Dynamics of the Kink Effect in InAlAs/InGaAs HEMT's

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***Abstract*— We have carried out pulsed measurements of the *kink effect* in InAlAs/InGaAs HEMT's on InP with nanosecond resolution. Our measurements show that the kink's characteristic time constant is strongly dependent on $V_{\rm DS}$, i.e., it drops by more than three decades, from 100 μs down to 50 ns, between low and high values of $V_{\rm DS}$. This suggests that the kink should not be operational for frequencies in the microwave and millimeter wave regimes. We also find that the kink turn-on dynamics correlate with impact ionization. In particular, the inverse of the kink's characteristic time constant follows a classical impact ionization behavior.**

I. Introduction

In the past, InAlAs/InGaAs high electron mobility transistors (HEMT's) have shown significant promise for low-noise and high-power millimeter-wave applications. A significant anomaly in their behavior is the *kink-effect*, a sudden rise in drain current at a certain drain-to-source voltage that results in high drain conductance and g_m compression, leading to reduced voltage gain and poor linearity. The physical origin of the kink is an issue of considerable contention at this time. Conventional wisdom has attributed the kink effect to traps or their interaction with high-fields or impact ionization (II) [1]–[3]. Recently, simulations [4] as well as light emission, channel-engineering and body contact experiments [5]–[7] have suggested a link between impact ionization and the kink. Indeed, measurements showing direct correlation between II and the kink have been presented [8]. Several models involving II have been proposed including pure II [9], an SOI-like mechanism [7], hole trap charging [10], and conductivity modulation of the source [11]–[13].

A new perspective on this problem can be obtained by studying the dynamics of the kink under pulsed operation. Besides providing insight about the origin of the kink, pulsed characterization has been proven to be a good predictor of large-signal high-frequency performance [14]. In this work we have carried out the first experimental characterization of the dynamics of the kink effect in InAlAs/InGaAs HEMT's with nanosecond resolution. Our findings show that the turn-on dynamics of the kink correlate with impact ionization.

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II. Experimental Details

As a vehicle for this study, we used a lattice-matched, MBE-grown, single-heterostructure HEMT. The layer structure consists of a 2550 Å InGaAs buffer, a 200 Å InGaAs channel, a 300 Å pseudo-insulator, and a 70 Å InGaAs cap. A delta-doped electron supply layer located 30 Å above the channel yields a sheet carrier concentration of 3.0×10^{12} cm^{-2}. Fabrication is identical to the devices reported in [8], [12]. Devices with gate lengths 1.2 μm and 2 μm were characterized. The devices exhibit $I_{D,\max} = 700$ mA/mm, $g_{m,\rm peak} = 540$ mS/mm, and $BV_{DS(\rm off)} \simeq 5$ V.

Characterization was carried out using a pulsed $I-V$ set-up in which the drain is biased via a DC power supply and a load resistance of 50 Ω. The gate is pulsed from below threshold to the desired gate-to-source voltage $V_{\rm GS}$. After a delay (T_d) from the gate pulse, the drain response $I_D(T_d) - V_{\rm DS}$ to such a pulse is captured by means of a track-and-hold amplifier. All components have a bandwidth of at least 4 GHz. The devices are in a coplanar 50 Ω environment and are probed *on wafer*. Further details on the operation of the setup as well as its validation can be found elsewhere [15].

III. Results and Discussion

Pulsed $I-V$ characteristics of an $L_g = 1.2$ μm device for 8 ns $\leq T_d \leq 10$ μs are shown in Fig. 1 for a wide range of $V_{\rm DS}$ and $V_{\rm GS}$ values. Two observations can be made: 1) there is no kink for short T_d (below 8 ns); 2) the kink turns-on first and rises faster the higher $V_{\rm DS}$ is. These observations are consistent with reports in the literature on output conductance measurements of both InAlAs/InGaAs/InP HEMT's [3] and InAlAs/InGaAs/InAlAs MESFET's [16] in which no kink is observed at high frequencies despite its prominence at DC. Similar results are obtained for the $L_g = 2$ μm device.

