Measurement-Based Large-Signal Diode Model, Automated Data Acquisition System, and Verification with On-Wafer Power and Harmonic Measurements

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ABSTRACT

A new relaxation-time large-signal table-based diode model for circuit simulation is presented. Also presented is a fully automated system which characterizes the device and generates the tabular data file used by the model. Excellent agreement between simulated and measured fundamental and second through fourth harmonic power levels is demonstrated for a MODFET diode up to frequencies of 48 GHz.

Introduction

A new relaxation-time large-signal table-based diode model has been implemented in the HP MDS simulator. It is based on experimental DC and small-signal S-parameter data as functions of bias. It has been successfully applied to GaAs MESFET, MODFET (HEMT), and varactor diodes in one or two-port configuration. The automated system presented here adaptively characterizes the diode over its entire safe operating range, taking more data where needed depending on the local nonlinearities of the DUT. The model generator constructs a complete large-signal model from the data, including parasitic extrinsic element values and bias-dependent functions from which device-specific nonlinear current-voltage and charge-voltage model constitutive relations are defined. Spline functions interpolate the tabulated nonlinear model functions during simulations. The validity of the model is confirmed by comparison of model simulations to measured DC data, small-signal S-parameter data versus bias and frequency, and extensive large-signal measurements of gain and harmonic levels versus output power at several bias points and different fundamental frequencies. The implemented nonlinear model in the circuit simulator, automated data acquisition system, and model generator system, comprise an integrated large-signal microwave diode modeling system for state-of-the-art nonlinear circuit simulation.

The Model

The model is composed of a bias-independent parasitic part and a bias-dependent part modeling the intrinsic junction behavior. This is illustrated in Figure 1. Charge-voltage relations for heterostructure and varactor diodes and current-voltage relations under reverse bias and breakdown conditions can be quite different from the simplified explicit formulas used by most large-signal models. The new model defines the intrinsic non-linear current-voltage and charge-voltage constitutive relations by means of appropriate spline interpolation of several bias-dependent functions computed directly from the data and tabulated in the model data-file. This approach ensures both excellent model accuracy and great flexibility by making the model largely independent of the device technology. The time-dependent output current is computed as the solution of a relaxation time differential equation, similar in form to those reported recently for non-quasi static FET models [1,2].

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The interpolation of the bias-dependent model functions with respect to the intrinsic voltage and the sampling of the device data in bias space are both critical for the correct model behavior. Naive interpolation and improper sampling rates can result in spline oscillations between discrete data points and cause convergence problems for the harmonic balance and transient analysis algorithms. The bias-points are adaptively computed by the automated system using a predictor corrector algorithm [1] based upon the device-specific DC current and intrinsic capacitance versus bias behavior. In addition, the simulator performs spline interpolation on functions of the data, rather than interpolating the data directly. This technique provides better extrapolation results than obtained by extrapolating the data directly. Figure 2 shows a comparison of a subset of the current-voltage relation between measured (discrete triangles), the new model (well-behaved curve) and a naive spline-interpolation (non-monotonic curve) of the measured current.

Automated Measurement-Based Modeling System

The automated data acquisition and model generator system is based on the HP 85122A parameter extraction test system, consisting of an HP 8510 network analyzer and HP 4142 DC source/monitor, with software implemented in the HP ICCAP program for measurement control and graphical interface. DC and single-frequency S-parameters are taken over the entire safe operating region of the device. The extrinsic parameters are extracted by means of single frequency small signal measurements with the device forward biased [3]. The link between the automated data acquisition/model generator system and the simulator is accomplished by the model data file containing the parasitic element values and the DC and other intrinsic model functions of the internal bias. This file, containing the device characterization, is the only input required by the simulator.

Figure 3 compares measured (x) and modeled (—) C-V nonlinear constitutive relations for a MODFET diode. The modeled curves are nearly identical to the measurements.

Figures 4 compare measured (4a) and simulated (4b) S_{11} versus bias and frequency for a varactor diode. Fourteen bias points are compared from V=-1.8 to V=+1.2 Volts. The frequency range is 1 GHz to 26 GHz. For each bias point, the agreement between simulations and measurements is very good over the entire frequency range, despite the fact that the model data-file was constructed from S-parameters measured at the *single frequency* of 3 GHz.

Large-Signal Verification

Figures 5a and 5b compare simulated (solid lines) to measured large-signal gain (▲) in dB, and second harmonic (.), third harmonic (+), and fourth harmonic (X) levels in dBc versus Output Power for a 48um two-port MODFET diode. The bias for this comparison is V=-0.5 volts and the fundamental frequency is 2 GHz. The agreement is excellent.

