

# A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs

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## Abstract

New measurements providing direct evidence linking the kink effect and impact ionization in InAlAs / InGaAs HEMTs are reported. Current kink models are not consistent with our findings. We propose a new mechanism, *barrier-induced hole pile-up* at the source, to explain the kink. The new model is shown to be consistent with both room temperature and low temperature measurements. These results allow formulation of a simple equivalent circuit model of the kink.

## Introduction

InAlAs / InGaAs high electron mobility transistors (HEMTs) show 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 the drain current at a certain drain-to-source voltage that results in high drain conductance and reduced voltage gain. Conventional wisdom suggests that traps are responsible for the kink. Most theories incorporating traps suggest that high fields and/or impact-ionization-generated holes charge traps either in the buffer [1,2] or in the insulator [3], leading to a shift in the threshold voltage. Such a theory, while plausible, is of little predictive value because of the large number of variables involved. It is therefore important to search for other physical origins of the kink that might be amenable to simple modeling in these devices.

Recent experiments have provided indirect evidence linking the kink and impact ionization [4]; however, it remains unclear how the two phenomena are connected. Using a specially-designed sidegate structure, we have carried out extensive characterization of the kink effect in a double-heterostructure InAlAs / InGaAs HEMT. Our measurements provide direct evidence linking the kink with impact ionization, while at the same time clearly showing that impact ionization current alone is not responsible for the kink. Careful analysis leads us to postulate a new mechanism of *barrier-induced hole pile-up* at the source to explain the kink, and to propose a simple equivalent circuit description of the phenomenon.

## Experimental

A cross-section of the MBE-grown, double-heterostructure HEMT used in this study is presented in fig. 1. The channel sheet carrier concentration is  $3.5 \times 10^{12} \text{ cm}^{-2}$ . Fabrication consists of device isolation via a mesa etch with a sidewall recess, a PECVD  $\text{Si}_3\text{N}_4$  layer for liftoff assistance, Au/Ge ohmic contacts, a selective gate recess, and Pt/Ti/Au gates and interconnects. Devices with gate lengths between  $0.6 \mu\text{m}$  and  $2 \mu\text{m}$  were characterized. The devices exhibit  $I_{D_{max}} = 520 \text{ mA/mm}$ ,  $g_{m_{peak}} = 440 \text{ mS/mm}$ , and  $BV_{DS(off)} \approx 8 \text{ V}$ .

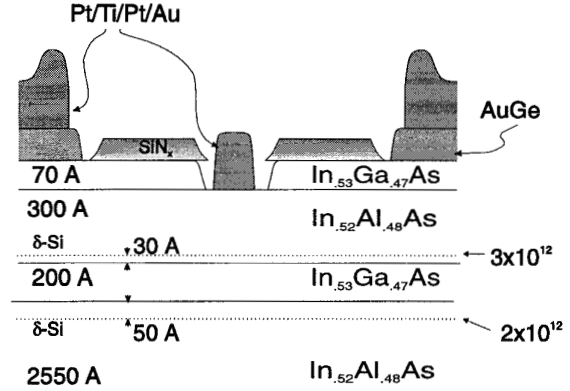


Figure 1: Schematic cross-section of InAlAs/InGaAs double-heterostructure HEMT used in this work.

A relationship between the kink and impact ionization has previously been postulated based on simulation results [5] as well as light emission and channel-engineering experiments [4]. However, these experiments only provided an indirect view of impact ionization. By using a specially designed sidegate structure [6], we have succeeded in *directly* tracking impact ionization in the device without perturbing its behavior. The sidegate structure consists of an ohmic contact on a  $40 \mu\text{m} \times 15 \mu\text{m}$  mesa located  $15 \mu\text{m}$  from the device under test. In the measurement, the sidegate is held at a large negative potential with respect to the source ( $V_{SG-S} = -20 \text{ V}$ ). This allows the sidegate to collect a small fraction of the holes generated by impact ionization, as sketched in the inset of fig. 2. Thus, the sidegate current should approximately track the impact ionization generation rate. Such behavior is observed in fig. 2, where the ratio of the net sidegate current to the drain current is plotted as a function of  $1/(V_{DS} - V_{DS(sat)})$  for typical values of  $V_{GS}$ . Throughout the device's range of operation,  $I_{SG}$  follows classical exponential impact ionization behavior.

