Ultrasensitive method for current noise measurements

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In this article we propose a method for current noise measurements which allows, at least in principle, the complete elimination of the noise introduced by the measurement amplifiers. We present a detailed circuit analysis which illustrates the advantages of the proposed measurement procedure with respect to the conventional techniques. The validity of this measurement method is confirmed by the results obtained by means of SPICE simulations and by measurements performed on a prototype circuit. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2149220]

I. INTRODUCTION

The study of the current fluctuations is one of the most sensitive and most general investigation method in the field of characterization of solid-state devices, since it supplies fundamental information regarding the understanding of charge transport mechanisms and the evaluation of the material defectiveness. A huge amount of experimental works has proven the validity of this investigation technique for the evaluation of the electronic device performance and reliability, especially for the particular case of complementary-metal-oxide-semiconductor (CMOS) devices.[1–12] The measurement of the flicker noise component associated with the drain and the gate current has been frequently used for the evaluation of the defect density at the semiconductor-dielectric interface and inside the dielectric layer.[1–8] The measurement of the shot-noise component associated with the gate current has been used for distinguishing between charge transport mechanisms due to pure tunneling (full shot noise) and charge transport mechanisms due to trap-assisted tunneling (suppressed shot noise).[10,11] The nanometric dimensions of the modern CMOS devices, characterized by channel length less than 100 nm, require the measurement of ultralow noise levels.

The problem of measuring ultralow noise levels can be addressed by means of two different approaches. The first approach consists of designing circuit topologies which minimize the power spectral densities of the equivalent input voltage and current noise of the preamplifiers.[13] The second approach consists of using measurement methods which take advantage of the uncorrelation between the noise due to the device under test and the noise introduced by the preamplifiers, in order to obtain a background noise of the entire measurement system significantly lower with respect to the noise due to the preamplifiers.[14–17] Recently, we have proposed a high sensitivity method for voltage noise measurements, which allows, at least in principle, the complete elimination of the noise introduced by the amplifiers used for the measurements.[18] In this work, starting from the same basic idea, we have developed and experimentally validated a high sensitivity method for current noise measurements, which allows, at least in principle, the complete elimination of the noise introduced by the measurement amplifiers.

The remainder of this work is organized as follows. Section II illustrates the cross-correlation method, which represents the most used high sensitive method for noise measurements, and its limitations. In Sec. III, we propose a method for current noise measurements which overcomes the limitations of the cross-correlation method. SPICE simulations and measurements validating the proposed model are presented in Sec. IV. In Sec. V we summarize our results.

II. THE CROSS-CORRELATION METHOD AND ITS LIMITATIONS

The cross-correlation method for noise measurements is based on the following idea: by amplifying the device under test (DUT) signal by means of two independent amplifiers and by evaluating the cross correlation of their outputs, one can completely suppress the effect of the noise sources of the two measurement amplifiers which result uncorrelated to one another.[1,14–16] It has been applied both for voltage and current noise measurements. A typical circuit configuration which allows to implement the cross-correlation method for the current noise measurements is reported in Fig. 1. In the virtual short circuit approximation, it can be easily proven that the two output voltages are given by

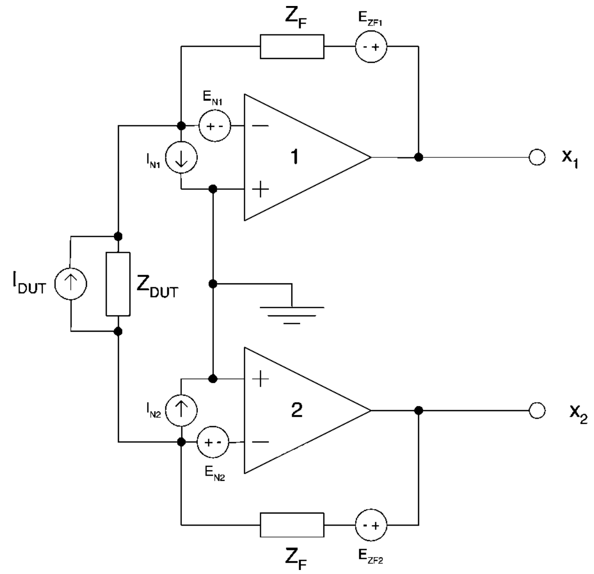

FIG. 1. Circuit configuration of the differential transimpedance amplifier for the measurement of the DUT current noise with the application of the cross-correlation technique.

