Bipolar feedback transistor integrated on detector with JFET for continuous reset

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Abstract

A monolithic system with a silicon detector, front-end electronics and a BJT reset device to be operated in a charge amplifier and in continuous resetting mode is presented.

1. Introduction

Among the structures that can be integrated on detectors to provide DC feedback in charge preamplifiers and contemporarily to remove the signal charge, we present a solution based on the use of a BJT embedded in the input JFET transistor. This solution aims to conjugate the exceptional performance in term of resolution obtained by integrating the front-end electronics on the detector chip [1] with the stability in the charge-to-voltage conversion of a charge amplifier [2]. This merging of the two concepts is only now feasible after few years of experience on integration of more simpler, although performing, signal amplification structures [3,4].

In order to maintain the advantages of integrated electronics (minimum input capacitance and matching between detector and input transistor), all the necessary elements connected to the detector anode have to be integrated on the detector chip, that is the input JFET, the feedback capacitance and the reset device. Although the BJT reset has been already proposed in a past discrete solution and operated in pulsed resetting mode [5], it is the first time that an integrated structure intended to operate in continuous mode is described. A test chip has been produced with this structure integrated in the center of a circular detector.

2. Working principles and design description

The working principle of the BJT reset is schematically shown in Fig. 1. The bipolar transistor is

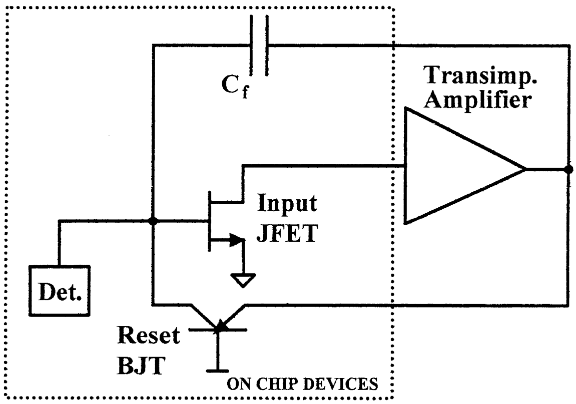

Fig. 1. Schematic representation of the charge amplifier showing the elements integrated on the detector chip: the input nJFET, the feedback capacitor and the reset BJT.

placed in the feedback loop of the charge amplifier in parallel to C_f, with the emitter connected to the output of the amplifier, the base to a convenient fixed potential and the collector to the detector anode. In the detail of our implementation, we exploit the advantages of the integration by embedding the reset BJT in the input nJFET, as shown in Fig. 2a. The gate of the input JFET acts as BJT collector, the BJT base is the channel of the JFET and the BJT emitter is an electrode next to the source, obtained by the same shallow p^+ implantation of the gate. These choices reduce the number of connections to the detector anode and therefore minimise the input capacitance of the circuit. A top view of the anode region is shown in Fig. 2b. The connection between the gate and the anode is provided by a metal layer. The feedback capacitance is obtained by a metal pad on top of the anode, separated by a thin oxide layer. Its value is about 50 fF.

Figs. 3a and b evidence that both nJFET and BJT operate independently and correctly although embedded in a single structure. Fig. 3a reports the characteristic curves of the nJFET as obtained experimentally when the leakage current is held to zero. The nJFET transistor shows a pinch off voltage $V_p \cong -2.2$ V, a saturation current $I_{DSS} \cong 300\ \mu A$ and a transconductance at the working point $g_m \cong 260\ \mu A/V$. To obtain the characteristic curves of the reset BJT, the BJT emitter has been held at ground while a current has been injected into the BJT base through the JFET source contacts in steps of 10 nA. The Drain of the JFET was held at 3 V during this measurement.

