Extraction of Substrate Parameters for RF MOSFETs Based on Four-Port Measurement

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***Abstract*—In this work, a new method for extracting substrate parameters of radio frequency (RF) metal oxide semiconductor field effect transistors (MOSFETs) based on four-port measurement is presented. A T-liked substrate resistance network is used and the values of all components in the cold MOSFETs were extracted directly from the four-port data between 250 MHz and 8.5 GHz. The output admittance Y_{22} can be well modeled up to 26.5 GHZ based on the extracted substrate resistances and the other extrinsic capacitances extracted from an active device.**

***Index Terms*—Four-port measurement, radio frequency (RF) metal oxide semiconductor field effect transistors (MOSFETs), substrate resistance.**

I. INTRODUCTION

It IS known that the substrate resistances have significant effect on output characteristics of radio frequency (RF) metal oxide semiconductor field effect transistors (MOSFETs) and can't be ignored. Recently, several extraction methods of substrate resistances have been reported [1]–[5]. However, the substrate resistances were simplified to a single substrate resistance [1]–[3] or were calculated by process parameters [4], earlier reports even optimized substrate resistances by curve fitting techniques [6]. It is due to that RF MOSFETs were always measured in conventional two-port common source configuration. As the source and substrate terminals are connected together, each resistance components in the entire substrate resistances network, such as resistances from source and drain to body, and body series resistance itself, will not be able to separate according to the insufficient information provided by two-port measurement data. In this work, an extraction method based on four-port measurement is proposed. All the components of the substrate network including junction capacitances and substrate resistances can be directly extracted from measured raw data.

II. FOUR-PORT MEASUREMENT AND EXTRACTION METHOD

In this study, the layout of the RF MOSFET is designed as gate, drain, source and body were connected individually to four signal pads. These four signal pads incorporated with a reference ground form a four-port ground-signal-ground (GSG) test structure and the RF MOSFET can be treated as a four-port device and characterized by four-port measurement [7]. Fig. 1 shows a small-signal equivalent circuit of a four-port MOSFET, in which g_{m} represents the transconductance and R_{ch} is the channel resistance. C_{gs} and C_{gd} represent the gate to source and gate to drain capacitances, respectively. C_{gb} is the capacitance between gate and body. C_{sb} and C_{db} represent the junction capacitance of source and drain, respectively. There is also a T-liked substrate resistance network consists of three resistances R_{sb}, R_{db}, and R_{bb}, which represent resistances from source and drain to body, and body series resistance, respectively.

A 4×4 Y-parameter matrix shown in (1) which represents the DUT can be obtained by four-port measurement and proper pad de-embedding.

$$\begin{bmatrix} i_g \\ i_{\mathrm{D}} \\ i_S \\ i_B \end{bmatrix} = \begin{bmatrix} Y_{\mathrm{GG}} & Y_{GD} & Y_{GS} & Y_{GB} \\ Y_{\mathrm{DG}} & Y_{\mathrm{DD}} & Y_{DS} & Y_{DB} \\ Y_{\mathrm{SG}} & Y_{\mathrm{SD}} & Y_{\mathrm{SS}} & Y_{SB} \\ Y_{BG} & Y_{\mathrm{BD}} & Y_{\mathrm{BS}} & Y_{\mathrm{BB}} \end{bmatrix} \begin{bmatrix} v_g \\ v_{\mathrm{D}} \\ v_S \\ v_B \end{bmatrix}. \tag{1}$$

While the bias voltage on each terminal is zero (cold device), the components inside the dash box of the equivalent circuit can be ignored. According to the definition of Y-parameters and (1), the 16 Y-parameters in (1) which represent the equivalent circuit in Fig. 1 can be obtained. However, six independent Y-parameters are sufficient to extract the components in the equivalent circuit for a cold device. Six independent Y-parameters including Y_{GG}, Y_{SG}, Y_{DG}, Y_{BS}, Y_{BD}, and Y_{SD} were derived in terms of the components in the small signal equivalent circuit of a cold device. The higher order terms of $(\omega C_{\mathrm{x}} R_{\mathrm{x}})$ were neglected because they are much smaller than $\omega C_{\mathrm{x}} R_{\mathrm{x}}$ and $(\omega C_{\mathrm{x}} R_{\mathrm{x}})^2$ within the measurement frequency range. And the six Y-parameters can be approximated as

