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Direct parameter-extraction method for MOSFET noise model from microwave noise figure measurement

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ABSTRACT

A new method for the determination of the four noise parameters of the metal oxide semiconductor field effect transistors (MOSFETs) based on the noise figure measurement system without microwave tuner is presented. The noise parameters are determined based on a set of analytical expressions of noise parameters by fitting the measured noise figure of the active device. These expressions are derived from an accurate small signal and noise equivalent circuit model, which takes into account the substrate parasitics, pad capacitances, and series inductances. On-wafer experimental verification is presented and a comparison with tuner based method is given. Good agreement is obtained between simulated and measured results for $0.5 \times 5 \times 16$ μm, $0.35 \times 5 \times 16$ μm and $0.18 \times 5 \times 16$ μm (gate length × number of gate fingers × unit gate width) MOSFETs.

1. Introduction

The submicrometer metal oxide semiconductor field effect transistors (MOSFETs) have shown excellent microwave and noise performance and are very attractive for radio frequency integrated circuit design (RFIC). The demand for higher levels of integration and higher operating frequencies has inspired the enormous advancements in CMOS technologies. As the channel length of a MOSFET is made smaller, the cutoff frequency increases significantly, enabling higher operating frequencies and lower noise performance. The complete characterization of these devices in terms of noise and scattering parameters is necessary for computer-aided design (CAD) of monolithic microwave integrated circuits (MMICs) or optoelectronic integrated circuits (OEICs) [1–5]. The full noise characterization of a MOSFET requires the determination of four noise parameters: minimum noise figure $F_{\min}$, noise resistance R_n, optimum source conductance G_{opt} and optimum source susceptance B_{opt} (or magnitude and phase of the optimum source reflection Γ_{opt}).

Most algorithms rely on the source–pull measurement technique to extract the noise parameters from a large set of parameters at a single frequency, e.g., by employing the correlation matrix method to de-embed the parasitics and to determine the intrinsic noise sources. A minimum of four independent measurements is required, however frequently more measurements are performed to achieve higher accuracy. Curve-fitting techniques are then used to determine the noise parameters. Although this method gives accurate results, it is time consuming and requires an expensive automatic broadband microwave tuner that involves complex calibration procedures.

Based on the matched source reflection 50 Ω measurement system (F_{50}) without automatic tuner, the semi-analytical methods have been used for determination of the four noise parameters for III–V compound semiconductor [6–8]. In this manuscript, which is a significant extension of our previous work in Gao et al. [7–9], a full analytical method to determine the four noise parameters of MOSFETs is proposed without any optimization. In comparison with previous publications [6–10], this method has the following advantages:

(1) A set of new expressions for the four noise parameters of Silicon-based MOSFETs is derived from an accurate noise equivalent circuit model that based on Pospieszalski model [11] without any assumptions and approximations. The effects which become important at higher frequencies such as the substrate parasitics, the pad capacitances and series inductances are taken into account.

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(2) Further simplified expressions for MOSFET noise parameters in the low frequency range are derived.
(3) All four noise parameters can be determined directly from noise figure on wafer measurement at low frequency range based on the accurate analytical expressions of noise parameters.

Such a method would be beneficial in acceptance testing and faster than full testing with a source tuner and more likely to be done with a test setup not requiring a tuner. However, an accurate small signal model parameters extraction is need.

The organization of the paper is as follows: Sections 2 and 3 are dedicated to the derivation of analytical expressions for the corresponding noise parameters based on an accurate noise model. The proposed method for determination of the noise parameters is introduced in Section 4. A comparison between the new expressions and experimental data measured on MOSFETs with different gate-length is presented in Section 5. The conclusion is given in Section 6.

2. Small signal and noise equivalent circuit model

From the circuit point of view, the MOSFET device can be treated as a black box of a noisy two port. As well known, the noise behavior of a linear noisy two-port network can be characterized by the four noise parameters, $F_{\min}$, R_n, G_{opt} and B_{opt}, with:

$$F = F_{\min} + \frac{R_n}{G_s}\left[(G_s - G_{opt})^2 + (B_s - B_{opt})^2\right] \tag{1}$$

where F is the noise figure, $Y_s = G_s + jB_s$ is the source admittance, and $Y_{opt} = G_{opt} + jB_{opt}$ is the optimum source admittance.

