Negative Photoresponse in Modulation Doped Field Effect Transistors (MODFET's): Theory and Experiment

Murilo A. Romero and Peter R. Herczfeld, *Fellow, IEEE*

Abstract— **A model for the mechanism of negative photoresponse, namely, the decrease of drain current under illumination, in AlGaAs/GaAs MODFET's is presented. Also, a comprehensive experimental study discussing the dependence of this phenomena on gate and drain to source bias voltages and optical power, as well as a comparison with devices that show the usual positive photoresponse, are 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. The above theory is supported by numerical solution of Poisson's and electron continuity equation, using the finite-elements method. Finally, the implications of the negative photoresponse on the high-speed photodetection properties of MODFET's devices are discussed.**

I. Introduction

THE OPTICAL illumination of MODFET's 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 MODFET transistors in order to optimize its 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 negative photoconductivity and there is some controversy in the literature regarding the origin of this effect.

In [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 band-to-band electron-hole generation in the GaAs layer is dominant, as in our case.

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The authors are with the Center for Microwave/Lightwave Engineering, Electrical and Computer Engineering Department, Drexel University, Philadelphia, PA 19104 USA.

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On the other hand, Thomasian and co-workers [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, which were 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 analyze 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 one to predict whether a particular device will display positive or negative drain current variation under optical illumination.

II. Devices Description

We have examined the optical detection properties of two distinct devices: an AlGaAs/GaAs single heterojunction, referred to as "conventional," and a doped InGaAs channel pseudomorphic structure.

The measured MODFET's were fabricated by General Electric and grown by MBE on top of a semi-insulating undoped LEC GaAs substrate. For the conventional devices the following growing sequence was employed: 1 μm 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 aluminum content was linearly graded from zero to 0.24, and a 200 Å thick GaAs cap layer (Si doped 4×10^{18} cm^{-3}).

Hall measurements at room temperature yielded electron mobility of 5292 cm^2/V.s and electron sheet density of 1.5 $\times$ 10^{12} cm^{-2}. The devices had the following geometry: gate length 0.25 μm, gate width 150 μm and gate to source and gate to drain spacing of 0.75 and 1.5 μm, respectively.

The second device utilized is a MODFET, also fabricated by GE, already described elsewhere [7]. The layer structure consists basically of an InGaAs planar doped channel (Indium content of 22%), placed in between an AlGaAs donor layer (also planar doped) and an AlGaAs/GaAs superlattice buffer.

The external geometry is given as follows: gate length 0.25 μm, gate width 75 μm and gate to source and gate to drain spacing 0.3 and 1.0 μm, respectively. Hall measurements at 300 K indicated an electron mobility of 3100 cm^2/V.s and

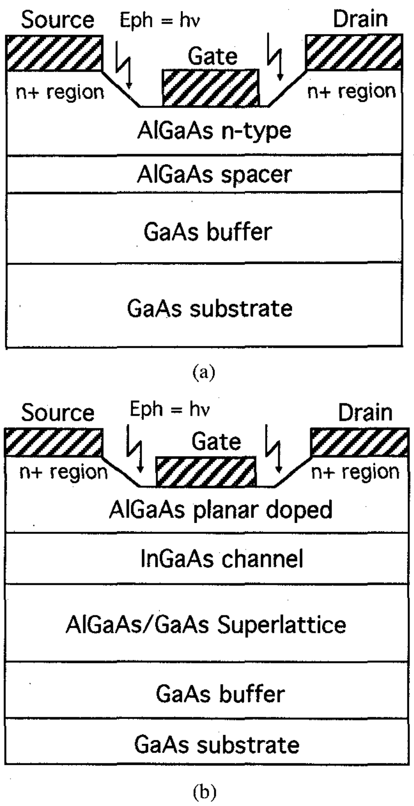

Fig. 1. Schematic cross-section for the devices studied in this work: (a) Conventional AlGaAs/GaAs single-heterojunction MODFET. (b) Doped InGaAs channel pseudomorphic MODFET.

electron sheet density of 4.2×10^{12} cm^{-2}. It is interesting to observe that, despite the lower mobility, these devices present higher transconductance and current density, when compared to conventional ones. The schematic cross-section of both structures is presented in Fig. 1. The conventional device was not passivated, in contrast with the pseudomorphic structure, coated with a layer of Silicon Nitride.

