16th IMEKO TC4 Symposium
Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements
Sept. 22-24, 2008, Florence, Italy

Low-cost current-to-voltage converter for DC measurements in a wide dynamic range

Pavel Protiva

Czech Technical University in Prague, Faculty of Electrical Engineering
Technická 2, 166 27 Prague 6, Czech Republic, e-mail: protip1@fel.cvut.cz

Abstract- A logarithmic current-to-voltage converter for measuring DC currents in a wide dynamic range (from 1 pA to 1 mA) is described here. The converter is based on an operational amplifier circuit with a standard commercially-available LED diode used as a nonlinear feedback. A temperature compensation method requiring only one reference amplifier was used. This significantly reduces the complexity and the resulting cost of the converter. The static transfer characteristics of the converter were measured and compared with the uncompensated case.

I. Introduction

Low DC current measurement is one of the most common tasks in research on the electrical properties of nanostructures. Current-to-voltage converters, usually based on operational amplifier circuits, are used for measuring low currents. In special cases, the measured current can change from the pA range to several hundreds of µA. It is not possible to measure this wide range of currents using a conventional fixed gain linear converter, whose dynamic range is limited to just four decades of current magnitude. Linear converters with range switching or logarithmic converters are used in such cases. Autoranging linear converters [1, 2] are based on switching the operational amplifier feedback resistance. The advantages of linear converters are their accuracy, given by feedback resistor tolerance, and their temperature stability. However, the very large value resistors (10 GΩ and more) that are required for measuring the lowest currents are expensive, noisy and unstable. Furthermore, the presence of switches contributes to leakage currents, which degrade the performance of the converter at low current ranges. This current-to-voltage converter is applied in investigating metal-oxide-metal (MIM) structures. The phenomena of electroforming [3] and negative differential resistance in the current voltage (I-V) characteristics of MIMs are not necessary reproducible processes. Abrupt changes caused by range switching may completely disable these experiments. Continuous measurement in a wide dynamic range without switching is enabled by the use of logarithmic converters. The output voltage of the logarithmic converter is compressed due to a nonlinear element with logarithmic I-V characteristics, which replaces the feedback resistance of the operational amplifier. Forward biased p-n junction diodes are normally used. The lower limit of the converter's dynamic range is defined by the reverse saturation current of the diode. Therefore, in order to measure currents in the pA range, it is required to select a nonlinear element with an extremely low reverse leakage current. Feedbacks with so-called ultralow-leakage diodes [4], p-n junctions of bipolar transistors or FETs [5], and LEDs made from wide bandgap semiconductors [6] have been described in the literature. These elements provide the widest range of input currents, but their I-V characteristics are considerably temperature dependent. Complex compensation circuits are used. Logarithmic converters with thermistor compensation [6, 7, 8] and a more sophisticated ratio technique [6, 9] have been reported. Four logarithmic amplifiers for one compensated converter are normally required. A converter utilizing only three amplifiers was presented in [9].

In this paper we describe a logarithmic converter suitable for measuring the I-V characteristics of MIM structures. The converter is capable of measuring DC currents from 1 pA to 1 mA. Standard commercially available LEDs are used in the feedback of an operational amplifier. A simplified temperature compensation method is proposed, which makes use of the known temperature dependence of the diode I-V characteristics.

II. Circuit principle and description

The circuit diagram of the converter is shown in Fig. 1. The converter includes a test and a reference channel, both containing an identical operational amplifier with a logarithmic feedback. LEDs, which provide excellent performance at very low currents [6], were used in the feedback.

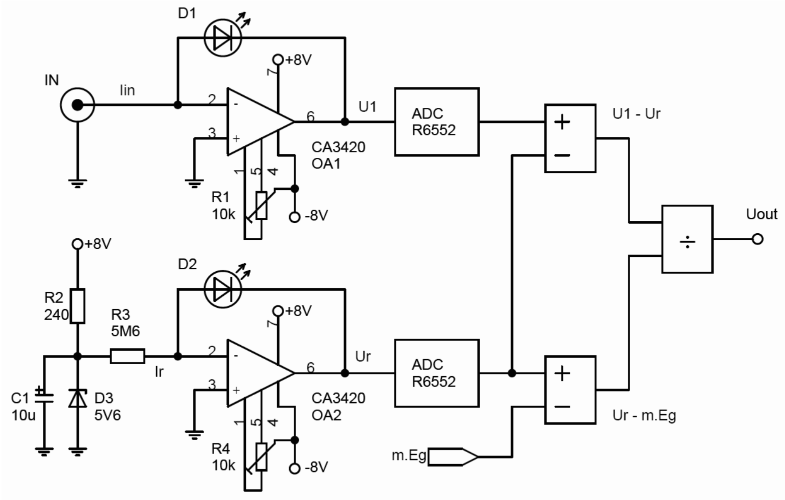

Figure 1. Circuit diagram of the logarithmic converter.

