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Gate length scaling study of InAlAs/InGaAs/InAsP composite channel HEMTs

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Abstract

The dependence of direct current and microwave performance of InGaAs/InAsP composite channel HEMTs on gate length is presented experimentally. Composite channel HEMTs with gate length from 1.13 μm to 0.15 μm were fabricated. Device characterization results showed the extrinsic transconductance increased from 498 mS/mm for 1.13 μm devices to 889 mS/mm for 0.15 μm gate devices, while the unity current gain cutoff frequency increased from 24 GHz to 190 GHz. A simple delay time analysis is employed to extract the effective carrier velocity (v_{eff}) of the composite channel. The v_{eff} is determined to be 1.9×10^7 cm/s. To our knowledge, this is the first systematic study on gate length scaling effect of composite channel HEMTs.
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Keywords: InP; InAsP; High electron mobility transistors; Composite channel

1. Introduction

InP-based InAlAs/InGaAs high electron mobility transistors (HEMTs) have demonstrated excellent high frequency and low noise performances. However, because of the small band gap of InGaAs channel, they suffer from strong impact ionization in the channel layer such as kink effect and low on-state breakdown voltage. To improve the device breakdown performance, larger bandgap materials such as InP and InAsP have been used as the channel materials for HEMT devices [1–3]. However, the electron mobility in InP and InAsP is lower than that in InGaAs. Therefore, to utilize the high mobility in InGaAs and high breakdown field in InP and InAsP, composite channel HEMTs in which the channel is consisted of InGaAs with high mobility and a sub-channel with high breakdown field have been proposed to improve the breakdown voltage and power performance [4–8]. Under a low electric field, electron transport is confined in the high mobility InGaAs main channel. Under a high electric field, electrons gain enough energy to transfer into the sub-channel, which has a larger bandgap thus higher breakdown field. Materials that have been considered for the sub-channel include InP [4], InAsP [5] and InGaAs with lower indium composition [6]. InP so far has received most of the research attention [4,7,8]. However, InAsP is more preferable as 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 optimize device performance. We have reported 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 with a unity current gain cutoff frequency (f_T) of 115 GHz [9]. In this paper, we present a systematic study on the gate length scaling of $In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs. The performances of device with gate lengths ranging from

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1.13 μm to 0.15 μm are reported. Electron saturation velocity is extracted and compared based on the delay time analysis.

2. Device structure and fabrication

The epilayer structure in this study was grown by a 2-inch Varian Gen II molecular beam epitaxy (MBE) system at a substrate temperature of 520 °C. Molecular forms of As_2 and P_2 were generated from valved cracker sources for arsenic and phosphorus, respectively. On the Fe-doped semi-insulating (1 0 0) InP substrate, an $In_{0.52}Al_{0.48}As$ buffer with InGaAs/InAlAs superlattices was first grown. The channel consisted of, from bottom to top, 40 Å of strained $InAs_{0.3}P_{0.7}$ doped to $2 \times 10^{18}\ cm^{-3}$, 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 ($6 \times 10^{12}\ cm^{-2}$) 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, a 400 Å heavily doped $In_{0.53}Ga_{0.47}As$ ($1 \times 10^{19}\ cm^{-3}$) cap layer was grown for Ohmic contacts. The doping in the bottom $InAs_{0.3}P_{0.7}$ 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. From the Vegard's law, the amount of compressive strain is around 0.97% at this arsenic composition. Hall measurement showed that the layer had a two-dimensional sheet carrier density of $3 \times 10^{12}\ cm^{-2}$ and a Hall electron mobility of 7300 $cm^2/V\,s$ at room temperature.

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 with Ge to Au atomic ratio of 12% were deposited by electron beam evaporation and annealed at 360 °C for 1 min in a furnace in N_2 ambient. Using transmission line model technique, Ohmic contact resistance is determined to be 0.03 Ω mm. The specific contact resistivity is $1.2 \times 10^{-7}\ \Omega\,cm^{-2}$. Mushroom shaped gate with different lengths were patterned using a tri-layer resist scheme by electron beam lithography followed by a two-step gate recess etching process. The InGaAs contact cap was first etched using a 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 actual gate lengths of devices are 0.15, 0.34, 0.58, 0.85 and 1.13 μm, respectively. The devices are not passivated. The drain to source spacing is 2 μm. The device gate width is 100 μm.

