Chapter 2. Physics of Heterostructure Field-Effect Transistors

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2.1 Introduction

Sponsors

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The goal of this project is to develop InAlAs/InGaAs heterostructure field-effect transistors suitable for millimeter-wave high-power applications. This is a key missing component for millimeter-wave radar and communication systems.

Our team has been involved on research of high-power InAlAs/InGaAs heterostructure field-effect transistors for several years. Two key contributions in the past have been (1) the demonstration that the use of AlAs-rich InAlAs pseudoinsulators substantially improves the breakdown voltage[1] and (2) the demonstration of selective recessed-mesa sidewall isolation to reduce gate leakage current.[2] We also recently identified the detailed physical mechanisms responsible for breakdown in InAlAs/-InGaAs HFETs.[3]

In the last period of performance, we have studied in detail the physical origin of the "kink effect" in InAlAs/InGaAs HFETs.[4] This important anomaly in the operation of these transistors deleteriously affects their power performance. Our physical understanding has culminated in the proposal of a new equivalent circuit model that successfully captures the kink. This will enable first-pass success in the design of future millimeter-wave systems based on these devices.

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

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

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[1] S.R. Bahl, W.J. Azzam, and J.A. del Alamo, "Strained-Insulator $In_xAl_{1-x}As/n^+-In_{0.53}Ga_{0.47}As$ Heterostructure Field-Effect Transistors," *IEEE Trans. Electr. Dev.* 38: 1986 (1991).

[2] S.R. Bahl and J.A. del Alamo, "Elimination of Mesa-Sidewall Gate-Leakage in InAlAs/InGaAs Heterostructures by Selective Sidewall Recessing," *IEEE Electr. Dev. Lett.* 13: 195 (1992).

[3] S.R. Bahl and J.A. del Alamo, "Physics of Breakdown in $InAlAs/n^+-InGaAs$ Heterostructure Field-Effect Transistors," *IEEE Trans. Electr. Dev.* 41: 2268 (1994); S.R. Bahl, J.A. del Alamo, J. Dickmann, and S. Schildberg, "Off-State Breakdown in InAlAs/InGaAs MODFETs," *IEEE Trans. Electr. Dev.* 42: 15 (1995).

[4] M. Somerville, J.A. del Alamo, and W. Hoke, "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs," *International Electron Devices Meeting*, Washington, D.C., December 10-13, p. 201, 1995.

charge traps either in the buffer[5] or in the insulator,[6] 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;[7] 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.

A cross-section of the MBE-grown, double-heterostructure HEMT used in this study is presented in figure 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 Si_3N_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 μm and 2 μm were characterized. The devices exhibit $I_{D_{max}}$ = 520 mA/mm, $g_{m_{peak}}$ = 440 mS/mm, and $BV_{DS(off)} \approx 8$ V.

A relationship between the kink and impact ionization has previously been postulated based on simulation results[8] as well as light emission and channel-engineering experiments.[7] However, these experiments only provided an indirect view of impact ionization. By using a specially designed sidegate structure,[9] 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 μm x 15 μm 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). This allows the sidegate to collect a small fraction of the holes generated by impact ionization, as sketched in the inset of figure 2. Thus, the sidegate current should approximately track the impact ionization generation rate. Such behavior is observed in figure 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 figure 3, we examine I_D and I_{SG} for $V_{GS} = 0$ V. The kink is clearly visible in I_D starting at $V_{DS} \approx 1$ 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 figure 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 $V_{DG} \approx 1.2$ 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 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.

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[5] A.S. Brown et al., "AlInAs-GaInAs HEMTs Utilizing Low-temperature AlInAs Buffers Grown by MBE," *IEEE Electr. Dev. Lett.* 10: 565 (1989); T. Zimmer et al., "Kink Effect in HEMT Structures: a Trap-related Semi-quantitative Model and an Empirical Approach for Spice Simulation," *Sol. State Electr.* 35: 1543 (1992).

