A Novel Approach to Extracting Small-Signal Model Parameters of Silicon MOSFET's

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***Abstract*—We present a simple and accurate method to extract a small-signal equivalent circuit model of Si MOSFET's, based on the novel approach to determining parasitic inductances and resistances by fitting the frequency response of new analytic expressions with Z-parameters. This method is proposed to overcome the serious problem that conventional cold-FET methods cannot be applied for MOSFET's, and is also superior to the traditional optimization of the entire model parameters to fit the measured S-parameters. In particular, this technique is simple and reliable because no additional measurements are needed. The excellent correspondence is achieved between modeled and measured S-parameters from 0.5 to 39.5 GHz.**

***Index Terms*— MOSFET, parameter extraction, small-signal model.**

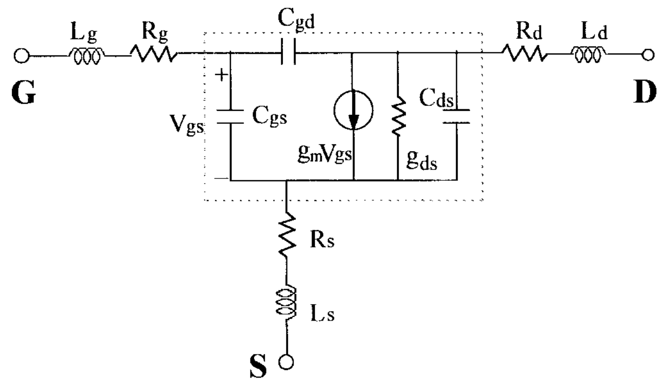

Fig. 1. A small-signal equivalent circuit model for a Si MOSFET.

I. Introduction

FOR MICROWAVE circuit applications, the development of silicon MOSFET's is currently going toward the increase of high-frequency performance under the strong driving force of robust and low-cost Si technologies [1], [2]. For the direct extraction of small-signal MOSFET equivalent circuits from S-parameters, parasitic inductances and resistances are initially determined and subsequently the rest of parameters are extracted from analytical formulations [3], [4]. The cold-FET method using S-parameter measurement of devices with forward-biased gate at $V_{\rm DS} = 0$ have been widely investigated to extract these inductances and resistances for GaAs MESFET's and HEMT's [3], [4]. However, this cold-FET method cannot be applicable to extract these parasitics of Si MOSFET's, because the dc gate current cannot flow due to the isolation between gate and rest of device. As a modified approach [5] for Si MOSFET's, parasitic resistances have been extracted from S-parameters at zero bias condition ($V_{\rm GS} = V_{\rm DS} = 0$), but the extraction of inductances has not been presented. This modified method requires extra measurements and may produce the uncertainties due to possible bias dependences in the extraction of source and drain resistances [6]. In this letter, as a different approach, we present a robust extraction of inductances and resistances for a Si MOSFET without any additional measurements, by performing the different curve-fitting to the frequency response of their Z-parameter equations for each parameters.

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II. Parameter Extraction

N-MOSFET's were fabricated on p-type 2 kΩ·cm high-resistivity (100) Si wafers using a standard twin-well CMOS process. The layout for n^+ poly gate is designed using multiple finger type with 0.8 μm length and 200 μm total gate width. S-parameters are measured at various bias conditions using on-wafer RF probes from 0.5 to 39.5 GHz, but in this letter we illustrate only two data sets measured at two different bias ($V_{\rm GS} = 1.0$ V, $I_{\rm ds} = 2.94$ mA, and $V_{\rm DS} = 5.0$ V for data set A; $V_{\rm GS} = 3.0$ V, $I_{\rm ds} = 31.9$ mA, and $V_{\rm DS} = 5.0$ V for data set B). In order to remove pad parasitics, the accurate de-embedding technique was carried out by subtracting parasitics of open pad structure without a device from measured S-parameters [7]. Fig. 1 shows a MOSFET small-signal equivalent circuit where $g_m = g_{\rm mo}\exp(-j\omega\tau)$.