III. Experimental Procedure

The MODFET's were mounted on a 25-mil-thick carrier in a coplanar waveguide (CPW) configuration. The device gate and drain pads were wire-bonded to the CPW center conductors while the source pads were wire-bonded to the ground plane, in order to obtain a common source configuration. The carrier was then placed in a microwave test fixture, fabricated by Design Techniques.

Illumination was provided by a pig-tailed ORTEL SL-1020 semiconductor laser diode ($\lambda = 0.83$ μm), making the AlGaAs transparent for the incident optical energy. The output multimode fiber was held 500 μm above the devices 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 (the calculations take into account the presence of passivation), we estimate that less than 1.0% of the available photons were actually being absorbed in either one of the devices.

A schematic diagram of our experimental setup is depicted in Fig. 2. It should be observed that no resistor was present at the gate biasing circuit, in order to avoid the so-called external photovoltaic effect [4]. Furthermore, in the high-speed measurements the laser was directly modulated at microwave frequencies and the optical link loss was displayed in a HP 8510 network analyzer. Since the relaxation oscillation frequency of the laser is about 10 GHz, these results will give a measure of the bandwidth of the MODFET photodetector.

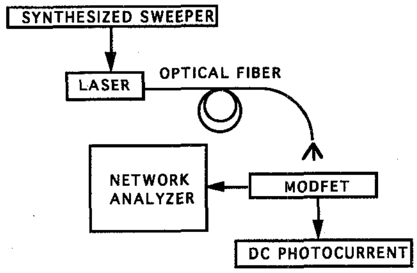

Fig. 2. Schematic diagram of the experimental setup.

IV. Experimental Results: DC Illumination

During the measurements, we monitored the photoresponse, defined as the difference in the drain output current under illumination and dark conditions:

$$I_{ph} = I_{ds} \quad \text{(illuminated)} - I_{ds} \quad \text{(dark)}. \tag{1}$$

Then, the responsivity is a useful figure of merit, defined as the ratio between the photoresponse and the optical power available at the fiber end:

$$R = \frac{I_{ph}}{P_{opt}}. \tag{2}$$

It should be stressed that the devices were standard microwave MODFET's, not designed for optical applications, presenting a very small coupling efficiency, of approximately 1.0%. The internal quantum efficiency of the MODFET's photodetectors would be actually two orders of magnitude greater than the values given below, if the absorbed optical power is explicitly accounted for in (2).

Bias dependence: In Fig. 3, we show the photoresponse, as a function of the drain to source voltage, for the conventional AlGaAs/GaAs structure. The gate to source voltage is used as a parameter and the optical power is kept fixed at 1.0 mW.

We observe negative photoresponse, i.e., the drain current decreases when the device is illuminated and, therefore, the responsivity is negative. Moreover, we find that the drain current variation becomes larger as the drain to source voltage is increased and when the device is biased closer to pinch-off condition, with $V_{gs} = -0.4$ V. Indeed, for $V_{gs} = 0.0$ V the drain current reduction under illumination is 1.17 mA, as opposed to 2.12 mA at the bias point $V_{gs} = -0.4$ V.

In Fig. 4, a similar measurement is presented, at the same bias points, $V_{gs} = 0.0$ V and $V_{gs} = -0.4$ V, for the InGaAs channel pseudomorphic structure. First of all, we observe a positive responsivity, as expected in any ordinary photodetector. Furthermore, the responsivity increases with V_{gs}, in contrast with the conventional device discussed above. The responsivity now reaches a maximum of 2.12 A/W at the bias point $V_{gs} = 0.0$ V, $V_{ds} = 1.7$ V. The peak value of the