To further analyze our results, we plot in Fig. 2(a) the kink current, ΔI_D, as a function of T_d for different values of $V_{\rm DS}$ and constant $V_{\rm GS}$ ($V_{\rm GS} = -0.9$ V), where ΔI_D is the drain current exceeding the "pre-kink" saturation drain current. As Fig. 1 shows, there is a small I_D transient of unknown origin for $V_{\rm DS}$ values below the kink. ΔI_D has been defined so as to correct for this [15]. We also plot ΔI_D as a function of T_d for constant $V_{\rm DS}$ and increasing $V_{\rm GS}$ in Fig. 2(b). The following characteristics of the kink are observed for increasing values of both $V_{\rm GS}$ and $V_{\rm DS}$: 1) the magnitude of ΔI_D increases (this is the standard DC behavior of the kink [8], [12]); 2) the rate

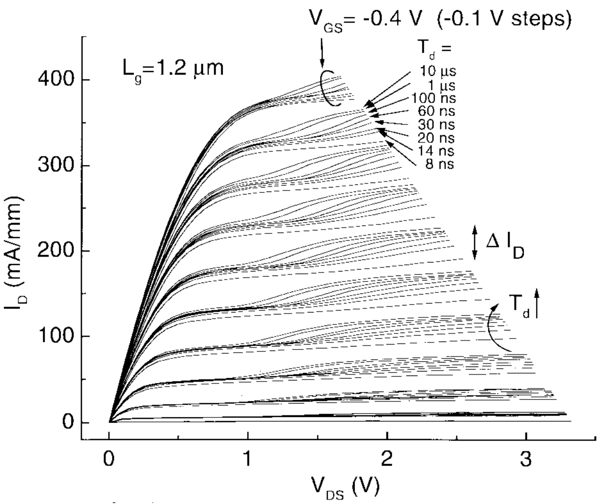

Fig. 1. Pulsed $I-V$ curves for varying delay times, T_d. No kink is seen below $T_d = 10$ ns. For a given $V_{\rm GS}$, the larger $V_{\rm DS}$, the earlier the kink turns on and the faster it saturates.

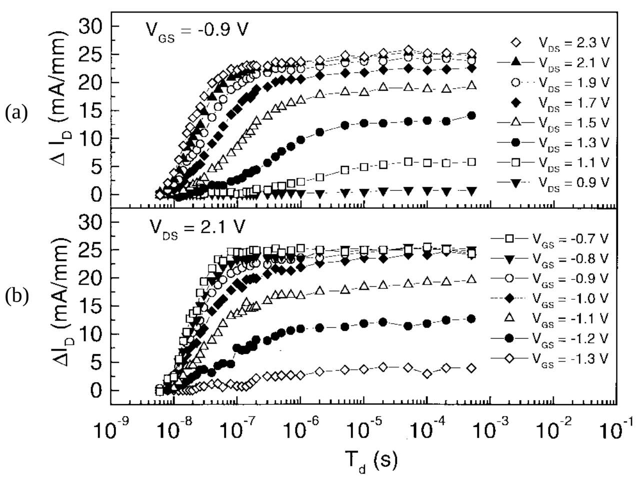

Fig. 2. ΔI_D as a function of T_d in a semilog scale. (a) Constant $V_{\rm GS}$ ($V_{\rm GS} = -0.9$ V) and varying $V_{\rm DS}$. (b) Constant $V_{\rm DS}$ ($V_{\rm DS} = 2.1$ V) and varying $V_{\rm GS}$.

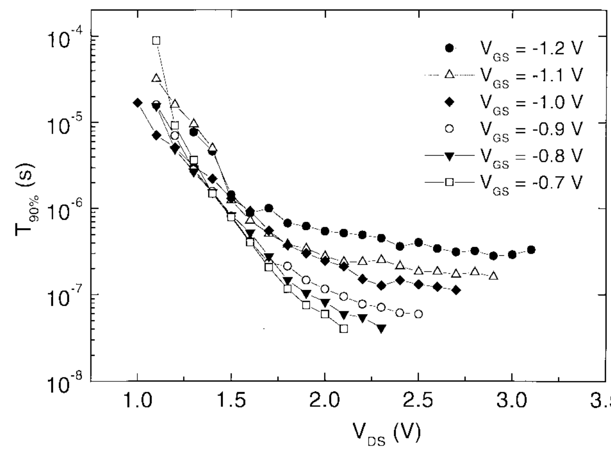

Fig. 3. $T_{90\%}$, the time it takes for the kink to reach 90% of its final DC value, as a function of $V_{\rm DS}$ for different values of $V_{\rm GS}$.

