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On the $\text{In}_x\text{Ga}_{1-x}\text{As}$ Channel Noise in InP HEMTs From 4 K to 300 K

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ABSTRACT The InP high-electron-mobility transistor (HEMT) is indispensable for low-noise amplifiers (LNAs) in radio astronomy and quantum computing. The composition of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel in the InP HEMT is known to influence the LNA noise performance. However, the various physical mechanisms responsible for noise generation are not fully characterized and understood. Here, we investigate the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel noise from 4 K to 300 K for 100-nm gate-length InP HEMTs with channel indium content of 53%, 60% and 70%. Channel noise was quantified by extracting the equivalent drain noise temperature T_d using both on-wafer and LNA-based measurements, covering 40–300 K and 4–40 K, respectively. The 60% indium channel InP HEMT exhibited the lowest channel noise across the full temperature range. The T_d extracted from on-wafer characterization was found to obey a parabolic temperature dependence which predicted the T_d at 4 K for all InP HEMTs in good agreement with LNA-based measurements. By expressing the channel noise as the sum of one thermal and one excess noise term, it was found that the former increased linearly with ambient temperature and dominated at 300 K. The channel noise at 4 K was determined by the excess noise term and exhibited a non-monotonic dependence on the channel indium content in the InP HEMT. The results suggest that the excess noise in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel originates not only from temperature-independent shot noise but also from impact ionization and real-space transfer noise.

INDEX TERMS Channel noise, channel indium content, excess noise, InP HEMT, LNA, thermal noise.

I. INTRODUCTION

The InP high-electron-mobility transistor (HEMT) is used to design cryogenic low-noise amplifiers (LNAs) with the highest gain and lowest noise from microwave up to mm-wave frequencies [1]. Such LNAs constitute critical front-end components in radio astronomy [2] and superconducting quantum computing readout systems [3]. The InP HEMT is the preferred active device for cryogenic LNAs because the low electron effective mass and high peak electron velocity of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel [4] in the transistor at low temperature enable a high current-gain cut-off frequency already at a drain current density I_d of a few tens of mA/mm [5]. This results in a minimum noise temperature of approximately 1 K at 6 GHz for the cryogenic

InP HEMT, the lowest among all transistor technologies [6]. A state-of-the-art 4–8 GHz hybrid InP HEMT cryogenic LNAs was reported more than a decade ago with an average noise temperature $T_{e,avg}$ of 1.6 K and an average gain of 44 dB at a total power dissipation of 4.2 mW [6]. Recently, a similar design was demonstrated with $T_{e,avg} = 1.4$ K at 2.1 mW [7]. The high gain at low drain current density also makes the cryogenic InP HEMT LNA uniquely suited for ultra-low-power operation, exhibiting $T_{e,avg} = 3.3$ K at a power of only 108 μW while maintaining an average gain of 21 dB for the 4–8 GHz band [8]. The outstanding low-noise properties of the InP HEMT have also been exploited in wide-band monolithic microwave integrated circuits for cryogenic applications; A 0.3–14 GHz LNA with $T_{e,avg} = 3.5$ K [9]

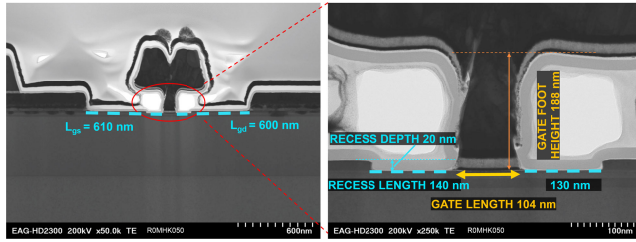


FIGURE 1. Cross-sectional STEM images of the fabricated InP HEMT. Left: overview of the T-shape gate showing source-gate spacing L_{gs} and drain-gate spacing L_{gd} ; the red circle marks the gate region magnified at right. Right: view of the recessed gate.

and a 70-96 GHz LNA with a minimum noise temperature of 22 K at 85 GHz [10]. Using a similar $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel structure, 8-18 GHz GaAs mHEMT LNAs were also reported with $T_{e,avg} = 4.2$ K [11], and $T_{e,avg} = 11.2$ K over 16 -50 GHz [12].

The noise performance of the cryogenic LNA has been shown to be highly sensitive to the channel indium content of the InP HEMT [13]. It was previously reported that the noise temperature for InP HEMTs was lower for 65% indium content channel than for 80% channel at 4 K [5]. Furthermore, it was also disclosed in [14] and [15] that increasing the channel indium content of the InP HEMT resulted in higher noise at 300 K. The generation of noise in the InP HEMT is dominated by the properties of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel and is due to several physical mechanisms which are not fully understood. Since thermal noise alone can not describe the channel noise in cryogenic field-effect transistors [16], [17], alternative noise sources have been proposed for the InP HEMT, e.g. suppressed shot noise [18], real-space transfer (RST) noise [19], [20], and impact ionization noise [14], [21]. In [8], we reported an optimum channel indium content of 60% for the lowest noise in the 4-8 GHz (C-band) InP HEMT LNA at 4 K. It was suggested that this was due to a combination of thermal noise and RST excess noise in the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel. However, the noise characterization was limited to 4 K, leaving the temperature dependence of the channel noise and its underlying mechanisms unresolved.

