

Analytical Noise Parameter Model of Short-Channel RF MOSFETs

Jongwook Jeon, Byung-Gook Park, Jong Duk Lee, and Hyungcheol Shin

Abstract—In this paper, a simple and improved noise parameter model of RF MOSFETs is developed and verified. Based on the analytical model of channel thermal noise, closed form expressions for four noise parameters are developed from proposed equivalent small signal circuit. The modeling results show an excellent agreement with the measured data of $0.13\mu\text{m}$ CMOS devices.

Index Terms—RF MOSFET, analytical modeling, channel thermal noise, small-signal modeling, noise parameters.

I. INTRODUCTION

Due to continuous reduction of minimum channel length in CMOS technologies in the recent years, CMOS has become a candidate for RF applications[1, 2]. However, when working at high frequencies with short-channel MOSFETs, the noise generated within the device itself is one of the key issues in the low noise RF circuit design[3]. Thus, a physics-based accurate modeling of high-frequency noise of deep-submicron MOSFETs is important for a low noise RF circuit. Channel thermal noise is the most dominant noise source of short-channel MOSFETs in high-frequency[3]. Four noise parameters (NF_{min} , $Y_{opt} = G_{opt} + jB_{opt}$, and R_n) are commonly used to specify the noise performance of devices and circuits[4]. The purpose of this work is to develop a new analytical noise parameter model of short channel MOSFETs to give an estimation of the noise

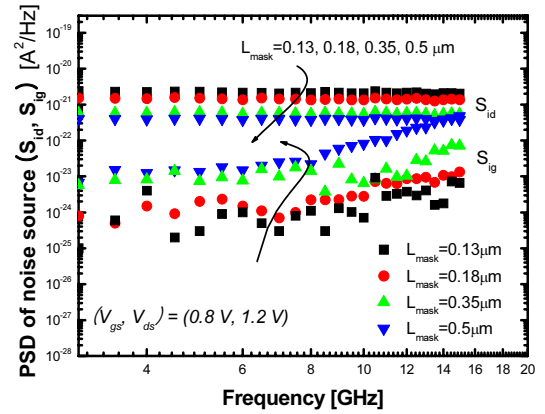


Fig. 1. Measured channel thermal noise and induced gate noise with different gate length.

performance of RF MOSFETs. The results are based on analysis of each thermal noise source in the MOSFETs. Comparisons were made between the proposed noise model and the measured noise data.

II. ANALYTICAL MODELING OF THERMAL NOISE AND NOISE PARAMETERS

1. Channel Thermal Noise Model

The thermal fluctuations in a gradual channel region of MOSFET cause the noise current, which is so called channel thermal noise[5]. It is well known that the channel thermal noise becomes larger as the gate length scales down because the channel conductance becomes larger[6]. The devices were fabricated by $0.13\mu\text{m}$ CMOS technology. The unit finger width and the number of fingers were $1.8\mu\text{m}$ and 64, respectively. Fig. 1 shows the extracted PSD of each noise source; channel thermal noise and induced gate noise. As shown in Fig. 1, compared with the PSD of channel thermal noise the

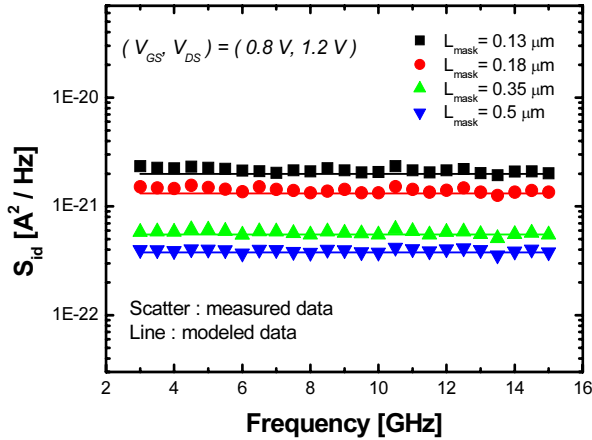


Fig. 2. Measured and modeled channel thermal noise as a function of frequency with different gate lengths.

