Chapter 2. Physics of InAlAs/InGaAs Heterostructure Field-Effect Transistors

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2.1 Introduction

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The goal of this project is to support the development of InAlAs/InGaAs heterostructure field-effect transistors for millimeter-wave high-power applications. This is a key component missing for millimeter-wave radar and communication systems.

In 1997, we developed a new definition of and measurement technique for on-state breakdown in high-electron mobility transistors (HEMTs). The technique, gate current extraction, is unambiguous, simple, and nondestructive. Using the gate current extraction technique in conjunction with sidegate and temperature-dependent measurements, we illuminate the different roles of thermionic field emission and impact ionization in HEMT breakdown. This physical understanding allows the creation of a phenomenological model for breakdown and demonstrates that, depending on device design, either on-state or off-state breakdown can limit maximum power.

Although great strides have been made in understanding and improving off-state breakdown (BV_{off}) in HEMTs,[1] work on the on-state breakdown voltage (BV_{on}) has been limited due to difficulties in defining and measuring this figure of merit. BV_{on} has been measured either by using a burnout criterion[2] or by requiring a significant upturn in the drain current[3] — a somewhat ambiguous and often destructive condition. In this work, we propose a simple, unambiguous, reproducible, and nondestructive gate current extraction measurement for BV_{on} . This method, in conjunction with detailed temperature-dependent measurements and sidegate measurements, reveals the roles of impact ionization and tunneling plus thermionic field emission (TFE) in BV_{on} and BV_{off} and allows us to develop a simple model for BV_{on} . We

1 C.S. Putnam, M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh, "Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 197; K.Y. Hur, R.A. McTaggart, B.W. LeBlanc, W.E. Hoke, A.B. Miller, T.E. Kazior, and L.M. Aucoin, "Double Recessed AlInAs/GaInAs/InP HEMTs with High Breakdown Voltages," *Proceedings of the IEEE GaAs IC Symposium*, 1995, p. 101; J. Dickmann, S. Schildberg, K. Riepe, B.E. Maile, A. Schurr, A. Geyer, and P. Narozny, "Breakdown Mechanisms in Pseudomorphic $InAlAs/In_xGa_{1-x}As$ High Electron Mobility Transistors on InP. I: Off-State," *Jpn. J. Appl. Phys. Pt. 1* 34(1) (1995); S.R. Bahl, J.A. del Alamo, J. Dickmann, and S. Schildberg, "Off-State Breakdown InAlAs/InGaAs MODFETs," *IEEE Trans. Electron Dev.* #42: 15 (1995); J.J. Brown, J.A. Pusi, M. Hu, A.E. Schmitz, D.P. Docter, J.B. Shealy, M.G. Case, M.A. Thompson, and L.D. Nguyen, "High-Efficiency GaAs-based pHEMT C-band Power Amplifier," *IEEE Micro. Guided Wave Lett.* 6: 91 (1996).

2 H. Rohdin, C. Su, N. Moll, A. Wakita, A. Nagy, V. Robbins, and M. Kauffman, "Semi-Analytical Analysis for Optimization of 0.1- μm InGaAs-channel MODFETs with Emphasis on On-State Breakdown and Reliability," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 357.

3 J. Dickmann, S. Schildberg, A. Geyer, B.E. Maile, A. Schurr, S. Heuthe, and P. Narozny, "Breakdown Mechanisms in the On-State Mode of Operation of InAlAs/InGaAs Pseudomorphic HEMTs," *Proceedings of the Sixth International Conference on Indium Phosphide and Related Materials*, Paris, France, 1994, p. 335.

find that, depending on device design, either BV_{off} or BV_{on} can limit the maximum power density of an HEMT.

