

A Low-Cost Pre-Amplifier for Low-Current Measurement with Temperature Compensation

Antonio C. C. Telles, Jair L. Emeri, Jr., Saulo Finco, and L. E. Seixas

Hardware Systems Design Research Group, Renato Archer Center for Information Technology, Campinas (SP), Brazil
E-mail: antonio.telles@cti.gov.br

Abstract— The electrical characterization of semiconductors devices, when submitted to ionizing radiation should be done in a large range of currents; however, the instrumentation with this ability is very expensive. This work proposes a low-cost circuit using commercial off-the-shelf components that enables the measurement of electrical currents in the order of pA range. The circuit presents an output current that is an amplified version of the current to be measured, using the exponential relationship between currents and voltages in Bipolar Junction Transistors (BJTs) and Metal Oxide Silicon Field Effect Transistors (MOSFETs) when operating in the weak inversion region. Furthermore, a block was introduced in order to compensate the gain's temperature dependence. The results showed that the operating range for the current to be measured was more than seven decades when using BJTs and five decades when using MOSFETs with high linearity. The circuit version using MOSFETs was able to measure currents as low as 100 fA. The current gain has also good linearity for over five decades. This circuit has a stable behavior for the range of 20 °C to 40 °C, because of the temperature compensation block.

Index Terms—log converters, weak inversion region, low currents measurement.

I. INTRODUCTION

CITAR (acronym in Portuguese for Radiation Tolerant Integrated Circuits) is a project involving many Brazilian research institutions and universities in the studies of ionizing radiation effects on semiconductors and the integrated circuits design by using the Radiation Hardness by Design (RHBD) approach. Among the results of CITAR, many devices with some new layout styles, e.g., the OCTO Metal Oxide Silicon Field Effect Transistors (MOSFETs) and Diamond MOSFETs were proposed and proved to be more tolerant to ionizing radiation than their conventional counterparts [1], [2].

The I-V characterization of such devices after being submitted to ionizing radiation is made measuring the drain-source current (I_{DS}) as a function of the gate-source voltage (V_{GS}). The current that will be measured varies by several orders of magnitude, since the device should be characterized even in subthreshold region, where the current is limited to the diffusion of charges in the channel. To measure the electrical DC parameters for semiconductor devices in their subthreshold region, precision SMUs (Source and Measurement Units) are required, because the electrical currents are smaller than 1 nA. However, this kind of instrument is very expensive.

A cheap alternative would be a transimpedance amplifier

(TIA). This kind of circuit, however, suffers with the drift of the output due to variations in offset and bias currents with the temperature. Also, they are not able to read in a broad range, needing a switching system if this feature is desired. Additionally, extremely high resistances are used if one wants to read very small currents.

A previous work [3] introduces a low-cost circuit, which aims to extend the current limit down to pA range, thus solving the limitation in the instrumentation used in CITAR Project. The circuit is a current amplifier and is based on the exponential relationships between currents and voltages of MOSFETs in weak inversion region and Bipolar Junction Transistors (BJTs). One of the conclusions of that study is that the voltage that controls the current gain should be a function of the temperature, in order to improve the stability of this gain, since a variation of 1 K causes a deviation of 7 % in this parameter.

In this work is presented a version using commercial off-the-shelf components of the current amplifier from [3]. The circuit is analyzed using MOSFETs and BJTs. A temperature compensation block is also introduced for the case of the circuit with BJTs. It is based on the thermal behavior of a diode-connected BJT. Section II presents the main circuit and explains the working principles for MOSFETs and BJTs. Section III presents the simulation results of the main circuit in various conditions. The complete circuit with temperature compensation is presented and analyzed in Section IV. This Section also brings the results from simulation in temperature. In Section V, the conclusions and future works are discussed.

II. THEORY OF OPERATION

The measurement method is based on the principle of log converters [4], [5]. A circuit for measuring currents higher than 10 nA using this principle is presented in [6]. Another log converter was able to measure eight decades of a photodetector current [7].

