Direct extraction of the channel thermal noise in metal-oxide-semiconductor field effect transistor from measurements of their rf noise parameters

Chih-Hung Chen and M. Jamal Deen
Electrical and Computer Engineering, McMaster University, Hamilton, Ontario L8S 4K1, Canada

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This article presents an extraction method to obtain the channel thermal noise in metal-oxide-semiconductor field effect transistor (MOSFETs) directly from the dc, scattering parameter and rf noise measurements. In this extraction method, the transconductance (\(g_m\)), output resistance (\(R_{DS}\)), and source and drain resistances (\(R_S\) and \(R_D\)) are obtained from dc measurements. The gate resistance (\(R_G\)) is extracted from scattering-parameter measurements, and the equivalent noise resistance (\(R_n\)) is obtained from rf noise measurements. This method has been verified by using the measured data of a 0.36 \(\mu \text{m}\) n-type MOSFET up to 18 GHz. Comparisons between simulated and measured characteristics of noise parameters versus frequency are also presented. © 2000 American Vacuum Society. [S0734-2101(00)07102-5]

I. INTRODUCTION

Because of the low cost and high levels of integration of complementary metal-oxide semiconductor (CMOS) technology, many high-speed or radio-frequency (rf) integrated circuits (ICs) which were fabricated exclusively by III–V or bipolar technologies are likely to be implemented in CMOS technology. However, when working at high frequencies, the noise generated within the device itself will play an increasingly important role in the overall noise performance of analog circuits. Therefore, high-frequency noise performance of metal-oxide-semiconductor field-effect transistor (MOSFETs) becomes an important issue after high unity-gain frequencies had been achieved. At these high frequencies, an accurate noise model for the channel thermal noise in MOSFETs is crucial for the design and simulation of rf CMOS circuits.

Presently, the models of the channel thermal noise are physics based, and they are then confirmed by the measured minimum noise figure (\(\text{NF}_{\text{min}}\)) of devices through the help of a device simulator or the device's small-signal model. However, the accuracy of the small-signal model, the values of model parameters used in simulation and the noise model itself will all affect the simulated noise parameters. These factors make the confirmation of the noise model more difficult, even when accurate noise parameters were measured. Therefore, obtaining the channel thermal noise of MOSFETs directly from measurements of their rf noise parameters is crucial in its noise modeling. This article presents a method to obtain the channel thermal noise directly from measurements of their dc characteristics, scattering parameters, and rf noise parameters. Physics-based noise models can then be verified from the extracted channel thermal noise results in a direct way.

II. DIRECT EXTRACTION OF THE CHANNEL THERMAL NOISE

A noisy two port may be presented by a noise-free two port and two noise current sources, one at the input port (\(i_1\)) and the other at the output port (\(i_2\)). From the noisy two-port network theory, the power spectral density of \(i_2\) can be obtained from

\[
\frac{|i_2|^2}{\Delta f} = 4kTR_n|Y_{21}|^2, \tag{1}
\]

where \(k\) is the Boltzmann’s constant, \(T\) is the absolute temperature, \(Y_{21}\) is the transadmittance from port 1 to port 2 of the noise-free two port and \(R_n\) is the equivalent noise resistance which is a resistance cascaded at the input port that will produce the same amount of noise power spectral density as \(i_2\) does at the output port.

Figure 1(a) shows the proposed noise model of a MOSFET that is used for predicting its rf noise performance. In Fig. 1(a), \(g_m\) is the transconductance, \(R_1\) is the channel resistance, \(R_{DS}\) is the output resistance, \(C_{SB}\) and \(C_{DB}\) are source-to-bulk and drain-to-bulk junction capacitances, respectively, and \(C_{GS}, C_{GD}\), and \(C_{GB}\) are gate-to-source, gate-to-drain, and gate-to-bulk capacitances, respectively.

For the noise sources, \(i_d\) is the channel thermal noise, \(i_g\) is the induced gate noise occurring at very high frequencies, \(i_{5}\) and \(i_{7}\) are the noise current sources caused by the source (\(R_s\)) and drain (\(R_D\)) resistances, \(i_{5}\) is the noise current source caused by the polysilicon gate resistance (\(R_G\)) and \(i_{DB}\) is the noise current source caused by the substrate resistance (\(R_{DB}\)).

At low frequencies (above the corner frequency of the flicker noise), the equivalent noise model can be simplified to that shown in Fig. 1(b). If we convert the noise current sources associated with the parasitic resistances to noise voltage sources and assume that all the admittances of the capacitances are approximately zero at low frequencies, then the noise power spectral density (\(\text{W}^2/\text{Hz}\)) of the total noise currents (\(i_2\)) at the output port can be obtained from...
\[
\frac{|i_2|^2}{\Delta f} = \frac{|i_{G_{\text{out}}}|^2}{\Delta f} + \frac{|i_{S_{\text{out}}}|^2}{\Delta f} + \frac{|i_{D_{\text{out}}}|^2}{\Delta f} + \frac{|i_{d_{\text{out}}}|^2}{\Delta f}
\]
\[
= 4kT R_n|Y_{21}|^2,
\]
where
\[
Y_{21} = \frac{g_m R_{DS}}{g_m R_S R_{DS} + R_D + R_S + R_{DS}}.
\]