induced gate noise can be ignored in 0.18 μm or shorter devices. The PSD of the total channel thermal noise is modeled as [7]

$$S_{id} = 4kT_o \cdot \frac{4V_{GT}^2 + 10V_o^2 + 7V_oV_{GT} + \frac{3}{2} \frac{V_o^3}{V_{GT} - V_o} \ln \left| \frac{2V_{GT} - V_o}{V_o} \right|}{3(V_{GT} - V_o)(V_{GT} + V_o)^2} mI_{DS} \quad (1)$$

where $V_{GT} = V_{GS} - V_{th}$, and $V_o = I_{DS} / WC_{ox}v_{sat}$. This analytical channel thermal noise model takes into account mobility degradation, channel length modulation and carrier heating effects due to the lateral electric field in short channel MOSFETs. Fig. 2 shows the used channel thermal noise model, eq. (1), accurately predicts each noise current of DUT.

2. Thermal Noise Sources From Parasitic Resistances

Substrate and gate resistance were obtained by using Y-parameter analysis from S-parameter measurement data. To investigate each contribution of thermal noise sources at the drain output terminal intrinsic g_m , g_{mb} and g_{ds} is needed, which are extracted from S-parameter

Table. 1. Summary of small signal parameter extraction results at $V_{GS} = 0.8V$ and $V_{DS} = 1.2V$.

| | g_m [mS] | g_{mb} [mS] | g_{ds} [mS] | $R_s = R_d$ [Ω] | R_{sub} [Ω] | R_g [Ω] |
|---------|------------|---------------|---------------|-----------------|---------------|-----------|
| 0.13 μm | 86.2 | 18.1 | 3.8 | 1.2 | 38.5 | 2.3 |
| 0.18 μm | 71.4 | 15.6 | 1.9 | 1.2 | 46.5 | 1.8 |

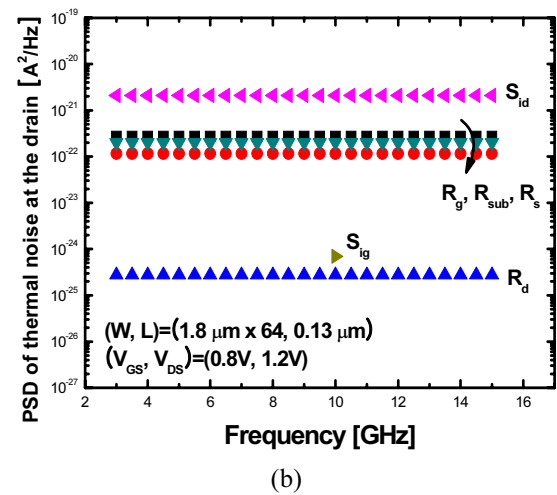
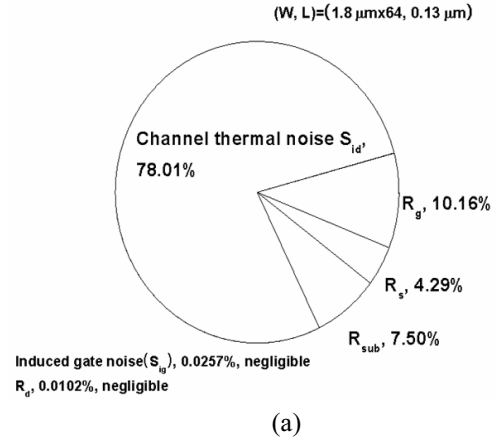


Fig. 3. (a) The contribution of each thermal noise source at drain output terminal and (b) power spectral density.

measurement[8]. Table. 1 shows the summary of extracted device parameters of 0.13 μm and 0.18 μm NMOSFET at $V_{GS} = 0.8V$ and $V_{DS} = 1.2V$. At the drain terminal, PSD of the thermal noise from each resistance in the MOSFET as well as the channel thermal noise is calculated as shown in Fig. 3. The channel thermal noise, noise from the substrate resistance, and noise from the gate resistance are the top three most important noise source in short-channel MOSFETs.