The equivalent circuit in Fig. 1 can be expressed by the following Z parameters:

$$Z_{11} = R_g + R_s + j\omega(L_g + L_s) + \frac{g_{\rm ds} - j\omega(C_{\rm gd} + C_{\rm ds})}{D} \quad (1)$$

$$Z_{12} = R_s + j\omega L_s + \frac{j\omega C_{\rm gd}}{D} \quad (2)$$

$$Z_{21} = R_s + j\omega L_s - \frac{g_m - j\omega C_{\rm gd}}{D} \quad (3)$$

$$Z_{22} = R_d + R_s + j\omega(L_d + L_s) + \frac{j\omega(C_{\rm gs} + C_{\rm gd})}{D} \quad (4)$$

where $D = Y_{11}^iY_{22}^i - Y_{12}^iY_{21}^i = -\omega^2(C_{\rm gs}C_{\rm ds} + C_{\rm gs}C_{\rm gd} + C_{\rm gd}C_{\rm ds}) + j\omega[g_mC_{\rm gd} + g_{\rm ds}(C_{\rm gs} + C_{\rm gd})]$, which is calculated from Y^i-parameters for intrinsic device in dotted box of Fig. 1.

Using (1)–(4), the following equations with real term are derived for resistances:

$$\mathrm{Re}(Z_{12}) = R_s + \frac{A_s}{\omega^2 + B} \tag{5}$$

$$\mathrm{Re}(Z_{22} - Z_{12}) = R_d + \frac{A_d}{\omega^2 + B} \tag{6}$$

$$\mathrm{Re}(Z_{11} - Z_{12}) = R_g + \frac{A_g}{\omega^2 + B}. \tag{7}$$

Also, the equations with imaginary term are derived for inductances as follows:

$$\frac{1}{\omega}\mathrm{Im}(Z_{12}) = L_s - \frac{E_s}{\omega^2 + B} \tag{8}$$

$$\frac{1}{\omega}\mathrm{Im}(Z_{22} - Z_{12}) = L_d - \frac{E_d}{\omega^2 + B} \tag{9}$$

$$\frac{1}{\omega}\mathrm{Im}(Z_{11} - Z_{12}) = L_g - \frac{E_g}{\omega^2 + B} - \frac{F_g}{\omega^2(\omega^2 + B)} \tag{10}$$

where B, A_s, A_d, A_g, E_s, E_d, E_g, and F_g are expressed as functions of intrinsic parameters and are constant values at fixed bias because intrinsic parameters are independent of frequency.

From the above equations, resistances and inductances are defined as the limiting values at infinite frequency. However, it is very difficult to measure these values directly because of the frequency limitations of the Network Analyzer. Thus, we developed an alternative approach that determines the limiting values by fitting their plot of (5)–(10) versus frequency over the measurement frequency range. The extraction accuracy is improved by fitting the data out to the higher frequencies above f_T, because the frequency-dependent terms related to intrinsic device in (5)–(10) are greatly reduced in this high-frequency region. The number of unknowns in the individual curve-fitting for each equation is much smaller than that in the traditional optimization of the full model parameters to fit measured S-parameters at a time using commercial software. Therefore, our approach is superior to the traditional method, which, with the large number of unknowns, may produce nonphysically extracted values depending on the initial values and numerical algorithm [3].

The extracted B values from each fitting curves ought to be theoretically same as shown in (5)–(10), but may differ each other because of possible errors associated with pad de-embedding or S-parameter measurement. Unlike conventional methods, this extraction accuracy can be easily checked by monitoring the degree of deviations in these B values. In this work, reasonably small deviations are found, indicating the reliable extraction. By finding the constant terms of (5)–(9) through the individual curve fits in Figs. 2 and 3, parasitics except for L_g are easily obtained to be $R_s = 6.3\ \Omega$, $R_d = 12.2\ \Omega$, $R_g = 20.1\ \Omega$, $L_s = 52$ pH, $L_d = 93$ pH for data set A; $R_s = 8.4\ \Omega$, $R_d = 11.1\ \Omega$, $R_g = 20.4\ \Omega$, $L_s = 51$ pH, $L_d = 99$ pH for data set B.

