

Microwave small-signal modelling of FinFETs using multi-parameter rational fitting method

D. Deschrijver, G. Avolio, D. Schreurs, T. Dhaene, G. Crupi and L. Knockaert

An effective approach based on a multi-parameter rational fitting technique is proposed to model the microwave small-signal response of active solid-state devices. The model is identified by fitting multi-bias scattering-parameter measurements and its analytical expression is implemented in a commercial microwave circuit simulator. The approach has been applied to the modelling of a silicon-based FinFET, and an excellent agreement is obtained between the measured data and model predictions.

Introduction: To continue the aggressive down-scaling of CMOS devices into the nanometer regime while counteracting short-channel effects, innovative strategies have been proposed in the last few years. Amongst others, novel structures have been developed and as a result the FinFET has emerged as a promising solution [1, 2] that is compatible with the standard CMOS technological process. A lot of studies have addressed the extraction of reliable and accurate FinFET models in the microwave frequency range. Typically, compact models [3] or equivalent circuit models (ECM) are employed to predict the microwave small-signal behaviour of active devices and both approaches are based on multi-bias multi-frequency scattering (S-) parameter measurements [4]. However, although measurements-based, some knowledge concerning the physics of the device is still required. On the contrary, black-box or behavioural approaches can be completely independent of the device's physics and have a broad validity range. To calculate a model, the use of a multi-parameter rational fitting technique, called multivariate orthonormal vector fitting [5] is investigated. Although the method was originally designed for the macromodelling of passive linear systems, this Letter shows that the approach can be promisingly applied to the compact modelling of active devices. Numerical results confirm that the calculated models are highly accurate. The models can be straightforwardly implemented in a circuit simulator.

Model description: Multi-parameter fitting techniques represent a successful strategy to approximate the behaviour of structures and devices in the high-frequency range. Hence, the multi-bias scattering parameters S_{ik} are approximated by a parameterised multivariate model. The model response changes as a function of frequency (f) and two electrical parameters: the gate voltage (V_G) and drain voltage (V_D).

$$S_{ik}(f, V_G, V_D) = \frac{N(\theta, f, V_G, V_D)}{D(\theta, f, V_G, V_D)} \quad (1)$$

$$= \frac{\sum_{n_1=1}^{P_f} \sum_{n_2=1}^{P_{V_G}} \sum_{n_3=1}^{P_{V_D}} c_{n_1 n_2 n_3} \Phi_{n_1}(f) \Psi_{n_2, n_3}(V_G, V_D)}{\sum_{n_1=1}^{P_f} \sum_{n_2=1}^{P_{V_G}} \sum_{n_3=1}^{P_{V_D}} \tilde{c}_{n_1 n_2 n_3} \Phi_{n_1}(f) \Psi_{n_2, n_3}(V_G, V_D)}$$

The functions Φ and Ψ are rational basis functions, which are defined in [5]. They describe the frequency-dependent and parameter-dependent characteristics of the data, respectively. Note that the number of basis functions (P) is chosen for each variable independently, according to the dynamic variation of the data. To identify the unknown model parameters $\theta = \{c'_{n_1 n_2 n_3}, \tilde{c}'_{n_1 n_2 n_3}\}$ in (1), the method in [5] is applied. It starts from an initial guess of model parameters θ^0 , and computes updated values in successive iteration steps ($t = 0, \dots, T$) by solving several least-squares problems:

$$\arg \min_{\theta} \left| \frac{N(\theta, f, V_G, V_D)}{D(\theta^{-1}, f, V_G, V_D)} - \frac{D(\theta, f, V_G, V_D)}{D(\theta^{-1}, f, V_G, V_D)} S_{ik}(f, V_G, V_D) \right|^2 \quad (2)$$

As the iteration proceeds, model (1) becomes an increasingly accurate approximation of the data. This process is repeated until convergence is reached. The procedure is well-known in the literature as the Sanathanan-Koerner iteration, and an elaborate explanation can be found in [5] and [6]. By combining (2) with a suitable weighting

scheme, the mean relative error per bias point can be minimised,

$$E_{ik}(V_G, V_D) = \frac{1}{N_f} \sum_{freq} \left| \frac{S_{ik}^{meas}(f, V_G, V_D) - S_{ik}^{model}(f, V_G, V_D)}{S_{ik}^{meas}(f, V_G, V_D)} \right| \quad (3)$$

where N_f corresponds to the number of the frequency samples per bias point.

