Manufacturable $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ Doped-channel HFETs with f_T and f_{max} over 170 GHz

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ABSTRACT

We demonstrate the fabrication and performance of 0.15 µm T-gate high-speed $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ doped-channel HFETs with non-alloyed ohmic contacts. A high peak trans-conductance of 718 mS/mm and a high maximum current density of 890 mA/mm were achieved. The ohmic contact was fabricated by using AuGe/Ni/Au deposited on highly doped InGaAs contact layer without high temperature alloy. The on-resistance of 1.2 Ω·mm was measured. The high doping InGaAs channel leads to excellent RF performance: f_t of 171 GHz and f_{max} of 186 GHz at V_{ds} = 1.5 V. These are the best results ever reported for doped-channel HFETs, which is comparable to other HFETs and HEMTs with same gate length. This result suggested that $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ doped-channel HFET is suitable for high-speed and high-power device application.

INTRIDUCTION

The future wireless application requires very high-speed devices. InGaAs/InP is one of the most promising materials in the high-speed electronic device family. The large Γ-L valley separation in InGaAs and InP allows for higher electron saturation velocity, which determines the device speed [1-3]. However, Fermi level pinning effect on InP limits the Schottky barrier height, therefore, leading to a large reverse bias gate leakage current. In order to improve the Schottky barrier height, large bandgap materials, like InAlAs, InAlP and InGaP, are used as gate materials. In this work, a strained InGaP layer was grown as Schottky barrier enhancement layer (SBEL) to improve the barrier height. Using InGaP SBEL has some advantages against AlInAs and AlInP. First, in this material system, the availability of selective etching between InGaAs and InGaP will greatly simplify the device fabrication and improve etching uniformity [4-6] by eliminated the needs for well controlled, timed etching processes. Secondly, InGaP doesn't contain Al, and therefore may not suffer from Al-related reliability problems [5-8].

Doped-channel HFETs have demonstrated great performance on device characteristics [9-11]. Also comparing with the complex structure of HEMTs, the doped-channel HFET has no critical thickness layers, which greatly simplifies the material growth. In this paper, we developed $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ 0.15 µm T-gate doped-channel HFETs with a very simple material structure and excellent DC and RF performance.

Cap layer	InP	Undoped	240 nm
Contact Layer	$In_{0.53}Ga_{0.47}As$	9.0 e+18 cm^{-3}	25 nm
SBEL	$In_{0.8}Ga_{0.2}P$	1.0 e+17 cm^{-3}	15 nm
Spacer	InP	1.0 e+17 cm^{-3}	2 nm
Channel	$In_{0.53}Ga_{0.47}As$	2.0 e+18 cm^{-3}	12 nm
Buffer Layer	InP	Undoped	40 nm
InP Substrate			

Fig. 1. Epitaxy structure of doped-channel $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ HFETs

MATERIAL GROWTH AND DEVICE FABRICATION

The $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As/InP$ DC-HFET structure is shown in Figure 1, which was grown by a Perkin Elmer (PHI) model 430P gas source molecular beam epitaxy (GSMBE) using solid In and Ga for the group III sources, elementary Si for the n-type dopant source and cracked AsH_3 and PH_3 for the group V sources. All the layer were grown at 470°C. First, a 400Å undoped InP buffer was grown on a (100) InP semi-insulating substrate, followed by a 120Å lattice-matched $In_{0.53}Ga_{0.47}As$ n-channel layer ($2.0\times10^{18}cm^{-3}$). Then, the 20Å InP spacer and 150Å $In_{0.8}Ga_{0.2}P$ SBEL, with doping density of $1.0\times10^{17}cm^{-3}$ were grown on top of the active channel. Finally, a 250Å heavily doped InGaAs layer was grown as the contact layer.

The device fabrication includes wet chemical mesa etching to isolate the active region, and traditional ohmic metal AuGe/Ni/Au was evaporated to form the ohmic contacts. With a cap doping of $1\times10^{19}cm^{-3}$, a typical contact resistance of 0.065 Ω·mm is obtained without high temperature alloy. The 0.15 µm T-gate was defined by E-beam direct writing using a tri-layer PMMA resist structure. The gate recess etch was conducted by using H_2SO_4: H_2O_2: H_2O based selective etching solution to etch the InGaAs and stopped at InGaP layer. Finally, the Pt/Ti/Pt/Au was evaporated to form the T-gate.

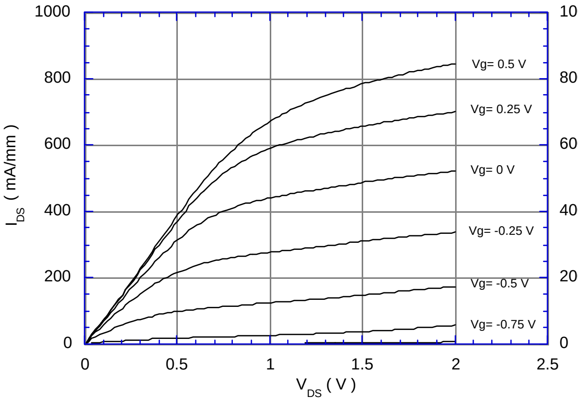

Fig. 2. I-V characteristics of 0.15 µm doped-channel $In_{0.8}Ga_{0.2}P$ /$In_{0.53}Ga_{0.47}As$/InP HFET; output conductance is 86 mS/mm at V_g = 0 V; top curve is at V_g = 0.5 V, step is –0.25 V; on-resistance is 1.2 Ω·mm.

