MICROWAVE PERFORMANCE OF OPTICALLY CONTROLLED MESFETS

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Abstract This paper presents the characterization of illuminated high-frequency active devices using a time-domain physical simulation model. The model is based on Boltzmann's Transport Equation (BTE), which accurately accounts for carrier transport in microwave and millimeter wave devices with sub-micrometer gate lengths. Illumination effects are accommodated in the model to represent carrier density changes inside the illuminated device. The simulation results are compared to available experimental records for a typical MESFET for validation purposes. The calculated y-parameters of the device show the profound effect of illumination on the microwave characteristics. These findings make the model an important tool for the design of active devices under illumination control.

1. INTRODUCTION

Optical technologies in modern telecommunication networks are rapidly advancing as more and more optical network elements are realized. The world is witnessing a continual rise in data transmission demand mainly due to the introduction of multimedia services. Optically controlled active devices (OCAD) take center-stage in the interface between the optical signal and the electronic equipment. In order to utilize the huge bandwidth offered by the optical technology, electronic active devices (e.g., detectors, amplifiers, mixers, etc.) need to be designed with optimal features.

Optical control of active devices has become particularly important for these technologies. A considerable amount of effort has been spent in the modeling and analysis of these devices over the last two decades. These efforts range from simplified theoretical treatment of illuminated MESFETs and extensive experimental investigation of the effects on small and large-signal characteristics [1]-[5], to more elaborate analytical and physical models [6]-[7]. A number of equivalent circuit models have also been derived and tested [8]-[9].

In this paper, a time-domain energy-based physical model that rigorously describes the physical processes taking place in optically controlled active devices is used for the study of microwave performance of a typical high-frequency MESFET under illumination. The model incorporates the fundamental device-radiation interactions by representing energy-dependent and non-isothermal characteristics of electron behavior, multi-dimensional carrier transport and optical effects.

2. DESCRIPTION OF THE MODEL

When the MESFET is intended for high-frequency operations, models based on the simplified drift-diffusion equations and local models are not adequate. Sub-picosecond transport takes place inside the device and hence quasi-static and equilibrium assumptions have to be avoided. A set of conservation equations can be obtained from the Boltzmann's transport equation [10]. These equations provide a time-dependent and self-consistent solution for carrier density, carrier energy and carrier momentum, and are given by

$$\frac{\partial n}{\partial t} + \nabla . (n v) = 0 \qquad (1)$$

$$\frac{\partial e}{\partial t} + v.\nabla e + \frac{1}{n}\nabla.(n k_B T v) = -q(E).v - \frac{e - e_o}{\tau_e} \qquad (2)$$

$$\frac{\partial (m v_{x,y})}{\partial t} + v.\nabla(m v_{x,y}) + \frac{q}{n}\frac{\partial}{\partial x,y}(n k_B T) = -q(E_{x,y}) - \frac{v_{x,y}}{\tau_m} \qquad (3)$$

The definitions of all quantities can be found in [10].

Similar equations are used for the hole transport. The generation rate, G, is a function of optical intensity, absorption coefficient and spatial distribution. It is given by

$$G = \phi \, \alpha \, e^{-\alpha y} \qquad (4)$$

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where ϕ is the transverse amplitude profile of the optical flux density and α is the optical absorption coefficient of the material. The recombination rate, R, includes the Shockley-Read-Hall process and the Auger recombination process. Extensive description and validation of this model and the numerical solution can be found in [10] and [11].

3. CHARACTERIZATION OF THE ILLUMINATED DEVICE

The structure of the GaAs MESFET used in the analysis is shown in figure 1 with basic parameters as listed in Table 1. The illumination is applied from the top side of the device and covers the electrodes and the spacing between them. The electrodes act as reflecting surfaces.

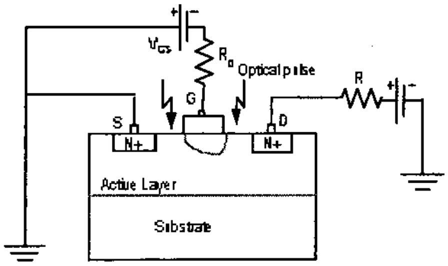


Figure 1. Circuit diagram of a GaAs MESFET under illumination.

Table 1. Device parameters used in the simulation.

Drain and source contacts	0.5 μm
Gate-source separation	1.0 μm
Gate-drain separation	1.0 μm
Device width	100 μm
Device thickness	1.0 μm
Active layer thickness	0.1 μm
Active layer doping	2×10^{17} cm^{-3}
Substrate doping	1×10^{14} cm^{-3}
Schottky barrier height	0.8 V
Optical flux density	2×10^{21} cm^{-2}.s^{-1}