In this paper, we present channel noise measurements for 100-nm gate-length InP HEMTs based on different indium channels for the full temperature range from 4 K to 300 K. Contributions from thermal and excess noise in the channel have been extracted using both on-wafer and LNA-based measurements. Variations in channel noise with different channel indium contents and temperatures were used to identify the physical mechanisms governing the noise in the InP HEMT.

II. EXPERIMENT

The InP HEMTs used for noise characterization were fabricated simultaneously in a 100-nm gate-length process [9]. The cross-section of the T-shape gate region is shown in Fig. 1 including dimensions, with source-gate spacing $L_{gs} = 610$ nm, drain-gate spacing $L_{gd} = 600$ nm, recess length of 140 nm and 130 nm for left and right, respectively. Apart

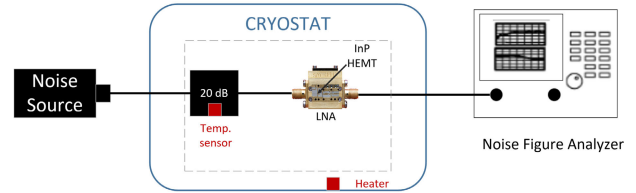


FIGURE 2. Schematic of the cryogenic noise measurement setup using an LNA module equipped with the InP HEMTs. The LNA is cooled to a temperature between 4 and 40 K inside a cryostat.

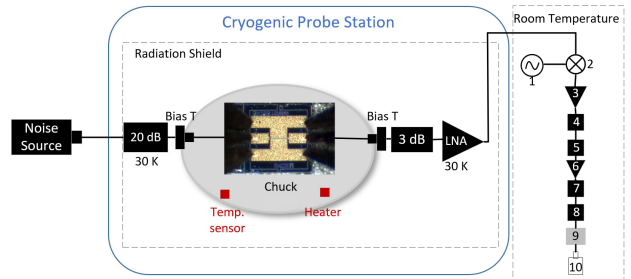


FIGURE 3. Schematic of the on-wafer noise measurement setup in a cryogenic probe station. The InP HEMT is probed on-wafer at temperatures from 40 to 300 K. The room-temperature measurement chain consists of (1) HMC-T2100 local oscillator, (2) M1-0220-P mixer, (3)-(4) low-noise amplification and attenuation, (5)-(8) bandpass filters, (9) variable attenuator, and (10) U8481A power sensor.

from the channel, the InP HEMTs had identical epitaxial structures, see details in [8]. The channel was a homogeneous $\text{In}_x\text{Ga}_{1-x}\text{As}$ layer with $x = 0.53, 0.60$, or 0.70 , and a thickness of 15, 20 and 10 nm, respectively. Under low-noise transistor operation, the two-dimensional electron gas (2DEG) will be closely located to the barrier/channel interface as seen from simulations [4], [5]. As a result, the differences in channel thickness are not expected to affect the channel noise in the InP HEMT [8].

Depending on the measurement ambient temperature T_a , two different setups were employed for estimating the InP HEMT noise from 4 K to 300 K. As a result, a high measurement accuracy was obtained in the full temperature range. At $40\text{ K} > T_a \geq 4\text{ K}$, a hybrid three-stage C-band LNA equipped with the InP HEMTs was used as shown in Fig. 2 [22], [23]. Provided the LNA gain was higher than 40 dB, the LNA $T_{e,avg}$ at 4 K was estimated to have an accuracy of 20% [8]. Since uncertainty in LNA noise measurement increased with temperature [24], an on-wafer setup was used for estimating transistor noise at $T_a \geq 40\text{ K}$. For this purpose, a cryogenic probe station was used as illustrated in Fig. 3 with a temperature sensor positioned in close proximity to the probed InP HEMT [25]. The accuracy of the system noise temperature T_{50} (with a 50-Ohm generator impedance) in the frequency range 4.0-7.2 GHz was estimated to 20% above 40 K [26]. For each channel indium content, five different InP HEMTs were measured. For each temperature and device, an average noise value was calculated from at least three independent noise measurements.

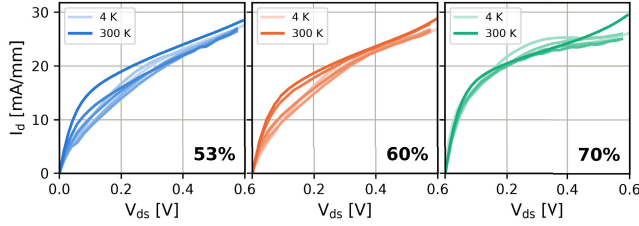


FIGURE 4. Measured output characteristics I_d - V_{ds} of the 53%, 60% and 70% indium channel InP HEMTs. Trace shading indicates the ambient temperature from $T_a = 4$ K (lightest) to 300 K (darkest).