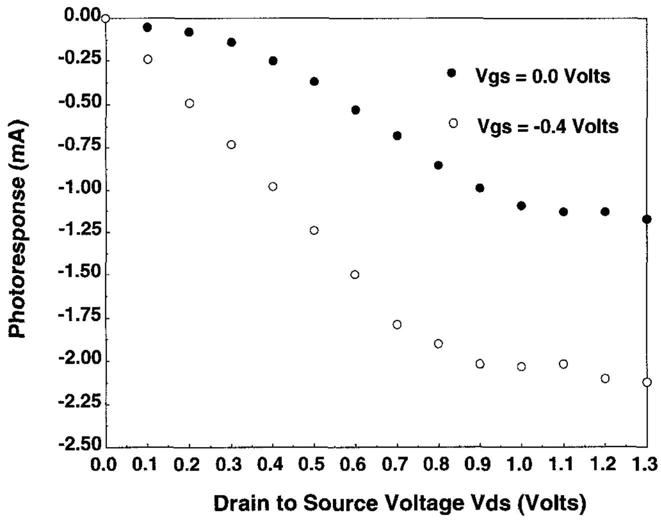

Fig. 3. Photoresponse as a function of drain to source voltage for the conventional structure.

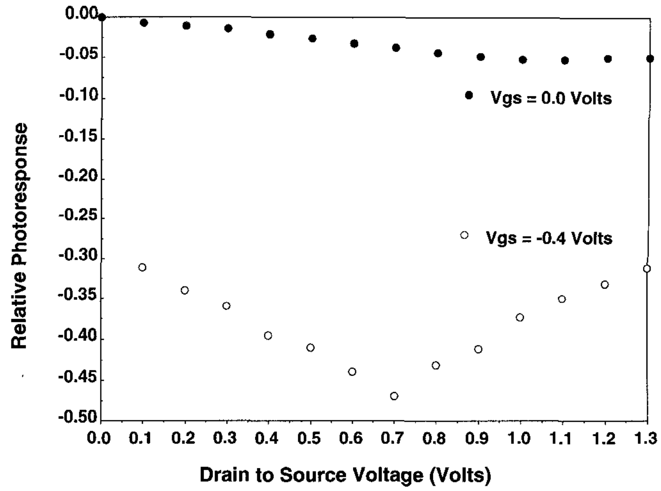

Fig. 5. Photoresponse as a function of drain to source voltage, normalized with respect to the dark current, for the conventional structure.

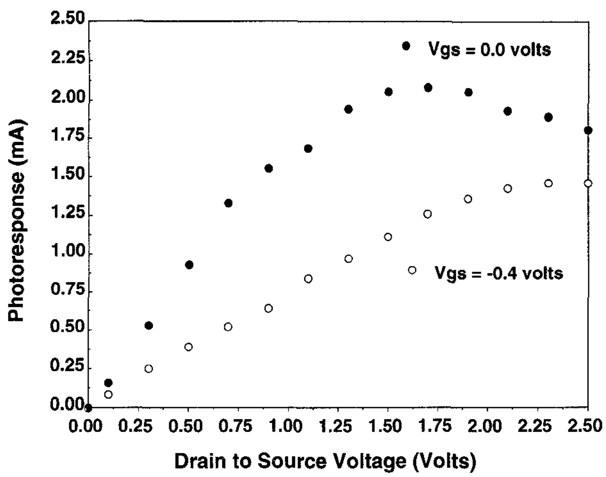

Fig. 4. Photoresponse as a function of drain to source voltage for the pseudomorphic structure.

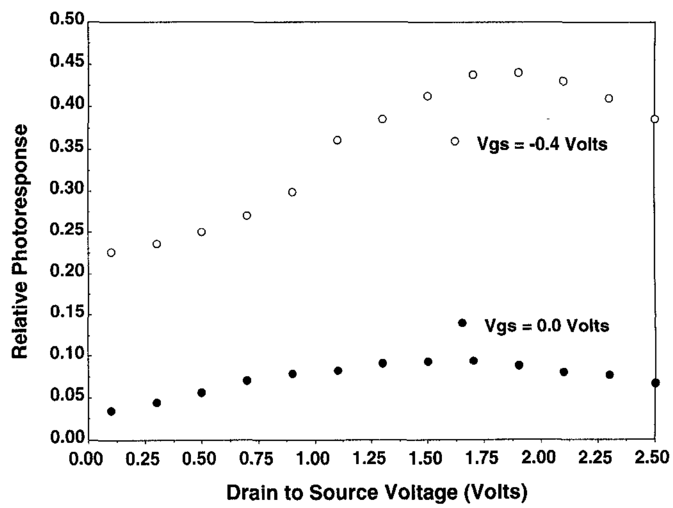

Fig. 6. Photoresponse as a function of drain to source voltage, normalized with respect to the dark current, for the pseudomorphic structure.

responsivity is relatively low for MODFET's photodetectors, although it compares favorably to regular p-i-n and MSM photodiodes. In fact, experiments conducted in our laboratory on devices with slightly different layer structure have yield a responsivity larger than 4.0 A/W.