[6] Y. Hori and M. Kuzuhara, "Improved Model for Kink Effect in AlGaAs/InGaAs Heterojunction FETs," *IEEE Trans. Electr. Dev.* 41: 2262 (1994).

[7] G.G. Zhou, A.F. Fischer-Colbrie, and J.S. Harris, "I-V Kink in InAlAs/InGaAs MODFETs Due to Weak Impact Ionization in the InGaAs Channel," *Sixth International Conference on InP and Related Materials*, Santa Barbara, California, March 1994, pp.435.

[8] K. Kunihiro, H. Yano, N. Goto, and Y. Ohno, "Numerical Analysis of Kink Effect in HJFET with a Heterobuffer Layer," *IEEE Trans. Electr. Dev.* 40: 493 (1993).

[9] A.A. Moolji, S.R. Bahl, and J.A. del Alamo, "Impact Ionization in InAlAs/InGaAs HFETs," *IEEE Electr. Dev. Lett.* 15: 313 (1994).

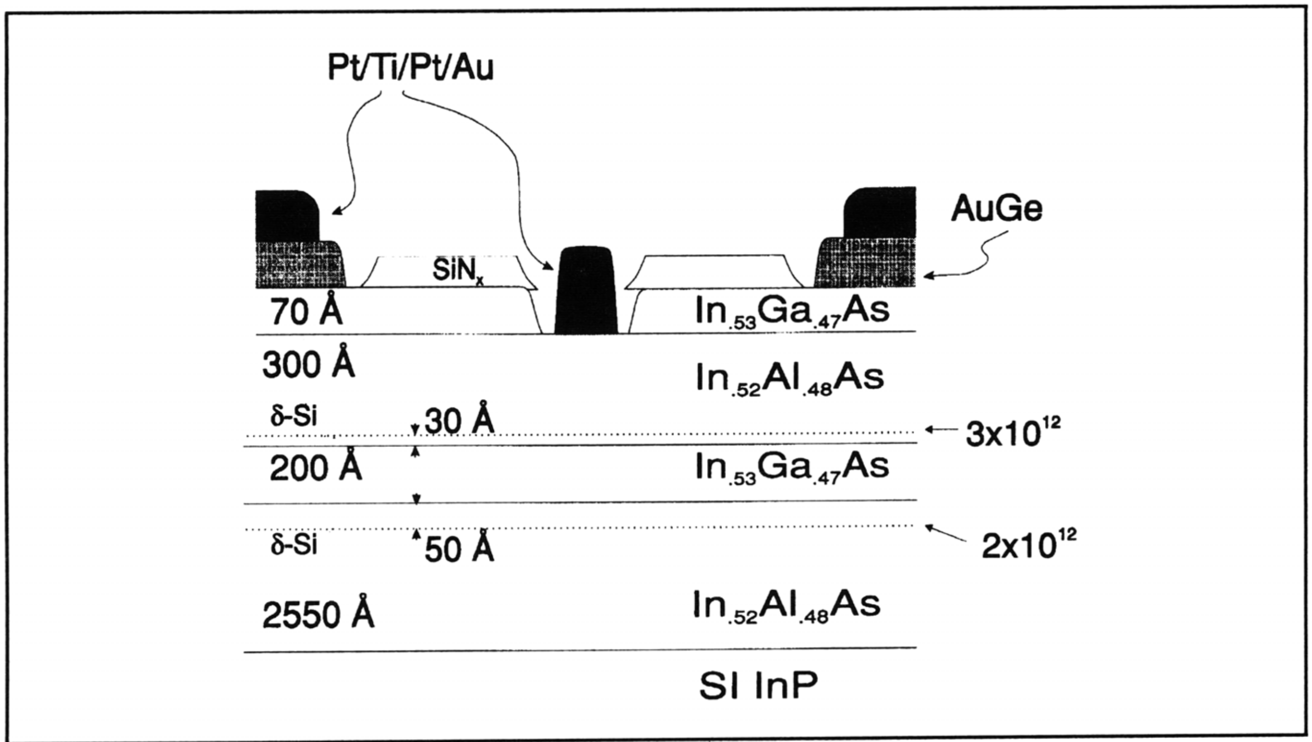

Figure 1. Schematic cross-section of InAlAs/InGaAs double-heterostructure HEMT used in this work.

