Off-State Breakdown in Power pHEMTs: the Impact of the Source

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Conventional wisdom suggests that in pseudomorphic high electron mobility transistors (pHEMTs), the field between the drain and the gate determines off-state breakdown, and that the drain to gate voltage therefore sets the breakdown voltage of the device. Thus, the two terminal breakdown voltage is a widely used figure of merit, and most models for breakdown focus on the depletion region in the gate-drain gap, while altogether ignoring the source. We present new measurements and simulations that demonstrate that for power pHEMTs, the electrostatic interaction of the *source* seriously degrades the device's *gate-drain* breakdown, and must be taken into consideration in device design.

As a vehicle for this study we have used a state-of-the-art L_G=0.25 µm double heterostructure pHEMT with excellent power performance (P_o= 1W, Gain= 11dB, and PAE=60% at 10 GHz for W_G=1200 µm) and high breakdown voltage (BV_{DG}=21 V at I_D=1 mA/mm). Fig. 1 presents a cross-section of the device. Conventional breakdown measurements reveal that at all temperatures and current conditions, BV_{DS} and BV_{DG} track each other, showing that off-state breakdown is determined by the drain-gate diode. In addition, at 1 mA/mm both BV_{DS} and BV_{DG} are temperature independent, indicating that the physical mechanism responsible for breakdown is tunneling from gate to drain.

Although our conventional measurements support the belief that breakdown is purely determined by V_{DG}, drain current injection measurements [1] show that the situation is not so simple. In Fig. 2 we plot typical BV_{DG} vs. V_{GS} at I_D=1mA/mm at both high and low temperatures. V_{DG} reaches a peak value of about 21 V at V_{GS}=-3 V, but then *drops by more than 10 V* as V_{GS} becomes more negative. Although V_{DG} is dropping, most of the drain current continues to flow from drain to gate. Furthermore, the characteristics are rather independent of temperature, indicating that tunnelling remains the dominant mechanism as V_{GS} changes. Reversing the source and drain shows a similar, albeit smaller effect of V_{GD} on BV_{SG}. Extensive additional experiments at different current criteria and in other bias configurations confirm our conclusion that the V_{GS} is seriously degrading the breakdown voltage of the drain-gate diode.

Consideration of the way lateral depletion is imaged on the gate offers an explanation for this source-induced breakdown degradation. Although lateral depletion is typically assumed to be imaged at the closest edge of the gate, careful examination of the electrostatics shows that such depletion is, in fact, imaged along the entire gate length even at high aspect ratios. Fig. 3 shows how this explains our results. In (3a) the device is biased such that the field at the drain end of the gate is sufficient to support 1 mA/mm of current on the drain-gate diode. When the gate to source voltage is made more negative (3b), the depletion region on the source side of the gate is extended. The source depletion-region charge is imaged across the entire gate length; thus, the total charge at the drain end of the gate is increased. This raises the field at the drain end of the gate, and results in increased current on the drain-gate diode. In order to bring the current back down to 1 mA/mm, the drain to gate voltage must be decreased, so that the field at the drain end of the gate is reduced to its original value (3c).

We have confirmed this mechanism with two-dimensional simulations using MEDICI HD-AAM. Fig. 4 shows the field magnitude directly beneath the gate at three bias conditions. As can be seen, making V_{GS} more negative produces a significant increase in field at the drain end of the gate, which can only be offset by a reduction in V_{DG}. Because of the greater extent of the drain depletion region, the drop in V_{DG} can be very large -- in this case, V_{DG} decreases 5 V, while V_{GS} only changes 2 V. Since tunneling is dominant, we expect that the constant current condition typical of the breakdown measurement equates to a constant field condition in the simulation. Thus, Fig. 5 plots measured BV_{DG} for three current conditions, and calculated V_{DG} for three field conditions. As can be seen, the agreement is excellent.

Our findings demonstrate that electrostatic interaction of the source with the drain-end of the gate has a major degrading impact on the off-state breakdown voltage of pHEMTs. This is relevant both for device modeling and for high-power device design, as in many amplifier topologies the gate voltage swings significantly below threshold. In high-power device design the source must be engineered with complete understanding of its impact on the breakdown voltage.

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[1] S.R. Bahl and J.A. del Alamo, TED **40**, 1558 (1993).

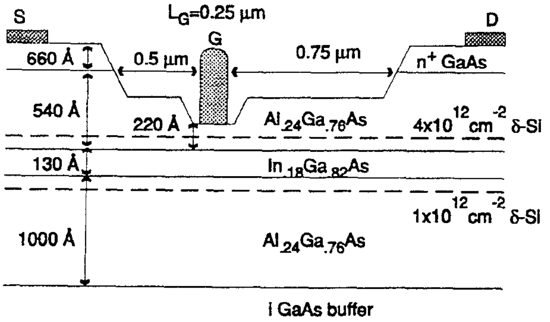

Figure 1: Device cross-section. Note asymmetric design for breakdown voltage enhancement.

