f_{max} = 433GHz from 0.1 ㎛ Γ-gate InGaAs/InAlAs/GaAs Metamorphic HEMTs

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Abstract — **In this work, we present the characteristics of the 0.1 ㎛ gate length InGaAs/InAlAs/GaAs metamorphic high electron mobility transistors (MHEMTs). The MHEMTs with Γ-shaped off-set gates (70 ㎛ width and 2 fingers) were fabricated using the double heterostructure epitaxial structure and characterized through the DC, Noise and RF measurements. Measured channel current density and transconductance (g_m) were 442 mA/mm and 409 mS/mm, respectively. Noise characteristics were measured in the frequency range from 50 GHz to 61 GHz, and show 1.8 dB at 50GHz. From RF measurements, 154 and 433 GHz were obtained for the cut-off frequency (f_T) and maximum frequency of oscillation (f_{max}), respectively. A superior f_{max} of 433 GHz achieved in the work is one of the first reports among the fabricated 0.1 ㎛ gate length MHEMTs.**

I. INTRODUCTION

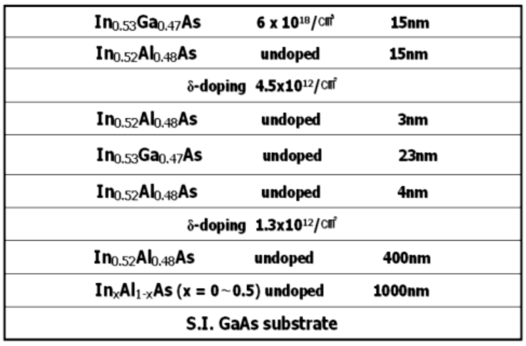
It is well known that InP-based HEMTs have better device performances than GaAs-based PHEMTs [1~4]. Excellent device performances of the InP-based HEMTs operating in W-band are mostly based on InAlAs/InGaAs /InP material system. However, InP-based wafers are more expansive and brittle than GaAs-based ones. And further-more production yields of InP HEMTs are lower because etching rates of InP-based materials are slower. In order to overcome these demerits, GaAs-based metarmorphic HEMTs (MHEMTs) have proposed because performance of GaAs-based MHEMTs is comparable with those of InP-based HEMTs.

In recent decades, active research efforts have been therefore made on GaAs-based metamorphic HEMTs (MHEMTs) to address the needs for both high microwave performance and low device cost. A use of metamorphic buffers on GaAs substrates is introduced to accommodate the lattice mismatch between the substrate and the active layers as well as to avoid InP substrates. By using the metamorphic buffers, unstrained InAlAs/-InGaAs heterostructures can be grown in a wide window of indium content for InGaAs channels, thereby exhibits comparable device performances with those of InP-based HEMTs. For examples, excellent maximum frequency of oscillation (f_{max}) results of 200 ~ 400 GHz have been introduced in recent MHEMTs adopting 0.1 ~0.2 ㎛ gate lengths [5~8]. Noise figures (NF) of 1.2 ~ 1.8 dB measured at 30 GHz have been also demonstrated in the MHEMTs by the recent works of Yoon [8] and Whelan [9].

In this paper, we present the high performance GaAs-based InGaAs/InAlAs MHEMTs which adopt a off-set Γ-shaped gate structure of 0.1 ㎛ gate length and double - doped epitaxial heterostructures with the metamorphic buffer of graded indium composition (0 ~ 0.5) in $In_xAl_{1-x}As$.

II. EPITAXIAL STRUCTURE AND DEVICE PROCESSING

GaAs-based epitaxial structures for MHEMTs were grown on 4-inch semi-insulating (SI) (100) GaAs substrates by molecular beam epitaxy (MBE).