The PRC model (Van der Ziel [12], Pucel [13] and Cappy [14]) has emerged as one of the most accurate and convenient ways to obtain the noise model parameters for FETs in the microwave simulators, such as ADS and so on. Following these pioneering works, Pospieszalski [11] proposed an alternative high frequency noise model. The aim of this model consists in dissociating the noise on the gate from the noise on the drain. Both above mentioned models are well suited to the case of MOSFET devices because the high frequency noise mechanisms are similar. The complete MOSFET small signal and noise equivalent circuit model is shown in Fig. 1. Fig. 1a shows the intrinsic and Fig. 1b shows the extrinsic network, respectively. The circuit model comprises the well-known small signal equivalent circuit, and eight noise sources $\overline{e_{pg}^2}, \overline{e_{pd}^2}, \overline{e_{sub}^2}, \overline{e_g^2}, \overline{e_d^2}, \overline{e_s^2}, \overline{e_{gs}^2}$ and $\overline{i_{ds}^2}$. The two uncorrelated current noise source $\overline{e_{gs}^2}$ and $\overline{i_{ds}^2}$ represent the internal noise sources of the intrinsic MOSFET, these two noise sources are characterized by their mean quadratic value in a bandwidth Δf centered on the frequency f, and can be given by the following expressions [11]:

$$\overline{e_{gs}^2} = 4kT_gR_{gs}\Delta f \tag{2}$$

$$\overline{i_{ds}^2} = 4kT_dg_{ds}\Delta f \tag{3}$$

where T_g and T_d are the equivalent noise temperature of the intrinsic resistance R_{gs} and output conductance g_{ds}, respectively.

The six noise sources $\overline{e_{pg}^2}, \overline{e_{pd}^2}, \overline{e_{sub}^2}, \overline{e_g^2}, \overline{e_d^2}$ and $\overline{e_s^2}$ represent the noisy behavior of the access resistances R_{pg}, R_{pd}, R_{sub}, R_g, R_d and R_s, and are simply given by

$$\overline{e_i^2} = 4kT_oR_i\Delta f(i = pg, pd, sub, g, d, s) \tag{4}$$

where q is the electronic charge, k is Boltzmann's constant, T_o is the ambient temperature, R_i is the resistance value.

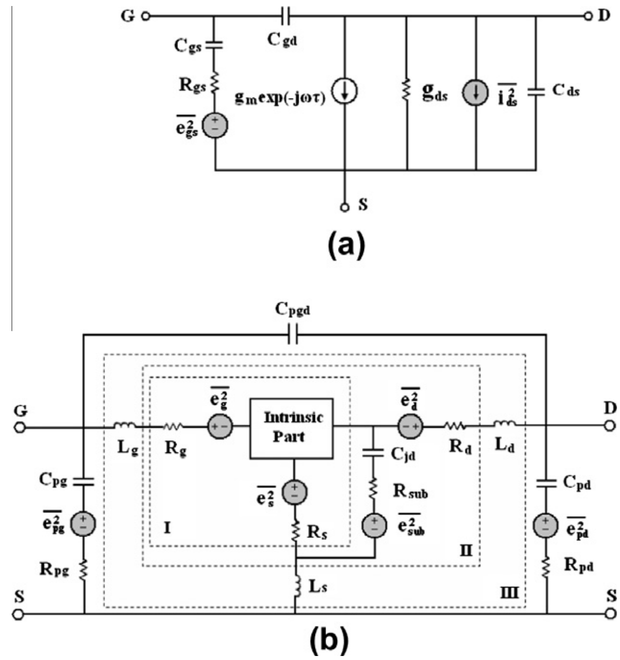

Fig. 1. MOSFET small signal and noise equivalent circuit model. (a) Intrinsic part (b) extrinsic part.

3. Derivation of noise parameters

Based on the noise correlation matrix technique [15], the expressions of the four noise parameters can be carried out as follows:

(1) Calculation of the admittance noise correlation matrix of MOSFET intrinsic part as follows:

$$C_{Y11}^{INT} = 4kT_g\Delta fR_{gs}\left|\frac{j\omega C_{gs}}{1 + j\omega C_{gs}R_{gs}}\right|^2 \tag{5}$$

$$C_{Y22}^{INT} = 4k\Delta f\left(T_dg_{ds} + T_gR_{gs}\left|\frac{g_m}{1 + j\omega C_{gs}R_{gs}}\right|^2\right) \tag{6}$$

$$C_{Y12}^{INT} = 4kT_g\Delta f\frac{g_m^*\omega C_{gs}R_g}{|1 + j\omega C_{gs}R_{gs}|^2} \tag{7}$$

The corresponding noise parameters of the intrinsic network can be expressed as follows:

$$R_n^{INT} = \frac{T_gR_{gs}}{T_ok_1} + \frac{T_dg_{ds}(1 + \omega^2C_{gs}^2R_{gs}^2)}{T_ok_1g_m^2} \tag{8}$$

$$B_{opt}^{INT} = -\omega\left(C_{gs} + C_{gd} - C_{gs}\frac{T_gR_{gs}}{T_oR_n}\right) \tag{9}$$

$$G_{opt}^{INT} = \omega C_{gs}\frac{\sqrt{k_1k_3(k_2 - k_3)}}{k_2} \tag{10}$$

$$F_{\min}^{INT} = 1 + 2k_4 + 2G_{opt}R_n \tag{11}$$

with

$$k_1 = 1 + \frac{2\omega^2C_{gd}(\tau + R_{gs}C_{gs})}{g_m}$$

$$k_2 = \frac{T_dg_{ds}}{T_og_m} + k_3$$