Cryogenic Kink Effect in InP pHEMTs: A Pulsed Measurements Study

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Abstract—We present a study based on pulsed measurement results of the kink effect observed on the $I-V$ output characteristics in InGaAs/InAlAs/InP pseudomorphic high-electron mobility transistors (InP pHEMTs) at cryogenic temperatures. Pulsed measurements were performed at 300 and 10 K. Gate and drain lags were observed at both temperatures with a strong increase upon cooling for the drain lag. To study the influence of surface traps in the kink, pulsed measurements of devices passivated by either atomic layer deposited Al$_2$O$_3$ or plasma enhanced chemical vapor deposited Si$_3$N$_4$ were compared with no significant differences at 10 K. The influence on the kink effect from the buffer was studied by comparing pulsed measurement data from an InP pHEMT with measurements on a GaAs metamorphic HEMT (GaAs mHEMT). For the GaAs mHEMT, an increase of the drain lag at 10 K was observed when compared with the InP pHEMT. Contrary to the InP HEMT, for the GaAs mHEMT the 0.1 $\mu$s pulses were short enough to eliminate the kink when using a quiescent point with $V_{DS} = 0$. The quality of the pinchoff was sensitive to pulse length and quiescent point for the InP pHEMT but not for the GaAs mHEMT.

Index Terms—Cryogenic, InGaAs/InAlAs/GaAs metamorphic HEMT (GaAs mHEMT), InGaAs/InAlAs/InP pseudomorphic high-electron mobility transistor (InP pHEMT), kink effect, low noise, pulsed measurements, traps.

I. INTRODUCTION

InAlAs/InGaAs high-electron mobility transistors (HEMTs) have in the last decade proven to be the best technology for lowest noise amplification, especially at cryogenic temperatures around 5–15 K. Recently, a record minimum noise temperature of 1 K at 6 GHz was reported for an InGaAs/InAlAs/InP pseudomorphic HEMT (InP pHEMT) at an ambient temperature of 10 K [1].

When working at cryogenic temperatures, a strong kink in the output current at low drain bias (around 0.4 V) has been observed in these record low noise InP pHEMTs (Fig. 1). Kink effect in InAlAs/InGaAs HEMTs is a complex phenomenon intensively studied at room temperature [2]–[4].

II. DEVICE FABRICATION AND MEASUREMENTS SETUP

An InP pHEMT Si$_3$N$_4$ passivated by plasma enhanced chemical vapor deposition (PECVD) was considered as a reference device. Epitaxial structure and fabrication process of this device have been described in [1]. We will refer to this device as InP pHEMT. To study the influence of the
passivation method and the buffer in the kink two more devices have been measured and compared with the InP pHEMT:

1) InGaAs/InAlAs/InP pHEMT Al$_2$O$_3$ passivated by atomic layer deposition (ALD). In this case, the device only differs from the InP pHEMT in the passivation process [13]. We will refer to this device as ALD-InP pHEMT.

2) InGaAs/InAlAs/GaAs metamorphic PECVD Si$_3$N$_4$ passivated HEMT that only differs from the InP pHEMT in the buffer and substrate [14]. Along the text we will refer to this device as GaAs mHEMT. Both InP pHEMT and GaAs mHEMT have the same active layers and were fabricated side by side following the same fabrication process.

For the pulsed measurements, a commercial dynamic $I$–$V$ analyzer [12], [15] that simultaneously applies pulses on gate and drain was used. To identify drain and gate lag, three different quiescent points ($V_{DS0}$ and $V_{GS0}$ in Fig. 2) were considered as follows.

i) $V_{DS0} = 0.0$ and $V_{GS0} = 0.0$.

ii) $V_{DS0} = 0.0$ and $V_{GS0} = −0.6$ V.

iii) $V_{DS0} = 1.0$ V and $V_{GS0} = −0.6$ V.

Gate lag can be observed when comparing i) and ii), and drain lag when comparing ii) and iii) [16]. Pulse lengths ($a$ in Fig. 2) of 0.1, 1, 10, 100, and 1000 $\mu$s, with 50-ms separation ($b$ in Fig. 2), have been considered.

### III. InP pHEMT Results

Fig. 1 shows static (nonpulsed) drain current $I_D$ versus drain voltage $V_{DS}$ of the InP pHEMT at 300 and 10 K. As shown in Fig. 1, at 10 K this device exhibits a very pronounced kink from $V_{DS}$ around 0.4 V. At 300 K, the kink is also present at the same bias but much less prominent.

