PERGAMON

Solid-State Electronics 43 (1999) 943–951

SOLID-STATE ELECTRONICS

# Parallel conduction and non-linear optoelectronic response of an n-channel pseudomorphic high electron mobility transistor

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Received 28 October 1998; received in revised form 21 January 1999

## Abstract

Optoelectronic properties of an n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ pseudomorphic high electron mobility transistor (PHEMT) have been characterized as a function of the drain voltage, the gate voltage and an optical stimulation with a wavelength $\lambda = 830$ nm. Physical mechanisms involved in the variation of optoelectronic performance are discussed and analytical models are provided for strong non-linear photoresponsivity. Parallel conduction caused by free electrons in the N-type $Al_{0.3}Ga_{0.7}As$ donor layers, which is qualitatively explained and analytically modeled, is believed to be one of the most dominant processes in the non-linear optoelectronic response of PHEMTs under high optical stimulation. © 1999 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

Monolithic co-integration of microwave and optical components on a single substrate, commonly known as microwave-photonics, is very important for the implementation of high-speed and high-capacity optical communication systems. In order to accomplish high photo-electric conversion efficiencies from optoelectronic semiconductor devices for microwave-photonics application systems, several different approaches with various high performance multiple terminal devices, such as heterojunction bipolar transistors (HBTs) and heterojunction field effect transistors (HFETs), are under active study [1–9]. Among them, the high electron mobility transistor (HEMT) has been confirmed to produce the best electrical characteristics over several hundreds of GHz. However, physical mechanisms involved in the optoelectronic response and electronic conduction processes, under simultaneous control of electrical and optical inputs, have not been clearly identified in HEMTs. It is still necessary to figure out physical mechanisms and to make analytical models for better description of the optoelectronic characteristics of HEMTs and for possible applications in high performance microwave-photonics systems [6,8,9].

In this paper, we report optoelectronic characteristics of an n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ pseudomorphic high electron mobility transistor (PHEMT) under optical illumination. Strong nonlinear optoelectronic responsivity of the drain current to the optical stimulation ($p_{opt}$), especially under high optical power, has been characterized and modeled. One of the dominant physical mechanisms in this optoelectronic observation is believed to be a result of parallel conduction via a parasitic MESFET, which is

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PII: S0038-1101(99)00047-7

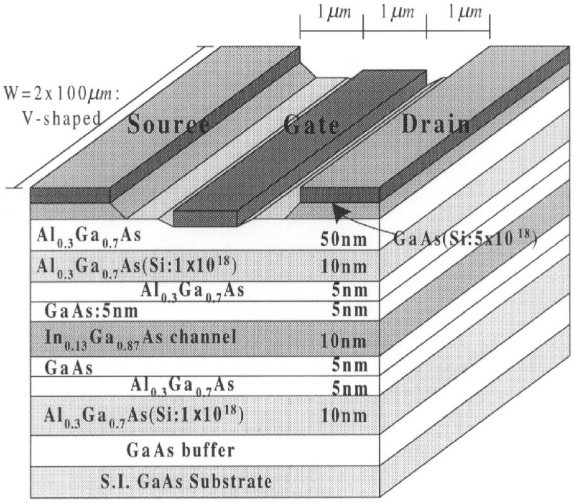

Fig. 1. Epitaxial and geometrical structure of an $Al_{0.3}Ga_{0.7}As$/GaAs/$In_{0.13}Ga_{0.87}As$ PHEMT grown on semi-insulating GaAs substrate by a gas source molecular beam epitaxy system.

formed by free carriers in the n-type $Al_{0.3}Ga_{0.7}As$ donor layer, induced by optically generated excess carriers. An analytical model is also provided for clear understanding of the non-linear photoresponsivity of PHEMTs under optoelectronic stimulation.

## 2. Photonic responses of an $Al_{0.3}Ga_{0.7}As$/GaAs/$In_{0.13}Ga_{0.87}As$ PHEMT

Epitaxial layers of an n-channel $Al_{0.3}Ga_{0.7}As$/GaAs/$In_{0.13}Ga_{0.87}As$ HEMT, as shown in and Fig. 1, have been grown on a semi-insulating GaAs substrate by a gas source molecular beam epitaxy system [7]. Symmetrical layer structures were adopted to achieve better carrier confinement and improved electron mobility in the pseudomorphic $In_{0.13}Ga_{0.87}As$ channel layer formed by the conduction band discontinuity in an $Al_{0.3}Ga_{0.7}As$/GaAs/$In_{0.13}Ga_{0.87}As$ two-step heterojunction system. By the Hall measurement technique at room temperature, we obtained $\mu_{\mathrm{cho}} = 5000$ cm$^2$/V·s and $n_{\mathrm{cho}} = 1.2 \times 10^{12}$ cm$^{-2}$ for the ungated low field mobility and the two-dimensional concentration of channel electrons, respectively. N-channel $Al_{0.3}Ga_{0.7}As$/GaAs/$In_{0.13}Ga_{0.87}As$ PHEMTs were fabricated using typical wet chemical etching and lift-off processes. Ti/Au and AuGe/Ni/Au multiple layer metallization was thermally evaporated for the