Figures 6a and 6b compare simulations and measurements under the same conditions as Figures 5, except now the diode is forward-biased to +0.5 V. Again the agreement is excellent, except perhaps for the fourth harmonic at very low power levels, where the large-signal measurement accuracy is questionable. The model even predicts the measured sharp depression in the fourth harmonic at about Pout = -10dBm.

Figures 7a and 7b compare simulated (solid lines) to measured large-signal gain (▲) in dB, and second harmonic (.), third harmonic (+), and fourth harmonic (X) levels in dBc versus Output Power for a 48um two-port MODFET diode. This time the diode is unbiased (V=0.0 Volts). The fundamental frequency is 2 GHz. The agreement is excellent except perhaps for the fourth harmonic at very low power levels, where the large-signal measurement accuracy is questionable.

Figures 8a and 8b compare simulations and measurements under the same conditions as Figures 7, except now the fundamental frequency for the measurements and simulations is 12GHz. Again the agreement is excellent. This proves the model, also extracted at the single frequency of 3GHz, accurately predicts large-signal performance of this device to at least 48GHz, which is the frequency of the fourth harmonic with respect to the 12 GHz fundamental.

The large-signal data was measured on the on-wafer power and harmonic measurement system reported in [4]. The system provides on-wafer, vector error-corrected power and harmonic levels and large-signal reflection coefficient.

Conclusions

The results and methodology presented above prove the measurement-based large-signal diode model and its associated automated data acquisition and model generator system yield accurate simulations of diode devices from diverse technologies over a wide variety of biases, frequencies, and input signal amplitudes. This makes the measurement-based modeling system a valid CAD tool for automated diode characterization and for large & small-signal analysis and design of circuits and systems where such devices are key components.

Acknowledgment

The authors thank Hewlett-Packard Management for supporting this work.

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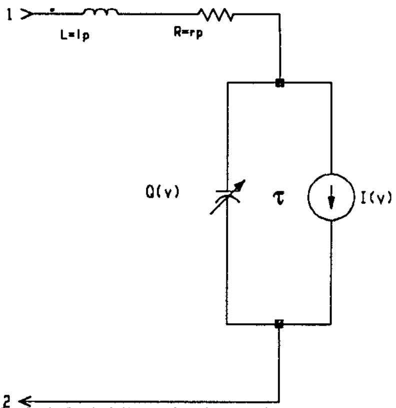

Figure 1: Diode Model "Equivalent Circuit". The intrinsic model is described by nonlinear constitutive relations I(V) and Q(V), and by a relaxation time τ. The model implements a large-signal relaxation-time differential equation for the instantaneous current.

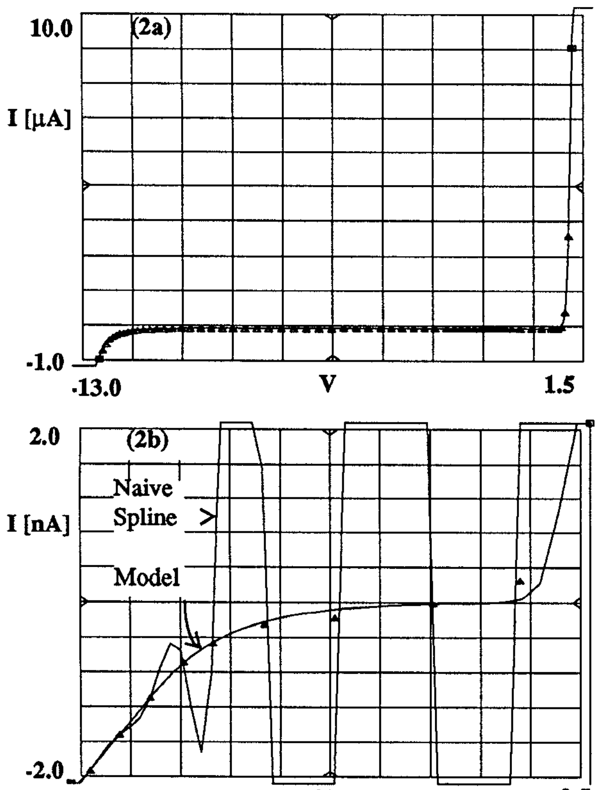

Figure 2: Measured (▲), modeled (well-behaved solid lines), and naive spline-interpolated (wavy solid lines) DC I-V relations for a MODFET Diode. (2a) From breakdown to full forward bias. (2b) Magnified scale near zero current. The model goes through all the data points except when the current is in the noise level (500 pA in this case). Problems associated with naive spline oscillations between data points are eliminated using this approach.

