Article

High-Performance InGaAs HEMTs on Si Substrates for RF Applications

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Abstract: In this paper, we have fabricated InGaAs high-electron-mobility transistors (HEMTs) on Si substrates. The InAlAs/InGaAs heterostructures were initially grown on InP substrates by molecular beam epitaxy (MBE), and the adhesive wafer bonding technique was employed to bond the InP substrates to Si substrates, thereby forming high-quality InGaAs channel on Si. The 120 nm gate length device shows a maximum drain current ($I_{D,max}$) of 569 mA/mm, and the maximum extrinsic transconductance ($g_{m,max}$) of 1112 mS/mm. The current gain cutoff frequency (f_T) is as high as 273 GHz and the maximum oscillation frequency (f_{MAX}) reaches 290 GHz. To the best of our knowledge, the $g_{m,max}$ and the f_T of our device are the highest ever reported in InGaAs channel HEMTs on Si substrates at given gate length above 100 nm.

Keywords: InGaAs HEMTs; Si substrates; wafer bonding; maximum extrinsic transconductance ($g_{m,max}$); current gain cutoff frequency (f_T)

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1. Introduction

The advancement of Si CMOS technology has brought revolutionary changes to microelectronics. Although Si has proven to be very suitable for digital processing and logic applications, it is not omnipotent. Limited by the inherent physical characteristics of the material, Si is inferior to some other materials such as III–V compound semiconductors in high-frequency applications.

InGaAs displays outstanding carrier transport properties including high electron effective mobility and high sheet carrier density, compared with Si-based materials. InGaAs channel high-electron-mobility transistors (HEMTs) have been used in millimeter-wave and even terahertz monolithic integrated circuits [1–4]. They play key roles in radio-astronomy and deep-space communication. InGaAs channel HEMTs are typically manufactured on either InP or GaAs substrates in commercial production. However, ideally InGaAs channel HEMTs should be integrated on Si substrates to utilize the infrastructure and technology established by Si CMOS to improve monolithic integration and reduce costs. There have been many attempts to integrate the InGaAs channel material on Si substrates. X. Zhou et al. [5] used MOCVD heteroepitaxy technology to grow InGaAs channel material on Si substrate, but required buffer layer thickness greater than 2 μm to reduce dislocation density, which was difficult to be compatible with Si CMOS process. N. Waldron et al. [6] developed the aspect-ratio-trapping technique for heterogeneous integration, but the consistency and defects of the materials are difficult to manage. Recently, wafer bonding technology has been widely used to realize the integration of InGaAs channel material on Si substrates [7–10]. Compared with the aforementioned technology, wafer bonding

can more easily form a high-quality InGaAs channel layer. Heterogeneous integration of InGaAs channel logic transistors on Si substrates has been reported in many published literature [11–14]. However, InGaAs channel RF devices on Si substrates have received little attention.

In this letter, we have developed InGaAs HEMTs on Si substrates for RF applications. The transfer of III–V heterostructures from InP substrates to Si substrates was realized through adhesive wafer bonding technology. Moreover, DC and RF characteristics of the fabricated 120 nm gate length HEMTs were reported. The fabricated HEMTs show high maximum extrinsic transconductance ($g_{m,max}$) and current gain cutoff frequency (f_T) attributable to a 70% indium content in the channel and a dielectric-assisted T-gate process that strictly suppresses series resistance.

2. Experiment

InGaAs HEMTs structures layers on Si substrates were manufactured using adhesive wafer bonding technique, as illustrated in Figure 1. The inverted HEMTs structures were grown using molecular beam epitaxy (MBE) on Semi-Insulating (SI) InP substrates with a 5 nm InP buffer layer and etching stopper layers (composed of 100 nm $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and 10 nm InP) between active layers and SI InP substrates. From the InP substrates side to the top, the inverted HEMT structures composed of a 40 nm Si-doped composite InGaAs cap layer, a 4 nm InP etching stopper layer, an 8 nm $\text{In}_{0.53}\text{Al}_{0.47}\text{As}$ Schottky barrier layer, Si delta doping layer with $5 \times 10^{12} \text{ cm}^{-2}$ doping concentration, a 3 nm $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ spacer layer, a 10 nm $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ channel layer, and a 200 nm $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ buffer. To prevent interface degradation, a 30 nm SiO_2 film was deposited by using plasma-enhanced chemical vapor deposition (PECVD). After cleaning, both the InP substrate and Si substrate were coated with an adhesion promoter layer (AP 3000, Dow Chemical) and a benzocyclobutene (BCB) layer (3022-46, Dow Chemical (Midland, MI, USA)). After 15 min of pre-curing, the formal wafer bonding was performed in a nitrogen environment. Finally, the InP substrate and the etching stopper layers were etched with hydrochloric acid and phosphorus acid/hydrogen peroxide mixed solution, and the InGaAs HEMTs structures layers were completed on the Si substrate. Figure 2 shows a $10 \mu\text{m} \times 10 \mu\text{m}$ atomic force microscopy (AFM) scan of the n-InGaAs cap layer after back etching. The root mean square (RMS) roughness of the cap layer is 0.236 nm, which is much lower than that grown by MOCVD [15,16].