This low peak responsivity occurs because the AlGaAs donor layer is transparent for the incident optical illumination. In addition, since the InGaAs channel is only a few hundred angstrons thick, most of the incident light is absorbed in the AlGaAs/GaAs superlattice region. This prevents the collection of a significant fraction of the photogenerated electrons and therefore degrades the photodetection performance of the device.

The decrease in responsivity for V_{ds} above 1.7 V (top curve, Fig. 4) is attributed to a two-dimensional effect caused by the longitudinal biasing field. For small values of drain bias voltages the responsivity increases because the photogenerated carrier velocity increases with V_{ds}. Beyond velocity saturation, a larger longitudinal field along the channel will cause the photoelectrons to drift towards the drain along the superlattice buffer, instead of being collected by the InGaAs channel, reducing the total photocurrent.

This phenomena will be described within the framework of a semi-analytical model for the positive photoconductive effect, in terms of drift-diffusion theory, as a function of the optical input (intensity, wavelength and modulation frequency) as well as biasing conditions, being prepared for publication [8].

Figs. 5 and 6 display again the photoresponse, now normalized to the dark drain current. These curves give a measure of the device's sensitivity to the optical illumination. We see that both structures are more sensitive when biased close to pinch-off. Furthermore, the dependence with gate to source voltage is slightly more pronounced for the conventional device (Fig. 5). In the case of the AlGaAs MODFET, the maximum relative sensitivity is -5.1% for $V_{gs} = 0.0$ V as opposed to -47.0% for $V_{gs} = -0.4$ V.

The pseudomorphic MODFET showed a similar sensitivity to light. A maximum drain current variation of 44.0% at $V_{ds} = 1.9$ V was obtained for $V_{gs} = -0.4$ V, when compared to 9.35%, for $V_{gs} = 0.0$ V.

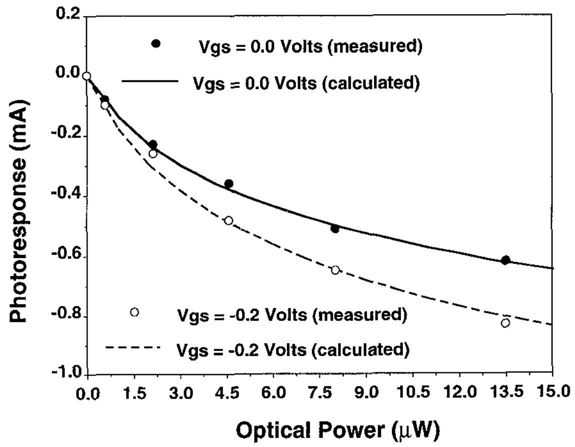

Fig. 7. Photoresponse as a function of the incident optical power for the conventional structure.

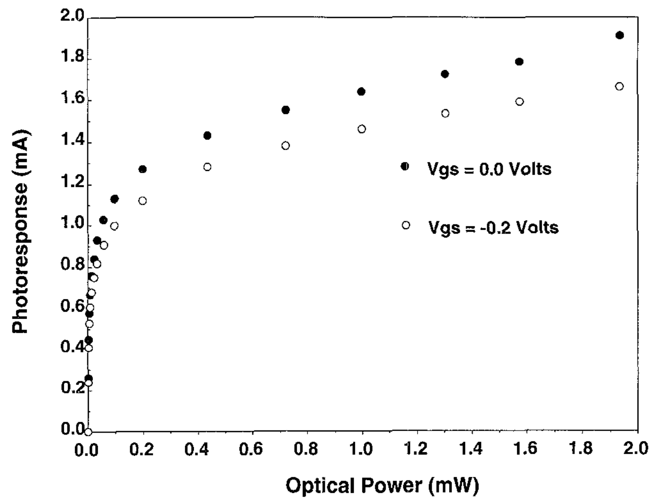

Fig. 8. Photoresponse as a function of the incident optical power for the pseudomorphic structure.