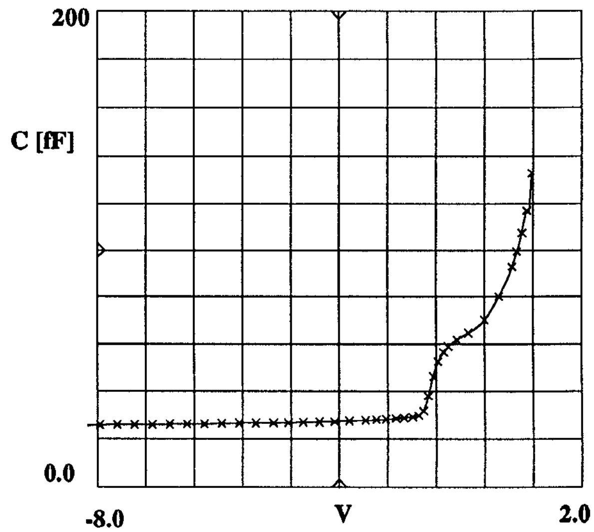

Figure 3: Measured (X) and Modeled (—) C-V Relation for MODFET Diode. The agreement with data is much better than that which can be obtained by fitting to fixed, "canned" model constitutive relations based on simplified physics or empirical expressions.

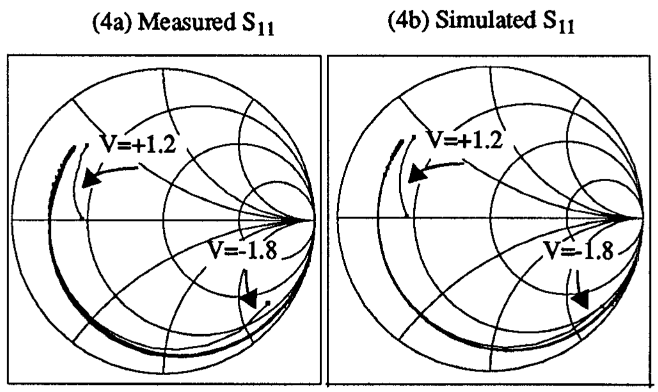

Figure 4: Measured (4a) and Simulated (4b) S_{11} versus frequency and bias for a Varactor Diode. There are fourteen bias points shown from V=-1.8 to +1.2 Volts. The frequencies range from 1GHz to 26GHz. Recall the model was constructed from data at the single frequency of 3 GHz.

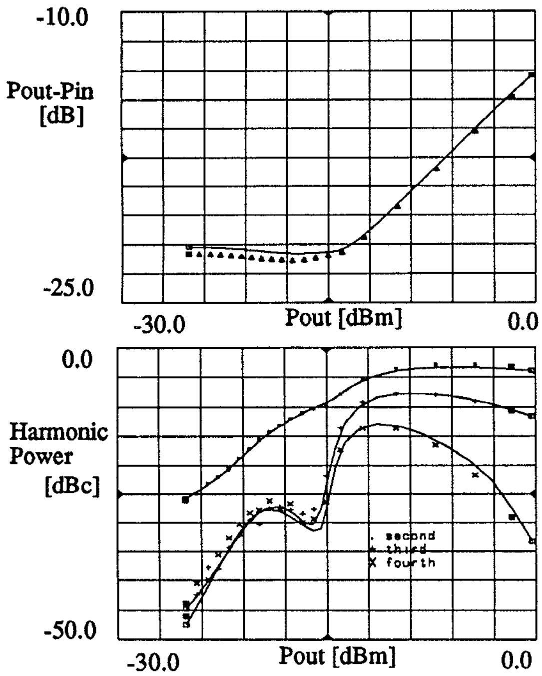

Figure5: Simulated (Solid Lines) and Measured gain (▲), Second harmonic levels (.), third harmonic levels (+) and fourth harmonic levels (X) vs. Output Power for a MOD-FET diode. Bias: V=-0.5. Fundamental Frequency 2 GHz.

