NEW MODFET SMALL SIGNAL CIRCUIT MODEL REQUIRED FOR MILLIMETER-WAVE MMIC DESIGN: EXTRACTION AND VALIDATION TO 120 GHZ

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ABSTRACT

A new MODFET circuit model required for millimeter-wave MMIC design has been developed, since it was found that the conventional MODFET circuit topology normally used was not able to accurately simulate measurement data above 75 GHz. This new model accounts for distributed effects in the transistor layout and includes a modified intrinsic transistor circuit topology. This circuit model has been experimentally validated by on-wafer S-parameter measurements performed to 120 GHz. This was made possible by the development of two advanced millimeter-wave on-wafer S-parameter measurement systems.

INTRODUCTION

In the development of millimeter-wave MMICs, cost reduction is a critical issue. Low development costs require MMIC performance to meet specifications at the first pass which can only be achieved if an accurate CAD design data base is available. For the active device, the MODFET, this requires the use in CAD tools of a scalable small signal equivalent circuit model that will accurately simulate the transistor S-parameters as a function of gate width. This model is generally determined from S-parameter measurements performed below 65 GHz while the frequencies of interest for future MMIC applications are above 75 GHz. Design of these MMICs therefore involves simulating the transistor performance by extrapolating beyond the measurement bandwidth. The validity of this extrapolation and hence the circuit models has, to date, not been routinely tested with S-parameter measurements at the frequencies of interest (> 75 GHz).

S-PARAMETER MEASUREMENTS SYSTEMS TO 120 GHZ

In order to extract and validate the circuit models used for MMIC design, two novel on-wafer S-parameter measurement systems based on the HP8510 Network Analyzer have been

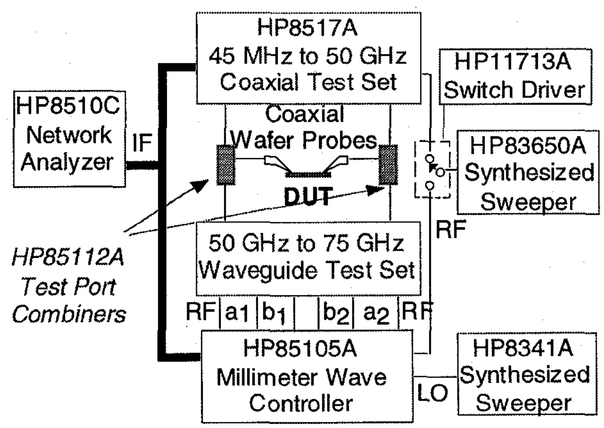

Fig. 1 A broad band 45 MHz to 75 GHz on-wafer S-parameter measurement system (coaxial 1.85mm wafer probes).

developed that extend the measurement bandwidth to 120 GHz. One system performs single contact broad band S-parameters from 45 MHz to 75 GHz using coaxial wafer probes (figure 1). This measurement bandwidth is achieved by using a diplexer to combine a 45 MHz to 50 GHz coaxial test-set with a 50 GHz to 75 GHz waveguide test-set [1].

The second system performs S-parameter measurements from 75 GHz to 120 GHz using waveguide wafer probes (figure 2). In this measurement system a 1 mm coaxial link has been used to separate the frequency sources (millimeter-wave multipliers) from the waveguide reflectometers. This allows the light weight waveguide reflectometers to be connected to the

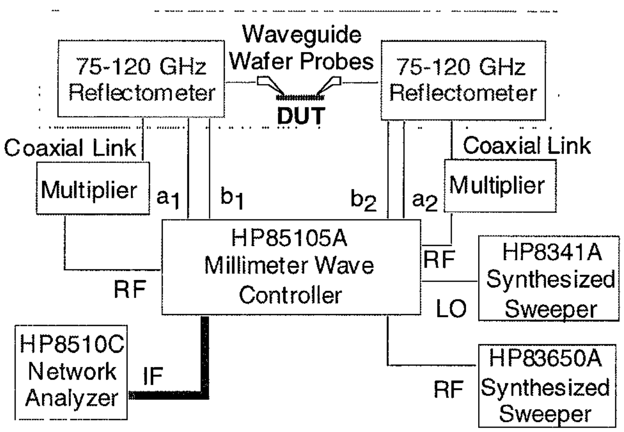

Fig. 2 A waveguide band 75 GHz to 110 GHz on-wafer S-parameter measurement system (waveguide V-Band wafer probes).

waveguide probes and placed directly on the probe station, thus improving measurement accuracy and stability. The performance of these measurement systems has been further improved using a calibration technique that accounts for the non-ideal behavior of the on-wafer calibration standards [1]. The measurement system control software combines the measurements performed on both systems and also extracts the equivalent circuit element values from the measured data.