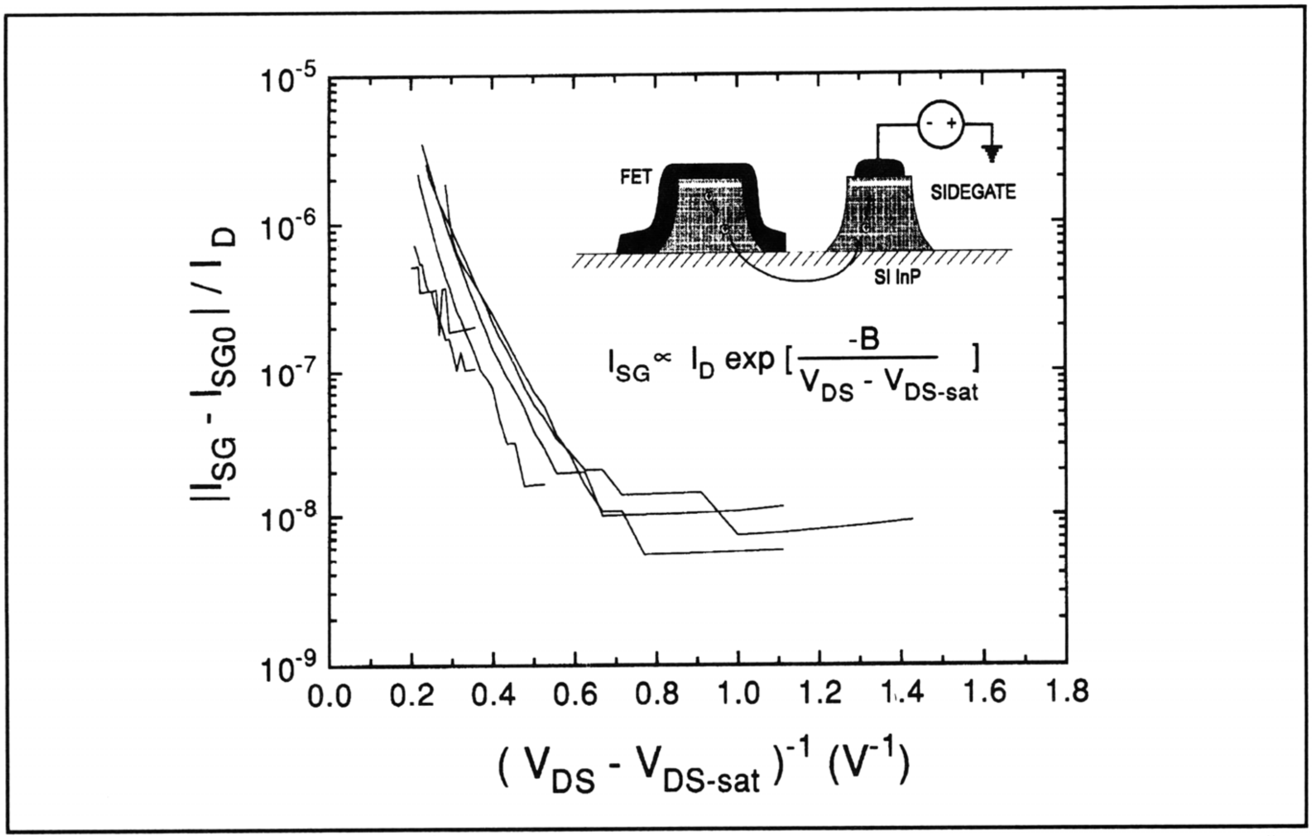

Figure 2. Semilog graph of $|I_{SB} - I_{SG0}|/I_D$ versus $1/(V_{DS} - V_{DS(sat)})$. The approximately exponential behavior at small $1/(V_{DS} - V_{DS(sat)})$ confirms the onset of impact ionization. $V_{SG-S} = -20$ V, $L_G = 2\ \mu m$, $T = 300$ K.