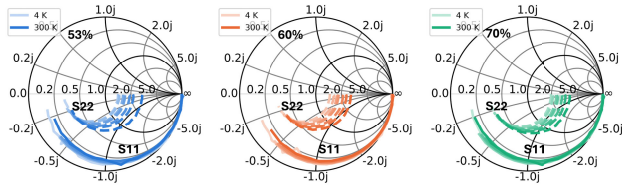


FIGURE 5. Measured input and output reflection coefficients S_{11} and S_{22} for 53%, 60% and 70% indium channel InP HEMTs at $V_{ds} = 0.5$ V and $I_d = 25$ mA/mm, for T_a from 4 K (lightest) to 300 K (darkest).

III. DC AND RF CHARACTERIZATION

Fig. 4 shows the measured I_d - V_{ds} for the three InP HEMTs from $T_a = 4$ K to 300 K. For each T_a , the gate voltage V_{gs} was tuned to give the I_d aimed for the noise measurements. The dependence on channel indium content is visible in the shape of the output characteristics. From drain voltage $V_{ds} \approx 0.5$ V, the 70% indium channel InP HEMTs exhibits a minor kink effect not seen for 53% and 60% devices, in agreement with Ref. [5], associated with impact ionization and surface traps [4].

Fig. 5 demonstrates the measured input and output reflection coefficients S_{11} and S_{22} at $I_d = 25$ mA/mm and $V_{ds} = 0.5$ V which corresponded to the bias conditions used in the noise measurements (Sec. IV). For a given device, the S_{11} plots for all T_a almost overlap completely, and the three indium channel compositions closely trace similar paths. S_{11} is essentially independent of T_a and the channel indium content, as expected when it is dominated by the pad and access parasitics rather than by the intrinsic transistor. S_{22} looks into the drain terminal and is dominated by the channel's output conductance g_{ds} . This parameter is set directly by the carrier transport in the channel which is strongly temperature-dependent as seen in S_{22} in Fig. 5.

The forward transmission $|S_{21}|$ (same bias as Fig. 5) is shown in Fig. 6. All devices show a single-pole roll-off from 17-23 dB at 100 MHz to unity gain at 50-60 GHz. Cooling raises $|S_{21}|$ by 1-3 dB relative to 300 K, consistent with the increase in electron mobility and transconductance on cooling. The $|S_{21}|$ exhibits a strong dependence on indium channel: the 70% indium channel InP HEMT shows the highest gain for all T_a , consistent with the approximately 1.5 dB higher gain observed for this device in the 4-8 GHz noise band reported in [8].

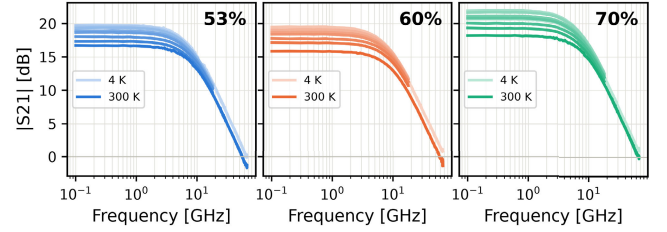


FIGURE 6. Measured forward transmission $|S_{21}|$ versus frequency for 53%, 60% and 70% indium channel InP HEMTs at $V_{ds} = 0.5$ V and $I_d = 25$ mA/mm. Trace shading indicates the ambient temperature from $T_a = 4$ K (lightest) to 300 K (darkest).

Taken together, cooling these InP HEMTs produces a modest and consistent increase in gain and drain current without altering the input impedance environment presented. Any difference in noise performance between the three devices is therefore expected to originate from the intrinsic $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel rather than in the passive access or matching conditions.

IV. NOISE CHARACTERIZATION AND DISCUSSION

InP HEMTs were biased at $V_{ds} = 0.5$ V and $I_d = 25$ mA/mm. On-wafer, this bias was applied directly to the individual InP HEMT. In the LNA, the three stages were dc-biased in parallel from a common supply at $V_{DS} = 0.725$ V and $I_D = 15$ mA. The difference between V_{DS} and V_{ds} is calculated from the bias network, so that each stage operated at $V_{ds} = 0.5$ V and $I_d = 25$ mA/mm. The two noise measurement methods therefore probe the InP HEMT at an identical device bias point. This corresponded to the lowest noise at 4 K and provided sufficient gain also at 300 K [8], [14]. The V_{gs} was adjusted at each temperature to maintain constant bias conditions. While the InP HEMTs measured using the LNA had gate widths of $4 \times 50 \mu\text{m}$, the InP HEMTs probed on-wafer were $2 \times 100 \mu\text{m}$. The resulting difference in gate resistance caused by the different layouts had a small effect on the gate thermal noise which was not significant for estimation of the channel noise [5]. The LNAs measured at 4 K had an average gain of 46 dB for 70% indium channel, and 42 dB for 53% and 60% indium channel InP HEMTs. The average gain of the InP HEMTs measured on-wafer was between 15.0 and 17.5 dB for 80-300 K, with the 70% indium channel exhibiting about 1.5 dB higher gain than 53% and 60% indium channel InP HEMTs. The amount of gain was sufficient for accurate noise estimation [14].