The gate inductance is extracted from the measured data at high frequencies, where the third term of (10) can be neglected compared to the second one. In the actual extraction, L_g of 108 pH for data set A and 110 pH for data set B were determined by performing the simple fitting repeatedly for (10) without the third term while increasing a lower bound frequency until the B value in (10) reaches that in the other equations. Except for this data, Figs. 2 and 3 show excellent correspondence between measured and fitted curves, which demonstrates the accuracy of the extracted values.

We have applied our method in several other devices with shorter gate length of 0.6 μm or different gate width of 10 to 600 μm, and found good agreements between measured and fitted curves in the curve-fitting for each parameters. Thus, we

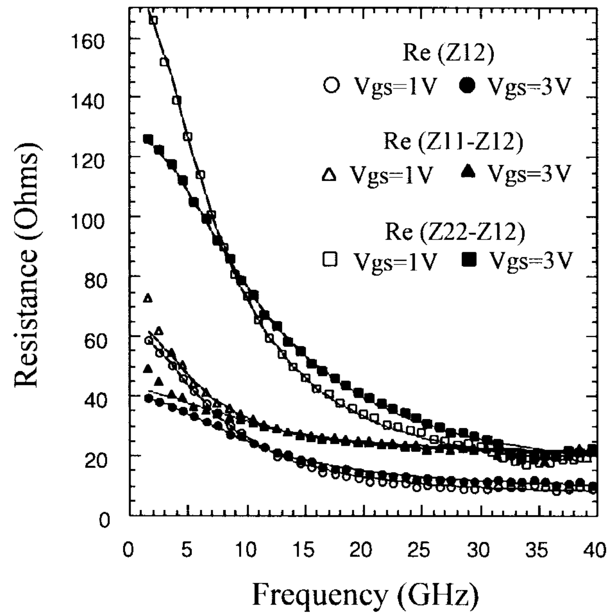

Fig. 2. The measured data and fitting curves of (5)–(7) versus frequency for extracting parasitic resistances for data sets A and B. The solid lines represent curve fits to their measured data.

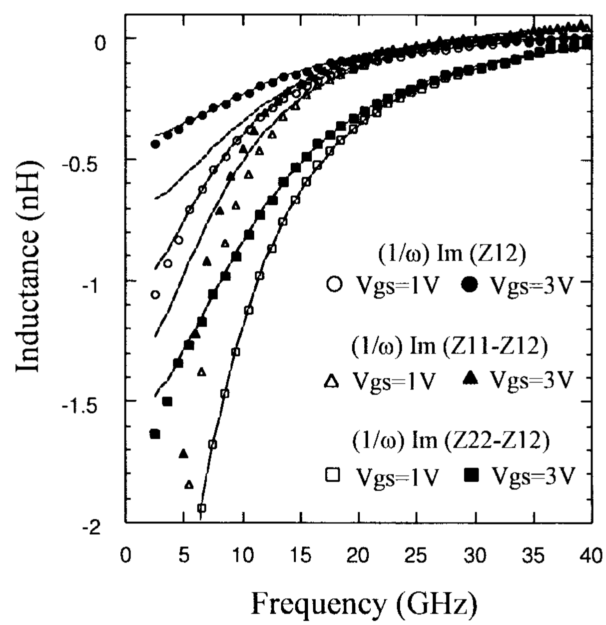

Fig. 3. The measured data and fitting curves of (8)–(10) versus frequency for extracting parasitic inductances for data sets A and B. The solid lines for $(1/\omega)\mathrm{Im}(Z_{12})$and $(1/\omega)\mathrm{Im}(Z_{22} - Z_{12})$ represent curve fits to their whole measured data, but the line for $(1/\omega)\mathrm{Im}(Z_{11} - Z_{12})$ indicates the fit of (10) without the third term to the high-frequency measured data.

