A STUDY ON THE NEGATIVE PHOTORESPONSE OF AlGaAs/GaAs MODFETs

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ABSTRACT

A model for the mechanism of negative photoresponse, i.e., the decrease of drain current under illumination, in AlGaAs/GaAs MODFETs is presented. Also, a comprehensive experimental study discussing the dependence of this phenomena on gate to source bias voltage and optical power is reported. The negative photoresponse is attributed to trapping of photogenerated carriers in the GaAs buffer layer, causing a change in the potential profile and consequent reduction in the number of carriers in the 2-DEG channel.

INTRODUCTION

The optical illumination of MODFETs and related structures has attracted a great deal of attention regarding the optical control of microwave devices and circuits [1] as well as high -speed photodetection [2]. Recently, the merging of microwave and optical devices on the same MMIC substrate was proposed [3]. In this case, the microwave signal is routed to the MMIC chip by optical means. This signal is then detected by a MODFET, acting as an "optical input port", and processed.

This type of application requires a comprehensive and systematic study of the optical response of MODFETs transistors in order to optimize its detection performance. In fact, the major mechanisms governing the photoresponse of these devices have been already identified [4] and most devices, as expected, show positive photoresponse when illuminated. However, several investigators [5-6], including ourselves, have observed the so-called negative photoconductivity and there is some controversy in the literature regarding the origin of this effect.

In reference [5], it was proposed that this phenomena is caused by pumping of electrons from the 2-DEG channel into the surrounding layers. Unfortunately, this explanation cannot account for negative photoresponse when there is band-to-band absorption in the GaAs layer, as in our case.

On the other hand, Thomasian [6] suggested that negative photoresponse was associated to a net transfer of charge from the 2-DEG channel to surface states on the top of the AlGaAs layer and to the occurrence of the kink effect in the DC output characteristics, not observed during our measurements. Furthermore, they did not observe negative photoresponse in the linear region of the MODFET I-V curves.

The purpose of this paper is to analyse the causes of the negative photoresponse and to provide a better understanding of the transport of optically generated carriers in the device. We propose a new theory, based on the trapping of photogenerated electrons into the GaAs layer, that allows better understanding of our experimental results and permits to predict whether a particular device will display positive or negative drain current variation under optical illumination.

DEVICE STRUCTURE AND EXPERIMENTAL RESULTS

The measured MODFETs were grown by MBE on top of an undoped GaAs substrate and the following growing sequence was employed : 1µm of undoped GaAs buffer, 30 Å thick undoped $Al_{0.24}Ga_{0.76}As$ spacer, 200 Å thick $Al_{0.24}Ga_{0.76}As$ layer (Silicon doped 10^{18} cm^{-3}), 200 Å of $Al_xGa_{1-x}As$ (Si doped 10^{18} cm^{-3}), where the aluminium content x was linearly graded from zero to 0.24, and a 200 Å thick GaAs cap layer (Si doped 4 x 10^{18} cm^{-3}).

The devices had the following geometry: gate length 0.25 mm, gate width 150 µm and gate to source and gate to drain spacing of 0.75 and 1.5 µm, respectively.

Illumination was provided by a pig-tailed laser diode (λ = 0.83 μm). The output fiber was held 1mm above the device and routed by a micropositioner to allow optimum light coupling. On the basis of the spot size, gate geometry and optical reflection at the surface of the device (there is no passivation), we estimate that only 2% of the available photons were actually being absorbed in the GaAs buffer layer.

During the measurements the photoresponse, defined as the difference in the drain output current under illumination and dark conditions, was monitored. In fig. 1, we show the negative photoresponse, normalized to the dark drain current, as a function of the gate to source voltage. The drain to source voltage was used as a parameter and the optical power was kept fixed at 1 mW.