For both methods of noise determination, the channel noise in the InP HEMT was extracted using the Pospieszalski model [27]. The intrinsic output conductance $g_{ds,i}$ was obtained from the InP HEMT small-signal model using S-parameter measurements for each temperature and bias point [28]. This procedure allowed extraction of the equivalent drain noise temperature T_d which was used to calculate the channel current noise power spectral density (PSD) $S_{id} = 4k_B T_d g_{ds,i}$, where k_B is the Boltzmann constant. For the LNA-based extraction, the package, bond wires, passive matching network were all fixed, and the input reference

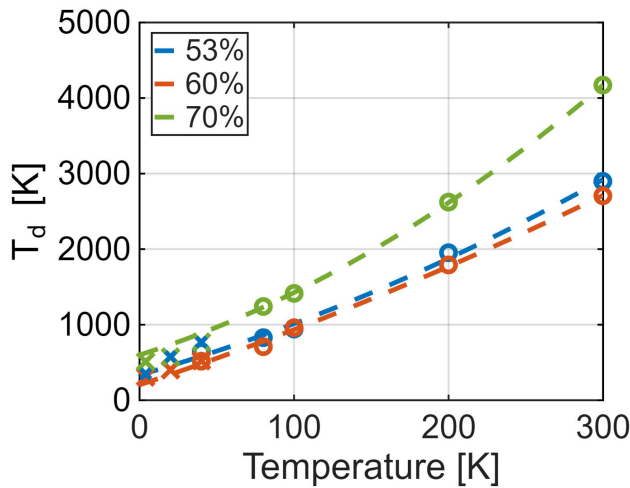


FIGURE 7. Equivalent drain noise temperature T_d versus ambient temperature for InP HEMTs with channel indium content of 53%, 60%, and 70%, biased at $V_{ds} = 0.5$ V and $I_d = 25$ mA/mm. Circles and crosses represent T_d values extracted from on-wafer and LNA noise measurements, respectively. Dashed lines are parabolic fits to the on-wafer data above 40 K, extrapolated to 4 K. The absence of on-wafer data below 80 K for the 70% indium channel InP HEMT was due to oscillations occurring during probing.

plane was set by a cold attenuator [24], leaving T_d of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel as the only free parameter. Because the three LNAs were identical in package, bond wires and matching network, their contributions to $T_{e,avg}$ were common to all three LNAs and bias-independent. As a result, $g_{ds,i}$ for the $\text{In}_x\text{Ga}_{1-x}\text{As}$ HEMT channel will be the dominant noise source at the optimum low-noise bias [8]. For $T_a \leq 10$ K, the gate noise temperature T_g in Pospieszalski's noise model was set to 10 K thus taking the device self-heating into account [29]. Above 10 K, T_g was set equal to T_a .

The extracted T_d from 4 K to 300 K is shown for all three InP HEMTs in Fig. 7. Both measurement methods display consistent trends with good agreement between the on-wafer and LNA results for the 53% and 60% indium devices below 40 K. Across the full temperature range, T_d is the lowest for the 60% indium channel HEMT, confirming the indium content dependence with the $T_{e,avg}$ of the 4–8 GHz LNA at 4 K previously reported [8]. The observed increase of T_d with T_a is consistent with earlier studies [30], [31], [32], [33], [34], [35]. Even though T_d also has been reported to be weakly dependent on temperature [36], it appears that for the low I_d applied here, a parabolic fit to the on-wafer data above 40 K provides a good description of the temperature dependence [37]; See dashed lines in Fig. 7. Furthermore, the tendency for the saturation of T_d at low temperatures is probably influenced by device self-heating [38]. Higher dc power dissipation is expected to result in stronger T_d saturation as the T_a decreases, consistent with the weaker saturation observed for T_d in our devices compared to those in [37].

