THE MESFET AS AN OPTICALLY ACTIVATED MICROWAVE SWITCH - THEORY AND EXPERIMENT

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Abstract

This paper presents a novel model for the optical switching of the MESFET. The model is based on basic principles, and predicts the optical switching performance as function of the optical signal parameters, the bias level and the device physics and geometry. The results and conclusions from the theory are verified by measurements. The new model can serve as a design tool for designing an optimal MESFET for optical switching purposes.

Introduction

The GaAs MESFET, the basic building block of MMICs, can be used as a photodetector embedded on the monolithic chip itself, and thus serve as an optical input port. A comprehensive model for the response under constant illumination has been presented recently by the authors ([1]). In the present paper theoretical and experimental investigations of the MESFET under pulsed light conditions are presented.

Several authors have investigated the optical switching properties of the MESFET and demonstrated its feasibility ([2]-[6]). The modelling presented here predicts the response of the MESFET to pulsed illumination. The model is based on basic principles, namely, the device physics. It predicts the performance as function of the optical excitation (intensity, wavelength, pulse properties), electrical bias and device physical parameters and geometry. Our theoretical as well as experimental results indicate that standard commercially available microwave MESFETs are not fast optical switches, and their response time runs in the microsecond range.

Our analysis of the MESFET ([1]) has shown that the optically induced drain current is made up of three main components: 1)photoconductive current in the active channel. 2)excess current due to the internal photovoltaic effect. 3)excess current due to the external photovoltaic effect. The photoconductive current is very small (submicroamp) due to the small size of the channel. The internal photovoltaic effect is appreciable (milliamp range). The external photovoltaic effect is the largest (tens of milliamps), and is the only effect that allows complete switching of the device. In view of the above, the analysis of the optical switching includes the internal and external photovoltaic effects.

The internal photovoltaic effect

The internal photovoltaic effect is associated with the barrier which exists at the epi/substrate interface due to the large doping step. The exact nature of this effect and its properties for constant illumination are explained in [1]. When the illumination is pulsed, there are rise and fall times associated with this process due to the existence of the barrier capacitance.

Detailed analysis of the pulsed-illuminated epi/substrate interface yields a nonlinear differential equation for the photovoltage across the barrier:

$$dV_{pi}/dt=\omega_0(1-V_{pi})-\omega_s V_{pi}(1-V_{pi})^{1/2}-\omega_b(1-V_{pi})^{1/2}[\exp(\beta_{bi}V_{pi})-1] \quad (1)$$

where V_{pi} is the normalized photovoltage. The three characteristic frequencies associated with this effect: ω_0 related to the optical signal of the light pulse, ω_s related to the substrate properties and ω_b related to the epi/substrate barrier. Eq. 1 is a nonlinear differential equation for V_{pi}, the solution to which yields its time waveform. For a given device ω_s and ω_b are constants, however, ω_0 depends on the optical power and wavelength. For a pulsed excitation, as is the case for switching, the solution to Eq. 1 is a distorted square wave with finite rise and fall times. The V_{ph} waveform is used to generate the drain current waveform, which is the measurable optical response. The solution to Eq. 1 is achieved numerically by use of MATLAB routine ODE45 with $V_{pi}(t=0)=0$. For low level illumination Eq. 1 simplifies to:

$$dV_{pi}/dt+(\omega_0 + \omega_s + \omega_b\ \beta_{bi})\ V_{pi} = \omega_0 \quad (2)$$

The solution to Eq. 2 for the rising portion of the pulse is:

$$V_{pi} = \{\omega_0/(\omega_0 + \omega_s + \omega_b\ \beta_{bi})\}[1 - \exp\{-(\omega_0 + \omega_s + \omega_b\ \beta_{bi})\ t\}] \quad (3)$$

and for the falling portion of the pulse:

$$V_{pi} = \{\omega_0/(\omega_0 + \omega_s + \omega_b\ \beta_{bi})\} \exp\{-(\omega_s + \omega_b\ \beta_{bi})\ t\} \quad (4)$$

From Eqs. 3,4 the rise time is around $t_r \sim 1/(\omega_0 + \omega_s + \omega_b\ \beta_{bi})$ and the fall time is around $t_f \sim 1/(\omega_s + \omega_b\ \beta_{bi})$. Since ω_0 is proportional to the optical power it is possible to reduce the rise time by increasing the optical power; however, for a given device the fall time is independent of the optical signal. For a typical microwave MESFET with high resistivity substrate (or buffer layer) ω_s is usually negligible. Inserting typical numbers in the above equations yields fall time around 1 microsecond, while the rise time can be decreased down to the nanosecond range by increasing the optical power.

