Investigation of Drain Noise in Cryogenic InP High Electron Mobility Transistors Using On-wafer *S*-parameter and Microwave Noise Characterization

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2022 Compound Semiconductor Week (CSW) | 978-1-6654-5340-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/CSW55288.2022.9930365

***Abstract*— We report the on-wafer characterization of *S*-parameters and microwave noise (T_{50}) of discrete InP HEMTs over a range of physical temperatures, 40 K – 300 K. From these data, we extract a small-signal model and the drain noise temperature (T_d) at each bias and temperature. We find that T_{50} exhibits a temperature dependence that is incompatible with a fixed T_d. In contrast, explaining the noise measurements requires T_d to change from ~ 2500 K at room temperature (RT) to ~ 400 K at cryogenic temperatures. This trend is consistent with the predictions of a theory of drain noise based on real-space transfer of electrons from the channel to the barrier [5].**

***Keywords*— High electron mobility transistors; low noise amplifiers, microwave noise; cryogenic electronics**

InP based HEMTs have become the mainstream in microwave low noise amplifiers due to their low noise characteristics [1]. While significant improvements have been made in their noise and frequency performance [2,3], a physics-based understanding of the origin of drain noise, which plays a critical role in the overall noise performance of HEMTs, is lacking. Existing noise models, such as [4], can model the total noise but fail to assign a physical mechanism, with the drain noise temperature T_d taken as a fitting parameter.

A recent theory attributes drain noise to microwave partition noise arising from real-space transfer (RST) [5]. In this mechanism, electrons are heated by the electric field under the gate to physical temperatures exceeding 1000 K, a sufficiently high temperature that some electrons may thermionically emit out of the channel into the barrier. Because the barrier mobility is substantially less than that of the channel, two dissimilar conduction pathways exist from source to drain, creating partition noise.

The theory makes several predictions, among them that T_d should exhibit a temperature dependence as temperature alters the fraction of electrons with sufficient energy to undergo thermionic emission. To test this prediction, we performed on-wafer *S*-parameter and noise characterization of discrete InP HEMTs at physical temperatures ranging from 40 – 300 K using a cryogenic probe station. At each temperature we extracted a small signal model (SSM) of the discrete HEMT and obtained T_d by fitting the modeled and measured T_{50}, where T_{50} is the noise temperature at generator impedance of 50 Ω.

Fig. 1 shows the *S*-parameters (a) and T_{50} (b) versus frequency at various physical temperatures. As has been reported, T_{50} exhibits a temperature dependence, with values ranging from ~ 10 K at 40 K to ~ 50 K at 300 K. The temperature dependence of *S*-parameters is not as pronounced but variation over the same temperature range is observed. Fig. 2 shows the measured and predicted T_{50} (a) and extracted T_d (b) versus physical temperature. The predicted T_{50} was obtained by using the extracted SSM at each physical temperature but fixing T_d at its RT value. There is a clear deviation between the measured and simulated T_{50}, indicating that T_d must exhibit a temperature dependence. This dependence is shown in Fig. 2(b). The drain temperature varies from $\sim 2500 \pm 400$ K at RT to $\sim 400 \pm 150$ K at 40 K.

We observe that the trend of T_d with physical temperature qualitatively agrees with the predicted trends of Fig. 3 of [5]. This observation supports the interpretation that drain noise arises from RST of electrons from channel to barrier. This physical understanding of the origin of drain noise will help to realize HEMTs with improved microwave noise performance.