The S_{id} at 4 K versus channel indium content is shown in Fig. 8, comparing values obtained from the LNA

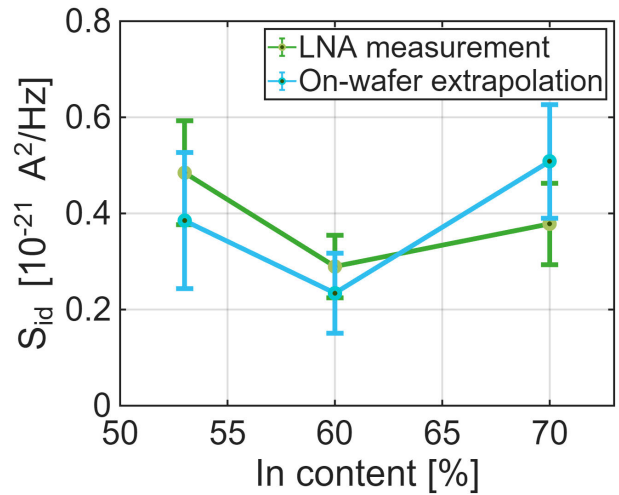


FIGURE 8. Channel current noise spectral density S_{id} at 4 K as a function of indium content x in $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel InP HEMTs. Green points show values extracted from LNA noise measurements. Blue points show values extrapolated to 4 K from the T_d model fitted to on-wafer measurements (Fig. 3); Error bars represent the combined measurement uncertainties and fitting errors.

measurements and the parabolic extrapolation of the on-wafer noise data to 4 K in Fig. 7. Both noise measurement methods display the same trend in S_{id} for varying channel indium content in the InP HEMT. This demonstrates that cryogenic noise performance at 4 K can be predicted without the need for dedicated cryogenic characterization at this temperature. It is confirmed that the 60% indium channel InP HEMT exhibits the lowest channel noise at cryogenic temperatures.

The observed temperature dependence of T_d in Fig. 7 indicates that the channel noise cannot be attributed only to suppressed shot noise [18]. The temperature dependence of T_d in a suppressed shot noise model can be expressed by:

$$T_d = \frac{qFI_d}{2k_B g_{ds,i}}, \quad (1)$$

where F is the Fano factor [39]. Assuming F is temperature independent, Eq. (1) predicts a two-fold change in T_d due to the variation of $g_{ds,i}$ between 4 K and 300 K for the InP HEMTs studied here. However, Fig. 7 demonstrates an increase with a factor of 6 in T_d from 4 K to 300 K. Similar discrepancies have been reported in [40] and also seen in the data in [35]. Hence the noise measurements in this study strongly suggest that the temperature dependence of T_d in the InP HEMTs reflects a physical mechanism for the channel noise beyond suppressed shot noise.

To analyze the origin of the channel noise, S_{id} can be decomposed into a thermal noise contribution $S_{id,th}$ and an excess noise contribution $S_{id,ex}$ [30]. The thermal noise PSD is expressed by $S_{id,th} = 4k_B T_a g_{ds0}$, where g_{ds0} is the output conductance at zero drain bias extracted from the $I_d - V_{ds}$ characteristics [41]. $S_{id,th}$ represents the equilibrium thermal noise contribution, corresponding to channel electrons in thermal equilibrium with the lattice at T_a . In 100-nm gate-length InP HEMTs operating in saturation, carriers near the

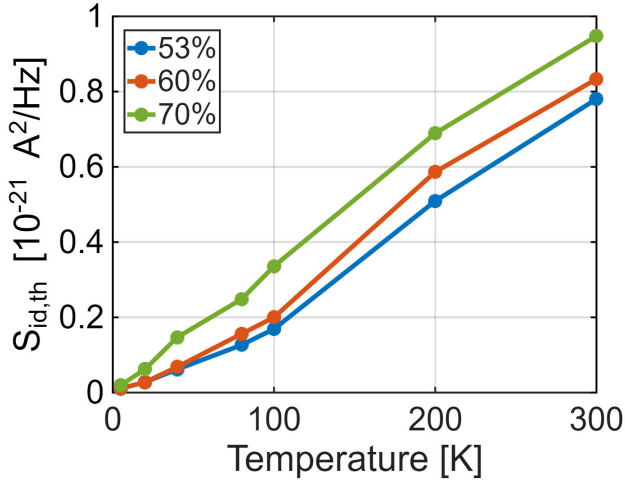


FIGURE 9. Thermal noise PSD $S_{id,th} = 4k_B T_a g_{ds0}$ versus ambient temperature for InP HEMTs with channel indium content of 53%, 60%, and 70%.

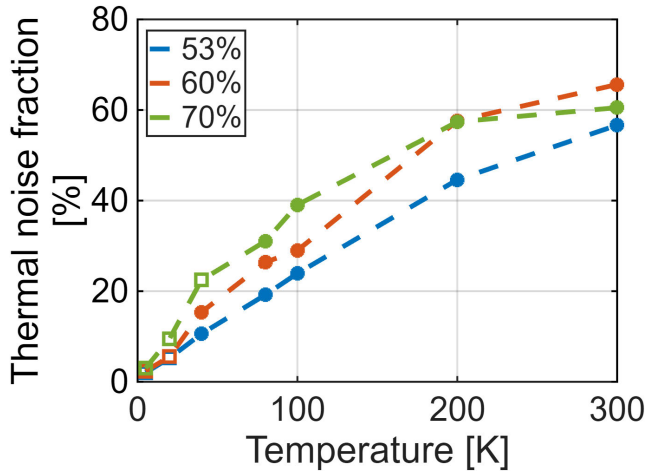


FIGURE 10. Fractional contribution of thermal noise to the total channel noise PSD $S_{id,th}/S_{id}$ versus ambient temperature for InP HEMTs with channel indium content of 53%, 60%, and 70%.