Using  $I_{SG}$  we can now explore the relationship between impact ionization and the kink effect. In fig. 3 we examine  $I_D$  and  $I_{SG}$  for  $V_{GS} = 0 \text{ V}$ . The kink is clearly visible in  $I_D$  starting at  $V_{DS} \approx 1 \text{ V}$ . The onset of the kink coincides with the appearance of  $I_{SG}$ . We have found that this is the case for other values of  $V_{GS}$ . This is clearly seen in fig. 4, which shows  $I_D$ ,  $I_G$ , and  $I_{SG}$  as a function of  $V_{DG}$  for different  $V_{GS}$  values. This figure illustrates a number of key characteristics of the kink: the kink in  $I_D$  occurs approximately at constant  $V_{DG} \approx 1.2 \text{ V}$ ; the size of the kink appears to increase with increasing  $V_{GS}$ ; and the onset of the kink coincides with the appearance of  $I_{SG}$  and

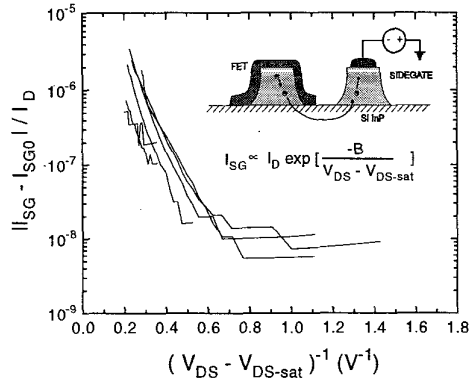


Figure 2: Semilog graph of  $|I_{SG} - I_{SG0}| / I_D$  vs.  $1/(V_{DS} - V_{DS(sat)})$ . The approximately exponential behavior at small  $1/(V_{DS} - V_{DS(sat)})$  confirms the onset of impact ionization.  $V_{SG-s} = -20$  V,  $L_G = 2 \mu\text{m}$ ,  $T = 300$  K.

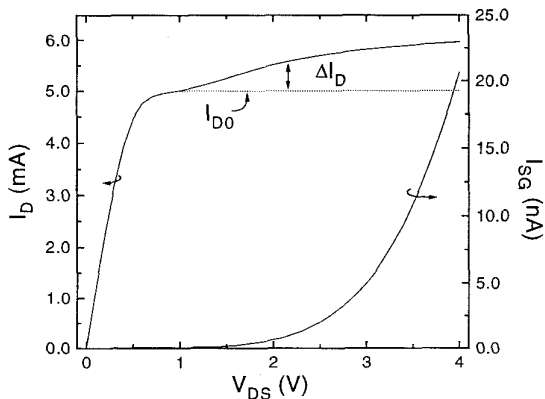


Figure 3: Drain and sidegate current at  $V_{GS} = 0$ . Note the saturation of the kink, in contrast with the exponential growth of the sidegate current.  $L_G = 2 \mu\text{m}$ ,  $T = 280$  K.

with a prominent rise in  $I_G$ , presumably due to hole collection by the gate. These facts unequivocally establish the connection between the kink and impact ionization.

### Discussion and New Model

Pure impact ionization has been proposed as an explanation for excess output conductance in InAlAs/InGaAs HEMTs [7]. In this model, additional drain current originates from the impact ionization generated holes and electrons. Such an explanation of the kink is not consistent with our experiments. If impact ionization alone were responsible for the kink, the shape of the kink would closely track the shape of the sidegate current. However, as seen in fig. 3, the kink saturates while the sidegate current grows strongly with  $V_{DS}$ . Clearly some other effect must be at work.