$$X_1 = -I_{\mathrm{DUT}}Z_F + E_{ZF1} + I_{N1}Z_F + E_{N1}\left[1 + \frac{Z_F}{Z_{\mathrm{DUT}}}\right] - E_{N2}\frac{Z_F}{Z_{\mathrm{DUT}}},$$

$$X_2 = +I_{\mathrm{DUT}}Z_F + E_{ZF2} + I_{N2}Z_F + E_{N2}\left[1 + \frac{Z_F}{Z_{\mathrm{DUT}}}\right] - E_{N1}\frac{Z_F}{Z_{\mathrm{DUT}}}, \tag{1}$$

where I_{DUT} represents the DUT current noise we want to measure, E_{ZF1} and E_{ZF2} are the voltage noise source of the feedback bipole, E_{N1} and E_{N2} are the equivalent input voltage noise (EIVN) of the two amplifiers, and I_{N1} and I_{N2} are their equivalent input current noise (EICN). By following the approach reported in Ref. 16, the cross correlation between the two outputs can be obtained by evaluating the difference between the the power spectral density (PSD) of the signal X_1-X_2 and the PSD of the signal X_1+X_2 and by dividing the result by 4. Since the sum and the difference between the two outputs are given by

$$S = X_1 + X_2 = E_{ZF1} + E_{ZF2} + I_{N1}Z_F + I_{N2}Z_F + E_{N1} + E_{N2},$$

$$D = X_1 - X_2 = -2I_{\mathrm{DUT}}Z_F + E_{ZF1} - E_{ZF2} + I_{N1}Z_F - I_{N2}Z_F + E_{N1}\left[1 + 2\frac{Z_F}{Z_{\mathrm{DUT}}}\right] - E_{N2}\left[1 + 2\frac{Z_F}{Z_{\mathrm{DUT}}}\right], \tag{2}$$

under the hypothesis that E_{N1}, E_{N2}, I_{N1}, and I_{N2} are uncorrelated, their corresponding PSDs are

$$S_S = E_{ZF1}^2 + E_{ZF2}^2 + |I_{N1}Z_F|^2 + |I_{N2}Z_F|^2 + E_{N1}^2 + E_{N2}^2,$$

$$S_D = 4|I_{\mathrm{DUT}}Z_F|^2 + E_{ZF1}^2 + E_{ZF2}^2 + |I_{N1}Z_F|^2 + |I_{N2}Z_F|^2 + E_{N1}^2\left|1 + 2\frac{Z_F}{Z_{\mathrm{DUT}}}\right|^2 + E_{N2}^2\left|1 + 2\frac{Z_F}{Z_{\mathrm{DUT}}}\right|^2. \tag{3}$$

It follows that the cross correlation between the outputs of the two channels can be obtained as

$$S_{12} = \frac{S_D - S_S}{4} = S_{\mathrm{DUT}} + S_{E_{N1}} + S_{E_{N2}}, \tag{4}$$

where

$$S_{\mathrm{DUT}} = |I_{\mathrm{DUT}}Z_F|^2,$$

$$S_{E_{N1}} = E_{N1}^2K_{EN}^2, \tag{5}$$

$$S_{E_{N2}} = E_{N2}^2K_{EN}^2,$$

with

$$K_{EN}^2 = \frac{1}{4}\left(\left|1 + 2\frac{Z_F}{Z_{\mathrm{DUT}}}\right|^2 - 1\right). \tag{6}$$

Equation (4) suggests that through the cross-correlation method it is possible to completely eliminate the effects of I_{N1}, I_{N2}, and E_{ZF1}, E_{ZF2} of the measurement amplifiers, which give rise to contributions uncorrelated with the DUT signal, but not the effects of E_{N1} and E_{N2}, whose contributions are partially correlated with the DUT signal. It is worth noting that the noise contribution due to the EIVN of the measurement amplifiers can be quite relevant in the case of low impedance DUT, as it is the case of capacitive devices (e.g., MOS structures) at high frequencies. The inability of this method to eliminate the measurement amplifier noise contribution correlated with the DUT signal represents the main drawback of the cross-correlation method and sets the limit to the maximum sensitivity which can be obtained by applying this method. In the next section we will propose a noise measurement method that is able to overcome this limitation.

