$In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ Pseudomorphic HEMT's on InP

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***Abstract*— The dc and microwave performance of an InAs channel HEMT is reported. Room-temperature electron mobility as high as 20 200 cm^2/Vs is measured, with a high carrier concentration of 2.7×10^{12} cm^{-2}. DC extrinsic transconductance of 714 mS/mm is measured and a unity-current-gain cut-off frequency of 50 GHz is obtained for a 1.1-μm gate length HEMT. The success of achieving superior Hall mobility and device performance is strongly dependent on the $In_xAl_{1-x}As$ buffer layer design that changes the lattice constant from lattice-matched $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$. The multiple $In_{0.52}Al_{0.48}As$/InAs monolayer superlattices buffer achieves the best performance as compared to the step-graded $In_xAl_{1-x}As$ and the uniform $In_{0.75}Al_{0.25}As$ buffer.**

I. INTRODUCTION

RECENTLY, InP-based $In_{0.53+x}Ga_{0.47-x}As/In_{0.52}Al_{0.48}As$ pseudomorphic high-electron-mobility-transistors (HEMT's) [1]–[6] have demonstrated superior high-frequency performance relative to other field-effect transistors (FET's) at equal gate length (L_g). It is shown both theoretically and experimentally that the performance can be further improved with increasing In composition in the $In_{0.53+x}Ga_{0.47-x}As$ channel, which are due to the lower electron effective mess, higher electron mobility and peak velocity, and better carrier confinement in the quantum well. Therefore record high unity-current-gain cut-off frequency (f_T) and f_T–L_g product of 340 GHz [2] and 57 GHz-μm [1] have been achieved in $In_{0.8}Ga_{0.2}As$ channel and $In_{0.77}Ga_{0.23}As/In_{0.25}Ga_{0.75}$ strain compensated channel, respectively. It is expected that the high-speed performance can be further improved if an InAs channel is used. However, the large lattice-mismatch between InAs channel and InP substrate is beyond the capability of our previous reported strain-compensated design [1], [7], [8], and three-dimensional (3-D) growth is generated. This rough growth front not only increases the interface roughness but also decreases both electron mobility and velocity, which may result in a degraded device performance.

In this letter, we present the successful growth of InAs channel HEMT structure. Room-temperature mobility of 20 200 cm^2/Vs is measured, with a carrier concentration of 2.7×10^{12} cm^{-2}. The merit of the InAs channel design is further confirmed by the high f_T of 50 GHz in a 1.1-μm device. Both the mobility and f_T are improved to the previous strain-compensated $In_{0.8}Ga_{0.2}As/In_{0.25}Ga_{0.75}As$ channel design.

II. DEVICE STRUCTURE AND FABRICATION

Our samples were grown in a molecular beam epitaxy (MBE) system. Typical growth rates were 0.8 μm/h for both $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$. The layer structure of InAs channel HEMT's is shown schematically in Fig. 1, which consists of a 200-nm $In_{0.52}Al_{0.48}As$ lattice-matched to InP, a 200-nm $In_xAl_{1-x}As$ buffer, an active channel, a 4-nm $In_{0.52}Al_{0.48}As$ spacer, a 4-nm $n^+ - In_{0.52}Al_{0.48}As$ donor layer, a 20-nm $In_{0.52}Al_{0.48}As$ Schottky layer and a 4-nm $n^+ - In_{0.75}Ga_{0.25}As$ ohmic contact layer. The active channel contains a 7-nm InAs layer, with two 1.5-nm $In_{0.75}Ga_{0.25}As$ interface smooth layers. The $In_xAl_{1-x}As$ buffer is used to transfer lattice constant from that of $In_{0.52}Al_{0.48}As$ to $In_{0.75}Al_{0.25}As$. Three buffers are designed to study the electron mobility and interface roughness: Structure 1 consists of a uniform $In_{0.75}Al_{0.25}As$; Structure 2 consists of a step-graded 60-nm $In_{0.59}Al_{0.41}As$/70-nm $In_{0.67}Al_{0.33}As$/70-nm $In_{0.75}Al_{0.25}As$; Structure 3 consists of multiple $In_{0.52}Al_{0.48}As$/InAs monolayer superlattices. Hall measurement was used to investigate the electron mobility and the carrier density of the HEMT structure. The HEMT's were fabricated by standard photolithography and lift-off techniques. Source and drain were formed by Ge/Au/Ni/Ti/Au (70/140/50/20/70-nm) ohmic contacts after mesa isolation. Next, the gate recess was carried out by a H_3PO_4: H_2O_2: H_2O slow etching solution. The recess was controlled by the source-drain currents. Finally, gate was formed by Ti (10-nm)/Au (300-nm) and device was completed by a second mesa etch to remove the overlap between gate and channel. The gate length was measured by a scanning electron microscope. Devices were measured by using a semiconductor parameter analyzer and a network analyzer.

