \(J_1\) and \(J_3\).

In equation (3) it has been assumed that the noise due to elements other than \(J_1, J_3, R_{BL}\) is negligible. This is a reasonable assumption. According to (3), the relative weight of the noise in \(J_3\) and \(J_1\) is given by the ratio \(g_{m3} / g_{m1}\). In the calorimetry preamplifier, where at room temperature, at a current of 5 mA in \(J_1\) (\(W = 11400 \mu\text{m}, L = 5 \mu\text{m}\)) and 2 mA in \(J_3\) (\(W = 800 \mu\text{m}, L = 10 \mu\text{m}\)), \(g_{m1} = 40 \text{ mA/V}, g_{m3} = 2 \text{ mA/V}\), the impact of \(J_3\) on the total input noise is only 2.5%. As the size of \(J_1\) is reduced, \(J_3\) cannot be scaled down below a certain width because it might turn out to be too small, resulting in an unacceptably low standing current in the input branch and a large spread in the value of this current.

A viable approach to keep \(g_{m3} / g_{m1}\) adequately low consists in reducing the ratio between the standing currents in \(J_3\) and \(J_1\). Such a reduction can be achieved by both acting on the size of \(J_3\), in order to bring its \(I_{DSS}\) to a fraction of a mA, and by fixing the current in \(J_1\) to a few mA through the external resistor \(R_{BL}\).

A spectrometry type preamplifier has been designed to match a 10 pF detector capacitance. The input device \(J_1\) has \(W = 1800 \mu\text{m}, L = 5 \mu\text{m}\), while \(J_3\) has \(W = 80 \mu\text{m}, L = 10 \mu\text{m}\). The \(I_{DSS}\) of \(J_3\) is 0.6 mA. At a total current in \(J_1\) of 2.6 mA obtained by adding through \(R_{BL}\) 2 mA to the 0.6 mA forced by \(J_3\), the \(g_{m3} / g_{m1}\) ratio is 0.07. This means that the degradation brought about by \(J_3\) on the total noise is \(= 3.5\%\), that is, quite acceptable.

To check the feasibility of the preamplifier, which is intended for applications in \(\gamma\)-ray spectrometry with Ge detectors, \(J_1\) has been implemented in the buried layer process and its noise behaviour investigated. The spectral density of its noise voltage is compared in figure 3 with that of a discrete device of equal \(W\) and \(L\) values. The two measurements were performed in conditions of equal transconductance values.

![Figure 3. Spectral density of noise voltage as a function of frequency for two devices working at the same \(g_m\) value, 7.5 mA/V: a) JFET part of a monolithic, buried layer circuit, with \(W = 1800 \mu\text{m}, L = 5 \mu\text{m}\) (\(I_D = 2.6 \text{ mA}\); b) discrete JFET of equal values of \(W\) and \(L\) (\(I_D = 1.5 \text{ mA}\)).](image)
Its channel may therefore be affected by point-like defects in a different way from the discrete device which operates at a smaller current.

From figure 3 it can be concluded that the JFET with $W = 1800 \mu m$, implemented on a buried-layer chip has retained the good noise behaviour of its discrete companion.

4. CONCLUSIONS

The buried-layer NJFET process has opened-up the possibility of realising monolithic charge-sensitive preamplifiers with a noise behaviour which closely tracks that of discrete JFET circuits. After being adopted in preamplifiers with a large input JFET to suit calorimetry applications, the buried layer process is now being extended to applications requiring considerably smaller input elements, as needed in the field of radiation spectrometry.

ACKNOWLEDGEMENTS

The contribution of G. Guerra in characterising the noise behaviour of discrete and monolithic NJFETs is acknowledged.

REFERENCES