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An Accurately Scalable Small-Signal Model for Millimeter-Wave HEMTs Based on Electromagnetic Simulation

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Abstract—By using some special passive structures and correction of boundary conditions a novel method to improve the electro-magnetic simulation accuracy is proposed. With this method many substrate parameters, such as thickness, loss, dielectric constant, loss tangent, sheet resistance, square capacitance and conductivity of the metal, can be described more accurately, and many high frequency effects caused by skin effects, parasitic effects, coupling between microstrip lines and fluctuation from the sheet resistance, etc. can also be simulated more precisely. An accurately scalable small-signal model for millimeter wave HEMTs is implemented and presented. Combined with distributed modeling, pulsed IV and S parameter measurements, this model can be made scalable freely. The measurements agree with simulated results very well, which also shows that this method applied to the scalable small signal model has a good consistency and accuracy.

1. INTRODUCTION

As we know, an accurate scalable device model is important and desired for all MMIC (monolithic microwave IC) designers; however, the difficulty of model scaling mainly focuses on two points: how to scale the single gate length of field-effect-transistor and how to scale the number of fingers. Conventional modeling methods are frustrated by several limiting factors: different geometrical structures of the devices make model scaling difficult; self-heating makes static DC IV characteristic scalable inaccurately; the distributed EM coupling effect grows with the frequency and generates bigger error when scaling. Equivalent circuit models are always related to the bias point and working frequency range and therefore limited by them.

Many people have done a lot of works to solve these problems. Some researchers are trying to find the ultimate modeling for devices by solving the Schrodinger and Possion equations, obtaining the circuit level representation of the carriers' movement in the channel. They hope to build a physical model whose scaling is irreverent to the geometrical structures, bias and frequency range. Goasguen et al. [1] tried a full wave method for device modeling and made some achievements. Robin et al. [2] used this method to model the device structure Imtiaz and El-Ghazaly [3], and Cidronali et al. [4] showed some reasonable trends of this method. However, this method encounters many difficulties, since the imperfections of the material and process are not controllable, and current numeric processing technique cannot fully describe the physical mechanism inside the channel. Some commercially available software, such as POSE and SILVCO, is still not able to provide an accurate physical models.

To improve the accuracy of the device scaling, some researchers combined the EM and equivalent circuit methods and created a semi-physical and semi-circuit model. Imtiaz and El-Ghazaly [5] proposed a model by using EM method to simulate the input and output matching network, but this model is not scalable. Laloue et al. [6] presented a method for the gate length and number of gates scaling. Tsai et al. [7] used EM method and generated the 2nd generation models with a less cost but wider frequency

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range. Hoque et al. [8] devised a distributed model for the signal traveling along the gate and achieved a very high accuracy in a fixed biasing supply.

All these efforts use EM method to improve the scalability and accuracy, but the accuracy of the EM simulation itself is not mentioned. It is quite evident that the error of EM simulation will be introduced to the separation of intrinsic and parasitic parameters and reduce the accuracy of scalability simultaneously. This paper proposes a new method to improve the accuracy of scalability by EM simulation based on ADS Moment. The boundary condition will greatly influence the accuracy of EM simulation. To model the parasitic parameter more precisely, the accuracy of EM simulation is analyzed. Conventionally the designer will use the generic substrate parameters provided by the foundry. However, each foundry and process has their subtle differences; the analysis of these differences will greatly contribute to the accuracy of EM simulation and the device modeling.

2. CORRECTION OF BOUNDARY SETTINGS IN EM SIMULATION

Because the accuracy of an EM simulation is closely relevant to the boundary settings, each semiconductor process and material for a same technology have their own subtle differences, so a common substrate setting cannot be applied to all foundries. To solve this problem, we designed some specific passive structure to improve accuracy of substrate setting. By comparing the calculated and measured results, the boundary settings are corrected correspondingly. With this correction, high frequency skin effect, substrate depth, substrate loss, coupling between micro strip lines, conductivity of the metal, parasitic inductance of via, fluctuation of resistors and capacitors can be modeled more accurately.

