Photoresponsive Characteristics of N-channel Pseudomorphic HEMT and MESFET Under Optical Stimulation for Possible Applications to Millimeter-Wave Photonics

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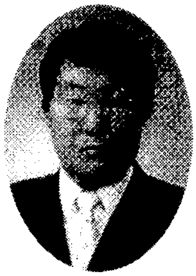

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ABSTRACT

Comparative photoresponsive current-voltage characteristics of n-channel PHEMT and MESFET on GaAs substrate, with $(W/L) = 200\mu m/1\mu m$ of gates, are reported as a function of electro-optical stimulation (P_{opt}, $\lambda = 830nm$) for the first time as far as we know. Significantly different photoresponses are observed in MESFET and PHEMT, mainly due to different optoelectronic mechanisms in the formation and current conduction of channel carriers. Under high optical power, high photoresponsity with a strong non-linearity with P_{opt}, predominantly due to a parallel conduction via a heavily doped $Al_{0.3}Ga_{0.7}As$ donor layer, was observed in PHEMT while the optically induced drain current has been very small but monotonically increasing with optical stimulation in GaAs MESFET. We also investigated differ-

ences in optically stimulated gate leakage currents and photonic gate responses on gate voltage and drain voltage as a function of P_{opt}. Based on the drain and gate responses to electro-optical stimulation, PHEMTs are expected to be a better candidate for high performance photonically responsive microwave device compared with MESFETs.

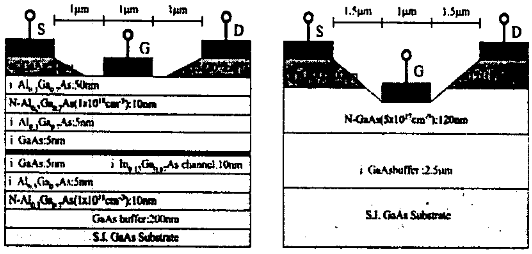
I. INTRODUCTION

Due to high cut-off frequency and large optical responsivity, pseudomorphic high electron mobility transistors (PHEMTs) and metal-semiconductor field effect transistors (MESFETs) are under active study as high performance photodetectors, as well as high current driving components, in monolithic integrated circuits of high frequency opto-electronic systems. However, photoresponsive current-voltage characteristics and corresponding electro-optical mechanisms in PHEMTs and MESFETs have not been completely identified [1~6].

In this paper, we report comparative photoresponsive current-voltage characteristics of n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}/As$ pseudomorphic HEMT (PHEMT) and GaAs MESFET ($N_{D,MESFET}$= $5\times10^{17}cm^{-3}$) under various optical stimulation (P_{opt}=85.6μW~7.0mW) with λ=830nm. Optical effects in the drain and gate currents are investigated as a function of electrical bias and optical illumination. Physical mechanisms in photoresponses (both photoconductive and photoelectric effects) in PHEMT and MESFET under optical stimulation are compared each other. Significant differences in the photoresponsive current-voltage characteristics are observed predominantly due to different electro-optical processes in the formation and current conduction of channel carriers in PHEMT and MESFET. We also investigated differences in the optically stimulated gate leakage current, which is detrimental source of noise and power consumption, on the gate voltage and drain voltage under optical illumination.

II. EPITAXIAL STRUCTURES AND DEVICE FABRICATION OF GaAs MESFET AND PHEMT

Epitaxial layer and device structures of n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ pseudomorphic high electron mobility transistor (PHEMT) and GaAs MESFET are shown in Figure 1 for comparison. Epitaxial layers were grown by a gas-source molecular beam epitaxy system (GSMBE) and a chemical beam epitaxy system (CBE) for PHEMT and MESFET, respectively. Similar fabrication processes, which include Au-Ge/Ni/Au for ohmic contact and Ti/Au for gate Schottky contact with a lift-off technique, are applied to both PHEMT and MESFET with V-shaped gates (W/L=200μm/1μm). Spacings between gate-to-source (Lgs) and gate-to-drain (L_{gd}) were $L_{gs}(=L_{gd})$=1.0μm for PHEMT and $L_{gs}(=L_{gd})$=1.5μm for MESFET, respectively. For proper recessed gate formation, a slow wet chemical etchant was used for obtaining a specified pinch-off voltage (~0.8V) in PHEMT and MESFET without



(a) PHEMT (b) MESFET

Figure 1. Epitaxial layer and device structure of n-channel GaAs MESFET and $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT with a V-shaped gate of (W/L)=200μm/1μm.

optical illumination. Electro-optical characterizations were performed on wafer with a passivating Si_3N_4 layer which is transparent to λ=830㎚ of optical illumination via pig-tailed optical fiber from optical source. All electro-optical measurement setup was kept the same during characterization in various electro-optical bias conditions for both PHEMT and MESFET. The optical power (P_{opt}) described in this paper is calibrated by an optical spectrum analyzer at the same distance from the end of the optical fiber so that it is very close to the real optical power delivered to PHEMT and MESFET under electro-optical characterization.

