0.25μm $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ Composite Channel HEMTs with an f_T of 115GHz

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Abstract— **In this paper we report growth, fabrication and charaterization of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs with a gate length of 0.25 μm. In comparison with InAlAs/InGaAs/InP composite channel HEMTs, these devices have better band structure for transferring electrons to the composite channel under high electric field, thus exhibit excellent DC and microwave performance with 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, this is the first report of InAlAs/InGaAs/InAsP composite channel HEMTs. The f_T is the highest ever reported for any composite channel HEMTs with the same gate length.**

I. Introduction

InAlAs/InGaAs HEMTs (high electron mobility transistors) have demonstrated excellent performance for high speed and low noise applications. Cut-off frequency as high as 562 GHz has been reported on 25 nm-gate-length devices with a $In_{0.7}Ga_{0.3}As$ pseudomorphic channel [1]. However, due to the small band gap of InGaAs channel layer, these devices suffer from high gate leakage current and low breakdown voltage.

One way to improve the breakdown voltage and power performance of these devices is adding a larger bandgap material to the InGaAs to form a composite channel structure. Materials which have been considered include InP [2], InAsP [3] and InGaAs with lower Indium composition [4]. In these structures, electrons will be moving in the high mobility InGaAs main channel under low electric field. Under high electric field, they can gain enough energy to transfer into the composite channel thus exploit its advantageous physical properties such as higher breakdown field and higher saturation electron velocity. InP so far received most of the research attention. Much progress in terms of breakdown voltage, speed, and microwave power has been reported [2] [5] [6]. However, as a novel material, InAsP is more preferable 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 optimize device performance. The effort on the growth of such InAlAs/InGaAs/InAsP HEMT structure has been explored [3], but no device work has been reported.

In this paper, we present our recent progress 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.

II. Device Structure and Fabrication

The epilayer structure studied for InGaAs/InAsP composite channel devices is shown in Fig.1. The layers were grown on Fe-doped semi-insulating (100) InP substrate by a 2-inch Varian Gen II Molecular Beam Epitaxy (MBE) system. On the InP substrate, an $In_{0.52}Al_{0.48}As$ buffer with InGaAs/InAlAs supperlattices was first grown. The channel is consisted of, from bottom up, 40 Å of strained $InAs_{0.3}P_{0.7}$ doped to $2\times10^{18} cm^{-3}$, 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 ($5 \times 10^{12}\ cm^{-2}$) 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 $In_{0.53}Ga_{0.47}As$ ($1 \times 10^{19}\ cm^{-3}$) was grown for ohmic contacts. The doping in the first $InAs_{0.3}P_{0.7}$ channel layer was designed to: (1). act as an extra carrier contribution layer to increase the sheet electron density in the 2-dimensional electron gas (2DEG); and (2). 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. Fig.2 shows the simulation result of depth profile of conduction band edge and electron concentration at equilibrium by solving Poisson and Schrodinger equation self-consistently in one dimension. At equilibrium, electrons will be mainly confined in the InGaAs channel. Under high electric field, at drain side, electrons will gain enough energy to overcome the conduction band offset between InGaAs/InAsP to take advantage of the high electron saturation velocity and higher breakdown field of InAsP. The device wafer has a two-dimensional sheet carrier density of $3 \times 10^{12}\ cm^{-2}$ and a Hall electron mobility of 7300 $cm^2/V{\cdot}$s at room temperature.

The device fabrication started with mesa isolation by dry etching using Cl_2/As 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 minute in a furnace in N_2 ambient. The contact resistance of the ohmic contact is measured by transmission line model (TLM) technique. Fig.3 shows the dependance of resistance on contact metal spacing. Contact resistance is determined to be 0.03 $\Omega \cdot mm$, and the specific

Cap	InGaAs	400Å	$1 \times 10^{19}\ cm^{-3}$
Etching stop	InP	60Å	undoped
Barrier	InAlAs	100Å	undoped
δ-doping	Si	–	$5 \times 10^{12}\ cm^{-2}$
Spacer	InAlAs	30Å	undoped
Channel	InGaAs	70Å	undoped
Channel	InAsP	40Å	undoped
Channel	InAsP	40Å	$2 \times 10^{18}\ cm^{-3}$
Buffer	InAlAs with supperlattice	3800Å	Undoped
Substrate	InP	–	Semi-insulating

Fig. 1. MBE-grown layer structure for InAlAs/InGaAs/InAsP composite channel HEMT on InP substrate.