The basic electrical circuit is a modification of the log converter and is illustrated in Fig. 1. M_0 and M_1 operate in the weak inversion region and in this case, their diffusion currents are given respectively by [8]

$$I_{DS0} = I_0 \cdot \exp[V_{GS0}/(nV_T)] \{1 - \exp[-V_{DS}/(nV_T)]\} \quad (1)$$

and

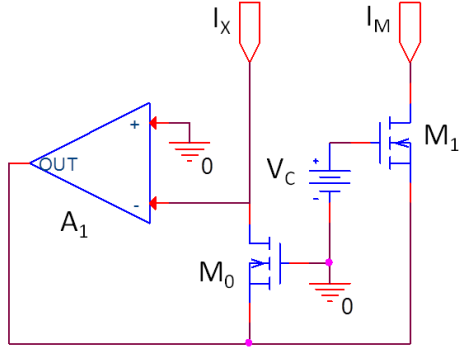


Fig. 1. Electrical diagram of the low-current measurement circuit.

$$I_{DSI} = I_0 \cdot \exp[V_{GS0}/(nV_T)] \{1 - \exp[-V_{DS}/(nV_T)]\}, \quad (2)$$

where V_T is the thermodynamic voltage, V_{GS0} and V_{GS1} are the gate-source voltages of M_0 and M_1 respectively, I_0 and n are related to geometry and technological parameters of the transistors [9] and V_{DS} is the drain-source voltage.

If V_{DS} is greater than $3nV_T$ (about 110 mV at room temperature), the last exponential term in (1) and (2) introduces an error of less than 5 %.

The op-amp adjusts V_{GS0} through feedback in order $I_{DS0} = I_X$ (the unknown current). V_{GS1} is given by

$$V_{GS1} = V_{GS0} + V_C. \quad (3)$$

Using (1), (2) and (3) and neglecting the exponential terms involving V_{DS} , one can prove that I_{DS1} is given by

$$I_{DS1} = I_M = I_X \cdot \exp[V_C/(nV_T)]. \quad (4)$$

Then the current to be read I_M is an amplified version of the unknown current. The relation between voltage and current is exponential, thus a small control voltage (V_C) can represent a great amplification factor.

A similar reasoning is made when M_0 and M_1 are replaced by BJTs. In this case the collector current I_C is given by the following approximate equation when V_{BE} (the base-emitter voltage) is higher than 80 mV at room temperature, with an error of less than 5 %:

$$I_C = I_S \cdot \exp(V_{BE}/V_T), \quad (5)$$

where I_S is the reverse saturation current of the transistor [9]. Due to the similarity between (1) or (2) and (5), it is evident that (4) applies for the circuit with BJTs, in this case with n equal to 1.

III. THE MAIN CIRCUIT

The main circuit uses the LMC6001, an op-amp with ultra-low bias current (25 fA maximum) [10]. The circuit was simulated using two MOSFETs and two BJTs from CD4007 and HFA3046 arrays, respectively [11], [12]. The simulation was done with Cadence OrCAD Capture at room temperature. A current source simulates I_X and a 600 mV

voltage source supplies I_M , in order that V_{DG} or V_{CB} of M_1 not become reverse biased.

I_M as a function of I_X for various gains is shown on Figs. 2 and 3, with the circuit using BJTs and MOSFETs respectively. That with MOSFETs is linear starting at 100 fA and with BJTs at 1 pA. Circuit with MOSFETs presents distortion for high values of output current, probably due to the entrance of M_1 at moderate inversion, where the equations are not valid anymore. Figs. 4 and 5 present I_M as a function of V_C for various values of I_X , using BJTs and MOSFETs respectively. Again, the circuit with MOSFETs has better performance starting from a lower current but for a smaller range. Analysis of the results shows that the operating range (minimum input current to maximum output current) for the circuit with MOSFETs is five decades starting at 100 fA and that with BJTs is seven decades starting at 1 pA. Table I presents the maximum errors for various gains and the input current they occur.