$$\mathrm{Im}\,[Y_{\mathrm{GG}}] \approx j\omega\,(C_{\mathrm{gso}} + C_{\mathrm{gdo}} + C_{\mathrm{gbo}}) \tag{2}$$

$$\mathrm{Im}\,[Y_{\mathrm{SG}}] \approx -j\omega C_{\mathrm{gso}} \tag{3}$$

$$\mathrm{Im}\,[Y_{\mathrm{DG}}] \approx -j\omega C_{\mathrm{gdo}} \tag{4}$$

$$\begin{aligned} Y_{\mathrm{BS}} \approx\, & j\omega C_{sbo} + \omega^2 {C_{sbo}}^2 (R_{\mathrm{sb}} + R_{\mathrm{bb}}) \\ & + \omega^2 C_{sbo} C_{dbo} R_{\mathrm{bb}} \end{aligned} \tag{5}$$

$$\begin{aligned} Y_{\mathrm{BD}} \approx\, & j\omega C_{dbo} + \omega^2 {C_{dbo}}^2 (R_{\mathrm{db}} + R_{\mathrm{bb}}) \\ & + \omega^2 C_{sbo} C_{dbo} R_{\mathrm{bb}} \end{aligned} \tag{6}$$

$$\mathrm{Re}\,[Y_{\mathrm{SD}}] \approx \omega^2 C_{sbo} C_{dbo} R_{\mathrm{bb}}. \tag{7}$$

The footnote "o" in C_{gso}, C_{gdo}, C_{gbo}, $C_{sbo,}$, and C_{dbo} denotes the values of these components in a cold device. According to (2)–(4), C_{gso}, C_{gdo} and C_{gbo} can be directly

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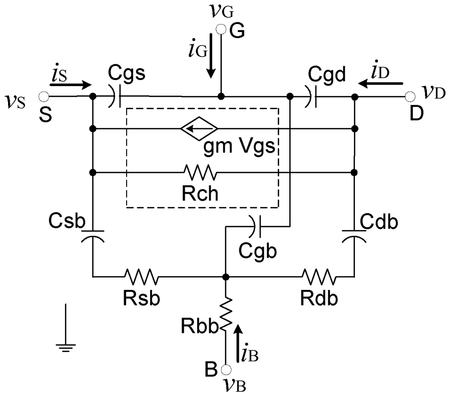

Fig. 1. Small-signal equivalent circuit of a four-port RF MOSFET. The components in dashed box are corresponded to the device operated in saturation region, and they are ignored while zero bias voltage is applied on each terminal.

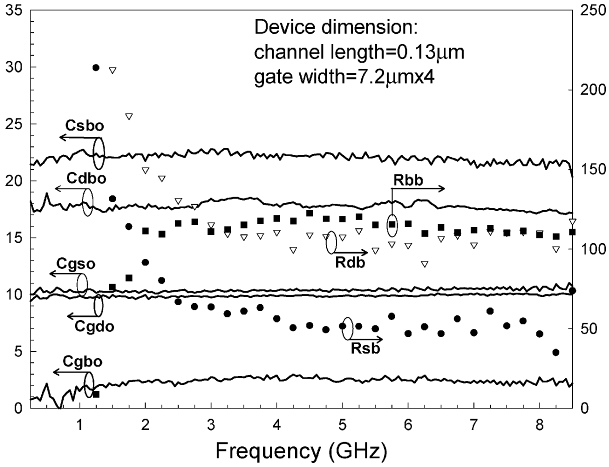

Fig. 2. Frequency dependence of C_{gso}, C_{gdo}, C_{gb}, C_{sb}, C_{db}, R_{sb}, R_{db}, and R_{bb} of a cold device extracted from Y-parameters measured by four-port measurement.

extracted from the imaginary part of Y_{SG}, Y_{DG} and Y_{GG}. From $\mathrm{Im}[Y_{\mathrm{BS}}]$ and $\mathrm{Im}[Y_{\mathrm{BD}}]$, C_{sbo} and C_{dbo} are also extracted. As the values of these five capacitances are known, R_{bb} can be obtained by (7), then R_{sb} and R_{db} can be extracted according to (5) and (6).