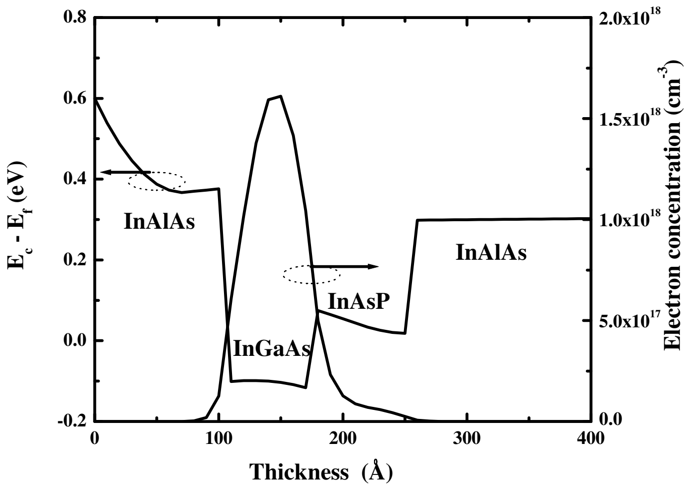

Fig. 2. Equilibrium conduction band diagram and electron distribution in composite channel HEMTs by solving Poisson and Schrodinger equation(thickness starts from barrier layer).

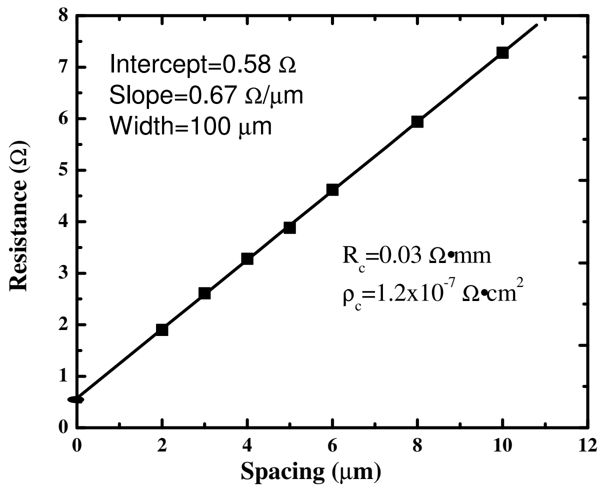

Fig. 3. Dependance of contact resistance on the spacing for TLM measurement.

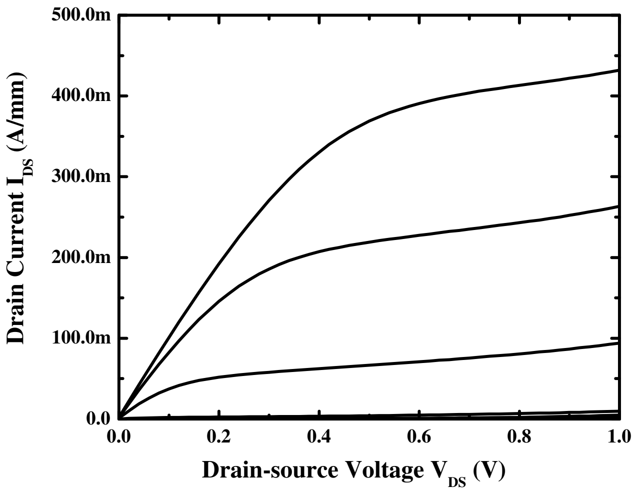

Fig. 4. DC I-V characteristic of a 0.25μm x 2 x 50 μm^2 composite channel HEMT.

contact resistivity is $1.2 \times 10^{-7} \Omega \cdot cm^{-2}$. 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-shaped gates were patterned by electron beam lithography with tri-layer resist. 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.

