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Effects of Light on a P-Channel InGaP/GaAs/InGaAs Double Heterojunction Pseudomorphic Modulation-Doped Field Effect Transistor

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We report on the effects of light on a p-channel $In_{0.49}Ga_{0.51}P/GaAs/In_{0.13}Ga_{0.87}As$ pseudomorphic modulation-doped field effect transistor (MODFET) with a 1 μm gate length. The threshold voltage (V_{th}), obtained in the saturation region, shows nonlinear behavior with an increase in the incident optical power (P_{opt}). We obtained threshold voltages ranging from V_{tho}=1.35 V at P_{opt}=0 mW to V_{th}=1.55 V at P_{opt}=2.15 mW. The photocurrent was -0.37 mA at V_{gs}=0 V and V_{ds}=-3.5 V with incident optical power of 2.15 mW. The photocurrent is defined as the difference between the drain current with optical illumination and that without optical input. The absolute value of the photocurrent increases nonlinearly with optical power. We observed that the saturated drain currents had a critical point at the gate-source voltage of 1.4 V. This property is expected to be related to nonlinearly increased channel opening under optical illumination, particularly at high gate-source voltages. The current gain cut-off frequency and the maximum frequency of oscillation were also observed to be improved under optical illumination.

KEYWORDS: MODFET, optical responses, P-channel

1. Introduction

The effects of light on microwave devices have attracted much interest because of possible applications to optoelectronic integrated circuits for high-speed modulation and detection in optical communication systems. However, photonic microwave reports on the effects of light on modulation-doped field effect transistors(MODFETs) have been concentrated on n-channel MODFETs.[1–5] The effect of light on p-channel MODFETs has not yet been characterized or reported in detail even though it is expected to be advantageous over n-channel MODFETs for some applications. In p-channel MODFETs, employing two-dimensional hole gas (2-DHG) with pseudomorphic double heterostructure improved DC and microwave performances can be achieved with increased excess channel carriers, particularly at low temperatures, due to higher carrier mobility,[6–8] Thus, the optical responses of p-channel MODFETs could be used for high-speed control of complementary logic elements in optoelectronic integrated circuits. In this paper, the effects of light on a p-channel InGaP/GaAs/InGaAs pseudomorphic MODFET grown on a GaAs substrate are reported.

2. Device Fabrication and Measurement

We fabricated and characterized a p-channel pseudomorphic MODFET with $In_{0.49}Ga_{0.51}P/GaAs/In_{0.13}Ga_{0.87}As$ modified heterostructure. A strained $In_{0.13}Ga_{0.87}As$ layer has been used as a channel, sandwiched between two $In_{0.49}Ga_{0.51}P$/GaAs heterojunctions. The epitaxial layers were grown using gas source molecular beam epitaxy on the GaAs substrate. The structure includes an undoped GaAs buffer layer (2000 Å), a p-type $In_{0.49}Ga_{0.51}P$ acceptor layer (100 Å, Be; 2×10^{18} cm^{-3}), an undoped $In_{0.49}Ga_{0.51}P$ spacer layer (50 Å), an undoped GaAs layer (50 Å), an undoped $In_{0.13}Ga_{0.87}As$ channel layer (100 Å), an undoped GaAs layer (50 Å), an undoped $In_{0.49}Ga_{0.51}P$ spacer layer (50 Å), a p-type $In_{0.49}Ga_{0.51}P$ acceptor layer (100 Å, Be; 2×10^{18} cm^{-3}), an undoped $In_{0.49}Ga_{0.51}P$ Schottky layer (500 Å), and a p^+GaAs cap layer (300 Å, Be; 3×10^{19} cm^{-3}). $In_{0.49}Ga_{0.51}P$ has a higher bandgap of 1.89 eV which is insensitive to optical modulation with wavelength $\lambda = 800$ nm. This pseudomorphic M ODFET structure, however, is expected to have a better carrier confinement and improved carrier transport of two-dimensional hole gas in the pseudomorphic channel layer, owing to a higher valence band offset between InGaP/GaAs/InGaAs heterojunctions. The Hall mobility and the density of 2-DHG in the pseudomorphic $In_{0.13}Ga_{0.87}As$ channel at 300 K were measured as 250 cm^2/V·s and 1.9×10^{12} cm^{-2}, respectively.