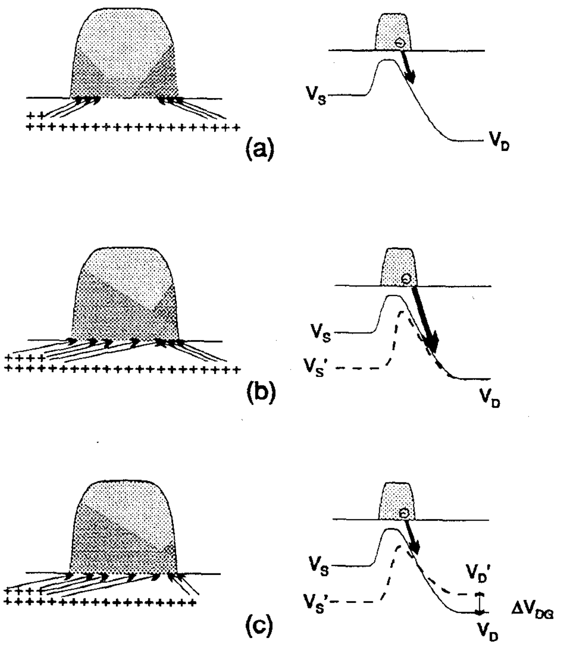

Figure 3: Proposed mechanism for source-induced breakdown reduction. Initially the device is biased such that the gate-drain diode supports 1 mA/mm of reverse leakage current (a). As V_{GS} is made more negative, the additional lateral depletion towards the source is partially imaged on the drain end of the gate. This increases the field at the drain end of the gate, yielding a larger tunneling current (b). In order to recover the original current level, V_{DG} must be reduced (c). Thus, the source significantly degrades drain-gate breakdown.

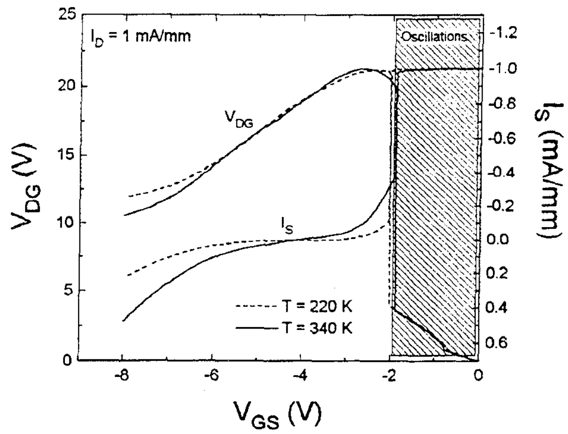

Figure 2: Drain current injection measurement of breakdown at I_D=1mA/mm. Note that V_{DG} drops substantially as V_{GS} is reduced, even as current continues to flow drain-to-gate.

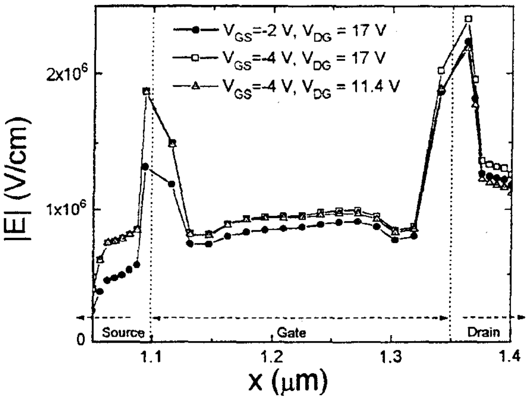

Figure 4: MEDICI simulations of electric field beneath the gate for three bias conditions. Breakdown is associated with the peak field at the drain end of the gate; as V_{GS} is made more negative, V_{DG} must be reduced in order to return the peak drain field to its original value.

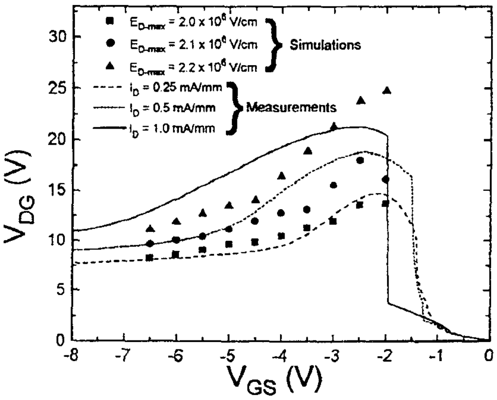

Figure 5: Comparison of contant current criteria measurements with constant field criteria MEDICI simulations. The simulations effectively capture the qualitative behavior of BV_{DG}.