$In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel high electron mobility transistors

D. Liu, M. Hudait, Y. Lin, H. Kim, S.A. Ringel and W. Lu

An $In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel high electron mobility transistor (HEMT) structure was grown by molecular beam epitaxy. Room-temperature Hall measurement showed that the device wafer had an electron mobility of 7300 cm^2/V s and a sheet electron density of 3×10^{12} cm^{-2}. The fabricated HEMT devices with a gate length of 0.25 μm exhibited excellent DC and microwave performance with a peak extrinsic transconductance of 888.3 mS/mm, a cutoff frequency (f_T) of 115 GHz, and a maximum frequency of oscillation of 137 GHz. This is believed to be the first report of InGaAs/InAsP composite channel HEMTs. The f_T is the highest ever reported for any composite channel HEMTs with the same gate length.

Introduction: InP-based composite channel high electron mobility transistors (HEMTs) are attractive to improve the breakdown voltage and power performance of InAlAs/InGaAs HEMTs [1–5]. In these structures, under low electric field, electron transport is confined in the high mobility InGaAs main channel. Under high electric field, electrons gain enough energy to transfer into the sub-channel, which has higher breakdown field and higher saturation electron velocity. Materials that have been considered for the sub-channel include InP [1], InAsP [2] and InGaAs with lower indium composition [3]. To date InP has received most of the research attention [1, 4, 5]. However, InAsP is more preferable compared with InP because it has a smaller conduction band offset at the InGaAs/InAsP interface, thus electrons can be more easily transferred into the InAsP sub-channel. Also, the composition of InAsP can be varied to optimise device performance. The growth of such InAlAs/InGaAs/InAsP HEMT structure has been explored [2], but no working device has been reported. In this Letter, we present our recent results on the growth and fabrication of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs. Devices with 0.25 μm gate length were fabricated and compared with other state-of-the-art composite channel InP-based HEMTs.

Device layer structure: The epilayer structure in this study was grown by a 2-inch Varian Gen II molecular beam epitaxy (MBE) system. On the Fe-doped semi-insulating (100) InP substrate, an $In_{0.52}Al_{0.48}As$ buffer with InGaAs/InAlAs supperlattices was first grown. The channel consisted of, from bottom up, 40 Å of strained $InAs_{0.3}P_{0.7}$ doped to 2×10^{18} cm^{-3}, 40 Å of undoped $InAs_{0.3}P_{0.7}$ and 70 Å $In_{0.53}Ga_{0.47}As$, followed by 30 Å-thick $In_{0.52}Al_{0.48}As$ spacer, Si-planar doping (5×10^{12} cm^{-2}) and 100 Å $In_{0.52}Al_{0.48}As$ Schottky barrier layer. A thin layer (60 Å) of InP is used as the etching stop layer to improve uniformity of gate recess etching. Finally, 400 Å heavily doped $In_{0.53}Ga_{0.47}As$ (1×10^{19} cm^{-3}) was grown for ohmic contacts. The doping in the first $InAs_{0.3}P_{0.7}$ channel layer was designed to (i) act as an extra carrier contribution layer to increase the sheet electron density in the two-dimensional electron gas (2DEG); and (ii) adjust the conduction band edge to form a triangle quantum well at the $InAs_{0.3}P_{0.7}$ and $In_{0.52}Al_{0.48}As$ interface. Hall measurement showed that the wafer had a two-dimensional sheet carrier density of 3×10^{12} cm^{-2} and a Hall electron mobility of 7300 cm^2/V s at room temperature.

Device fabrication: The device fabrication started with mesa isolation by dry etching using Cl_2/Ar plasma in an inductively coupled plasma reactive ion etching system (ICP-RIE). Ge/Au/Ni/Au ohmic contacts were deposited by electron beam evaporation and annealed at 360°C for 1 min in a furnace in N_2 ambient. Using the transmission line model technique, ohmic contact resistance is determined to be 0.03 Ω mm. The specific contact resistivity is 1.2×10^{-7} $\Omega\, cm^{-2}$. To our knowledge, this is the lowest contact resistance achieved on heavily doped $In_{0.53}Ga_{0.47}As$. 0.25 μm-long mushroom gates were patterned using a tri-layer resist scheme by electron beam lithography. A two-step gate recess etching process was employed. The InGaAs contact cap was first etched using selective etchant of citric acid/H_2O_2 mixture. Then the InP etching stop layer was removed by Ar plasma in ICP-RIE. Finally, Ti/Pt/Au was deposited as Schottky gate contacts. The devices are not passivated. The drain-to-source spacing is 2 μm. The gate width is 100 μm.

Results: DC characteristics of InGaAs/InAsP composite channel HEMTs were measured on wafer using an Agilent 4156 semiconductor parameter analyser. The I-V characteristics are shown in Fig. 1. The maximum drain current at $V_{GS} = 0.2$ V and $V_{DS} = 1$ V is 432 mA/mm. The devices pinch off well at a gate voltage of −0.5 V. The I-V curves show no kink effect, which is a clear sign that the strong impact ionisation in InGaAs was successfully suppressed by using InAsP as the sub-channel. Fig. 2 shows the device transfer characteristics. During the measurement, the drain-source bias was fixed at 0.8 V. The maximum extrinsic transconductance (g_m) is 888.3 mS/mm at $V_{GS} = -0.01$ V. Threshold voltage, which is defined as the gate-bias intercept by extrapolating the drain current curve from the peak g_m position in transfer characteristics, was determined to be −0.29 V.