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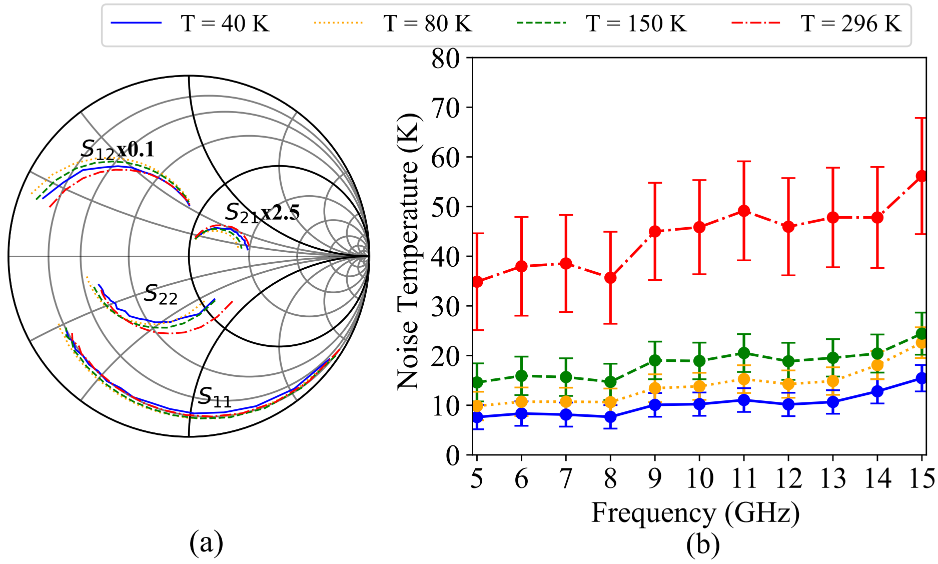

Fig. 1. Measured *S*-parameters (a) and noise temperature T_{50} (b) versus frequency from 40 K to 300 K. The V_{DS} and I_{DS} were fixed at V_{DS}=0.6 V and I_{DS}= 5 mA at all temperatures. The error bars in (b) were determined by propagating the uncertainties of the measurement setup, from the noise source to power meter, through the computation of the Y-factor.

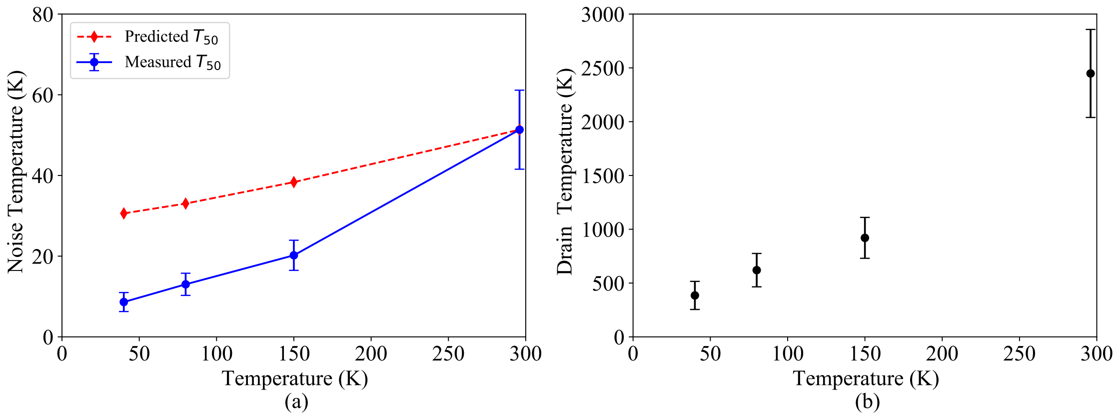

Fig. 2. Measured and predicted T_{50} versus physical temperature (a) and drain temperature versus physical temperature (b). The predicted T_{50} was estimated by extracting a SSM at each T_{ph} but keeping T_d constant at the RT value. V_{DS} and I_{DS} were fixed at V_{DS}= 0.6 V and I_{DS}= 5 mA at all temperatures. The data in (a) are at 12 GHz. The error bars for T_d were determined by calculating T_d for the minimum and maximum values of T_{50} within the error bars and were found to range from ±150 K to ±400 K, depending on physical temperature and the uncertainty in T_{50}.