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Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments

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Abstract

We present results of an experimental and theoretical study of the temperature dependence of the off-state breakdown voltage of InAlAs/InGaAs high electron mobility transistors (HEMTs). We find that the breakdown voltage (BV) has a negative temperature coefficient that is more prominent for lower values of the extrinsic sheet carrier concentration (n_s). Structural parameters such as the insulator thickness and top-to-bottom delta doping ratio have little effect on BV if n_s is held constant. These results are consistent with an extension of a new tunneling model for breakdown in HEMTs to include thermionic-field emission.

I. Introduction

InAlAs/InGaAs high electron mobility transistors (HEMTs) show promise for millimeter wave power applications. Recent years have seen significant improvements in the off-state breakdown voltage (BV), a key parameter for power (1-6). However, this work has been mainly empirical due to the lack of a predictive model. This has hindered first-pass design success.

Conventional understanding has held impact ionization or a combination of tunneling and impact ionization as the dominant mechanism for HEMT breakdown (7,8). Recently however, based on mounting experimental evidence suggesting that breakdown in HEMTs is largely determined by tunneling and/or thermionic-field emission, a 0 K predictive model for tunneling-limited breakdown was presented (9). The model, however, is incomplete without including a mechanism describing the temperature dependence of breakdown. An understanding of the temperature dependence of breakdown is important in itself since power HEMTs must operate at a wide range of temperatures. To address this, we have carried out careful temperature-dependent BV measurements on several state-of-the-art InAlAs/InGaAs HEMTs with well controlled values of sheet carrier concentration in the channel. Our work shows that an extension of the tunneling-limited breakdown model to finite temperatures successfully predicts all the experimental results.

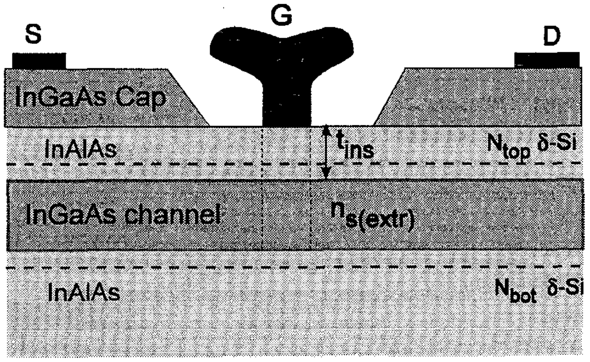

Figure 1: Cross section of the HEMTs under study.

II. Experimental

The devices used in this work are 0.1 μm T-gate double heterostructure InP HEMTs with a thin undoped cap fabricated by Lockheed Martin (Fig. 1). Several heterostructures with different insulator thicknesses, total doping levels and top to bottom delta doping ratios were grown. These design variations yielded wafers with sheet carrier concentrations from 2.82×10^{12} cm^{-2} to 3.66×10^{12} cm^{-2}. The fabrication process features a selective gate recess (10), allowing precise control of V_T and the value of the sheet carrier concentration in the extrinsic regions, $n_{s(extrinsic)}$.

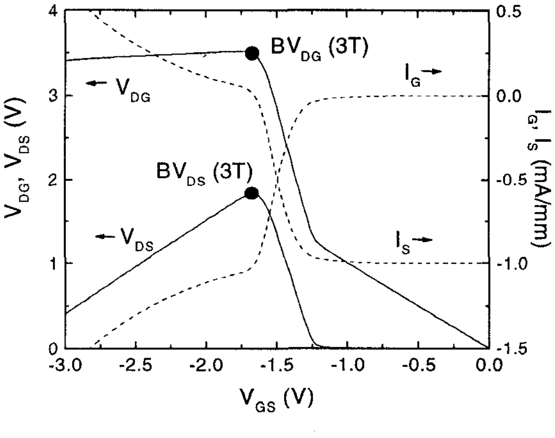

Figure 2: The drain current injection (3-terminal) breakdown voltage measurement for one of the devices under study. 1 mA/mm is injected into the drain and V_{GS} is swept from on-state to off-state.