The presented model is capable of simulating the effect of illumination on the small signal characteristics of the active device. This characterization is very important in the control of the device by light energy. The y-parameters are simulated by following a standard technique [12] in which a small perturbation is introduced at one port (contact) and the changes in the other port (contact) are sensed. The elements of the admittance matrix are given by:

$$y_{ij}(f) = \frac{F\{i_i(t) - I_i(to)\}}{F\{v_i(t) - V_i(to)\}} \quad \text{(i=1: input, i=2: output)} \quad (5)$$

where F stands for the Fourier transform, small letters are for total quantity and capital letters for DC quantities. A square light pulse function is applied at t=to for the evaluation of these elements. The amplitude of the step should be fairly low to avoid large spikes of displacement current in the response [12]. For example, to evaluate the y_{12} element, the device is simulated under DC steady state condition. Next, the light pulse function is applied at the top surface of the device. The current at the gate side and the output voltage at the drain side are recorded in time. Figure 2 shows the time evolution of the drain current in response to a 30-picosecond square optical pulse for three different gate lengths with gate resistance $R_g = 0$. The response rise time is shorter for shorter gate lengths. Also, shorter gate lengths allow more current to pass through the conducting channel resulting in higher drain current amplitude.

The effect of the gate resistance on the device response is also studied. Plots of the drain current of a 0.2 μm device with different R_g values are shown in figure 3. With the presence of the external gate resistance, the positive bias generated by the hole current in the gate circuit reduces the effective depletion region under the gate. This will result in an increase in the amplitude of the drain current.

Next, the microwave performance of the device is considered. The y-parameters have been the favorite of many high-frequency analog engineers for many years.

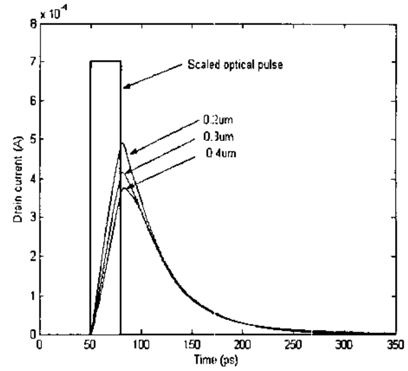


Figure 2. Time-domain evolution of the drain current in response to a square finite-duration optical pulse.

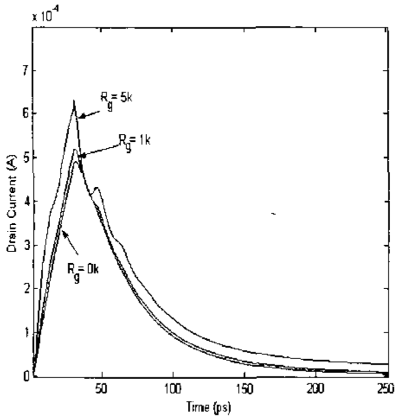
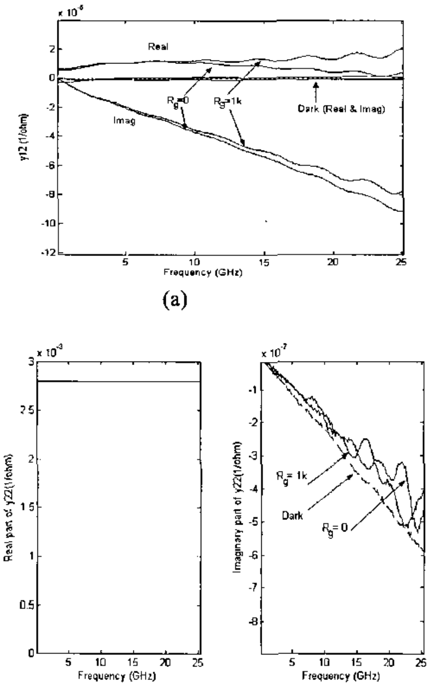


Figure 3. The effect of the presence of an external gate resistance R_g on the device drain current



(a)

(b)

Figure 4. Frequency analysis of a 0.2 µm device under illumination, a) y_{12} and b) y_{22}.

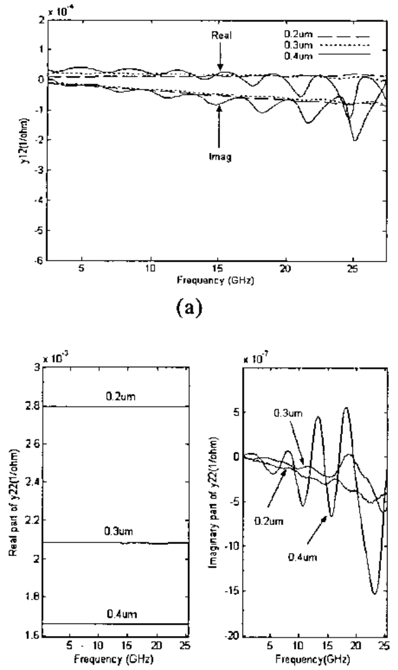
Y-parameters provide insights into circuit behavior not as apparent as with the more popular s-parameters. Although s-parameters suit single-stage designs, modeling techniques that are impedance independent, namely y-parameters suit IC designs best. Although the simulations give enough data to calculate all y-parameters, emphasis here will be given to y_{12} and y_{22} only, because these two parameters provide the required representation of the frequency response. Figure 4 shows plots of y_{12} and y_{22} for a 0.2 µm device for three different cases. The real and imaginary parts of the admittance in the dark case are very small. This is because the gate current in this case is mainly the very small displacement current. When an optical pulse is applied, y_{12} real and imaginary parts change appreciably. Similar effects and observations have been reported in [9]

