Modulation-doped $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ field-effect transistors

Jenn-Ming Kuo
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

Yi-Jen Chan[a] and Dimitris Pavlidis
Center for High Frequency Microelectronics, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109

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$In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ pseudomorphic modulation-doped field-effect transistors (MODFETs) were realized for the first time by gas-source molecular beam epitaxy on GaAs substrates. Extrinsic transconductances of 173 and 283 mS/mm at 300 and 77 K, respectively, were measured for MODFETs with a 1 μm long and 75 μm wide gate. The devices showed very good pinch-off characteristics, and the output conductance was only 1.3 mS/mm. Extremely high Schottky barrier height (0.92 eV) and low gate leakage current ($I_{rev} < 250$ nA at $V_{GS} = -5$ V) were achieved. The gate breakdown voltage was -17 V. No I-V collapse was observed at 77 K. Microwave measurements showed that the current gain cutoff frequency f_T of the devices was 11.5 GHz and the maximum frequency of oscillation f_{max}, was 26 GHz. These results demonstrate the promising potential of pseudomorphic $In_{0.48}Al_{0.52}P$/InGaAs MODFETs as high frequency and high power devices.

AlGaAs/InGaAs pseudomorphic modulation-doped field-effect transistors (MODFETs) have demonstrated excellent low noise and high power performance at microwave frequencies.[1,2] In these structures, the large conduction-band discontinuity at the AlGaAs/InGaAs heterointerface allows for a high two-dimensional electron gas (2DEG) concentration. The InGaAs channel also offers superior electron transport properties compared to conventional GaAs channels used in AlGaAs/GaAs MODFETs, due to a lower electron effective mass and larger Γ-L valley separation. However, the disadvantage of this material system is the presence of DX centers in $Al_xGa_{1-x}As$ ($x > 0.22$).[3] The DX centers can be avoided by lowering the Al content, but the carrier confinement and the sheet carrier density are compromised. Other barrier materials lattice matched to GaAs are therefore necessary to be explored.

An excellent alternative is $In_{0.48}(Al_xGa_{1-x})_{0.52}P$ because the $In_{0.48}(Al_xGa_{1-x})_{0.52}P$/GaAs heterojunction gives the largest band-gap difference ΔE_g of all III-V semiconductor heterojunctions lattice matched to GaAs. Previously, InGaP/GaAs heterostructures have been grown and characterized by several groups.[4–7] Ultralow interface recombination velocity and extremely high electron mobility have been reported. The InGaP/GaAs MODFETs also show no current collapse and have very small threshold voltage shift at cryogenic temperatures, indicating that the content of DX centers is very low for InGaP.[8] In addition, the conduction band discontinuity (ΔE_C) for the $In_{0.48}(Al_xGa_{1-x})_{0.52}P$/GaAs heterojunction increases linearly with increasing Al composition (x) from 0 to 0.7, and reaches a maximum value (0.38 eV) at $x=0.7$.[9] For $0.7 < x < 1.0$, the band structure becomes indirect and the conduction-band discontinuity slightly decreases toward 0.31 eV with increasing Al composition.[9] Overall, the maximum ΔE_C achieved in this material system is larger than the values feasible with the $Al_xGa_{1-x}As$/GaAs system where $\Delta E_C = 0.17$ eV for $x=0.22$. Furthermore, the $In_{0.48}(Al_xGa_{1-x})_{0.52}P/In_{0.2}Ga_{0.8}As$ pseudomorphic modulation-doped structure has larger ΔE_C in comparison with its $In_{0.48}(Al_xGa_{1-x})_{0.52}P$/GaAs counterpart. Hence, it can provide better electron confinement and higher 2DEG while preserving the electron transport properties of InGaAs channel. The existence of high selectivity of chemical etching between GaAs and InAlP[10] also may enable improved gate recess control, and therefore may provide better threshold voltage uniformity.

We report in this letter the growth and fabrication of the first $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ pseudomorphic MODFETs on GaAs substrates by gas-source molecular beam epitaxy (GSMBE). The dc and microwave characteristics of 1 μm gate length devices are presented. Cryogenic temperature operation and threshold voltage (V_{th}) shift are evaluated. The results of bias stress tests are also reported.

