Accurate Millimeter-wave Large Signal Modeling of Planar Schottky Varactor Diodes

S. Lucyszyn *, G. Green ** and I. D. Robertson *

* Communications Research Group
Department of Electronic & Electrical Engineering.
King's College, University of London, Strand, London, WC2R 2LS, England

** GEC-Marconi Materials Technology Limited
Caswell, Towcester, Northants, NN12 8EQ, England

ABSTRACT

A large signal model for GaAs Planar Schottky Varactor Diodes (PSVDs) is presented which maintains a high level of accuracy into the millimetric frequency range -- for both forward and reverse bias. Using this new model, the simulated performance for a number of PSVD structures gave accurate predictions up to 40GHz.

INTRODUCTION

Voltage tunable capacitors are commonly found in monolithic analog phase shifter [1] and voltage controlled oscillator [2] applications. For a monolithic realization of the voltage tunable capacitor, planar-type varactor diodes are used. Here, the varactor diode can be realized by connecting together the drain and source terminations of a standard-implant MESFET -- resulting in a single Schottky junction. The bias potential is then applied across the drain/source and gate terminations. Unlike the well characterized mesa-type varactor diode, these Planar Schottky Varactor Diodes (PSVDs) do not require: air bridges and additional selective ion implantation/MBE or VPE grown layers. As a result, PSVDs are less expensive to produce than the equivalent mesa-type varactor diodes. However, PSVDs have not been widely used, since accurate microwave frequency models were unavailable.

Previous attempts to characterize GaAs PSVDs [2,3] focused on the intrinsic elements of the device. As a result, these over simplified equivalent circuit models were inaccurate at microwave frequencies. Also, the models were restricted to the reverse bias only. When the reverse bias potential decreases to zero, the junction capacitance increases. However, this capacitance continues to increase as the forward bias potential is increased from zero to its built-in barrier potential (approx. 0.7-0.8V). As a result, a very significant increase in the total capacitance ratio can be achieved if both reverse and forward bias are applied.

A new model for GaAs PSVDs is presented. Here, the significant extrinsic elements are combined with the reverse and forward bias intrinsic elements of the low frequency model. In addition, frequency and delay models are included. The result is a large signal model which is accurate, well into the millimetric frequency range, with reverse and forward bias applied.

MODELING

The new model for the GaAs PSVD is shown in Fig. 1. As with the previous low frequency models, the distributed resistance and capacitance of the active layer are transformed into an equivalent 1st order network -- represented by Rs(v) and Cj(v). The model accommodates forward bias with the junction leakage resistance, Rj(v). This resistance is effectively open circuit with reverse bias. The extrinsic parameters are based on the physical structure of the device. Here the drain/source capacitance to ground is represented by Ck; the gate capacitance to ground is represented by Cak; the combined series inductance of the gate, drain and source

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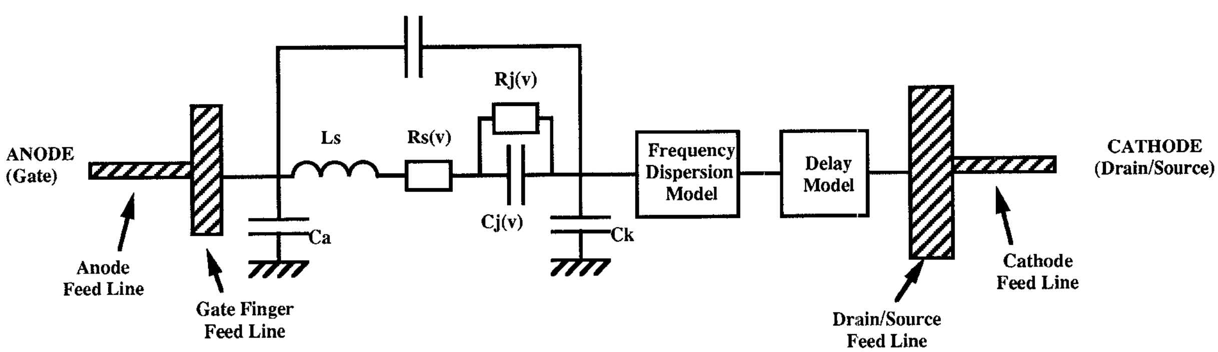

Fig. 1: Millimeter-wave large signal model for GaAs PSVDs

fingers are represented by Ls; and the combined series resistance associated with the gate, drain and source fingers are included in Rs(v).