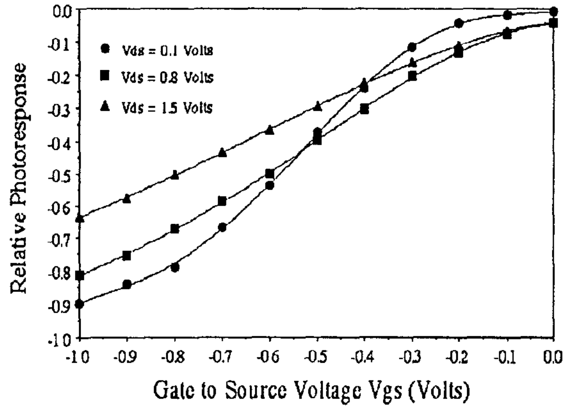


Fig. 1 Photoresponse as a function of the gate to source voltage, normalized with respect to the dark drain current.

The results displayed at figure 1 give a measure of the device's sensitivity to the optical illumination. Our experimental data indicates that the sensitivity is a strong function of the voltage V_{gs} and that the negative photoresponse effect is much more pronounced when the device is driven deeply below threshold. In fact, a variation of 90% in the drain current was observed at the bias point V_{ds} = 0.1 Volts, V_{gs} = -1.0 Volt.

In figure 2 we plot again the photoresponse, not normalized. It can be observed that the drain current variation is fairly constant for values of Vgs below the nominal threshold voltage (V_{off} = -0.48 V) and starts to reduce as the gate to source bias voltage approaches zero.

Next, we measured the photoresponse versus incident optical power, for a given bias point. Some of the results are shown in figure 3, where V_{gs} was used as a parameter.The drain to source voltage was kept constant at 1.0 Volt.

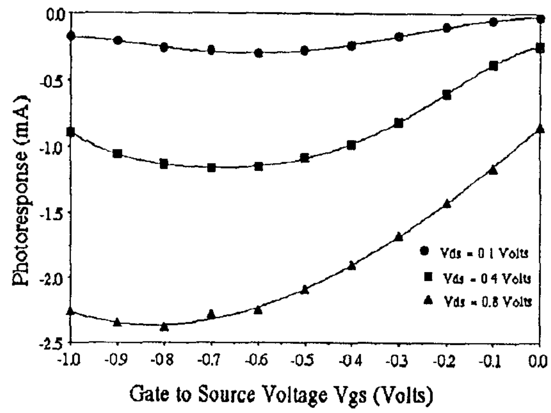


Fig. 2 Photoresponse as a function of the gate to source voltage.

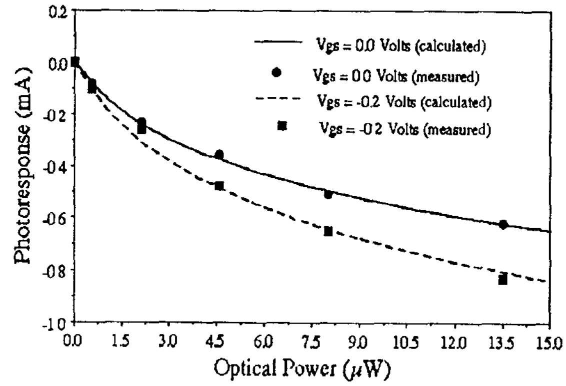


Fig. 3 Photoresponse as a function of the incident optical power. The calculated curves use expression (1). For V_{gs} = 0.0 Volts (plain line) the curve-fitting parameters are I_{pho} = -0.27 mA and P_O = 1.5 μW. For Vgs = -0.2 Volts (dashed line) the curve-fitting parameters are I_{pho} = -0.35 mA and P_O = 1.5 μW.

For low power levels we observed a logarithmic dependence and the photoresponse-optical power relationship is given by:

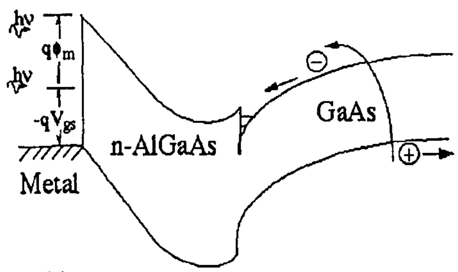
$$I_{ph} = I_{pho} \ln (P/P_O + 1) \qquad (1)$$

where Iph is the photoresponse, P is the optical power and I_{pho} and P_O are parameters of curve fitting, I_{pho} being voltage dependent. For power levels above 50 μW saturation occurs and the photoresponse becomes almost independent on the incident optical power.