The output voltage of the operational amplifier OA1 is given by

$$U_1 = \frac{mnkT}{q} \ln \frac{I_{in}}{I_s}, \tag{1}$$

where m is the number of diodes connected in series, n is the diode ideality factor, k is Boltzmann's constant, q the electronic charge, I_{in} the measured input current, and I_s is the reverse saturation current. The temperature dependent saturation current I_s can be cancelled by subtracting the output voltage U_r of the reference channel, which is fed with constant reference current I_r:

$$U_1 - U_r = \frac{mnkT}{q} \left(\ln I_{in} - \ln I_r \right), \tag{2}$$

where all feedback diodes are considered to be identical and at the same temperature. The second temperature dependent term $mnkT/q$ may be removed by thermistor compensation or by a ratio technique, as described in the literature [6, 7, 8, 9]. We suggest a simplified method based on the known temperature dependence of the diode I-V characteristics.
A basic model of the reverse saturation current temperature dependence, frequently used in computer simulation programs (SPICE), is described by the equation

$$I_S = I_0 \left(\frac{T}{T_0} \right)^{\frac{X_{TI}}{n}} e^{\frac{qE_g}{nk}\left(\frac{1}{T_0} - \frac{1}{T} \right)}, \tag{3}$$

where I_0 is the saturation current measured at the reference temperature, T_0 is the reference temperature (300 K), X_{TI} is the saturation current temperature parameter (3 for p-n diodes), and E_g is the bandgap width. After taking into account the dominant temperature dependent exponential term only, I_s can be approximated as

$$I_s = K_1 e^{-\frac{qE_g}{nkT}} \tag{4}$$

where K_1 is a temperature independent constant. After substituting I_s into the equation for U_r, we get

$$U_r = \frac{mnkT}{q} \left(\ln I_r - \ln K_1 + \frac{qE_g}{nkT} \right) = \frac{mnkT}{q} K_2 + mE_g, \tag{5}$$

where K_2 is a constant that can be determined by calibration. Therefore, if we subtract a constant value of $m \cdot E_g$ from the reference voltage U_r, we get an expression which helps us to cancel the $mnkT/q$ term in eq. (2). The compensated output voltage is

$$U_{out} = \frac{U_1 - U_r}{U_r - mE_g}. \tag{6}$$

Then the resulting measured input current of OA1 is given as

$$\log I = \frac{K_2 U_{out} + \ln I_r}{\ln 10}. \qquad (7)$$

Both for the test channel and for the reference channel, we selected low input current BiMOS operational amplifiers CA3420 (Intersil). As the feedback diodes, we chose commercially available InGaN blue LEDs in the SMD package, whose bandgap E_g is reported to lie in the region 2.4–4.5 eV [10]. The exact value was experimentally obtained by fitting output voltages U_{out} for several temperatures. LED diodes were selected randomly and two were always connected in series to increase the signal to noise ratio. The reference current (approx. 1 µA) is derived from a voltage stabilizer, based on a temperature compensated Zener diode. The outputs of the test and reference channels were measured by digital multimeters (Advantest R6552) with an RS-232 interface. The resulting input current was computed according to eq. (6) and (7) in Matlab software.

III. Results and discussion

Uncompensated output voltage U_1 against the input current I_{in} at four different temperatures is shown in Fig. 2. The measured characteristics differ from the ideal shape given by eq. (1). This is due to the influence of the generation-recombination current at low bias and the parasitic serial resistance of the diode, which must be taken into consideration at higher currents.

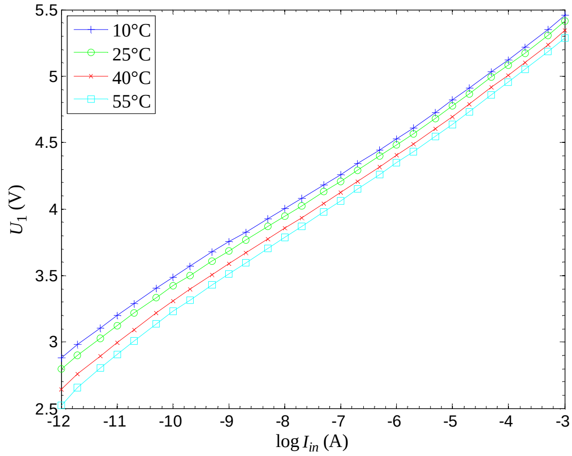

Figure 2. Uncompensated output voltage U_1 at four different temperatures.