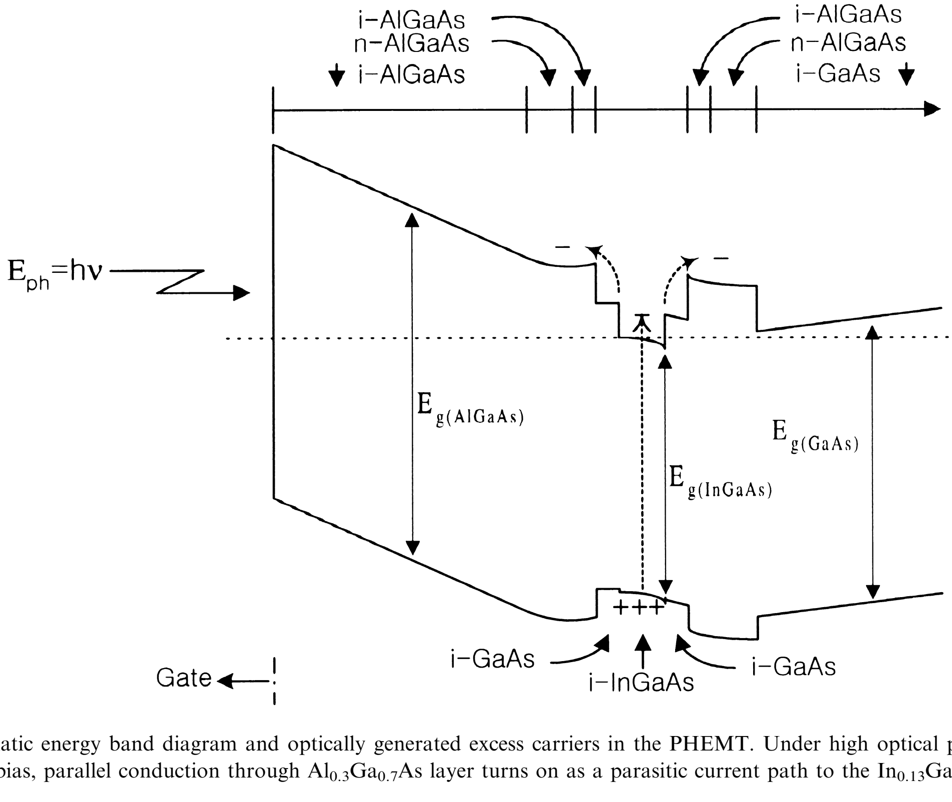

Fig. 2. Schematic energy band diagram and optically generated excess carriers in the PHEMT. Under high optical power or large positive gate bias, parallel conduction through $Al_{0.3}Ga_{0.7}As$ layer turns on as a parasitic current path to the $In_{0.13}Ga_{0.87}As$ channel HEMT.

Schottky gate and n-type source/drain ohmic contacts, respectively.

The gate length, the gate width and the spacings between the gate and the source/drain have been chosen to be $L_g = 1$ μm, $W = 200$ μm and $L_{gs} = L_{gd} = 1$ μm. A V-shaped dual-gate structure has been selected in the experiment expecting better optoelectronic responsivity and improved confinement of optical signal of the n-channel PHEMT under conversion characterization.

Optoelectronic performance of an n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT has been characterized on wafer by combining the HP-4156A semiconductor parameter analyzer, the HP-8510B vector network analyzer and the Spectra-Physics laser diode module with $\lambda = 830$ nm. We delivered a constant optical power ($p_{opt} = 0$, 3, 20 and 30 (mW) on the display of the optical module) at the surface of the device under characterization via a pig-tailed optical fiber.

The energy band diagram and excess carrier generation processes under illumination in the n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT is schematically illustrated in Fig. 2. There may be some contribution of photoresponsivity in $Al_{0.3}Ga_{0.7}As$ layers to the optical input due to excited carriers from deep levels in silicon-doped $Al_{0.3}Ga_{0.7}As$. However, $Al_{0.3}Ga_{0.7}As$ donor and spacer layers, with an energy bandgap $E_g \sim 1.86$ eV, is not expected to have significant responsivity to the incident photons with $\lambda = 830$ nm, which corresponds to $h\nu = 1.55$ eV. In the case of $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT, the GaAs spacer ($E_g \sim 1.43$ eV) and $In_{0.13}Ga_{0.87}As$ channel ($E_g \sim 1.33$ eV) layer have the most significant contribution to the optoelectronic responsivity to the optical input with $\lambda = 830$ nm. As a result, the excess electron–hole pairs are generated dominantly in the GaAs and $In_{0.13}Ga_{0.87}As$ layers under optical stimulation.

Optically stimulated excess electrons are swept to the pseudomorphic $In_{0.13}Ga_{0.87}As$ channel and form an excess channel, which is known as a *photoconductive effect*, in the two-dimensional electron gas channel. Photogenerated excess carriers also contribute to the change in the effective gate voltage, which is also known as a *photoelectric effect*. The photoelectric effect in n-channel PHEMTs typically appears as a variation of parasitic gate capacitances under optical input. Both photoconductive and photoelectric effects contribute to the variation of dc and microwave characteristics of n-channel PHEMTs under optoelectronic control.