Figure 1. Process flow for the InGaAs HEMTs structures layers on Si substrates fabrication by using adhesive wafer bonding technique.

Figure 2. AFM images of the n-InGaAs cap layer for the scan area of $10\ \mu\text{m} \times 10\ \mu\text{m}$.

The device structure of InGaAs HEMTs on Si substrates and the band diagram of the heterojunction are shown in Figure 3. In the device fabrication, mesa isolation was achieved using phosphorus acid/hydrogen peroxide mixed solution and hydrochloric acid/phosphorus acid mixed solution by wet chemical etching. Optical lithography was used to define S/D ohmic contacts, which were made of Ti/Pt/Au metal. Afterward, as a hard mask for gate recess, around 5 nm SiO_2 was formed on the surface using PECVD. The T-shaped gating process consisted of gate e-beam lithography, SiO_2 etching, recess, and metallization. E-beam lithography was used to define the gate pattern, which was then transferred to the SiO_2 layer via reactive ion etching (RIE). The gate recess was formed by wet chemical etching with a mixture of phosphoric acid/hydrogen peroxide solution. By strictly controlling the width of the gate recess to achieve the lowest possible series resistance. The Ti/Pt/Au T-shaped gate metal was e-beam evaporated and lifted off, with the gate area defined as $2 \times (0.12 \times 50)\ \mu\text{m}^2$. Finally, as surface passivation in the active region, a 20 nm Si_3N_4 layer was formed through PECVD. The cross-sectional focused ion beam (FIB) image of the T-gate region of the fabricated HEMTs on Si substrates is shown in Figure 4. The gate length can be determined as 120 nm.

Figure 3. The schematic cross section of the passivated InGaAs HEMTs on Si substrates and the band diagram of the heterojunction.

Figure 4. Cross-sectional FIB image of 120 nm T-gate.

3. Result and Discussion

The DC performance of devices is carried out at room temperature through the HP4142 semiconductor parameter analyzer. Figure 5 shows the I_D - V_D output characteristics for a 120 nm gate length InGaAs HEMTs on Si substrates at room temperature with a gate bias from -1 V to 0 V in the step of 0.1 V. The device demonstrates superior pinch-off characteristics. The maximum drain current ($I_{D,max}$) is 569 mA/mm at $V_G = 0$ V and $V_D = 0.8$ V.

Figure 5. Output characteristics of the InGaAs HEMTs on Si substrates.

Figure 6 shows the transfer characteristic of InGaAs HEMTs on Si substrates. Benefit from an indium content of 70% in the channel, the maximum extrinsic transconductance of 1112 mS/mm was achieved at $V_G = -0.4$ V and $V_D = 0.8$ V. The threshold voltage of InGaAs HEMTs is about -0.63 V. The subthreshold-swing (S) and drain induced barrier lowering (DIBL) were 150 mV/dec and 100 mV/V, respectively.

Figure 6. Transfer characteristics of the InGaAs HEMTs on Si substrates.

Figure 7 shows the gate current leakage characteristic of the HEMTs. Although the manufactured devices exhibit sufficiently small gate leakage currents, impact ionization cannot be ignored at high V_D . Impact ionization has been shown to have a negative impact on the RF and noise characteristics of HEMTs [17]. Future experiments can suppress impact ionization by using compound channels [18].

Figure 7. Gate current leakage characteristic of the InGaAs HEMTs on Si substrates.