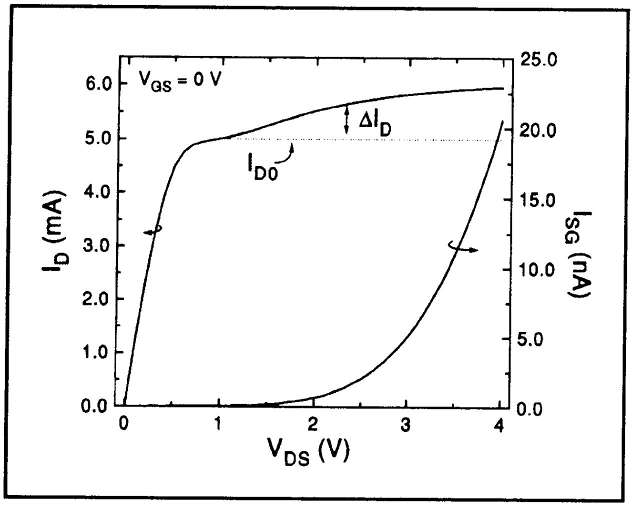

Figure 3. Drain and sidegate current at V_{GS} = 0. Note the saturation of the kink, in contrast with the exponential growth of the sidegate current. L_G = 2 μm, T = 280 K.

Pure impact ionization has been proposed as an explanation for excess output conductance in InAlAs/InGaAs HEMTs.[10] 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 figure 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.[11] 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,[12] two facts make this explanation unlikely for current 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.

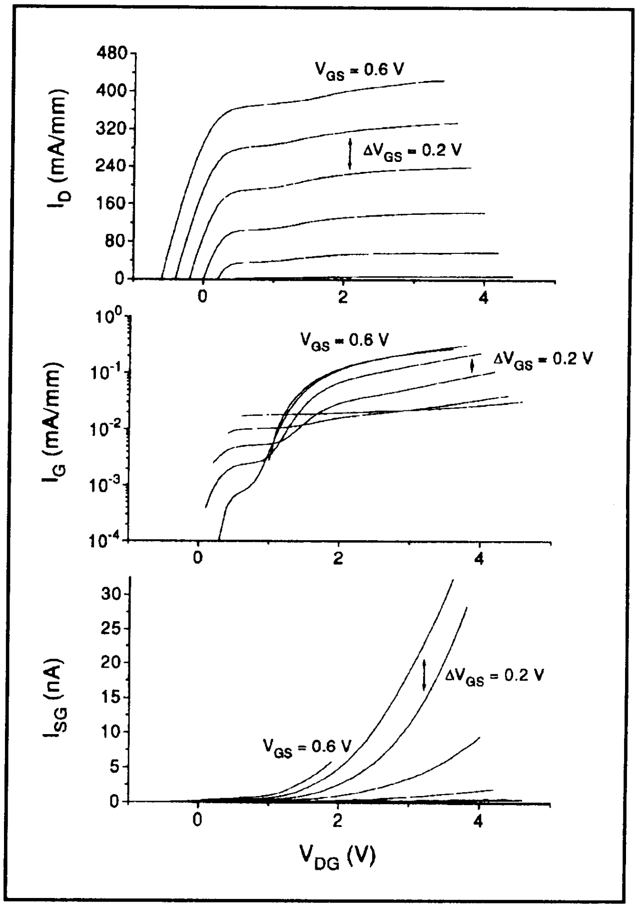

Figure 4. Drain, gate, and sidegate currents for different values of V_{GS}. The onset of the kink directly corresponds with the onset of the sidegate current and a significant increase in gate current. L_G = 2 μm, T = 300 K.