3. Noise Parameter Modeling

It is well known that a noisy two port can be represented by the same noiseless two-port network with an input-referred noise voltage source v_n having a PSD of $S_v = 4kTR_n$ and an input-referred noise current source i_n having a PSD of $S_i = 4kTG_n$ [9]. S_v and S_i depend on the internal physical noise sources and they are, therefore,

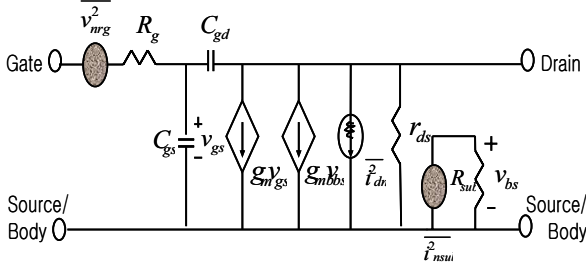


Fig. 4. Small-signal equivalent circuit for noise analysis.

generally correlated. Their cross-correlation can be taken into account by using cross-correlation admittance Y_c defined as

$$Y_c \equiv \frac{\overline{i_n v_n^*}}{v_n^2} = G_c + jB_c \quad (2)$$

To characterize noise four parameters we need to formulate following four parameters ; R_n , G_n , G_c , and B_c . Based on the analysis of thermal noise sources of the short-channel MOSFET in section 2 and 3 we propose an improved equivalent small signal circuit of MOSFETs for noise characterization as shown in Fig. 4, which includes channel thermal noise source, substrate, and gate resistance. The equivalent noise voltage(v_n) and current(i_n) source as shown in Fig. 2 are determined as

$$v_n = v_{nrg} + \frac{i_{dn}}{Y_{21}} + \frac{g_{mb} R_{sub} i_{nsub}}{Y_{21}} \quad (3.1)$$

$$i_n = \frac{Y_{11}}{Y_{21}} i_{dn} + \frac{Y_{11}}{Y_{21}} g_{mb} R_{sub} i_{nsub} \quad (3.2)$$

The Y-parameters of the noiseless MOSFET can be obtained from the proposed small-signal circuit shown in Fig. 4 as

$$\begin{aligned} Y_{11} &= \frac{j\omega C_{gg}}{1 + j\omega C_{gg} R_g} \\ Y_{12} &= -\frac{j\omega C_{gd}}{1 + j\omega C_{gg} R_g} \\ Y_{21} &= \frac{g_m - j\omega C_{gd}}{1 + j\omega C_{gg} R_g} \\ Y_{22} &= \frac{1}{r_{ds}} + j\omega C_{gd} + \frac{j\omega C_{gd} R_g (g_m - j\omega C_{gd})}{1 + j\omega C_{gg} R_g} \end{aligned} \quad (4.1-4)$$

where $C_{gg} = C_{gs} + C_{gd}$. By using equation (3) and (4) the parameters of R_n , G_n , G_c , and B_c are calculated as

$$R_n \approx R_g + \frac{1}{|Y_{21}|^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right), \quad G_n \approx \frac{|Y_{11}|^2}{|Y_{21}|^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right) \quad (5.1-4)$$

$$G_c \approx \frac{1}{R_n} \left\{ \frac{\text{Re}[Y_{11}]}{|Y_{21}|^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right) \right\}, \quad B_c \approx \frac{1}{R_n} \left\{ \frac{\text{Im}[Y_{11}]}{|Y_{21}|^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right) \right\}$$

where S_{id} represents the PSD of channel thermal noise and we ignore induced gate noise and its correlation with channel thermal noise based on the analysis in section 2. The four noise parameters including R_n , G_{opt} , B_{opt} , and NF_{min} can be expressed as a function of R_n , G_n , G_c , and B_c [10].

$$NF_{min} = 1 + 2R_n(G_{opt} + G_c)$$

$$Y_{opt} = G_{opt} + jB_{opt} = \sqrt{\frac{G_n}{R_n} - B_c^2} - jB_c \quad (6.1-2)$$

The four noise parameters, therefore, can be obtained from equation (6) and (5) as following.