The fabricated p-channel pseudomorphic MODFET had a gate length $L_g = 1\,\mu$m, a gate width $W_g = 240\,\mu$m, a gate-source spacing $L_{gs} = 1.5\,\mu$m, and a gate-drain spacing $L_{gd} = 1.5\,\mu$m. We chose π-shaped gate structure for better control and focusing of optical input to a selected area of device under characterization. Mesa structure has been obtained for the isolation of the device using a chemical wet etching process. Au-Zn/Cr/Au and Ti/Au multiple layer metallization processes have been used for the ohmic contact and the gate Schottky contact, respectively. We used a selective etching technique during the gate recess process to achieve better thickness control. The Schottky gate metal of $L_g = 1\,\mu$m was deposited on the wide bandgap InGaP layer, with the expectation of a higher Schottky barrier and thus reduced gate leakage and improved input dynamic range. The plasma enhanced chemical vapor deposition (PECVD)-grown silicon nitride (1000 Å) was deposited for passivation of the fabricated devices before electrical and photonic characterization.

For the measurement of the optically controlled electrical characteristics of the fabricated $In_{0.49}Ga_{0.51}P/GaAs/In_{0.13}Ga_{0.87}As$ p-channel MODFET, a continuous laser diode source with $\lambda = 800$ nm, HP 4156A semiconductor parameter analyzer, and HP 8510B network analyzer were combined. The optical source was routed via an optical fiber (cleaved multi-mode fiber, minimum illumination diameter of 25 μm, numerical aperture of 0.275) to the p-channel MODFET by bringing the fiber-end within close proximity of the surface of the device such that the light spot covered the entire active area of the π-shaped MODFET (approximately 200 μm in diameter).

3. Experimental Results

When a p-channel MODFET device is optically illuminated by photons of energy equal to or greater than the semiconductor band gap, free electron-hole pairs are generated in the active layers. The major photoeffects of illumination on the p-channel MODFET are band-to-band photon absorption in the InGaAs channel and the GaAs spacer layers. As a result of these photogenerated electron-hole pairs, the channel carrier density is increased resulting in an increase in the drain current due to the photoconductivity. Photogenerated excess carriers also affect effective gate voltage due to the photovoltaic effect which contributes to a change in the total depletion region under the gate. Due to the modulated depletion width, the DC and microwave characteristics of the MODFET will be modulated by modulated conductivity of the channel and parasitic capacitances in the device under photonic illumination. The drain current-voltage characteristics are shown in Fig. 1 and are compared with those under incident optical power of 2.15 mW. Without optical illumination, we obtained the drain current I_{ds}^{dark}=−4.34 mA at V_{gs}=0 V and V_{ds}=−3.5 V. The measured transconductance (g_m) of the p-channel MODFET was 27 mS/mm with the gate-source voltage V_{gs}=−0.2 V and drain-source voltage V_{ds}=−3.5 V. Under optical illumination with P_{opt}=2.15 mW, we obtained I_{ds}^{light}=−4.71 mA under the same bias conditions (V_{gs}=0 V and V_{ds}=−3.5 V). Therefore, the photocurrent, $I_{ph} = I_{ds}^{light} - I_{ds}^{dark}$, was measured to be −0.37 mA, which is expected to be strongly dependent upon bias conditions and optical input power levels.