Concerning the dynamic of the reset mechanism, a positive rise of the output of the preamplifier, due to electrons collected to the anode, forces positive the emitter of the BJT that injects holes ($I_{emitter}$) into the base (JFET channel) where they diffuse towards two collecting electrodes: the JFET gate and the isolation guard (Fig. 4a). The holes collected by the JFET gate (I_{gate}) are the ones of interest for the reset and they are forced by the feedback loop to equal the electrons collected from the detector. The holes collected by the isolation guard are driven toward the contact at fixed potential, and do not contribute to the reset. The ratio $I_{gate}/I_{emitter}$ defines the transport factor α of the reset BJT. Fig. 4b shows $I_{emitter}$ and I_{gate} as a function of the emitter voltage when the nJFET is correctly biased in its operating condition. The ratio at the current level of interest (about $I_{gate} = 10$ pA) gives $\alpha \cong 1/1000$. The lateral reset BJT seems not to be disturbed nor by the much larger current toward the isolation guard nor by the JFET action, and vice versa.

3. Signal output

Due to the exponential relationship between collector current and base–emitter voltage of the reset device, the δ-response of the charge amplifier depends on the signal amplitude, Q/C_f, and on the leakage current, I_{leak}, as

$$V_{out}(t) = V_T \ln\left[\frac{1}{1-(1-e^{-(Q/C_f)/V_T})\, e^{-t/(C_f V_T/I_{leak})}}\right]. \qquad (1)$$

For small output steps ($Q/C_f \ll V_T = 25$ mV) the output pulse is

$$V_{out}(t) \cong \frac{Q}{C_f}\, e^{-t/(C_f V_T/I_{leak})} \qquad (2)$$

as shown in curve (a) of Fig. 5. In this case the reset BJT behaves as an almost fixed resistor of value