III. THE PROPOSED METHOD

The residual noise contributions $S_{E_{N1}}$, $S_{E_{N2}}$ can be eliminated by means of the circuit configuration reported in Fig. 2. The measurement procedure can be divided in three different steps. In the first step, we remove the amplifiers 3 and 4 from the circuit, and, with the switches S_1 and S_2 closed, we measure the cross-correlation spectrum between the outputs of the amplifiers 1 and 2. Since in this measurement condition we obtain the same circuit of Fig. 1, as suggested by Eq. (4), the cross correlation is

$$S_{1,2} = S_{\mathrm{DUT}} + S_{E_{N1}} + S_{E_{N2}}. \tag{7}$$

In the second step, we remove the amplifiers 1 and 2 from the circuit, we insert the amplifiers 3 and 4 in place of the amplifiers 1 and 2, and, with the switches S_1 and S_2 still closed, we measure the cross-correlation spectrum between the outputs of the amplifiers 3 and 4,

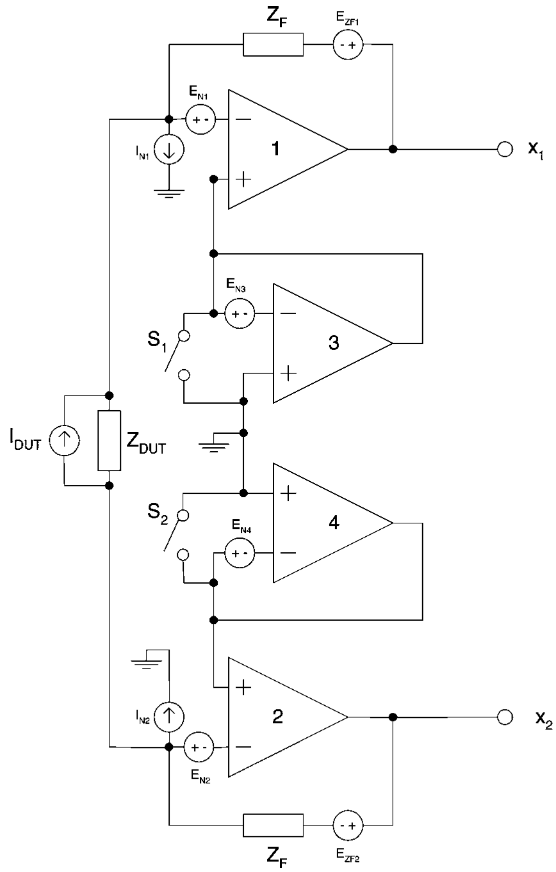

FIG. 2. Circuit configuration of the proposed instrument for electron device current noise measurements.

$$S_{3,4}=S_{\mathrm{DUT}}+S_{E_{N3}}+S_{E_{N4}}. \tag{8}$$

In the third step, all the four amplifiers are inserted in the circuit, as shown in Fig. 2, with the switches S_1 and S_2 open. In this measurement condition, the outputs of the amplifiers 1 and 2 are given by

$$X_1=-I_{\mathrm{DUT}}Z_F+E_{ZF1}+I_{N1}Z_F+(E_{N1}+E_{N3})\left[1+\frac{Z_F}{Z_{\mathrm{DUT}}}\right]-(E_{N2}+E_{N4})\frac{Z_F}{Z_{\mathrm{DUT}}},$$

$$X_2=+I_{\mathrm{DUT}}Z_F+E_{ZF2}+I_{N2}Z_F+(E_{N2}+E_{N4})\left[1+\frac{Z_F}{Z_{\mathrm{DUT}}}\right]-(E_{N1}+E_{N3})\frac{Z_F}{Z_{\mathrm{DUT}}}. \tag{9}$$

Note that for the sake of clarity we have not indicated in the circuit of Fig. 2 the EICN sources associated with the noninverting inputs of the amplifiers 1 and 2 and the EICN sources associated with the inverting inputs of the amplifiers 3 and 4.[19] It can be easily verified that these noise sources have no effects on X_1 and X_2. The sum and the difference between X_1 and X_2 are given by

$$S=E_{ZF1}+E_{ZF2}+I_{N1}Z_F+I_{N2}Z_F+E_{N1}+E_{N2}+E_{N3}+E_{N4},$$

$$D=-2I_{\mathrm{DUT}}Z_F+E_{ZF1}-E_{ZF2}+I_{N1}Z_F-I_{N2}Z_F+(E_{N1}+E_{N3})\times\left[1+2\frac{Z_F}{Z_{\mathrm{DUT}}}\right]-(E_{N2}+E_{N4})\left[1+2\frac{Z_F}{Z_{\mathrm{DUT}}}\right], \tag{10}$$