The RF performance of devices is carried out at room temperature through the Agilent E8363B PNA vector network analyzer from 0.1 GHz to 40 GHz. On-wafer S-parameters of the InGaAs HEMTs on Si substrates were measured and extracted. Before measurement, the devices were de-embedded by using on-wafer open and short pad structures to exclude the parasitic effect. The values of current gain (H_{21}), maximum available gain and maxi-

imum stable gain (MAG/MSG), Mason's unilateral gain (U), and stability factor (k) were calculated using the following Equations (1)–(6), and were plotted in Figure 8.

$$H_{21} = \frac{-2S_{21}}{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}, \quad (1)$$

$$\text{MAG} = \frac{|S_{21}|}{|S_{12}|} \left(k - \sqrt{k^2 - 1} \right) \quad k > 1, |\Delta| < 1 \quad (2)$$

$$\text{MSG} = \frac{|S_{21}|}{|S_{12}|} \quad k < 1, |\Delta| < 1, \quad (3)$$

$$U = \frac{|(S_{21}/S_{12}) - 1|^2}{2k|S_{21}/S_{12}| - 2\text{Re}[S_{21}/S_{12}]}, \quad (4)$$

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2 \cdot |S_{12}S_{21}|}, \quad (5)$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21}, \quad (6)$$

Figure 8. RF characteristics of the HEMTs at $V_G = -0.4$ V and $V_D = 0.8$ V.

In addition, the small-signal model of HEMTs fabricated on Si substrates was made at the $g_{m,max}$ point of $V_G = -0.4$ V and $V_D = 0.8$ V. The device modeling parameters are tweaked until the S-parameters match closely with the measured parameters, as shown in Figure 8. Since the limitation of test frequency, f_T and maximum oscillation frequency (f_{MAX}), were obtained by extrapolating the simulated curve of H_{21} and MAG/MSG. The extrapolated f_T and f_{MAX} were 273 and 290 GHz, respectively. The f_T and f_{MAX} are expressed by Equations (7) and (8).

$$f_T = \frac{g_{mi}}{2\pi(C_{gs} + C_{gd})[1 + g_{ds}(R_s + R_d)] + C_{gd} \cdot g_{mi}(R_s + R_d)}, \quad (7)$$

$$f_{MAX} = \frac{f_{T,int}}{\sqrt{4g_{ds}(R_g + R_i + R_s) + \frac{2C_{gd}}{C_{gs}} \left(\frac{C_{gd}}{C_{gs}} + g_{mi}(R_i + R_s) \right)}}, \quad (8)$$

where g_{mi} is the intrinsic transconductance, C_{gs} and C_{gd} are the parasitic capacitances from gate to source and gate to drain, respectively; g_{ds} is conductance between drain and source;

R_s , R_d and R_g are the parasitic resistances of source, drain and gate, respectively. R_i is the intrinsic resistance in the channel region. $f_{T,int}$ represents the cut-off frequency of the intrinsic part of HEMTs without parasitic resistance and capacitance. From Equations (7) and (8) we can know that C_{gs} , C_{gd} , R_s and R_d are the key parasitic parameters that affect f_T and f_{MAX} [19]. Especially, R_s and R_d have a great impact on f_T . In our device manufacturing process, R_s and R_d were effectively restricted by controlling the etching of the gate recesses, thus improving f_T . The extraction of parameters through the small-signal model further confirms our viewpoint. Table 1 summarizes the small-signal modeling parameters of InGaAs HEMTs on Si substrates at the $g_{m,max}$ point of $V_G = -0.4$ V and $V_D = 0.8$ V.

Table 1. The parameters of the small-signal equivalent circuit of devices.

C_{gs} (fF)	C_{gd} (fF)	C_{ds} (fF)	g_{ds} (mS)	R_s (Ω)	R_d (Ω)	R_g (Ω)	R_i (Ω)	g_{mi} (mS)	Tau (fs)
62.1	9.5	11.5	10	1.6	4.5	3	7.5	116	400

The performance of our fabricated device and other reported InGaAs channel transistors on Si substrates are summarized in Table 2. Our 120 nm gate length device exhibits $g_{m,max} = 1112$ mS/mm and $f_T = 273$ GHz, which are the highest values reported in the InGaAs channel transistors on Si substrates at given L_G above 100 nm as far as we know.

Table 2. Comparison with published InGaAs channel transistors on Si substrates.

Reference	L_G (nm)	Channel	$I_{D,max}$ (mA/mm)	$g_{m,max}$ (mS/mm)	f_T (GHz)	f_{MAX} (GHz)
[7]	125	In _{0.53} Ga _{0.47} As/InAs/In _{0.53} Ga _{0.47} As	650	500	227	187
[15]	150	In _{0.30} Ga _{0.70} As	160	-	60	-
[20]	400	In _{0.18} Ga _{0.82} As	150	155	5.5	13
[21]	120	In _{0.53} Ga _{0.47} As	450	770	185	290
This work	120	In _{0.7} Ga _{0.3} As	569	1112	273	290