Under various optical inputs ($p_{opt} = 0$, 3, 20 and 30 (mW)) at the surface of the PHEMT under characterization, a photoconductive component, established by the excess photoelectrons in the $In_{0.13}Ga_{0.87}As$ channel, contributes to the increase of the total drain current. Considering an optical absorption mechanisms in the n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT, the intensity of optical power $\psi(y)$ at a cumulative distance $(y)$ of photoresponsive region from the surface, in the direction from the surface to the substrate, can be described by

$$\psi(y) = \psi_{opt}\exp(-\alpha y)\,(\mathrm{mW/cm^2}), \tag{1}$$

where $\psi_{opt}$ is the photonic intensity (defined as $p_{opt}$/effective area) at the surface of the device and $\alpha$ is a wavelength-dependent absorption coefficient in each region ($\alpha_{InGaAs} = 0.89 \times 10^5$ ($\mathrm{cm^{-1}}$), $\alpha_{GaAs} = 0.70 \times 10^4$ ($\mathrm{cm^{-1}}$)) [10]. Note that the intensity of the optical power decreases exponentially with distance through the semiconductor material. These absorbed photon fluxes create excess electron–hole pairs and contribute to the modulation of dc and high frequency characteristics of PHEMTs through both photoconductive and photoelectric effects under optical stimulation.

The generation rate $g(y)$ of excess electron–hole pairs under optical stimulation can be described by

$$g(y) = \frac{\alpha\psi(y)}{h\nu}\,(1/(\mathrm{cm^3\,s})) \tag{2}$$

where $h\nu$ is the energy of an incident photon.

Considering the excess carrier lifetime ($\tau$), which is a strong function of the total carrier concentration ($n = n_o + \delta n$) and thus a function of the optical stimulation, the two-dimensional density of total photo-generated excess carriers ($\delta n$) in the photoresponsive layer can be described by

$$\delta n = \int_0^d g(y)\tau\,\mathrm{d}y = \frac{\psi_{opt}\tau}{h\nu}[1 - \exp(-\alpha d_{eff})] \equiv K_o p_{opt} \quad (\mathrm{cm^{-3}}) \tag{3}$$

where $d_{eff}$ is an effective thickness of the photoresponsive layer in the PHEMT and $K_o$ is a constant combining optical power and excess carriers.

Total excess carrier concentration $\delta n$ includes excess channel carriers ($\delta n_{HEMT}$) and excess carrier concentration in the $Al_{0.3}Ga_{0.7}As$ layer ($\delta n_{MESFET}$) which is responsible for a strong non-linear response of the PHEMT due to the parallel conduction with AlGaAs MESFET.

Based on this analytical model, it is expected to have linear dependence of both channel conductivity and the drain current on the optical stimulation $p_{opt}$ for a given structure. Due to other secondary physical mechanisms such as a parallel conduction through a bypass layer with extremely low carrier mobility, however, a strong non-linearity is observed in PHEMTs under high optical stimulation.