and the corresponding PSDs are

$$S_S=E_{ZF1}^2+E_{ZF2}^2+|I_{N1}Z_F|^2+|I_{N2}Z_F|^2+E_{N1}^2+E_{N2}^2+E_{N3}^2+E_{N4}^2,$$

$$S_D=4|I_{\mathrm{DUT}}Z_F|^2+E_{ZF1}^2+E_{ZF2}^2+|I_{N1}Z_F|^2+|I_{N2}Z_F|^2+(E_{N1}^2+E_{N3}^2)\left|1+2\frac{Z_F}{Z_{\mathrm{DUT}}}\right|^2+(E_{N2}^2+E_{N4}^2)\left|1+2\frac{Z_F}{Z_{\mathrm{DUT}}}\right|^2. \tag{11}$$

It follows that the cross correlation between the outputs of the two channels can be obtained as

$$S_{1,2,3,4}=\frac{S_D-S_S}{4}=S_{\mathrm{DUT}}+S_{E_{N1}}+S_{E_{N2}}+S_{E_{N3}}+S_{E_{N4}}, \tag{12}$$

where

$$S_{E_{N1}}=E_{N1}^2K_{EN}^2,\quad S_{E_{N2}}=E_{N2}^2K_{EN}^2,\quad S_{E_{N3}}=E_{N3}^2K_{EN}^2,\quad S_{E_{N4}}=E_{N4}^2K_{EN}^2. \tag{13}$$

At this point it is apparent that we can evaluate the power spectrum of the voltage noise generated by the DUT alone by taking the sum,

$$S_{\mathrm{DUT}}=S_{1,2}+S_{3,4}-S_{1,2,3,4}. \tag{14}$$

It is important to note that this measurement procedure allows the elimination of the contribution of the EIVN sources of the amplifiers without requiring either the measurement of the DUT impedance or the estimation of the EIVN of the amplifiers.

The validity of our method is based on the virtual short circuit approximation. If this assumption is not verified, the noise contribution associated to I_{N1}, I_{N2}, and E_{ZF1}, E_{ZF2} cannot be completely eliminated neither by the cross-correlation procedure nor by the proposed three-step measurement method. In order to clarify this point, let us consider a single transimpedance amplifier constituted by an operational amplifier with a feedback impedance Z_F and a DUT impedance Z_{DUT} connected between the inverting input and ground. It can be easily verified that the magnitude of the loop gain is given by