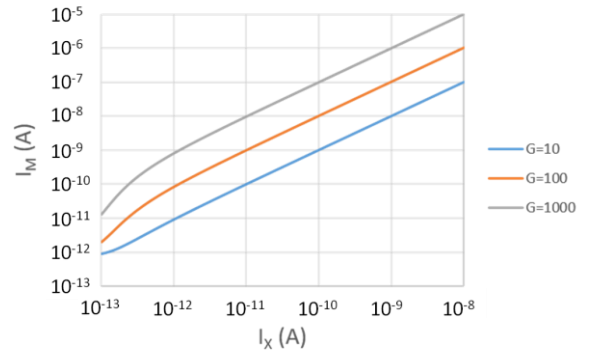


Fig. 2. I_M as a function of I_X for various gains (circuit with BJTs).

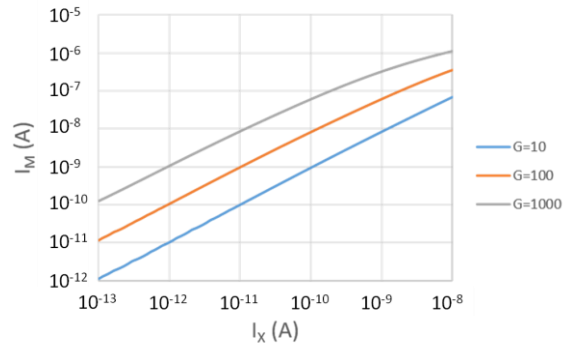


Fig. 3. I_M as a function of I_X for various gains (circuit with MOSFETs).

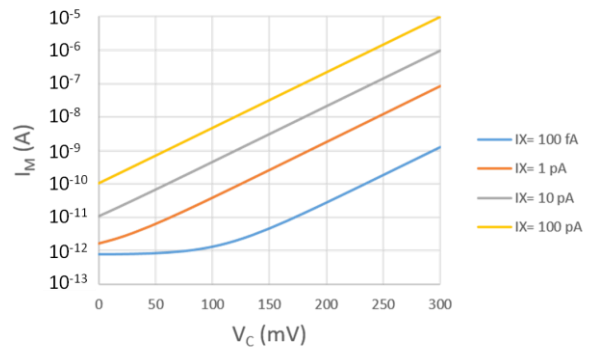


Fig. 4. I_M as a function of V_C for various currents (circuit with BJTs).

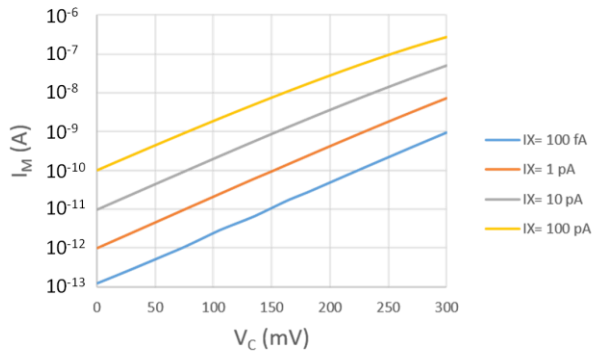


Fig. 5. I_M as a function of V_C for various currents (circuit with MOSFETs).

Table I. Maximum gain errors of the circuit.

Gain	Circuit with MOSFETs	Circuit with BJTs
10	-1.493 dB @ 10 nA	-0.433 dB @ 1 pA
100	-4.413 dB @ 10 nA	-0.809 dB @ 1 pA
1000	-9.469 dB @ 10 nA	-0.841 dB @ 1 pA

Obs.: the minimum current range of the circuit with BJTs is 1 pA

IV. THE CIRCUIT WITH TEMPERATURE COMPENSATION

The complete circuit with temperature compensation is illustrated at Fig. 6.

