Optimization of InGaAs Channel for Cryogenic InP HEMT 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
junjiel@chalmers.se

***Abstract*—The noise temperature was measured for InP HEMTs in cryogenic low-noise amplifiers (LNAs) with channel indium content varied from 53% to 70%. The Hall measurements for all the epitaxial structures and dc characteristics of InP HEMTs were characterized. The 4–8 GHz LNA with lattice-matched channel InP HEMTs has the highest noise temperature at 5 K. The LNAs with 60% and 70% channel exhibited similar noise of 1.4 K at the optimum noise bias at 5 K. The 60% channel InP HEMT showed the lowest drain noise temperature with 10.5 mW power consumption and the lowest LNA noise at low power with 3.3 K for 100 µW. The results indicate that there is an optimum indium channel composition for InP HEMTs in cryogenic LNAs.**

Keywords—Cryogenic; low noise amplifier; InP HEMT; InGaAs channel; noise

The applications of cryogenic InP HEMT low-noise amplifiers (LNAs) are found from radio astronomy to quantum computing due to the superior noise provided by the InP HEMTs among all FETs [1,2]. However, the state-of-the-art minimum average noise temperature of the InP HEMT LNA reported for C band (4-8 GHz) is still about ten times higher than the quantum noise limit [2,3]. According to the Fukui semi-empirical noise equation, higher electron mobility should be targeted for lower noise [4]. Indeed, it has been reported that a indium richer channel does provide higher mobility but not always promise lower noise at cryogenic temperature [5,6]. This motivates for a study on the optimum channel composition of the InP HEMT for cryogenic LNA noise performance. Here we report the noise temperature of cryogenic C-band LNAs based on InP HEMTs with channel indium content changing from 53% to 70%.

Except for the channel, the InP HEMT epitaxial structures grown in this study were identical as shown in Fig. 1. The thickness for 53% (X53), 60% (X60) and 70% (X70) indium channel was 15 nm, 20 nm and 10 nm, respectively. The latter thickness was smaller due to the higher lattice mismatch of 70% indium channel compared to 53% and 60%. The electron sheet carrier concentration n_{sh} for all channels was about 2×10^{12} cm^{-2} as determined by the Hall measurements. The n_{sh} did not vary with temperature whereas the electron mobility μ increased with reduced temperature as demonstrated in Fig. 2. The significant increase of μ at 5 K with higher indium content was observed as expected. The Hall measurement results corroborated that all epitaxial materials used for InP HEMTs were of high quality and displayed expected differences with respect to the channel indium content.

100 nm gate-length, 4×50 µm gate-width InP HEMTs were fabricated using the method described in Ref. [3] with an additional oxygen plasma cleaning prior to the gate passivation. The output dc characteristics at 5 K for the InP HEMTs with different channel indium content are plotted in Fig. 3. The kink effect appearing at elevated bias was caused by the surface traps introduced by the plasma cleaning. However, the kink effect will not affect the noise performance since it occurs far from the low-noise bias used in the cryogenic LNAs (overdrive voltage $V_{ov} = V_{gs} - V_{th} < 0.15$ V, $I_d \approx 25$ mA/mm). At $V_{ov} = 0.9$ V, the maximum drain current at $V_{ds} = 0.8$ V was more than 800 mA/mm for X53 and X70 which was 25% higher than X60.

Fig. 4 shows the gain and noise performance of InP HEMTs measured in 4–8 GHz LNAs at the optimum noise bias at 5 K [7,8]. The LNA with X70 revealed the highest gain of 46 dB whereas X53 and X60 had similar gain of 42 dB. The average noise temperature $T_{e,avg}$ for all LNAs was very comparable with 1.5 K for X53 and 1.4 K for X60 and X70. The drain noise temperature extracted using a small-signal model depicted a minimum at 60% indium at the optimum noise bias which is inconsistent with the μ compared in Fig. 5. In Fig. 6, the LNA with X60 exhibited the lowest $T_{e,avg} = 3.3$ K at a low power dc bias at 100 µW. Compared with the state-of-the-art 300 µW cryogenic LNA noise of 3.2 K using 65% indium channel [6], the X60 LNA in this study demonstrated a lower noise of 2.3 K at 300 µW in the same frequency band. The result suggests that the 60% indium channel for the InP HEMT is the optimum for the low-noise and low-power cryogenic LNA in this study.

1. J. Webber et al., IEEE Trans. Microw. Theory Tech. 50, 3, 986-995 (2002)
2. J.C. Bardin, IEEE Journal. Microw. 1, 1, 403-427 (2021)
3. J Li, et al., IEEE Electron Device Lett. 43, 7, 1029-1032 (2022)
4. H. Fukui, IEEE Trans. Electron Devices, 26, 7, 1032-1037 (1979)
5. D.C. Ruiz, et al., IEEE Trans. Electron Devices, 66, 11, 4685-4691 (2019)
6. E. Cha, et al., IEEE/MTT-S, 20054552 (2020)
7. N. Wadefalk et al., IEEE Trans. Microw. Theory Tech., 51, 6, 1705-1711 (2003)
8. J. L. Cano et al., IEEE Trans. Microw. Theory Tech. 58, 9, 2504-2510 (2010)

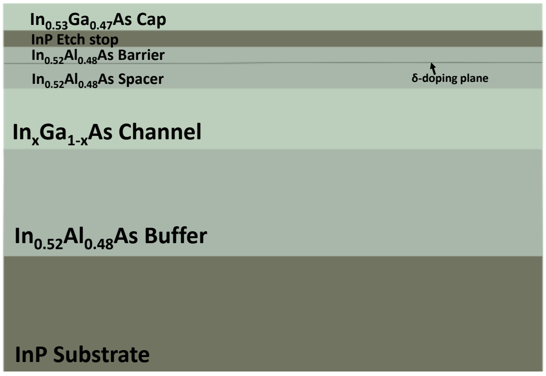

Fig. 1. Schematic of InP HEMT epitaxial layers with channel indium content X = 53%, 60% and 70% used in this work.