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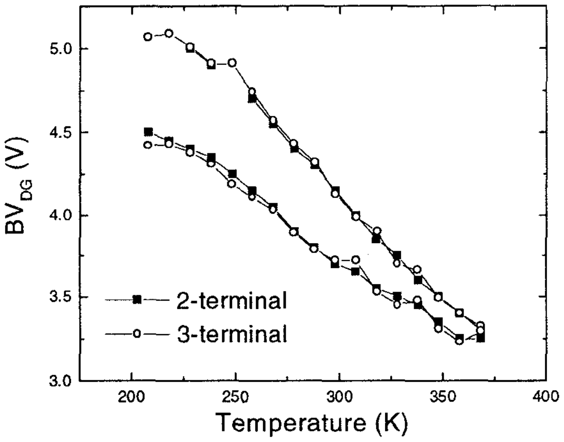

Figure 3: Temperature dependent breakdown voltage measurements for two representative devices using both a two-terminal and a three-terminal technique. Both techniques yield the same BV indicating breakdown is a gate-drain phenomenon.

To establish the breakdown path, we began our analysis by looking at 2- and 3-terminal measurements of the breakdown voltage (7). The 2-terminal technique involves only the standard reverse gate diode characteristics. BV$_{DG}$ is extracted where the gate current reaches 1 mA/mm with the source left floating.

For a more complete investigation of the breakdown of the device, we used the 3-terminal drain current injection technique (7). In this measurement, a 1 mA/mm current is injected into to the drain with the source grounded and the gate voltage is swept from the on-state through threshold into the off-state. The results of this technique on a typical device at room temperature are plotted in Fig. 2. BV$_{DG}$ is extracted at the point where I$_S$ goes to 0, and BV$_{DS}$ is defined as the peak in the V$_{DS}$ curve. V$_{DG}$ remains fairly constant once it reaches BV$_{DG}$. This is an indication that the breakdown we are observing takes place in the drain-gate diode and channel breakdown is not coming into play. This hypothesis is further supported by the comparison of 2-terminal and 3-terminal measurements in Fig. 3. BV(2T) tracks BV(3T) almost exactly for the entire temperature range studied. Armed with this evidence and the fact that the currents are very well behaved, we conclude that the breakdown path is in fact between the gate and the drain and that the 2-terminal measurement is sufficient to evaluate it.

Fig. 4 shows 2-terminal measurements of BV$_{DG}$ for a large number of room temperature measurements on each of the wafers under study. Each point represents the average of the measurements and the error bars indicate the standard deviation. BV exhibits a clear dependence on $n_{s(extrinsic)}$: higher values of $n_{s(extrinsic)}$ result in lower breakdown voltages. It does not, however, show significant correlation with most parameters, such as the insulator thickness and the delta doping ratio.

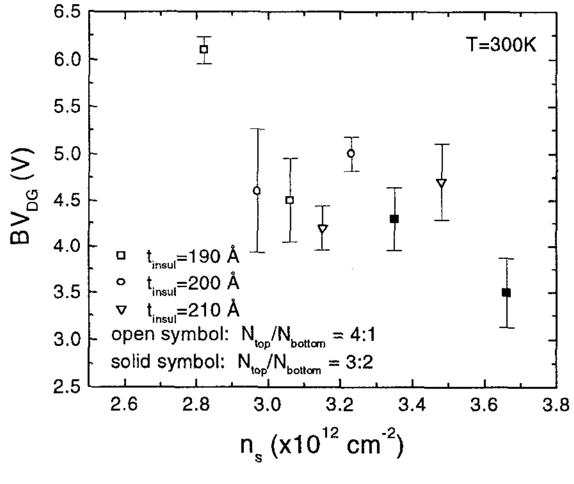

Figure 4: Plot of BV$_{DG}$ vs. $n_{s(extrinsic)}$ for all wafers under study. Each data point and error bar represent data from several devices on each wafer.