The epitaxial layers were grown in an Intevac Gen II GSMBE system on 2-in. semi-insulating (100) GaAs substrates. Epitaxial growth was carried out using As_2 and P_2 molecular beams produced by thermal decomposition of the gaseous hydrides AsH_3 and PH_3. The use of gas sources provided a means of rapidly switching between InAlP and InGaAs growth while maintaining precise control of the group V molecular flux. Conventional elemental Al, In, and Ga effusion cells were used to supply the group III beams. In order to minimize the interdiffusion of the GaAs/InAlP interface, cracked AsH_3 and PH_3 were injected separately from two independent crackers equipped with conductance-balanced vent/run valves. Switching between AsH_3 and PH_3 was controlled by the vent/run valves and shutters in front of both injectors. The hydride cracker temperatures were held at 1100 °C. The growth rate of GaAs and InAlP was 0.45 and 0.9 μm/h, respectively. Lattice mismatch within $\Delta a/a = 5\times10^{-4}$ was easily

[a]Present address: Department of Electrical Engineering, National Central University, Chung-Li, Taiwan.

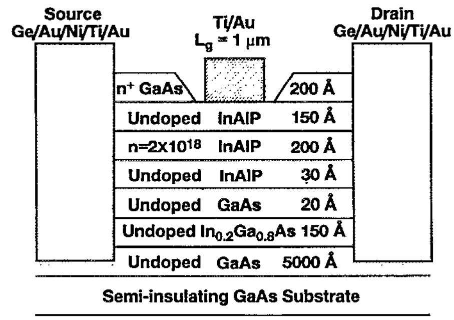

FIG. 1. Schematic cross section of the $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ pseudomorphic MODFET.

obtained with a calibration run of InAlP. Electrochemical *C-V* profiles were used to characterize test wafers with staircase doping profile of Si in InAlP. Mobilities and sheet-electron concentrations of the InAlP/InGaAs modulation-doped heterostructures were measured by Hall measurements at 300 and 77 K.

The device cross section is shown in Fig. 1. A 5000 Å thick undoped GaAs buffer was grown, followed by a 150 Å undoped $In_{0.2}Ga_{0.8}As$ pseudomorphic channel, and 20 Å GaAs and 30 Å InAlP undoped spacers. A 200 Å InAlP Si-doped layer ($n=2\times10^{18}$ cm^{-3}) provided the donors, and a 150 Å undoped InAlP was used to improve the Schottky contact. Finally a 200 Å n^+-GaAs cap was used to reduce contact resistance.

Devices were processed using conventional optical lithography. A $NH_4OH/H_2O_2/H_2O$ (10:4:500) solution was used for etching both GaAs and InGaAs layers. This etchant proved to be selective for InAlP, only attacking GaAs and InGaAs. It provides therefore a way to deposit the gate metal on the undoped InAlP without any risk of uncontrolled gate recess variation, as would for example be the case for etching the InAlP donor or Schottky layer. The etching of InAlP for the mesas was achieved using a HCl/H_2O solution.[10] This solution does not etch GaAs or InGaAs. Switching from the $NH_4OH/H_2O_2/H_2O$ solution to HCl/H_2O was necessary to complete the mesa. This had, however, a significant effect on the etching characteristics and the surface morphology of the resulting layers. Ohmic contacts were realized using Ge/Au/Ni/Ti/Au (700/1400/500/200/1000 Å) followed by a 40 s 420 °C hot-plate anneal. After etching the top n^+ GaAs layer, 1 μm long gates (Ti/Au, 500/2000 Å) were deposited and defined by liftoff process.

The Hall mobility was 5390 cm^2/V s and 27 300 cm^2/V s at 300 and 77 K, respectively, while the corresponding values for the sheet charge density were 2.24 $\times10^{12}$ and 1.55×10^{12} cm^{-2}. After removing the top GaAs cap layer, mobilities increased to 6880 cm^2/V s at 300 K and 29 700 cm^2/V s at 77 K while the corresponding sheet carrier densities became 1.32×10^{12} and 1.3×10^{12} cm^{-2}, respectively. The sheet charge density only increased 5% under illumination at 77 K. This indicates that deep trap effects are not significant in this material system. Figure 2(a) shows the room temperature *I-V* characteristics of a device with a gate of 1×75 μm. The output conductance was only 1.3 mS/mm. The g_m-V_{GS} and $I_{DS}-V_{GS}$ transfer characteristics of the same device are shown in Fig. 2(b). The maximum extrinsic transconductance was 173 mS/mm at 300 K with $V_{DS}=2.0$ V. Extremely low gate reverse leakage current ($I_{rev}<250$ nA at $V_{GS}=-5$ V for a 1×75 μm^2 gate device) was achieved. The gate breakdown voltage was -17 V. This high value is due to the high band gap of InAlP. A 0.92 eV Schottky barrier height was evaluated from *C-V* measurements. The turn-on voltage was 0.7 V and the value of the ideality factor was 1.27, indicating that thermionic emission and diffusion are the dominant mechanisms of current flow. These results demonstrate the high quality of the undoped InAlP layer.