4. Conclusions

We have demonstrated InGaAs HEMTs on Si substrates for RF applications. The 120 nm gate length device exhibits good DC and RF performances featuring $g_{m,max} = 1112$ mS/mm and $f_T = 273$ GHz, which are the highest values reported in InGaAs channel transistors on Si substrates above $L_G = 100$ nm. These results show the potential for InGaAs HEMTs in future high-frequency applications on Si substrates.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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References

1. Liu, Y.; Zhang, B.; Feng, Y.; Zhao, X.; Wang, J.; Ji, D.; Yang, Y.; Fan, Y. A G-band Balanced Power Amplifier based on InP HEMT Technology. In Proceedings of the 2020 IEEE MTT-S International Wireless Symposium (IWS), Shanghai, China, 20–23 September 2020; pp. 1–3. [\[CrossRef\]](#)
2. Hamada, H.; Tsutsumi, T.; Matsuzaki, H.; Sugiyama, H.; Nosaka, H. 475-GHz 20-dB-Gain InP-HEMT Power Amplifier Using Neutralized Common-Source Architecture. In Proceedings of the 2020 IEEE/MTT-S International Microwave Symposium (IMS), Los Angeles, CA, USA, 4–6 August 2020; pp. 1121–1124. [\[CrossRef\]](#)
3. Hamada, H.; Tsutsumi, T.; Itami, G.; Sugiyama, H.; Matsuzaki, H.; Okada, K.; Nosaka, H. 300-GHz 120-Gb/s Wireless Transceiver with High-Output-Power and High-Gain Power Amplifier Based on 80-nm InP-HEMT Technology. In Proceedings of the 2019 IEEE BiCMOS and Compound semiconductor Integrated Circuits and Technology Symposium (BCICTS), Nashville, TN, USA, 3–6 November 2019; pp. 1–4. [\[CrossRef\]](#)
4. Mei, X.; Yoshida, W.; Lange, M.; Lee, J.; Zhou, J.; Liu, P.H.; Leong, K.; Zamora, A.; Padilla, J.; Sarkozy, S.; Lai, R.; Deal, W.R. First Demonstration of Amplification at 1 THz Using 25-nm InP High Electron Mobility Transistor Process. *IEEE Electron. Device Lett.* **2015**, *36*, 327–329. [\[CrossRef\]](#)
5. Zhou, X.; Li, Q.; Tang, C.W.; Lau, K.M. 30nm enhancement-mode In_{0.53}Ga_{0.47}As MOSFETs on Si substrates grown by MOCVD exhibiting high transconductance and low on-resistance. In Proceedings of the 2012 International Electron Devices Meeting, San Francisco, CA, USA, 10–13 December 2012; pp. 32.5.1–32.5.4. [\[CrossRef\]](#)
6. Waldron, N.; Wang, G.; Nguyen, N.D.; Orzali, T.; Merckling, C.; Brammertz, G.; Ong, P.; Winderickx, G.; Hellings, G.; Eneman, G.; et al. Integration of InGaAs Channel n-MOS Devices on 200mm Si Wafers Using the Aspect-Ratio-Trapping Technique. *ECS Trans.* **2012**, *45*, 115–128. [\[CrossRef\]](#)
7. Jeong, J.; Kim, S.K.; Kim, J.; Geum, D.M.; Park, J.; Jang, J.H.; Kim, S. Stackable InGaAs-on-Insulator HEMTs for Monolithic 3-D Integration. *IEEE Trans. Electron Devices* **2021**, *68*, 2205–2211. [\[CrossRef\]](#)
8. Tessmann, A.; Leuther, A.; Heinz, F.; Bernhardt, F.; John, L.; Massler, H.; Czornomaz, L.; Merkle, T. 20-nm In_{0.8}Ga_{0.2}As MOSHEMT MMIC Technology on Silicon. *IEEE J. Solid-State Circuits* **2019**, *54*, 2411–2418. [\[CrossRef\]](#)
9. Zota, C.B.; Convertino, C.; Baumgartner, Y.; Sousa, M.; Caimi, D.; Czornomaz, L. High Performance Quantum Well InGaAs-On-Si MOSFETs With sub-20 nm Gate Length For RF Applications. In Proceedings of the 2018 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 1–5 December 2018; pp. 39.4.1–39.4.4. [\[CrossRef\]](#)
10. Vandooren, A.; Franco, J.; Parvais, B.; Wu, Z.; Witters, L.; Walke, A.; Li, W.; Peng, L.; Desphande, V.; Bufler, F.M.; et al. 3D sequential stacked planar devices on 300 mm wafers featuring replacement metal gate junction-less top devices processed at 525 °C with improved reliability. In Proceedings of the 2018 IEEE Symposium on VLSI Technology, Honolulu, HI, USA, 18–22 June 2018; pp. 69–70. [\[CrossRef\]](#)
