OPTICALLY CONTROLLED GaAs MMIC SWITCH USING A MESFET AS AN OPTICAL DETECTOR

A. Paolella*, A. Madjar+, P. R. Herczfeld+, and D. Sturzebecher*

* US ARMY LABCOM, Electronics Tech. and Devices Lab., Ft Monmouth, N.J.
+Center for Microwave-Lightwave Engineering, Drexel Univ., Philadelphia, PA.

ABSTRACT

Optical control of microwave devices, particularly MMIC, is a rapidly growing research area. The GaAs MESFET is the prime candidate as the optical detector for MMIC applications. In this paper a theoretical analysis is presented, which accurately predicts the photocurrents in MESFETs operated in the pinched off mode. The analysis includes both photovoltaic and photoconductive effects. The paper also describes the operation of an optically triggered MMIC switch using the MMIC switch as the detector.

INTRODUCTION

With the advent of MMIC technology more complex microwave circuits and functions are integrated into smaller areas. The control of MMIC chips and MMIC based modules is usually achieved by remotely located components and subsystems. Utilizing metallic cables and wires for interconnects poses problems with respect to size and weight and interference from undesired electromagnetic radiation. Lightwaves, transmitted via optical fibers, represent an attractive alternative for the distribution of control signals to MMIC chips. Ideally, one would like to interface the optical input with the MMICs directly. However, PIN photodiodes, commonly used with fiber optic systems, are not compatible with standard MMIC processing schemes. Here a GaAs MESFET is used as an optical detector. The output of the MESFET, the demodulated control signal, is passed through a conditioning circuit, serving as an interface between the optical receiver and the functional circuit (switch, phase shifter, etc) which is to be controlled.

The MESFET has been used as an optical detector and control device in microwave applications by several investigators[1-5]. Of the many advantages of using the MESFET as an optical detector, the most notable is compatibility with GaAs MMIC technology. De Salles[6,7] has performed a thorough experimental and theoretical characterization on the MESFET emphasizing the photovoltaic effect, which can be used to increase the drain current and change the gate capacitance. His analysis is concentrated on the active region of the device, photocurrent in the substrate is ignored. Darling[8] has developed a perturbation analysis to account for the photoconductive effect under low level illumination.

This paper demonstrates the optical control of an MMIC switch by a MESFET photodetector. Also presented is a novel model of the illuminated MESFET, the important features of which are as follows:

1. The device is operated in the normally off mode (beyond pinch-off).
2. Both photovoltaic and photoconductive effects are considered.
3. The photocurrent in the semi-insulating substrate under the gate depletion region is considered.
4. Leakage current between the drain and source bonding pads via the substrate is considered.
5. The analysis is based on approximate analytical solution of the semiconductor transport equations.
6. The light intensity and wavelength are taken into account explicitly.
7. The change in the potential barrier between the epitaxial layer and the substrate due to illumination is considered.

This paper is divided into two parts. First an improved model of the illuminated MESFET is presented, which serves as a tool to optimize its performance. The wavelength dependence of the response is emphasized, since it influences the relative contribution of the photovoltaic and photoconductive effects. The second part focuses on an application; a light triggered MMIC switch using the MESFET as a detector.

MMIC MESFET PHOTODETECTOR --- ANALYTICAL CONSIDERATIONS

In this section a brief description of the analytical model for the illuminated MESFET is presented. (A more extensive treatment of the problem will be published elsewhere.) A cross sectional view of the device is presented in Fig.1. The device is constructed on a Cr-doped semi-insulating substrate with a 2 micron buffer layer. Then an n-type epitaxial layer doped around 10^{17} cm^{-3} is grown on top of the buffer to serve as the active layer, which is etched in the form of a mesa. The bonding pads are located on the substrate itself (not on the mesa), and the drain and source electrodes are deposited on top of the epi layer, and form ohmic contacts. The mesa is etched in the gate region to obtain the desired current, and the gate Schottky metalization is vacuum deposited.

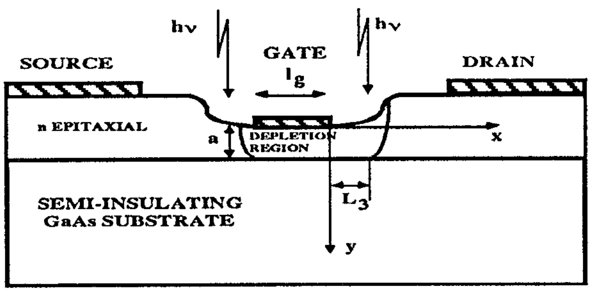

Fig. 1 Cross sectional view of the MESFET

When the device is illuminated by light, with photon energy (hv) larger then the bandgap of the material (1.41ev for GaAs), each photon generates an electron-hole pair. These excess carriers alter the electrical performance of the device in several ways. In general, one can identify two effects:

- **Photoconductivity**--increase in the carrier density of the material, resulting in enhanced drain current and in a decrease of the parasitic resistances.
- **Photovoltaic**--increase in the gate current, which can be enhanced with an external gate resistor to alter the gate to source voltage reducing the depletion layer in the channel, thereby changing the drain current as well as the device capacitances.