2.2 A New Measurement Technique for On-State Breakdown Voltage

Figure 1 depicts the measurement technique for BV_{on}. I_G is held constant at a desired value (a typical condition is 1 mA/mm), and I_D is ramped from I_G to some reasonable value (typically $\frac{1}{5}$ I_{Dmax}). This technique traces a locus of V_{DS} versus I_D for constant I_G; we define this locus as BV_{on}. This definition is sensible in several respects: (1) it ramps from BV_{off} which is usually defined as I_G=I_D=1 mA/mm; (2) it defines a locus of significant gate conductance; (3) as seen below, it measures a locus of constant impact ionization, which has been associated with burnout.[4]

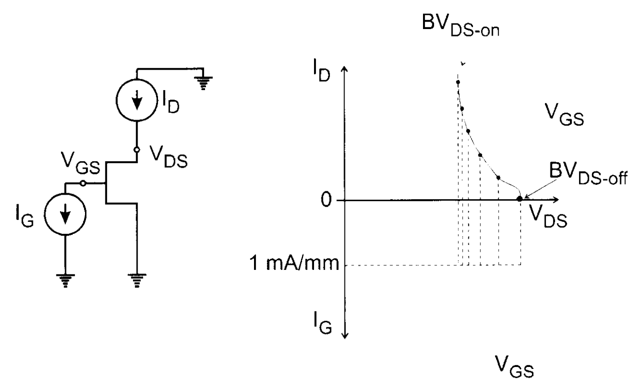


Figure 1. Gate current extraction measurement technique for BV_{on}. A constant current (typically 1 mA/mm) is extracted from the gate while I_D is swept from the off-state (1 mA/mm) to the on-state (200 mA/mm). The technique traces a breakdown locus of V_{DS} versus I_D.

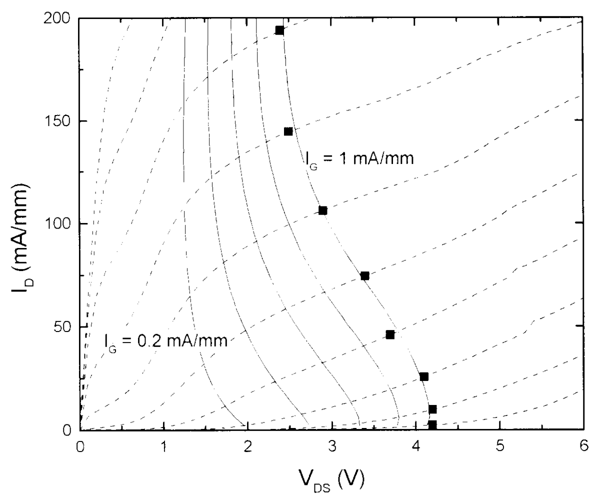


Figure 2. BV_{on} versus I_D for 0.1 lm InAlAs/InGaAs HEMT for different values of I_G . The data are superimposed on the output characteristics. As an independent verification of the technique, the points on the output characteristics at which I_G = 1 mA/mm are plotted as well. The constant I_G criteria additionally tracks the sudden rise of drain conductance often associated with BV_{on} .

The technique is illustrated on a state-of-the-art 0.1 μm InAlAs/InGaAs HEMT[5] in Figure 2, where BV_{on} loci for several values of I_G are superimposed on the output characteristics. As the device is turned on, BV_{on} drops from 4.2 V (BV_{off}) to less than 2.5 V. For $V_{DS} > BV_{on}$, the drain conductance begins to rise, indicating that the device is approaching a dangerous bias region. Such an interpretation is supported by burnout measurements. Figure 3 plots the results of burnout measurements on one sample. As can be seen, the gate current extraction technique accurately predicts the dangerous bias region. Measurements on a variety of samples confirm the view that on-state burnout occurs at an approximately constant gate current (Figure 4).

4 H. Rohdin, C. Su, N. Moll, A. Wakita, A. Nagy, V. Robbins, and M. Kauffman, "Semi-Analytical Analysis for Optimization of 0.1- μm InGaAs-channel MODFETs with Emphasis on On-State Breakdown and Reliability," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 357.

5 C.S. Putnam, M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh, "Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 197.

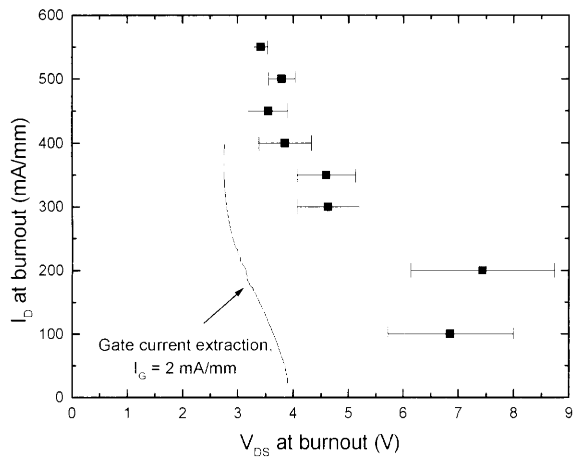


Figure 3. Comparison of gate current extraction and burnout measurements. Burnout is determined by injecting a constant drain current and gradually increasing the magnitude of the gate current.