The external photovoltaic effect

Large optical response of the MESFET can be achieved by introducing a large resistor in the gate circuit, thus utilizing the optically induced gate current to generate photovoltage across the gate junction, which causes change in the drain current.

The exact analysis of the gate circuit under pulsed illumination yields a nonlinear differential equation for the normalized source to gate voltage under illumination:

$$dV/dt=w_{Rx}(V_{ggn}-V)V^{1/2} + w_{bx}V^{1/2}[\exp(b_g f_b)\exp(-b_g V_p V)-1] - w_{0x}V^{1/2} \quad (5)$$

where $V=(V_{sg}+\phi_b)/V_p$ is the normalized source to gate voltage, $V_{ggn}=(V_{gg}+\phi_b)/V_p$ is the normalized gate bias, ϕ_b is the built-in potential of the gate junction, V_p is the pinchoff voltage. The three characteristic frequencies governing the speed of the external photovoltaic effect: the external gate circuit frequency, ω_{Rx}, the gate junction barrier frequency, ω_{bx}, and the optical signal related frequency, ω_{0x}. The frequencies ω_{Rx} and ω_{bx} are constant for a given device, while ω_{0x} is proportional to the light intensity. If the bias and illumination level are such that the gate junction is reverse biased under illumination the exponential term is negligible and Eq. 5 simplifies to:

$$dV/dt = \omega_{Rx}(V_{ggn}-V)\ V^{1/2} - (\omega_{0x}+\omega_{bx})V^{1/2} \quad (6)$$

The solution to Eq. 6 for the rising part of the pulse is:

$$V=V_{ggn}K^2\{[1+K\tanh(w_c t)]/[K+\tanh(w_c t)]\}^2 \quad (7)$$

where: $K=\{1-(\omega_{0x}+\omega_{bx})/(V_{ggn}\omega_{Rx})\}^{1/2}$ and $\omega_c=0.5\omega_{Rx}K(V_{ggn})^{1/2}$. From Eq. 7 we conclude: a) in the steady state (t approaches infinity) $V=V_{ggn}K^2$, which is the boundary condition for the falling part of the pulse. b) the rise time is in the order of $tr \sim 1/\omega_c$, and is an increasing function of the optical power. Conclusion (b) is explained by the fact that the gate resistor is constant while the gate capacitance is an increasing function of the optical power. It should be emphasized that this conclusion is valid only for reverse biased gate junction . When the gate is forward biased by the illumination the above trend in fact reverses because then the effective resistance is dominated by the low forward biased gate junction resistance, which decreases strongly with the applied optical power. For the falling part of the pulse the solution to Eq. 6 is:

$$V=V_{ggn}\{(1-K_1\exp[-\omega_{Rx}(V_{ggn})^{1/2}t])/(1+K_1\exp[-\omega_{Rx}(V_{ggn})^{1/2}t])\}^2 \quad (8)$$

where $K_1=(1-K)/(1+K)$. From Eq. 8 it is seen that the fall time is in the order of $1/[\omega_{Rx}(V_{ggn})^{1/2}]$, which is independent on the optical signal.

Simulation

The results of the numerical solution to Eqs. 1 and 5 are depicted in Fig. 1. The optical power density is 5×10^5 w/m^2 (Fig. 1(a)) and 1×10^5 w/m^2 (Fig. 1(b)). The optical pulse width is 1 microsecond. The response due to the internal photovoltaic effect alone is depicted by a dashed line as well as in an enlarged version in the insert. The response associated with the total photovoltaic effect is shown by solid line. The response corresponding to the internal effect alone is limited in size to a few milliamps. The total response, however, is seen to be much larger (tens of milliamps). For the total response the rise and fall times are in the submicrosec range for reasonable optical power levels. For the internal photovoltaic effect alone - the rise time is around 0.1 microsec and the fall time is about 2 microsec for large optical power density. A large increase in rise time occurs for lower optical power levels, as shown in Fig. 1(b); however, the fall time is the same for the two power levels.