Both of these effects are calculated by solving the differential equations governing charge transport in the semiconductor subject to appropriate boundary conditions.

The objective of the analysis is to compute the optically induced drain and gate currents. From Fig. 1, one can reason that since the device is in pinch-off state, the optically induced drain current is due to carriers generated in the substrate.

The gate current is composed of two components: the first is due to the total number of holes generated in the depletion region, the second to the diffusion of holes from the channel to the depletion region ($J_p=qD_p dp_{opt}/dy$ at $y=a$). For the pinched-off device there is no channel, so only the first component contributes to the current. Thus the gate current is:

$$I_g=qFwL_3(1-e^{-\alpha a})(1+((v_{sg}+\phi_b)/(v_{sg}+v_{ds}+\phi_b))^{1/2}) \quad (1)$$

where w is the total gate width, L_3 is the extension of the depletion region beyond the gate toward the drain, ϕ_b is the built in potential of the gate junction, q is the electron charge, F is the photon flux per unit area per unit time, α is the absorption coefficient, a is the epitaxial layer thickness.

The gate current represents the photovoltaic effect. Loading the gate by a large resistor generates a phovoltage across the gate source junction. If the resistor and the optical power density are sufficiently large, nearly open circuit conditions exist, and the gate voltage is "pinned" to a small positive voltage. Under this condition the channel is practically open, resulting in a dramatic increase (gain) of the drain current.

The direct photoconductive current in the drain is composed of two components: 1) the photocurrent in the substrate (or buffer layer) below the epitaxial layer; 2) leakage current in the substrate between the drain and source bonding pads. To compute the photo-induced current in the substrate one can adapt phototransistor theory, which yields the following expression:

$$I_{sub}=qFw(l_{gs}+l_{gd})(e^{-\alpha(a-\delta)}-e^{-\alpha a})(1-e^{-qvds/kT})\beta \quad (2)$$

where,

$$\beta=\cosh(l_g/L_b)/(\cosh(l_g/L_b)-1) \quad (3)$$

$$L_b=(D_{ns}\,\tau_{ns})^{1/2} \quad (4)$$

l_{gs},l_{gd} are source/gate and drain/gate spacings, δ is the epi/substrate barrier thickness, D_{ns} is the electron diffusion coefficient in the substrate, τ_{ns} is the recombination lifetime of the electrons in the substrate, l_g is the gate length.

Since the source and drain bonding pads form Schottky barriers on the substrate, the expression for leakage current is computed by using the Schottky barrier optical detector theory:

$$I_{leak}=qFw_s d(1-e^{-\alpha d}) \quad (6)$$

where,

$$d=(2\varepsilon(v_{ds}+\phi_b)/(qN_{dsub}))^{1/2} \quad (7)$$

N_{dsub} is the doping level of the substrate, w_s is the total width of parallel sections of drain and source pads, ε is the dielectric constant of the substrate.

OPTICALLY CONTROLLED GaAs MMIC SWITCH

An optically controlled GaAs MMIC switch was constructed and tested using the MESFET detector discussed in this paper. The experimental setup is shown in Fig.2. The microwave switch is contained on a single GaAs MMIC chip manufactured by MA/COM. The switching function is controlled by two voltage settings, V_1 and V_2. To switch the microwave input signal to OUTPUT 1, the required voltages are V_1=0.0 and V_2=-7.0 volts. To switch the microwave input signal to OUTPUT 2, the voltages needed are V_1=-7.0 and V_2=0.0 volts. The control circuitry is fabricated on a single 1 inch squared, 25 mil alumina substrate using laser trimmed thick film resistors, and unpackaged op-amps.The GaAs MMIC switch was mounted on a separate 25 mil alumina substrate which contained lines for the control voltages, and three 50 ohm microstrip transmission lines for the microwave signals.

The circuit operation is presented below. The MESFET optical detector is biased near pinch-off by a gate-to-source voltage (V_{gs}) of -3.75 volts, such that the drain-to-source voltage (V_{DS}) is 3.0 volts. Under optical illumination the device begins to conduct current through R_D and the required change in V_{DS} of 0.5 volts is obtained. The optical source used is a fiber coupled LED operating at a peak wavelength of 835 nm. The light is routed via a mutli-mode fiber with core-cladding diameters of 100 and 140 μm respectively. Optimum coupling efficiency of the optical power into the device is realized when the fiber height is adjusted such that the spot size uniformly and completely illuminates the device. The optical filling factor K_f, is the ratio of the exposed active GaAs area of the MESFET divided by the optical spot size and is equal to 0.057 for the device under consideration.The optical intensity needed to provide the 0.5 volt change is 25 μw.