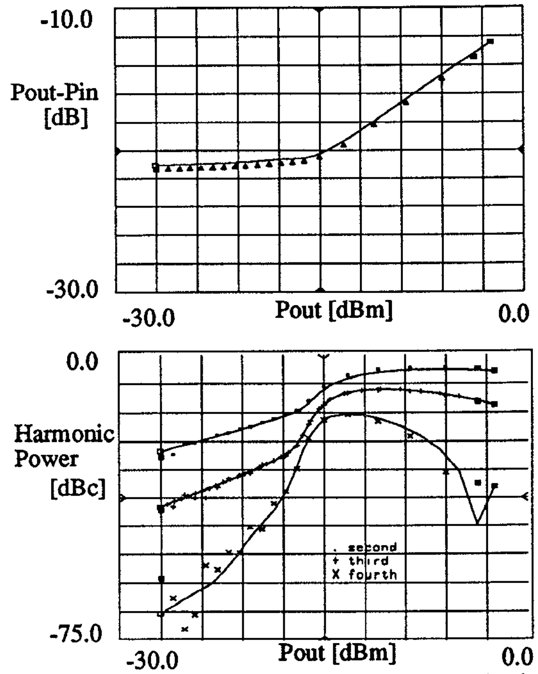

Figure7: Simulated (Solid Lines) and Measured gain(▲), Second harmonic levels (.), third harmonic levels (+) and fourth harmonic levels (X) vs. Output Power for a MOD-FET diode. Bias: V=0. Fundamental Frequency 2GHz.

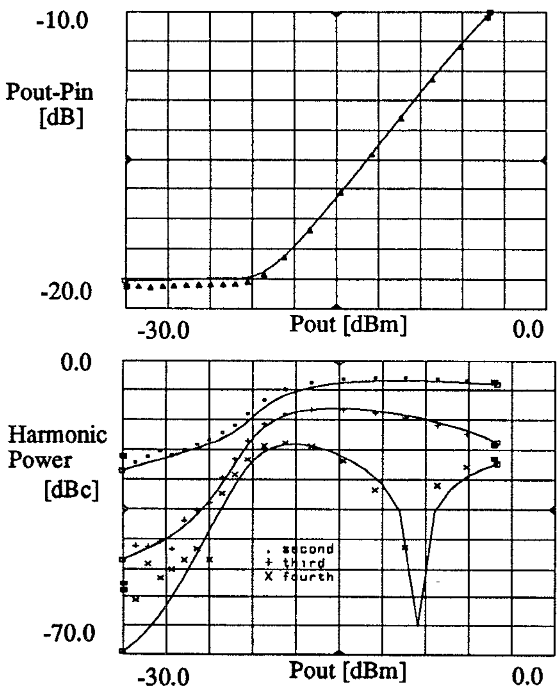

Figure6: Simulated (Solid Lines) and Measured gain (▲), Second harmonic levels (.), third harmonic levels (+) and fourth harmonic levels (X) vs. Output Power for a MOD-FET diode. Bias: V=+0.5. Fundamental Frequency 2 GHz.

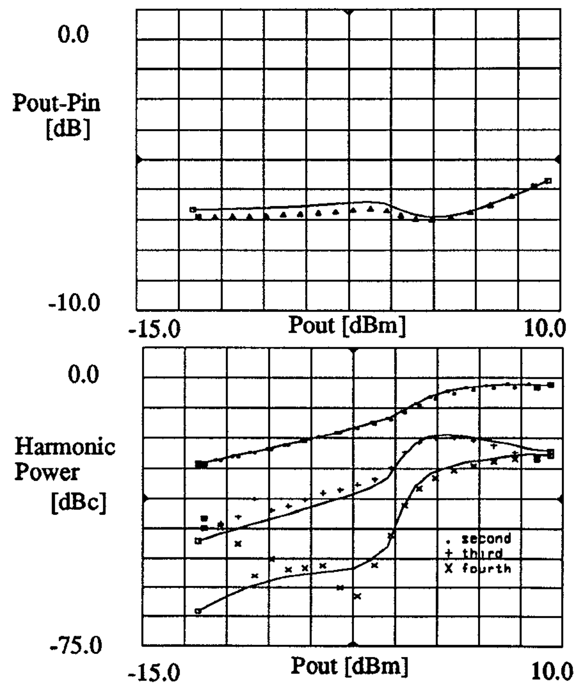

Figure 8: Simulated (Solid Lines) and Measured gain (▲), Second harmonic levels (.), third harmonic levels (+) and fourth harmonic levels (X) vs. Output Power for a MOD-FET diode. Bias: V=0. Fundamental Frequency 12GHz.