III. RESULTS AND DISCUSSION

The measured Hall data for three different $In_xAl_{1-x}As$ buffers are summarized in Table I. Structure 1 with a uniform $In_{0.75}Al_{0.25}As$ buffer shows a degraded electron mobility of 5800 cm^2/Vs as compared to lattice-matched $In_{0.53}Ga_{0.47}As$ channel, which has a typical value of 10 000–11 000 cm^2/Vs [2], [8] at the same carrier density. This is due to the strain-induced 3-D growth and rough interface of $InAs/In_{0.52}Al_{0.48}As$. Although the step-graded

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4 nm	**$In_{0.75}Ga_{0.25}As$**
20 nm	**$In_{0.52}Al_{0.48}As$**
4 nm	**n^+-$In_{0.52}Al_{0.48}As$**
4 nm	**$In_{0.52}Al_{0.48}As$**
1.5 nm	**$In_{0.75}Ga_{0.25}As$**
7 nm	**InAs**
1.5 nm	**$In_{0.75}Ga_{0.25}As$**
200 nm	**$In_xAl_{1-x}As$ buffer**
200 nm	**$In_{0.52}Al_{0.48}As$**
	S.I InP

Fig. 1. Layer structure of $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT's. The $In_xAl_{1-x}As$ buffer changes In composition from 0.52 to 0.75: Structure 1: uniform $In_{0.75}Al_{0.25}As$; Structure 2: graded 60-nm $In_{0.59}Al_{0.41}As$/70-nm $In_{0.67}Al_{0.33}As$/70-nm $In_{0.75}Al_{0.25}As$; Structure 3: multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices.

TABLE I

MEASURED HALL DATA FOR $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ PSEUDOMORPHIC HEMT'S WITH DIFFERENT $In_xAl_{1-x}As$ BUFFER DESIGN

	Mobility (cm^2/Vs)		Carrier density (cm^{-2})	
$In_xAl_{1-x}As$	300K	77K	300K	77K
Structure 1	5,800	24,000	$1.7x10^{12}$	$1.2x10^{12}$
Structure 2	11,900	51,000	$2.1x10^{12}$	$1.7x10^{12}$
Structure 3	20,200	128,000	$2.7x10^{12}$	$2.6x10^{12}$

1. uniform $In_{0.75}Al_{0.25}As$
2. graded 60-nm $In_{0.59}Al_{0.41}As$/70-nm $In_{0.67}Al_{0.33}As$/70-nm $In_{0.75}Al_{0.25}As$
3. multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices

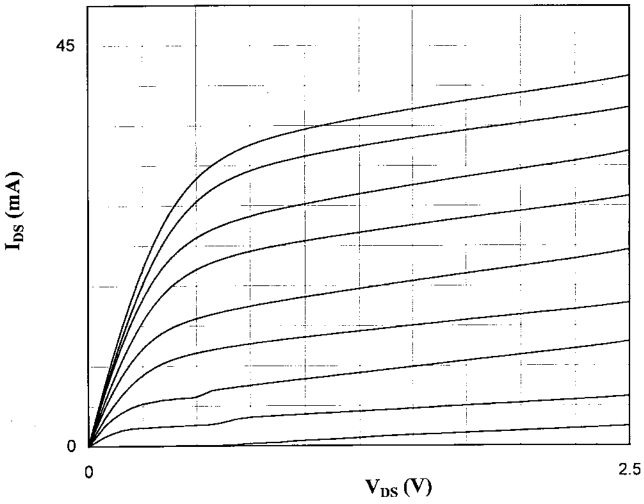

Fig. 2. I–V characteristics of a typical 1.1-μm $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT with multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices buffer ($V_{GS} = -0.2$ V/step, 0.4-V top curve).