Optical power dependence: Next, we investigated the photoresponse versus incident optical power, for a given bias point, for the device that yields negative photoresponse. The results are shown in Fig. 7, where V_{gs} was used as a parameter while the drain to source voltage was kept constant at 1.0 V. For low illumination levels the photoresponse is a logarithmic function of the optical power, written as:

$$I_{ph} = I_{pho} \ln(P/P_o + 1) \quad (3)$$

where I_{ph} is the photoresponse, P is the optical power and I_{pho} and P_o are parameters of curve fitting, I_{pho} being voltage dependent. In this particular case, for $V_{gs} = 0.0$ V, the values used were $I_{pho} = -0.27$ mA and $P_o = 1.5$ μW. For $V_{gs} = -0.2$ V we had $I_{pho} = -0.35$ mA and $P_o = 1.5$ μW. For power levels above 50 μW saturation occurs and, if the intensity of illumination is further increased, the drain current will start to rise and slowly approaches its previously recorded dark value.

The results regarding the pseudomorphic structure are shown in Fig. 8. A logarithmic function is again seen, although the photocurrent increases steadily with optical power. Fig. 8 indicates that the responsivity is, in fact, dependent on optical power and that the device presents extremely high gain for low levels of illumination. For example, for an incident optical power of 530 nW, we recorded a photocurrent of 0.26 mA, corresponding to a responsivity of 490.6 A/W, much higher than the values presented in the previous section, where the optical power was kept at 1.0 mW.

It is interesting to note that conventional photoconductive models [4] predict a linear relation between optical power and photoresponse, under low-injection conditions. Here, however, this result does not hold even for very low power levels, indicating that the photodetection in MODFET's is not strictly photoconductive but governed by a more complex combination of physical mechanisms [8].

V. The Negative Photoresponse: Model and Numerical Simulation

Both negative and positive photoresponse have been reported in conventional AlGaAs/GaAs MODFET's with similar layer structures. The two process are illustrated in Fig. 9. 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, band-to-band 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 2-DEG channel (Fig. 9(a)), increasing the drain current.

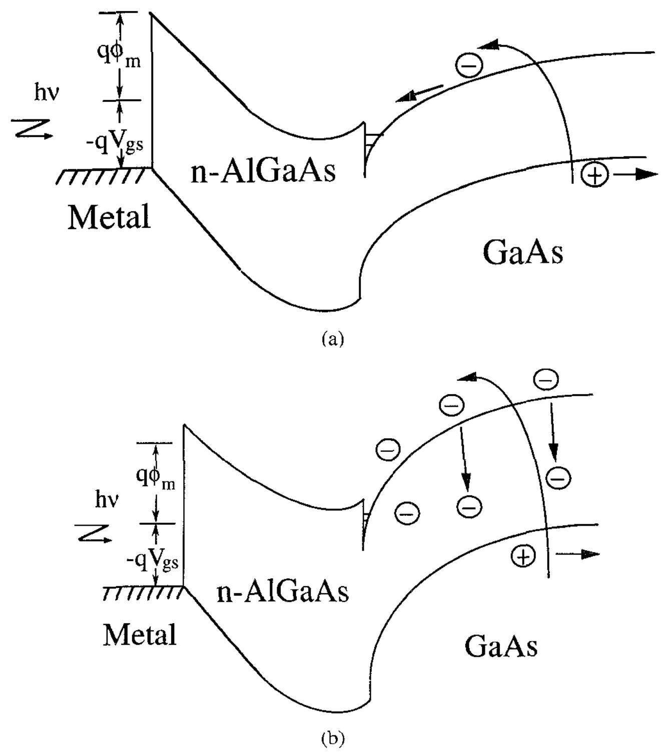

Fig. 9. Absorption of photons and generation of electron-hole pair in the GaAs layer. (a) The positive photoresponse, when electron are collected by the 2-DEG channel. (b) The negative photoresponse, when electron are stored in the buffer layer.