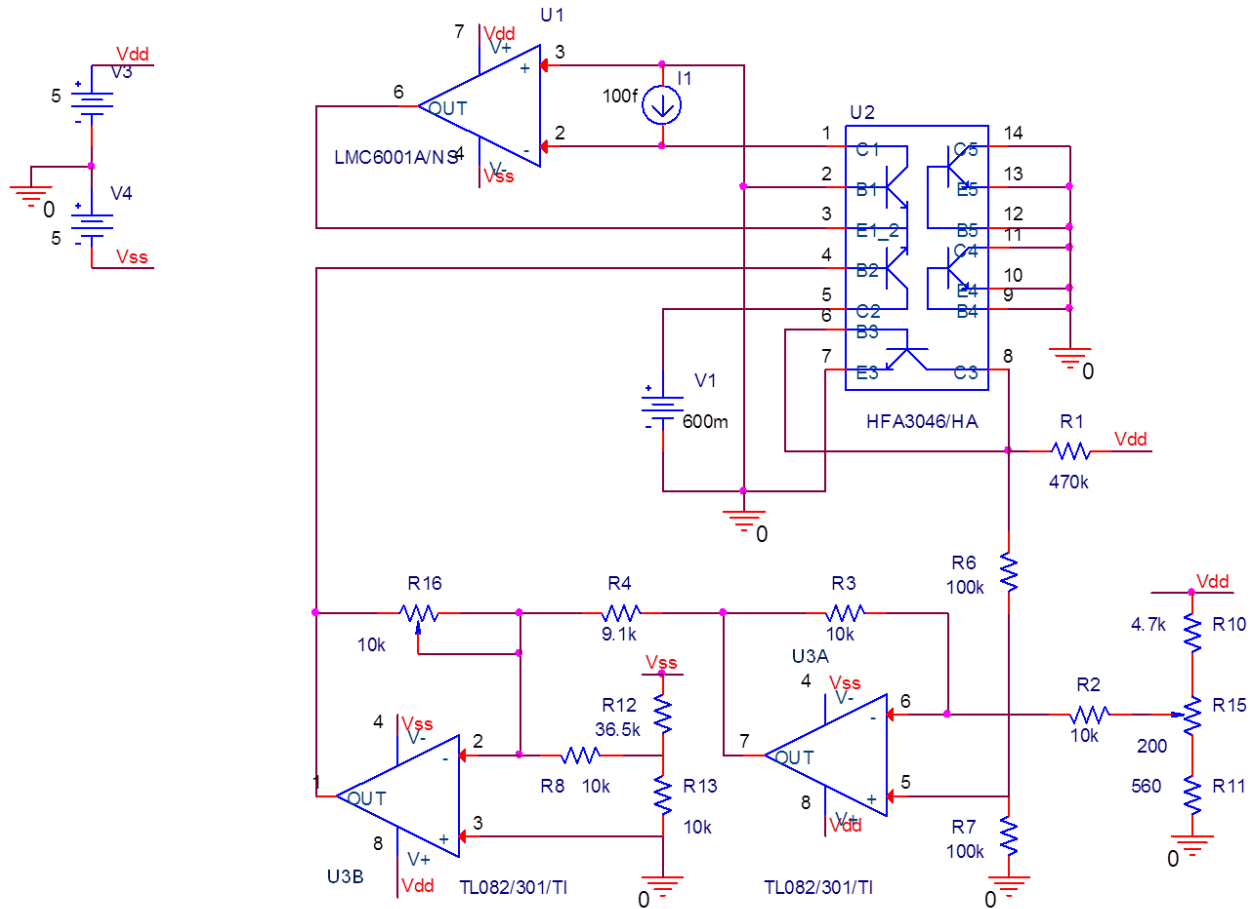


Fig. 6. Electrical diagram of the current amplifier with temperature compensation.

Q1 and Q2 (the devices with terminals E1, B1, C1 and E2, B2, C2 respectively) from HFA3046 are the transistors of the current amplifier.

The junction voltage of diode-connected Q3 (the device with terminals E3, B3, C3) has a temperature ratio of about -2 mV/K, with a slight dependence of the junction current [13]. U3A is configured to subtract a fraction of V_{DD} from V_{BE} of Q3.

R15 is adjusted in order the output voltage of U3A be nulled at room temperature. With this adjustment, the variation of the voltage at this node is only related to the temperature variation with the same ratio of the junction voltage of Q3. This temperature variable voltage is summed with -600 mV derived from the power supply.