The threshold voltage, which was obtained from the current-voltage characteristics in the saturation region of operation, is shown in Fig. 2 as a function of incident optical power biased at V_{ds}=−3.5 V. Under photonic illumination, optically generated electrons will drift toward the gate and will contribute to a decrease in effective gate voltage (photovoltaic effect) while optically generated holes will be collected in the pseudomorphic quantum well channel layer (photoconductive effect). The thickness and carrier concentration of the channel would be modulated according to the change, due to the photovoltaic effect in the gate depletion region of the p-channel MODFET. Under photonic excitation, the optical input acts as an optically controlled gate. The threshold voltage was increased under optical illumination due to the photovoltaic effect. This change in the threshold voltage is due to negatively charged electrons which drift in the space charge region under the gate. The threshold voltage shows nonlinear behavior ranging from $V_{tho} = 1.35$ V at P_{opt}=0 mW to $V_{th} = 1.55$ V at P_{opt}=2.15 mW with increasing incident optical power. At high incident optical power, the change in the threshold voltage appears to be saturated by the photovoltaic effect, which modulated the channel and the space charge region.

The photocurrent as a function of the gate-source voltage for various drain-source voltages is also shown in Fig. 3 at a fixed incident optical power of 2.15 mW. The photocurrent shows small variation with drain-source bias for a given gate-source voltage above the threshold voltage of 1.55 V. However, it increases with increasing drain-source bias for gate voltages below the threshold voltage, which is due to increased channel conductivity. Therefore, we observe that good optical response is obtained at a high drain-source voltage and low gate-source voltage near pinch-off which has wide depletion region for optical sensitivity.

The photocurrent as a function of the incident optical power for the p-channel MODFET at V_{ds}=−3.5 V and V_{gs}=0 V is shown in Fig. 4. The absolute value of the photocurrent increases with the incident optical power. The photocurrent is very sensitive at low optical incident power and finally saturates at high optical power levels.

The ratio of saturated drain currents, ($I_{dss}^{light}/I_{dss}^{dark}$), is shown in Fig. 5 as a function of the gate-source voltage at a fixed incident optical power of 2.15 mW and V_{ds}=−3.5 . The ratio

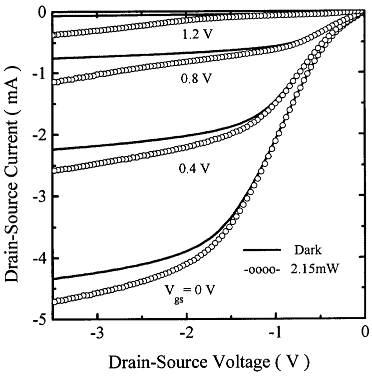

Fig. 1. Electrical characteristics of a p-channel pseudomorphic MODFET under incident optical power P_{opt}=2.15 mW and V_{gs}=0 to 1.2 V (step=0.4 V).

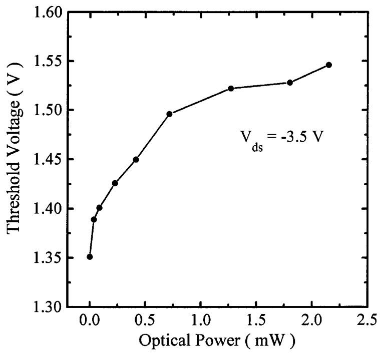

Fig. 2. The threshold voltage as a function of incident optical power at V_{ds}=−3.5 V.

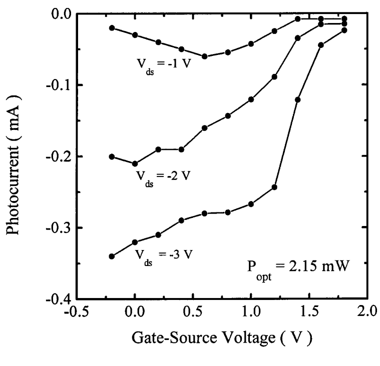

Fig. 3. The photocurrent as a function of the gate-source voltage for various drain-source voltages at a fixed incident optical power of 2.15 mW.

