SMWD 2023, KTH Royal Institute of Technology, Stockholm, 23rd – 25th May 2023

Epitaxial Optimization of the InP HEMT for Cryogenic Low-Noise Amplifiers

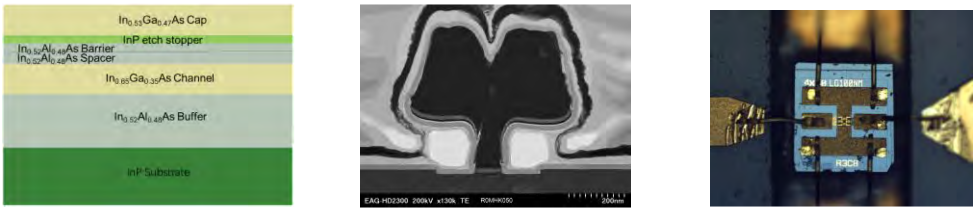
Junjie. Li [(1)], Johan. Bergsten [(2)], Arsalan. Pourkabirian [(2)], Niklas. Wadefalk [(2)], and Jan. Grahn [(1)]
(1) Department of Microtechnology and Nanoscience, Chalmers University of Technology, Gothenburg, Sweden
(2) Low Noise Factory AB, Gothenburg, Sweden

Summary

We report how epitaxial optimization of the InP HEMT improves state-of-the-art noise performance for cryogenic C-band low-noise amplifiers of interest in physics and astronomy applications.

1. Introduction

The InP HEMT has proven to provide the lowest noise figure among all FETs at microwave frequencies [1]. As a result, cryogenic InP HEMT LNAs have been used in the most sensitive detectors such as receivers for radio astronomy and readout of microwave qubits in quantum computing systems [2, 3]. The noise figure for the best InP HEMT cryogenic LNA, however, is still almost one order of magnitude higher than the quantum noise limit [3, 4]. It has been shown that engineering of the InP HEMT epitaxial structure (Figure 1(a)) plays a decisive role for the LNA noise performance and this becomes even more critical under cryogenic operation [4]. In this study, the influence of spacer thickness and channel indium content on the noise performance in InP HEMTs for cryogenic LNAs is investigated. The transistors measured in this study all have 4×50-µm wide and 100-nm long T-shape gates illustrated in Figure 1(b) [5]. The diced InP HEMTs were mounted in three-stage C-band hybrid LNAs for noise measurements as demonstrated in Figure 1(c) [6].



(a) (b) (c)

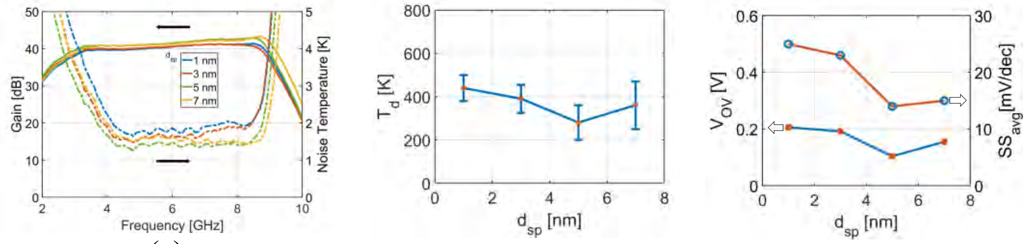
Figure 1. (a) Schematic of the epitaxial stack used in InP HEMT fabrication. (b) Cross-section STEM image of the 100-nm gate-length InP HEMT in the gate region. (c) Photo of an InP HEMT mounted by bond-wires.

2. Spacer thickness

In Figure 2(a), the amplifier experimental data measured at the optimum noise bias for each LNA at 5 K revealed differences between the InP HEMTs with varying spacer thickness d_{sp} of 1, 3, 5 and 7 nm. All InP HEMTs had identical channel indium content of 65% and channel thickness of 15 nm. All LNAs exhibited similar gain of around 40 dB. The LNA with 5 nm spacer InP HEMTs exhibited the lowest measured average noise temperature $T_{e,avg}$ of 1.4 K in 4-8 GHz which is on a par with the best result previously reported for this frequency band [4]. The noise generated in the InP HEMTs was quantified by the drain noise temperature T_d plotted in Figure 2(b) [5]. It was observed that T_d showed a minimum for InP HEMT with d_{sp} = 5 nm. The variation of T_d with d_{sp} was explained by a real-space transfer mechanism from channel to barrier based on (1) the observation of a negative differential resistance in the InP HEMT at elevated biases and (2) the correspondence between the overdrive voltage V_{ov} and T_d demonstrated in Figure 2(c) [5]. The correlation between the average subthreshold swing SS_{avg} and T_d at 5 K depicted in Figure 2(c). This means that the SS_{avg} at 5 K of the InP HEMT may serve as a rapid assessment of anticipated noise performance in the cryogenic HEMT LNA [7].