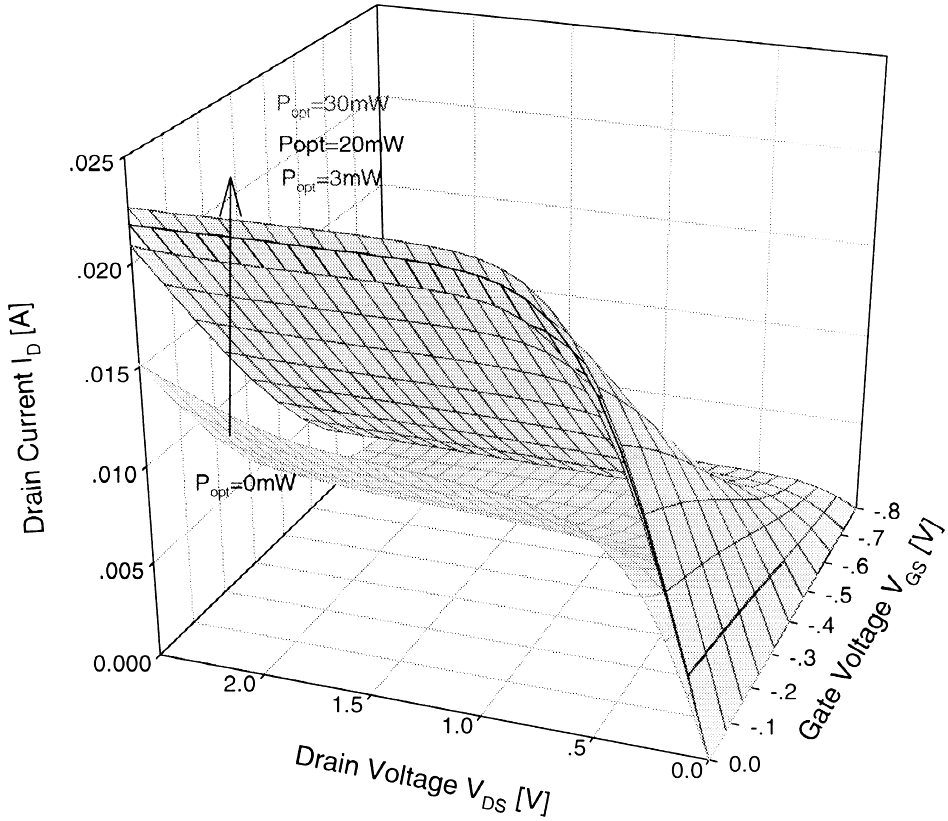

Fig. 3. Current–voltage characteristics of a PHEMT under optical illumination with $V_{GS}=0$ and −0.4 V. Strong nonlinear dependence is observed under high optical input $p_{opt}$. ($p_{opt}=0$, 3, 20 and 30 (mW)).

## 3. Optoelectronic current–voltage characteristics of a PHEMT

Optoelectronic responses of an n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT under optical stimulation are characterized. Optical power-dependent current–voltage characteristics are shown in Fig. 3 for $p_{opt}=0$, 3, 20 and 30 (mW). As shown in Fig. 3 and Fig. 4, the drain current ($I_D$) and the transconductance ($g_m$) show a strong non-linearity on the optical stimulation. Especially under high optical power, the drain current and the transconductance are almost saturated over $p_{opt}>3$ (mW). We also note that the output conductance ($g_{ds}=\Delta I_D/\Delta V_{DS}|_{sat}$) is significantly suppressed in the saturation region at high drain voltage ($V_{DS}$) while the channel conductivity ($g_{ch}=\Delta I_D/\Delta V_{DS}|_{linear}$) at small $V_{DS}$ is significantly improved due to increased channel carrier concentration under optical illumination.

A strong non-linear responsivity of the PHEMT on optical power under high optical stimulation can be qualitatively described by the relationship between the total drain current ($I_D$) and total available conduction carriers including electrically induced channel carriers ($n_{cho}$), optically generated excess carriers in the channel ($\delta n_{HEMT}$) and excess carriers in the $Al_{0.3}Ga_{0.7}As$ donor layers ($\delta n_{MESFET}$). In other words, the total drain current is a sum of the drain current ($I_{Do}$) via the 2-dimensional $In_{0.13}Ga_{0.87}As$ channel layer and the other drain current ($I_{D,MESFET}$) through partially conductive $Al_{0.3}Ga_{0.7}As$ donor layers. More current components, depending on the structure and bias conditions, can be included in the current–voltage characteristics of the PHEMT under optical illumination or high gate bias without optical input [11,12].

Considering only two dominant current components, $I_{Do}$ and $I_{D,MESFET}$, the total drain current ($I_D$) can be described as

$$I_D = \sum_i I_{Di} \cong I_{Do} + I_{D,MESFET}. \tag{4}$$

Each current component, in the linear region of operation for simplicity of an analysis, can be obtained from

$$I_{Di} = q n_{chi} \mu_{ni} \varepsilon_i W, \tag{5}$$

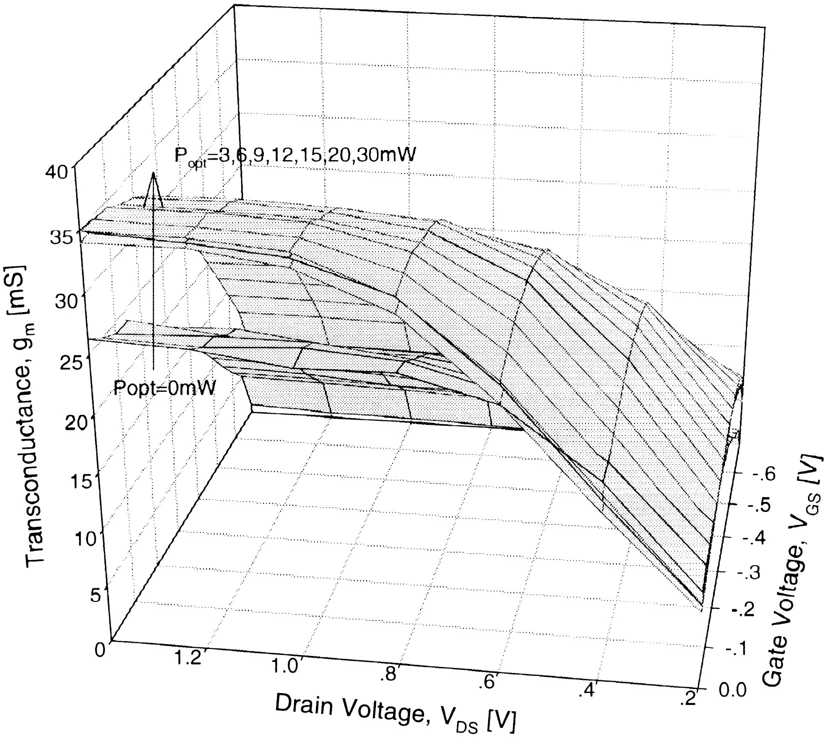

Fig. 4. Transconductance characteristics ($g_m$) of a PHEMT as a function of $V_{DS}$ and $V_{GS}$ under optical stimulation. Bias point for maximal transconductances moves with increasing the optical stimulation for $p_{opt} > 3$ mW.

where $W$, $n_{chi}$, $\mu_{ni}$ and $\varepsilon_i$ mean a width, a two-dimensional carrier density, a carrier mobility and an electric field in each current path, respectively.