This paper, 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. 9(b)). In order to satisfy the charge-neutrality condition and as a consequence of the increase of negative charge in the bulk GaAs, the potential profile across the buffer will be modified so that the conduction band edge is raised with respect to the Fermi level and the number of carriers in the 2-DEG channel will decrease, resulting in an overall reduction of the output current.

In order to verify the validity of the model described above and calculate the reduction in the drain current as a function of the photogenerated trapped charge density we have numerically solved the Poisson and electron continuity equations for the conventional AlGaAs/GaAs MODFET, using the software MEDICI [9], a two-dimensional semiconductor simulator.

Consistently with our model, we assume that the illumination will cause a net increase in the negative charge trapped in the buffer. The main goal of the simulation is to demonstrate that this increase will induce a reduction in the channel current, as observed experimentally, and calculate its magnitude.

The software MEDICI employs the finite-elements method to solve the semiconductor equations. The electrons in the conducting channel are described by the Joyce–Dixon approximation of the Fermi integral and, in our simulations, the negative charge in the buffer layer is allowed to vary in order to account for the photogenerated trapped charge and permit a fitting to our experimental data. Therefore, the Poisson's equation for the GaAs region is written as

$$\frac{d^2\phi_2}{dx^2} = \frac{q}{\varepsilon_2}[n_s + N_T + N_a^-] \tag{4}$$

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, N_a^- ionized shallow acceptors concentration in the buffer and n_s, the electron concentration in the conducting channel, is assumed to obey the following three-dimensional degenerate statistics [10]:

$$\frac{q\phi_2}{kT} = \ln\frac{n_s}{N_c} + A_1\frac{n_s}{N_c} + A_2\left(\frac{n_s}{N_c}\right)^2 \cdots \tag{5}$$

in the equation above N_c is the effective density of states in the conduction band of the GaAs and A_2 and A_1 are numerical coefficients, assuming the values of 0.353 and 0.0575, respectively [10].

In Figs. 10 and 11, we plot again the relative photoresponse as a function of gate to source voltage, for $V_{ds} = 1.0$ V and $V_{ds} = 0.5$ V, respectively, comparing theoretical and experimental results. In all bias points simulated we have used the same parameters: $N_a^- = 1013\ \mathrm{cm}^{-3}$ and $N_T = 5.0 \times 10^{14}\ \mathrm{cm}^{-3}$ as the background doping and photogenerated stored charge, respectively.

Our theoretical analysis, supported by 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 close to pinch-off conditions. It should be noted that the agreement between the experimental results and the simulation described above is excellent. The difference between measured and calculated values is less than 2% for most bias points.

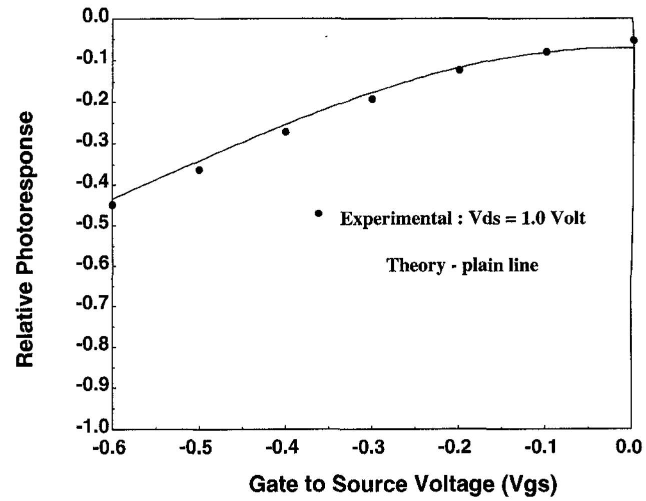

Fig. 10. Relative photoresponse as a function of gate to source voltage: theory versus experiment for $V_{ds} = 1.0$ V.

