PHYSICALLY BASED CIRCUIT MODEL OF GaAs MESFET AS AN OPTICAL PORT FOR MICROWAVE SYSTEMS

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ABSTRACT

A GaAs MESFET large signal equivalent circuit model with optical illumination effects has been developed. The model includes accurate representation of the drain current dependence upon the operating voltages under different operational conditions. The model for the GaAs MESFET was implemented into the well-known circuit simulation program, PSpice. Simulated results obtained are shown to compare well with the measured results with a good fit to measured GaAs MESFET I/V characteristics over a wide bias voltage range and under both dark and illumination conditions. The RF response of the MESFET is also modelled and simulated.
Such a circuit model is important in the design of optically controlled microwave circuits involving a GaAs MESFET as an optical interface.

INTRODUCTION

Many systems now involve both optical and microwave sub-systems;therefore much interest has been shown in a straight-forward interface between optical and microwave components [1]. Optical control has many advantages for complex microwave systems, such as size reduction, signal isolation and immunity to interference [2]. As a large number of microwave sub-systems in the future are likely to be in the form of single monolithic GaAs integrated circuits, an efficient optical detector with fast response, suitable for integration into monolithic circuits is highly desirable. With the MESFET already the dominant active component in MMICs, its configuration as a photodetector is highly relevant. Moreover, the possibility of making use of the optical sensitivity of the MESFET to form an additional signal input port or control mechanism justifies an increased interest in the physical mechanisms which occur when a MESFET is illuminated.
This paper presents an equivalent circuit model based on the physical behaviour of MESFETs under optical illumination. The circuit model has been implemented in PSpice, but could be readily implemented into microwave CAD packages, important in MMIC design.

OPTICAL EFFECTS ON MESFET

The optical illumination of a MESFET has three main effects:-
(1) A photoconductive effect [3] - which is evident as an increase in the channel current due to the increase in the number of carriers and therefore the channel conductivity. This effect has a lower frequency rolloff when the photoconductive carrier life-time is longer than the carrier transit time under the gate which leads to the normal photoconductive gain. Some gain at higher frequencies is obtained due to differing carrier velocities where electrons are collected at a faster rate than the holes; this causes the injection of extra carriers which produces the gain.
(2) An external photovoltaic effect[4] - which is related to photocurrent generation in the gate junction, this current will flow through the gate load impedance and hence modulate the instantaneous gate voltage.
(3) An internal photovoltaic effect[5] [6] - which is related to carrier generation in the channel-buffer-substrate or channel-substrate junction. It gives rise to a modulation of the drain current due to a modulation of the effective channel height; this arises from the modulation of the junction voltage by a developed photovoltage across the junction. This effect has a relatively low frequency response.

There has been considerable discussion of these effects[6] [7]. Madjar [6] has presented an analytical model for the GaAs MESFET which includes the optical response effects described above. Our approach is different in that the effects of the photogenerated carriers are incorporated directly into an equivalent circuit model. Whereas Madjar's approach provides analytic solutions for the individual effects, a circuit simulator (PSpice) is employed in this work to model the combined

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effects of illumination, and simulated results are presented. The equivalent circuit approach described here facilitates full circuit simulation which will be important in MMIC design.

Fig.1 shows the main effects of illumination on MESFET characteristics. Measured Id/Vgs and Id/Vds characteristics of a MESFET device, under both dark and illuminated conditions are shown in Fig.2 and Fig.3(a). The effects of illumination on the device characteristics are clearly apparent. Fig.4(a) shows the logarithmic relationship between drain current and incident optical power; this logarithmic response is characteristic of photovoltaic effects at a quasi-open circuit diode. These results demonstrate that the internal photovoltaic effect dominates the changes in the static characteristics of the device under illumination.