Even with a linear relation of excess carriers with optical illumination ($p_{opt}$), as expected in Eq. (3), the total drain current cannot be observed as a linear function of $p_{opt}$ in the optically controlled PHEMTs for given $V_{DS}$ and $V_{GS}$. Under high optical input or large gate bias, excess carriers are divided into two main current paths; one via undoped $In_{0.13}Ga_{0.87}As$ and GaAs channel layers with extremely high electron mobility ($\delta n_{HEMT}$, $\mu_{HEMT}$) and the other via a heavily doped $Al_{0.3}Ga_{0.7}As$ donor layer with extremely low mobility ($\delta n_{MESFET}$, $\mu_{MESFET}$). Therefore, a strong non-linearity of the drain current can be observed in the $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT under high optical power. This can be partially explained by the reduction of carrier lifetime ($\tau_i = 1/[\alpha_{ri}(n_{chi} + \delta n_{chi})]$), which causes a reduced effective generation rate. However, a parallel conduction through heavily doped n-type $Al_{0.3}Ga_{0.7}As$ donor layers, which limit electrical performances and is expected to be non-conductive under normal operating conditions, may be the main cause of the nonlinear responsivity of PHEMTs under high optical input.

With a parasitic MESFET turned on under a high optical input, the total conductivity ($\sigma_T$) of the PHEMT with a parallel conduction can be described by

$$\sigma_T = \sum_i \sigma_i \cong \sigma_{HEMT} + \sigma_{MESFET}, \tag{6}$$

where the conductivity of each current path can be obtained from

$$\sigma_i = q n_{chi} \mu_{chi}. \tag{7}$$

Under low optical illumination, the total conductivity can be predominantly determined by the excess carriers in the $In_{0.13}Ga_{0.87}As$ channel layer. Therefore, it is described by

$$\begin{aligned} \sigma_T &= q(\mu_{HEMT} n_{HEMT} + \mu_{MESFET} n_{MESFET}) \\ &= q\{\mu_{HEMT}(n_{HEMT} + \delta n_{HEMT}) + \mu_{MESFET}(n_{MESFET} \\ &\quad + \delta n_{MESFET})\} \\ &\cong q\mu_{HEMT}(n_{HEMT} + \delta n_{HEMT}) \end{aligned} \tag{8}$$