EXTRACTION CONCEPT

The circuit model element values are extracted from an appropriate sequence of measurements performed on both the active transistor and "test" structures. Extraction of the element values from measurement data was made possible by a generalized description of the circuit model formulated from series and parallel connections of simple Z- and Y-matrix two port circuits (shells). The element values are then determined independently by converting the measured S-parameters to Y- or Z-parameters and performing a set of matrix inversions and subtractions [2-4]. The scaleable circuit model commonly used contains an active (intrinsic) Y-matrix, in series with a parasitic Z-matrix, in parallel with a parasitic Y-matrix (figure 3) and thus involves the extraction of 17 element values. *A "rule of thumb" for independent extraction of these element values is that each shell requires a unique set of measurements.* In order to determine the parasitic Y-matrix, for example, a number of "test" structures were developed, a MODFET structure without an active region, in which the gate width was varied. Measurement of these structures allows the direct extraction of the parasitic pad capacitances (c_{gsp}, c_{cdp}, c_{dsp}). The parasitic Z-matrix (l_g, l_d, l_s, r_g, r_d, r_s) was extracted from cold FET measurements, forward bias on the gate with V_{ds} = 0 V. After stripping these parasitics from a set of measured S-parameters the intrinsic model (g_m, τ, r_{gs}, c_{gs}, r_{gd}, c_{gd}, g_{ds}, c_{ds}) can then be directly extracted. It was found previous matched the measured S-parameters up to 75 GHz and were successfully used in the design of MMIC operating up to 80 GHz [5,6].

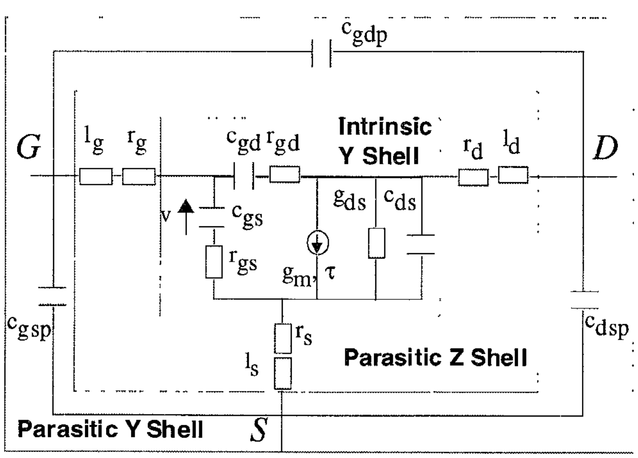

Fig. 3 Simple Small Signal Equivalent Circuit Model commonly used for modelling MODFETs which contains 17 circuit model elements.

EXTRACTION AND VERIFICATION OF MODELS TO 120 GHZ

In order to model accurately the measured S-parameters up to 120 GHz, however, it was found that the circuit model topology must be modified, as shown in figure 4. First the parasitic Y- and Z- parameters have to be distributed between four shells. This modification is required in order to account for the distributive effects associated with the finite dimensions of the transistor layout. Secondly the intrinsic output capacitance c_{ds} must be located outside the parasitic resistances r_d, r_s (see figures 4 and 6). This modification indicates that the extrinsic fringing electric fields between the drain and source metallizations are the dominant contribution to the output capacitance. Figure 5 shows the comparison between measured and

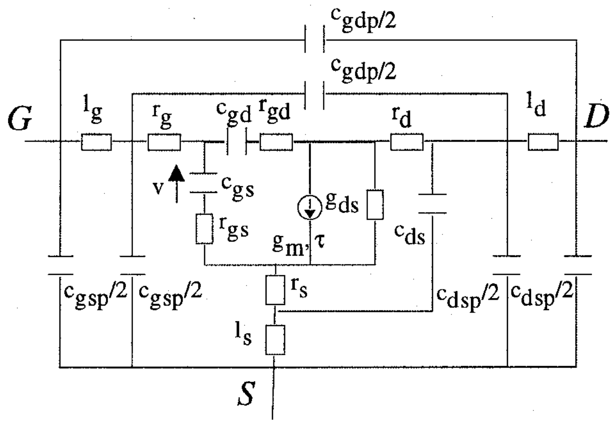

Fig. 4 Small Signal Equivalent Circuit Model required for modelling MODFETs to 120 GHz. The parastics are distributed and the output capacitance is relocated. However, the number of circuit model element values is still 17.

modeled S-parameters for the pinched-off MODFET. This excellent agreement is only achieved if the distributed parasitic circuit topology and the extracted intrinsic circuit model shown in figure 6 are used. Note the absence of any series resistance in the transistor output circuit indicating the location of c_{ds} outside the