The kink effect in SOI MOSFETs is known to be a result of impact ionization generated holes flowing through the  $p$ -type buffer into the  $n^+$  source [8]. This hole current forward biases the buffer-source  $p$ - $n$  junction, thereby providing additional drive to the transistor. While such an hypothesis may be appropriate in some HEMT designs [5,9], two facts make this explanation unlikely for current

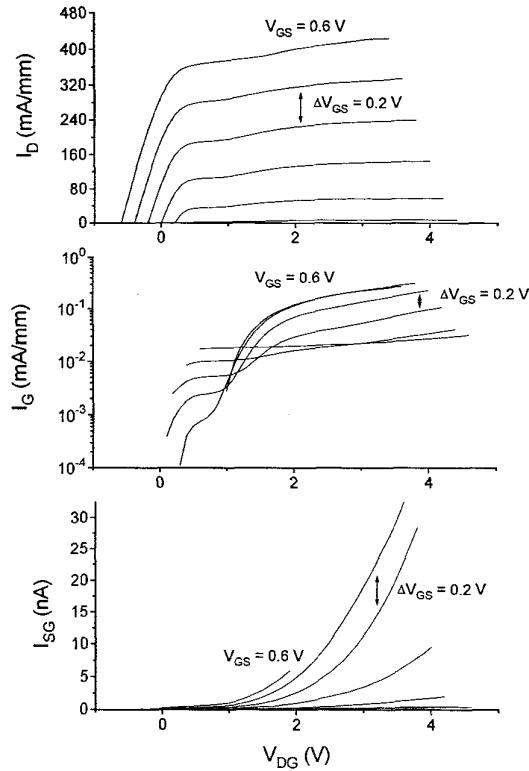


Figure 4: Drain, gate, and sidegate currents for different values of  $V_{GS}$ . The onset of the kink directly corresponds with the onset of the sidegate current and a significant increase in gate current.  $L_G = 2 \mu\text{m}$ ,  $T = 300$  K.

InAlAs/InGaAs HEMT designs. First, the presence of a significant valence band discontinuity (0.2 eV) between the channel and the buffer should confine most holes to the narrow channel. In addition, the fact that the channel and the buffer are undoped makes a parasitic bipolar effect less plausible.

Simulation results have recently suggested another possible explanation for the kink, source resistance reduction [10]. In this model, holes drift into the low field source-gate region, where they diffuse and recombine. To maintain quasi-neutrality, the electron concentration must be increased, resulting in reduced source resistance. If this were the case, the excess current would be of the form

$$\Delta I_D = g_{m0} I_D \Delta R \quad (1)$$

where  $g_{m0}$  and  $I_D$  are “pre-kink” values, and  $\Delta R$  is the drop in source resistance brought about by the hole accumulation. Since  $|\Delta R|$  should increase with increasing  $I_D$ , the kink current  $\Delta I_D$  would be superlinear in  $I_D$  according to this hypothesis. In order to evaluate this hypothesis, we plot in fig. 5 the magnitude of the kink, extracted for constant  $V_{DS} - V_{DS(sat)} = 3$  V, versus  $I_D$ . This measurement clearly indicates that the kink has a sublinear  $I_D$  dependence, which is inconsistent with source resistance reduction.

Although simple source resistance reduction does not appear to explain our results, recent reports of light emission from the extrinsic source [11] and kink suppression

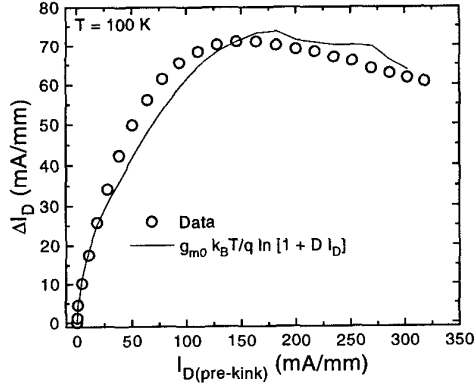


Figure 5: Kink magnitude extracted for  $V_{DS} - V_{DS(sat)} = 3$  V at low temperature as a function of  $I_D$ . The solid line theoretical fit is discussed later in the text.  $L_G = 0.8$   $\mu\text{m}$ .