It will be found that Ca<<Ck, since the gate length of the MESFET is much smaller than those of the drain and source. In order to accurately characterize the varactor diodes, at microwave frequencies, a frequency dispersion model and a delay model are required. The latter is required since the lumped element model does not take into account the physical length of the gate fingers. In addition, the feed lines and their associated discontinuities must be accurately modeled. Here, foundry specific models must be used for the microstrip feed lines.

OPTIMIZATION

Once the significant extrinsic elements have been identified, their values can be determined using 2-port measurements. As a starting point, the amplitude and phase measurements of the anode voltage reflection coefficient, S_{11}, and the anode-to-cathode voltage transmission coefficient, S_{21}, were taken at zero bias. With realistic initial estimates for the element values, along with measurements taken from d.c. up to high microwave frequencies, a good optimization algorithm produces values that quickly converge to the correct values. Equal weighting was applied to all responses, across the whole frequency range.

When zero bias convergence has taken place, the voltage dependency of Rs(v), Cj(v) and Rj(v) can be determined. Here, the optimization was performed only on the magnitude of the S_{11} response, about its dip, since the location of this dip is highly sensitive to the voltage dependency of the element values. The error function formulation was performed by the method of least squares. The optimization algorithm utilized the gradient of the resulting error function, so as to converge on its minimum value. This method of optimization is least sensitive to variations in the element values. As a test for zero bias convergence, the error function produced by the optimization algorithm should remain relatively constant for all bias potentials.

RESULTS

A number of different standard-implant PSVD structures were accurately characterized. These experimental devices were fabricated at the GEC-Marconi (Caswell) foundry, using their standard F20 process. The 0.5µm MESFETs used to make the PSVDs had 1, 2, 4 and 6 gate fingers, with gate widths of 25, 75 and 150µm. It was found that all the model element values, in all the devices, were easily scalable -- according to the number of fingers and the length of the gate fingers.

A CASCADE Summit 9000 probe station and a HP8510B automatic network analyzer were used to perform measurements between 0.05 to 40.05GHz. Each device was measured at 40 different bias points, from +0.5 to -8V. Fig. 2 shows a photomicrograph of the 900µm PSVD (6 gate fingers, 150µm wide) being probed. For this device, the bias dependant characteristics of Rs(v), Cj(v) and Rj(v) for this device can be seen in Fig. 3. The corresponding measured and modeled responses at 5 different bias points are shown in Fig. 4. From the power and phase responses in Fig. 4, it can be seen that the PSVD is accurately characterized. This high level of accuracy was also achieved with all the other devices.

