Determining Dominant Breakdown Mechanisms in InP HEMTs

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***Abstract*—We present a new technique for determining the dominant breakdown mechanism in InAlAs/InGaAs high-electron mobility transistors. By exploiting *both* the temperature dependence and the bias dependence of different physical mechanisms, we are able to discriminate impact ionization gate current from tunneling and thermionic field emission gate current in these devices. Our results suggest that doping level of the supply layers plays a key role in determining the relative importance of these two effects.**

***Index Terms*—HEMT, impact ionization, InAlAs, InGaAs, tunneling.**

I. INTRODUCTION

InAlAs/InGaAs high-electron mobility transistors (HEMTs) are very promising for millimeter-wave power and photonic applications [1]; however, they often suffer from poor off-state breakdown. The cause of this behavior is a subject of debate—it has been variously claimed that impact ionization (II), thermionic field emission (TFE), tunneling, or some combination thereof are responsible for off-state breakdown [2]–[6]. Furthermore, different devices may suffer from different breakdown mechanisms, depending on the details of the design (insulator thickness, recess, channel composition, and so forth).

Clearly it is desirable to know which mechanism dominates breakdown in a particular device, as this facilitates intelligent design improvements. In most material systems, one can easily determine breakdown mechanism through temperature dependent measurements. Unfortunately, determination of breakdown mechanism in InAlAs/InGaAs devices is substantially more challenging, because of the anomalous positive temperature dependence of II in InGaAs [5]. This temperature dependence implies that the breakdown voltage drops with increasing temperature regardless of whether the dominant physical mechanism is electron emission from the gate or II within the channel.

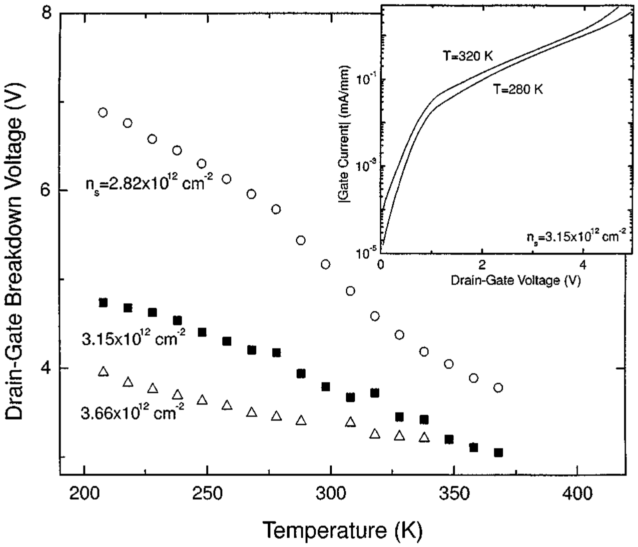

Fig. 1. Off-state breakdown voltage as a function of temperature for a variety of 0.1 μm InAlAs/InGaAs HEMT designs. In all cases, the breakdown voltage decreases with increasing temperature. The inset shows typical drain-gate diode characteristics for the medium n_s device.

We have previously utilized sidegate measurements to determine the dominant mechanism in off-state breakdown, but such measurements do not allow device-to-device comparison, nor do they quantify the relative importance of II and tunneling [7]. In addition, in many industrial processes sidegate structures are not available. In this work we develop a novel, straight-forward approach to determining which mechanism dominates off-state breakdown. Using our measurement technique, we conclude that doping level is crucial in determining the relative importance of these two effects.

II. EXPERIMENTAL

As a vehicle for this work we have used three high-performance, strained channel, double heterostructure InAlAs/In$_{0.67}$Ga$_{0.33}$As HEMTs, described in [4]. All have $L_G \approx 0.1$ μm with gate-drain spacing $L_{DG} \approx 1$ μm, as well as identical insulator and channel thicknesses. A selective gate recess was used to improve device uniformity. The only major difference among the three devices is sheet carrier concentration, which ranges from 2.82×10^{12} cm^{-2} (low n_s) to 3.66×10^{12} cm^{-2} (high n_s).

