Comparison of Photoresponsive Drain Conduction and Gate Leakage in N-Channel Pseudomorphic HEMT and MESFET under Electro-Optical Stimulations

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***Abstract*—Photoresponsive drain conduction and gate leakage characteristics of n-channel PHEMT and MESFET are comparatively reported as a function of electro-optical stimulation (V_{GS}, V_{DS}, P_{opt}; $\lambda = 830$ nm). Both in PHEMT and MESFET, a strong nonlinearity of drain photoresponse (R) with P_{opt} was observed and can be modeled empirically as $R = \kappa P_{opt}^{-\beta}$ ($\kappa_{PHEMT} \gg \kappa_{MESFET}$) where model parameters κ and β accommodate differences in device/epitaxial structures and electrical biases. Gate leakage current was linearly increasing with P_{opt} while it was independent of V_{DS} in both PHEMT and MESFET. However, I_G was a strong function of V_{GS} in PHEMT while it was almost independent in MESFET due to suppressed modulation of photoresponsive depletion width with heavy channel doping. Photonic gate response (R_{pG}), on the other hand, was observed to be constant in MESFET while it was a strong function of electrical bias in PHEMT.**

***Index Terms*—Gate leakage, HEMT, MESFET, optical control, photoresponse.**

I. INTRODUCTION

PSEUDOMORPHIC high electron mobility transistors (PHEMT's) and metal-semiconductor field effect transistors (MESFET's) are under active study, due to high cut-off frequency and good optical responsivity, as high performance photodetectors and photonic-microwave components in monolithic optoelectronic integrated circuits. In spite of their usefulness in photonic-microwave systems, photoresponsive mechanisms in PHEMT's and MESFET's have not been sufficiently characterized due to complicated mechanisms [1]–[7]. This is because photoresponsive characteristics of FET's depend strongly on geometrical structures (W/L-ratio, periphery, spacing) and epitaxial layers (composition, doping, thickness) as well as growth conditions (substrate temperature, growth rate).

In this letter, we compared photoresponsive characteristics of n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT and GaAs MESFET under various optical stimulations with $\lambda = 830$ nm. Optical effects on the drain and reverse gate currents are investigated as a function of electrical bias (gate voltage; V_{GS} and drain voltage; V_{DS}) and optical power (P_{opt}). We also provided an empirical model of nonlinear photoresponse in PHEMT and MESFET as a function of P_{opt}.

II. PHOTORESPONSIVE DRAIN CONDUCTION IN PHEMT AND MESFET

N-channel epitaxial layers were grown by GSMBE for PHEMT [2] and CBE for MESFET. MESFET layers include an n^+ GaAs layer (Si:5 $\times$ 10^{18} cm^{-3}) for ohmic contacts, a GaAs layer (Si:5 $\times$ 10^{17} cm^{-3}, 0.12 μm) for channel, and undoped GaAs buffer (2.5 μm) layer were grown on semi-insulating GaAs layers. Same fabrication processes, which include Au-Ge/Ni/Au for ohmic and Ti/Au for Schottky contacts with a lift-off technique, are applied to devices with V-shaped gates (W/L = 200 μm/1 μm, $L_{gs} = L_{gd} = 1.0$ μm for PHEMT and $L_{gs} = L_{gd} = 1.5$ μm for MESFET). For a proper recessed gate formation, a slow wet etchant was used for obtaining a specific pinch-off voltage ($V_p \sim 0.8$ V). Measurement setup (combining HP4145B, HP8510B, and Spectra-Physics laser diode module) was kept the same during characterization in various electro-optical biases. Direct optical illumination (λ = 830 nm, P_{opt} = 0 $\sim$ 7.0 mW) was delivered close to the surface of DUT on wafer via optical fiber [2].