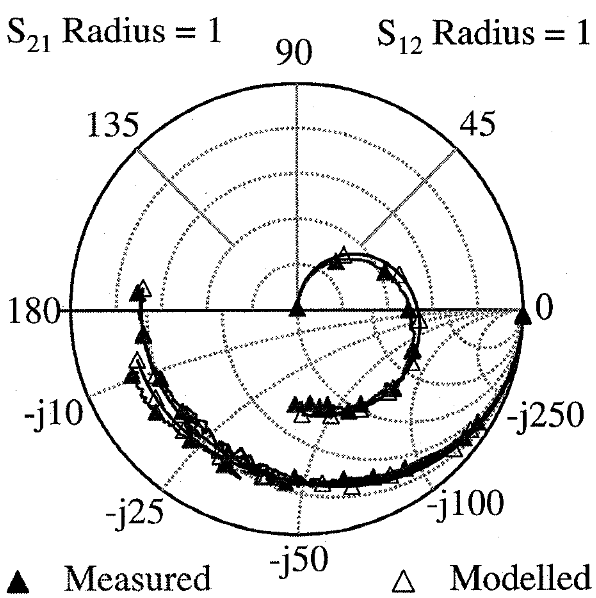

Fig. 5 Comparision between measured and modelled S-parameters of a 0.15 x 100 μm^2 MODFET biased in pinch-off (V_{gs}=-1.5 V V_{ds}=0 V) from 0.5 GHz to 118.5 GHz (Symbols every 13.5 GHz).

parasitic resistances r_d, r_s.

It is important to note that in this work the increased bandwidth was used only to optimize the circuit topology, the number of independent extracted element values remained constant. The more complex circuit must still be extracted using the previously described procedure, since the extracted parasitic element values were found to be frequency independent to 120 GHz. Increasing the number of independent circuit elements to be extracted would require the introduction of additional "test" structures. *Figure 7 shows the excellent agreement that can be achieved between the measured S-parameters and the modeled S-parameters using the new scalable extracted circuit model for a 100 x 0.15 μm^2 PMODFET.*

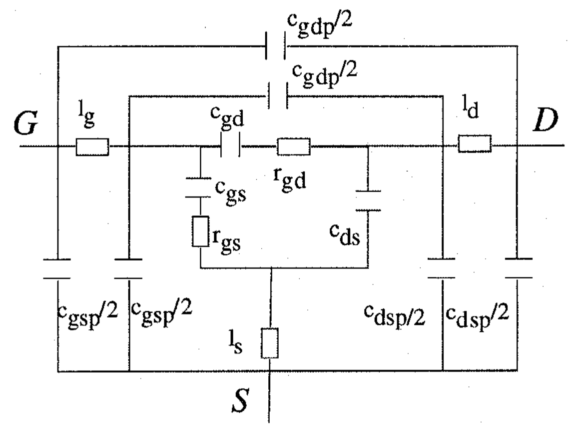

Fig. 6 Small Signal Equivalent Circuit Model required to model the pinched-off MODFET to 120 GHz. The parastics must be distributed and the extract circuit has no series resistance in the output circuit.

CONCLUSION

A simple physically valid MODFET circuit model has been developed that can model correctly the measured S-parameters to 120 GHz. The development of this model involved the formulation of parameter extraction techniques and determination of the correct model circuit topology. For model verification broad band on-wafer S-parameter measurement systems covering the frequency band from 45 MHz to 120 GHz were developed. The determined circuit models have been used successfully in the design and realization of a number of high performance millimeter-wave MMICs.

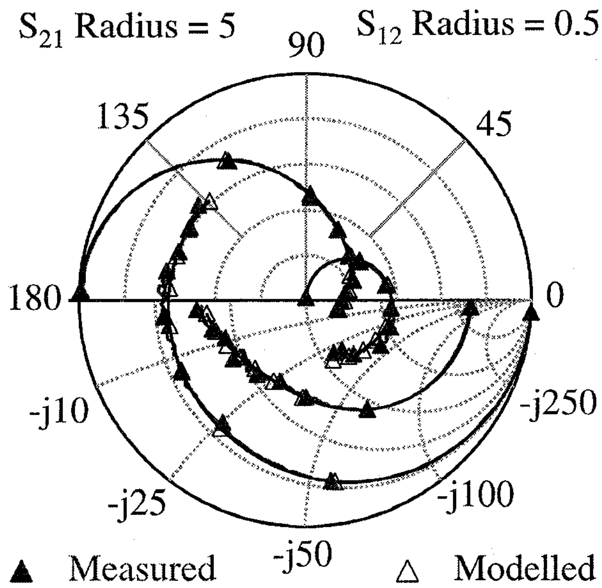

Fig. 7 Comparision between measured and modelled S-parameters of a 0.15 x 100 μm^2 MODFET biased for low noise (V_{ds}=2.5 V I_{ds}=100 mA/mm) from 0.5 GHz to 118.5 GHz (Symbols every 13.5 GHz).

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	Active	Passive
INTRINSIC		
Cgs pF/mm	0.87	0.29
Rgs Ω-mm	0.4	1.0
Cgd pF/mm	0.18	0.31
Rgd Ω-mm	2.0	1.75
Gds mS/mm	41	-
Cds pF/mm	0.18	0.18
Gm mS/mm	760	-
τ psec	0.4	-
Z-SHELLs		
Rg Ω-mm	0.35	-
Rd Ω-mm	0.38	-
Rs Ω-mm	0.38	-
Lg pF	37.5	37.5
Ld pF	32.5	32.5
Ls pF	2.5	2.5
Y-SHELLs		
Cgsp fF	13	13
Cgsp fF	6	6
Cds fF	11	11

Table 1 Extracted Circuit Model Element values of a 0.15 x 100 μm^2 MODFET.