The purpose of designing those passive structure is to generate the wanted resonate frequency, which can be easily marked in measurement and used to verify the boundary settings. As long as the process is stable, the wanted resonate frequency will maintain the fixed location theoretically and the boundary settings is also unique because those settings need to match all passive structure's EM simulation simultaneously. However, the actual processes always have certain fluctuations, and these normal fluctuations can also impact on the variation of the resonant frequency, and then the material parameters will need to be corrected by statistical analysis through many times of measured results. These structures are shown in Figure 1, and they are high and low impedance lines structures, LC resonate structures, capacitors over the via hole resonating structures, cross resonating structures, fan-shaped resonating structures, air bridge impedance lines, etc.

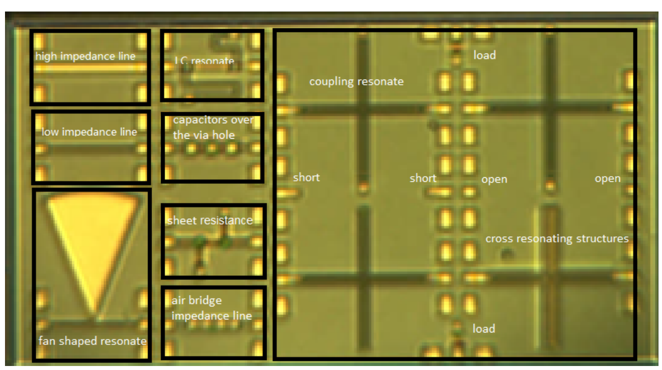
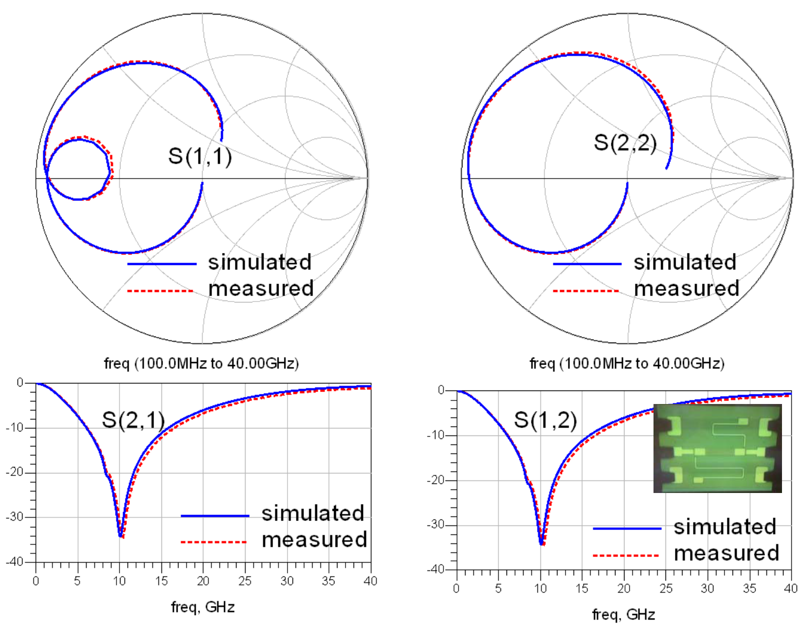


Figure 1. The passive structure for correction of EM simulation.