U3B works as inverting adder and its output has thus a voltage proportional to 600 mV+2mV/K. The value of R4 was slightly modified using simulations in order to obtain the desired temperature ratio.

The output voltage of U3B is adjusted by R16, which generates the control voltage of the current amplifier. The temperature variation of this node compensates that due to V_T in (4), adapted for BJTs. U3A and U3B are two op-amps from TL082, but can be any dual op-amp IC, preferably with low temperature drift in the offset voltage.

The circuit was simulated at a temperature range of 20 °C to 40 °C, since it should be applied in lab environment. Fig. 7 shows I_X at various temperatures as a function of I_M for a gain of 1000, which one can observe a significant dispersion. Fig. 8 is the same as the previous one, with the application of the temperature compensation. Curves are now superposed, proving that the compensation was effective.

Fig. 9 shows I_X as for various gains and I_M of 1 pA, as a function of the temperature. Curves are quite flat, and maximum deviation of the ideal value was 0.9 dB at the gain of 100. Deviations should be explained by the thermal behavior of the bias input current of U1 and by second order effects of the BJTs, when submitted to small currents. This can be verified in Fig. 10, which shows I_M for various values of I_X and gain of 100, as a function of the temperature. One can observe that the curves become flatter when the input current is increased.

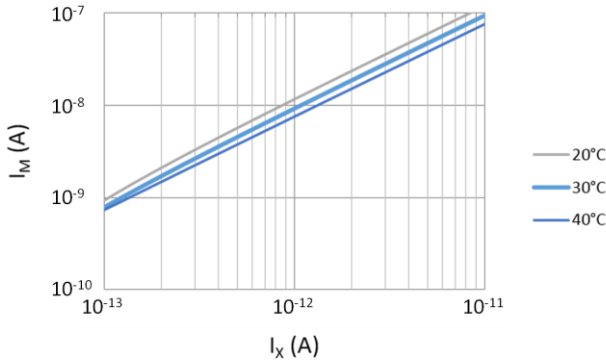


Fig. 7. I_M as a function of I_X for various temperatures (gain of 1000).

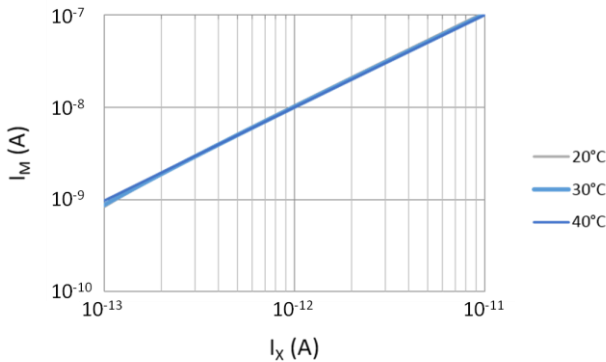


Fig. 8. Same as Fig. 7 using the temperature compensation block.

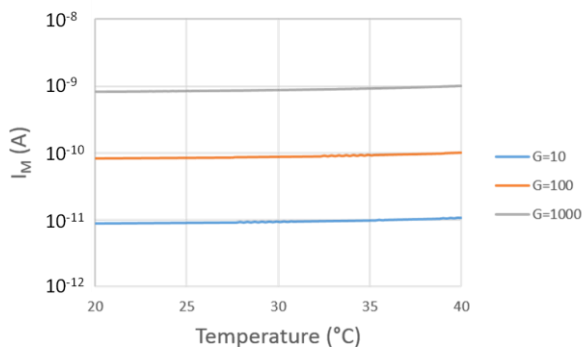


Fig. 9. I_M as a function of temperature for various gains ($I_X = 1$ pA).