III. RESULTS AND DISCUSSIONS

Three 0.13-μm nMOSFETs with different gate widths were characterized on wafer by Agilent E5071B 4-port network analyzer and cascade microwave probes from 250 MHz to 8.5 GHz. The gate widths of the devices are 3.6 μm× 4, 7.2 μm× 4, and 12 μm× 4, respectively. A 16-entry 4×4 S-parameter matrix was obtained and transformed to 4×4 Y-parameters. The parasitics of test pad were de-embedded by open and short dummy structures. Fig. 2 shows the extracted results of C_{gso}, C_{gdo}, C_{gbo}, C_{sbo}, C_{dbo}, R_{sb}, R_{db}, and R_{bb} for the device with gate width of $7.2 * 4$ μm. The values of the capacitances are almost constant among the measuring frequency. However, the extracted R_{sb}, R_{db}, and R_{bb} below 2.5 GHz are irregular because the effect of substrate resistances on the output characteristics of RF MOSFETs is minor at lower frequency range. The real parts of Y_{BD}, Y_{BS} and Y_{BB} are very small at frequency below 2.5 GHz, and will be limited by the measurement error. It makes the values of substrate resistances are valid from 2.5 GHz to 8.5 GHz in this study.

TABLE I
PARAMETERS EXTRACTED FROM COLD DEVICES

	C_{gso} (fF)	C_{gdo} (fF)	C_{sbo} (fF)	C_{dbo} (fF)	C_{gbo} (fF)	R_{db} (Ω)	R_{sb} (Ω)	R_{bb} (Ω)
M1 $3.6\mu m\times 4$	5.9	5.5	11.5	9.2	1.1	260	160	175
M2 $7.2\mu m\times 4$	10.3	9.8	22	18	2.5	100	50	115
M3 $12\mu m\times 4$	16.3	15.6	37	29.5	4.5	50	15	77

The extracted parameters of three 0.13 μm RF MOSFETs with different dimensions. The gate widths of these three devices are 3.6×4 μm, 7.2×4 μm, 12×4 μm, respectively.

Table I lists the capacitances and resistances extracted from the three cold devices with different dimensions. Because of the even gate finger number, there is one more source junction than the drain junctions. These three devices are structurally unsymmetrical, the extracted values do tell this point. The scalability of these parameters with the device dimension is also observed.

The substrate resistances are unable to be extracted from a MOSFET biased in active region, because of the more significant intrinsic components (g_{m}, R_{ch}) in active region. However, since the substrate resistances have weak dependence on the bias condition [1], the corresponding values extracted from a cold device can be used in an active device. To verify the extracted substrate resistances, the bias dependent components g_{m}, R_{ch}, C_{gd}, C_{gs}, C_{db}, C_{sb}, and C_{gb} in Fig. 1 were extracted from 4-port measurement data of the four-port device biased in active region ($\mathrm{V}_g = \mathrm{V_D} = 1$ V, $\mathrm{V}_S = \mathrm{V}_B = 0$ V). R_{ch} was directly extracted from the real part of Y_{DD} at low frequency range while the substrate coupling effect is minor [6]. g_{m} was extracted from the real part of Y_{DG} at low frequency range [6]. And the C_{gd}, C_{gs}, C_{db} were extracted according to (2)–(4). C_{sb}, and C_{gb} were extracted from the imaginary part of (5) and (6). The equivalent circuit in Fig. 1 incorporated with the substrate resistances extracted from cold devices and the bias dependent components extracted from active devices were simulated by ADS software. The simulation data of output admittance Y_{DD} were compared with the output admittance of common source RF MOSFETs measured by conventional two-port method. The results were shown in Fig. 3 and good agreement between the simulation and measurement data up to 26.5 GHz was obtained. The modeling results of bias dependence of Y_{DD} are also shown in the inset of Fig. 3.

The validity of (5)–(7) were verified by comparing the four-port measurement data and the simulated data of the equivalent circuit of cold devices (Fig. 1 with g_{m}, R_{ch} removed). The results of M3 devices were shown in Figs. 4 and 5. It indicates the assumption of neglected the higher order terms of $(\omega C_{\mathrm{x}} R_{\mathrm{x}})$ is reasonable within the measurement frequency (< 8.5 GHz). Figs. 4 and 5 also demonstrate the results of the six Y-parameters of active M3 device. The differences between measurement and simulated data were also small.

