Towards ultralow-noise cryogenic InP high electron mobility transistors: investigation of physical origins of microwave noise

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InP based HEMTs are widely used in microwave low-noise amplifiers due to their outstanding low-noise performance. State-of-art cryogenic devices now reach around 3-5$\times$ the quantum noise limit in 1 – 100 GHz. Over the past three decades, the reduction in noise has primarily been achieved via advancement of microfabrication techniques and geometric transistor scaling. However, further improvement of the noise performance requires a physics-based understanding of the origin of microwave noise. The output noise, also known as drain noise, is presently described by a fitting parameter denoted the drain noise temperature (T_d) which lacks an accepted physical origin. A recent theory attributes drain noise to the sum of thermal noise arising from hot electrons in the HEMT channel and the partition noise arising from real-space transfer (RST) from channel to barrier layer (I. Esho, A.Y. Choi, A.J. Minnich, ”Theory of drain noise in high electron mobility transistors based on real-space transfer” J. Appl. Phys., vol. 131, issue 8, Feb. 2022). In this mechanism, electrons are heated by the electric field under the gate to physical temperatures exceeding 1000 K, leading to thermionic emission of electrons out of the channel and into the barrier. The differing mobility of the channel and barrier films leads to partition noise as electrons jump back and forth between the films and thereby cause fluctuations in the channel conductance. The theory makes several predictions, among them that T_d should exhibit a dependence on temperature as temperature alters the fraction of electrons with sufficient energy to undergo thermionic emission. However, experimental data to test this theory have been lacking.

To test this prediction, we used a cryogenic probe station to measure the on-wafer S-parameters and microwave noise temperature with 50 Ω source impedance (T_{50}) of discrete InP HEMTs over a range of physical temperatures (T_{ph}), 40 K – 300 K. From these data, we extracted a small-signal model and the drain noise temperature (T_d) at each bias and T_{ph}. We find that drain noise T_d exhibits a temperature dependence that cannot be explained if the drain noise source were only thermal. In particular, T_d is observed to vary nonlinearly with T_{ph}, from a value of 600 K at cryogenic temperatures to 2000 K at room temperature, as shown in Fig. 5 of (B. Gabritchidze, K. Cleary, A. C. Readhead, A. J. Minnich, ”A Physical Model for Drain Noise in High Electron Mobility Transistors: Theory and Experiment”,arXiv:2209.02858, Apr. 2023). The observed trend is consistent with the RST theory of drain noise. This finding suggests that HEMTs with improved noise performance could be achievable by altering the alloy compositions of the channel and barrier films to increase the conduction band offset which confines electrons in the quantum well, thereby suppressing RST noise. Using our noise model, the magnitude of noise temperature reduction is calculated to be around 30-50% over a range of physical temperatures.