3. Indium channel content

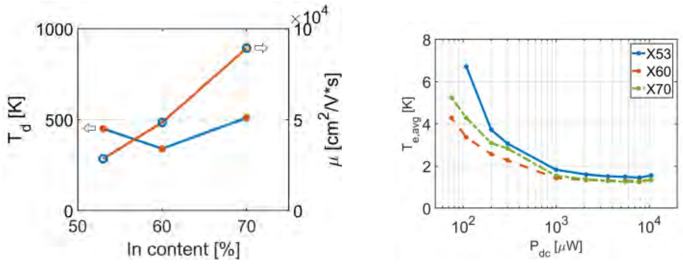
A previous study claimed that 80% indium channel InP HEMT exhibited significantly higher noise than a 65% indium channel InP HEMT [4]. Therefore, it is worth searching for the optimum channel composition of the InP HEMT for cryogenic LNA noise performance. The three epitaxial structures with d_{sp} = 5 nm used in this study were grown with channel indium content of 53% (X53), 60% (X60) and 70% (X70) and channel thickness of 20 nm, 20 nm and 10 nm, respectively.



(a) (b) (c)

Figure 2. (a) The measured gain and noise temperature of 4-8 GHz LNAs integrated with the InP HEMTs with d_{sp} = 1 , 3 , 5 and 7 nm at 5 K using the optimum noise bias for each LNA. (b) The T_d of the InP HEMT extracted at the optimum noise bias at 5 K. (c) The V_{ov} at optimum noise gate bias and the SS_{avg} of the InP HEMTs versus spacer thickness at 5 K.

The extracted T_d suggested a minimum at 60% indium at the optimum noise bias which was inconsistent with the electron channel mobility μ compared in Figure 3(a). In Figure 3(b), the LNA with X60 exhibited the lowest $T_{e,avg}$ as a function of dc power P_{dc}. For P_{dc} = 100 µW, the $T_{e,avg}$ was only 3.3 K.



(a) (b)

Figure 3. (a) The T_d extracted at optimum noise bias and the μ of the InP HEMT versus indium channel content at 5 K. (b) The $T_{e,avg}$ versus P_{dc} for LNAs with 53%, 60% and 70% indium channel at 5 K.

4. Conclusion

The channel noise estimated by T_d of the cryogenic InP HEMTs has been studied by varying spacer thickness from 1 to 7 nm and channel indium content from 53% to 70%. It was found that the T_d exhibited a clear minimum at 5 nm spacer thickness and 60% indium channel in this study. The results were used to demonstrate state-of-the-art InP HEMTs for cryogenic LNAs in C-band. Such circuits are of interest in sensitive detection of faint microwave signals in physics and astronomy.

5. Acknowledgements

The author would like to thank Alexei Kalaboukhov from Chalmers University of Technology, Jörgen Stenarson and Estefany Santana from Low Noise Factory AB and Austin Minnich and his group from California Institute of Technology.

References

[1]. J. C. Bardin, "Cryogenic Low-Noise Amplifiers: Noise Performance and Power Dissipation," *IEEE Solid-State Circuits Magazine*, **13**, 2, June 2021, pp. 22-35, doi: 10.1109/MSSC.2021.3072803.

[2]. J. C. Webber and M. W. Pospieszalski, "Microwave instrumentation for radio astronomy," *IEEE Transactions on Microwave Theory and Techniques*, **50**, 3, March 2002, pp. 986-995, doi: 10.1109/22.989982.

[3]. J. C. Bardin, D. H. Slichter and D. J. Reilly, "Microwaves in Quantum Computing," *IEEE Journal of Microwaves*, **1**, 1, Jan. 2021, pp. 403-427, doi: 10.1109/JMW.2020.3034071.

[4]. E. Cha et al., "A 300-µW Cryogenic HEMT LNA for Quantum Computing," *2020 IEEE/MTT-S International Microwave Symposium (IMS)*, Los Angeles, CA, USA, 2020, pp. 1299-1302, doi: 10.1109/IMS30576.2020.9223865.

[5]. J. Li et al., "Influence of Spacer Thickness on the Noise Performance in InP HEMTs for Cryogenic LNAs," *IEEE Electron Device Letters*, **43**, 7, July 2022, pp. 1029-1032, doi: 10.1109/LED.2022.3178613.

[6]. N. Wadefalk et al., "Cryogenic wide-band ultra-low-noise IF amplifiers operating at ultra-low DC power," *IEEE Trans. on Microwave Theory and Techniques*, **51**, 6, June 2003, pp. 1705-1711, doi: 10.1109/TMTT.2003.812570.

[7]. J. Li, A. Pourkabirian, J. Bergsten, N. Wadefalk and J. Grahn, "On the relation between rf noise and subthreshold swing in InP HEMTs for cryogenic LNAs," *2022 Asia-Pacific Microwave Conference*, Yokohama, Japan, 2022, pp. 10-12.