These different doping levels lead to substantially different off-state breakdown voltages, as Fig. 1 shows. Here we have measured breakdown ($|I_G| = 1$ mA/mm) as a function of temperature using the drain current injection technique [8]. As has been previously observed in other devices [3], BV consistently decreases with increasing temperature. Interestingly, in the low n_s device, the slope and curvature of $\mathrm{BV}(T)$ change abruptly at

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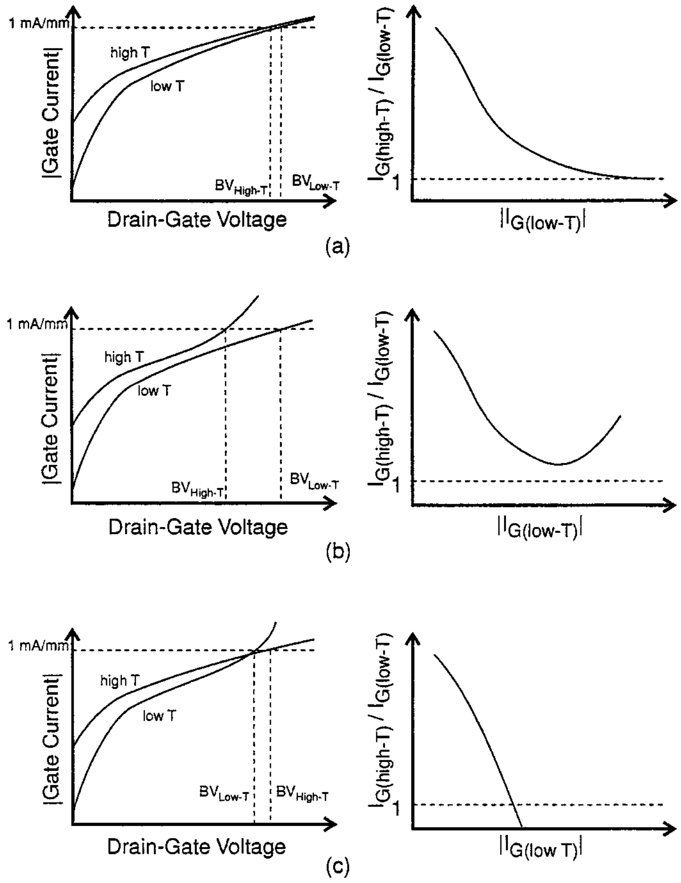

Fig. 2. Illustration of high-T versus low- T behavior of the gate current for three different breakdown mechanisms. The left set of figures sketches the gate current at two temperatures; the right set shows the ratio of the high temperature gate current to the low temperature gate current. (a) Behavior for a tunneling/TFE limited breakdown; (b) Behavior of impact ionization with a positive temperature coefficient, such as in InAlAs/InGaAs HEMTS; (c) Behavior of impact ionization with a negative temperature coefficient, such as in AlGaAs/InGaAs pHEMTs. Although both (a) and (b) have similar breakdown-temperature behavior, the $I_{G(\text{high-}T)}$ versus $I_{G(\text{low-}T)}$ behavior is markedly different.

around 280 K. This suggests that a different mechanism might be responsible for breakdown at higher temperatures in the low n_s device.