Without optical input, saturated drain currents (I_{DSS}) were observed to be 13 mA in PHEMT and 32 mA in MESFET at V_{GS} = 0.0 V as shown in Fig. 1. A strong nonlinear photonic response in the drain current (I_D) of PHEMT was observed [2], [8], [9] while the optically induced drain current (I_{Dp}) was monotonically but merely increasing with P_{opt} in MESFET. Channel length modulation in PHEMT was significantly suppressed by the enhanced channel conductivity (*photoconductive effect*) under optical stimulation. As shown in Figs. 1 and 2, output resistance ($r_{ds} = 1/(dI_D/dV_{DS})$) in PHEMT was significantly improved from $r_{dso} = 200\,\Omega$ at $P_{opt} = 0$ to $r_{ds} =$ 670 kΩ at P_{opt} = 7.0 mW while it was constant at r_{ds} = 590 Ω in MESFET over all optical power. Constant channel length modulation (r_{ds} = constant) in MESFET, for both with- and without optical input (P_{opt} = 0 $\sim$ 5.12 mW), was observed as a result of high density of carriers in the GaAs channel layer [8]. Pinch-off voltages (V_p) at $P_{opt} = 0$ mW were measured to be

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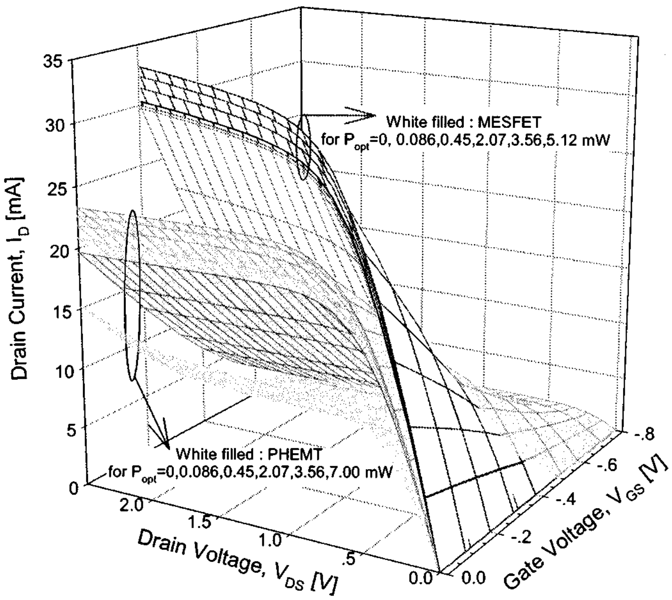

Fig. 1. Variation of photoresponsive drain current (I_D) in PHEMT and MESFET as a function of V_{DS}, V_{GS}, and calibrated optical power P_{opt} under optical stimulation ($\lambda = 830$ nm).

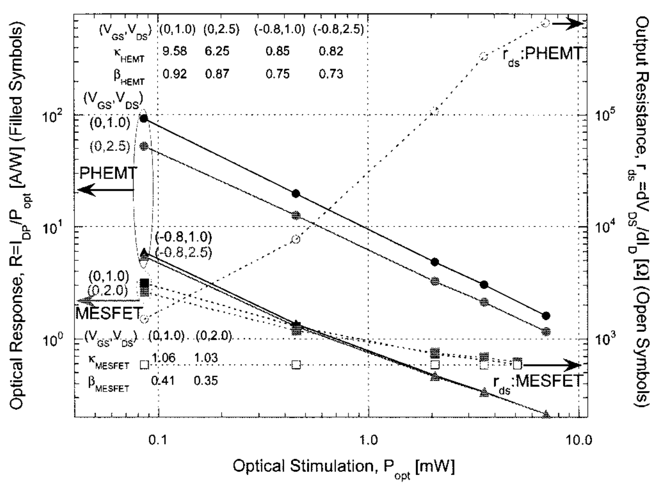

Fig. 2. Variation of optically stimulated photoresponse $(R = I_{Dp}/P_{opt})$, empirically modeled as $R = \kappa P_{opt}^{-\beta}$ $(\kappa_{PHEMT} \gg \kappa_{MESFET})$, and output resistance (r_{ds}) in PHEMT and GaAs MESFET as a function of P_{opt} under optical stimulation.

V_{po} = {-}0.838 V and −0.804 V for PHEMT and MESFET, respectively. With $P_{opt} = 3.56$ mW, pinch-off voltages were changed to $V_{p(3.56\text{mW})} = -1.033$ V and −0.836 V, which correspond to optically induced photovoltages $V_{opt} = 195$ mV and 32 mV, for PHEMT and MESFET, respectively. Increasing but considerably small V_{opt} was observed in MESFET with P_{opt}.