CIRCUIT REPRESENTATION OF MESFET UNDER ILLUMINATION

The circuit used to model the MESFET under illumination is shown in Fig.5. The drain current Id is represented by a modified Statz model [8]. The circuit model includes all of the main effects of illumination. Ipdg and Ipsg represent the gate photocurrents from both drain and source sides; they modulate the instantaneous gate voltage by flowing through Rg, this in turn has an effect on the drain current through the device transconductance. Ipch represents the photoconductive current in the channel; as this is a channel current the model incorporates a similar dependence on the gate and drain biases as is shown by the dark drain current, Id.

Ips represents the photo-carriers induced in the channel-buffer-substrate junction. These carriers modulate the voltage across the junction represented by diode,Ds, which is connected in series with the large substrate resistance, Rs,. There is an interdependent relationship between Ips and the developed voltage across the junction and this was incorporated in the model of Ips in the form of an equation relating the current to the incident optical power. The equation must be solved iteratively outside of PSpice; a polynomial expression for the solution is used in the equivalent circuit simulation.

Fig.2 and Fig.3(b) also show MESFET Id/Vgs and Id/Vds characteristics obtained from the model implemented using the PSpice simulation package. The modelled results fit well with the experimental measurements. There is some discrepancy around pinchoff but this may be due to an increased importance of buffer layer conductivity under high optical powers.

In Fig.4(b) the simulated result for the relationship between the drain photocurrent and the incident optical power is shown and it too compares well with the experimental results.

MODELLING THE RF RESPONSE

The RF response can be simulated by incorporating the frequency dependence of each of the illumination effects into the model.

For the external photovoltaic effect, the two gate photocurrents were modelled with the equation [9]:

$$i_{pv}(\omega) = G_c(w_d,\Phi)\,\frac{\sin\left(\frac{\omega t_g}{2}\right)}{\left(\frac{\omega t_g}{2}\right)}\left(\frac{1}{1 + j\,\frac{\omega t_g}{2}}\right)$$

where G_d represents the carrier photogeneration rate in the depletion region of width w_d , and t_g is the carrier transit time through the gate depletion zone.

The modulated photoconductive current in the channel can be modelled as [10]:

$$i_{pc}(\omega) = G_c(h_c\,,\,\Phi)\left(\frac{\tau_r}{t_{sd}}\,\frac{1}{(1 + j\omega\tau_r)} + \frac{K}{1 + j\omega\, t_{sd}}\right)$$

where G_{ch} is the carrier photogeneration rate in the channel, which is a function of the channel opening, h_c , and the incident photon flux density, Φ . τ is the carrier life-time and t_{sd} is the transit time of carriers through the channel. The second term represents the gain due to the differing carrier velocities.

The frequency response of the internal photovoltaic effect is modelled through the following expression for the time-varying component of the photogenerated carriers in the channel-buffer-substrate junction:

$$i_{ps} = G_c(w_n\,,\,\Phi)\left[\frac{K_1}{1+j\omega t_1} + \frac{K_2}{1+j\omega t_2} + \ldots\right]$$

where t_n represent the different trap life-times and k_n are multiplying factors. G_c is the carrier photogeneration rate in the channel-buffer-substrate junction and w_n is the width of this junction.

Fig.6 shows the simulated and the measured results for the RF response of the MESFET under illumination. The simulated results obtained show that the RF response of the MESFET under illumination can be modelled using the circuit model presented, and it can give accurate results provided that carriers transit times, life-times and trap levels are known.

CONCLUSION

In conclusion, the optical response mechanisms in a MESFET device have been reported, and a novel physically based circuit model has been used to simulate the device response. The simulation results have been shown to compare favourably with experimental measurements.

