Direct Correlation Between Impact Ionization and the Kink Effect in InAlAs/InGaAs HEMT's

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Abstract— **We present new, unmistakable experimental evidence directly linking the kink effect with impact ionization in the channel of InAlAs/InGaAs HEMT's on InP. Through the use of a sidegate structure, we confirm that the impact ionization coefficient obeys the classic exponential dependence on the inverse electric field at the drain end of the gate, and that the onset of the kink strongly coincides with the onset of impact ionization in the devices we consider. These measurements illuminate the functional relationship between the kink and impact ionization, and therefore will allow assessment of the numerous impact-ionization related kink mechanisms that have recently been suggested in the literature.**

I. INTRODUCTION

InAlAs/InGaAs high electron mobility transistors (HEMT's) show significant promise for low-noise and high-power millimeter-wave applications. An important anomaly in their behavior is the *kink effect*, a sudden rise in the 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 source of the kink is an issue of considerable contention at this time. Conventional wisdom and some experiments suggest that traps cause the kink: high fields charge traps in the buffer or in the insulator, leading to a shift in threshold voltage [1]–[3]. On the other hand, recent simulations [4] as well as light emission, channel-engineering, and body contact experiments [5]–[7] suggest a link between impact ionization and the kink. This work has led to several new models for the kink, including an SOI-like mechanism [4], [7], hole trap charging [8], source resistance reduction [9], and hole pile-up in the extrinsic source [10].

Unfortunately, it is difficult to assess the competing kink models with current experimental data, because the experiments thus far presented only *indirectly* demonstrate the link between impact ionization and the kink. A *direct* sampling of the multiplication rate in the channel would allow us to assess the extent to which the kink is associated with impact ionization. To achieve this, we have used a specially designed sidegate structure, which allows us to track impact ionization in the device without perturbing its behavior. Our measurements provide direct evidence linking the kink with impact ionization. Furthermore, this work provides critical insight into the functional dependence of the kink on the impact ionization rate, which should facilitate improved kink models.

II. EXPERIMENTAL DETAILS

We have used a lattice-matched, MBE-grown, double-heterostructure HEMT as a vehicle for this study. The layer structure consists of a 2550 Å InAlAs buffer, a 200 Å InGaAs channel, a 300 Å InAlAs pseudo-insulator, and a 70 Å InGaAs cap. Delta-doped electron supply layers located 30 Å above the channel and 50 Å below the channel yield a sheet carrier concentration of 3.2×10^{12} cm^{-2}. Fabrication consists of device isolation via a mesa etch with a sidewall recess, a PECVD Si_3N_4 layer for liftoff assistance, Au/Ge ohmic contacts, a selective gate recess, and Pt/Ti/Pt/Au gates and interconnects. Devices with $L_G = 2$ μm were characterized. The devices exhibit $I_{D_{max}} \approx 500$ mA/mm, $g_{m_{peak}} \approx 400$ mS/mm, and $BV_{DS(off)} \approx 8$ V.

In order to track impact ionization in these devices, we have used a specially designed sidegate structure [11]. The sidegate structure consists of an ohmic contact on a $40\mu m \times 15\mu m$ mesa located 15 μm from the device under test. In the measurement, the sidegate is held at a large negative potential with respect to the source ($V_{SG-S} = -20$ V), allowing collection of a small fraction of the holes generated by impact ionization. Measurement of device characteristics with and without the sidegate biased confirm that the sidegate has little impact on the device.

Although previous work leads us to expect that the sidegate current will act as an efficient monitor of impact ionization [11], it is important first to establish the relationship between the sidegate current and impact ionization in an InAlAs/InGaAs HEMT. Fig. 1 plots typical measured drain, gate, and sidegate current as a function of the gate voltage. The "bell" shape in both I_G and I_{SG} is a clear signature of impact ionization [11]. As the device is first turned on, impact ionization is limited by the electron concentration, and therefore increases as I_D rises. Some fraction of the generated holes are collected by the gate and by the sidegate, making I_G and I_{SG} more negative. When V_{GS} is made more positive, though, the field at the drain end of the device drops, and the multiplication rate's exponential field dependence begins to limit the impact ionization current. It is important to note that the change in I_G is not a good gauge of the ionization rate, as the gate's ability to extract holes from the channel depends strongly on bias [11]. Since the sidegate remains at a constant bias, the rise in I_{SG} should be a much better

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Manuscript received February 6, 1996; revised April 10, 1996. This work was supported in part by Raytheon Co., the Joint Services Electronics Program under Grant DAAH04-95-1-0038, and a National Science Foundation Presidential Young Investigator award 915 7305-ECS.