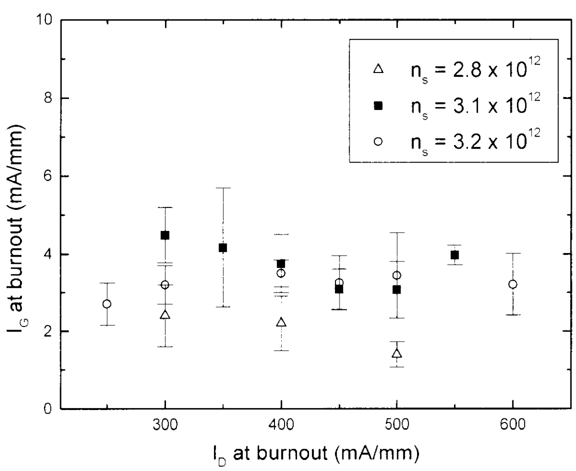


Figure 4. Burnout measurements on several samples. Once the device is in the on-state, burnout appears to occur at a constant gate current.

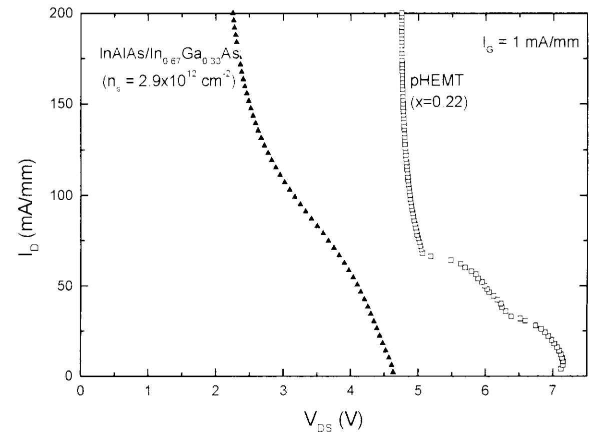


Figure 5. BV_{on} for an InAlAs/In0.67Ga0.33As HEMT and an AlGaAs/InGaAs pHEMT at I_G=1mA/mm. Both devices show a significant drop in breakdown as I_D is increased.

For comparison, we have also measured BV_{on} in a high-performance AlGaAs/InGaAs pHEMT at I_G=1 mA/mm (Figure 5). Both devices show similar characteristics: BV_{on} drops as the device is turned on, and then becomes fairly constant at higher values of I_D.

2.3 On-State Breakdown Physics

Figure 6 presents a picture of the physics of BV_{on}. In the off-state (a), I_G is almost purely TFE.[6] However, as I_D rises, (b) impact ionization starts to generate holes which escape to the gate.[7] To maintain constant I_G, V_{DG} must drop and so does V_{DS}. Once the device is fully on, BV_{on} becomes more vertical, due to the exponential dependence of impact ionization on field (c).

6 C.S. Putnam, M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh, "Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 197; M.H. Somerville and J.A. del Alamo, "A Model for Tunneling-Limited Breakdown in High-Power HEMTs," *Proceedings of the International Electron Devices Meeting*, San Francisco, California, 1996, p. 35.

7 G. Meneghesso, A. Mion, A. Neviani, M. Matloubian, J. Brown, M. Hafizi, T. Liu, C. Canali, M. Pavesi, M. Manfredi, and E. Zanoni, "Effects of Channel Quantization and Temperature on Off-State and On-State Breakdown in Composite Channel and Conventional InP-based HEMTs," *Proceedings of the International Electron Devices Meeting*, San Francisco, California, 1996, p. 43.