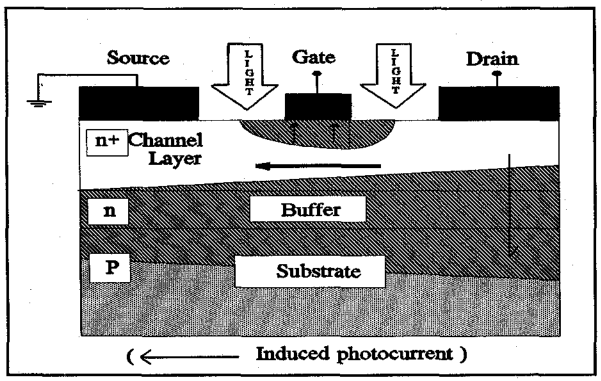

Figure 1 Principle Optical detection mechanism in MESFET

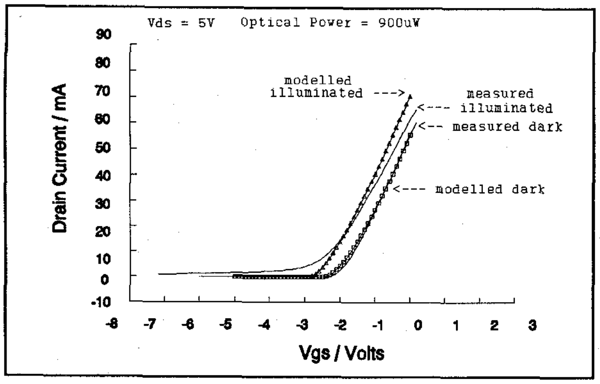

Figure 2 Drain current vs Gate-Source voltage characteristics of MESFET under dark and illumination

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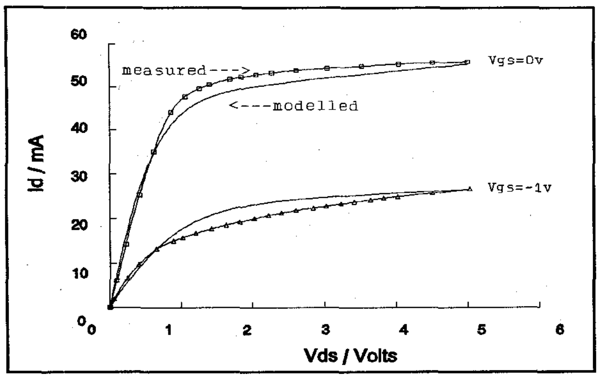

Figure 3(a) Drain current vs Drain-Source voltage characteristics of MESFET under dark condition.

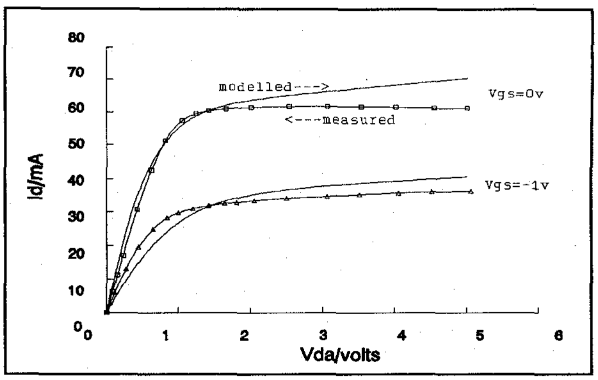

Figure 3(b) Drain current vs Drain-Source voltage characteristics of MESFET under illumination conditions.

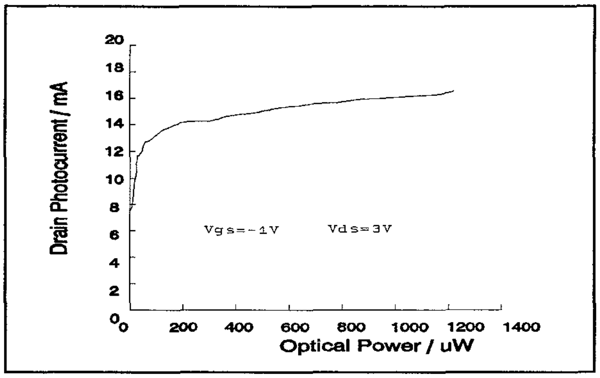

Figure 4(a) Measured MESFET drain photocurrent dependence on incident optical power.