drain end of the channel are heated significantly above T_a , with an electron temperature T_e typically above 1000 K [19], [42]. The channel noise originating from these hot electrons is captured in $S_{id,ex}$. The $S_{id,th}$ provides a lower bound for the thermal noise. $S_{id,th}$ is shown versus T_a in Fig. 9 and reveals a linear temperature dependence. $S_{id,th}$ increases with indium content, as higher indium content yields higher electron mobility and thus higher g_{ds0} [8]. The fractional contribution of $S_{id,th}$ to the total channel noise S_{id} , illustrated in Fig. 10, confirms that the thermal noise accounts for the majority of S_{id} at room temperature and becomes negligible at 4 K.

The excess noise $S_{id,ex} = S_{id} - S_{id,th}$, plotted versus T_a in Fig. 11, remains essentially independent of temperature for all three indium compositions, confirming that $S_{id,ex}$ dominates the total channel noise at 4 K [43]. The temperature independence of $S_{id,ex}$ is consistent with a shot-noise-like origin. The Fano factor for excess noise $F_{ex} = \frac{S_{id,ex}}{2qI_d}$, where

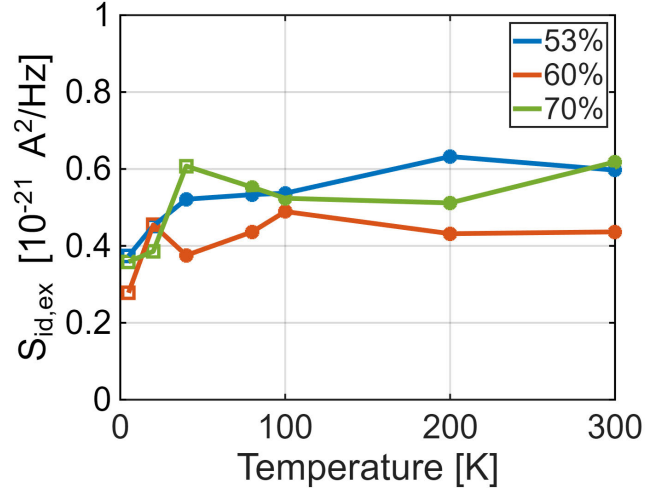


FIGURE 11. Excess noise PSD $S_{id,ex}$ versus ambient temperature for InP HEMTs with channel indium content of 53%, 60%, and 70%. Solid markers: values extracted from on-wafer noise measurements; open markers: values extracted from LNA measurements.

$\overline{S_{id,ex}}$ denotes averaging over the measured temperature range 4–300 K, exhibits values of 0.33, 0.26, and 0.32 for the 53%, 60%, and 70% indium channels, respectively. The 60% indium channel shows the lowest excess noise, with F_{ex} approximately 20% lower than the other two channel compositions. In the suppressed shot noise model, F is determined by the gate length and I_d [18], [39]. Since gate length and I_d are identical for all three devices, the observed variation of $S_{id,ex}$ with indium content can not be exclusively attributed to a suppressed shot noise mechanism.

We now discuss two hot-electron mechanisms which may be involved in generation of channel noise for the InP HEMTs: impact ionization, in which energetic channel carriers generate additional electron-hole pairs [44], and RST where hot electrons are emitted from the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel into the InAlAs barrier [42]. Both noise mechanisms depend on the channel indium composition of the InP HEMT but in different ways.

Impact ionization requires the charge carriers in the 2DEG to acquire sufficient energy to generate electron-hole pairs. In 100-nm gate-length InP HEMTs, Monte Carlo simulations indicates that the peak electric field under the gate exceeds this energy even at the low-noise bias point for 53% indium channel [45]. Impact ionization is strongly dependent on the bandgap E_g of the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel [46]. The E_g at 300 K of the channel follows the bowing parameterization [47]:

$$E_g(x) = (1-x)E_{g,\text{GaAs}} + xE_{g,\text{InAs}} - Cx(1-x), \quad (2)$$

with $C = 0.477 \text{ eV}$, $E_{g,\text{GaAs}} = 1.52 \text{ eV}$ and $E_{g,\text{InAs}} = 0.42 \text{ eV}$ [47]. Eq. (2) gives $E_g = 0.82, 0.74$ and 0.65 eV for $x = 0.53, 0.60$ and 0.70 , respectively. Since the 60% and 70% channels are pseudomorphically strained, these values are a conservative lower bound on E_g . For the InP HEMTs studied here, the 70% indium channel device has the narrowest E_g and will suffer from the strongest impact ionization noise [46]. This