$$R_n = R_g + \frac{1}{|Y_{21}|^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right) \approx R_g + \frac{1}{g_m^2} \left(\frac{S_{id}}{4kT} + g_{mb}^2 R_{sub} \right)$$

$$B_{opt} = -\frac{\text{Im}[Y_{11}] \cdot (S_{id}/4kT + g_{mb}^2 R_{sub})}{|Y_{21}|^2 R_g + S_{id}/4kT + g_{mb}^2 R_{sub}} \approx -\left(\frac{f}{f_T} \right) \frac{S_{id}/4kT + g_{mb}^2 R_{sub}}{g_m R_n}$$

$$\begin{aligned} G_{opt} &= \frac{|Y_{11}| |Y_{21}| \sqrt{R_g (S_{id}/4kT + g_{mb}^2 R_{sub})}}{|Y_{21}|^2 R_g + S_{id}/4kT + g_{mb}^2 R_{sub}} \\ &\approx \left(\frac{f}{f_T} \right) \frac{\sqrt{R_g (S_{id}/4kT + g_{mb}^2 R_{sub})}}{R_n} \end{aligned} \quad (7.1-4)$$

$$\begin{aligned} NF_{min} &= 1 + \frac{2}{|Y_{21}|^2} \left\{ |Y_{11}| |Y_{21}| \sqrt{R_g (S_{id}/4kT + g_{mb}^2 R_{sub})} + \text{Re}[Y_{11}] (S_{id}/4kT + g_{mb}^2 R_{sub}) \right\} \\ &\approx 1 + 2 \left\{ \frac{f}{f_T} \sqrt{R_g (S_{id}/4kT + g_{mb}^2 R_{sub})} \right\} \left\{ 1 + \frac{f}{f_T} \sqrt{R_g (S_{id}/4kT + g_{mb}^2 R_{sub})} \right\} \end{aligned}$$

where $f_T = g_m/(2\pi C_{gg})$ is the unity gain frequency.

III. EXPERIMENTAL RESULTS

Noise parameters of short-channel MOSFETs obtained from proposed noise parameter equations (7.1-4) are

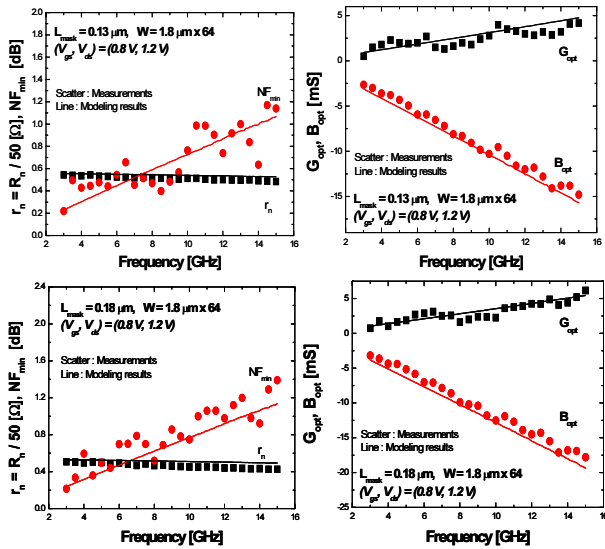


Fig. 5. Measured and modeled noise parameters of MOSFET as a function of frequency with $L_{mask} = 0.13 \mu m$ and $0.18 \mu m$.

compared with measured noise parameters. Test devices have $W=1.8 \mu m \times 64$, and $L=0.13 \mu m$ and $0.18 \mu m$. The comparison between predicted and measured MOSFETs noise parameters at $V_{GS}=0.8V$ and $V_{DS}=1.2V$ versus frequency as shown in Fig. 5. In Fig. 5, we verified the derived noise parameter equations, eq. (7.1-4), are accurate by comparison with the measurements.

IV. CONCLUSIONS

In this paper, new noise parameter equations were proposed and verified with $0.13 \mu m$ RF MOSFETs. Before this task, channel thermal noise modeling and analysis of noise sources from parasitic resistance was performed. Based on the analysis of each noise source, a noise equivalent circuit is proposed. From this circuit, noise parameter equations were derived and verified with measurements. The proposed noise parameter equations accurately predicts noise performance of RF MOSFET. Using the model, the noise performance can be predicted from S-parameter of the device without any noise measurement.

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Jongwook Jeon was born in Ma-San, Korea, on July 7, 1981. He received the B.S. degree from School of Information and Communication Engineering from the Sungkyunkwan University, Suwon, Korea, in 2004, and he is currently pursuing the the Ph.D. degree in Electrical Engineering at the Seoul National University, Seoul, Korea. His current research interests are RF CMOS noise modeling and circuit design.