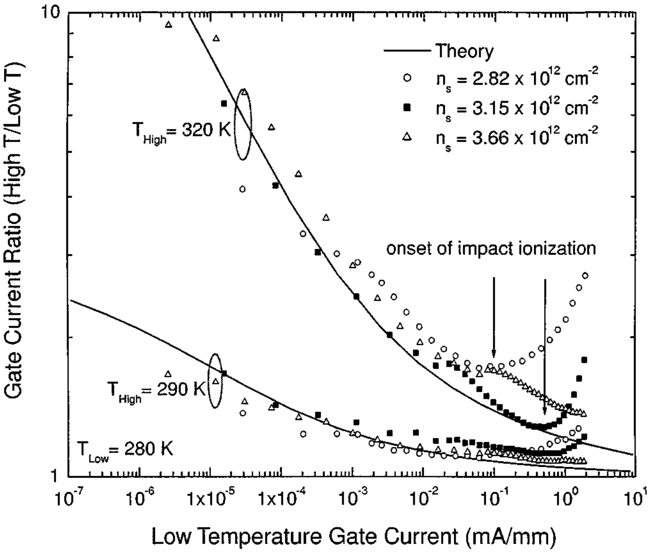

Fig. 3. High temperature—low temperature gate current ratios versus low temperature gate current. Data is presented for two different choices of high temperature ($T = 290$ K and $T = 320$ K), in order to show the generality of the measurement technique. All three devices follow the TFE-tunneling theory lines at lower currents, but devices with lower n_s values diverge as $I_{G(\text{low-}T)}$ increases. This upturn indicates a transition to the regime in which impact ionization is significant. The transition appears to occur at a slightly lower current level in the $T = 320$ K case, as would be expected due to the positive temperature dependence of impact ionization in InGaAs.

III. The Gate Current Ratio Measurement

We have also measured the gate-drain diode characteristics (source floating) at each temperature (see, e.g., the inset of Fig. 1). These measurements can be used to illuminate the breakdown mechanism by recognizing that although both TFE and II *increase* with increasing temperature, they have *opposite* temperature dependencies as a function of bias. Fig. 2 illustrates how this can be done. Here we compare the hypothetical drain-gate breakdown behavior of three devices: a TFE-dominated device [Fig. 2(a)], an II-dominated device in a material system such as InAlAs/InGaAs [Fig. 2(b)], and an II-dominated device in a material system such as AlGaAs/GaAs [Fig. 2(c)]. In tunneling-TFE dominated breakdown, low-temperature and high-temperature reverse gate characteristics should converge at higher biases. This is because as V_{DG} is increased, the proportion of tunneling to thermionic emission increases. In II-dominated breakdown, on the other hand, the behavior of the gate current with temperature is very different. For InAlAs/InGaAs devices, high-temperature and low-temperature currents should *diverge* as V_{DG} is increased, due to IIs positive temperature dependence. Finally, devices in which II has a negative temperature coefficient, such as GaAs pHEMTs [9] should display the classic "twist" in the gate current characteristics [10] [Fig. 2(c)].

This leads us to propose a simple measurement: for a given value of V_{DG}, take the ratio of the gate current measured at a high temperature to the gate current measured at a lower temperature. The behavior of this ratio as a function of V_{DG} or I_G gives significant insight into the physics of I_G. Fig. 2(a) shows how this ratio would behave in the case of a TFE/tunneling limited breakdown mechanism: as I_G at high temperature increases, the ratio of high to low temperature gate current should drop and eventually approach 1 as fields beneath the gate increase, yielding relatively more tunneling current. On the other hand, when II becomes important in the InAlAs/InGaAs system, we would expect this ratio to begin rising with increasing I_G—see Fig. 2(b). Lastly, if II has a negative temperature dependence, the ratio drops below unity—see Fig. 2(c).

Fig. 3 plots the results of a calculation of $I_{G(\text{high-}T)}$ and $I_{G(\text{low-}T)}$ due to tunneling and TFE for the same temperatures and gate length as used in the measurement. The calculation is a simple, one-dimensional model that assumes a uniform field under the gate (see, for example [11]). By using fields that range from 0 V/cm up to 3×10^6 V/cm, we can examine the behavior of the ratio from a purely thermionic emission case to a tunneling-dominated case; as expected, the calculated ratio approaches 1 at high fields where tunneling dominates. Although this calculation does not model the spatial distribution of the gate field, it is reasonable to expect that any mixture of tunneling and TFE will *approximately* follow this theory line.

