Chapter 2. Physics of Heterostructure Field-Effect Transistors

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2.1 Introduction

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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 pseudosinsulators 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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charge traps either in the buffer or in the insulator, 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; 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 $3.5 \times 10^{12}$ cm$^{-2}$. Fabrication consists of device isolation via a mesa etch with a sidewall recess, a PECVD Si$_3$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 $\mu$m and 2 $\mu$m were characterized. The devices exhibit $I_{DSS} = 520$ mA/mm, $g_{m} = 440$ mS/mm, and $V_{DSS(tot)} \approx 8$ V.

A relationship between the kink and impact ionization has previously been postulated based on simulation results as well as light emission and channel-engineering experiments. However, these experiments only provided an indirect view of impact ionization. By using a specially designed sidegate structure, 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 $\mu$m x 15 $\mu$m mesa located 15 $\mu$m from the device under test. In the measurement, the sidegate is held at a large negative potential with respect to the source ($V_{SG} = -20$ 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.

Using $I_{DG}$, we can now explore the relationship between impact ionization and the kink effect. In figure 3, we examine $I_{D}$ and $I_{DG}$ 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 $I_{DG}$. 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 $I_{DG}$ 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 $I_{DG}$ and with a prominent rise in $I_{DG}$, presumably due to hole collection by the gate. These facts unequivocally establish the connection between the kink and impact ionization.

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Chapter 2. Heterostructure Field-Effect Transistors

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

Figure 2. Semilog graph of $\frac{|I_{SG} - I_{SG0}|}{I_0}$ 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. $V_{G0} = -20$ V, $L_0 = 2 \mu m$, $T = 300$ K.
Pure impact ionization has been proposed as an explanation for excess output conductance in InAlAs/InGaAs HEMTs. 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. 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, 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.

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

\[ \frac{I_{D}}{L} = \frac{I_{D}}{2} = \frac{K}{L} \times \frac{V_{DS}}{2} \]

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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.


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. $L_a = 0.8 \mu m$.

\[ \Delta I_D = g_{m0} I_D \Delta R \]  

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 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\textsuperscript{14} and kink suppression by means of a buried p-layer\textsuperscript{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:

\[ \Delta I_D = g_{m0}V_{kink} \]  

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

\[ V_{kink} \propto \frac{k_B T}{q} \ln \left( \frac{n_0 + p}{n_0} \right) \]  

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

\[ p \propto I_{impact} \propto I_D \exp \left( \frac{-B}{V_{DS} - V_{DS(sat)}} \right) \]  

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

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

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,

\[ \Delta I_D \bigg|_{\text{large } V_{ds}} \propto \frac{-1}{V_{DS} - V_{DS(sat)}} \]  

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

Chapter 2. Heterostructure Field-Effect Transistors

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),

\[
\Delta I_D \propto g_m 0 \frac{k_B T}{q} \ln [1 + C L_{SG}] \tag{7}
\]

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 \(g_m 0\) and \(I_D\):

\[
\Delta I_D \propto g_m 0 \frac{k_B T}{q} \ln [1 + D I_D] \tag{8}
\]

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. \(V_{DS} - V_{DS(sat)}\). \(L_g = 0.8 \, \mu m\).
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.

2.3 Publications


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.