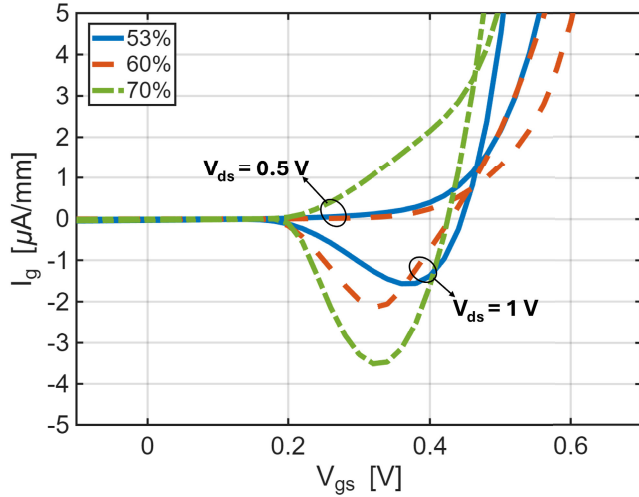


FIGURE 12. Gate current I_g versus V_{gs} at $V_{ds} = 0.5\text{ V}$ and 1 V at 4 K for InP HEMTs with channel indium content of 53%, 60%, and 70%.

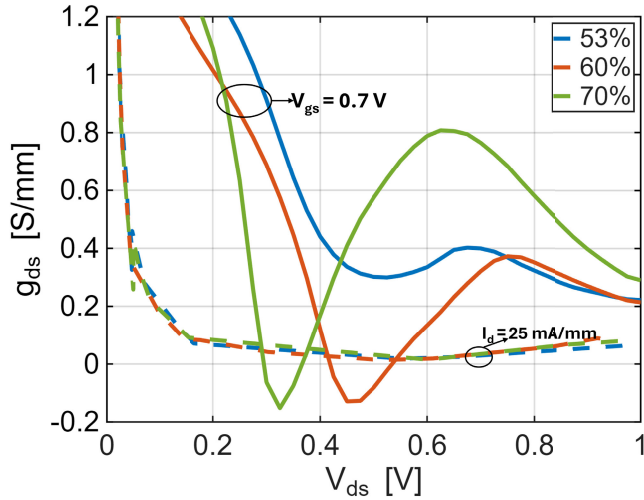


FIGURE 13. Output conductance g_{ds} versus V_{ds} at 4 K for the 53%, 60% and 70% indium channel InP HEMTs. Dashed lines: V_{gs} adjusted at each V_{ds} to keep $I_d = 25\text{ mA}/\text{mm}$, the noise-measurement bias. Solid lines: fixed $V_{gs} = 0.7\text{ V}$.

is confirmed by the measured gate current I_g at the low-noise bias ($V_{ds} = 0.5\text{ V}$, $V_{gs} = 0.22 - 0.26\text{ V}$ for $I_d = 25\text{ mA}/\text{mm}$) plotted in Fig. 12, where the 70% device shows one order of magnitude higher I_g (80 nA at 4 K , 110 nA at 300 K) than the 53% and 60% devices (5 and 3 nA at 4 K , 10 and 30 nA at 300 K , respectively). Although I_g itself is too small to significantly contribute to the channel noise via gate shot noise ($2qI_g \sim 10^{-26}\text{ A}^2/\text{Hz}$), its elevated value is a well-established indicator of enhanced impact ionization noise [48]. The bell-shaped curves for I_g at $V_{ds} = 1\text{ V}$ is also a characteristic for impact ionization [49] accompanied by an increase in g_{ds} extracted from the $I_d - V_{ds}$ characteristics as shown in Fig. 13. The presence of impact ionization taking place in the InP HEMT may create excess noise in the channel also under the low-noise bias conditions used here as suggested by Monte Carlo simulations [50] and experimental data [21]. The elevated excess noise observed for the 70%

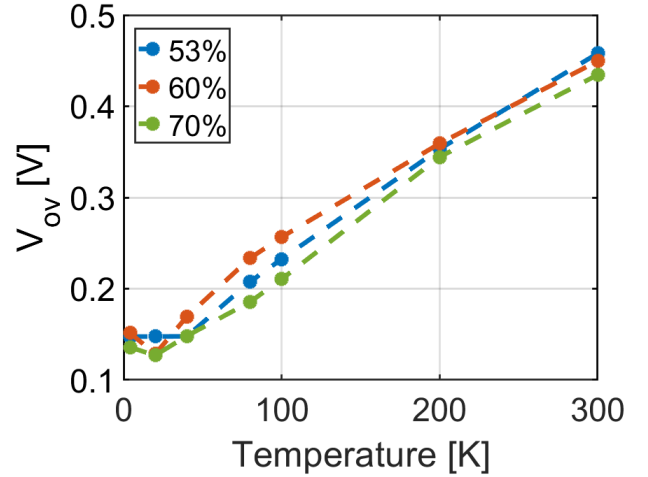


FIGURE 14. Overdrive voltage V_{ov} versus ambient temperature for InP HEMTs with channel indium content of 53%, 60%, and 70%.

indium channel device may therefore be associated with a stronger noise contribution originating from impact ionization taking place in the channel of the InP HEMT.