3. Results and discussion

The DC characteristics of the composite channel HEMTs were measured on wafer using an Agilent 4156 Semiconductor Parameter Analyzer. Fig. 1a shows the typical *I–V* characteristics of 0.34 μm gate devices. No kink effect is observed in the *I–V* characteristics, which is a clear sign that the impact ionization in $In_{0.53}Ga_{0.47}As$ is successfully suppressed by the $In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel structure. The maximum drain current is measured to be 353 mA/mm at bias of $V_{ds} = 1.2$ V and $V_{gs} = 0.2$ V. The devices are well pinched off at $V_{gs} = -0.5$ V. Extrinsic transfer characteristic at $V_{ds} = 1$ V for a device with 0.34 μm gate length is shown in Fig. 1b. The threshold voltage, which is defined as the gate–bias intercept by linearly extrapolating drain current curve from the peak g_m position in transfer characteristics, is determined to be −0.32 V. The DC parameters of devices with different gate lengths are compared. When the gate length shrank from 1.13 μm to 0.15 μm, the maximum current increased from 179 mA/mm (bias at $V_{ds} = 2$ V, $V_{gs} = 0.2$ V) to 421 mA/mm (bias at $V_{ds} = 1$ V, $V_{gs} = 0.2$ V). The threshold voltage shifted from −0.14 V to −0.32 V. Fig. 2 shows the dependence of maximum extrinsic transconductance (g_m) on gate. The peak g_m values range from

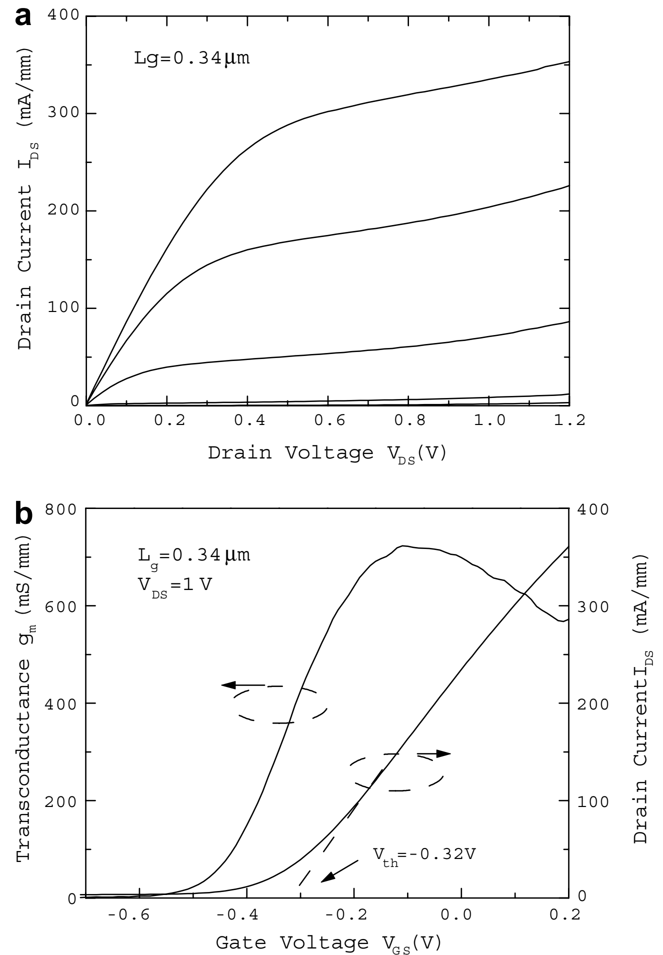

Fig. 1. (a) The current–voltage characteristics of a typical composite channel HEMT with $L_g = 0.34$ μm and $W_g = 100$ μm. The gate–bias was swept from −0.6 V to 0.2 V in a step of 0.2 V. (b) Extrinsic transfer characteristics of a typical composite channel HEMT with $L_g = 0.34$ μm and $W_g = 100$ μm at $V_{ds} = 1$ V.

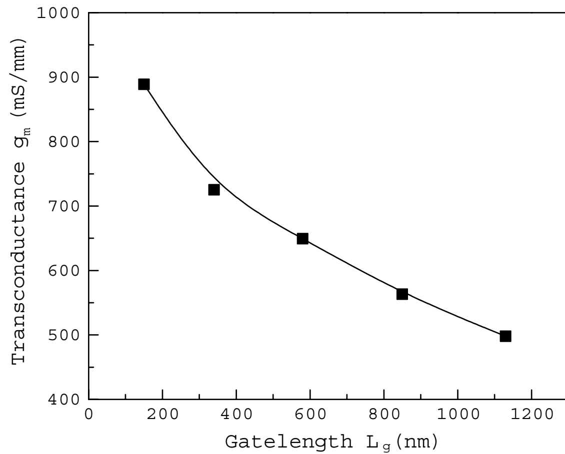

Fig. 2. Dependence of peak extrinsic transconductance on gate length.

498 mS/mm for 1.13 μm devices to 889 mS/mm for 0.15 μm devices.

The microwave characterization of the devices was performed on-wafer by *S*-parameter measurement with an Agilent 8510C network analyzer from 1 GHz to 40 GHz. The f_T and maximum oscillation frequency (f_{max}) were determined by extrapolating the $|H_{21}|^2$ and maximum available gain (MAG)/maximum stability gain (MSG) at a −20 dB/decade slope using least square fitting. Fig. 3 shows the dependence of f_T and f_{max} on gate length. The f_T increases exponentially from 24 GHz to 190 GHz with the gate length decreasing from 1.13 μm to 0.15 μm. The f_{max} values range from 54 GHz to 150 GHz for devices with the same gate length range. The inset is a typical microwave characteristics with $f_T = 86$ GHz and $f_{max} = 110$ GHz for the 0.34 μm gate length devices.