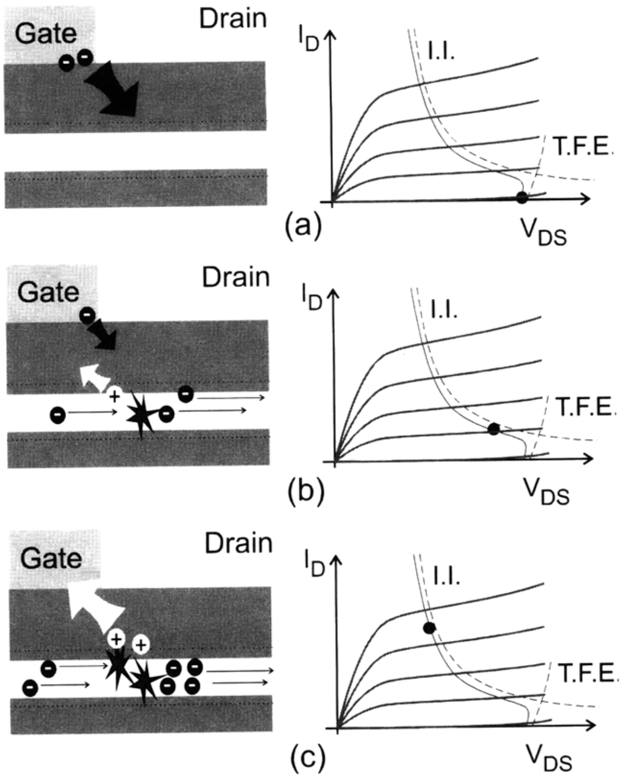


Figure 6. Mechanisms for breakdown. (a) Close to threshold, I_G is almost purely tunneling and thermionic field emission. (b) and (c) As the device is turned, impact ionization in the channel produces holes, which escape to the gate. In order to support a constant I_G, V_{DG} must drop.

To test the validity of our picture, we have performed temperature-dependent measurements of BV_{on} and BV_{off} (Figure 7). BV_{off} in both types of HEMTs exhibits a negative temperature coefficient, consistent with TFE. However, BV_{on} in the pHEMT exhibits a small but significant (50 mV) rise as temperature is increased. The transition from a negative to a positive temperature coefficient is a clear signature of a transition from TFE to impact ionization. In contrast, the temperature dependence of BV_{on} for the InAlAs/InGaAs HEMT is negative. This is consistent with the recent demonstration of a negative temperature coefficient for impact ionization in this material system.[8]

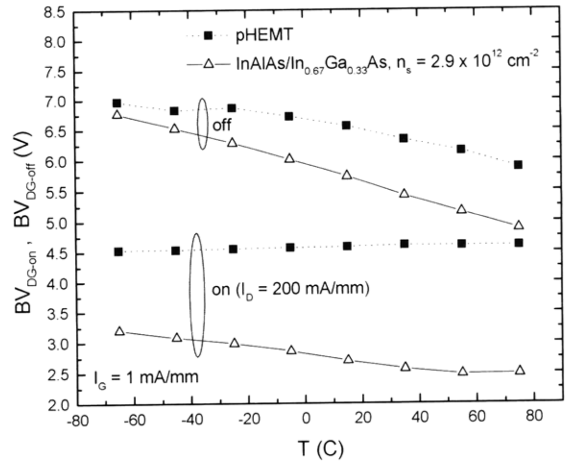


Figure 7. Temperature dependence of BV_{off} (I_G=I_D=1mA/mm) and BV_{on} (I_D=200 mA/mm, I_G=1mA/mm) in an AlGaAs/InGaAs pHEMT and a strained channel InAlAs/InGaAs HEMT.

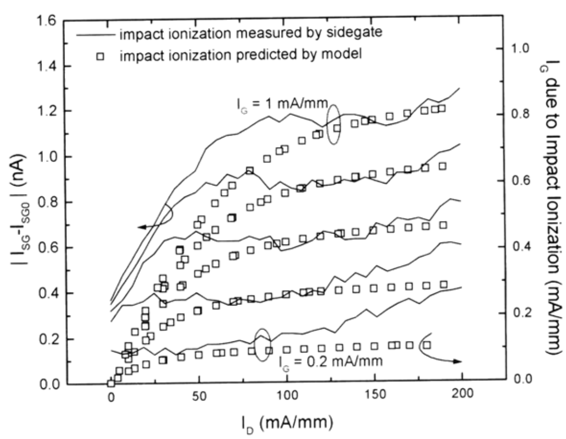


Figure 8. Sidegate current measured during on-state breakdown measurement (V_{SG}= -50 V). The rise and saturation of I_{SG} demonstrate the transition from the TFE-dominated off-state to the II-dominated on-state. Also plotted are the simple model's predictions for impact ionization current; as can be seen, the model agrees well with the sidegate measurements.