Ⅲ. PHOTORESPONSIVE CURRENT-VOLTAGE CHARACTERISTICS OF PHEMT AND MESFET UNDER OPTICAL STIMULATION

Photoresponsive electro-optical current-voltage characteristics of n-channel PHEMT and GaAs MESFET are measured under various electrical biases and optical stimulation on wafer. Direct optical illumination (λ =830㎚) was delivered to the surface of device under test via optical fiber. Without optical illumination, the saturated drain current (I_{DSS}) was observed to be 13mA for PHEMT and 32mA for n-channel GaAs MESFET at the gate-source voltage V_{GS}=0.0V as shown in Figure 2. A strong non-linear photonic response in the drain current (I_D) due to a parallel conduction in PHEMT was observed while the optically induced drain current has been monotonically increasing with optical stimulation in GaAs MESFET [2, 7, 8].

Without optical illumination, we observed a strong channel length modulation (CLM) effect in the drain current-voltage (I_D-V_{DS}) characteristics of the n-channel $Al_{0.3}Ga_{0.7}As/GaAs/In_{0.13}Ga_{0.87}As$ PHEMT while no CLM effect was appeared in GaAs MESFET in the saturation mode of operation over all gate bias, as shown in Figure 2. The discrepancy in the CLM effect between PHEMT and MESFET is supposed to be caused by the modulation of depleted channel region near the drain contact. Heavy channel carrier concentration ($N_{D,MESFET}=5\times10^{17}cm^{-3}$) in the MESFET resulted less variation of effective channel length compared with that of relatively low channel carrier concentration in the PHEMT. Channel length modulation effect was significantly suppressed due to enhanced channel conductivity, which is known as the photoconductive effect, with optically generated excess ehp's, especially in PHEMT, under optical illumination.

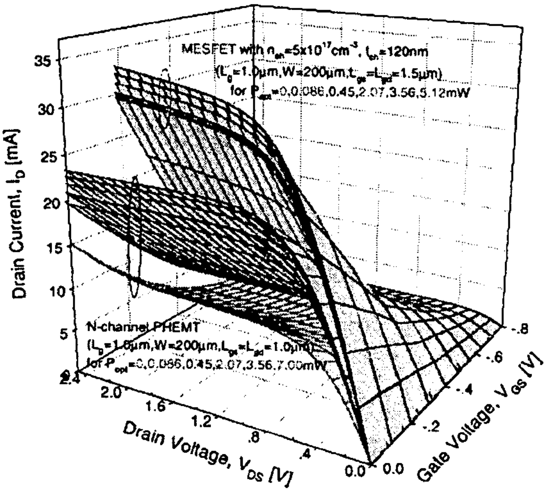


Figure 2. Variation of photoresponsive drain current (I_D) in MESFET and PHEMT as a function of V_{DS}, V_{GS}, and Popt under optical stimulation (λ=830㎚).

Pinch-off voltages (V_p), obtained from the square law of the drain current as a function of the effective gate voltage (I_D-$V_{GS,eff}$)-relation in the saturation mode of operation, were V_{po}=-0.838V and -0.804V for PHEMT and MESFET, respectively. With P_{opt}=3.56mW, we obtained pinch-off voltages $V_{p(3.56mW)}$=-1.033V and -0.836V, which correspond to photovoltage V_{opt}=195mV and 32mV, for PHEMT and MESFET, respectively, as in Figure 3. In the case of GaAs MESFET, optically generated photovoltage, which is known as the result of photovoltaic effect, was relatively small even though it was monotonically increasing with optical power over all applied optical power (P_{opt}=85.6μW to 5.12mW). Contrary to the MESFET, however, monotonic increase with Popt was observed in the n-channel PHEMT for P_{opt}=85.6μW to 7.0mW.