Byung-Gook Park (M'90) received the B.S. and M.S. degrees in electronics engineering from Seoul National University, Seoul, Korea, in 1982 and 1984, respectively, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1990. From 1990 to 1993, he was with AT&T Bell Laboratories, Murray Hill, NJ, where he contributed to the development of 0.1- μm CMOS and its characterization. From 1993 to 1994, he was with Texas Instruments, Dallas, TX, developing 0.25- μm CMOS. In 1994, he joined the School of Electrical Engineering, Seoul National University, as an assistant professor. He is currently a full professor. He has been in charge of the research of Inter-university Semiconductor Research Center (ISRC) in Seoul National University since 2003 as the chief of the research department. His current research interests are nanoscale CMOS devices, Si single-electron devices, nonvolatile memory devices, and organic electroluminescent displays. Dr. Park was a member of the International Electron Devices Meeting Subcommittee on Solid State Devices from 2001 to 2002 and worked for Silicon Nanoelectronics Workshop 2005 as a program chair.



Jong Duk Lee received the Ph.D. degree from the Department of Physics at the University of North Carolina at Chapel Hill in 1975. He was an Assistant Professor in the Department of Electronics Engineering at Kyungpook National University from 1975 to 1978. In 1978, he studied microelectric technology in HP-ICL at Palo Alto, CA, USA, and soon afterward worked for the Korea Institute of Electronic Technology (KIET) as the director of the semiconductor division. He established the KIET Kumi Facility and introduced the first polysilicon gate technology in Korea by developing 4K SRAM, 32K and 64K Mask ROM's, and one-chip 8-bit microcomputer. In July 1983, he moved to the Department of Electronics Engineering of Seoul National University, which has been merged to School of Electrical Engineering in 1992, where he is now a Professor. He established the Inter-university Semiconductor Research Center (ISRC) in 1985, and served as the director from 1987 to 1989. He served as the chairman of the Electronics Engineering Department from 1994 to 1996. He worked for Samsung SDI Co., Ltd. as the Head of Display R&D Center for a year on the leave of SNU in 1996. He was the member of the steering committee for IVMC (International Vacuum Microelectronics Conference) from 1997-2001 and KCS (Korean Conference on Semiconductors) from 1998-2008. He was the conference chairman of IVMC '97 and KCS '98 who led the IVMC '97 and the KCS '98 successfully. He was also the member of IEDM (International Electron Devices Meeting) Subcommittee on Detectors, Sensors and Displays operated by IEEE Electron Devices Society from 1998 to 1999. He was elected to the first president of the Korean Information Display Society in June 1999 and had served until Dec. 31, 2001. His current research interests include sub-0.1 μm CMOS structure and technology, CMOS image sensors, FED (Field Emission Display), and organic LEDs and TFTs. Now he is a member of IEEE, ECS, AVS, SID, KPS, KVS, IEEK, and KSS.



Hyungcheol Shin received the B.S. and M. S. degree in electronics engineering from Seoul National University, Seoul, Korea, in 1985 and 1987, respectively, and the Ph. D. degree in electrical engineering from the University of California,

Berkeley, in 1993. From 1994 to 1996, he was with Motorola Advanced Custom Technologies, as a Senior Device Engineer. In 1996, he joined the Department of Electrical Engineering and Computer Sciences at the Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1996 as an Assistant Professor. During his sabbatical leave from 2001 to 2002, he was with Berkana Wireless, CA, as a Staff Scientist in charge of CMOS RF modeling. In 2003, he joined the Department of Electrical Engineering and Computer Science at the Seoul National University, Seoul, as an Associate Professor, where he is a Professor. His current research interests include RF and noise characteristics in nano-scale CMOS devices and circuits. He has published over 300 technical papers in international journals and conference proceedings and also wrote a chapter in a Japanese book on plasma charging damage and a Korean book on semiconductor devices. He has served as a committee member of several international conferences, including International Electron Devices Meeting. He is a Lifetime Member of IEEK and received the Second Best Paper Award from the American Vacuum Society in 1991. He also received the Excellent Teaching Award from the Department of Electrical Engineering and Computer Sciences at KAIST in 1998 and Seoul National University in 2005. In 1999, he received The Haedong Paper Award from the Institute of Electronics Engineers of Korea (IEEK). He is listed in Who's Who in the World.