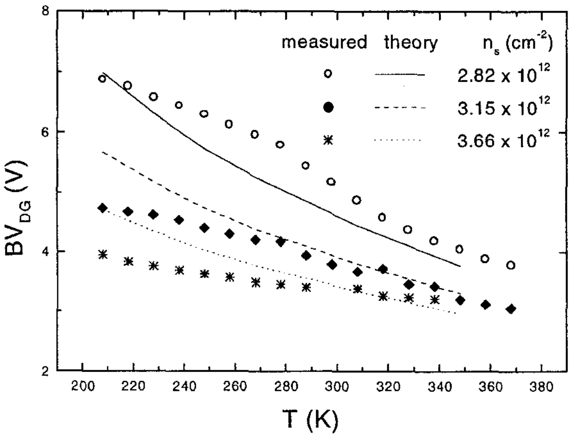

Figure 5: Experimental and theoretical temperature dependence of breakdown voltage for different values of $n_{s(extrinsic)}$. Theory lines correspond to ϕ_B=0.63eV and the measured $n_{s(extrinsic)}$.

In Fig. 5 we see BV results for three of the wafers in the sample set as a function of temperature. We observe that BV is a well-behaved function of temperature. It has a negative temperature dependence, and the temperature coefficient decreases for higher values of $n_{s(extrinsic)}$.

To complete our study, we have measured the temperature dependent characteristics of the gate current. We have found that I$_G$ is thermally activated. This is evident in an Arrhenius plot of I_G/T^2 for one of the samples shown in Fig. 6. The activation energy depends on bias. This is consistent with a thermionic-field emission model for the gate current. The evolution of the activation energy with V$_{DG}$ is shown in Fig. 7 for several samples. Comparison with a simple model (discussed below) allows for the extraction of

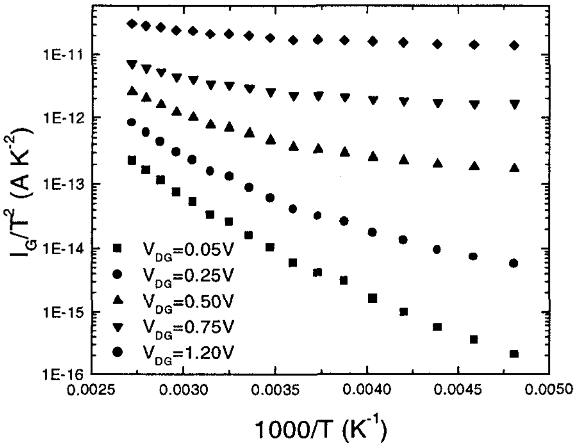

Figure 6: Arrhenius plot of the gate current. The activation energy decreases as V_{DG} increases and approaches V_T.

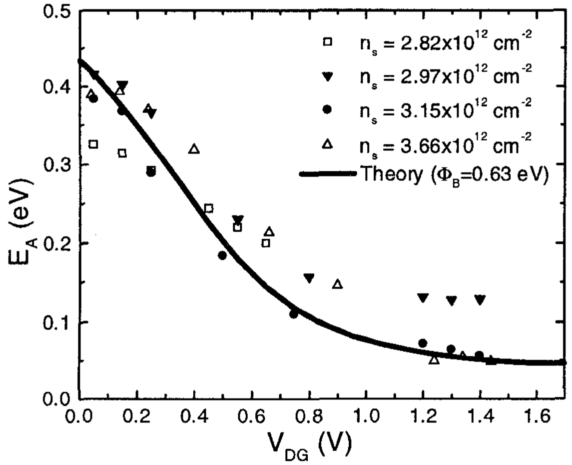

Figure 7: Activation energy of I_G at various bias values for different samples.

the Schottky barrier height of the gate which is found to be 0.63eV.