Fig. 3 shows the computed output voltage U_{out} of the converter at four different temperatures. It is seen that U_{out} is now well temperature compensated with the exception of small deviations in the high current range, where the resistance of the diode begins to dominate. The value of E_g equal to 3.1 provides the best compensation.

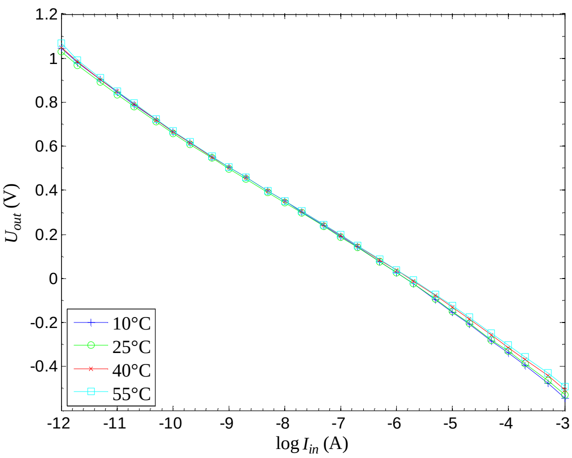

Figure 3. Compensated output voltage U_{out} of the converter at four different temperatures.

These results were compared to the results obtained using Keithley 487 and Keithley 617 picoammeters. The computed input current showed a maximal error of 6 %, where the error in the middle and low current ranges did not exceed 3 %. One possible source of error is the temperature dependence of E_g, which was not taken into consideration. However, in the temperature range of interest this dependence may be neglected [11].

IV. Conclusion

We have designed a logarithmic current-to-voltage converter capable of measuring DC currents from 1 pA to 1 mA (9 decades). A simplified temperature compensation method has been presented, which makes use of the known temperature dependence of the diode I-V characteristics. Compared to the thermistor compensation or ratio technique, our method provides similar results but requires fewer components. Only two logarithmic amplifiers, one in the test channel and one in the reference channel, are used. The converter was calibrated using Keithley 487 and 617 picoammeters and it has shown a maximal error of 6 % in a wide dynamic and temperature range. The converter has now been included in our automatic system for measuring the I-V characteristics of MIM structures.

Acknowledgment

This work was partially supported by the Grant Agency of the Czech Republic under project 102/08/H018. The components for constructing the converter were also funded by the Grant Agency of the Czech Republic under project 102/06/1106.

References

[1] Shaw, S.; Chang, R., ”A novel wide range electrometer with quasilinear output”, *Review of Scientific Instruments*, vol. 68, no. 10, pp. 3917-19, 1997.
[2] Acharya, Y., ”A wide range linear electrometer”, *Review of Scientific Instruments*, vol. 71, no. 6, pp. 2585-8, 2000.
[3] Dearnaley, G.; Stoneham, A. M.; Morgan, D. V., ”Electrical phenomena in amorphous oxide films”, *Reports on Progress in Physics*, vol. 33, no. 11, pp. 1129-91, 1970
[4] Durig, U.; Novotny, L.; Michel, B.; Stalder, A., ”Logarithmic current-to-voltage converter for local probe microscopy”, *Rev. Sci. Instrum.*, vol. 68, no. 10, pp. 3814-16, 1997.
[5] Mészáros, G.; Li, C.; Pobelov, I.; Wandlowski, T., ”Current measurements in a wide dynamic range – applications in electrochemical nanotechnology”, *Nanotechnology*, vol. 18, no. 42, 424004 (8pp), 2007.
[6] Acharya, Y.; Aggarwal, A., ”Logarithmic current electrometer using light emitting diodes”, *Measurement Science & Technology*, vol. 7, no. 2, pp. 151-6, 1996.
[7] Acharya, Y. B.; Tikekar, S. G., ”Low-current temperature compensated bipolar log-ratio amplifier”, *Review of Scientific Instruments*, vol. 64, no. 6, pp. 1652-4, 1993.
[8] Acharya, Y. B., ”Logarithmic current electrometer using commercially available current conveyor AD844”, *International Journal of Electronics*, vol. 93, no. 4, pp. 223-9, 2006.
[9] Acharya, Y.; Vyavahare, P., ”A low-current logarithmic LED electrometer”, *IEEE Transactions on Instrumentation and Measurement*, vol. 49, no. 1, pp. 5-9, 2000.
[10] Vurgaftman, I.; Meyer, J.; Ram-Mohan, L., ”Band parameters for III-V compound semiconductors and their alloys”, *Journal of Applied Physics*, vol. 89, no. 11, pp. 5815-75,2001.
[11] Steiner, T., *Semiconductor Nanostructures for Optoelectronic Applications*, Artech House Inc., 2004.