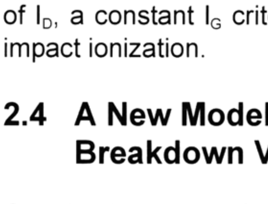
8 G. Meneghesso, A. Mion, A. Neviani, M. Matloubian, J. Brown, M. Hafizi, T. Liu, C. Canali, M. Pavesi, M. Manfredi, and E. Zanoni, "Effects of Channel Quantization and Temperature on Off-State and On-State Breakdown in Composite Channel and Conventional InP-based HEMTs," *Proceedings of the International Electron Devices Meeting*, San Francisco, California, 1996, p. 43.

To confirm the physical mechanisms in the InAlAs/InGaAs HEMT, we have directly monitored hole generation through a sidegate[9] while the locus of BV_{on} is traced (Figure 8). When the device is off, the sidegate current is minimal and independent of I_G, indicating that TFE dominates breakdown in the off-state. However, as I_D is increased, the sidegate current first rises as impact ionization turns on and then saturates for I_D > 80 mA/mm. Furthermore, the saturated sidegate current scales with I_G. This indicates that the gate's hole collection efficiency does not depend much on I_G or I_D and that, for sufficiently high values of I_D, a constant I_G criterion corresponds to constant impact ionization.

2.4 A New Model for On-state Breakdown Voltage

Our simple picture of BV_{on} leads to a phenomenological model that can assist device and circuit designers (Figure 9). There are two components in I_G : TFE and impact ionization. We have previously shown that TFE depends mainly on the extrinsic sheet carrier concentration, the gate Schottky barrier height, and V_{DG} .[10] Proper calculation of the impact ionization current requires precise knowledge of the fields in the channel and the ionization rate. It is possible, however, to simplify the problem using the experimentally verified expression[11]:

$$I_{ii} = A \exp(-B/V_{DS}-V_{DS\text{-}sat})$$



$$I_{gate} = I_{TFE} + I_{ii}$$

$$I_{TFE} = f(n_{sextr}, V_{DG}, \phi_B)$$

$$I_{ii} = A\, I_D \exp\left(\frac{-B}{V_{DS}-V_{DS\text{-}sat}}\right)$$

Figure 9. Elements of BV model. For a given V_{DG} and I_D, I_G is determined by the fraction of the holes generated by impact ionization that are extracted by the gate and by the number of electrons which escape from the gate due to TFE and tunneling.

B can be independently determined from sidegate measurements; A is a scaling constant that depends on device design. The model accurately predicts the I_G characteristics (Figure 10), BV_{on} loci (Figure 11), and impact ionization rate measured by the sidegate (Figure 8).

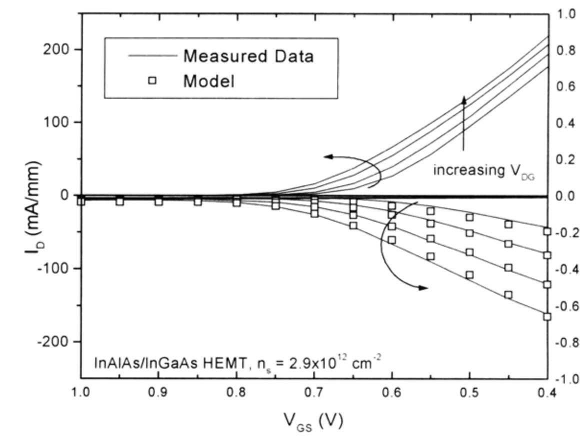


Figure 10. Comparison of measured and modeled gate current characteristics for InAlAs/InGaAs HEMT.