RST noise in the InP HEMT arises because the electrical transport properties differ substantially between the $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel and the InAlAs barrier [42]. Following [19], the RST contribution to the drain noise temperature can be written as

$$T_{d,\text{RST}} = \frac{q^2 v_d^2 n_{s,2} \tau_{\text{RST}}}{k_B g'_{ds,i} L}, \quad n_{s,2} = \gamma \eta n_{s,1}, \quad (3)$$

where v_d is the electron drift velocity in the channel, τ_{RST} the characteristic channel-to-barrier transfer time, $g'_{ds,i} = g_{ds,i}/W$ the intrinsic output conductance per unit gate width, L the length of the hot-electron region at the drain end of the channel, $n_{s,1}$ the channel sheet carrier density in that region, $n_{s,2}$ the sheet density of electrons transferred into the barrier, and γ the emission probability. η is the transferred fraction of electrons that transfer from the channel to the barrier which depends exponentially on the conduction band offset ΔE_c at the InGaAs/InAlAs interface through $\eta = \exp\left[-\frac{\Delta E_c - qV_{ov}}{k_B T_e}\right]$. In [19] the exponent is written with V_{gs} ; here it is expressed through the overdrive voltage $V_{ov} = V_{gs} - V_{th}$, where V_{th} is the threshold voltage, thus allowing fair comparison between different devices [20]. Since V_{ov} is similar for the three devices (Fig. 14), V_{ov} contribution to the RST noise largely cancels in a comparison between them. Evaluating $\exp(-\Delta E_c/k_B T_e)$ at $T_e = 1000\text{ K}$ [19], [42] using $\Delta E_c = 0.52, 0.64$, and 0.68 eV [51] yields 2.4×10^{-3} , 6.0×10^{-4} and 3.7×10^{-4} for the 53%, 60% and 70% indium channels, respectively [51]. This is a four-fold reduction of the transferred fraction from 53% to 60% indium and a further 1.6-fold reduction from 60% to 70%. The remaining quantities in Eq. (3) vary much more weakly with channel indium content than this exponential, meaning that ΔE_c governs the composition dependence of the RST noise. Indeed, recent experimental evidence by varying barrier compositions in InGaAs/InAlAs quantum wells has

confirmed that RST contributes to microwave noise, supporting the hypothesis that RST noise is part of the channel noise in our InP HEMTs [52].

Both RST and impact ionization require hot electrons with $T_e \gg T_a$. Since T_e is primarily determined by the electric field under low-noise bias [19], [45], the variation of T_a from 4 K to 300 K represents a negligible perturbation to T_e compared to the field-induced heating. Both Eqs. (2) and (3) depend on the channel indium content with opposite sign. As a result, the non-monotonic dependence of excess noise on channel indium content in Fig. 11 can be understood from the combination of RST and impact ionization both contributing to channel noise. For the 53% indium channel device, the small ΔE_c means higher probability for RST, elevating the excess noise. For the 70% indium channel device, the narrow bandgap promotes impact ionization, also increasing the excess noise. The 60% indium channel device achieves the optimal balance between impact ionization and RST noise resulting in the lowest $S_{id,ex}$.

V. CONCLUSION

We have investigated the channel noise from 4 K to 300 K for 100-nm gate-length InP HEMTs with $\text{In}_x\text{Ga}_{1-x}\text{As}$ channel indium content ranging from 53% to 70%. Two different noise measurement methods were utilized, one based on on-wafer probing above 40 K and one using an LNA below 40 K. The two methods yielded consistent results across the full temperature range, confirming the reliability of the noise characterization. The 60% indium channel InP HEMT exhibited the lowest T_d across the entire temperature range. The on-wafer noise data above 40 K was fitted with a parabolic function and extrapolated to 4 K, showing good agreement with the LNA measurement results. The channel noise comprised a thermal noise contribution dominating at 300 K and a temperature-independent excess noise contribution dominating at 4 K. The non-monotonic dependence of $S_{id,ex}$ on channel indium content for fixed gate length and bias could not be explained by only taking suppressed shot noise into account. It is therefore suggested that excess noise in the channel also must be attributed to additional hot-electron mechanisms, specifically impact ionization and RST. These noise mechanisms exhibit opposite dependencies on channel indium content through ΔE_c and E_g , resulting in the observed minimum excess noise for the 60% indium channel HEMTs. The results suggest that further advancement of InP HEMT LNA performance for radio astronomy and quantum computing should focus on reducing channel noise not only from suppressed shot noise but also from impact ionization and RST noise.

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