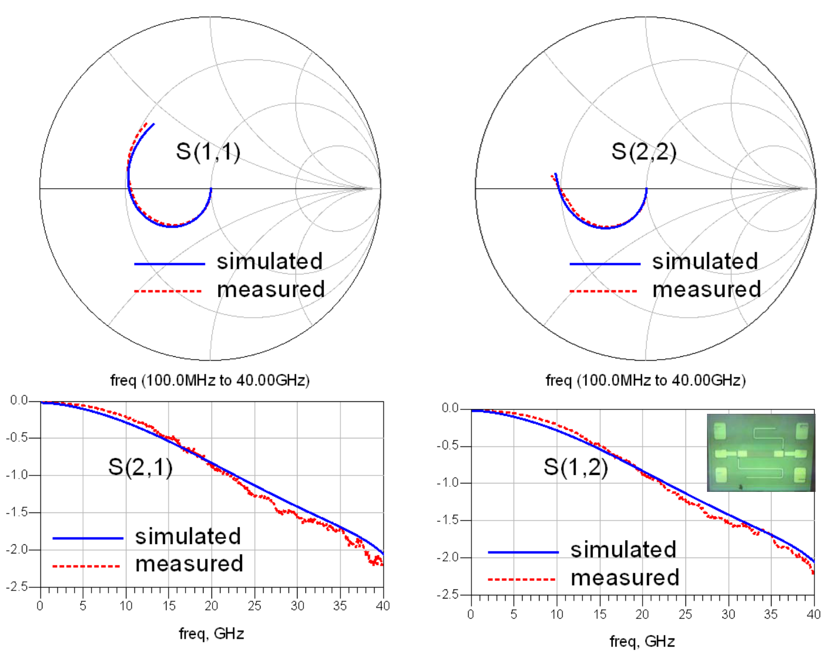
Because these parameters influence each other, the passive structures should be de-embedded by a suitable order. Firstly, the substrate thickness and loss tangent are corrected, secondly the dielectric constant of SiN, then the via inductance, finally the sheet resistance and fringe coupling between metals. Those structures are fabricated using NEDI 0.15 μm pHEMT, and the simulated results are optimized by using ADS Momentum with the measured results. Some fitting results of measured and simulated curve are shown in Figure 2, then the final substrate parameters are derived as the follows: substrate thickness of 53 μm, dielectric constant of 12.8, loss tangent of 0.015, SiN thickness of 0.24 μm, dielectric constant of 6.8, loss tangent of 0.019.

3. SCALABLE MODELING

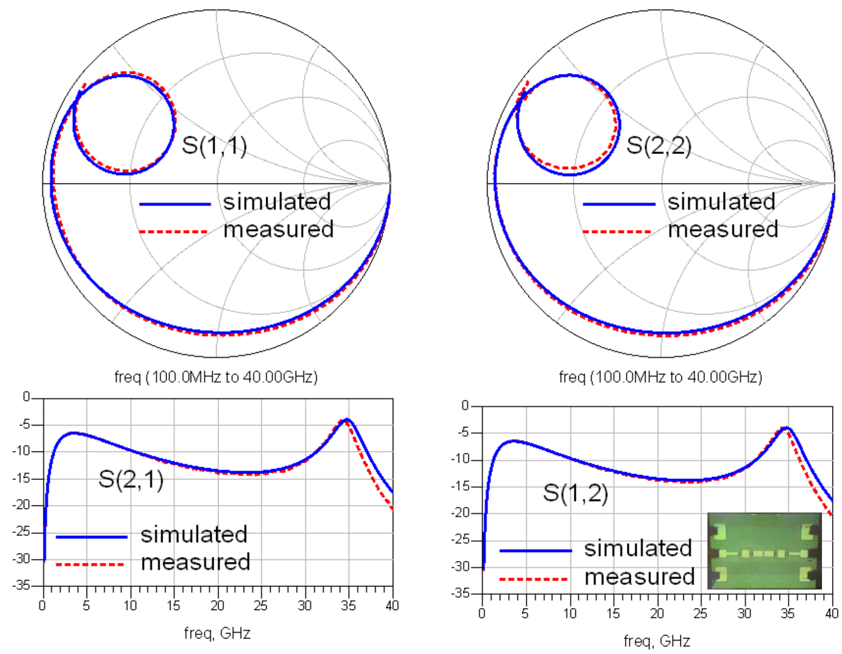
Because the self-heating [9] is inevitable during the static IV measurement, it makes the device IV characteristics difficult to scale precisely. There are also some dispersive errors [10] caused by the low-frequency dispersion between the simulated and measured AC conductances. In the past, a shunt RC network is added to compensate this error [11]. But this method cannot represent accurate characteristics of the conductance versus bias in a wide supply range, which makes this model available for only a limited V_{gs} range. To eliminate the low frequency dispersion effect, some researchers shunt an AC current source [12] to compensate the dispersive error during S parameter simulation. By this way, the device model will extend the range of V_{gs} by separation of the DC and AC simulations. Nevertheless, this method still cannot make the g_m dispersion agree with the R_{ds} dispersion [13, 14], which will always drive the model to nonconvergent.