$In_{0.53}Ga_{0.47}As$	6×10^{18}/㎠	15nm
$In_{0.52}Al_{0.48}As$	undoped	15nm
δ-doping	4.5×10^{12}/㎠	
$In_{0.52}Al_{0.48}As$	undoped	3nm
$In_{0.53}Ga_{0.47}As$	undoped	23nm
$In_{0.52}Al_{0.48}As$	undoped	4nm
δ-doping	1.3×10^{12}/㎠	
$In_{0.52}Al_{0.48}As$	undoped	400nm
$In_xAl_{1-x}As$ (x = 0~0.5)	undoped	1000nm
S.I. GaAs substrate		

Fig. 1. Epitaxial structures of InGaAs/InAlAs/GaAs MHEMTs with double delta dopings

A cross-sectional schematic of the grown structure is shown in Fig. 1. 1 ㎛ thick $In_xAl_{1-x}As$ graded buffer layers were grown on SI GaAs substrates by varying the indium mole fraction from 0 to 50 %, thereafter 400 nm-thick $In_{0.52}Al_{0.48}As$ buffers were grown to protect active layers from the potential impurities coming from the underlying structures. A top the buffers, the active layers with 23 nm $In_{0.53}Ga_{0.47}As$ channel layers were grown with the double Si δ-dopings. Very thin n^+ $In_{0.53}Ga_{0.47}As$ cap layers were then grown to provide ohmic contacts at the source and drain regions. Measured electron sheet density and Hall mobility of the grown epitaxial layers at room temperature are about 3.4×10^{12} /cm^2 and 9700 cm^2/V·sec, respectively.

Fig. 2 shows a plane view of the fabricated Γ-shaped off-set gate MHEMTs with an unit gate width of 70 ㎛ and 2 gate fingers (hereafter we call it 70×2 ㎛). In the structure, the gate electrode is located at an off-set position from the center toward the source [10].

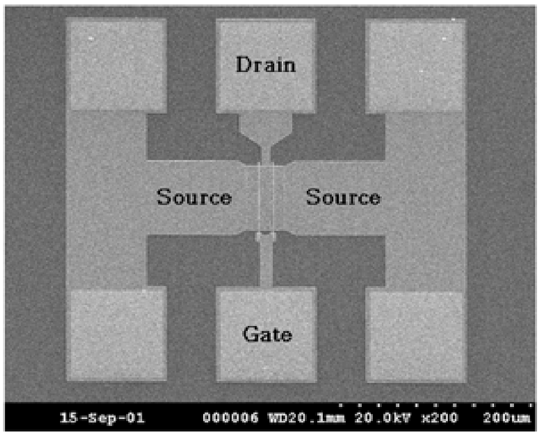


Fig. 2. Plane view of a typical MHEMT with a 0.1㎛ gate length (70x2 ㎛ gate fingers)

The structural improvement of the off-set gate by reducing the distance between the source and the gate enhances the f_T and the maximum stable gain (MSG) by minimizing the gate-to-drain capacitance (C_{gd}) as well as the drain resistance (R_d) [11]. In our devices, the spacings between source and drain and source and gate foot were 3 and 1.3 ㎛, respectively.

The MHEMTs were fabricated in the following sequences. First, mesa etching was performed to provide isolated active areas by removing 200 nm thickness in an etchant of phosphoric acid/H_2O_2/H_2O (1:1:60) followed by the formation of ohmic contacts using the thermal evaporation of AuGe/Ni/Au (125/28/160 nm) layers and the rapid thermal annealing at 320 ℃ for 30 sec. The measured specific contact resistance of the ohmic contacts was $\sim 1\times10^{-7}\ \Omega\cdot\text{cm}^2$. Gate recess was done by etching the cap layers in a phosphoric acid /H_2O_2/H_2O (1:1:1000) solution.

0.1 ㎛ Γ-shaped gate was patterned by the lift-off with the PMMA/P(MMA-MAA)/PMMA(100/600/200 nm) using an 30 keV electron beam lithography system. Schottky contacts were formed by Ti/Au(50/400 nm) evaporation. Prior to the air-bridge interconnection, 78 nm Si_3N_4 passivation layers were deposited in a plasma enhanced chemical vapor deposition (PECVD) system. A perspective view of the fabricated MHEMT gate with the Si_3N_4 passivation layer is shown in Fig. 3.