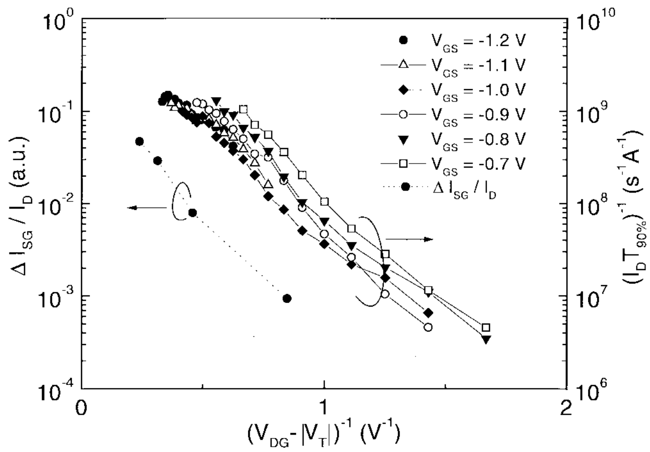

Fig. 4. $1/(I_D \times T_{90\%})$ and $\Delta I_{\rm SG}/I_D$ as a function of $(V_{\rm DG} - |V_T|)^{-1}$. $1/T_{90\%}$, just as the sidegate current, follows a classical impact ionization behavior.

at which ΔI_D builds-up increases; and 3) the saturation of ΔI_D gets sharper.

These two figures allow us to focus our attention on the rise time of the kink, $T_{90\%}$, the time for ΔI_D to rise to 90% of its final value. To the first order, $T_{90\%}$ is proportional to the characteristic time constant of the kink and consequently is a parameter of interest in circuit applications. We plot $T_{90\%}$ as a function of $V_{\rm DS}$ and increasing values of $V_{\rm GS}$ in Fig. 3. As it can be seen, $T_{90\%}$ is found to be a strong function of $V_{\rm DS}$ and $V_{\rm GS}$: it drops by more than three decades, from $\sim$100 μs down to $\sim$50 ns, as $V_{\rm DS}$ increases from 0.9–2.4 V and $V_{\rm GS}$ from -1.3 V up to -0.7 V. In particular, we observe that for small values of $V_{\rm DS}$ ($V_{\rm DS} \leq 1.6$ V), $T_{90\%}$ decreases exponentially with $V_{\rm DS}$; on the other hand, for large values of $V_{\rm DS}$ ($V_{\rm DS} \geq 2.2$ V), $T_{90\%}$ becomes independent of $V_{\rm DS}$. Clearly, the dynamics of the kink are not characterized by a single time constant that is independent of $V_{\rm DS}$ and $V_{\rm GS}$. Furthermore, the above results suggest that the kink should not respond at frequencies in the millimeter-wave range. This is because we find that the kink does not begin to build-up until a few nano-seconds and therefore it has no time to follow the signal if the operating frequency is high enough. This has already been observed in small-signal output conductance measurements in InAlAs/InGaAs/InP HEMT's [3].

Our experiments allow us to explore the connection between the kink effect and impact ionization from a different angle. If impact ionization is at the heart of the kink, then one can expect that the turn-on transient of the kink is accelerated the higher the impact ionization rate is. Hence, it is reasonable to expect a relationship between the rise time of the kink, $T_{90\%}$, and the impact ionization rate, which is proportional to $\sim I_D \, \exp -(B/(V_{\rm DS} - V_{DS,\rm sat}))$. In fact we observe such a relationship in our data. Fig. 4 plots the inverse of $I_D \times T_{90\%}$ as a function of $(V_{\rm DG} - |V_T|)^{-1}$ in a semilogarithmic scale ($V_{\rm DG} - |V_T|$ is nearly identical to $V_{\rm DS} - V_{DS,\rm sat}$). For all values of $V_{\rm GS}$, all data points fall on a straight line. This is a classical impact ionization behavior. As shown, the slope of this line is identical to the normalized sidegate current $\Delta I_{\rm SG}/I_D$ which is well known to map the impact ionization rate in this family of devices [8], [17]. Although a detailed model that establishes the physical meaning of $T_{90\%}$ still needs to be developed, the data shown in Fig. 4 gives strong credibility to impact-ionization-based theories for the kink effect.

Our observations about the dynamics of the kink are consistent with kink models that emphasize the role of impact ionized holes, such as the SOI-like model [7], hole trap charging model [10], and conductivity modulation of the source induced by hole accumulation [11]–[13]. More detailed work is required to discriminate among these models.

IV. Conclusions

In summary, we have carried out for the first time pulsed measurements of the kink dynamics of InAlAs/InGaAs HEMT's with nanosecond resolution. The kink's characteristic time constant is strongly dependent on V_{DS} and V_{GS}. Time constants between 100 μs and 50 ns have been observed. This suggests that the kink should not be operational for frequencies in the microwave and millimeter wave regimes. The inverse of $T_{90\%}$ is found to follow a classical impact ionization behavior.

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