Drain photoresponse $(R = I_{Dp}/P_{opt})$, defined as the ratio of optically induced drain current to the optical power, is the sum of photoconductive (PC) response $(R_{PC} \equiv \partial I_{Dp,PC}/\partial P_{opt} = R_{PC,InGaAs} + R_{PC,AlGaAs}$; modulation of channel conductivity) and photovoltaic (PV) response $(R_{PV} \equiv \partial I_{Dp,PV}/\partial P_{opt}$; modulation of depletion width and effective channel thickness). Dominant mechanism depends strongly on P_{opt}-dependent variations of the depletion width (W_{scr}) and carrier density in a specific layer which are determined by the epitaxial structure and electrical bias. Under low P_{opt} below the onset of a parallel conduction via heavily doped $Al_{0.3}Ga_{0.7}As$ donor layer, therefore, PC-effect dominant photoresponse in PHEMT can be described as $R_{PHEMT,low} \cong R_{PC,InGaAs}$. However, $R_{PHEMT,high}$ under high P_{opt} above the onset of a parallel conduction can be written as $R_{PHEMT,high} \cong R_{PC,AlGaAs}$ which shows a very poor photoresponse due to a low electron mobility in heavily doped $Al_{0.3}Ga_{0.7}As$ donor layer. Considering photonic absorption, generation, and collection mechanisms of excess carriers in the channel which contribute to the PC effect in PHEMT, R_{PC} can be analytically written as

$$R_{PC} \approx \kappa_{PC} P_{opt}^{-\beta_{PC}}. \tag{1}$$

With a high channel doping for improved transconductance in MESFET, both PC and PV effects are much less sensitive to the optical input due to high channel carrier density and suppressed modulation of the depletion region. Therefore, $R_{PC,MESFET}$ is very small due to high channel doping and $R_{PV,MESFET}$ is small but believed to be more dominant photoresponsive mechnanism in MESFET. PV effect dominant-photoresponse in MESFET with a high channel carrier density, on the other hand, can be described by $R_{MESFET} = R_{PC,MESFET} + R_{PV,MESFET} \cong R_{PV,MESFET}$. Combining P_{opt}-dependent characteristic parameters (V_{opt}, W_{scr}) in PV effect-dominant MESFET, we can also obtain analytical relationship as

$$R_{PV} \approx \kappa_{PV} P_{opt}^{-\beta_{PV}}. \tag{2}$$

This can be also applied to the photoresponse of PHEMT under high P_{opt}, in which optical response is governed by the heavily doped donor layer due to the onset of the parasitic $Al_{0.3}Ga_{0.7}As$ MESFET. Photonic drain current variations in MESFET over all P_{opt}, which were shown in Fig. 1 as a function of P_{opt}, also look very similar to that of PHEMT under high P_{opt}. This is thought to be a strong evidence of a parallel conduction-limited photoresponse in PHEMT under high P_{opt} [2], [8].

Characterized photoresponses of PHEMT and MESFET are shown as a function of P_{opt} with output resistances (r_{ds}) in Fig. 2. Photoresponse decreases monotonically with P_{opt} over all electro-optical stimulations. Photoresponse of PHEMT under high P_{opt} was limited by the parallel conduction via the $Al_{0.3}Ga_{0.7}As$ donor layer, which has very poor conductivity due to extremely low carrier mobility [2], [9]. In the case of MESFET, significantly low and monotonic decrease in photoresponse ($R_{MESFET} = 3.12$ A/W at $P_{opt} = 85.6$ μW and 0.59 A/W at $P_{opt} = 5.12$ mW) was observed over all P_{opt}. For MESFET under near pinch-off condition, photoresponse was extremely lower than other bias conditions and that in PHEMT. Combining both photoconductive and photovoltaic effects, photoresponses in PHEMT and MESFET can be analytically and semiempirically modeled as

$$R = \kappa P_{opt}^{-\beta} (P_{opt} \text{ in [mW] and } R \text{ in [A/W]}) \tag{3}$$