where $\delta n_{HEMT}$ is proportional to the optical stimulation Eq. (3) as

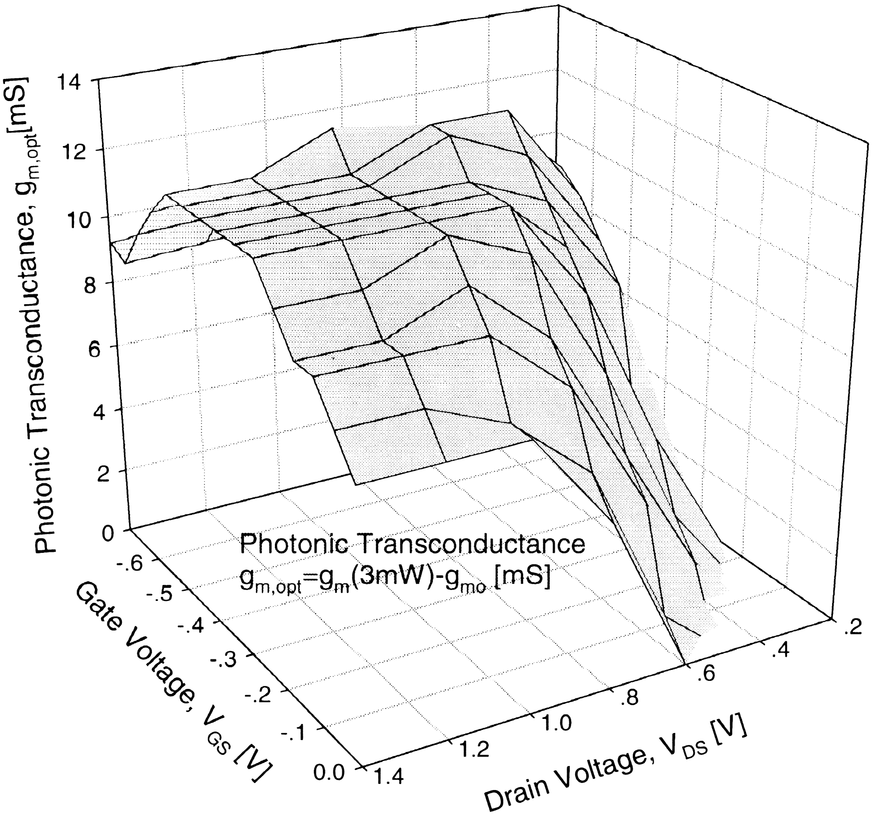

Fig. 5. Optically induced transconductance $g_{\mathrm{m,opt}}$ ($g_{\mathrm{m,opt}}=g_{\mathrm{m}}-g_{\mathrm{mo}}$) as a function of $V_{\mathrm{DS}}$ and $V_{\mathrm{GS}}$ for optical power = 3 mW. The $g_{\mathrm{m,opt}}$ for $p_{\mathrm{opt}}>3$ mW are saturated and have the same value as that for $p_{\mathrm{opt}}>3$ mW.

$$\delta n_{\mathrm{HEMT}} \cong K_{\mathrm{o}} p_{\mathrm{opt}}. \tag{9}$$

Therefore, the total conductivity and the drain current of the PHEMT increases linearly with incident optical power. We also note that electron mobility ($\mu_{\mathrm{HEMT}}$) in the pseudomorphic $\mathrm{In_{0.13}Ga_{0.87}As}$ layer is much higher than that in the parasitic $\mathrm{Al_{0.3}Ga_{0.7}As}$ MESFET ($\mu_{\mathrm{MESFET}}$) due to a heavy effective mass and a severe ionized impurity scattering in the heavily doped $\mathrm{Al_{0.3}Ga_{0.7}As}$ donor layer.

However, under high optical power with parasitic MESFET turned on, the total conductivity can be described by

$$\begin{aligned}\sigma_{\mathrm{T}} &= q(\mu_{\mathrm{HEMT}} n_{\mathrm{HEMT}} + \mu_{\mathrm{MESFET}} n_{\mathrm{MESFET}}) \\ &= q\{\mu_{\mathrm{HEMT}}(n_{\mathrm{HEMT}} + \delta n_{\mathrm{HEMT,max}}) \\ &\quad + \mu_{\mathrm{MESFET}}(n_{\mathrm{MESFET}} + \delta n_{\mathrm{MESFET}})\} \\ &= q\mu_{\mathrm{HEMT}} n_{\mathrm{HEMT,max}} + q\mu_{\mathrm{MESFET}} \delta n_{\mathrm{MESFET}}\end{aligned} \tag{10}$$

and conductivity in the pseudomorphic $\mathrm{In_{0.13}Ga_{0.87}As}$ channel layer is saturated due to an overflow of excess carriers into $\mathrm{Al_{0.3}Ga_{0.7}As}$ layer. Although there are increased excess carriers in the $\mathrm{Al_{0.3}Ga_{0.7}As}$ layer, a contribution to the total drain current is not so significant because the mobility of electrons is extremely low compared with that in the $\mathrm{In_{0.13}Ga_{0.87}As}$ channel layer. Thus, the total conductivity or the drain current of the PHEMT under high optical stimulation is almost saturated or merely increasing with $p_{\mathrm{opt}}$.

On the other aspect of the optical response of the PHEMT under either high gate voltage or high optical input, the total transconductance $g_{\mathrm{m}}$, as shown in Fig. 4 for the PHEMT as a function of $V_{\mathrm{DS}}$, $V_{\mathrm{GS}}$ and $p_{\mathrm{opt}}$, can be described by two dominant components as

$$g_{\mathrm{m}} \equiv \partial I_{\mathrm{d}}/\partial V_{\mathrm{gs}} = \sum_i g_{\mathrm{m}i} = g_{\mathrm{m,HEMT}} + g_{\mathrm{m,MESFET}} \tag{11}$$

where $g_{\mathrm{m,HEMT}}$ and $g_{\mathrm{m,MESFET}}$ mean transconductances by the InGaAs layer and AlGaAs layer, respectively. We also note that the transconductance $g_{\mathrm{m}}$ depends on the conductivity or the product of mobility and carrier concentration. Transconductance of PHEMT under optical stimulation can be described by

$$g_m = \frac{\partial I_d}{\partial V_{gs}} = \frac{\partial I_d}{\partial n} \cdot \frac{\partial n}{\partial V_{gs}} \propto \sum_i n_{chi}\mu_{chi} =$$

$$\sum_i n_{cho} + \delta n_{chi})\mu_{chi} \tag{12}$$

Each component in the total transconductance ($g_{mi} \propto \sigma_i = qn_{chi}\mu_{chi}$) is proportional to the product of carrier density ($n_{chi}$) and mobility ($\mu_{chi}$). Among them, $g_{m,\text{HEMT}}$ reaches the maximum value, as explained in the conductance variation, and then decreases due to saturated maximum channel carrier concentration ($n_{ch,max}$) under high optical illumination. The other component, $g_{m,\text{MESFET}}$, still increases with increased optical power because additional excess carriers contribute to the increase of $\delta n_{\text{MESFET}}$. However, it doesn't contribute so much to the total transconductance because the mobility of electrons, in the heavily doped $Al_{0.3}Ga_{0.7}As$ donor layers, is known to be extremely low due to a severe ionized impurity scattering and a large effective mass. Therefore, an additional increase of the optical power won't be effective in the improved responsivity of the total drain current and the transconductance under high optical illumination.