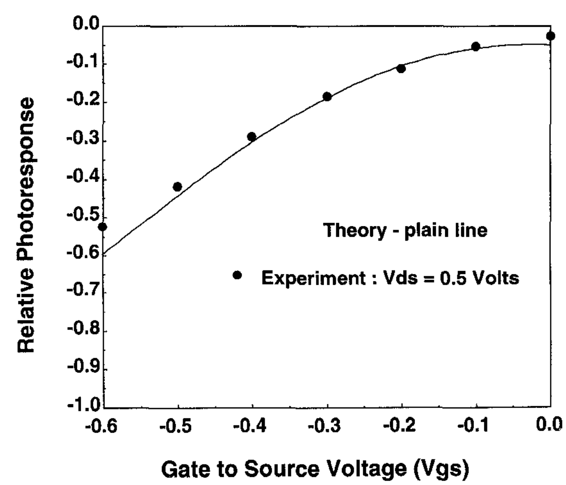

Fig. 11. Relative photoresponse as a function of gate to source voltage: theory versus experiment for $V_{ds} = 0.5$ V.

In summary, according to the present model, for low power levels most of the photogenerated electrons will be captured by empty deep traps, causing a change in the potential profile that originates the negative photoresponse. As the optical power increases, the deep-levels will be filled out, and a larger fraction of the photoelectrons will reach the 2-DEG channel (or recombine with free holes) and the drain current will eventually start to raise towards the previously recorded dark value, as observed experimentally.

VI. Discussion

Even though the results achieved in the above simulation were quite satisfactory, additional studies are required to establish that such density of traps is indeed present in the device, since no DLTS or spectral measurements were performed on those samples. However, the technical literature [11] suggests that trapping effects can be attributed to two different sources:

1) Electron traps in the buffer layer: five electron traps, the so-called M series, consisting of levels M1...M5 have been consistently observed in MBE grown GaAs.

   Furthermore, it is well known that impurities from the semi-insulating can out-diffuse into the epitaxial layers and introduce trapping states during the growing process. In fact, recent work [12] have associated the presence of Carbon and Silicon impurities at the substrate/buffer interface to shifts in the threshold voltage as well as poor pinch-off characteristics of AlGaAs/GaAs MODFET's.
2) Defect energy levels in the SI LEC substrate: since the thickness of the epitaxial buffer layer is comparable to the light absorption coefficient in GaAs at 830 nm, electron-hole pair generation in the substrate will be significant. Indeed, all MODFET devices that exhibit negative photoresponse have a structure [5], [6] that has the GaAs buffer placed directly over the substrate, indicating that this layer plays a major role in the negative photoconductivity phenomena.

The most commonly observed level in undoped GaAs crystals is the EL2, which compensates for carbon shallow acceptors and is responsible for the semi-insulating characteristic of high purity GaAs. Since this level is a deep-double donor, negative photoresponse would be induced by donor neutralization, through electron capture. Indeed, recent work [13], published after our initial communication of negative photoresponse in MODFET's [14] attributes the persistent negative photoconductivity in AlGaAs/GaAs heterojunctions to electron trapping in empty EL2 levels.

VII. Experimental Results: Modulated Illumination

We have also studied the frequency response of the devices to light modulated at RF and microwave frequencies. Regarding high-speed photodetection, the performance of the conventional AlGaAs/GaAs MODFET is very poor. In fact, the detected signal is below the noise floor of the network analyzer, even at 45 MHz. We have used standard lock-in amplifying techniques (Stanford Research Systems SR510 lock-in amplifier) and a Tektronix 7256P Spectrum Analyzer to identify the bandwidth of the negative photoresponse, approximately 200 kHz.

This value is consistent with our negative photoresponse model. The frequency response will be dictated by the electron capture and emission rates, due to the trapping/detrapping mechanism. Therefore, deep level traps will typically have a response speed in the kHz range and the negative photoresponse will be a slow process. Consequently, if high-speed photodetection is to be achieved, the negative photoresponse effect has to be suppressed, through the minimization of trapping centers density.