Simulation results have recently suggested another possible explanation for the kink, source resistance reduction.[13] 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

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[10] M. Chertouk et al., "Metamorphic InAlAs/InGaAs HEMTs on GaAs Substrates with Composite Channels and f_{max} of 350 GHz," *Seventh International Conference of InP and Related Materials,* Sapporo, Japan, 1995, p. 737.

[11] K. Kato, T. Wada, and K. Taniguchi, "Analysis of Kink Characteristics in SOI MOSFETs Using Two Carrier Modeling," *IEEE Trans. Electr. Dev.* ED-32: 458 (1985).

[12] K. Kunihiro, H. Yano, N. Goto, and Y. Ohno, "Numerical Analysis of Kink Effect in HJFET with a Heterobuffer Layer," *IEEE Trans. Electr. Dev.* 40: 493 (1993); B. Brar and H. Kroemer, "Influence of Impact Ionization on the Drain Conductance of InAs/AlSb Quantum Well HFETs," in press.

[13] T. Enoki, T. Kobayashi, and Y. Ishii, "Device Technologies for InP-based HEMTs and their Applications to ICs," *IEEE GaAs IC Symposium,* 337-339, 1994.

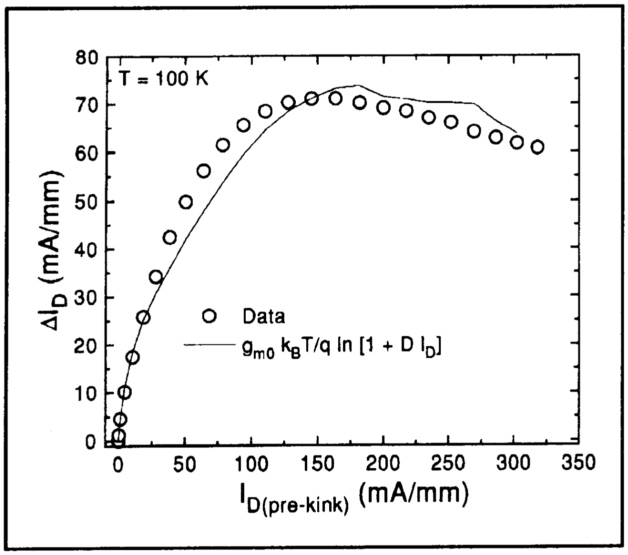

Figure 5. Kink magnitude extracted for $V_{DS} - V_{DS(sat)} = 3$ V at low temperature as a function of I_D. The solid line theoretical fit is discussed later in the text. $L_G = 0.8$ μm.

$$\Delta I_D = g_{m0} I_D \Delta R \tag{1}$$

where g_{m0} and I_D are "pre-kink" values, and ΔR is the drop in source resistance brought about by the hole accumulation. Since $|\Delta R|$ should increase with increasing I_D, the kink current ΔI_D would be superlinear in I_D according to this hypothesis. In order to evaluate this hypothesis, we plot in figure 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[14] and kink suppression by means of a buried p-layer[15] 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 (figure 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:

$$\Delta I_D = g_{m0} V_{kink} \tag{2}$$

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

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

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

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

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

$$\Delta I_D \propto$$

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

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

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

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[14] N. Shigekawa, T. Enoki, T. Furuta, and H. Ito, "Electroluminescence of InAlAs/InGaAs HEMTs Lattice-matched to InP Substrates," in press.

[15] B. Brar and H. Kroemer, "Influence of Impact Ionization on the Drain Conductance of InAs/AlSb Quantum Well HFETs," in press; T. Suemitsu, T. Enoki, Y. Ishii, "Body Contacts in InP-based InAlAs/InGaAs HEMTs and Their Effects on Breakdown Voltage and Kink Suppression," *Electr. Lett.* 31: 758 (1995).