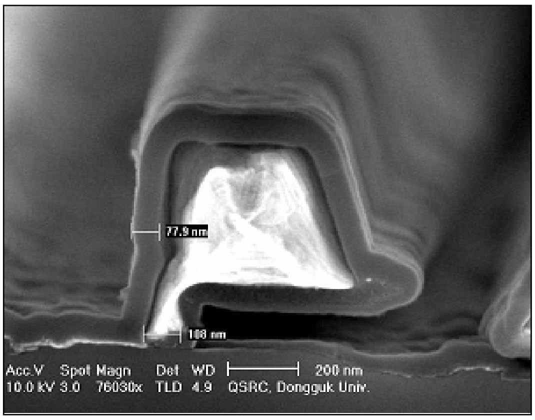


Fig. 3. SEM micrograph of the fabricated 0.1 ㎛ Γ-gate

III. DC AND MILLIMETER-WAVE CHARACTERISTICS

The fabricated 70x2 ㎛ MHEMTs with a 0.1 ㎛ gate length were characterized by measuring the DC, noise and RF performances. DC characteristics, such as I-V and g_m, were measured in a HP4156A DC parameter analyzer, and the measurement results of the MHEMTs with a 3 ㎛ source-drain spacing are shown in Fig. 4 and Fig. 5, respectively.

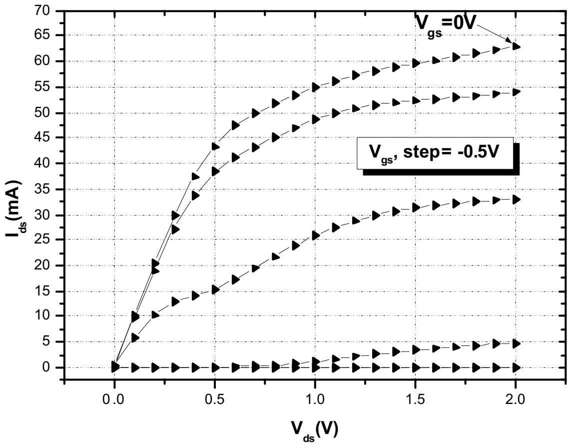


Fig. 4. Drain current (I_{ds}) as a function of source-to-drain voltage(V_{ds})

As shown in Fig. 4, typical saturation drain-source current (I_{dss}) and pinch-off voltage (V_p) of the fabricated devices were 62 mA (442 mA/mm) and -1.7 V, respectively. The breakdown voltage (V_{br}) of the device (source-drain spacing of 3 ㎛) was about 3 V.

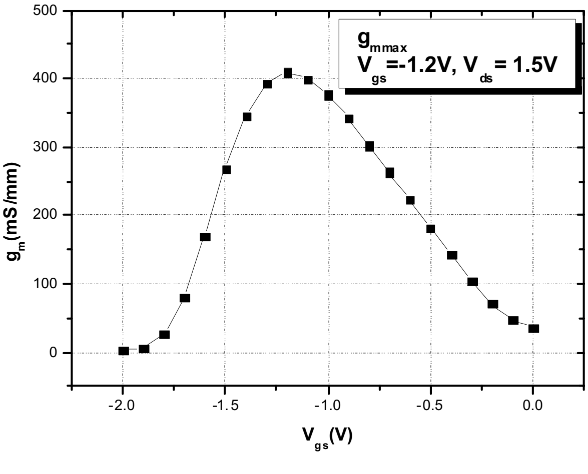


Fig. 5. Extrinsic transconductance (g_m) as a function of source-to-gate voltage (V_{gs})

The measured maximum extrinsic transconductance (g_{mmax}) was 409 mS/mm at a drain voltage (V_d) of 1.5 V and a gate voltage (V_g) of -1.2 V as shown in Fig. 5.

The RF measurements were performed in a frequency range of 0.5 ~ 50 GHz using a HP 8510C network analyzer.