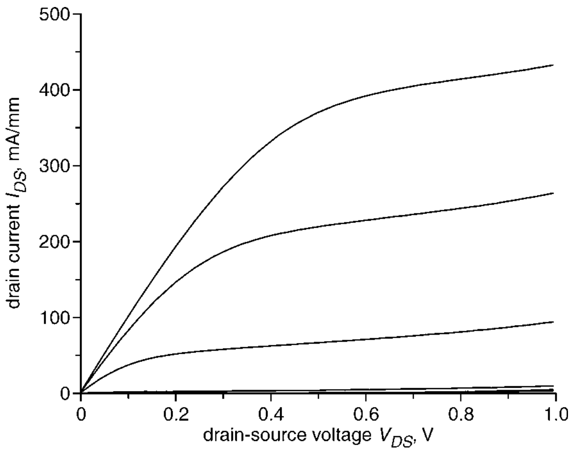

Fig. 1 *DC I-V characteristic of 0.25 × 2 × 50 μm composite channel HEMT*

Gate biased from −0.6 to 0.2 V in steps of −0.2 V

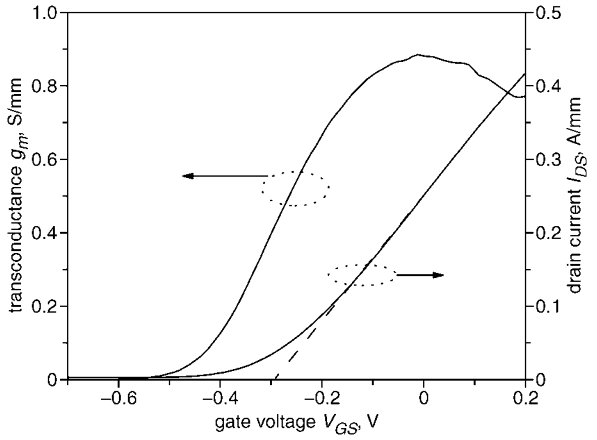

Fig. 2 *Transfer characteristic of 0.25 × 2 × 50 μm composite channel HEMT*

Drain biased at 0.8 V

The small-signal microwave characteristics of the composite channel HEMT were measured using an Agilent 8510C network analyser from 1 to 40 GHz. The optimum bias condition for the highest gain was determined to be $V_{GS} = 0.02$ V and $V_{DS} = 0.8$ V. Fig. 3 shows the dependence of intrinsic current gain ($|H_{21}|^2$) and maximum stabile/available gain (MSG/MAG) on frequency for a typical device. The cutoff frequency (f_T) is determined to be 115 GHz by extrapolating the $|H_{21}|^2$ at −20 dB/dec. The maximum frequency of oscillation (f_{max}) is 137 GHz. The f_T, to our knowledge, is the highest ever reported for InP-based composite channel HEMTs with 0.25 μm gate length. It confirms that InAsP has great potential as a composite channel material for high-speed field effect transistors.

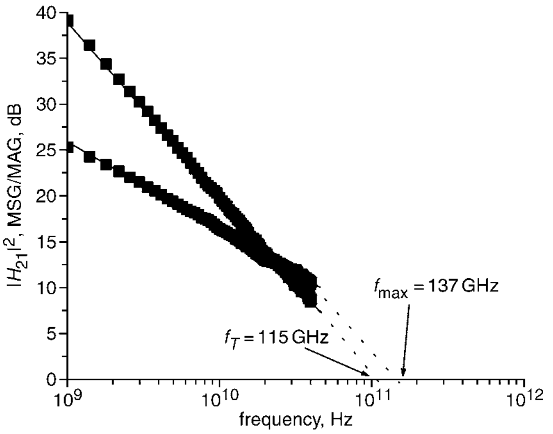

Fig. 3 *Current gain and maximum stable/available gain characteristics of typical 0.25 × 2 × 50 µm composite channel HEMT*

Conclusions: We have demonstrated the first high-performance $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs. The novel device layer structure in which $InAs_{0.3}P_{0.7}$ was used as the composite channel was grown by MBE. The 0.25 µm devices exhibited a peak extrinsic transconductance of 888.3 mS/mm, an f_T of 115 GHz, and an f_{max} of 137 GHz. To our knowledge, the f_T is the highest ever reported in the literature for composite channel HEMTs with the same gate length. The excellent device performance is attributed to successful layer structure design, high quality material growth, extremely low contact resistance, and effective control in gate recess etching.

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D. Liu, M. Hudait, Y. Lin, H. Kim, S.A. Ringel and W. Lu (*Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43210, USA*)

E-mail: lu@ece.osu.edu

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