III. New Model for BV

In our experiments, we have observed that breakdown is a purely drain-gate phenomenon, $n_{s(extrinsic)}$ is the only structural parameter that significantly affects BV, the reverse-biased gate current is a well-behaved function showing temperature activation throughout, and BV has a negative temperature dependence that is more prominent for lower $n_{s(extrinsic)}$.

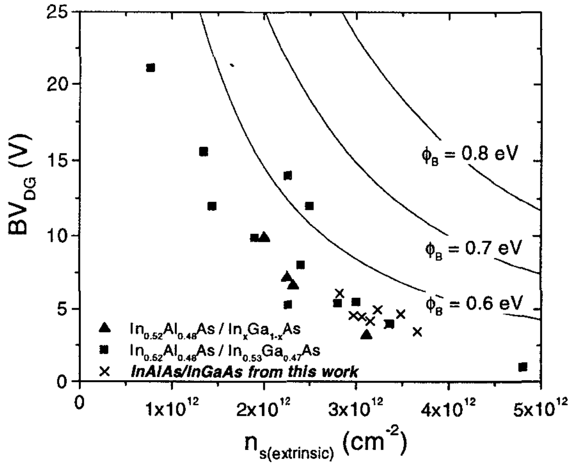

Figure 8: BV_{DG} vs. $n_{s(extrinsic)}$ for InAlAs/InGaAs HEMTs from the literaure and this work. The lines represent theoretical limits of BV on devices with the indicated Schottky barrier height.

The new tunneling-limited model for BV (9) concludes that there should be a nearly inverse relationship between BV and $n_{s(extrinsic)}$ and that BV should be rather insensitive to other structural parameters. Fig. 8 presents BV vs. $n_{s(extrinsic)}$ results for leading devices in the literature and theory lines based on the tunneling-limited model for the Schottky barrier heights indicated. The results from our sample set correspond very well to the theoretical and experimental trends offered in the literature, leading us to conclude to the first order that the tunneling-limited model is appropriate for these devices. According to the model, calculations for the off-state breakdown current are dominated by a peak in the electric field under the gate at its drain end. This peak results from a depletion region extending into the extrinsic channel at the drain end of the gate. This model suggests that $n_{s(extrinsic)}$ is the only structural parameter that has a significant impact on the magnitude of the peak in the electric field and, therefore, BV.

The tunneling model alone, however, does not include any temperature dependence and therefore does not help in explaining our experimental observations on the temperature dependence. In incorporating temperature dependence effects, it is important to recognize that the electrostatics of the problem near breakdown are unlikely to be much affected by T. This is because of the high aspect ratio of the depletion region in the drain of the device. Therefore, we can still use 0 K electrostatics in our revised model. On the other hand, for a given field distribution underneath the gate, the gate current is strongly affected by temperature. The tunneling model needs to be extended to include thermionic-field emission as well as thermionic emission over the gate Schottky barrier (11). This does not complicate the model in a significant way since these current components depend only on ϕ_B, the Schottky barrier height of the gate, and the electric field.

If the gate current is determined primarily by tunneling and thermionic-field emission in the gate Schottky diode, currents from different samples should match if the field configuration under the gate is the same and they have the same ϕ_B. In fact, we have found that if we match the gate