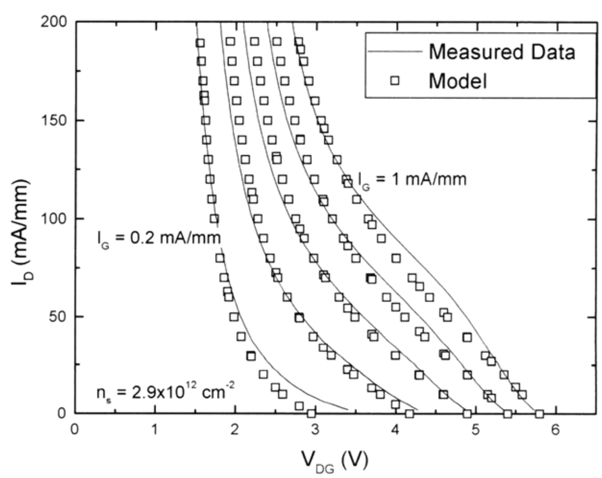


Figure 11. Comparison of measured and modeled breakdown contours InAlAs/InGaAs HEMT for different I_G criteria.

9 A.A. Moolji, S.R. Bahl, and J.A. del Alamo, "Impact Ionization in InAlAs/InGaAs HFETs," *IEEE Electron Dev. Lett.* 15: 313 (1994).

10 C.S. Putnam, M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh, "Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments," *Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, MA, May 11-15, 1997, p. 197; M.H. Somerville and J.A. del Alamo, "A Model for Tunneling-Limited Breakdown in High-Power HEMTs," *Proceedings of the International Electron Devices Meeting*, San Francisco, California, 1996, p. 35.

11 A.A. Moolji, S.R. Bahl, and J.A. del Alamo, "Impact Ionization in InAlAs/InGaAs HFETs," *IEEE Electron Dev. Lett.* 15: 313 (1994).

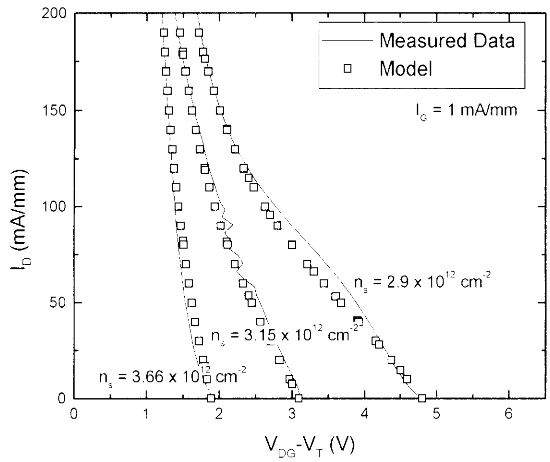


Figure 12. Comparison of measured and modeled breakdown contours for three different InAlAs/ InGaAs HEMTs at I_G=1mA/mm.

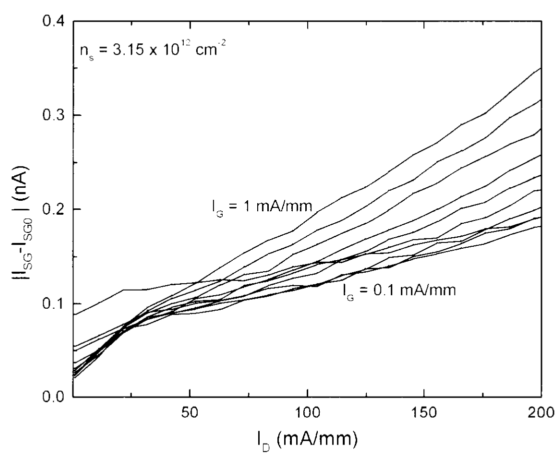


Figure 13. Sidegate current for InAlAs/InGaAs HEMT with higher n_s. The fact that the sidegate current does not saturate indicates the relative importance of TFE up to high values of I_D.

