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***Abstract* — 4 - 8 GHz low-noise amplifiers (LNAs) based on InP high electron mobility transistors (InP HEMTs) with different spacer thickness in the InAlAs-InGaAs heterostructure were fabricated and characterized at 5 K. A variation in the lowest average noise temperature of the LNA was observed with spacer thickness. We here report that the subthreshold swing (*SS*) at 5 K for the HEMT exhibited similar dependence with spacer thickness as the lowest average noise temperature of the LNA. This suggests that low-temperature characterization of *SS* for the HEMT can be used as a rapid assessment of anticipated noise performance in the cryogenic HEMT LNA.**

Index Terms — Cryogenic, InP HEMT, low-noise amplifier, noise, subthreshold swing

I. Introduction

The InP high electron mobility transistor (InP HEMT) offering the lowest noise temperature for the cryogenic low noise amplifier (LNA) are highly demanded in applications of microwave and mm-wave receivers for radio astronomy, space communication, and, more recently, in quantum computing [1]. Since the noise performance of the HEMT at low temperature cannot be measured directly on-wafer with high accuracy, the dc parameter $\sqrt{I_{ds}}/g_m$ is often used as a guide for predicting the optimum noise bias between various devices [2]. The $\sqrt{I_{ds}}/g_m$ originates from the Pospieszalski empirical model for the HEMT and is particularly useful for noise assessment of cryogenic transistors. Here we report on the subthreshold swing (*SS*) of the InP HEMT as an alternative rapid indicator of its rf noise performance at cryogenic temperature. We have fabricated cryogenic 4-8 GHz InP HEMTs LNAs with different spacer thickness in the InAlAs-InGaAs heterostructure. The measured differences in average noise temperature between the cryogenic HEMT LNAs were found to correlate well with the measured *SS* of the HEMTs at the same temperature.

II. Device Technology

The InP HEMTs were made from epitaxial structures described in Ref. [3] which is shown in the inset of Fig.1. The spacer thickness d_{sp}, *i.e.* the distance between the top of the InGaAs channel and the δ-doped plane in the InAlAs, varied between 1, 3, 5 and 7 nm. The total thickness of the barrier (the InAlAs layer above the δ-doped layer) and the spacer layer was 9 nm for all structures.

InP HEMTs using epitaxial layers with different d_{sp} were fabricated simultaneously employing the device process described in Ref. [4]. The transistor gate length and gate width were 100 nm and 4×50 μm, respectively. Fig. 1 shows a cross-sectional scanning transmission electron microscopy (STEM) image of the gate region for a finalized InP HEMT (d_{sp} = 3 nm). The STEM image reveals a well-controlled symmetric recess with 125 nm distance at each side of the 100 nm long T-shaped gate. Furthermore, the in-diffusion of Pt beneath the gate, defining the gate-to-channel distance, is clearly observed [4].

III. Results

The dc characteristics of the InP HEMTs were characterized on-wafer at 5 K. The drain current I_d and gate current I_g of the InP HEMTs with different spacer thickness all showed expected behavior [3]. The drain current versus gate voltage in

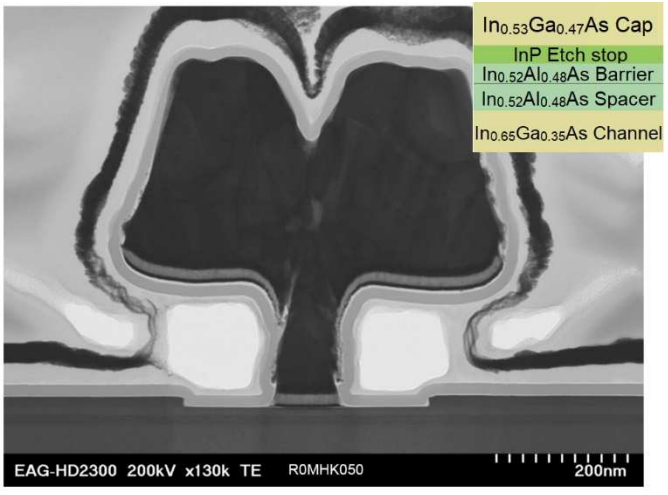

Fig. 1. STEM image of the 100 nm-length gate of the InP HEMT with d_{sp} = 3 nm. The inset: epitaxial stack of the InP HEMT.