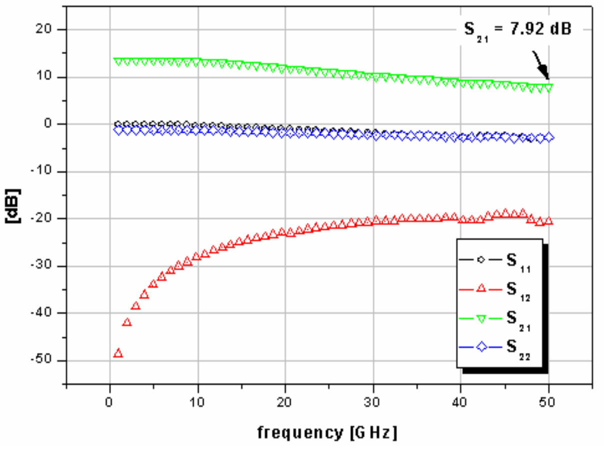


Fig. 6. S_{21} gain characteristics of the MHEMTs

As shown in Fig. 6, a high S_{21} gain (7.92 dB) was obtained at a millimeter-wave frequency of 50 GHz. Shown in Fig. 7 are the measured h_{21} gain, S_{21} gain and the maximum stable gain (MSG) versus the frequency obtained from the MHEMTs. And in Fig. 7, The devices exhibit a f_T of 154 GHz and a f_{max} of 433 GHz, respectively, from the extrapolation of h_{21} and MSG for a device biased at a peak transconductance.

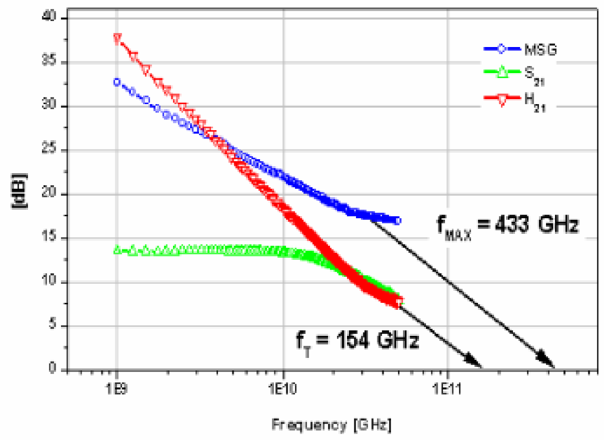


Fig. 7. f_T and f_{max} characteristics of the MHEMTs

The measured f_{max} of 433 GHz is one of the best data reported in 0.1 ㎛ MHEMTs thus far [5,6], which are responsible for the optimized structures including the epitaxial layers and off-set gate geometry as well as our process maturity.

Noise characteristics of the fabricated MHEMTs were also measured using a HP 8970B noise figure meter in a frequency range of 50 ~ 62 GHz, and a very low noise figure less than 3 dB was obtained as shown in Fig. 8.

IV. CONCLUSION

0.1 ㎛ gate length MHEMTs with a off-set Γ-gate structure were fabricated using a InGaAs/InAlAs metamorphic epitaxial structures grown on GaAs substrates, and were characterized through the DC, RF and noise measurements. Measured channel current density and g_m were 442 mA/mm and 409 mS/mm, respectively. From the RF measurements, 154 and 433 GHz were obtained for f_T and f_{max}, respectively. The f_{max} measured from our devices is one of the best performances reported among the 0.1 ㎛ gate length MHEMTs operating in millimeter wave frequency range. A very low noise figure less than 3 dB in a frequency range of 50 ~ 63 GHz was also obtained from the fabricated MHEMTs.