Experimental results

The conclusions from the theoretical modelling above are verified by experimental results. The measurements were performed on a FUJITSU FSX51X MESFET. The MESFET was illuminated by a pulsed GaAs diode laser operating at 850 nm. The light pulse was 20-30 microsecond long to allow the MESFET to reach steady state condition. The resulting drain current pulse was monitored by an oscilloscope. The measured rise and fall times are depicted in Fig. 2 for two values of gate-to-source voltage. The results for no gate resistor (internal p. v. effect alone) are shown in Fig. 2(a) and those for 470k gate resistor are shown in Fig. 2(b). The experimental results show that the rise time is a decreasing function of the optical power, while the fall time is a very weak function of optical power, which agrees with the theory.

References

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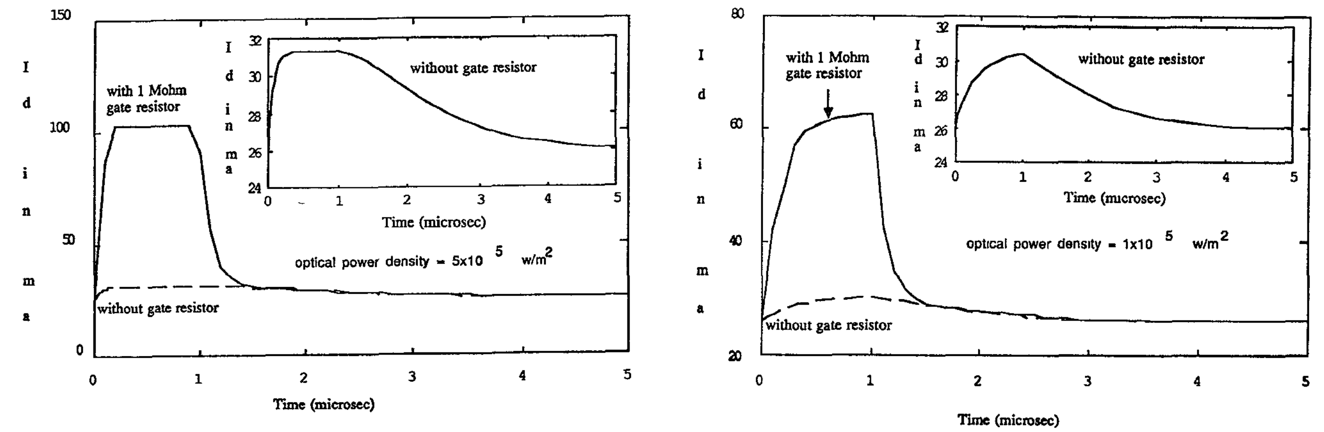
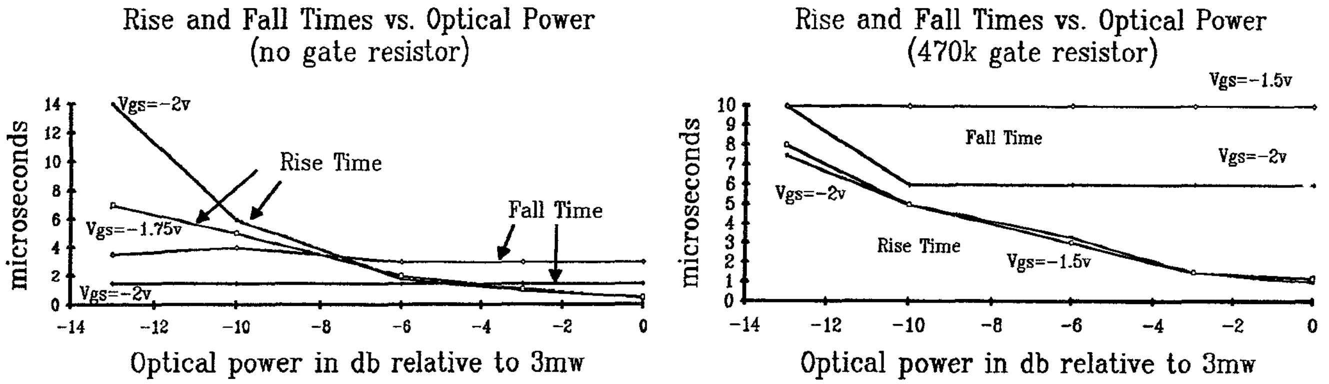


(a) (b)

Fig.1 Drain current optical pulse response of the MESFET (solid line - total, dashed line and insert - internal). optical power density = (a) 5×10^5 w/m^2 (b) 1×10^5 w/m^2



(a) (b)

Fig. 2 Rise and fall times for the FUJITSU MESFET operated under pulsed illumination (a) without gate resistor (b) with a 470k gate resistor.