(a)



(b)



(c)

Figure 2. Fitting results of measured and simulated curve for some passive structure. (a) Short-circuit-lines resonating structure; (b) open-circuit-lines resonating structure; (c) capacitors-over-via resonating structure.

It has been proved that the dispersion effect is caused by the internal defects in the channel: some carriers are trapped in DC condition while released during AC operation, which will make the DC g_m lower than the AC g_m. Pulsed IV and S parameter measurements will solve the dispersion and self-heating problem, realize the IV curves proportional to the gate length and number of gates, and the simulated S parameter matches very well with the measured one at low frequency. The supply range is also extended. In fact, most current device models cannot perfectly characterize the device for full bias voltage supply, especially in a sub-threshold range.

In order to scale the number of gate fingers accurately in the high frequency range, the non-scalable parts must be separated from device layout firstly. Because devices have different active regions, the scaling will be limited seriously, and an EM simulation is used to characterize these non-scalable parts. Figure 3 shows the EM simulated structure of different HEMTs. The finger numbers and gate widths are $2 * 70\,\mu$m, $2 * 80\,\mu$m, $4 * 60\,\mu$m, $4 * 80\,\mu$m, $6 * 50\,\mu$m and $6 * 40\,\mu$m, respectively.

To make the S parameter scalable precisely, pulsed IV and S parameter measurement are applied to these devices. The device layout is partitioned with the above mentioned method. It is believed that different gate fingers in the active range have the same intrinsic behavior. With this assumption, the multi-fingers model is simplified and equivalent to the single finger model. Thus the number of fingers is scalable.

The microwave distributed behavior [15, 16] along the gate and drain must be taken into account during the high frequency modeling. As a result, the distributed equivalent circuit is introduced. Different single gate widths are represented by a set of sub-circuits in serial. And the signal loss along the gate and drain is modeled. An example on a $6 * 50\,\mu$m device is shown in Figure 4.

4. VERIFICATION OF THE MODELS

The pulsed IV curves were tested with $100\,\mu$s duration and 10% duty circle. There are some errors in the linear region because the supply has an internal resistance, and the devices has a certain processing scatter. Therefore, the fitted IV curves at the low voltage region will be affected obviously, especially for the small periphery device. Finally, by releasing the precision in linear region, the HEMT model is mainly extracted on the devices for $2*70\,\mu$m, $2*80\,\mu$m, $4*60\,\mu$m, $4*80\,\mu$m, $6*50\,\mu$m, and $6*40\,\mu$m. The