To estimate the saturation electron velocity in the composite channel layer, a simple delay time analysis is employed [10]. The total delay time τ_{total} can be calculated by:

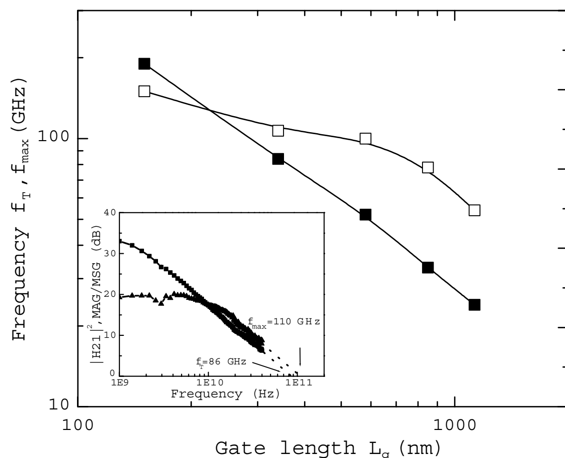

Fig. 3. Dependence of f_T (filled) and f_{max} (hollow) on gate length. Inset: microwave performance of 0.34 μm gate length HEMT. Extrapolation at 20 dB/decade gives $f_T = 86$ GHz and $f_{max} = 110$ GHz.

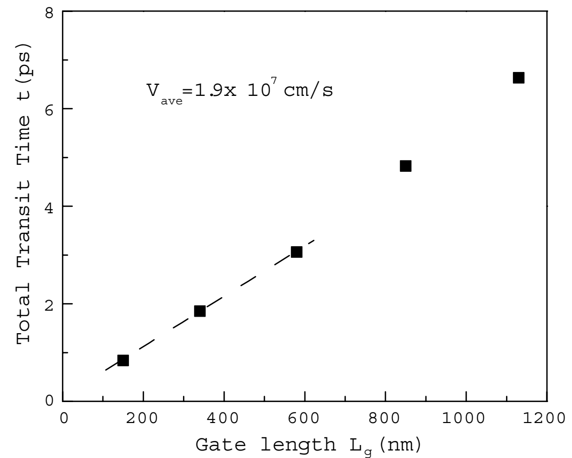

Fig. 4. Dependence of total delay time on gate length of InGaAs/InAsP composite channel HEMTs.

$$\tau_{total} = \frac{1}{2\pi f_T} = \tau_{cc} + C_{gd}(R_s + R_d) + \frac{\Delta L}{v_{eff}} + \frac{L_g}{v_{eff}} = \tau_{ex} + \frac{L_g}{v_{eff}}. \quad (1)$$

Here ΔL is the extension of the effective gate length and is treated as a constant in this range of gate length, v_s is the effective carrier velocity in the channel, τ_{cc} is the channel charging time, and C_{gd} is the feed back capacitance and the R_s and R_d are parasitic source and drain resistance. By plotting the $\frac{1}{2\pi f_T}$ as a function of gate length, we can extract the effective carrier velocity (v_s) and τ_{ex} from the slope and intercept of linear fitting. Fig. 4 shows the dependence of τ_{total} on gate length. In the $In_{0.52}Ga_{0.48}As/InAs_{0.3}P_{0.7}$ composite channel, a larger critical field is expected than that in $In_{0.52}Ga_{0.48}As$ (∼5 kV/cm). So, the onset gate length of the saturation velocity model could be much shorter than the case of $In_{0.52}Ga_{0.48}As$ channel [11]. The τ_{total} for 0.15, 0.34 and 0.58 μm gate devices were used in the calculation. The v_s is estimated to be 1.9×10^7 cm/s, while τ_{ex} is 0.74 ps. Despite the excellent f_T and f_{max} performance, as expected, the effective carrier velocity of our $In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs is lower than the reported value (2.7×10^7 cm/s) for lattice-matched $In_{0.53}Ga_{0.47}As$ single-channel HEMTs [10,12], but close to the reported value (2.1×10^7 cm/s) for pseudomorphic $InAs_{0.6}P_{0.4}$ single-channel devices [1]. It is most likely due to the n-type doping in the bottom layer of composite channel, which introduces ionized impurity scattering.

4. Conclusion

The dependence of direct current and microwave performance of $In_{0.53}Ga_{0.47}As/InAs_{0.3}P_{0.7}$ composite channel HEMTs on gate length is presented. Composite channel HEMTs with gate lengths from 1.13 μm to 0.15 μm have been fabricated and characterized. The devices exhibited an extrinsic transconductance of 498 mS/mm for 1.13 μm devices, and 889 mS/mm for 0.15 μm devices. The f_T values

range from 24 GHz to 190 GHz and the f_{max} values are in the range of 54–150 GHz. The effective carrier velocity extracted based on the delay time method is 1.9×10^7 cm/s. To our knowledge, this is the first report of gate length scaling study on the performance of composite-channel HEMTs.

Acknowledgement

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