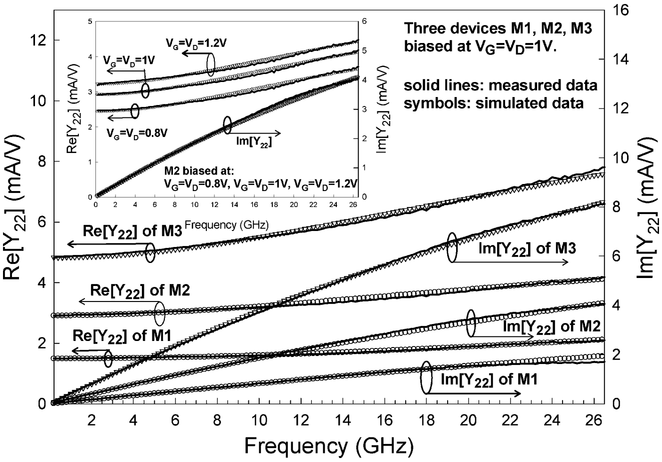

Fig. 3. Measured and simulated Y_{22} of three different conventional two-port common-source RF MOSFETs biased at $V_g = 1$ V, $V_D = 1$ V. The two-port simulation is performed based on the proposed small-signal equivalent circuit in Fig. 1 with the source and substrate terminals grounded. The modeling results of the device M2 with different bias are also shown in the inset.

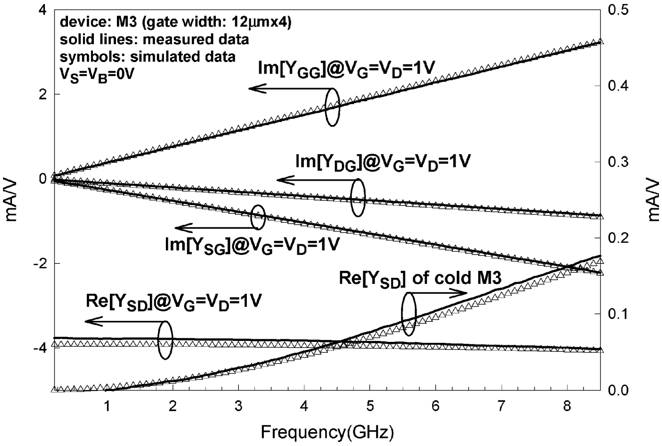

Fig. 4. Measured and simulated $\mathrm{Im}[Y_{GG}]$, $\mathrm{Im}[Y_{DG}]$, $\mathrm{Im}[Y_{SG}]$, $\mathrm{Re}[Y_{SD}]$ of M3 device, the $\mathrm{Re}[Y_{SD}]$ include both active and cold condition.

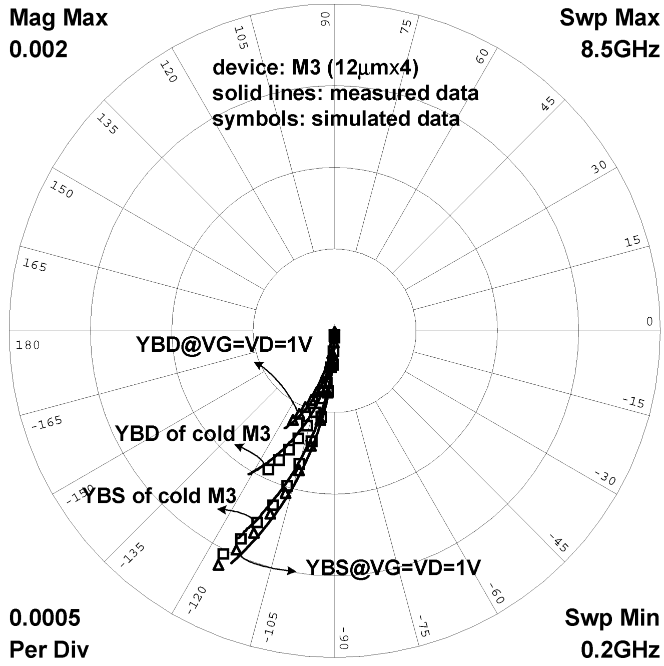

Fig. 5. Measured and simulated YBS and YBD of M3 device in both active and cold condition.

IV. CONCLUSION

An extraction method for substrate resistances and extrinsic capacitances of RF MOSFETs based on four-port measurement are demonstrated for the first time. A T-liked substrate resistance network is proposed and the components are extracted from four-port measurement data directly and simply. The extracted values show scaling with the device dimension, and the proposed substrate network well models the substrate loss of RF MOSFETs up to 26.5 GHz for different dimensions and bias voltages.

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