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Publisher Item Identifier S 0741-3106(96)07529-5.

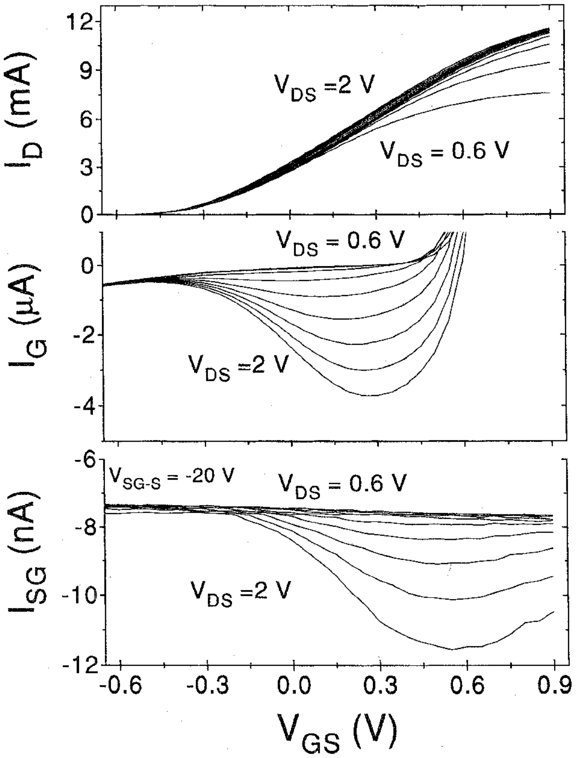

Fig. 1. I_D, I_G, and I_{SG} as a function of V_{GS} with V_{DS} stepped from 0.6 V to 2 V. Note the hump in both the gate current and the sidegate current, indicating the presence of impact ionization in the device.

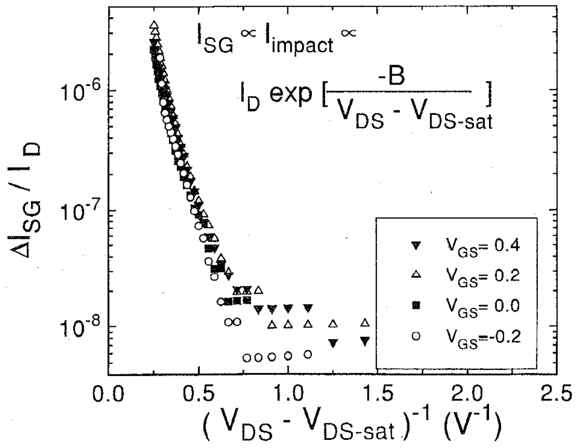

Fig. 2. Semilog graph of $\Delta I_{SG}/I_D$ versus $1/(V_{DS} - V_{DS(sat)})$ for different values of V_{GS} on a typical device. ΔI_{SG} is defined as $| I_{SG} - I_{SG0} |$, where I_{SG0} is the constant background sidegate current measured at $V_{GD} = V_{GS}$. The straight line behavior at small $1/(V_{DS} - V_{DS(sat)})$ confirms the onset of impact ionization. $V_{SG-S} = -20$ V.

measure of the ionization rate. Confirmation of this is found in Fig. 2, where the ratio of the rise in sidegate current, ΔI_{SG}, to the drain current is plotted as a function of $1/(V_{DS} - V_{DS(sat)})$ for several values of V_{GS}. Throughout the device's range of operation, ΔI_{SG} follows classical exponential impact ionization behavior. Thus, our work shows that ΔI_{SG} is a good monitor for impact ionization in InAlAs/InGaAs HEMT's.