by means of a buried  $p$ -layer [9,12] motivate us to explore further the possible significance of holes in the kink effect. As the source-resistance reduction model suggests, holes can drift through the channel and invade the extrinsic source. Particularly effective hole pile-up might arise if there is a potential barrier at the source. Such a barrier can occur between the ohmic contact's  $n^+$ -region and the channel, or at the transition between the capped and uncapped portions. If this is the case, the ohmic drop in conjunction with the barrier creates a triangular well where holes can accumulate. Any pile-up of holes reduces the ohmic drop in the region immediately adjoining the barrier (Fig. 6). This provides an extra gate drive,  $V_{kink}$ , to the transistor.

A simple first-order analysis of this hypothesis provides a number of key dependences in the behavior of the kink that can be tested. An additional drive on the gate results in increased current:

$$\Delta I_D = g_{m0} V_{kink} \quad (2)$$

The kink voltage is to first order determined by the excess hole concentration at the barrier:

$$V_{kink} \propto \frac{k_B T}{q} \ln\left(\frac{n_0 + p}{n_0}\right) \quad (3)$$

In the classical description of impact ionization, the ionization rate is proportional to the exponential of the inverse of the field in the high field region. The excess hole concentration at the barrier will be proportional to the impact ionization generation rate, so

$$p \propto I_{impact} \propto I_D \exp\left(\frac{-B}{V_{DS} - V_{DS(sat)}}\right) \quad (4)$$

where  $B$  is a constant. Plugging (4) into (3) and (2), we obtain

$$\Delta I_D \propto g_{m0} \frac{k_B T}{q} \ln\left[1 + A I_D \exp\left(\frac{-B}{V_{DS} - V_{DS(sat)}}\right)\right] \quad (5)$$

where  $A$  is another constant.

In examining (5), we note first that when the hole accumulation is large with respect to the pre-kink electron

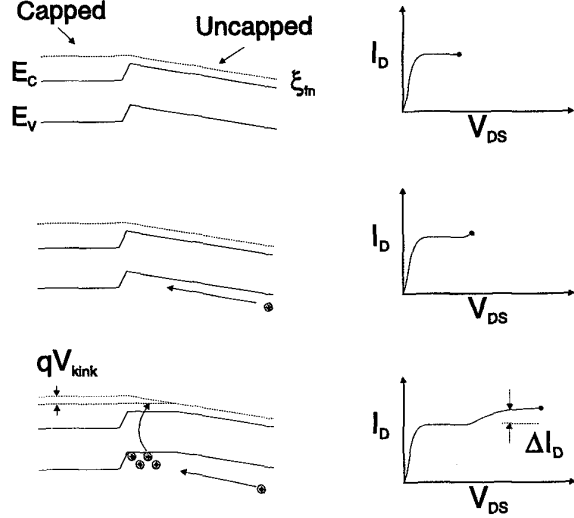


Figure 6: Postulated kink mechanism. Holes generated by impact ionization drift into the extrinsic source and accumulate in the well formed by the barrier and the ohmic drop. The resulting reduction in extrinsic voltage results in increased drive to the transistor.

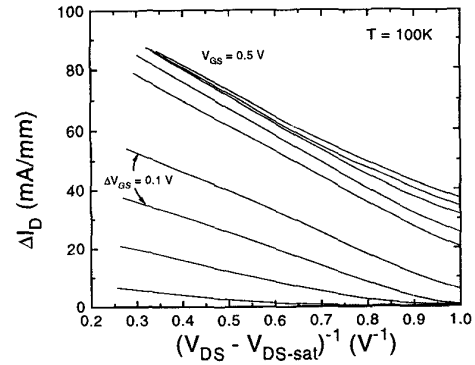


Figure 7: Kink magnitude vs.  $V_{DS} - V_{DS(sat)}$ .  $L_G = 0.8$   $\mu\text{m}$ .

concentration, the exponential term dominates, so that at large  $V_{DS}$  values,

$$\Delta I_D |_{large V_{DS}} \propto \frac{-1}{V_{DS} - V_{DS(sat)}} \quad (6)$$

Such a dependence is observed in our experiments, as shown in Fig. 7.