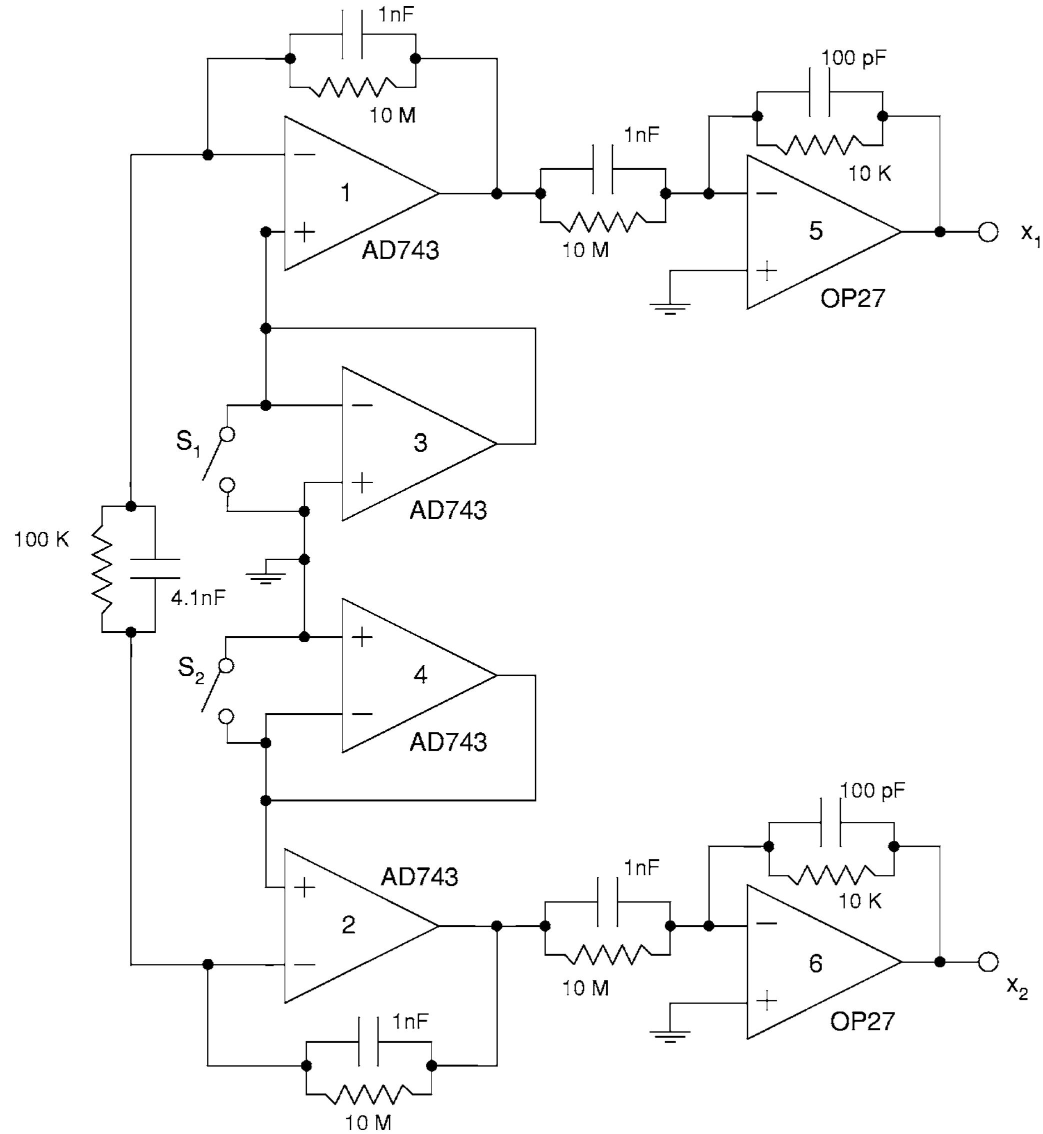

FIG. 3. A circuit prototype implementing the configuration presented in Fig. 2. The DUT consists of a 100 kΩ resistor in parallel with a 4.1 nF capacitor.

$$|\beta A| = \left| \frac{Z_{\mathrm{DUT}} \| Z_{\mathrm{IN}}}{Z_{\mathrm{DUT}} \| Z_{\mathrm{IN}} + Z_F} A_V \right|, \tag{15}$$

where Z_{IN} is the input impedance of the operational amplifier and A_V is the voltage gain of the operational amplifier. For the validity of the virtual short circuit approximation, it is necessary that $|\beta A| \gg 1$. This condition could not be satisfied at higher frequencies in the case of small bandwith operational amplifiers and/or $|Z_F| \gg |Z_{\mathrm{DUT}} \| Z_{\mathrm{IN}}|$, which can occur for a large capacitive DUT (e.g., MOS capacitors). This problem can be partially solved by employing large bandwidth transimpedance amplifier circuit topologies, as the one proposed in Ref. 20.

IV. EXPERIMENTAL VALIDATION

In order to verify the validity of the proposed method, we have used the circuit shown in Fig. 3. We used as a DUT the parallel between a resistor $R_{\mathrm{DUT}}=100$ kΩ and a capacitor $C_{\mathrm{DUT}}=4.1$ nF. Note that since in the explored frequency range the magnitude of the input impedance of the transimpedance amplifiers are significantly lower than $|Z_{\mathrm{DUT}}|$, the current associated to the thermal noise of R_{DUT} flows in the transimpedance amplifiers, thus the curent power spectrum due to the thermal noise of R_{DUT} is not influenced by the shunting effect of C_{DUT}. Consequently, in the explored frequency range the curent power spectrum associated to the DUT is white with an expected value,

$$S_{\mathrm{DUT}} = \frac{4kT}{R_{\mathrm{DUT}}} = 1.66 \times 10^{-25}\ \mathrm{A}^2/\mathrm{Hz}. \tag{16}$$