TABLE I

INTRINSIC SMALL-SIGNAL MODELLING PARAMETERS AT THE OPTIMUM NOISE BIAS FOR THE INP HEMTS AT 5 K

d_{sp} (nm)	C_{gs} (fF)	C_{gd} (fF)	C_{ds} (fF)	g_{ds} (mS)	g_{mi} (mS)	R_j (Ω)	R_i (Ω)
1	115	44	60	19	210	21	1
3	119	47	56	19	213	22	1.2
5	114	47	56	18	199	21	1.3
7	112	39	52	13	174	22	1.2

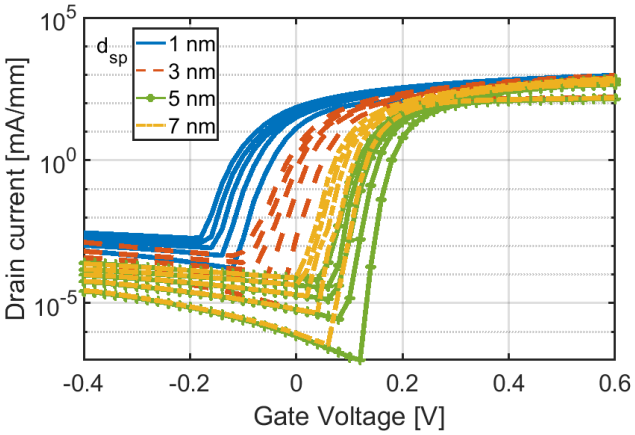

Fig. 2. Drain current versus gate voltage. V_{ds} = 0.1 – 0.9 V in steps of 0.2 V. Temperature was 5 K.

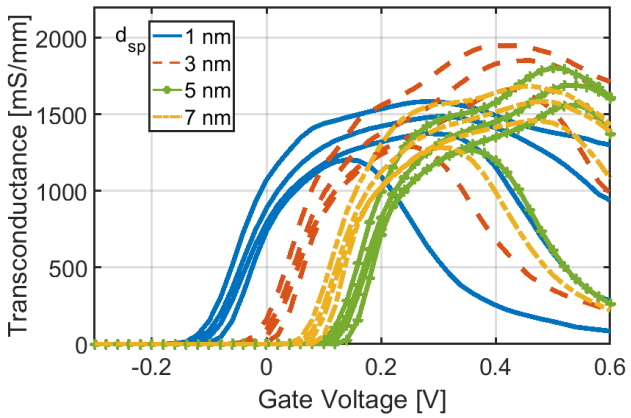

Fig. 3. The transconductance versus gate voltage. V_{ds} = 0.2 – 0.8 V in steps of 0.2 V. Temperature was 5 K.

log scale is plotted in Fig. 2. The *SS* at V_{ds} = 0.1 V showed that InP HEMTs with d_{sp} = 1 and 3 nm have higher *SS* of 24 and 20 mV/dec compared with d_{sp} = 5 and 7 nm with *SS* of 12 and 13 mV/dec, respectively. The latter values of *SS* are among the lowest reported for a field-effect transistor yet still much beyond the theoretical Boltzmann limit (k_BT/q)ln10 at these low temperatures [5].

Fig. 3 presents the transconductance of the InP HEMTs with different spacer thickness at V_{ds} = 0.2 – 0.8 V in steps of 0.2 V. The InP HEMT with d_{sp} = 3 nm exhibited the highest peak transconductance at 5 K which is consistent with its higher current driving capacity at elevated drain and gate [3]. Fig. 3 also demonstrates the variation in threshold voltage V_{th} [3]. The intrinsic small-signal parameters for the investigated InP HEMTs at the optimum noise bias were extracted and are presented in Table I. The extraction was based on an equivalent small-signal HEMT model using the measured S-parameters [6]. It is observed that the various InP HEMTs displayed similar small-signal values which was reasonable since they had identical geometries.

Four three-stage 4–8 GHz hybrid LNAs were assembled using the InP HEMTs with different spacer thickness [7]. The gain and noise of the amplifiers were measured at 5 K [8]. When biased at V_{DS} = 0.7 V, I_D = 15.0 mA, LNAs with d_{sp} = 5 and 7 nm of the InP HEMTs exhibited higher gain and lower noise than LNAs with d_{sp} = 1 and 3 nm as shown in Fig. 4. To find the lowest noise for each LNA, we measured the noise with sweeping drain current and voltage. Fig. 5 depicts the average noise temperature T_{avg} of the LNAs at different biases. The

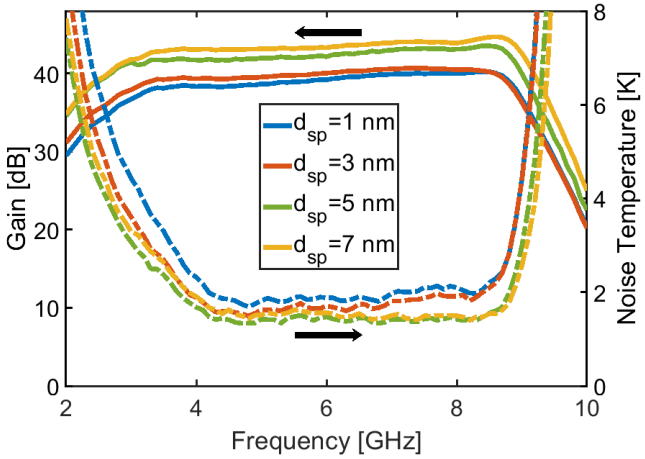

Fig. 4. The measured gain (solid) and noise temperature (dashed) of three-stage 4-8 GHz hybrid LNAs integrated with the InP HEMT with d_{sp} = 1 (blue), 3 (red), 5 (green) and 7 nm (yellow) at bias of V_{DS}=0.7 V, I_D=15.0 mA. Temperature was 5 K.