Also plotted on Fig. 3 are the results of temperature-dependent measurements of I_{G} in our InAlAs/InGaAs HEMTs. The $I_{\mathrm{G(high\text{-}}T)}/I_{\mathrm{G(low\text{-}}T)}$ ratios are obtained using diode measurements taken at $T_{\mathrm{low}} = 280$ K and at two different high temperatures, $T_{\mathrm{high}} = 290$ K and $T_{\mathrm{high}} = 320$ K. By choosing temperatures that are relatively close to 300 K, we can reduce the impact of other temperature-dependent parameters (e.g., threshold voltage), and can determine the importance of II and TFE at room temperature. Results from two different high temperatures show the generality of the technique.

Examining first the $I_{\mathrm{G(high\text{-}}T)}/I_{\mathrm{G(low\text{-}}T)}$ ratios for the high n_s device, we see that although the ratio exhibits a small local minimum at $|I_{\mathrm{G}}| = 0.1$ mA/mm (due to the observed temperature dependence of the threshold voltage, as can be seen in the inset of Fig. 1), the ratio essentially follows the expected TFE/tunneling behavior throughout the measurement. Thus, this device appears to be dominated by TFE up to well above $|I_{\mathrm{G}}| = 1$ mA/mm. On the other hand, the $I_{\mathrm{G(high\text{-}}T)}/I_{\mathrm{G(low\text{-}}T)}$ ratios for the lower n_s devices follow the TFE/tunneling behavior up to some reasonably high current value, but then abruptly begin to rise with increasing $|I_{\mathrm{G}}|$. This is a clear signature of a transition to a region in which II is contributing to the gate current. The device with a moderate n_s value makes this transition at $|I_{\mathrm{G}}| = 1$ mA/mm; the low n_s device diverges from TFE at slightly below $|I_{\mathrm{G}}| = 0.1$ mA/mm.

Comparison of the 290/280 and 320/280 gate current ratios reveals a slight shift in the location of the onset of II: II appears to become important at slightly lower currents for $T = 320$ K. Such behavior is expected, due to the positive temperature dependence of II. However, even in the low n_s case, TFE still may be responsible for a sizable portion of the gate current at $|I_{\mathrm{G}}| = 1$ mA/mm: by doing an apparent linear extrapolation of the $T = 320$ K low n_s two terminal gate-drain diode characteristics in the pre-II regime, we estimate that II accounts for perhaps 30–40% of gate current at breakdown. Such an estimation is also supported by examination of the gate current ratio.

The importance of II in the low n_s device helps us understand the change in curvature observed in Fig. 1—in this device, II becomes an important contributor to off-state breakdown at around $T = 280$ K, while in the other two devices, TFE dominates throughout the temperature range. These results also explain the ongoing debate as to the roles of II and tunneling/TFE in different devices. In the case of high n_s devices, tunneling/TFE appears to be the only consideration for $\mathrm{BV_{off}}$. Thus, one would expect high n_s devices with different channel compositions but similar n_s values to show similar breakdown voltages [2], [9]. On the other hand, as n_s is decreased, the relative importance of II grows. This illuminates work on lightly doped devices which showed a BV_{off} dependence on channel composition and quantization, as well as signatures of II in breakdown [3], [6], [12].

IV. SUMMARY AND CONCLUSION

In summary, we have demonstrated a new technique for analyzing the dominant breakdown mechanism in InAlAs/InGaAs HEMTs. By examining the ratio of gate currents at two different temperatures, we can identify the bias condition at which II becomes relevant. Our measurements suggest carrier concentration is a major consideration in determining the importance of II; in particular, II plays an important role in the lightly doped HEMT, while more highly doped devices are dominated by thermionic field emission and tunneling in the off-state.

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