DISCUSSION

Both negative and positive photoresponse have been reported in AlGaAs/GaAs MODFETs with similar layer structures. The two process are illustrated in figure 4. The mechanism responsible for positive photoconductivity can be explained as follows: if the energy of the incident photons is less than the bandgap of the AlGaAs but greater than of the GaAs, carrier generation will occur only in the buffer layer. The built-in electric field associated with the band bending of the heterojunction will sweep the photoelectrons to the DEG channel (fig. 4a), increasing the drain current.

(a)



(b)

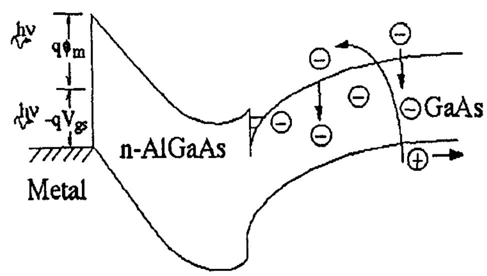


Fig. 4 Absorption of photons and generation of electron -hole pairs in the GaAs layers. Fig. 4a illustrates the positive photoresponse, when electrons are collected by the 2-DEG channel. Fig. 4b shows the negative photoresponse, when electrons are stored in the buffer layer.

This article, however, is concerned with the origin of negative photoresponse . We postulate that this phenomena is caused by the presence of deep traps in the GaAs layer. Now, instead of being collected by the drain, most of the photogenerated carriers will become stored into the buffer (fig.4b). In order to satisfy the charge-neutrality condition and as a consequence of the increase of negative charge in the bulk GaAs , the electric field profile across the buffer will be modified in such a way that the number of carriers in the 2-DEG channel will decrease, resulting in an overall reduction of the output current.

To calculate this reduction in the drain current as a function of the photogenerated trapped charge density we have solved the Poisson equation for the AlGaAs/GaAs heterojunction, subjected to the customary boundary conditions.

The approach used here is similar to the one proposed in [7], however, we included the trapping of photogenerated carriers into the model. Therefore, the Poisson's equation for the GaAs region is written as :

$$\frac{d^2\phi_2}{dx^2} = \frac{q}{\varepsilon_2}[n_s + N_T] \qquad (2)$$

where ϕ_2 is the potential profile and ε_2 is the dielectric constant of the GaAs layer. N_T represents the total photogenerated trapped charge and n_s the electron concentration in the conducting channel. The solution of the Poisson equation is then used to calculate the 2-DEG electron concentration versus gate to source voltage [8].

Once this charge-control relation between n_s and V_{gs} is obtained, we compute the drain current variation. Therefore, our theory allows one to understand the experimental results (figs 1 and 2) as a consequence of a photoinduced shift in the effective gate to source voltage V_{gs}', defined as:

$$V_{gs}' = V_{gs} - V_{off} \qquad (3)$$

where V_{off} is the threshold voltage for the MODFET.

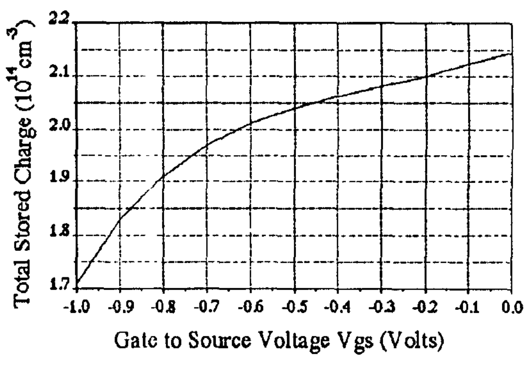


Fig. 5 Total amount of trapped charge required to produce a change of 1.0 mA in the drain current, as a function of the gate to source bias.