The direct relationship between the sidegate current and impact ionization generation rate further implies that the kink should be predicted by the sidegate current. In particular, from (4) and (5),

$$\Delta I_D \propto g_{m0} \frac{k_B T}{q} \ln[1 + C I_{SG}] \quad (7)$$

with  $C$  another constant. We observe this in fig. 8.

Finally, if  $V_{DS} - V_{DS(sat)}$  is held constant, the kink should be a simple function of  $g_{m0}$  and  $I_D$ :

$$\Delta I_D \propto g_{m0} \frac{k_B T}{q} \ln[1 + D I_D] \quad (8)$$

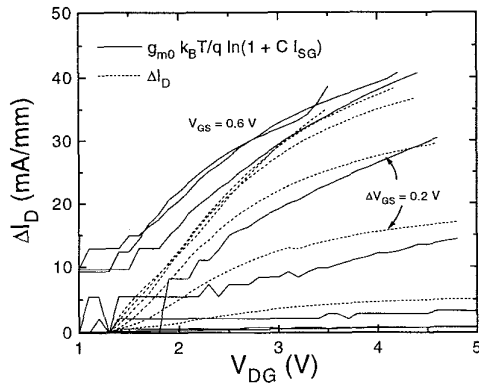


Figure 8: Comparison of the kink current,  $\Delta I_D$ , with the kink predicted by the sidegate current.  $L_G = 2 \mu\text{m}$ ,  $T = 280 \text{ K}$ .

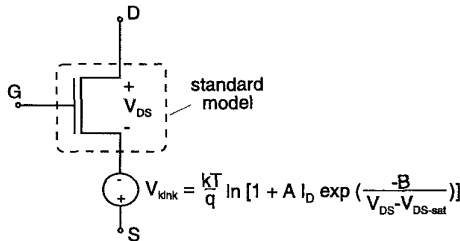


Figure 9: Proposed equivalent circuit model. A new element with only two bias-independent parameters is required to model the kink completely.

with  $D$  also a constant. Such a dependence explains our experimental observation of fig. 5.

### Equivalent Circuit Model

The understanding provided by this physical model allows us to build a simple equivalent circuit model description of the kink. A new model element needs to be added in series with the intrinsic source of the FET (Fig. 9) that represents the additional drive provided by the hole pile-up. This element is a voltage source that is controlled by  $V_{DS}$  and  $I_D$ . Only two parameters are required to fit completely the characteristics of the transistor (Fig. 10). Although the form of this model is very similar to those used in SOI MOSFETs, the physics at play are significantly different.

### Conclusions

We have postulated a new physical model for the kink effect in InAlAs/InGaAs HEMTs. The kink arises from hole pile up at a potential barrier in the source of the device that brings about a reduction of the ohmic drop at the source. This results in extra gate drive to the transistor. Our findings have allowed us to formulate a simple equivalent model description of the kink effect in these devices.

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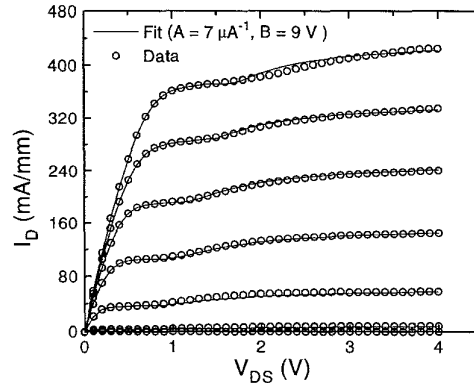


Figure 10: Comparison of model predictions for the kink with measured device characteristics.  $L_G = 2 \mu\text{m}$ ,  $T = 280 \text{ K}$ .

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