Reduction of Noise Temperature in Cryogenic InP HEMT Low Noise Amplifiers with Increased Spacer Thickness in InAlAs-InGaAs-InP Heterostructures

Junjie Li[1], Arsalan Pourkabirian[2], Johan Bergsten[2], Eunjung Cha[1], Alexei Kalaboukhov[1], 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 impact of InP HEMT spacer thickness on cryogenic performance in low noise amplifiers (LNAs) has been investigated. 100 nm gate-length InP HEMTs based on InAlAs-InGaAs-InP heterostructures with different spacer thickness (1 nm, 3 nm and 5 nm) were fabricated. The Hall measurements, simulated band structures and dc characteristics of InP HEMTs were compared for all the three different epitaxial structures at 5 K. The noise performance of the InP HEMT was studied using a three-stage 4–8 GHz hybrid LNA at 5 K. All LNAs yielded an average gain above 30 dB across the whole band. When biased for optimal low noise operation, the LNA with 5 nm spacer thickness InP HEMTs achieved an average noise temperature of 1.3 K. The LNAs with spacer thickness of 1 nm and 3 nm InP HEMTs exhibited a higher average noise temperature of 1.9 K and 1.7 K, respectively. The reduction in LNA noise temperature with increased spacer thickness was observed to correlate with a strongly enhanced electron mobility in the InP HEMT structure at 5 K.**

Keywords—Cryogenic; low noise amplifier; InP HEMT; spacer thickness; noise

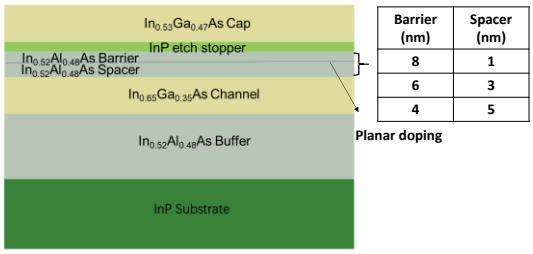
C-band (4-8 GHz) cryogenic InP HEMT low noise amplifiers (LNAs) are highly demanded in quantum computing systems for the readout of qubits at the 4 K stage [1]. The thermal noise which originates from the kinetic energy of the charge carriers in the 2DEG channel constitutes one of the dominating noise sources in the HEMT [2]. It is well known that engineering of the InP HEMT epitaxial structure plays a decisive role for the HEMT performance [3]. From photoluminescence investigations on HEMT epitaxial structures, it was demonstrated that the scattering of carriers in the channel was dependent upon spacer thickness [4]. This suggests that the spacer design plays a role in the HEMT LNA noise performance. Here we report the noise temperature of cryogenic C-band LNAs based on InP HEMTs with different spacer thickness.

Fig. 1 shows the schematic of InP HEMT epitaxial layers with three different spacer thicknesses of 1, 3 and 5 nm. The InAlAs barrier thickness above the spacer was adjusted correspondingly to keep the total gate-to-channel distance constant. In Fig.2, Hall measurements revealed a strong dependence on the electron mobility as a function of spacer thickness at 5 K compared to 300 K. In contrast, sheet carrier concentration was relatively insensitive to spacer thicknesses. The band structure and electron density at 5 K has been simulated using the measured electron mobilities, see Fig.3. The energy barriers of the channel are almost the same for all three structures. The main difference is the distance between delta doping energy well and the 2DEG channel.

4×50 μm,gate-width 100 nm gate-length InP HEMTs were fabricated using the method described in Ref. [5]. The output dc characteristics at 5 K of the InP HEMTs with different spacer thickness are plotted in Fig. 4. The 1 nm spacer InP HEMT exhibited the lowest current driving capability whereas the 3 nm and 5 nm spacer InP HEMTs were similar. The threshold voltage shifted toward more positive values with increased spacer thickness. The gate leakage bell shape seen in Fig. 5 suggests that the 5 nm spacer InP HEMT has the lowest impact ionization [6]. All devices exhibited relatively low gate current leakage (< 0.1 μA/mm) at their optimum low-noise bias, which implies that the gate leakage will not degrade the noise temperature in the C-band LNA [5].

The noise performance of InP HEMTs was investigated in a three-stage 4–8 GHz hybrid LNA employing the measurement method described in [7,8]. The noise of the LNA at 300 K was comparable for all three spacers with an average noise temperature (Te,avg) of about 28 K. The gain of the LNAs at 300 K was similar to that of 5 K and increased with spacer thickness. The noise of the LNAs biased at the optimum point at 5 K decreased with the spacer thickness in the frequency band as shown in Fig. 6 where the LNA with 5 nm spacer InP HEMTs exhibited the lowest Te,avg of 1.3 K. The reduction of noise is correlated with an observed increase in electron mobilities, indicating that 2DEG charge carriers experience less scattering from the delta doping plane with thicker spacer.

1. F. Arute *et al*., Nature, 574, 505-510 (2019)
2. J.B. Johnson, Phys. Rev. 32, 97-109 (1928)
3. D.C. Ruiz, *et al*., IEEE Trans. Electron Devices, 66, 11, 4685-4691 (2019)
4. X. Cao *et al*., Journal of Crystal Growth, 231, 520-524 (2001)
5. E. Cha *et al*., IEEE Trans. Microw. Theory Tech., 66, 11, 4860–4869 (2018)
6. A. A. Moolji *et al*., IEEE Electron Devices Letters, 15, 8, 313–315 (1994)
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)



Barrier (nm)	Spacer (nm)
8	1
6	3
4	5

Fig. 1. Schematic of InP HEMT epitaxial layers with three different spacer thickness used in this work.