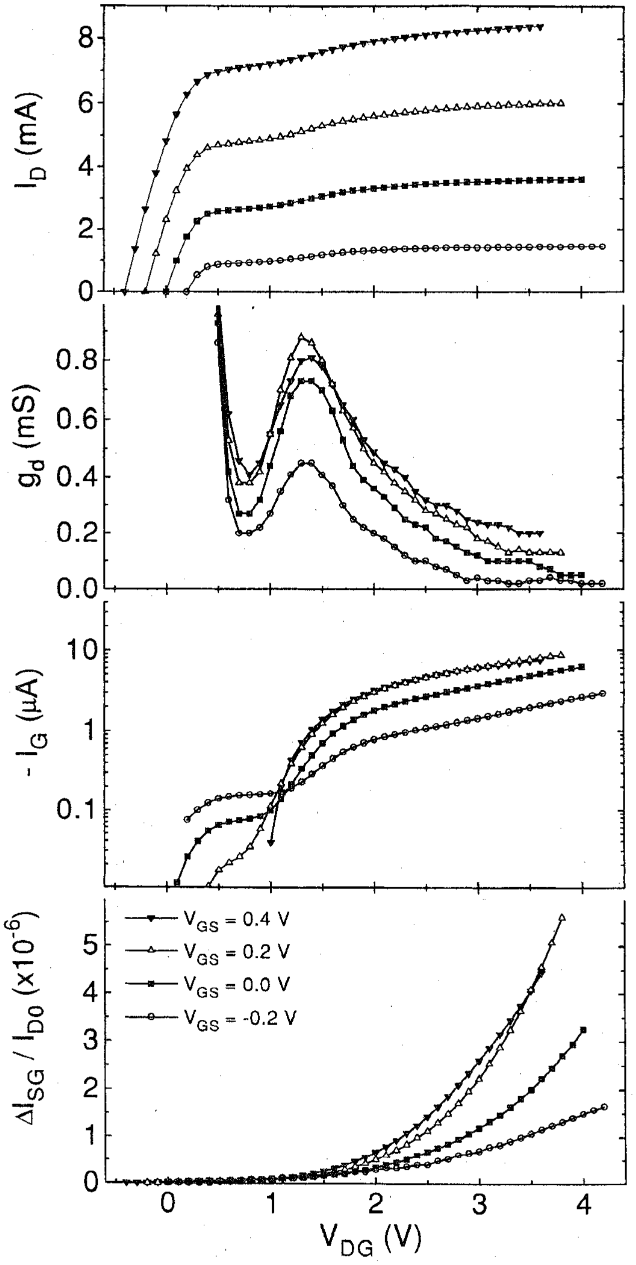

Fig. 3. I_D, g_d, $-I_G$, and $\Delta I_{SG}/I_{D0}$ as a function of V_{DG} at four different gate voltages (I_{D0} is defined as the "pre-kink" drain current in the saturation region). The onset of the kink strongly coincides with the appearance of ΔI_{SG}.

III. RESULTS AND DISCUSSION

Having established that the sidegate tracks impact ionization in the device, we can now use ΔI_{SG} to explore the relationship between impact ionization and the kink effect. In Fig. 3 we examine I_D, g_d, $-I_G$, and $\Delta I_{SG}/I_{D0}$ as a function of V_{DG} for a variety of V_{GS} conditions. The graphs display a number of characteristics that strongly link the kink with impact ionization. First, the onset of the kink, defined at the minimum in g_d, occurs approximately at constant $V_{DG} \approx 0.7$ V, suggesting that the kink is a function of the gate to drain field, as one would expect for an impact ionization related mechanism. As has been previously observed in InAs channel HEMT's, the kink coincides with a prominent rise in I_G [12]; such a rise in I_G is presumably due to hole collection as impact ionization becomes significant in the device. Most importantly, at all four bias conditions, the onset of the kink coincides with appearance of ΔI_{SG}, indicating that impact ionization is significant with respect to the background generation rate, and unequivocally establishing the connection between impact ionization and the kink.

Comparison of the shape of the kink and the sidegate current provides further clues about the relationship between impact ionization and the kink. The kink exhibits a saturating behavior, while the sidegate current rises almost exponentially in the range of biases considered. Clearly the kink in our device is not purely impact ionization current, as has been suggested elsewhere [13], [14]. The kink's saturating behavior is arguably consistent with a number of the current kink models, including hole trap charging [8], floating body effects [4], source resistance reduction [9], and barrier-induced hole pileup [10]. At this point, most of these models are purely qualitative. More quantitative models should now be possible through the use of the measurements presented here.

IV. CONCLUSIONS

We have presented new measurements of the kink effect and impact ionization in an InAlAs/InGaAs HEMT. Our measurements provide direct evidence linking the kink effect with impact ionization, and illuminate the functional relationship between the two phenomena. This knowledge will allow assessment of existing kink models, and should assist in the creation of more quantitative descriptions of the kink.

V. ACKNOWLEDGMENT

The authors would like to thank T. Enoki, Y. Ishii, and N. Shigekawa of NTT Corp. for useful discussions.

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