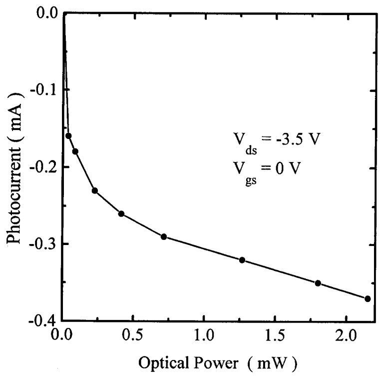

Fig. 4. The photocurrent as a function of the incident optical power for a p-channel MODFET with V_{ds}=−3.5 V and V_{gs}=0 V.

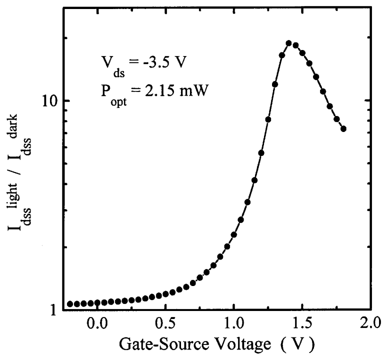

Fig. 5. The ratio of the saturated drain currents ($I_{dss}^{light}/I_{dss}^{dark}$) as a function of the gate-source voltage at a fixed incident optical power of 2.15 mW.

of the saturated drain currents for p-channel MODFET was increased with increasing gate-source voltage below V_{gs} = 1.4 V, whereas it was decreased above V_{gs}=1.4 V. The ratio of the saturated drain currents had a critical point at V_{gs}=1.4 V. This property is related to a nonlinear increased channel opening under optical illumination, particularly at high gate-source voltages.

Frequency-dependent microwave characteristics are measured and plotted in Fig. 6 for V_{gs}=0.8 V and V_{ds}=−2.4 V. Due to the photoconductive and photovoltaic effects, the current gain cut-off frequency (f_T) and the maximum oscillation frequency (f_{max}) were found to be 1.76 GHz and 3.46 GHz, respectively. These improvements are expected to be due to the photoconductive and photovoltaic effects under optical illumination. Maximum improvement in microwave performance was observed near pinch-off mode of operation. Under an optical power P_{opt}=2.15 mW, we observed a 9.3% improvement in f_T and a 4% improvement in f_{max}, compared to those under non-illumination.

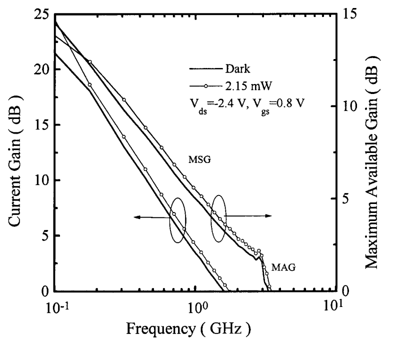

Fig. 6. Current gain cut-off frequency and maximum oscillation frequency curve under V_{gs}=0.8 V and V_{ds}=−2.4 V in dark and with an incident optical power of 2.15 mW.

4. Conclusion

A p-channel $In_{0.49}Ga_{0.51}P/GaAs/In_{0.13}Ga_{0.87}As$ pseudomorphic MODFET with a 1 μm gate length has been fabricated and characterized with and without optical illumunation for DC performances. The photocurrent of the device was −0.37 mA at V_{gs}=0 V and V_{ds}=−3.5 V with incident optical power of 2.15 mW. The absolute value of the threshold voltage shows nonlinear behavior from V_{tho}=1.35 V to V_{th}=1.55 V with increasing incident optical power. This result is due to the photovoltaic effect. We observed that the photocurrent with the gate-source voltage was related to the threshold votage and has an inverse slope of exponent with increasing incident optical power. The ratio of the saturated drain currents had a critical point at V_{gs}=1.4 V. Under the optical illumination, current gain cut-off frequency and maximum frequency of oscillation were improved. The good optical responses of the p-channel MODFET could be applied to optically controlled electronic circuits.

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