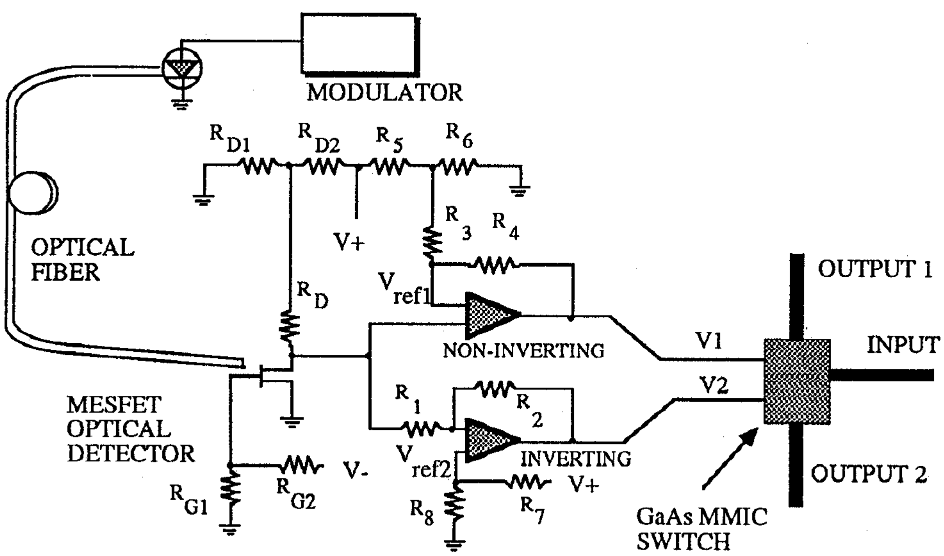

Fig. 2 Opitcally controlled GaAs MMIC Switch.

The drain of the MESFET is connected to two high speed operational amplifiers each with a voltage gain of 14 (23 dB) and a gain-bandwidth product of 400 MHz. One op-amp operates in the inverting and the other in the non-inverting mode. The non-inverting op-amp has a reference voltage, V_{ref1}=3.0. In the absence of illumination, V_{DS}=3.0 volts, and the difference in the input voltage of the non-inverting op-amp is 0.0 volts, and therefore the output voltage, V_1, is 0.0 volts. The inverting op-amp has a reference voltage of V_{ref2}=2.5 volts. Again with V_{DS}=3.0 volts, a difference of 0.5 volts exits at the input of the inverting op-amp. The gain is such that the output V_2 is -7.0 volts. With these conditions, OUTPUT 1 is in the low loss state, and OUTPUT 2 is in the isolation state. When the MESFET is illuminated, V_{DS} changes form 3.0 to 2.5 volts and the outputs of the op-amps switch states, thereby switching the microwave signal from OUTPUT 1 to OUTPUT 2.

A photograph of the final assembled circuit is shown in Fig. 3. A 10 GHz microwave signal with an input power of 10 dBm was applied to the input of the switch. The LED was modulated and switching of the microwave signal between designated ports was observed with 20 dB of isolation and 1.5 dB of insertion loss.The circuit was tested at a modulation rate of 1 MHz (or 1 µs), limited in speed only by the presently used LED.

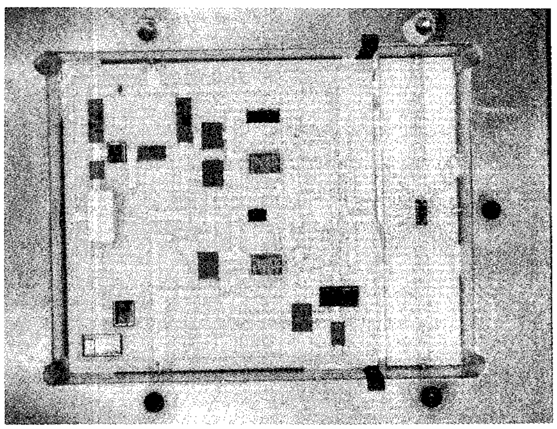

Figure 3. Photograph of Optically Controlled GaAs MMIC Switch

CONCLUSION

An analytical model for the optical response of GaAs MESFET is presented here. It features some new aspects, such as the wavelenght and intensity dependence of the MESFET under different biasing conditions. The theory and computer simulations shows good agreement with experimental results. The model can serve as a tool for the optimal design of optically controlled MMIC and MIC using the MESFET as the photosensitive element.

This MESFET optical detector was used to control an optically triggered microwave switching employing standard, commercially available MMICs and low cost, off the shelf electrooptic components.

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