lowest T_{avg} of LNA with d_{sp} = 1, 3, 5 and 7 nm were 1.9, 1.7, 1.4 and 1.6 K, respectively. The optimum noise biases for the LNA were V_{DS} =0.75 V, I_D =18.0 mA for d_{sp} = 1 nm, V_{DS} =0.73 V, I_D=16.8 mA for d_{sp} = 3 nm, V_{DS}=0.51 V, I_D=12.0 mA for d_{sp} = 5 and V_{DS} =0.61 V, I_D =9.0 mA for d_{sp} = 7 nm, respectively [3].

In Fig. 6, the HEMT LNA average noise temperature, $\sqrt{I_{ds}}/g_m$, and SS are plotted versus spacer thickness, all measured at 5 K. The $\sqrt{I_{ds}}/g_m$ in Fig. 6(b) does not show a fully consistent relation with the average noise temperature in

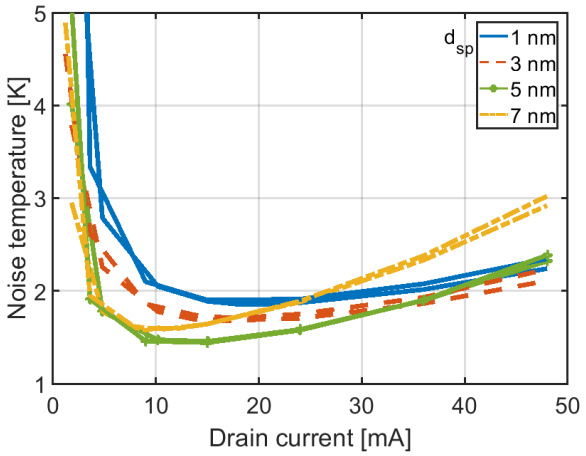

Fig. 5. The average noise temperature T_{avg} of LNAs integrated with the InP HEMT with d_{sp} = 1 (blue), 3 (red), 5 (green) and 7 nm (yellow) versus LNA drain current I_D at drain bias of V_{ds}=0.325 V and 0.475 V.

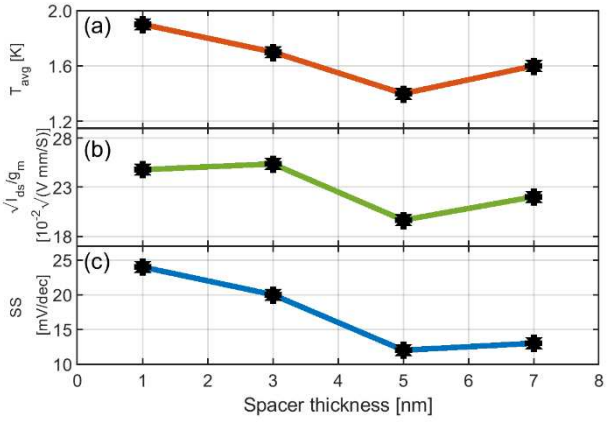

Fig. 6. (a) The T_{avg} (red) of the LNAs extracted at optimum noise bias. (b) $\sqrt{I_{ds}/g_m}$ (green) at optimum noise bias of the InP HEMTs. (c) *SS* (blue) of the InP HEMTs extracted at V_{ds}=0.1 V. All curves in (a), (b) and (c) as a function of spacer thickness at 5 K.

Fig. 6(a). In contrast, the SS in Fig. 6(c) demonstrates an excellent correspondence with the measured noise in the HEMT LNAs. *SS* reflects the ability to switch off the transistor. A lower *SS* means a higher g_m/I_d ratio which is important for the noise properties. At this low temperature, it is expected that *SS* is independent of temperature and depends on a band tail energy parameter and a body-effect coefficient [5]. One explanation of our data is that the *SS* in Fig. 6(c) captures the amount of scattering for the 2DEG carriers as a function of position of the δ-doped plane in the HEMT reflecting the rf noise performance of the LNA. Hence the *SS* measurement at low temperature might be able to serve as an efficient tool to identify the best InP HEMT for the cryogenic LNA.

IV. Conclusion

The T_{avg} of the cryogenic LNAs has been studied using InP HEMTs with a spacer thickness variation from 1 to 7 nm in the InAlAs-InGaAs heterostructure. It was found that the LNA with 5 nm spacer InP HEMT exhibited a clear minimum in noise with T_{avg} = 1.4 K. The similarity between the dependance of T_{avg} (at optimum noise bias) and *SS* (at low drain voltage) with d_{sp} suggests that *SS* serves as an indicator for the expected rf noise variation in the cryogenic HEMT LNA.

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