Here, \(i_{G_{\text{out}}}, i_{S_{\text{out}}}, i_{D_{\text{out}}},\) and \(i_{d_{\text{out}}}\) are the noise currents contributed at the output port by \(i_G, i_S, i_D,\) and the channel thermal noise \((i_d)\), respectively, and they are given by
\[
\frac{|i_{G_{\text{out}}}|^2}{\Delta f} = 4kT g_m R_{DS} \left( \frac{g_m R_{DS}}{g_m R_S R_{DS} + R_D + R_S + R_{DS}} \right)^2,
\]
\[
\frac{|i_{S_{\text{out}}}|^2}{\Delta f} = 4kT g_S \left( \frac{1 + g_S R_{DS}}{g_m R_S R_{DS} + R_D + R_S + R_{DS}} \right)^2,
\]
\[
\frac{|i_{D_{\text{out}}}|^2}{\Delta f} = 4kT R_D \left( \frac{1}{g_m R_S R_{DS} + R_D + R_S + R_{DS}} \right)^2,
\]
and
\[
\frac{|i_{d_{\text{out}}}|^2}{\Delta f} = |i_d|^2 \left( \frac{R_{DS}}{g_m R_S R_{DS} + R_D + R_S + R_{DS}} \right)^2.
\]

The induced gate noise \((i_g)\) and its correlation with the channel thermal noise are negligible at low frequencies and are therefore neglected in Eq. (2). In addition, because \(C_{DB}\) causes an open circuit at low frequencies, then there is no noise current contributed by \(i_{DB}\) at the output port. Substituting Eqs. (3)–(7) in Eq. (2), the power spectral density of the channel thermal noise in MOSFETs can be calculated from
\[
\frac{|i_d|^2}{\Delta f} = 4kT \left( R_{no} - R_G - R_S \right) g_m^2 \left( \frac{2g_m R_S}{R_{DS}} - \frac{R_D + R_S}{R_{DS}^2} \right),
\]
where \(R_{no}\) is the equivalent noise resistance extrapolated at low frequencies from the measured \(R_n\) versus frequency characteristics.

III. MEASUREMENTS AND DISCUSSIONS

A 0.36 \(\mu\)m \(n\)-channel MOSFET which consists ten 12 \(\mu\)m wide transistors connected in parallel and was fabricated in a 0.25 \(\mu\)m CMOS technology by Conexant Systems Inc., is used as the device-under-test (DUT). The device is biased at \(V_{DS}=1.0\) V and \(V_{GS}=0.9\) V \((I_{DS}=3.09\) mA and the unity current gain frequency \(f_T=16.3\) GHz). Based on the measured \(s\) parameters and the parameter extraction method described in Ref. 7 for obtaining the element values in the small-signal model, the extracted values of the model ele-
ments in Fig. 1(a) are \( g_m = 16.5 \) mS, \( R_G = 9.2 \) Ω, \( R_S = R_D = 1 \) Ω, \( R_i = 9.91 \) Ω, \( R_{DS} = 2.56 \) kΩ, \( R_{DB} = 11.5 \) Ω, \( C_{GB} = 0 \) F, \( C_{GS} = 133 \) fF, \( C_{GD} = 36.8 \) fF, and \( C_{DB} = 125 \) fF.

In addition, by extrapolating the \( R_n \) versus frequency characteristics at low frequencies, \( R_{no} = 80 \) Ω for this bias condition. Based on these element values and Eq. (8), the power spectral density of the channel thermal noise \( i_d^2 \) in this device is \( 3.18 \times 10^{-22} \) A²/Hz at this bias condition.

In order to confirm the extracted \( i_d^2 \), four noise parameters (minimum noise figure \( NF_{min} \), equivalent noise resistance \( R_n \), and optimized source resistance \( R_{opt} \) and reactance \( X_{opt} \)) are calculated based on Fig. 1(a) by using the calculation method described in Refs. 8 and 9. Figures 2 and 3 show the measured and simulated \( NF_{min} \) and \( r_n (R_n \) normalized to \( 50\Omega \) versus frequency characteristics by using the measured \( y \) parameters without including the induced gate noise \( [i_d^2 \text{ in Fig. 1(a)}] \) and its correlation with the channel thermal noise \( [i_d^2 \text{ in Fig. 1(a)}] \).

In Figs. 2 and 3, the solid lines are the simulated results based on the \( i_d^2 \) from Eq. (8) and the dashed lines are based on the equation \( i_d^2 = 8kTg_m/3 \) which was suggested for long channel transistors but underestimates \( NF_{min} \) and \( r_n \) for submicron transistors. These results show that the calculated channel thermal noise based on the simple expression \( i_d^2 = 8kTg_m/3 \) cannot be used to predict the channel thermal noise of submicron MOSFETs biased in the saturation region.10

Figures 4 and 5 show the measured and simulated \( R_{opt} \) and \( L_{opt} \) (\( X_{opt} \) divided by \( 2\pi f \), where \( f \) is the operating frequency) versus frequency characteristics. In general, the extracted \( i_d^2 \) from Eq. (8) can give very good agreement between the simulations and measurements for all the four noise parameters of MOSFETs without any parameter fitting of the measured noise parameters. Results at other biases, \( I_{DS} = 0.3 \) mA (\( V_{GS} = 0.64 \) V and \( f_T = 5 \) GHz) and \( I_{DS} = 1.0 \) mA (\( V_{GS} = 0.74 \) V and \( f_T = 10 \) GHz) were just as good those presented here.
IV. CONCLUSIONS

A method to directly extract the channel thermal noise in MOSFETs has been presented and verified by measurements. This technique removed the influence of inaccurate small-signal model or ac parameter fitting from characterizing the channel thermal noise of MOSFETs. Very good agreement between the simulated and measured noise parameters has been achieved up to 18 GHz without including the induced gate noise and its correlation with the channel thermal noise.

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