As the frequency increases, the imaginary part of y_{12} increases with negative polarities implying capacitive element. The real part of y_{12} displays a different behavior; it increases with frequency when the value of R_g is increased. This observation together with the result in figure 3 lead to the conclusion that R_g can be used to improve the amplitude of the output signal but on the expense of the response bandwidth. Y_{22} is another important parameter, because it assists designers in the selection of driven load. The real part of y_{22} represent the device output admittance and it is a weak function of frequency as shown in figure 4. It also improves as the device gate length is decreased because the channel becomes more conductive (see figure 5). The imaginary part of y_{22} represents the reactive part of the output admittance including the drain-gate and drain-source capacitances. When the device is under illumination, the depletion region under the gate is reduced and hence the drain-gate capacitance becomes lower. This effect is evident in figure4.

It is interesting to study the effect of the device gate length on the microwave performance in the presence of optical excitation. Plots of y_{12} and y_{22} for devices with different gate lengths are shown in figure 5a and 5b respectively. The performance of a 0.4 µm is only acceptable at lower frequencies. For smaller gate lengths, the depletion layer is smaller which is reflected in the lower values of the reactive part of y_{22}. On the other hand, because the conducting part of the device is larger for smaller gate lengths the real part of y_{22} is larger.

4. CONCLUSIONS

In this paper a time-domain physical model is used to characterize the microwave performance of high-frequency MESFETs under illumination conditions. Specifically, time evolution of drain current in response to optical pulse is analyzed. Also the y-parameters were calculated to investigate the frequency response of the device under several situations. It was found that illumination provides an elegant and effective technique to manipulate the behavior of the device and hence control its response.



(a)

(b)

Figure 5. The effect of device gate length on the frequency response under illumination with $R_g = 0$, a) y_{12} and b) y_{22}.

Future work related to this issue includes the investigation of the structural modifications to improve the optical properties of the device. More studies can be conducted using this model including the effect of optical intensity, device dimensions and device biasing.

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REFERENCES

[1] A. A. DeSalles, "Optical control of GaAs MESFET's," IEEE Trans. Microwave Theory Tech., vol. MTT-31, pp. 812-820, 1983.

[2] H. Mizuno, "Microwave characteristics of an optically controlled GaAs MESFET," IEEE Trans. Microwave Theory Tech., vol. MTT-31, pp. 596-600, 1983.

[3] J. L. Gautier, D. Pasquet, and P. Pouvil, "Optical effects on the static and dynamic characteristics of a GaAs MESFET," IEEE Trans. Microwave Theory Tech., vol. MTT-33, pp. 819-822, 1985.

[4] R. N. Simons and K. B. Bhasin, "Analysis of optically controlled microwave/millimeter-wave device structures," IEEE Trans. Microwave Theory Tech., vol. MTT-34, pp. 1349-1355, 1986.

[5] R. N. Simons, "Microwave performance of an optically controlled AlGaAs/GaAs high electron mobility transistor and GaAs MESFET," IEEE Trans. Microwave Theory Tech., vol. MTT-35, pp. 1444-1455, 1987.

[6] S. Mishra, B. B. Pal, and R. Khan, "Optically controlled ion-implanted GaAs MESFET characteristics with opaque gate," IEEE Trans. Electron Devices, vol. 45, pp. 78-84, Jan. 1998.

[7] S. Kawasaki, M. Kimura, H. Shiomi, T. Wakabayashi, M. Funabashi, and K. Ohata, "Optical control of MMIC oscillators and model parameter analysis of an illuminated FET at the Ka and V-band IEEE MTT-S Microwave Simp. Dig., pp. 1287-1290, 1995.

[8] H. Shiomi, M. Yoneyama, T. shibata, E. sano, and S. Kawasaki, "A simple microwave oscillator photodetector operating with optical signals designed by an illuminated FET model," MWP'96 Technical Digest, pp. 281-284, 1996.

[9] S. Kawasaki, H. Shiomi, and K. Matsugatani, "A novel FET model including an illumination intensity parameter for simulation of optically controlled millimeter-wave oscillators," IEEE Trans. Microwave Theory Tech., vol. 46, pp. 820-828, 1998.

[10] M. Alsunaidi, S. Hammadi and S. El-Ghazaly, "A parallel implementation of a two-dimensional hydrodynamic model for microwave semiconductor devices including inertia effects in momentum relaxation," Int. J. Numer. Model., vol. 10, pp. 107-119, 1997.

[11] M. A. Alsunaidi, T. Kuwayama and S. Kawasaki, "Numerical Characterization of Optically Controlled MESFETs Using an Energy-Dependent Physical Simulation Model," IEICE Trans. Electronics, vol 7, pp. 869-874, July 2001.

[12] S. Laux, Techniques for small-signal analysis of semiconductor devices, IEEE Transactions on Computer-Aided Design, vol. 4, pp. 472-477, October, 1985.