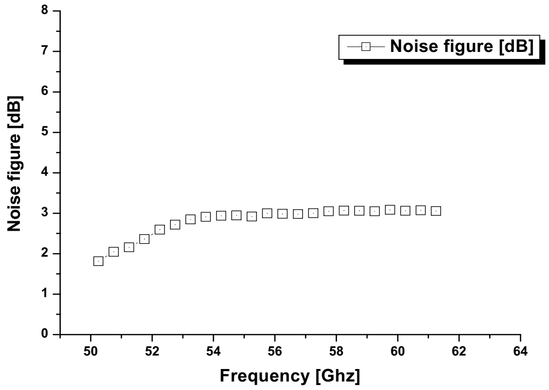


Fig. 8. Noise figure versus the frequency of the MHEMTs with a source-drain spacing of 3 ㎛

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REFERENCES

[1] L. D. Nguyen, A.S. Brown, M.A. Thompson, and L.M Jelloian, “50 nm Self-Aligned Gate Pseudomorphic AlInAs/GaInAs High Electron Mobility Transistors.” *IEEE Trans. Electron Devices*, vol. 39, no. 9, pp. 2007-2014, Sept. 1992.

[2] M. Wojtowicz, R.Lai, D.C. Streit, G.I. Ng, T.R. Block, K.L. Tan, P.H. Liu, A.K. Freudenthal, and R.M. Dia, “0.10㎛ Graded InGaAs Channel InP HEMT with 305 GHz f_T and 340 GHz f_{max},” *IEEE Electron Device Lett.* vol. 15, pp. 477-479, Nov. 1994.

[3] A Endoh, Y. Yamashita, M. Higashiwaki, K. Hikosaka, M. Mimura, S. Hiyamizu, and T. Maysui, “ High f_T 50-nm-Gate Lattice-Matched InAlAs/InGaAs HEMTs,” *12th Int. Conf. on InP and Related Mtls.*, pp. 87-89, 2000

[4] P. M. Smith, S.M.J. Riu, M.Y. Kao, P. Ho, S.C. Wang, K.H.G. Duh, S.T. Fu and P.C. Chao, “W-band High Efficiency InP-Based Power HEMT with 600 GHz f_{max},” *IEEE Microwave and Guided wave Lett.*, vol. 5, no. 7, pp. 230-232, July. 1995.

[5] D. C. Dumka, W. E. Hoke, P. J. Lemonias, G.Cueva, and I.Adesida,”Metamorphic$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT on GaAs substrate with fT over200GHz”, *IEEE IEDM*, 783, 1999

[6] C. S. Whelan, W. E. Hoke, R. A. McTaggart, P. S. Lyman, P. F. Marsh, R. E. Leoni III, S. J. Lichwala, and T. E. Kazior, "High breakdown voltage InAlGaAs/$In_{0.32}Ga_{0.68}$ As metamorphic HEMT for microwave and mm-wave power applications", *IEEE MTT-s Digest*,1187, 1999

[7] C. Gassler, V. Ziegler, C. Wolk, R. Deufel, F. –J. Berlec, "Metamorphic HFETs on GaAs with InP-subchannels for device performance improvements",*IEEE IEDM*, 11, 2000

[8] H. S. Yoon, J. H. Lee, J. Y. Shim, S. J. Kim, D. M. Kang, J. Y. Hong, W. J Chang, K. H Lee, "Low noise characteristics of double-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}$ As power metamorphic HEMT on GaAs substrate with wide head T-shaped gate," *Indium Phosphide and Related Materials*, 201, 2002

[9] C. S. Whelan, W. F. Hoke, R. A. McTaggart, M. Lardizabal, P. S. Lyman, P. F. Marsh, T.E. Kazior, "Low noise $In_{0.32}(AlGa)_{0.68}As/In_{0.43}Ga_{0.57}As$ metamorphic HEMT on GaAs substrate with 850 mW output power density," *IEEE Electron Device Letters* , 21, 5, 2000

[10] W. S. Sul. D.H. Shin and J.K. Rhee, "Sub 0.1 μm asymmetric Γ-gate PHEMT process using electron beam lithography," *in proceedings of Materials Research Society 2002 Spring Meeting*, San Francisco, CA, p. 169, Apr. 2002.

[11] Suemitsu T, Enoki T, Yokoyama H, Ishii Y, "Improved recess-gate structure for sub 0.1 ㎛ gate InP-based HEMTs," *Japanese Journal of Applied Physics*, 37, 1365. 1998