Under low optical input, the transconductance increases linearly with optical power and can be described by

$$\begin{aligned} g_m &= K_1(n_{\text{HEMT}} + \delta n_{\text{HEMT}})\mu_{\text{HEMT}} + K_2(n_{\text{MESFET}} \\ &\quad + \delta n_{\text{MESFET}})\mu_{chi} \\ &\cong K_1(n_{\text{HEMT}} + \delta n_{\text{HEMT}})\mu_{\text{HEMT}} \\ &= g_{mo} + K_1 K_o \mu_{\text{HEMT}} p_{opt}, \end{aligned} \tag{13}$$

because $n_{\text{HEMT}} \gg n_{\text{MESFET}}$, $\delta n_{\text{HEMT}} \gg \delta n_{\text{MESFET}}$ and $\mu_{\text{HEMT}} \gg \mu_{\text{MESFET}}$. $K_1$ and $K_2$ are also chosen as proportionality factors in the transconductance and they depend on the structure of the device as well as optical inputs.

However, due to the saturated excess carrier concentration in the $In_{0.13}Ga_{0.87}As$ layer under high optical stimulation, the optically induced excess transconductance is also saturated as is the case for the drain current. As a result, the transconductance under high optical power can be written as

$$\begin{aligned} g_m &= g_{mo} + K_3 K_o \mu_{\text{HEMT}} \delta n_{\text{HEMT,max}} \\ &\quad + K_2 K_o \mu_{\text{MESFET}} p_{opt} \end{aligned} \tag{14}$$

where $g_{mo}$ is electrically induced channel carriers, $\delta n_{\text{HEMT,max}}$ is the maximum excess channel carrier concentration which is independent of optical power under high optical stimulation and $K_3$ is a proportionality factor to the saturation of optically induced channel carriers. Although the third component is proportional to the optical power, it is very small contribution to the increase of total transconductance due to extremely low value of $\mu_{\text{MESFET}}$ in the $Al_{0.3}Ga_{0.7}As$ donor layer.

In other words, a differential increase in the drain current with optical input ($g_{m,opt}$), as shown in Fig. 5 for $p_{opt} = 3$ mW, which is defined as

$$g_{m,opt} = g_m - g_{mo}, \tag{15}$$

is observed to be very small under high optical stimulation. This is because the conductivity is limited by the poor performance $Al_{0.3}Ga_{0.7}As$ MESFET connected parallel to the high performance $In_{0.13}Ga_{0.87}As$ channel PHEMT. This parallel conduction have been also reported in the HEMTs, where channel carrier concentration is saturated under high gate voltage without optical illumination [7].

A parallel conduction, caused by a parasitic current path with a partially neutralized $Al_{0.3}Ga_{0.7}As$ donor layer, can be turned on without reaching the maximum carrier concentration ($n_{\text{HEMT,max}}$) with optical illumination. Some of the carriers in the parasitic $Al_{0.3}Ga_{0.7}As$ MESFET layer, which neutralizes and makes $Al_{0.3}Ga_{0.7}As$ donor layer conductive, can be contributed from the excited and transferred carriers from the conduction band of $In_{0.13}Ga_{0.87}As$ and GaAs layers. Excited carriers from the deep levels in the n-type $Al_{0.3}Ga_{0.7}As$ donor layers also contribute to the conduction of $Al_{0.3}Ga_{0.7}As$ donor layer. With high channel carrier concentration ($-n_{\text{HEMT,max}}$) under gate bias far above pinch-off voltage ($V_p$), excess electrons generated by the band-to-band transition from the valence band to the conduction band in $In_{0.13}Ga_{0.87}As$ and GaAs layers directly contribute to the parallel conduction in the $Al_{0.3}Ga_{0.7}As$ layer.

In other words, excess carrier concentration and conductivity, under high optical input, can be summarized as

$$\delta n = \delta n_{\text{HEMT}} + \delta n_{\text{MESFET}} = \delta n_{\text{HEMT,max}} + \delta n_{\text{MESFET}}$$

$$\frac{d\delta n}{dp_{opt}} = \frac{dn_{\text{HEMT}}}{dp_{opt}} + \frac{d\delta n_{\text{MESFET}}}{dp_{opt}} \approx \frac{d\delta n_{\text{MESFET}}}{dp_{opt}} \tag{16}$$

and

$$\sigma_T = \sigma_{\text{HEMT}} + \sigma_{\text{MESFET}} = \sigma_{\text{HEMT,max}} + \sigma_{\text{MESFET}}$$

$$\frac{d\sigma_T}{dp_{opt}} = \frac{d\sigma_{\text{HEMT}}}{dp_{opt}} + \frac{d\sigma_{\text{MESFET}}}{dp_{opt}} \approx \frac{d\sigma_{\text{MESFET}}}{dp_{opt}}, \tag{17}$$

respectively.