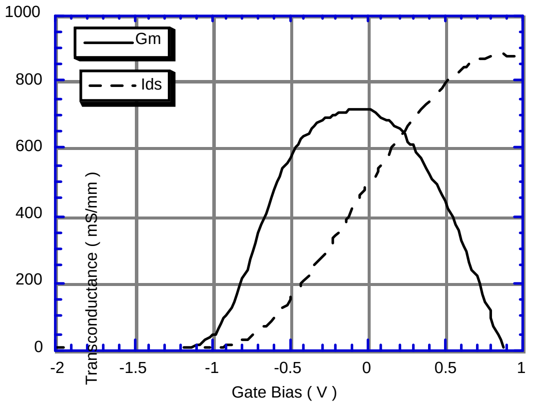

Fig. 3. Transfer characteristics of doped-channel $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As$ /InP HFET; peak Gm is 718 mS/mm at I_{dss} = 487 mA/mm, V_g = 0 V; $I_{DS,\ max}$ is 890 mA/mm at V_g = 0.9 V; pinch-off voltage is –1.18 V; W=100 µm.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The output I-V characteristics of 0.15 µm HFET are shown in the Figure 2. The device output characteristics show a sharp pinch-off behavior and no kink effect. A high maximum output current density of 890 mA/mm at V_{DS} = 1.5 V, V_g= 0.9 V was achieved due to the high channel doping. Transconductance and I_{ds} dependence of V_g curves were conducted at V_{ds} = 1.5 V by sweeping V_g, which are shown in Figure 3. A high extrinsic transconductance of 718 mS/mm at I_{ds} = 487 mA/mm, and a low output conductance of 86 mS/mm were measured at Gm peak. The device pinch-off voltage, –1.18 V, was measured at I_{ds} = 1 mA/mm. The gate to drain diode characteristics is shown in Figure 4. Schottky barrier height of 0.64 V and gate-to-drain breakdown voltage -2.4 V can be estimated from the plot. Due to the gate leakage current, the transconductance begins to fall off quickly and deviate from the simulation result at certain forward gate bias.

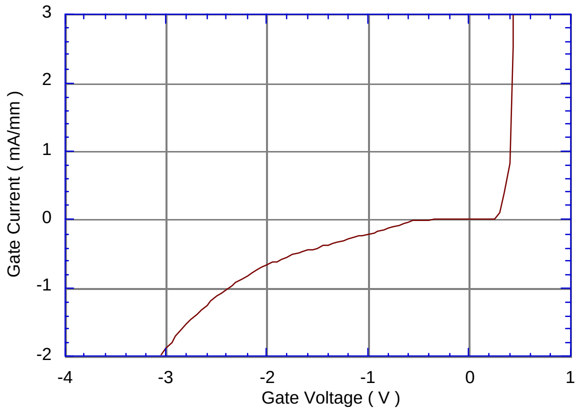

Fig. 4. Gate diode characteristics of doped-channel $In_{0.8}Ga_{0.2}P$ /$In_{0.53}Ga_{0.47}As$/InP HFET with L_g = 0.15 µm, W =100 µm.

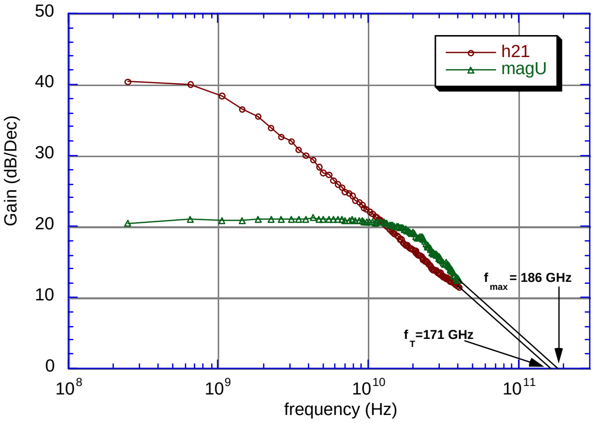

Fig. 5. Power gain (MAG) and current gain (H21) curves for 0.15 µm doped-channel $In_{0.8}Ga_{0.2}P/In_{0.53}Ga_{0.47}As$/InP HFET with gate width of 100 µm at V_{DS} = 1.5 V, V_g = 0 V.

The device RF characteristics were determined from S-parameter measurements with an HP8510 network analyzer. The measured $|H_{21}|$ and MAG_{max} values are shown in Figure 5 as a function of frequency from 0.25-40.25 GHz at V_{ds} = 1.5 V and V_g = 0 V. The unity current gain cutoff frequency f_t of 171 GHz is determined by extrapolating a –20 dB/decade line from $|H_{21}|$ to the unity gain point. Similarly, the value for f_{max} of 186 GHz is found by extrapolating maximum avaliable gain (MAG) to the unity gain point. A f_{max}/f_T ratio of 1.1 has been obtained. The cutoff frequency f_T and f_{max} are the best results ever reported for doped-channel HFETs. Compared to HEMTs with same gate length, ft of 171 GHz is higher than 100 GHz of AlGaAs/InGaAs pHEMT's [12], and 130 GHz of InAlAs/InGaAs HEMT's [13], [14].

In summary, we have achieved excellent DC and RF performance on doped-channel In$_{0.8}$Ga$_{0.2}$P/In$_{0.53}$Ga$_{0.47}$As/InP HFETs, which is comparable to those of other works of InGaAs channel HEMTs with same gate length. The results indicate that the electron saturation velocity under high electrical field, not the electron mobility, is the key factor determining the device speed. The use of InGaP barriers makes selective etching available to improve the device uniformity, also avoids Al-related reliability issues. By introducing the channel doping, a high output current density can be obtained. The excellent device performance and manufacturability demonstrate that doped-channel In$_{0.8}$Ga$_{0.2}$P/In$_{0.53}$Ga$_{0.47}$As/InP HFET is suitable for high-speed and high-power applications.

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