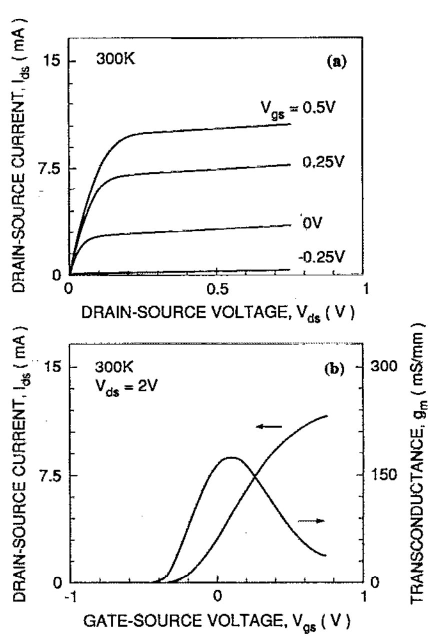

FIG. 2. (a) Room-temperature current-voltage characteristics of the InAlP/InGaAs MODFET with a gate of 1×75 μm. (b) Transfer characteristics of the same device. Excellent pinchoff and saturation behavior are evident with a peak transconductance of 173 mS/mm at $V_{DS}=2.0$ V.

The microwave performance of the InAlP/InGaAs pseudomorphic MODFETs were measured from 1 to 26.5 GHz using a Cascade Microtech on-wafer prober and an HP8510 automated network analyzer. Figure 3 shows short-circuit current gain and maximum available gain as a

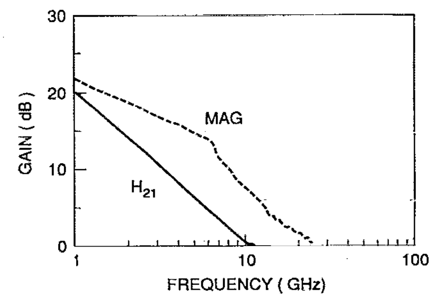

FIG. 3. Maximum available gain (MAG) and short-circuit current gain ($20\log|h_{21}|$) of $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ MODFET. Measurements were performed at the bias of the peak g_m position.

function of frequency for the devices. As can be seen, a maximum oscillation frequency of $f_{max}=26$ GHz and a current gain cutoff frequency of $f_T=11.5$ GHz have been obtained for 1 μm gate length devices. Optimization of the growth conditions and further refinements in the structure and processing of the pseudomorphic InAlP/InGaAs MODFETs can improve their dc and microwave performance.

One crucial test for these devices is the dc characteristics at 77 K in the dark. The devices showed a maximum transconductance of 283 mS/mm with no *I-V* collapse at 77 K, in contrast to $Al_xGa_{1-x}As/GaAs$ MODFETs with $x>0.22$. When the devices were illuminated, the curves remained virtually unchanged and completely returned to their original values when the source of illumination was removed. The threshold voltage at 77 K increased to -0.18 V, representing a shift of only 30 mV from 300 K. This amount of threshold shift is much smaller than that of $Al_{0.15}Ga_{0.85}As/In_xGa_{1-x}As$ $(0.05<x<0.2)$ MODFETs,[11] indicating that the *DX*-like trap density in InAlP is not severe. The small threshold voltage shift (18 mV) caused by stress bias tests also indicates that there is not an inordinate number of *DX* centers in the InAlP grown by GSMBE. The details of the stress bias tests will be published elsewhere.

In conclusion, we have demonstrated a new pseudomorphic MODFET using GSMBE grown $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ heterostructures. Extrinsic transconductance as high as 173 and 283 mS/mm has been measured at 300 and 77 K, respectively, for a 1 μm long gate device. No *I-V* collapse was found at 77 K and the threshold voltage shift was only 30 mV from 300 K. Bias stress tests were also applied, and the corresponding threshold shift was only 18 mV. These results suggest that *DX*-like trap effects are not significant in InAlP. Preliminary microwave measurements also demonstrate the promising potential of pseudomorphic $In_{0.48}Al_{0.52}P/In_{0.2}Ga_{0.8}As$ MODFETs as high frequency and high power devices.

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