As shown in Fig. 5, the points at which the transconductance reaches the maximum value are shifted to a lower gate voltage with increased optical illumination. This is, as explained in Section 2, mainly due to different excess carrier concentration in the $In_{0.13}Ga_{0.87}As$ channel with modulated optical powers, which, in turn, requires higher gate voltage for smaller optical power in order to reach the same maximum channel carrier concentration ($n_{\mathrm{HEMT,max}}$) as a threshold of the parallel conduction in a specific PHEMT structure.

This analytical explanation and parallel conduction model agree well with experimentally observed current–voltage characteristics, including the strong nonlinearity, of optically controlled PHEMTs as shown in Figs. 3–5. We note that the transcoductance reaches maximum value at $V_{\mathrm{GS}}=-0.1\sim-0.3$ (V) under high optical power ($p_{\mathrm{opt}}=20$ and 30 (mW)) while it still increases with increasing gate voltage under low optical input ($p_{\mathrm{opt}}=0$ and 3 (mW)). We also note, as shown in Figs. 4 and 5, that the differential drain current and the differential transconductance decreases as $p_{\mathrm{opt}}$ is increased in the bias point where the channel carrier concentration is below the maximum channel carrier concentration.

Among other characteristic parameters in PHEMTs, the channel length modulation effect ($\mathrm{d}I_{\mathrm{D}}/\mathrm{d}V_{\mathrm{DS}}$ for $V_{\mathrm{DS}}>V_{\mathrm{DSAT}}$), which is a detrimental parameter in applications of high performance PHEMTs to photonic-microwave systems, has been significantly suppressed under optical illumination. Under optical illumination, increased excess channel carrier concentration contributes to the enhancement of channel conductivity. Therefore, the drain current with a channel length modulation under saturation mode can be described by

$$I_{\mathrm{D}}=I_{\mathrm{Do}}\frac{L}{L_{\mathrm{eff}}}=I_{\mathrm{Do}}\frac{L}{L-\Delta L}=I_{\mathrm{Do}}(1+\lambda V_{\mathrm{DS}}). \tag{18}$$

The channel length modulation parameter $\lambda$ due to high drain voltage can be described by

$$\lambda=\frac{L-L_{\mathrm{eff}}}{L_{\mathrm{eff}}\cdot V_{\mathrm{DS}}}, \tag{19}$$

where $L$ and $L_{\mathrm{eff}}$ ($=L-\Delta L$) are defined as a metallurgical gate length and an effect channel length, respectively.

Considering optically stimulated excess carriers, $\delta n\cong K_{\mathrm{o}}p_{\mathrm{opt}}$, the effective channel length can be written as

$$\begin{aligned}L_{\mathrm{eff}}&=-\left(\frac{n_{\mathrm{ch}}}{n_{\mathrm{ch}}+\delta n}\right)\frac{2d}{\pi}\sinh^{-1}\left[\frac{\pi(V_{\mathrm{DS}}-V_{\mathrm{DSAT}})}{2dE_{\mathrm{C}}}\right]\\&\cong-\left(\frac{n_{\mathrm{ch}}}{n_{\mathrm{ch}}+K_2p_{\mathrm{opt}}}\right)\frac{2d}{\pi}\sinh^{-1}\left[\frac{\pi(V_{\mathrm{DS}}-V_{\mathrm{DSAT}})}{2dE_{\mathrm{C}}}\right],\end{aligned} \tag{20}$$

where $I_{\mathrm{Do}}$ is an ideal drain current without channel length modulation and $E_{\mathrm{C}}$ is a critical electric field at pinch-off drain voltage ($V_{\mathrm{DSAT}}$) [13,14]. With high excess channel carriers either by high optical illumination or large positive gate bias on n-channel PHEMTs, the channel length modulation effect can be significantly reduced. Suppressed channel length modulation, due to increased channel conductivity with optically generated excess carriers, can be seen explicitly in Fig. 3.

## 4. Conclusion

In conclusion, optoelectronic characteristics of an n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.78}As$ pseudomorphic high electron mobility transistor has been measured and analyzed on wafer as a function of the drain voltage, the gate voltage and an optical stimulation with $\lambda=830$ nm. Physical mechanisms involved in the variation of optoelectronic performances are characterized. Strong non-linear photoresponsivity with optical power is observed at high optical input power. A parallel conduction by the n-type $Al_{0.3}Ga_{0.7}As$ donor layers, caused by carriers excited or transferred from the GaAs and $In_{0.13}Ga_{0.87}As$ layers, is believed to be one of the most dominant processes in the optoelectronic characteristics of PHEMTs under high optical power. We also observed that there is a threshold gate voltage for parallel conduction or a saturation of the drain current. The above strongly depends on the optical input as overflow of carriers into the $Al_{0.3}Ga_{0.7}As$ layer is dependent on the maximum channel carrier concentration for a given PHEMT structure.

## Acknowledgements

This work was supported in part by the KOSEF contract No. 981-0908-029-2.

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