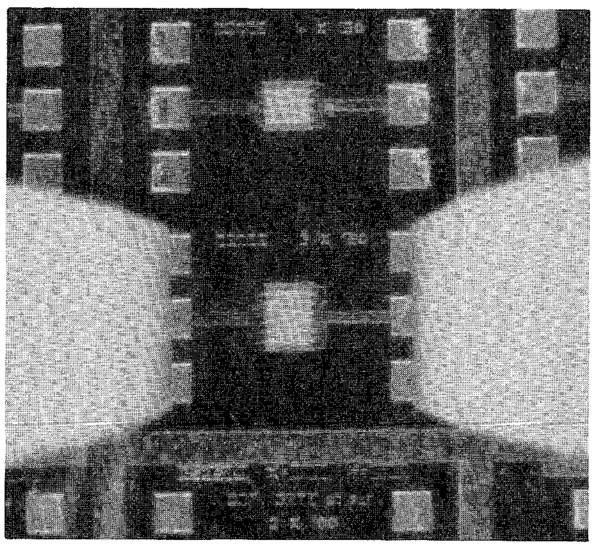

Fig. 2: On-wafer probing of an experimental 900µm PSVD

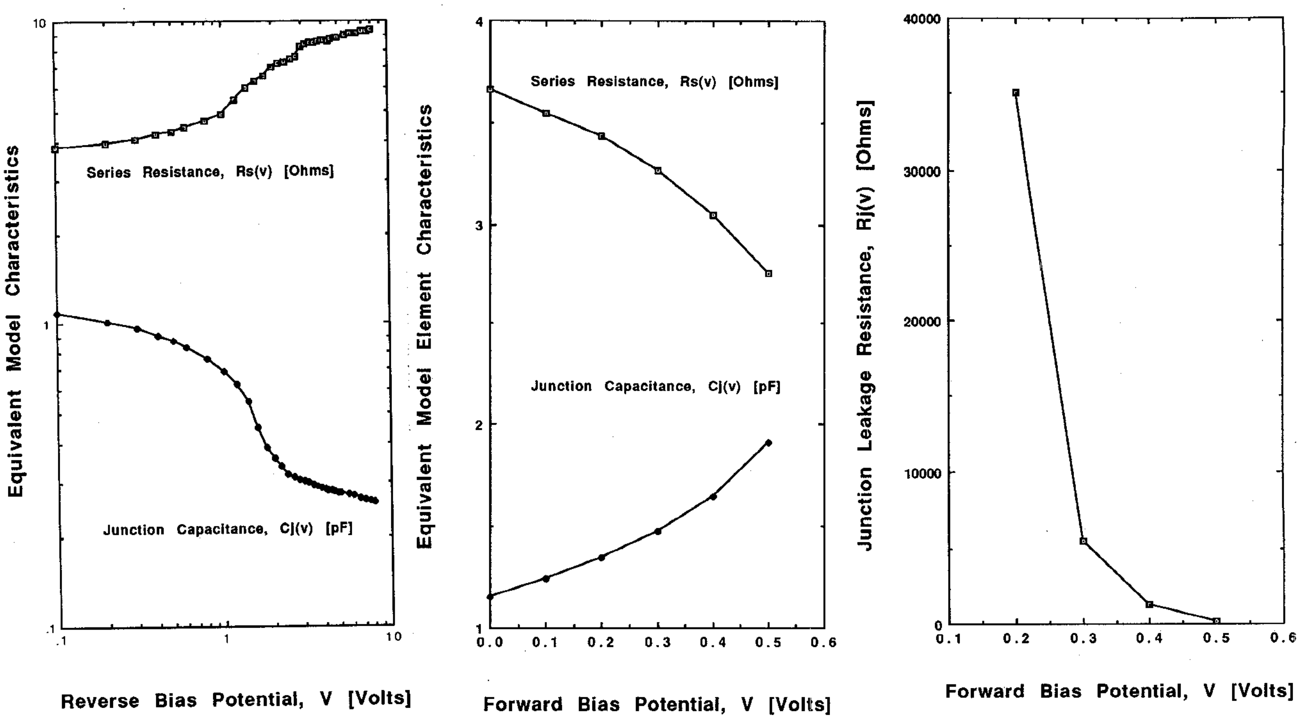

Fig. 3: Bias dependant characteristics of the 900μm PSVD

DISCUSSION

The characteristic dip in the return loss responses, seen in Fig. 4, is primarily the result of the interaction between Cj(v) and the effective total capacitance to ground. However, this capacitance is not only attributed to Ca, Ck and the capacitances associated with the feed lines. To enable on-wafer probing, the anode and cathode microstrip feed lines were connected to Coplanar Waveguide (CPW) probe pads. The 'signal' pad was modeled in the same way as the feed lines. In addition, a very significant fringe capacitance to ground, of 0.01pF, was also required. The majority of this capacitance is attributed to the stray capacitance between the 'signal' and its adjacent 'ground' pads.

CONCLUSIONS

A general large signal model for GaAs PSVDs has been presented which has shown to maintain a high level of accuracy, well into the millimetric frequency range. The model includes frequency dispersion and delay, as well as extrinsic elements. In addition, the necessity of modeling the CPW probe pads has been identified. With forward bias included in the model, the junction capacitance ratio of the standard-implant PSVDs was shown to be increased from Cj(0V)/Cj(-8V)=4.1 to Cj(+0.5V)/Cj(-8V)=6.5. This ratio can be much further increased, if the forward bias is increased further and the reverse bias is reduced to just below the breakdown potential.