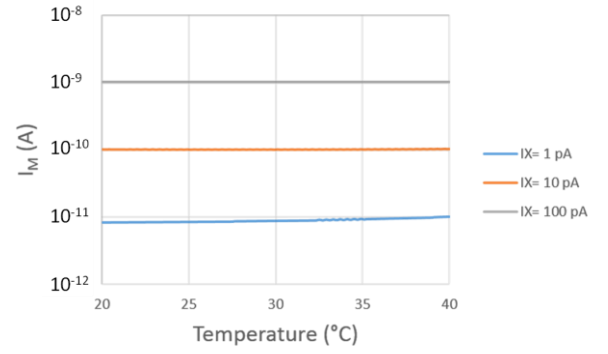


Fig. 10. I_M as a function of the temperature for various values of I_X (gain of 100).

V. CONCLUSIONS AND FUTURE WORKS

A very low-cost current amplifier using commercial off-the shelf components was proposed and evaluated through simulations. The circuit presents, in the best case with BJTs, the operating range of seven decades. The range using MOSFETs is five decades, although with a lower current limit. The relation between the output current and the control voltage also shows very good linearity for five decades. The current amplifier enables that SMUs like PXI-4132 (National Instruments) from CITAR participants be used to measure currents down to 1 pA.

When compared with TIAs, the circuit provides a very broad and continuous range of amplification, using conventional components even when reading currents at the range of pA.

The circuit presented good stability in temperature due to the compensation block, reducing this way the variation of the gain. A future work should be the design of a temperature compensation circuit by using MOSFETs biased at weak inversion region.

Despite the promising simulated results, the real leakage currents are quite difficult to predict by simulation and depend on constructive aspects.

Thus, the validation of the concept only will be possible with the construction of a prototype to evaluate the effects of leakage currents in the performance of the circuit.

If the test board presents good results, an integrated circuit using MOSFETs and BJTs is intended to be designed in XT06 technology from X-FAB (0.6 μ m SOI CMOS).

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REFERENCES

- [1] L. E. Seixas, O. L. González, R. G. Vaz, A. C. C. Telles, S. Finco, and S. P. Gimenez, "Minimizing the TID effects due to gamma rays by using diamond layout for MOSFETs". *Journal of Materials Science - Materials in Electronics*, v. 35, p. 4339 - 4351, 2019.

- [2] L. Fino, D. Flandre, and S. P. Gimenez, "Boosting the total ionizing dose tolerance of digital switches by using OCTO SOI MOSFET". *IOP - Semiconductor Science Technology*, v. 30, 105024 (12 pp), 2015.
- [3] A. C. C. Telles, J. L. Emeri, Jr., S. Finco, and L. E. Seixas, "A low-cost pre-amplifier for current measurement in sub-nA range". *Proceedings of XIII Workshop on Semiconductors and Micro & Nano Technologies – SEMINATEC 2018*, Sao Bernardo dos Campos (SP), Brazil, April 2018.
- [4] "Application Note 30: Log converters", *Linear Application Handbook*, pp. 66-69, National Semiconductors, 1994.
- [5] "Application Note 311: Theory and applications of log converters", *Linear Application Handbook*, pp. 797-801, National Semiconductors, 1994.
- [6] T. Reagan, J. Munson, G. Zimmer, and M. Stokowski (orgs.), "Six decade (10nA to 10mA) current log amplifier", *Application Note 105*, p. AN105-64, Linear Technology, December 2005.
- [7] R. J. Widlar, R. A. Pease, and M. Yamatake, "Application Note 242: Applying a new precision op amp", *Linear Application Handbook*, pp. 501-516, National Semiconductors, 1994.
- [8] Y. Tsividis and C. Mc Andrew, *Operation and Modeling of the MOS Transistor*, 3rd ed., Oxford University Press, 2010.
- [9] P. R. Gray, P. J. Hurst, S. H. Lewis, and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits*, 5th. ed., Wiley, 2009.
- [10] Datasheet of LMC6001. Available at: <https://www.ti.com>.
- [11] Datasheet of CD4007. Available at: <https://www.ti.com>.
- [12] Datasheet of HFA3046. Available at: <https://www.renesas.com>.
- [13] J. Fraden, *Handbook of Modern Sensors: Physics, Design and Applications*, 3rd ed., Springer, 2004.