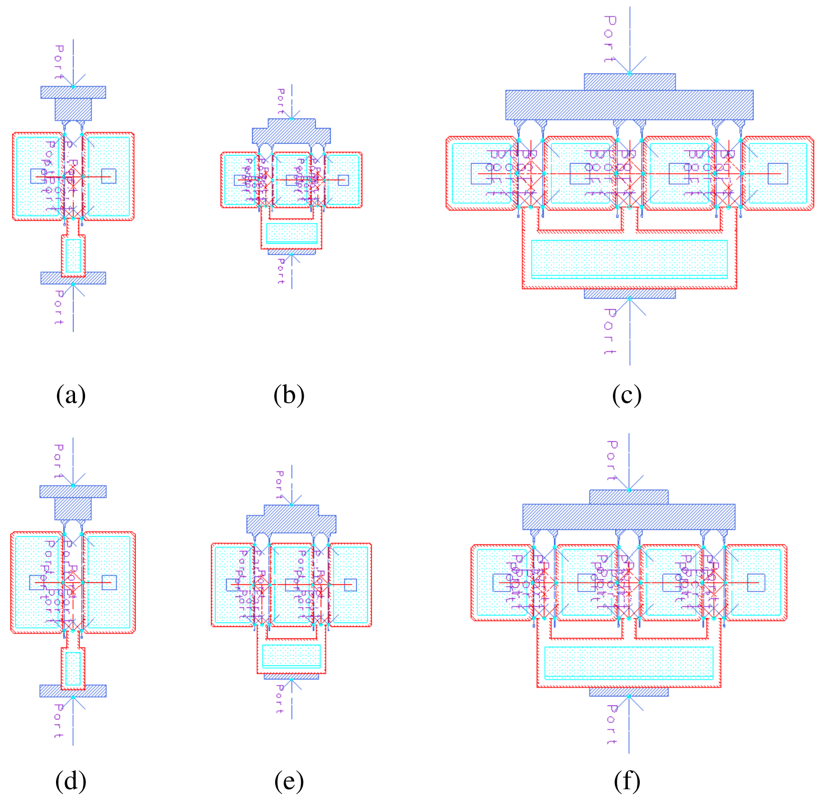


Figure 3. The EM simulated structure of different HEMTs. (a) $2 * 70\,\mu\text{m}$; (b) $4 * 60\,\mu\text{m}$; (c) $6 * 40\,\mu\text{m}$; (d) $2 * 80\,\mu\text{m}$; (e) $4 * 80\,\mu\text{m}$; (f) $6 * 50\,\mu\text{m}$.

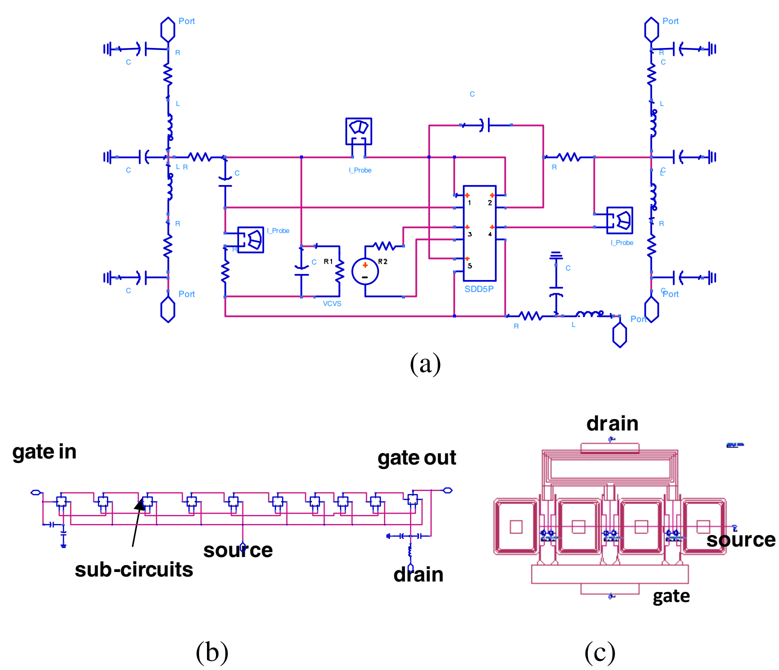


Figure 4. Sub-circuits and the EM simulated model of $6 * 50\,\mu\text{m}$ HEMT. (a) The equivalent-circuits modeling in the sub-circuits; (b) the distributed model structure of the single $50\,\mu\text{m}$ finger HEMT; (c) the overall model.

scalability is derived based on those gate widths and number of fingers. Each unit model can be used to scale into arbitrary gate widths or number of fingers. Figure 5 shows the measured and simulated IV curves fitted very well.