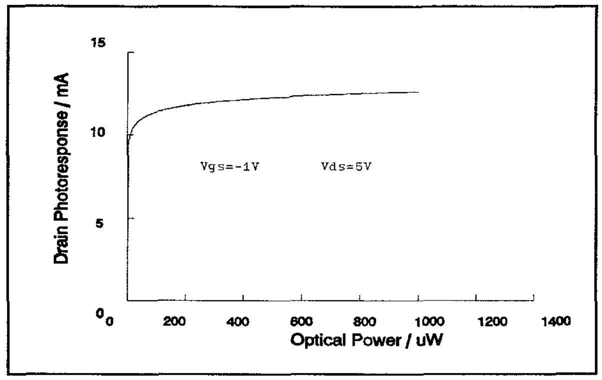

Figure 4(b) Simulated MESFET drain photocurrent dependence on incident optical power.

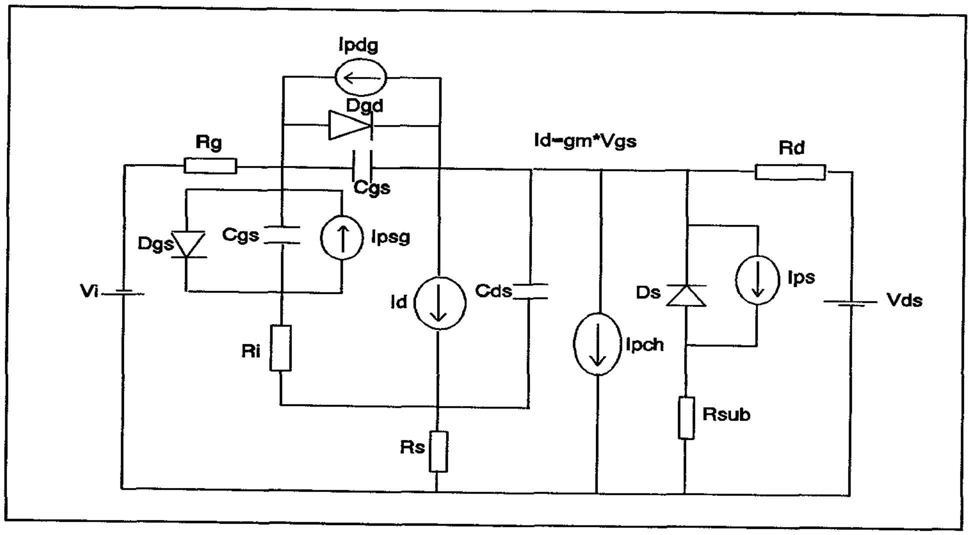

Figure 5 Physically based circuit model for GaAs MESFET device under illumination

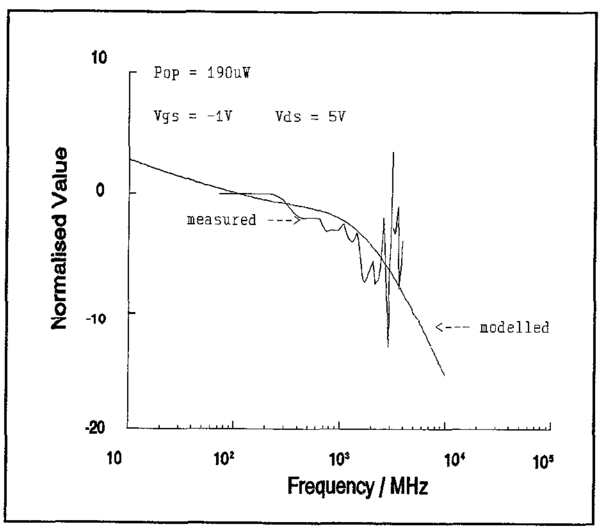

Figure 6 The simulated and measured RF response of the GaAs MESFET under illumination.

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