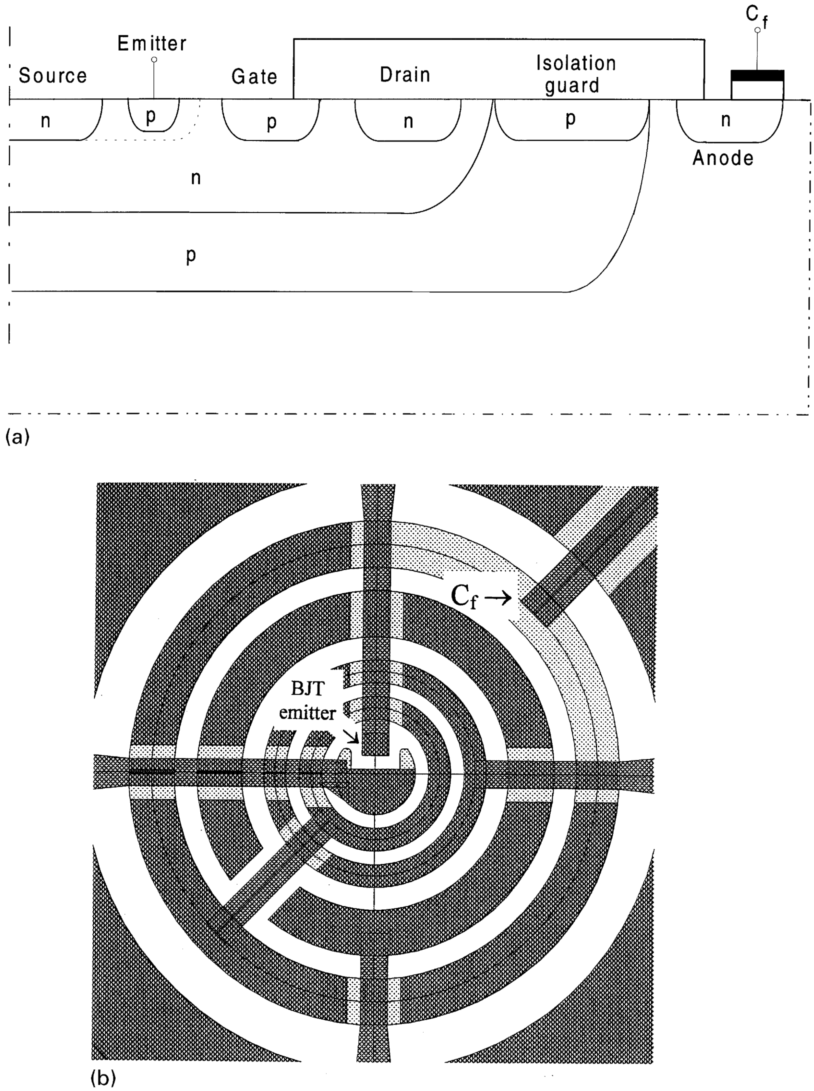

Fig. 2. (a) Schematic cross section of the on-chip electronics. (b) Top view of the anode region and on-chip electronics of the circular drift detector. The four rings are, from the outer to the inner, the anode, the isolation guard, the drain and the gate. In the center the source and the small BJT emitter are visible. The diameter of the outer ring (anode) is 110 μm. Energy and doses of the implants are the same as reported in Ref. [1].

$R = V_T/I_{leak}$ in parallel to C_f, and the discharge is almost exponential. For large output steps, instead, the output response (1) departs from an exponential as shown in curve (b) of Fig. 5. In particular, due to relationship (1), the resetting current is larger and the return to zero of the decay is faster compared to the situation with a fixed resistor, for which the relationship is linear. Note that in a silicon detector few hundreds micrometer thick the situation of Fig. 5a holds. The leakage and amplitude dependent tails can be compensated in a following stage by re-using a copy of the current injected into the emitter of the reset mechanism or by adding an external high value resistor connected in series

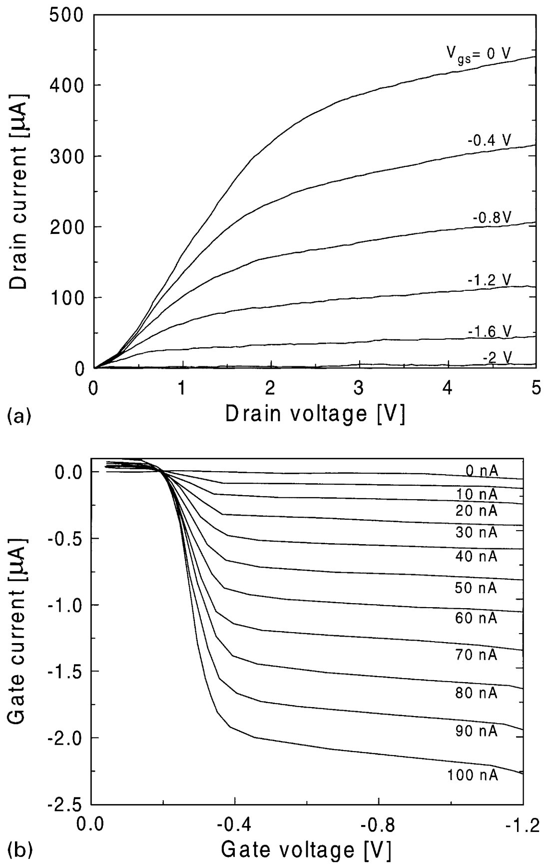

Fig. 3. (a) Characteristic curves of the nJFET with the BJT emitter grounded. (b) Characteristic curves of the reset BJT. In (b) the voltage applied to the gate of the JFET represents the potential difference between the collector and the emitter of the BJT. While tracing the BJT curves, the nJFET was operated with $V_D = +3$ V.

between the output of the preamplifier and the emitter of the BJT.

The BJT, through the emitter–base voltage, also stabilises the output DC voltage to a value few hundreds of millivolts above ground level.

4. Noise considerations

The reset BJT adds the full shot noise of its collector current to the shot noise of the detector leakage current. This factor of two in the parallel noise with respect to an ideal noiseless reset (never