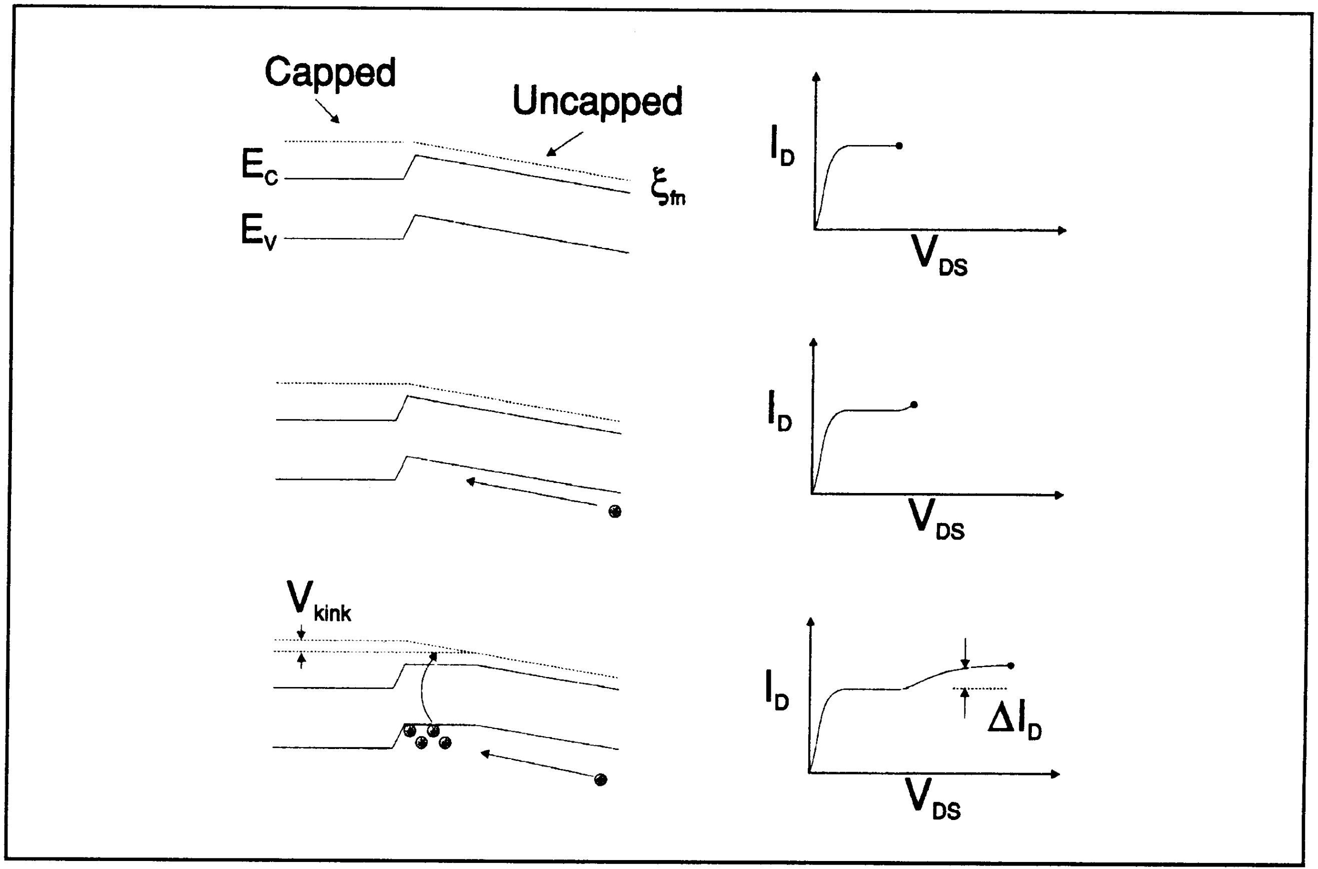


Figure 6. Postulated kink mechanism. Holes generated by impact ionization drift into the extrinsic source and accumulate in the well formed by the barrier and the ohmic drop. The resulting reduction in extrinsic voltage results in increased drive to the transistor.

Such a dependence is observed in our experiments, as shown in figure 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),

$$\Delta I_D \propto g_{m0} \frac{k_B T}{q} \ln\,[1 + CI_{SG}] \qquad (7)$$

with C another constant. We observe this in figure 8.