Fig. 3 shows the output conductance $g_{DS}$ versus the drain bias. For $V_{DS} > 0.35$ V and $V_{GS} > 0.1$ V (region A), the kink phenomenon results in a strong increase of $g_{DS}$. The low $V_{DS}$ where the kink appears, considering an InGaAs channel HEMT [11], suggest that the kink is not due to impact ionization. The gate current $I_G$ versus gate bias $V_{GS}$ is plotted in Fig. 4 at both 300 and 10 K. No bell shape, indicative of impact ionization [10], [11], [17], is observed in the gate current at $V_{DS} 0.35$ V. Moreover, in agreement with the previous results for InGaAs-based devices [18], Fig. 4 indicates a decrease in impact ionization when decreasing temperature. On the other hand, the kink is clearly enhanced at 10 K (Fig. 1). This excludes impact ionization as the dominant cause of the observed kink in the $I$–$V$ of Fig. 1. A second small kink is observed, in this case for $V_{DS} ≥ 0.7$ V. This kink can be observed in the increase of $g_{DS}$ in region B in Fig. 3. This is the typical kink from impact ionization.

To investigate traps as possible cause of the kink, pulsed measurements have been performed on this InP pHEMT at 300 and 10 K. Fig. 5 shows static results and pulsed measurements with the shortest pulses of our setup (0.1 $\mu$s) at 300 and 10 K for the three different quiescent points i)–iii). Gate lag was observed at both 300 and 10 K with a slight increase at 10 K compared with 300 K. Gate lag is commonly associated with surface traps [16], [19], [20]. Drain lag, commonly associated with traps in the buffer [16], was also observed in the InP pHEMT. This drain lag showed a pronounced increase at 10 K compared with 300 K indicating an increase of ionized traps in the buffer at 10 K. An increase of the channel resistance, whose origin may be related to the activation of traps that deplete the channel, was observed when biasing the pulses from quiescent point iii) [Fig. 5(b)]. These traps fill fast (getting negatively charged) when the drain current starts to flow through the device, and the trapped electrons are only released when the drain bias is above 0.6 V. The effect of these traps was more evident at 10 K than
at 300 K probably due to the thermal release of trapped electrons. This behavior of the traps appears to be the origin of the kink observed in the static current at 10 K. Although pulsed measurements performed from $V_{DS0} = 0.0$ [pulse types i) and ii)] reduce the kink when reducing the length of the pulse (Fig. 6), the 0.1 $\mu$s pulses were still longer than the capture time of the traps, and therefore not short enough to suppress the kink, neither at 300 K nor at 10 K.

Fig. 7 shows the transconductance $g_m$ of the InP pHEMT at 300 and 10 K for the 0.1 $\mu$s pulses generated from the three quiescent points i)–iii) at $V_{DS} = 0.6$ V. For low $V_{GS}$, $g_m$ was clearly affected by the quiescent point. The slope of $g_m$ close to pinchoff, or quality of pinchoff, (area under the square in Fig. 7), is critical for the noise [21] and was clearly affected by the different pulses. This suggests that the negative charge consequence of the ionized traps, could be involved in the depletion of the channel. On the contrary, for positive $V_{GS}$, $g_m$ was independent of the quiescent point conditions of the pulse and only the previously observed shift in the threshold voltage $V_T$ of 0.1 V was observed upon cooling [1]. A dip in the maximum of the transconductance is also observed for certain quiescent points (Fig. 7).

IV. INFLUENCE OF THE PASSIVATION METHOD:
Si$_3$N$_4$ PECVD versus Al$_2$O$_3$ ALD

To explore the influence that the surface traps have on the kink, the pulsed measurements of the InP pHEMT were compared with the ones from a device with the same fabrication process but ALD Al$_2$O$_3$ passivated (ALD-InP pHEMT) [13].

Fig. 8 shows the static and pulsed measurement data for the ALD-InP pHEMT at 300 and 10 K using the three quiescent points with the shortest pulse (0.1 $\mu$s). At 300 K, differences were observed when comparing the results of the ALD-InP pHEMT [Fig. 8(a)] with the InP pHEMT [Fig. 5(a)]. The static $I$–$V$ curves of the ALD-InP pHEMT at 300 K [Fig. 8(a)] had an improved performance with a reduction of the kink, being the results very close to the ones with quiescent point i). The gate lag, related with the traps in the surface, increased when the ALD passivation method is applied. At 10 K, no significant differences in the kink, drain and gate lags were observed in ALD-InP pHEMT [Fig. 8(b)] compared with InP pHEMT [Fig. 5(b)].