Results: The investigated device is a triple-gate FinFET fabricated in fully depleted silicon-on-insulator nMOSFET technology [4] with a 60 nm gate length and a 45.6 μm gate width. Multi-bias and multi-frequency S-parameters have been measured with a vector network analyser. The frequency was swept from 500 MHz to 50 GHz and both the DC gate (V_G) and drain voltages (V_D) were varied from 0 to 1.2 V. The extracted model has been implemented and simulated with the Advanced Design System[®] (ADS) circuit simulator. To verify the capability of the model to reproduce experimental results for the tested active solid-state device over a wide range of the input parameters, the comparison between measurements and simulations is illustrated in Figs. 1–3. Particularly, in Figs. 1 and 2 the modelled and measured S-parameters are shown against the frequency and at two different bias conditions (i.e. $V_G = 0$ V and $V_D = 0$ V, $V_G = 0.6$ V and $V_D = 0.6$ V).

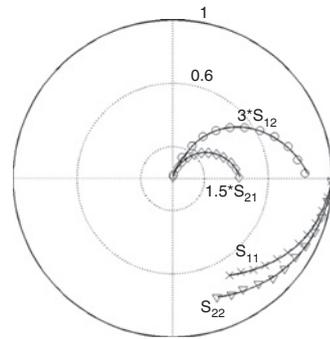


Fig. 1 Frequency dependent S-parameters at $V_G = 0$ V and $V_D = 0$ V: model predictions (line) against measurements (symbols)

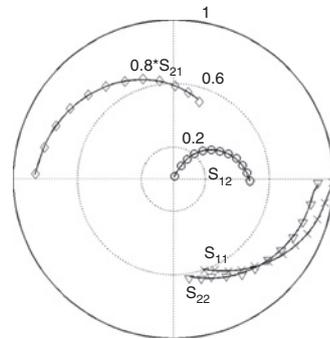


Fig. 2 Frequency dependent S-parameters at $V_G = 0.6$ V and $V_D = 0.6$ V: model predictions (line) against measurements (symbols)

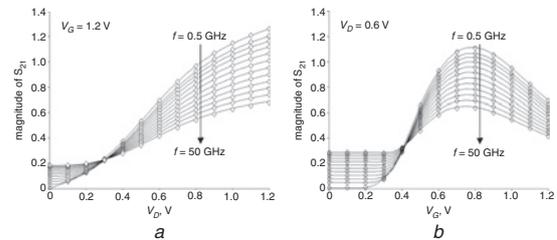


Fig. 3 Magnitude of S_{21} against input parameters. $V_G = 1.2$ V (Fig. 3a); $V_D = 0.6$ V (Fig. 3b)

— model predictions
 ◇ measured S_{21}

In Fig. 3, the magnitude S_{21} is shown against the input parameters with V_G fixed at 1.2 V in Fig. 3a, and V_D fixed at 0.6 V in Fig. 3b. A good agreement between the experiments and the model simulations

is achieved over a wide range of bias and frequency conditions, which further confirms the suitability of the multi-parameter rational fitting approach for modelling active devices. In Table 1, the low values of the relative errors averaged over all the measured bias points and the maximum errors are reported to highlight the level of accuracy obtained with the proposed modelling approach.

Table 1: Percentage average and maximum relative errors

	$E_{\text{avg}}, \%$	$E_{\text{max}}, \%$
S_{11}	0.5	0.8
S_{12}	1.0	2.5
S_{21}	1.1	5.6
S_{22}	0.7	3.3

Conclusion: A robust multi-parameter rational fitting technique has been exploited for modelling the microwave small-signal behaviour of FinFETs. A good agreement between model predictions and experimental data is achieved over a wide range of operating conditions. Furthermore, the model can be readily implemented in a commercial circuit simulator.

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