Optical responses of PHEMT and MESFET, defined as the ratio of optically increased drain current to the optical illumination ($R=I_p/P_{opt}$ [A/W]), were extracted and are shown in Figure 3, as a function of P_{opt} with optically generated photovoltages under an assumption that the drain current in the saturation mode of operation (V_{GS}=0.0V, V_{DS}=1.0V) is a quadratic function of effective gate voltage ($V_{GS,eff}=V_{GS}-V_P$). Very high optical responsivity under low optical input (R=92.2[A/W] at P_{opt}=85.6μW) was obtained while an extremely low optical responsivity was measured under high optical stimulation (R=3.04[A/W] at 3.56mW and R=1.57[A/W] at P_{opt}=7.0mW). Monotonic decrease in optical responsivity was measured in PHEMT (filled circles) with increased optical illumination. This variation in the optical response is believed to be due to a parallel conduction of $Al_{0.3}Ga_{0.7}As$ donor layer, which has very electrical conductivity due to extremely low carrier mobility, as explained in the previous report. In the case of GaAs MESFET (filled squares) as shown in Figure 3, on the other hand, extremely low and almost constant optical responsivity (R=3.12[A/W] at P_{opt}=85.6μ W and R=0.587[A/W] at P_{opt}=5.12mW) was obtained over all optical stimulation. Constant optical responsivity in PHEMT under high optical power, which was appeared in Figure 2 as function of Popt, also looks very similar to that of GaAs MESFET with heavy channel doping concentration. This is thought to be a strong evidence of a parallel conduction in the PHEMT under high optical power [2, 7].

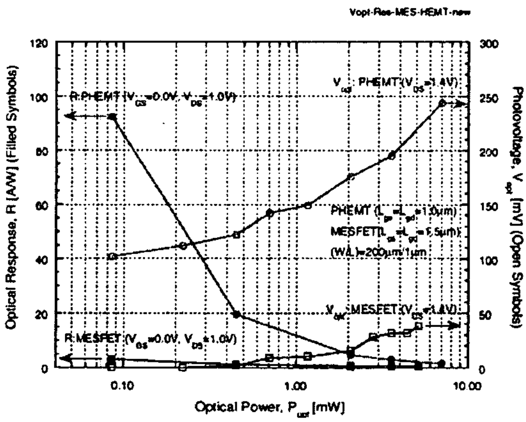


Figure 3. Variation of optically stimulated photoresponse ($R=I_{Dp}/P_{opt}$) and photovoltage (V_{opt}) in GaAs MESFET and PHEMT as a function of P_{opt} under optical stimulation.

Variations of the gate leakage current (I_G) in PHEMT and MESFET, which is known to be detrimental source of noise and power consumption, were also investigated and plotted in Figure 4 as a function of V_{DS}, V_{GS}, and P_{opt}. Increased gate leakage currents, both in MESFET adn in PHEMT, are observed with increased optical illumination. For a specific electro-optical bias condition (V_{GS}, V_{DS}, P_{opt}), smaller gate leakage current was observed in PHEMT compared with that obtained in MESFET. This is due to a higher Schottky barrier formed on the undoped wide bandgap $Al_{0.3}Ga_{0.7}As$ layer (E_g=1.76eV) in PHEMT while relatively low Schottky barrier formed on heavily doped small bandgap GaAs layer (E_g=1.43eV) in MESFET. However, the gate leakage was 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 stimulation. We note that there is a generation current due to the collection of optically generated excess carriers in the space charge region under the gate as well as thermionic emission of optically generated excess carriers overcoming reduced built-in energy barrier due to the photovoltage. Considering the dominant component in the gate leakage current as a generation and collection of optically generated excess holes in the depletion region under the gate in PHEMT and MESFET, optically induced gate leakage current is predominantly controlled by P_{opt}. Less dependence of the gate current in MESFET on the gate voltage is probably due to heavy channel doping concentration which has suppressed modulation of space charge region with reverse gate voltage [1].

The photonic gate response, which is defined as the ratio of optically stimulated gate leakage current to the optical power ($R_{pG}=I_{Gp}/P_{opt}$) are also comparably shown in Figure 5. Contrary to the optical response (R) of the drain current to the optical input, which is monotonically decreasing with P_{opt}, the photonic gate current response (R_{pG}) in the MESFET was almost independent of P_{opt} over all investigated optical power range. With increasing P_{opt}, more optically generated holes(G_{opt}) are available to be collected to the gate and form the photonic gate current. However, the thickness of the space charge region (X_{scr}) under the gate, which contributes to the generation current ($J_{gen}\sim qG_{opt}X_{scr}$), is almost insensitive to the effective gate voltage ($V_{GS,eff}=V_{GS}-V_{opt}$) due to heavy channel doping concentration. Therefore, an increased gate leakage current is observed due to more optically generated holes with P_{opt} while a constant photonic gate response is observed due to a constant rate of optically generated holes per unit optical power with a fixed space charge region.