With accurate ultra-wideband modeling of GaAs PSVDs, these relatively low cost devices are expected to achieve greater popularity in microwave, millimeter-wave, wideband and ultra-wideband applications. The model presented has already been successfully employed in a decade bandwidth analog phase shifter [4].

ACKNOWLEDGEMENTS

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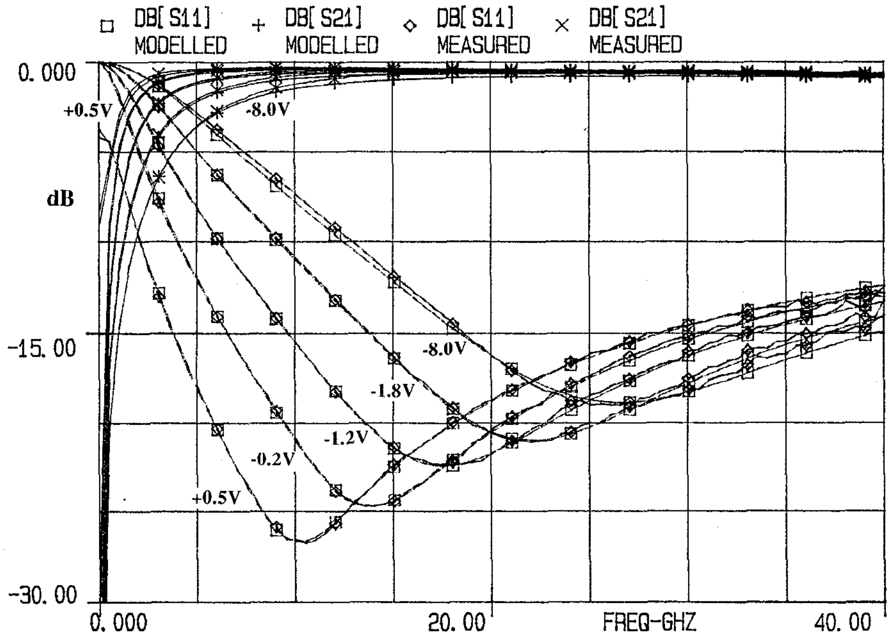
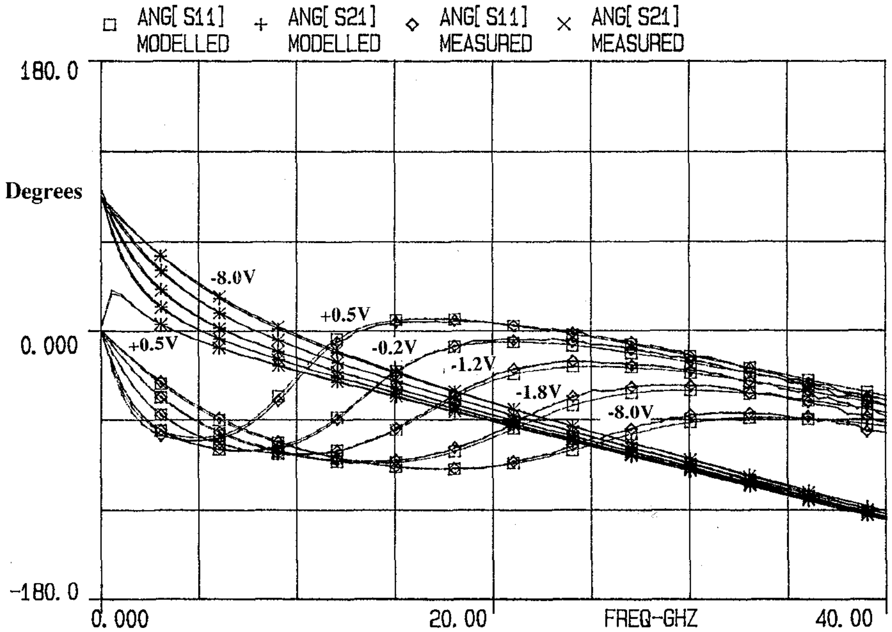


Power Responses



Phase Responses

Fig. 4: Measured and modeled responses of the 900μm PSVD