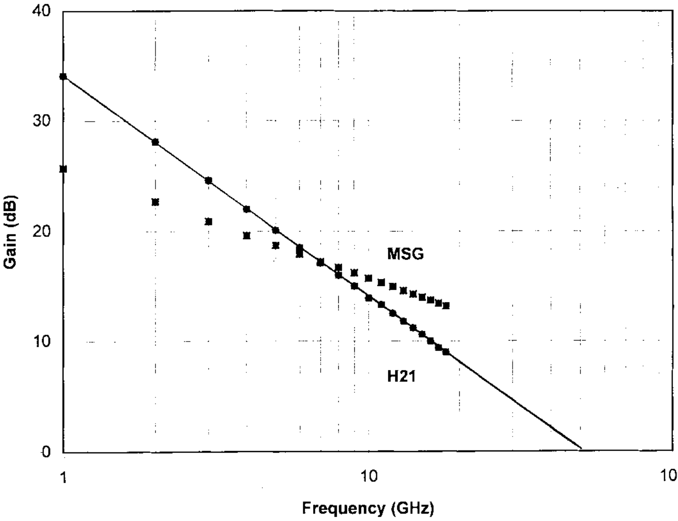

Fig. 3. Gain versus frequency for a typical 1.1-μm $In_{0.52}Al_{0.48}As/InAs/In_xAl_{1-x}As$ pseudomorphic HEMT with multiple $InAs/In_{0.52}Al_{0.48}As$ monolayer superlattices buffer.

$In_xAl_{1-x}As$ buffer (Structure 2) shows improved mobility of 11 900 cm^2/Vs, this value is still far below the mobility of 15 200 cm^2/Vs in a $In_{0.8}Ga_{0.20}As/In_{0.25}Ga_{0.75}As$ channel design [7], [8]. In contrast, significant improvement of electron mobility is achieved by using the multiple $In_{0.52}Al_{0.48}As/InAs$ monolayer superlattices buffer (Structure 3), and a mobility of 20 200 cm^2/Vs is obtained. The measured carrier density of HEMT with $In_{0.52}Al_{0.48}As/InAs$ monolayer superlattices buffer is 2.7×10^{12} cm^{-2}, which is also the highest value as compared to the other two structures. The higher carrier density in this structure may be due to the reduced traps/deep levels in the $In_xAl_{1-x}As$ buffer, which is also confirmed from the negligible carrier density change between room-temperature and 77 K. Possible reason for achieving good Hall data may be due to that the strained monolayer superlattice can preserve a relatively smooth growth front and reduced deep recombination levels. Similar effect was also reported in InAs/InGaAs short-period superlattice [8]. However, due to the limited improvement of 77 K mobility of 128 000 cm^2/Vs in InAs channel (Structure 3) to 123 100 cm^2/Vs in $In_{0.80}Ga_{0.20}As/In_{0.25}Ga_{0.75}As$ [7], [8], there is still interface roughness in $In_{0.52}Al_{0.48}As/InAs$ that limits the 77 K mobility.

We have used the structure of InAs channel with high electron mobility $InAs/In_{0.5}Al_{0.5}As$ buffer to fabricate devices. Fig. 2 shows the room-temperature drain I–V characteristics of a 1.1×50-μm^2 gate HEMT. The device did not show a complete pinch-off, which may be due to either the buffer leakage or the impact ionization in small bandgap InAs. However, it has also reported that the pinch-off characteristic is related to the gate recess, [1] and a low-temperature grown buffer can suppress the buffer leakage. Further detailed analysis is required to identify the leakage mechanism. The device has a peak extrinsic transconductance (g_m) of 714 mS/mm, and small kinks in I–V curves are only observed at low device currents. Because the measured extrinsic g_m is strongly related to the recess depth and gate-to-channel capacitance (C_{gs}), therefore RF measurement is required to further characterize the device performance. Microwave characterization was performed from 0.1 to 18 GHz using a CASCADE on-wafer probe and network analyzer. Fig. 3 shows the calculated current gain (H_{21}) and maximum stable gain (MSG) from measured S-parameters. The device was biased at $V_{\mathrm{ds}} = 2.5$ V and $V_{\mathrm{gs}} = -0.3$ V. An extrapolated f_T of 50 GHz is obtained from the 1.1-μm gate length device, which demonstrate the excellent RF performance of device. It is not surprising that the HEMT's fabricated using InAs channel have superior f_T, which is primary dominated by the small electron effective mass in InAs than that of $\mathrm{In}_{0.53+x}\mathrm{Ga}_{0.47-x}\mathrm{As}$ channel [1]–[6].

IV. CONCLUSIONS

We have investigated the InAs channel HEMT's grown on InP. The $\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As/InAs}$ monolayer superlattice buffer achieves the best Hall mobility by changing the lattice constant from lattice-matched $\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}$ to $\mathrm{In}_{0.75}\mathrm{Al}_{0.25}\mathrm{As}$. Room-temperature electron mobility as high as 20 200 cm^2/Vs is measured, with a high carrier concentration of 2.7×10^{12} cm^{-2}. DC extrinsic transconductance of 714 mS/mm is measured and a f_T of 50 GHz is obtained for a 1.1-μm gate length HEMT.

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