11. Lee, S.; Kim, S.K.; Han, J.; Song, J.D.; Jun, D.; Kim, S. Epitaxial Lift-Off Technology for Large Size III–V-on-Insulator Substrate. *IEEE Electron. Device Lett.* **2019**, *40*, 1732–1735. [\[CrossRef\]](#)
12. Kim, S.K.; Shim, J.; Geum, D.; Kim, J.; Kim, C.Z.; Kim, H.; Song, J.D.; Choi, S.; Kim, D.H.; Choi, W.J.; et al. Impact of Ground Plane Doping and Bottom-Gate Biasing on Electrical Properties in In_{0.53}Ga_{0.47}As-OI MOSFETs and Donor Wafer Reusability Toward Monolithic 3-D Integration With In_{0.53}Ga_{0.47}As Channel. *IEEE Trans. Electron Devices* **2018**, *65*, 1862–1868. [\[CrossRef\]](#)
13. Convertino, C.; Zota, C.; Sant, S.; Eltes, F.; Sousa, M.; Caimi, D.; Schenk, A.; Czornomaz, L. InGaAs-on-Insulator FinFETs with Reduced Off-Current and Record Performance. In Proceedings of the 2018 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 1–5 December 2018; pp. 39.2.1–39.2.4. [\[CrossRef\]](#)
14. Takagi, S.; Ahn, D.H.; Gotow, T.; Noguchi, M.; Nishi, K.; Kim, S.; Yokoyama, M.; Chang, C.; Yoon, S.; Yokoyama, C.; et al. III–V-based low power CMOS devices on Si platform. In Proceedings of the 2017 IEEE International Conference on IC Design and Technology (ICICDT), Austin, TX, USA, 23–25 May 2017; pp. 1–4. [\[CrossRef\]](#)
15. Yadav, S.; Kumar, A.; Nguyen, X.S.; Lee, K.H.; Liu, Z.; Xing, W.; Masudy-Panah, S.; Lee, K.; Tan, C.S.; Fitzgerald, E.A.; et al. High mobility In_{0.30}Ga_{0.70}As MOSHEMTs on low threading dislocation density 200 mm Si substrates: A technology enabler towards heterogeneous integration of low noise and medium power amplifiers with Si CMOS. In Proceedings of the 2017 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 2–6 December 2017; pp. 17.4.1–17.4.4. [\[CrossRef\]](#)
16. Nguyen, X.S.; Yadav, S.; Lee, K.H.; Kohen, D.; Kumar, A.; Made, R.I.; Lee, K.E.K.; Chua, S.J.; Gong, X.; Fitzgerald, E.A. MOCVD Growth of High Quality InGaAs HEMT Layers on Large Scale Si Wafers for Heterogeneous Integration With Si CMOS. *IEEE Trans. Semicond. Manuf.* **2017**, *30*, 456–461. [\[CrossRef\]](#)
17. Reuter, R.; Agethen, M.; Auer, U.; Waasen, S.v.; Peters, D.; Brockerhoff, W.; Tegude, F.J. Investigation and modeling of impact ionization with regard to the RF and noise behavior of HFET. *IEEE Trans. Microw. Theory Tech.* **1997**, *45*, 977–983. [\[CrossRef\]](#)
18. Ruiz, D.C.; Saranovac, T.; Han, D.; Ostinelli, O.; Bolognesi, C.R. Impact Ionization Control in 50 nm Low-Noise High-Speed InP HEMTs with InAs Channel Insets. In Proceedings of the 2019 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 7–11 December 2019; pp. 9.3.1–9.3.4. [\[CrossRef\]](#)
19. del Alamo, J.A. Nanometre-scale electronics with III–V compound semiconductors. *Nature* **2011**, *479*, 317–323. [nature10677](#). [\[CrossRef\]](#) [\[PubMed\]](#)

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20. Chang, E.Y.; Huang, J.C.; Lin, Y.C.; Hsieh, Y.C.; Chang, C.Y. AlGaAs/InGaAs High Electron Mobility Transistor Grown on Si Substrate with Ge/GexSi1-xMetamorphic Buffer Layers. *Jpn. J. Appl. Phys.* **2008**, *47*, 7069–7072. [[CrossRef](#)]
 21. Bollaert, S.; Wallaert, X.; Lepilliet, S.; Cappy, A.; Jalaguier, E.; Pocas, S.; Aspar, B. 0.12 μm transferred-substrate In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As HEMTs on silicon wafer. *IEEE Electron. Device Lett.* **2002**, *23*, 73–75. [[CrossRef](#)]