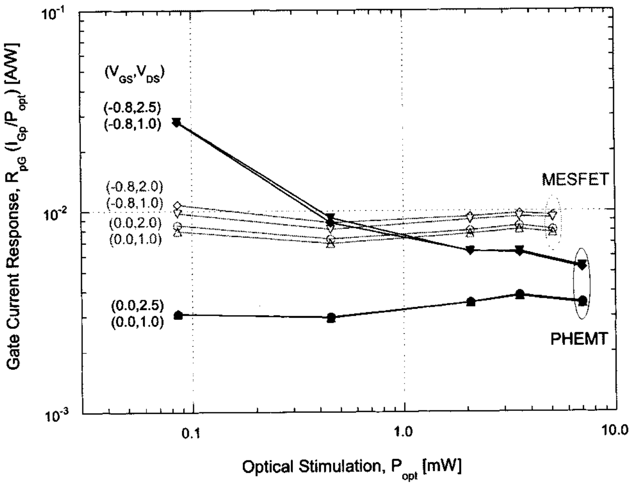

Fig. 3. Photonic gate response ($R_{pG} = I_{Gp}/P_{opt}$) of PHEMT and MESFET as a function of electro-optical stimulation.

where κ and β accommodate differences in devices/epitaxial layers and bias conditions. This model agrees well with experimental observations in PHEMT and MESFET as shown in Fig. 2. As summarized in Fig. 3, higher κ-value ($\kappa_{PHEMT} =$ 9.58:6.25 A/W; $V_{GS} = 0$, $V_{DS} = 1.0$:2.5 V), which depends strongly on both epitaxial structure and electrical bias, has been observed in PHEMT than that in MESFET ($\kappa_{MESFET} =$ 1.06:1.03 A/W; $V_{GS} = 0$, $V_{DS} = 1.0$:2.5 V). For a specific device, considerably smaller κ-values are obtained near pinch-off condition ($\kappa_{HEMT} =$ 0.85:0.82 A/W; $V_{GS} = V_p = -0.8$ V, $V_{DS} = 1.0$:2.5 V) in which the photovoltaic effect is expected to be dominant. However, β depends only on the epitaxial structure ($\beta_{PHEMT} = \sim 0.9$; $V_{GS} = 0$ and ~ 0.75; $V_{GS} = -0.8$) but is almost independent of operating point for a specific device. Below the onset of a parallel conduction via $Al_{0.3}Ga_{0.7}As$ donor layer, very high photoresponse ($R_{PHEMT} = 92.2$ A/W; $P_{opt} = 85.6$ μW) was observed in PHEMT. However, extremely low and monotonically decreasing photoresponse ($d \log R/d \log P_{opt} = -\beta$) in both PHEMT and MESFET was observed over all optical power.

III. Photoresponsive Gate Leakage in PHEMT and MESFET

Variation of the gate leakage, known as a detrimental source of noise and performance degradation, was investigated as a function of V_{DS}, V_{GS}, and P_{opt}. Gate current (I_G) under optical stimulation can be described as a sum of a) gate current ($I_{G,gen} \cong qA\gamma P_{opt} W_{scr}$) due to optical generation and successive collection of ehp's in the space charge region, b) gate current ($I_{G,PE} = I_{GSo} \exp(V_{opt}/V_{th})$) due to photo-assisted thermionic emission of excess ehp's from gate to channel, and c) gate current ($I_{G,trap} = q\nu_{eff} W L \eta N_{trap} P_{opt}$) due to photo-excited carriers from traps/interface states in Si-doped AlGaAs layer and heterointerfaces. Increased gate leakage was observed with increasing P_{opt} under negative V_{GS} ($V_{GS} = 0 \sim V_p$) in both MESFET and PHEMT. For a specific P_{opt}, smaller gate leakage was observed in PHEMT compared with that in MESFET over $V_{GS} = 0 \sim V_p$. This is due to a higher Schottky barrier formed on the undoped $Al_{0.3}Ga_{0.7}As$ layer ($E_g = 1.76$ eV) in PHEMT while relatively low Schottky barrier formed on heavily doped GaAs layer ($E_g = 1.43$ eV) in MESFET. However, the gate leakage was increasing with a reverse gate voltage (a strong function of V_{GS}) in PHEMT while it was almost independent of V_{GS} and V_{DS} in the MESFET for a specific optical power.