In figure 5, we present the total amount of trapped charge required to induce a 1.0mA reduction in the drain current, as a function of the gate to source voltage. Since our Poisson solver is uni-dimensional, the results are strictly valid only for small values of V_{ds}. However, the essential features of the negative photoresponse phenomena are prevalent. We note, for example, that when the device is deeply pinched-off significantly less trapped charge is needed to yield a given reduction in the drain current. This is in good agreement with our experiments (see fig. 1).

Additional studies are required to establish that such density of traps is indeed present in the GaAs layer. However, it is well known that impurities from the substrate can be incorporated into the epitaxial layers during the growing process and introduce trapping states [9]. In fact, common to all devices that exhibit negative photoresponse is a structure where the GaAs layer was placed directly over the substrate.

Finally, we investigated the frequency response to modulated light of the devices that present negative photoresponse. The cut-off frequencies for these devices are of the order of a few hundred kHz. In contrast, we found that, for devices that exhibit positive photoconductivity, the frequency response ranges from a few hundred Mhz up to several (2-4) GHz.

Direct comparison between the two types of devices is not feasible since their structures are not identical. However, we can safely argue that when trapping mechanism are dominant the speed of the detector suffers. Therefore, this is yet another indication that negative photoresponse is caused by traps. Conversely, if high-speed operation is to be achieved, the trapping centers density have to be minimized.

CONCLUSIONS

A study of the negative photoresponse of AlGaAs/GaAs MODFET, observed by several investigators, was presented. Extensive experimental characterization of this phenomena regarding its dependence on bias voltages and optical power was performed. The negative photoresponse was explained in terms of the increase of the stored charge in the buffer layer, inducing a reduction in the number of 2-DEG electrons.

If MODFETs structures are to be used as high speed optical input ports of MMICs, the negative photoresponse phenomena has to be understood and then suppressed. Based on our present studies we suggest that this can be accomplished by using more sophisticated structures, where the optical absorption occurs in a layer that is physically separated from the substrate, to prevent contamination during the growing process

ACKNOWLEDGMENTS

The authors would like to thank P.M. Smith (General Electric Company) for providing the MODFETs and A. Rothwarf and B. Nabet for several helpful discussions.

This work was supported by GE Electronics Laboratory, CNPq (Brazilian Research Council) and NSF Grant INT 900-2289.

REFERENCES

[1] - A..J. Seeds and A.A. de Salles, "Optical Control of Microwave Semiconductor Devices," IEEE Transactions on Microwave Theory and Techniques, Vol. 38, No. 5, May 1990, pp. 577-585.

[2] - M.Z. Martin et al., "High-Speed Optical Response of Pseudomorphic InGaAs High Electron Mobility Transistors", IEEE Photonics Technology Letters, Vol. 4, No. 9, September 1992, pp. 1012-1014.

[3] - P.R. Herczfeld, "Monolithic Microwave-Photonic Integrated Circuits: a Possible Follow-up to MIMIC," Microwave Journal, Vol. 35, No. 1, January 1992, pp. 64-78.

[4] - A. A. de Salles and M.A. Romero, "AlGaAs/GaAs HEMTs under Optical Illumination", IEEE Transactions on Microwave Theory and Techniques, Vol. 39, No. 12, December 1991, pp. 2010-2017.

[5] - C.S. Chang et al., "Negative Photoconductivity in High Electron Mobility Transistor", Applied Physics Letters, December 1987, pp. 2233-2235.

[6] - A. Thomasian et al., "Mechanism of Kink Effect Related to Negative Photoconductivity in AlGaAs/GaAs HEMTs", Electronic Letters, Vol 25, No. 4, May 1989, pp. 738-739.

[7] - A. Eskandarian, "Determination of the Small-Signal Parameters of an AlGaAs/GaAs MODFET", IEEE Transactions on Electron Devices, Vol 35, No. 11, November 1986, pp. 1793-1801.

[8] - H. Rohdin and P.Roblin, "A MODFET DC Model with Improved Pinchoff and Saturation Characteristics ," IEEE Transactions on Electron Devices, Vol. 33, May 1986, pp. 664-672

[9] - M.R. Brozel et al., "Diffusion of Transition Elements in GaAs and InP", Electronic Letters, Vol. 17, No. 15, July 1981,pp. 532-533.