Even though a reduction of the kink was observed for the static $I$–$V$ for the ALD-InP pHEMT compared with InP pHEMT at 300 K, no similar decrease was noted at 10 K. As a result, it appears that the surface traps in the studied devices do not seem to be the main cause of the $I$–$V$ kink at cryogenic temperatures.
V. INFLUENCE OF THE BUFFER: InP pHEMT VERSUS GaAs mHEMT

To study the influence in the kink of the traps in the buffer, pulsed measurements were performed on a GaAs mHEMT that only differed from the InP pHEMT in the buffer and substrate [14].

In Fig. 9, static and the pulsed measurement results from the three different quiescent points [i)–iii)] with the shortest pulses (0.1 \( \mu \)s) for the GaAs mHEMT at 300 and 10 K are plotted. At 300 K, only a decrease of the gate lag has been observed when comparing the pulsed measurements data of the GaAs mHEMT [Fig. 9(a)] with the ones of the InP pHEMT [Fig. 5(a)]. Significant differences between the results of the InP pHEMT [Fig. 5(b)] and the ones of the mHEMT [Fig. 9(b)] were observed at 10 K. The drain lag increase appearing when cooling down to 10 K the InP HEMT, was enhanced in the case of the GaAs mHEMT. For the GaAs mHEMT, the 0.1 \( \mu \)s pulses from null drain bias [quiescent points i) and ii)] are short enough for not suffering any trap influence and reach saturation in the \( I-V \) curves [Fig. 9(b)]. Gate lag is not present in the GaAs mHEMT at either 300 or 10 K, whereas in the case of the InP pHEMT, gate lag was clearly observed. This can be clearly observed in Fig. 10, where pulses of 0.1, 10, and 1000 \( \mu \)s from quiescent points i) and ii) are compared for the InP pHEMT and
the GaAs mHEMT at 300 and 10 K. Another observation is that, in the case of the InP pHEMT, the bias of influence of the traps is invariant with temperature (around 0.2 V < $V_{DS}$ < 0.65 V at both 300 and 10 K) [see the arrows in Fig. 10(a) and (c)], but for the GaAs mHEMT becomes temperature dependent [see the arrows in Fig. 10(b) and (d)].

Fig. 11 shows the $g_m$ of the GaAs mHEMT at 300 and 10 K for the 0.1 $\mu$s pulses generated from the three quiescent points. In contrast to the previously presented results for the InP pHEMT (Fig. 7), no influence of the pulsed measurements was observed on the transconductance of the InP mHEMT.

Despite of the lack of differences between the pulsed measurements results of the GaAs mHEMT and InP pHEMT at 300 K, significant differences were found at 10 K between these two devices, revealing an important role of the buffer in the cryogenic performance of these devices.

VI. CONCLUSION

In this paper, a study of the kink effect that appears at cryogenic temperatures in InGaAs HEMTs has been presented. Impact ionization has been excluded as a possible cause of the kink, leaving traps in the buffer or in the recess as the most plausible explanation. Pulsed measurements at 300 and 10 K have been performed. Drain and gate lags have been observed in InP pHEMT at both 300 and 10 K with a strong enhancement of the drain lag when decreasing the temperature. Influence from the surface traps has been studied by comparing the pulsed measurements of two different passivation methods (Al$_2$O$_3$ ALD and Si$_3$N$_4$ PECVD). Despite that at 300 K, there is a decrease of the kink in the static characteristics together with an increase of the gate lag when using Al$_2$O$_3$ ALD, no significant differences were observed between the two passivation methods at 10 K. Pulsed measurement of a GaAs mHEMT, which only differs from the InP pHEMT in the buffer, have been performed. The observed increase of the drain lag at 10 K compared with 300 K observed for the InP, was enhanced in the case of the GaAs mHEMT. Contrary to the InP pHEMT results, the 0.1 $\mu$s long pulses have demonstrated to be fast enough to eliminate the kink, and the slope of $g_m$ close to pinchoff was shown not sensitive to pulse lengths and pulse quiescent points. The presented results suggest that traps in the buffer or in the InAlAs/GaAs interfaces are crucial for the cryogenic behavior of InP pHEMTs, influencing also the pinchoff conditions, crucial for the low-noise performance of the devices.

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REFERENCES


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