The photonic gate response (the ratio of optically induced gate leakage to the optical power: $R_{pG} = dI_{Gp}/dP_{opt}$) was compared in Fig. 3. Contrary to the drain photoresponse, which was monotonically decreasing with P_{opt} ($R = \kappa P_{opt}^{-\beta}$), $R_{pG,MESFET}$ in MESFET was independent of P_{opt} ($R_{pG,MESFET} = 8 \sim 9$ mA/W). However, $R_{pG,PHEMT}$ in PHEMT was a strong function of V_{GS} and P_{opt} while $R_{pG,MESFET}$ in MESFET was almost independent of P_{opt}, V_{GS}, and V_{DS}. Based on the photoresponsive leakage mechanisms, the photonic gate response can be described as $R_{pG} = R_{pG,gen} + R_{pG,PE} + R_{pG,trap}$ where $R_{pG,gen} = \partial I_{G,gen}/\partial P_{opt}$, $R_{pG,PE} = \partial I_{G,PE}/\partial P_{opt}$, $R_{pG,trap} = \partial I_{G,trap}/\partial P_{opt}$.

Comparing gate leakage mechanisms with experimental observation, the dominant leakage mechanism in MESFET under optical illumination is thought to be $I_{G,gen}$, which is due to generation of ehp's in SCR and thus proportional to P_{opt}. Less dependence of the I_G on V_{GS} in MESFET is due to a high channel carrier population which has suppressed modulation of W_{scr} with a reverse V_{GS} [1]. However, the thickness of SCR, which contributes to the photo-generated gate current ($I_{gen} \propto W_{scr}$), is insensitive to the effective gate voltage ($V_{GS,eff} = V_{GS} - V_{po} + V_{opt} \cong V_{GS} - V_{po}$) due to high carrier density.

In the case of PHEMT, even though considerably suppressed photonic gate response than that in MESFET, it was quite different from that of MESFET under large negative V_{GS} at low P_{opt}. Photonic gate response in PHEMT was as high as $R_{pG,PHEMT} = 27.9$ mA/W at $V_{GS} = -0.8$ V while it was decreased to 3.0 mA/W at $V_{GS} = 0.0$ V under the same $P_{opt} = 85.6$ mW and V_{DS}. At $V_{GS} = 0.0$ V, $R_{pG,PHEMT}$ was increasing monotonically with P_{opt} ($R_{PG,PHEMT} = 3.0$ mA/W; $P_{opt} = 85.6$ μW to 3.8 mA/W at $P_{opt} = 7.0$ mW). However, $R_{pG,PHEMT}$ at $V_{GS} = -0.8$ V(near pinch-off bias) was observed to be 27.9 mA/W; $P_{opt} = 85.6$ μW, decreasing down to 5.2 mA/W at $P_{opt} = 7.0$ mW. Dominant gate leakage mechanism in PHEMT under optical stimulation includes $I_{G,PE}$ and $I_{G,trap}$ as well as $I_{G,gen}$, which is dominant process at near pinch-off gate bias with $V_{GS} \cong V_P$. Differences in the photonic gate responses in PHEMT and MESFET are primarily due to epitaxial structure, Schottky barrier height, and traps and interface states in multiple heterostructures.

We note that the gate lekage is almost independent of the drain bias (V_{DS}) in both PHEMT and MESFET. This is because the increased V_{DS} above the saturation voltage ($V_{DS} > V_{DS,sat}$) is confined to a very small region of the pinched channel under the gate very close to the drain. So, the modulation/expansion of W_{scr} under optical illumination is limited to a very small part of the channel. Therefore, I_{Gp} is almost independent of V_{DS} under optical illumination. Less channel length modulation under optical stimulation is another evidence of this observation.

IV. Conclusion

Photoresponsive drain conduction and gate leakage characteristics of PHEMT and MESFET were experimentally compared as a function of electro-optical biases. Empirical model for nonlinear photoresponse in PHEMT and MESFET was proposed as $R = \kappa P_{opt}^{-\beta}$ where κ and β model differences in device structures and electrical biases. Gate leakage was a strong function of V_{GS} in PHEMT while it was almost constant in MESFET due to suppressed modulation of the SCR with heavy channel doping. Photonic gate response, on the other hand, was observed to be constant in MESFET while it was a strong function of electrical bias in PHEMT. Based on experimental observations, photonic gate leakage in MESFET was thought to be mainly caused by optical generation of ehp's in the SCR while it was governed by photo-assisted thermionic emission and photo-excitation of carriers from traps as well as generation of carriers in the SCR in PHEMT.

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