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

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

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

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 (figure 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 (figure 10).

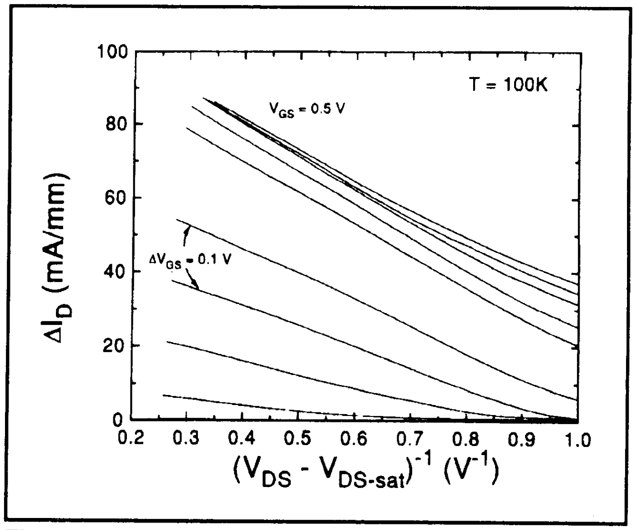


Figure 7. Kink magnitude vs. V_{DS} - $V_{DS(sat)}$. L_G = 0.8 μm.

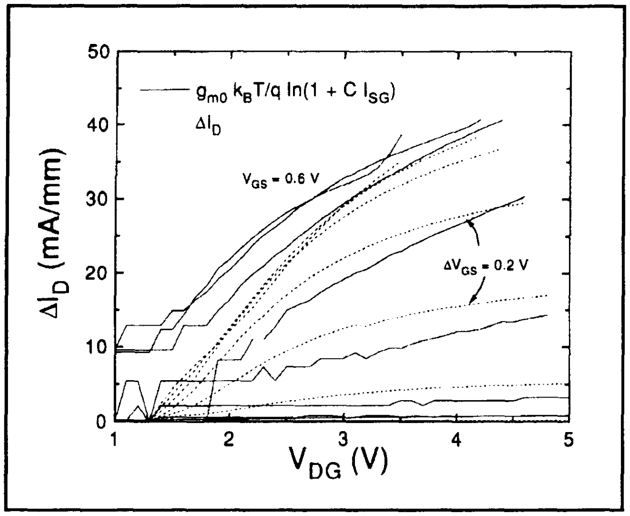


Figure 8. Comparison of the kink current, ΔI_D, with the kink predicted by the sidegate current. $L_G = 2\ \mu m$, $T = 280$ K.

Although the form of this model is very similar to those used in SOI MOSFETs, the physics at play are significantly different.

In conclusion, 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.

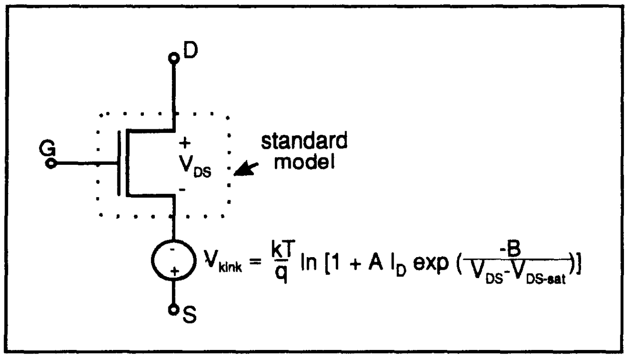


Figure 9. Proposed equivalent circuit model. A new element with only two bias-independent parameters is required to model the kink completely.

