Determining Dominant Breakdown Mechanisms in InAlAs/InGaAs HEMTs

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InAlAs/InGaAs High Electron Mobility Transistors (HEMTs) are very promising for millimeter-wave power and photonic applications; 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, Thermionic Field Emission (TFE), tunneling, or some combination thereof are responsible for off-state breakdown. Furthermore, different devices may suffer from different breakdown mechanisms, depending on the details of the design (insulator thickness, recess, channel composition, and so forth).

Of course, intelligent device design requires knowledge of which mechanism dominates breakdown in a particular device. Unfortunately, such determination in InAlAs/InGaAs devices has traditionally been difficult, because of the anomalous positive temperature dependence of impact ionization in InGaAs. To address this problem, we have recently proposed a novel, straightforward approach to determining which mechanism dominates off-state breakdown. As a vehicle for this work we have used three high performance, strained channel, double heterostructure InAlAs/InGaAs HEMTs with 0.1 µm gates. All samples were nominally identical except for their sheet carrier concentration, which ranged from 2.8×10^{12} cm^{-2} to $3.7 \times 10\ 10^{12}$ cm^{-2}. Measurements of off-state breakdown showed that these different doping levels lead to substantially different off-state breakdown voltages. As had been previously observed in other devices, the breakdown voltage decreased with increasing temperature in all three cases. This conventional measurement alone, however, is insufficient for determining the physics of breakdown.

We have been able to illuminate the breakdown mechanism by recognizing a key difference between TFE and impact ionization: although both mechanisms become stronger with increasing temperature, they have *opposite* temperature dependencies as a function of bias. A simple measurement allows us to exploit this: for a given value of drain-gate voltage, 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 drain-gate voltage or gate current gives significant insight into the physics of breakdown: so long as TFE is dominant, the ratio should decrease with increasing bias. On the other hand, as impact ionization becomes important, we expect the ratio to begin to increase with increasing bias.

Figure 22 shows the results of this measurement for several devices and different temperatures. Also plotted are lines showing the expected behavior of the ratio for pure TFE. As can be seen, the ratio essentially follows the expected TFE/tunneling behavior for low currents in all three devices. However, at higher currents, the ratio abruptly begins to rise in the more lightly doped devices. This is a clear signature of a transition to a region in which impact ionization is contributing to the gate current. The device with a moderate doping level makes this transition at a gate current of around 1 mA/m; the lightly doped device diverges from TFE at slightly below $|I_G| = 0.1$ mA/mm. However, even in this low doping case, our calculations indicate that TFE is still responsible for a sizable portion (about 65%) of the gate current at breakdown.

These results help resolve the ongoing debate as to the roles of impact ionization and tunneling/TFE in different devices. In addition, our work leads us to suggest methods for improving performance of InAlAs/InGaAs devices. In the case of highly doped devices, tunneling/TFE appears to be the only consideration for off-state breakdown, so it should be possible to modify channel composition for improved transport without penalty, and to improve breakdown voltage by changing insulator design. On the other hand, as the sheet carrier concentration is decreased, the importance of impact ionization grows, so breakdown engineering must rely on approaches that suppress multiplication, such as composite channels, channel quantization, and recess engineering.

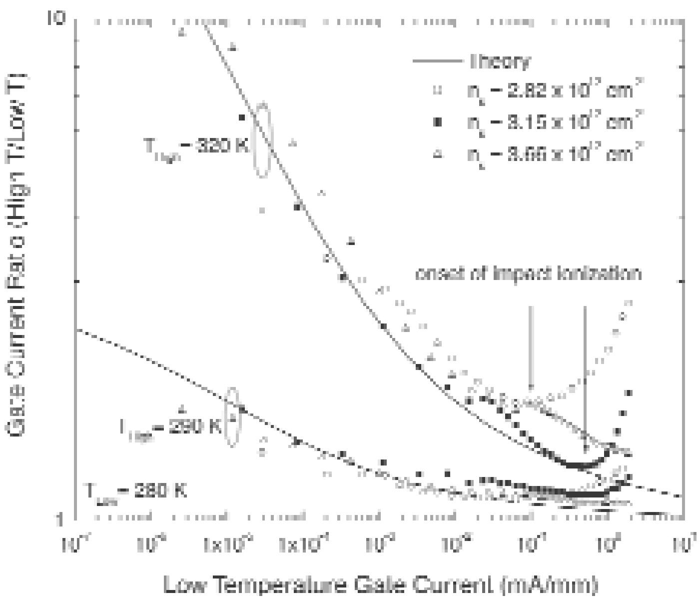

Fig. 22: High temperature - low temperature gate current ratios versus low temperature gate current of InAlAs/InGaAs HEMTs. All three devices follow the TFE-tunneling theory lines at lower currents, but devices with lower carrier concentrations diverge as low temperature gate current increases. This upturn indicates a transition to the regime in which impact ionization is significant.