The measured and simulated small signal S parameters of six sets of HEMT device are shown in Figure 6, which shows that the measured results agree with the simulated ones very well at different bias (V_{gs}: $-0.9 \sim -0.4$ V; V_{ds}: $4 \sim 6$ V). Obviously, pulsed IV measurement can eliminate the device's dispersion effect, and consequently the accuracy of AC parameter extraction is improved. It also

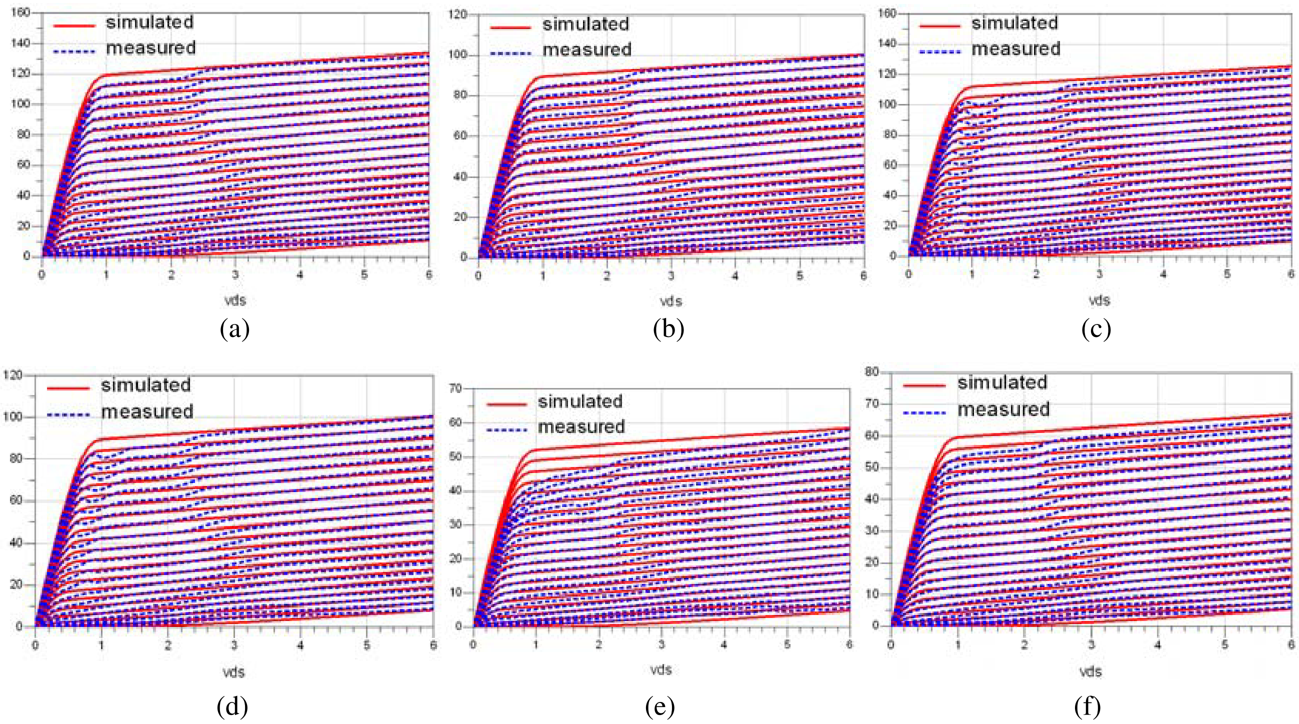
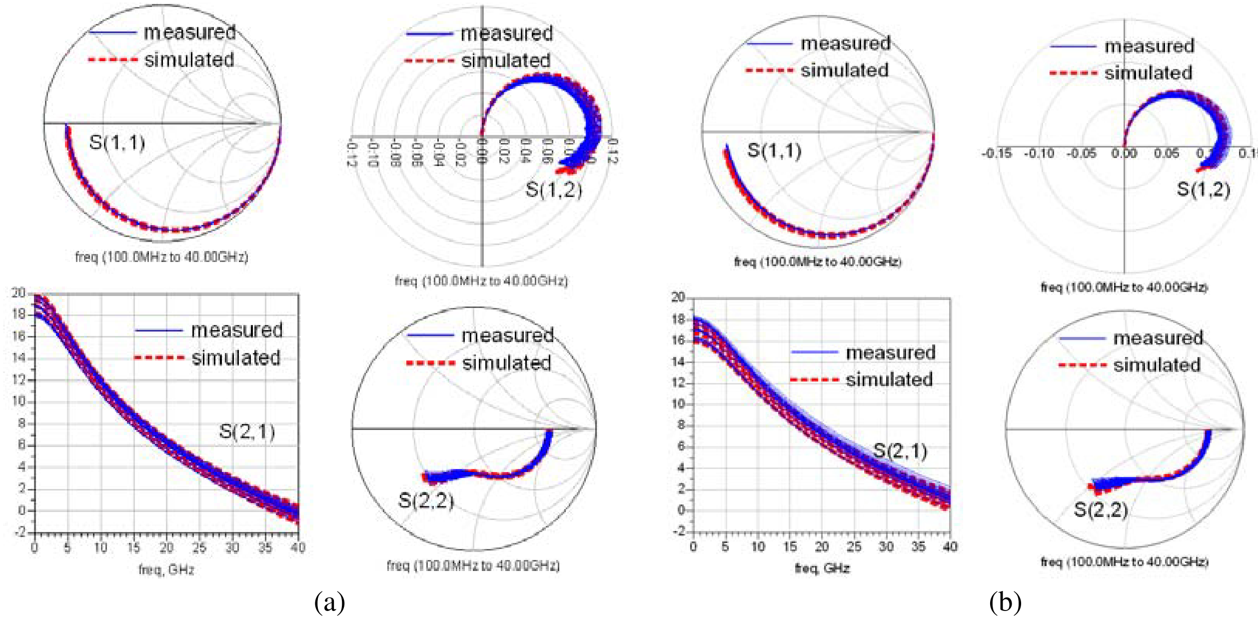