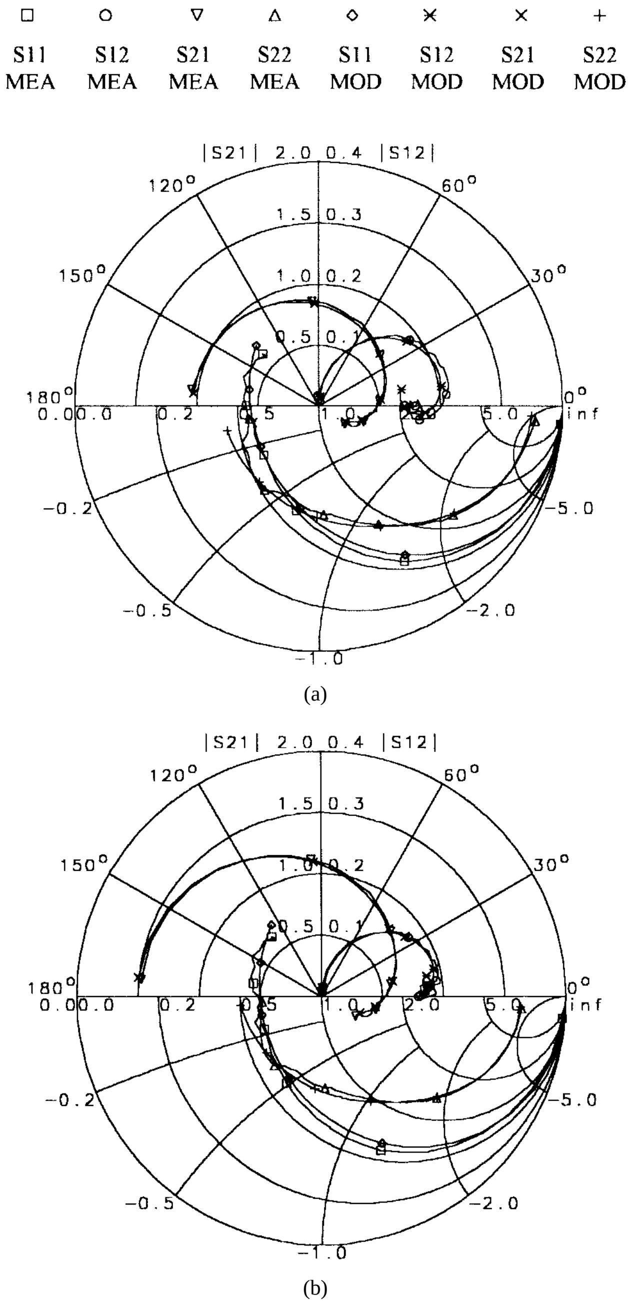

Fig. 4. Measured (MES) and modeled (MOD) S-parameters from 0.5 to 39.5 GHz for the following bias points: (a) $V_{\rm GS} = 1$ V and $V_{\rm DS} = 5$ V (data set A) and (b) $V_{\rm GS} = 3$ V and $V_{\rm DS} = 5$ V (data set B).

believe that this method may work for other devices. After the extracted resistances and inductances are subtracted from measured S-parameters, intrinsic parameters in Fig. 1 were determined by the previously reported method using analytical equations of Y^i-parameters [5]. These extracted parameters are $C_{\rm gs} = 0.152$ pF, $C_{\rm gd} = 0.051$ pF, $C_{\rm ds} = 0.068$ pF, $g_{\rm ds} = 1.47$ mS, $g_{\rm mo} = 12.2$ mS, and $\tau = 4.3$ ps for data set A; $C_{\rm gs} = 0.19$ pF, $C_{\rm gd} = 0.051$ pF, $C_{\rm ds} = 0.071$ pF, $g_{\rm ds} = 2.44$ mS, $g_{\rm mo} = 20.2$ mS, and $\tau = 3.5$ ps for data set B. In Fig. 4, two sets of modeled S-parameters agree well with their measured S-parameters from 0.5 to 39.5 GHz. Good correspondence verifies that all parameters extracted from our technique are accurate and reliable.

III. Conclusion

A simple technique has been described for determining small-signal model parameters of silicon MOSFET's directly. This technique is based on the determination of parasitic inductances and resistances using the independent curve-fitting of their new analytical Z-parameter formulations over the frequency range of measurement. Unlike previous methods that need additional dc or S-parameter measurement, this new technique requires only one set of S-parameters measured at normal operating bias point for extracting model parameters. This allows us to extract equivalent circuit parameters in a more direct and straightforward manner without possible uncertainties due to extra measurements.

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