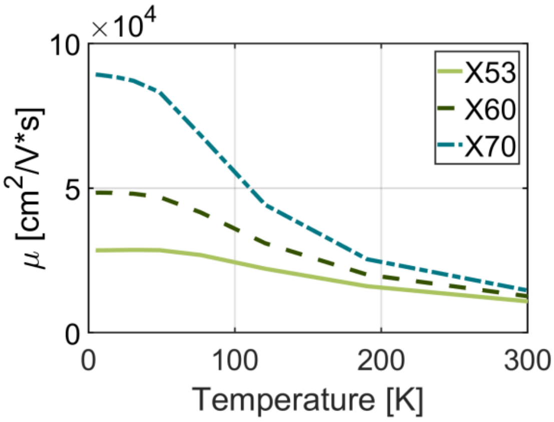

Fig. 2. The Hall electron mobility μ versus temperature from 5 K to 300 K for the structures of 53% (light green solid), 60% (dark green dashed) and 70% (blue dash-dot) indium channel without cap layers.

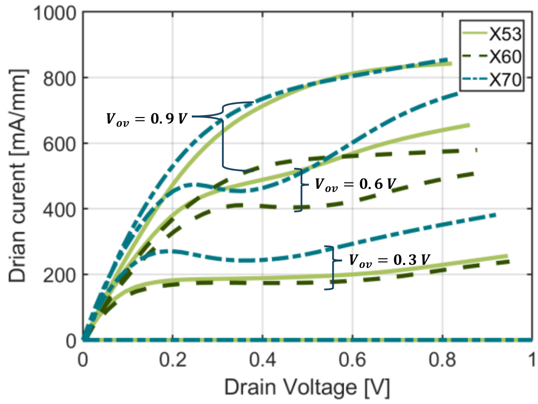

Fig. 3. The *I-V* characteristics of the 100 nm gate length InP HEMT using 4 × 50 µm gate-width layout with channel indium of 53% (light green solid), 60% (dark green dashed) and 70% (blue dash-dot) at 5 K. V_{th} was 0.08 V, 0.14 V and 0.17 V for 53%, 60% and 70% indium channel, respectively.

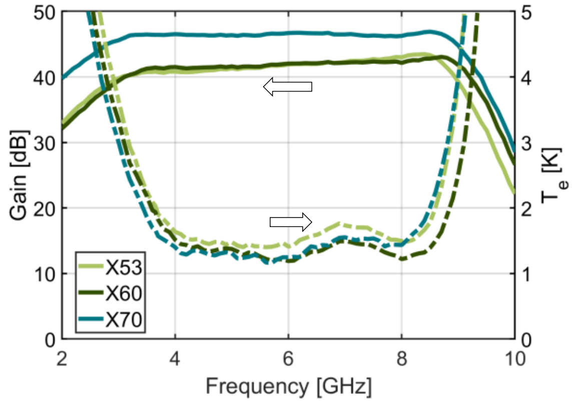

Fig. 4. The measured gain (solid) and noise temperature (dashed) of three-stage 4-8 GHz hybrid LNAs integrated with the 100 nm InP HEMT with channel indium content of 53% (light green), 60% (dark green) and 70% (blue) at the ambient temperature of 5 K. The optimum noise bias for all LNAs was V_{DS} = 0.7 V and I_D = 15 mA.

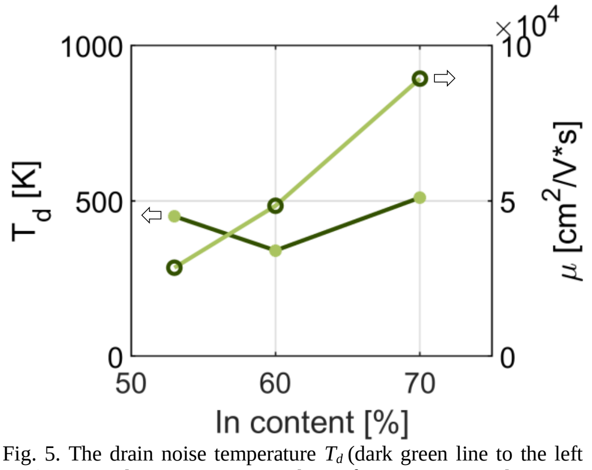

Fig. 5. The drain noise temperature T_d (dark green line to the left axis) extracted at optimum noise bias of V_{DS} = 0.7 V and I_D = 15 mA and Hall electron mobility μ (light green line to the right axis) of the InP HEMT as a function of channel indium content at 5 K.

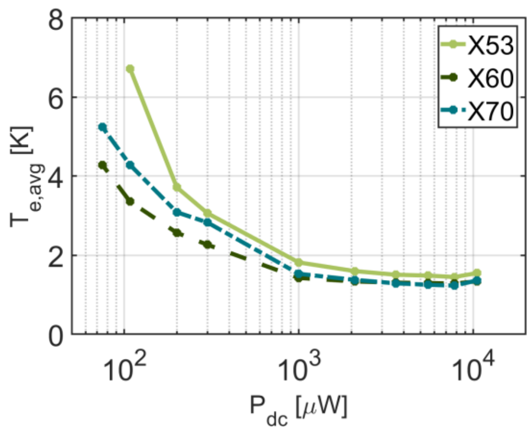

Fig. 6. The average noise temperature as a function of dc power dissipation P_{dc} for InP HEMT LNAs with 53% (light green solid), 60% (dark green dashed) and 70% (blue dash-dot) indium channel at 5 K.