To explore the impact of design parameters on BV_{on}, we have measured a sample set of 0.1 μm InAlAs/ InGaAs HEMTs with varying values of extrinsic sheet carrier concentrations (n_s) (Figure 12).[12] The model works well for all three devices. Interestingly, increasing n_s results in much more vertical BV_{on} contours. It is striking that three devices with such different BV_{off} values (1.9 V to 4.7 V) approach similar BV_{on} values (1.2 V to 1.7 V at 200 mA/mm). Our model explains this behavior: in the higher n_s devices, BV_{off} is low; thus the field in the channel is lower, and the device moves more slowly into impact ionization. As a result, BV_{on} only degrades slightly. This view is supported by the model and by sidegate measurements on the higher n_s devices (Figure 13), which show that these HEMTs move gradually into impact ionization. The devices' similarity in BV_{on} seems to suggest that improvements in BV_{off} are not meaningful; however, examination of allowable load lines on each device (Figure 14) makes it clear that the transition from BV_{off} to BV_{on} is crucial to a device's power potential, as has been previously noted in MESFETs.[13]

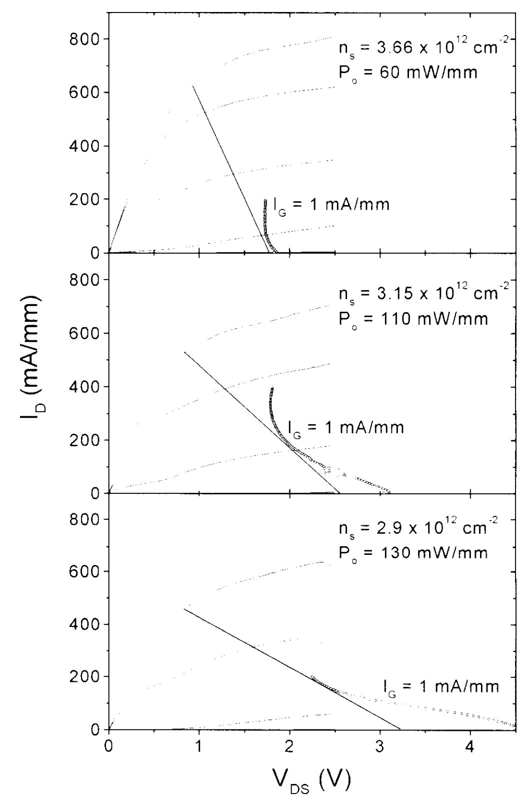


Figure 14. Comparison of power load lines for three InAlAs/InGaAs HEMTs. Due to transition from BV_{off} to BV_{on} one can bias the low n_s device for greater power output.

12 C.S. Putnam, M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh, "Temperature Dependence of Breakdown Voltage in InAlAs/ InGaAs HEMTs: Theory and Experiments," *Proceedings of the Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, p. 197.

13 T.A. Winslow, D. Fan, and R.J. Trew, "Gate-Drain Breakdown Effects Upon the Large Signal Performance of GaAs MESFETs," *IEEE Micro. Theory Tech. Sym. Digest*, p. 315 (1990).

2.5 Conclusions

In summary, we have presented an unambiguous definition and a simple, nondestructive measurement for BV_{on} in HEMTs. Both BV_{off} and BV_{on} must be considered when designing a power device.

2.6 Publications

Ernst, A.N., M.H. Somerville, and J.A. del Alamo. "Dynamics of the Kink Effect in InAlAs/InGaAs HEMTs." *Proceedings Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, May 1997, pp. 353-56.

Ernst, A.N., M.H. Somerville, and J.A. del Alamo. "Dynamics of the Kink Effect in InAlAs/InGaAs HEMTs." *IEEE Electron Dev. Lett.* 18(12): 613-15 (1997).

Ernst, A.N., M.H. Somerville, and J.A. del Alamo. "A New Z11 Impedance Technique to Extract Mobility and Sheet Carrier Concentration in HFETs." *IEEE Trans. Electron Dev.* 45(1): 9-13 (1998).

Putnam, C.S., M.H. Somerville, J.A. del Alamo, P.C. Chao, and K.G. Duh. "Temperature Dependence of Breakdown Voltage in InAlAs/InGaAs HEMTs: Theory and Experiments." *Proceedings Ninth International Conference on Indium Phosphide and Related Materials*, Hyannis, Massachusetts, May 11-15, 1997, pp. 197-200.

Somerville, M.H., R. Blanchard, J.A. del Alamo, G. Duh, and P.C. Chao. "On-State Breakdown in High-Power HEMTs: Measurements and Modeling." *Proceedings International Electron Devices Meeting*, Washington, DC, 1997, pp. 553-56.