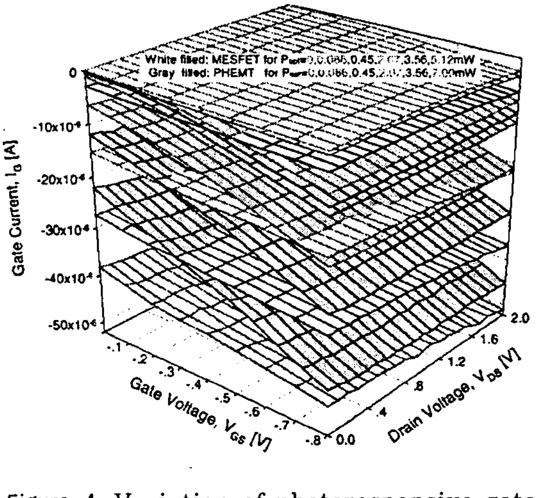


Figure 4. Variation of photoresponsive gate leakage current (I_G) in GaAs MESFET and PHEMT as a function of V_{DS}, V_{GS}, and P_{opt} under optical stimulation (λ=830nm).

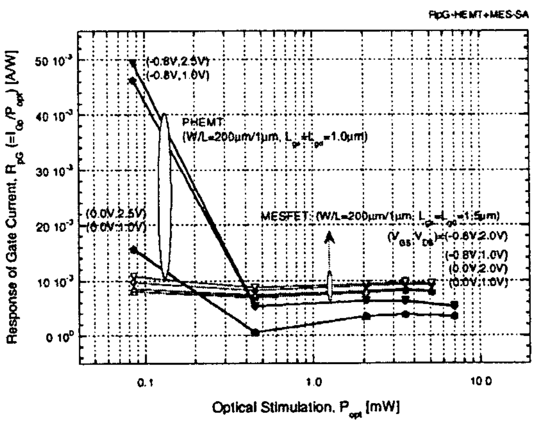


Figure 5. Photonic gate response ($R_{pG}=I_{Gp}/P_{opt}$) of MESFET and PHEMT as a function of electro-optical stimulation.

In the case of PHEMT, on the other hand, the photonic gate response was significantly different from that of MESFET, especially at low optical power with P_{opt}=85.6μW. High photonic gate current response R_{Gp}=15.57 [mA/W] at P_{opt}=85.6μW was sharply dropped to R_{Gp}=0.58[mA/W] at P_{opt}=0.45mW and then almost independent of Popt over all optical stimulation to 7.0mW (R_{Gp}=3.48 [mA/W] at P_{opt}=7.0mW). Much higher photonic gate response was also observed at more negative gate voltage (R_{Gp}=46.24 [mA/W] at V_{GS}=-0.8V, V_{DS}=1.0V, P_{opt}=85.6μW). Below the onset of a parallel conduction (P_{opt}<85.6μW) via $Al_{0.3}Ga_{0.7}As$ donor layer, a high photonic gate response is observed due to the generation and successive collection of optically excited holes in the fully depleted donor layer and the undoped $Al_{0.3}Ga_{0.7}As$ Schottky layer under the gate. Above the onset of a parallel conduction through a conductive $Al_{0.3}Ga_{0.7}As$ donor layer ($N_{D,HEMT}=1\times10^{18}cm^{-3}$) under a high optical power (P_{opt}>0.45mW), the space charge region which contributes to optical generation and collection of holes to the gate, is limited to the undoped $Al_{0.3}Ga_{0.7}As$ Schottky layer. Therefore, a constant photonic gate response is observed in PHEMT under high optical power while the gate leakage current is still increasing with P_{opt} which is the same observation as in GaAs MESFET with a channel doping concentration $N_{D,MESFET}=5\times10^{17}cm^{-3}$.

Ⅳ. CONCLUSION

Comparative photoresponsive current-voltage characteristics of n-channel PHEMT and MESFET, with $(W/L)=$ =200㎛/1㎛ of the gate, are investigated as a function of electro-optical stimulation (V_{GS}, V_{DS}, P_{opt} with λ =830㎚). Both photoconductive and photoelectric effects in the drain and gate currents are investigated in the photoresponsive mechanisms under optical stimulation. Significant difference in photoresponses are observed in PHEMT and MESFET, mainly due to different mechanisms in the formation of channel carriers. A strong non-linear photonic response in the drain current due to a parallel conduction through the $Al_{0.3}Ga_{0.7}As$ donor layer in PHEMT was observed while the optically induced drain current has been very low but monotonically increasing with optical stimulation in GaAs MESFET. We also observed differences in the optically stimulated gate leakage current on gate voltage and drain voltage under optical illumination. Based on higher drain current response and suppressed gate leakage current response to optical stimulation, compared with MESFET, PHEMT is expected to be a better candidate for high performance microwave-photonic responsive device in monolithic optoelectronic integrated circuit applications.

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