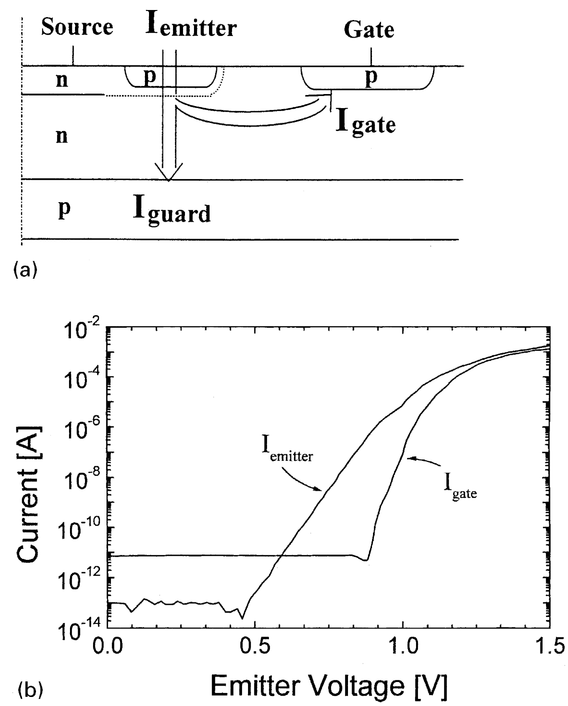

Fig. 4. (a) Enlarged cross section of the BJT region, showing the resetting currents. (b) Experimental behaviour of $I_{emitter}$ and I_{gate} as a function of the emitter voltage ($V_S = 0$ V, $V_G = -0.5$ V, $V_{DS} = 3$ V, $I_D \cong 0.4$ mA).

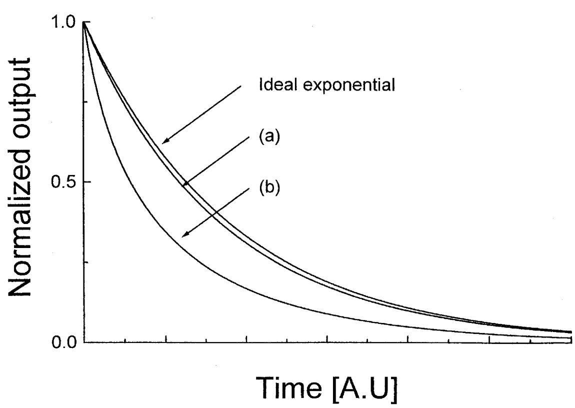

Fig. 5. δ-response of the charge amplifier with $C_f = 60$ fF and a BJT in the feedback loop. The figure compares the response – curve (a) – to a small signal ($Q/C_f = 0.2V_T$, equivalent to the signal from an ^{55}Fe source) and the response – curve (b) – to a large signal ($Q/C_f = 2V_T$, equivalent to the signal from a 60 keV line) with the ideal exponential decay having $R = V_T/I_{leak}$.

achieved in practice except than with pulsed reset systems) affects the resolution less and less as the leakage current decreases and the shaping time is reduced. Moreover, the best detectors have their performance limited by the $1/f$ series noise of the input JFET and therefore the added time-invariant parallel noise contribution is negligible. Note that the adaptive reset performed by the BJT always produces the lowest possible noise for the actual I_{leak}.

An additional noise contribution rises when large output steps occur (situation of Fig. 5b), namely the time variant noise due to the variation along the pulse of the equivalent resistance $1/g_m$ of the reset device. This noise is related to the Poisson fluctuations of the reset charge that has effectively been injected to the input node during the measuring time of the pulse. This noise contribution is therefore very small when the time discharge of the preamplifier is long with respect to the shaping time of the pulse, as it is often the case in this type of detectors (for example, with $I_{leak} = 10$ pA, $1/g_m = 2.5$ GΩ, giving a time discharge of the preamplifier of the order of few hundreds of μs, to be compared with 1 μs of the best shaping times). For the reasons mentioned before, this time-variant noise contribution is negligible in X-ray spectroscopy with silicon detectors.

5. Conclusions

The paper has discussed an integrated solution to operate a silicon drift detector with a charge preamplifier that uses a bipolar transistor in the feedback loop for charge reset. The proposed compact solution minimizes anode and FET capacitances to compete in resolution with the available integrated source–follower solutions and to gain in DC stabilisation. The first experimental DC measurements on test structures have evidenced that both the nJFET and the BJT, although embedded in a single structure, operate independently and correctly. A custom preamplifier, that matches the integrated devices, is under realisation to perform first spectroscopic measurements.

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