III. Results and discussion

DC characteristics of 0.25 x 2 x 50 μm^2 gate InGaAs/InAsP composite channel HEMTs were measured on wafer with Agilent 4156 Semiconductor Parameter Analyzer. The I-V characteristics are shown in Fig.4. The maximum current at V_{GS} = 0.2 V and V_{DS} = 1 V is 432 mA/mm. The devices pinch off well at gate voltage of -0.5 V. The I-V curves show no kink effect, which is a clear sign that the strong impact ionization in InGaAs was successfully suppressed by using InAsP as composite channel. Fig.5 shows the device transfer characteristics. During the measurement, the drain-source voltage was biased at 0.8 V. The maximum extrinsic transconductance achieved is 888.3 mS/mm at V_{GS} = -0.01 V.

The small signal microwave charateristics of the composite channel HEMT were measured using an Agilent 8510C network analyzer from 1 GHz 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.6 shows the dependance of intrinsic current gain ($|H21|^2$) and maximum stabile/available gain (MSG/MSG) on frequency for a typical device. The cutoff frequency (f_T) determined to be 115 GHz by extrapolating the $|H21|^2$ at -20dB/dec. The maximum frequency of oscillation (f_{max}) is 137 GHz. The f_T is, to our knowledge, the highest ever reported for InP-based composite channel HEMTs with 0.25 μm gate length. It confirms that InAsP has great potential

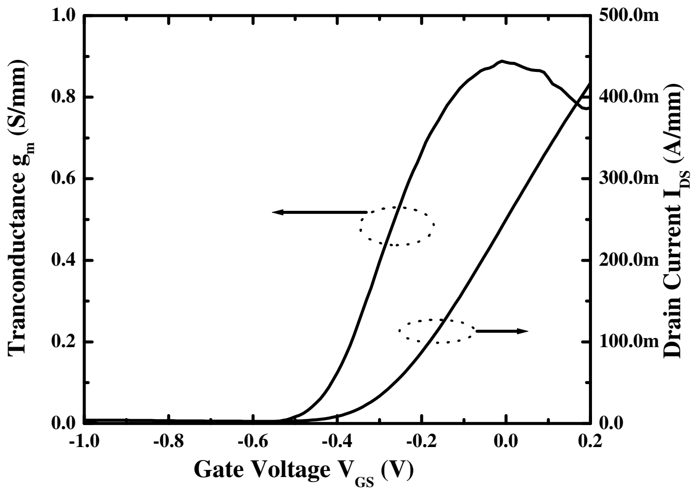

Fig. 5. Transfer characteristic of a 0.25 x 2 x 50 μm^2 composite channel HEMT.

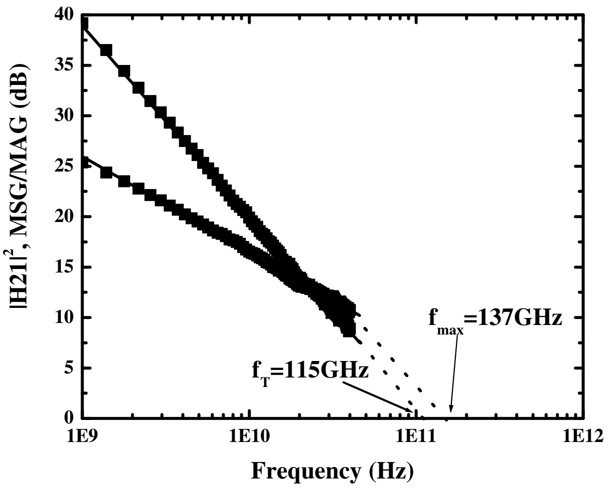

Fig. 6. Current gain and maximum stable/available gain characteristics of a typical 0.25μm x 2 x 50 μm2 composite channel HEMT.

as composite channel material for high speed applications. The excellent device performance can be attributed to successful layer structure design, high quality MBE material growth, extremely low ohmic contact resistance and effective control in gate recess etching.

IV. Conclusion

In summary, we have reported our most recent result of 0.25 μm $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs. Novel device layer structure using $InAs_{0.3}P_{0.7}$ as composite channel was grown by MBE. These devices exhibited excellent DC and microwave performance with a peak extrinsic transconductance of 888.3mS/mm and an f_T of 115 GHz. To our knowledge, this is the first report of InAlAs/InGaAs/InAsP composite channel HEMTs. The f_T is also the highest ever reported in 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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