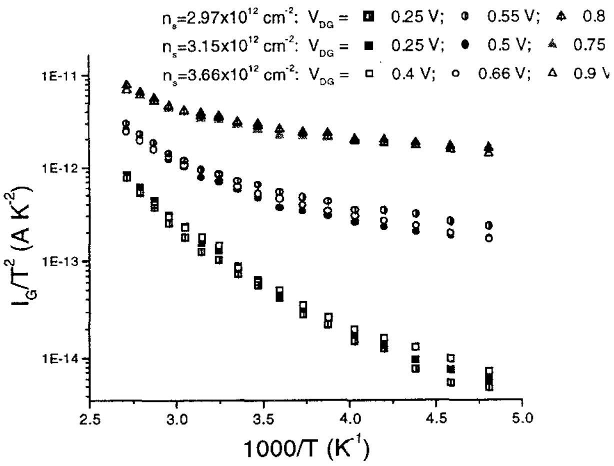

Figure 9: "Universal behavior" of I_G across samples. I_G vs. T dependence is identical for different samples if proper value of V_{DG} is selected.

currents on different samples at any given temperature, the evolution of those gate currents with temperature is identical if V_{DG} is held constant and above threshold. This "universal" behavior is shown in Fig. 9.

Fig. 5 shows calculations of BV_{DG} based on the extracted Schottky barrier height and the known value of $n_{s(extrinsic)}$ for the three measured samples shown. The qualitative agreement is fairly good especially given that the model does not take into consideration non-idealities such as the presence of a cap recess. As before, once ϕ_B and $n_{s(extrinsic)}$ are independently determined, there are no adjustable parameters in this theory. The reason for the reduced temperature coefficient for increased $n_{s(extrinsic)}$ is now obvious. For higher $n_{s(extrinsic)}$, tunneling plays a more significant role in the current and thus the effect of temperature (thermionic-field emission) is smaller.

As a further confirmation of the theory, we investigate the bias dependence of the gate current at various temperatures. In Fig. 10 we see the reverse bias current for the drain-gate Schottky diode near each extreme of the temperature range studied. The current grows strongly as a function of bias when the channel is on (V_{GD} < -1.3 V) but grows more slowly past threshold. Only at currents above 1 mA/mm and high temperatures does the current begin to grow significantly again. The theory, which has no adjustable parameters, provides an excellent prediction of the bias dependence of the current at both temperature extremes. Above threshold (V_{DG} < 1.3 V), the field under the gate is directly controlled by V_{DG}, hence I_G shows a strong dependence on V_{DG}. Below threshold (V_{DG} > 1.3 V), the current grows more slowly since a fraction of V_{DG} is consumed opening the depletion region towards the drain (9). I_G only begins to deviate for currents well above 1 mA/mm. This may be due to the onset of impact ionization in the channel. Considering this might be important to describe the on-state breakdown voltage.

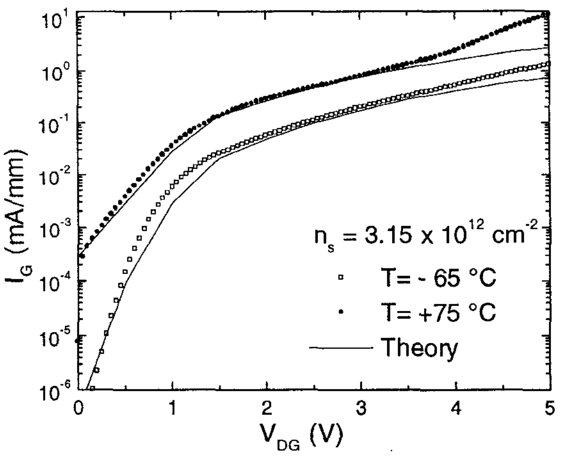

Figure 10: Experimental and theoretical bias dependence of I_G at the temperature extremes for a sample with $n_{s(extrinsic)}$= 3.15 x 10^{12} cm^{-2}.

IV. Conclusions

In summary, we have investigated the temperature dependence of off-state breakdown in InAlAs/InGaAs power HEMTs and found that the results are in good agreement with a tunneling/thermionic-field emission theory. BV has a negative temperature coefficient that is more prominent for a lower $n_{s(extrinsic)}$. The theory predicts well the bias dependence of the reverse diode current and the temperature dependence of BV_{DG} as well as the actual values of BV_{DG}.

V. Acknowledgments

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