Figure 5. Measured and simulated IV curve for different size of HEMTs. (a) $4 * 80\,\mu\text{m}$; (b) $4 * 60\,\mu\text{m}$; (c) $6 * 50\,\mu\text{m}$; (d) $6 * 40\,\mu\text{m}$; (e) $2 * 70\,\mu\text{m}$; (f) $2 * 80\,\mu\text{m}$.



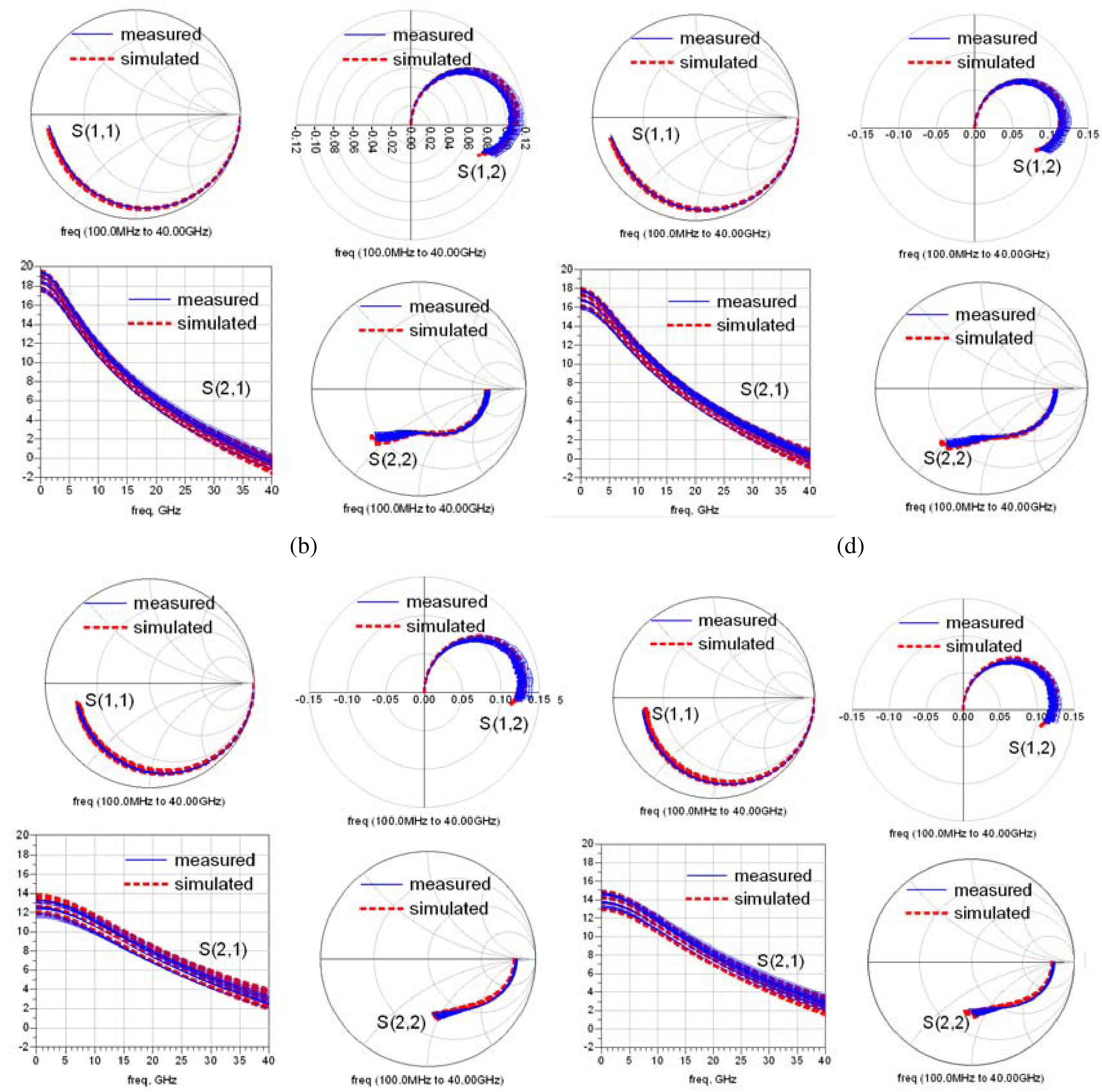


Figure 6. Measured and simulated S parameter for different size HEMTs. (a) $4 * 80\,\mu\text{m}$; (b) $4 * 60\,\mu\text{m}$; (c) $6 * 50\,\mu\text{m}$; (d) $6 * 40\,\mu\text{m}$; (e) $2 * 70\,\mu\text{m}$; (f) $2 * 80\,\mu\text{m}$.

demonstrates that this model has a good scalability from DC to 40 GHz and proves the accuracy of EM simulation for device modeling.

5. CONCLUSION

In this paper, a series of special passive structures are designed to correct the boundary conditions in EM simulation which improves the accuracy of the EM simulation effectively. Moreover, the pulsed IV and S parameter measurement are used to improve the model's scalability at high frequencies. The measurement results show that this model can be scalable to arbitral gate widths and number of fingers.

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