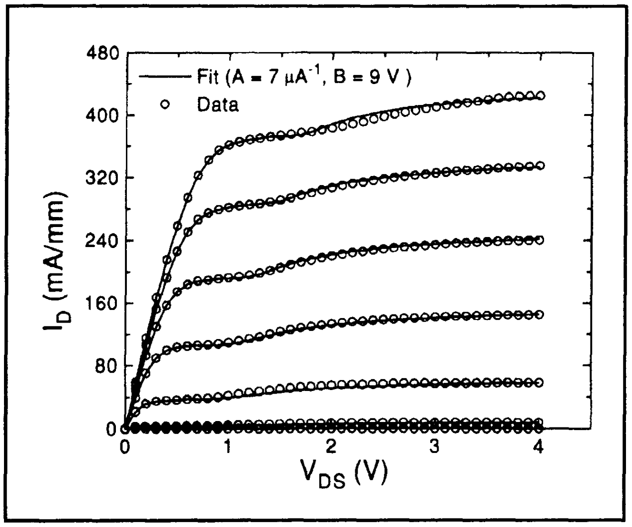


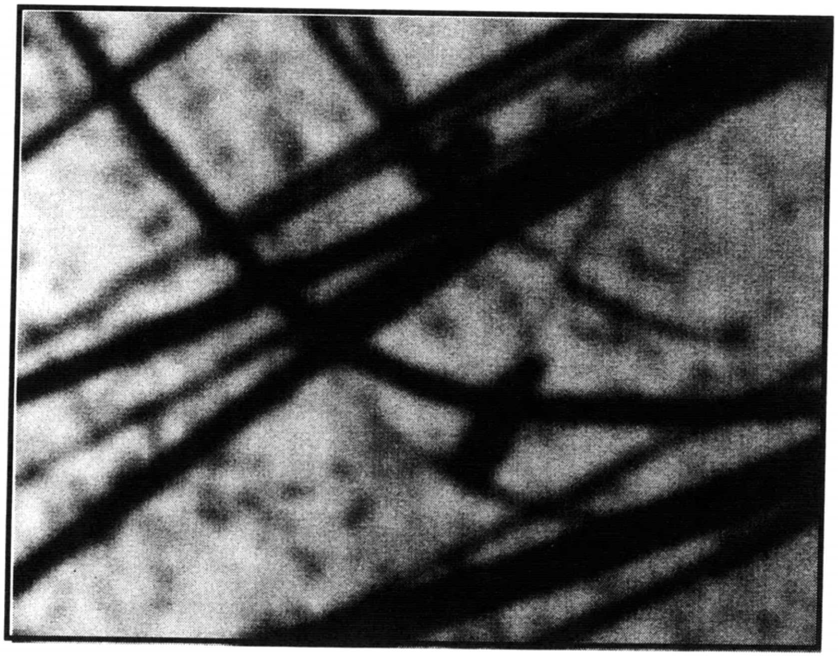
Figure 10. Comparison of model predictions for the kink with measured device characteristics. $L_G = 2\ \mu m$, $T = 280$ K.

2.3 Publications

Bahl, S.R., J.A. del Alamo, J. Dickmann, and S. Schildberg. "Off-State Breakdown in InAlAs/-InGaAs MODFETs." *IEEE Trans. Electr. Dev.* 42: 15-22 (1995).

Berthold, S., E. Zanoni, C. Canali, M. Pavesi, M. Pecchini, M. Manfredi, S.R. Bahl, and J.A. del Alamo. "Impact Ionization and Light Emission in InAlAs/InGaAs Heterostructure Field-Effect Transistors." *IEEE Trans. Electr. Dev.* 42: 752-759 (1995).

Somerville, M.H., J.A. del Alamo, and W. Hoke. "A New Physical Model for the Kink Effect on InAlAs/InGaAs HEMTs." *Proceedings of the International Electron Devices Meeting.* Washington, D.C., December 1995, p. 221.



A cathodoluminescence micrograph from a 1 μm-thick ZnSe layer on a Zn-exposed, (2x4) reconstructed, 8 monolayer thick GaAs layer on a 4 μm graded InGaP layer. The surface was imaged at the ZnSe wavelength at a magnification of 1700x using a probe current of 32 nA and an acceleration voltage of 20 kV. The sample was grown in the Chemical Beam Epitaxy Laboratory which is under the direction of Professor Leslie A. Kolodziejski.