Indeed, we found that, for devices that exhibit positive photoconductivity, the 3-dB bandwidth can be as large as a few hundred MHz and the device presents useful photodetection performance well within the GHz range, the main limitation regarding speed being the photogenerated hole transit time [8]. A typical frequency response for one of the devices tested in our laboratory is given in Fig. 12, where the 0-dB level is

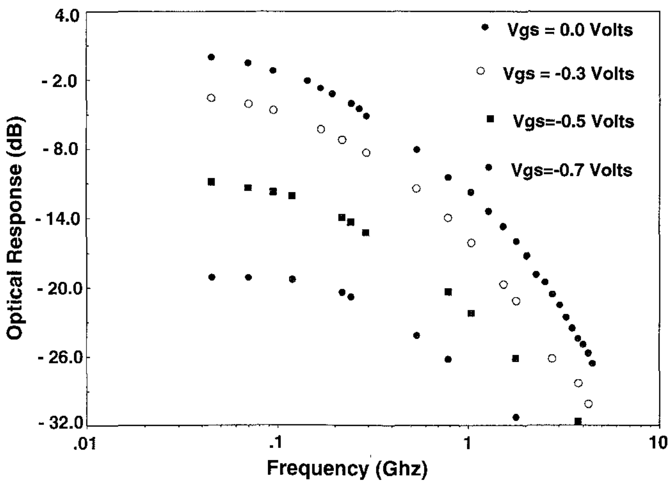

Fig. 12. Frequency response for a pseudomorphic MODFET photodetector. The semiconductor laser is directly modulated up to 5.0 GHz, the drain to sorce bias voltage was set at $V_{ds} = 1.0$ V. The gate to sorce bias point was varied between 0.0 and −0.7 V and a maximum bandwidth of 300 MHz was observed.

arbitrarily set at the value corresponding to 45 MHz for $V_{gs} = 0.0$ V. The drain to source bias point is set to $V_{ds} = 1.0$ V and the gate to source voltage was varied from 0.0 V up to −0.7 V. The optical power was kept at 2.0 mW, with an associated modulation index of 0.2. Since the laser relaxation frequency is about 10.0 GHz, its frequency response will not degrade the overall optical link performance.

A maximum bandwidth of approximately 300 MHz was observed when the device is operated at $V_{gs} = -0.7$ V. Furthermore, it is interesting to observe that the slope in Fig. 12 is frequency dependent and does not follow a 6-dB/octave decay rate. This phenomena has been also observed in MESFET's photodetectors and attributed to hole trapping, leading to an increased electron effective lifetime [15]. Further details of our high-speed measurements as well as theoretical considerations will be reported elsewhere.

VIII. Conclusion

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 and a comparison with devices that present positive photoresponse was carried out.

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. Very good agreement was obtained between our experimental data and a numerical solution of Poisson's and electron continuity equations.

If MODFET's structures are to be used as high speed optical input ports of MMIC's, the negative photoresponse phenomena has to be understood and suppressed. On the basis of our present studies we suggest that this suppression can be accomplished by use of more sophisticated structures, wherein the optical absorption occurs in a layer that is physically separated from the substrate, preventing eventual contamination during the growing process.

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Murilo A. Romero was born in Rio de Janeiro, Brazil, in 1965. He received the B.S. and M.S. degrees from Pontifical Catholic University of Rio de Janeiro in 1988 and 1991, respectively, both in electrical engineering. Since 1991 he has been pursuing a Ph.D. degree at Drexel University, working on the modeling of microwave transistors under optical illumination.

His research interests are optical-microwave interactions in solid state devices and the modeling and simulation of semiconductor structures. He has published 15 research papers and is a recipient of a fellowship from the Brazilian Research Council (CNPq).

Peter R. Herczfeld (S'66–M'67–SM'89–F'91) was born in Budapest, Hungary, in 1936 and is now a U.S. citizen. He received the B.S. degree in physics from Colorado State University in 1961, the M.S. degree in physics in 1963, and the Ph.D. degree in electrical engineering in 1967, both from the University of Minnesota.

Since 1967 he has been on the faculty of Drexel University, where he is a professor of electrical and computer engineering. He has published over 250 papers in solid state electronics, microwaves, photonics, solar energy, and biomedical engineering. He is the Director of the Center for Microwave-Lightwave Engineering at Drexel, a Center of Excellence which conducts research in microwaves and photonics, and he has served as project director for more than seventy sponsored projects.

A member of SPIE and ISEC, Dr. Herczfeld is recipient of several research and publication awards, including the Microwave Prize.