In order to verify the effectiveness of our method, we have intentionally increased the effect of the EIVN of the measurement amplifiers, by decreasing the DUT impedance at higher frequencies with the insertion of C_{DUT} in parallel with R_{DUT}. To increase the bandwidth of the transimpedance amplifiers, we have used the circuit topology proposed in Ref. 20. To implement the amplifiers 1, 2, 3, and 4 in Fig. 3, we have chosen the ultralow noise operational amplifier AD743, which is characterized by an EIVN of 2.9 nV/$\sqrt{\mathrm{Hz}}$ at 10 kHz, and an EICN of 6.9 fA/$\sqrt{\mathrm{Hz}}$ at 1 kHz. The operational amplifiers 5 and 6 are implemented with the OP27, which is characterized by an EIVN of 3 nV/$\sqrt{\mathrm{Hz}}$ at 100 Hz

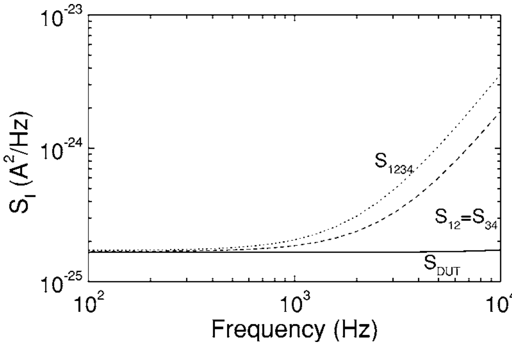

FIG. 4. Simulated input referred cross spectra obtained by connecting the DUT to (a) the first couple of amplifiers, (b) the second couple of amplifiers, and (c) all four amplifiers. The extracted power spectrum of the current noise generated by the DUT is also reported.

and an EICN of 0.6 pA/$\sqrt{\text{Hz}}$ at 100 Hz. We have chosen the OP27 for the amplifiers 5 and 6 because it presents a gain-bandwidth product of 8 MHz, which is higher with respect to the case of the AD743.

We have applied the proposed method by using the results obtained by means of SPICE simulations and by measurements performed on the circuit of Fig. 3. A perfect agreement has been obtained between the simulated spectra (see Fig. 4) and the measured spectra (see Fig. 5). By following the three-step measurement procedure described in the previous section, we have correctly extracted the PSD of the DUT signal in both cases (Figs. 4 and 5). It is important to underline that although at higher frequencies the effect of the EIVN strongly increases due to the decrease of the DUT impedance, the extracted S_{DUT} results quite constant, as it was expected. The average error between the PSD of the DUT signal extracted by the measured spectra and the expected DUT thermal noise in the bandwidth between $f=2$ kHz and $f=9.8$ kHz, where the EIVN effect is up to 10 dB higher with respect to S_{DUT}, is about 3%.

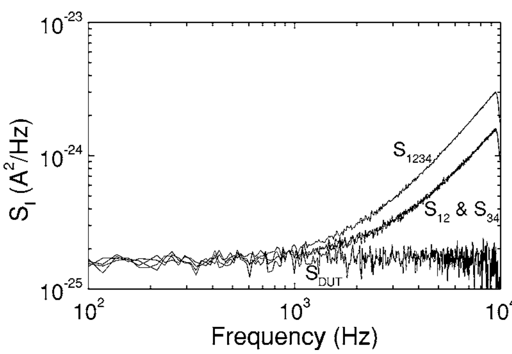

FIG. 5. Measured input referred cross spectra obtained by connecting the DUT to (a) the first couple of amplifiers, (b) the second couple of amplifiers, and (c) all four amplifiers. The extracted power spectrum of the current noise generated by the DUT is also reported. The spectra rolloff at about 10 kHz is due to the antialiasing filters.

V. DISCUSSION

In this work, we have presented an original ultrasensitive method for the measurement of electron device current noise, which allows, at least in principle, the complete elimination of the noise introduced by the measurement amplifiers. This is obtained by resorting to the conventional cross-correlation technique for the elimination of the contribution of the EICN of the amplifiers and by resorting to a three-step measurement procedure using different amplifier configurations in order to subtract the contribution of the EIVN of the amplifiers. It is important to underline that the method application does not require either the estimation of the EIVN and of the EICN of the operational amplifiers, or the estimation of the DUT impedance. The implications of the validity of the virtual short circuit approximation on the method application have also been discussed. We have reported SPICE simulations and measurements on a prototype circuit which confirm the validity of the proposed ultrasensitive technique for the current noise measurements.

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