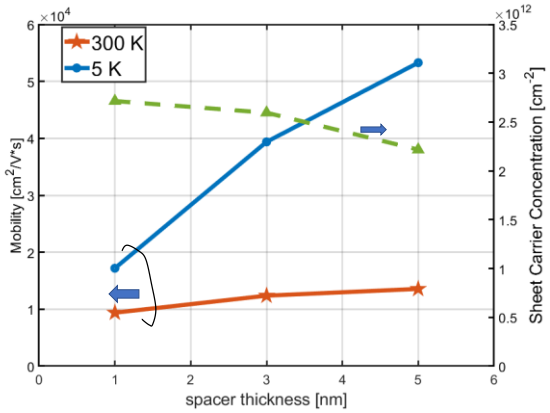


Fig. 2. The measurement data of the three structures without cap layers. The sheet carrier concentration at 300 K (green dashed line) and electron mobility at both 5 K (blue circle solid line) and 300 K (red star solid line) versus spacer thickness.

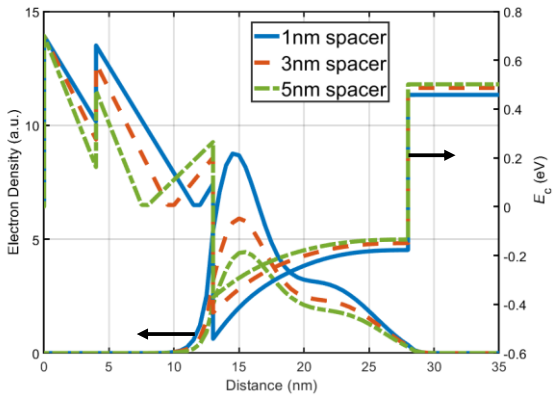


Fig. 3. Simulated band structure and 2DEG electron density for spacer thickness of 1nm (blue solid), 3 nm (red dashed) and 5 nm (green dash-dot). The δ doping was adjusted according to the measured Hall mobility at 5 K.

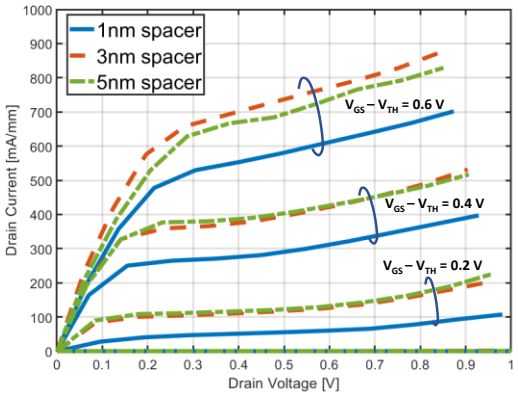


Fig. 4. The *I-V* characteristics of the 100 nm gate length InP HEMT using 4 × 50 μm gate-width layout with spacer thickness of 1 nm (blue solid), 3 nm (red dashed) and 5 nm (green dash-dot) at 5 K. V_{TH} was -0.3 V, -0.2 V and 0 V for 1 nm, 3 nm and 5 nm spacer, respectively.

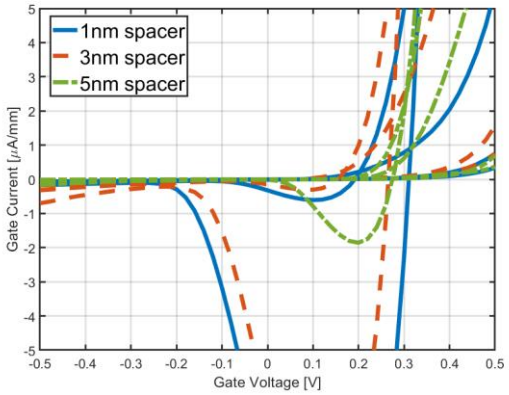


Fig. 5. Gate current of the 100 nm gate-length InP HEMT with spacer thickness of 1 nm (blue solid), 3 nm (red dashed) and 5 nm (green dash-dot) at 5 K. V_{DS} = 0.1 – 0.9 V in steps of 0.2 V.

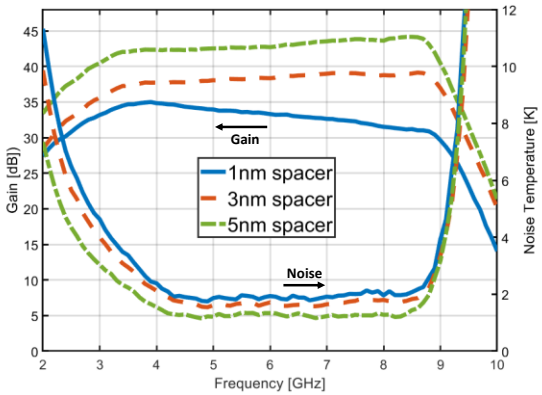


Fig. 6. The measured gain and noise temperature of three-stage 4-8 GHz hybrid LNAs integrated with the 100 nm InP HEMT with spacer thickness of 1 nm (blue solid), 3 nm (red dashed) and 5 nm (green dash-dot) at the ambient temperature of 5 K. The optimum noise bias for all LNAs was V_D = 0.7 V and I_D = 18 mA.