Millimeter-Wave Power InP HEMTs: Challenges and Prospects

J. A. del Alamo, M. H. Somerville, and R. R. Blanchard

Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ABSTRACT

At this time, GaAs PHEMTs exhibit higher power output than InP HEMTs at 60 and 94 GHz. InP HEMTs, however, feature power-added efficiency values that exceed GaAs PHEMTs by about 5 to 20 percentage points at 94 GHz. As a consequence, InP HEMTs remain a superior candidate for millimeter-wave power applications. The reason for the inferior output power of InP HEMTs lies in their relatively small on-state and off-state breakdown voltages. This paper reviews the state of the art of millimeter-wave power HEMT technology as well as recent advances in understanding of breakdown phenomena. It also discusses the prospects and challenges facing InP HEMTs in performance, reliability and low-cost manufacturing.

INTRODUCTION: STATE-OF-THE-ART OF POWER InP HEMTS

The use of InAlAs/InGaAs HEMTs (InP HEMTs for short) in low-noise applications is well established. The suitability of these devices for millimeter-wave power amplification is still a matter of debate. This can be understood from an examination of reported power measurements of InP HEMTs and GaAs Pseudomorphic HEMTs (PHEMTs) in the millimeter-wave regime. Fig. 1 plots power-added efficiency (PAE) and gain as a function of output power for devices, MMICs and modules at 60 and 94 GHz. At 60 GHz, Fig. 1 (left), power levels in excess of 1 W have already been demonstrated using GaAs PHEMTs. In contrast, InP HEMTs have only delivered about 300 mW. For similar power levels, InP HEMTs exhibit about the same PAE as GaAs PHEMTs. Since GaAs PHEMT technology is significantly more mature, two- and even three- stage MMIC amplifiers have already been demonstrated. In consequence, GaAs PHEMT technology can deliver higher power with significantly higher gain when compared with InP HEMTs.

At 94 GHz, Fig. 1 (right), GaAs right shows that PHEMT technology delivers more power than InP HEMT technology, 350 mW vs. 130 mW. Due to the higher maturity of GaAs PHEMTs, their gain is comparable to that of InP HEMTs. The most interesting feature of this graph is the dramatically higher power-added efficiency of InP HEMTs when compared to GaAs PHEMTs. For sub-100 mW demonstrations, InP features PAE values in the 20 to 35% range. In contrast, GaAs does not exceed 15%.

The origin of these differences can be clarified by Fig. 2, which shows the power density reported at 94 GHz as a function of the drain-source bias voltage. One important reason for the improved power output of GaAs PHEMTs when compared with InP HEMTs is the over 1.5 V higher voltage they withstand. This stems directly from the higher breakdown voltage of GaAs PHEMTs over InP HEMTs. In spite of this, Fig. 2 also shows that the power density of GaAs PHEMTs per unit voltage in general lags below that of InP HEMTs. The higher current drivability of InP HEMTs and the higher thermal conductivity of its substrate contribute to this. A similar picture emerges at 60 GHz.

The superior PAE of InP HEMTs at 94 GHz warrants its continuous development for millimeter-wave power applications. Further progress will stem from overall technology maturity coupled with a relentless drive to achieve physical understanding and engineer the breakdown voltage (BV). In the rest of this paper, we review recent progress on the state of understanding of BV in InP HEMTs. We also discuss key issues facing InP power HEMTs on their way to millimeter-wave system insertion.

RECENT PROGRESS IN UNDERSTANDING OF BREAKDOWN VOLTAGE

When discussing breakdown voltage in HEMTs, it is important to distinguish between on-state and off-state BV. As their names suggest, BV_{off} is defined with the channel turned off, while BV_{on} applies when the transistor is on. Which one of these BV's limits power operation is a matter of current debate.

In well designed and manufactured HEMTs, there are two physical mechanisms that can dominate the physics of breakdown: i) impact ionization (II) of channel electrons, and ii) tunneling or thermionic-field emission (TFE) of gate electrons. In GaAs PHEMTs, it is possible to separate these two paths through the temperature dependence of BV. As Fig. 3 shows, BV_{off} is TFE dominated (negative temperature coefficient) and BV_{on} is II dominated (positive TC). For InP HEMTs, the situation is complicated by the fact that the TC of II for $In_xGa_{1-x}As$ experiences a sign reversal at some point between x=0.25 and x=0.53, as shown by Meneghesso et al. (1). In consequence, in InP HEMTs, both BV_{off} and BV_{on} exhibit a negative TC (Fig. 3). It is possible however to unambiguously determine the dominant mechanism responsible for BV in InP HEMTs by means of a sidegate test structure that monitors hole generation in the channel (Somerville et al. (2)). In this way, it has been established that in InP HEMTs, similarly to PHEMTs, BV_{off} is TFE dominated while BV_{on} is II-dominated.

A simple physics-based model has been recently developed for BV_{off} (Somerville and del Alamo (3), Putnam et al. (4)). This model exploits the high aspect ratio of the electrostatics of a well designed power HEMT at breakdown to accurately model tunneling and TFE. This model has allowed the identification of the Schottky barrier height of the gate metal, φ_B, and the sheet carrier concentration in the extrinsic channel, n_s, as the two key parameters determining BV_{off}. Though relatively simple, this model predicts well the absolute value of BV_{off} as well as its temperature evolution (4). The model also explains the superior values of BV_{off} observed in PHEMTs when compared to InP HEMTs. They arise from the about 0.1 eV enhanced φ_B that is obtained on AlGaAs over $In_{0.52}Al_{0.48}As$. The model further suggests that, contrary to conventional wisdom, the InAs composition of the channel of InP HEMTs is of relatively secondary importance for BV_{off}. This is observed in a statistical study of reported BV_{off} data (Fig. 4).

The state of understanding of BV_{on} in HEMTs is much less developed. An entirely physics-based model of BV_{on} is yet to be developed. However, a simple phenomenological model for II coupled with TFE has been shown to give good agreement (2). This model illuminates the shifting relative importance of II and TFE at breakdown as the device is turned on (Fig. 5). In devices with low values of n_s , BV_{off} is high and the field at BV_{off} is rather spread out on the drain. As a result, as the device is turned on, II increases quickly and BV degrades rapidly. In contrast, if n_s is high, BV_{off} is low and the field on the drain is confined to a small region. In consequence, when the device is turned on, II builds up gradually and the BV_{on} characteristics are rather vertical. While a similar mechanism occurs in PHEMTs, the lower II rate results in a relatively smaller BV degradation when the device is turned on.

Until recently, a high BV_{off} was believed to be essential to enhancing power output. It has now become clear that due to the high channel II rate, BV_{on} in InP HEMTs constitutes the power bottleneck for many designs. This is illustrated in Fig. 6. Strategies that enhance BV_{off} do not necessarily improve BV_{on} nor the maximum power. For example, if φ_B in a typical power InP HEMT could be enhanced so that BV_{off} is increased by 2-3V, the change in BV_{on} would be minimal and the output power would not change significantly. On the contrary, for InP HEMTs, significant improvements in power density can only be obtained by adequate management of impact ionization. We discuss this in more detail in the next section.

CHALLENGES AND PROSPECTS

Realizing the full potential of InP HEMTs for power applications demands meeting challenges in at least three fronts: 1) performance, 2) reliability, and 3) low-cost manufacturing.

Improving millimeter-wave power performance calls for enhancements in the voltage handling capability of the device. Basically, this means improvements in BV_{off} and BV_{on}. BV_{off} can only be meaningfully increased by enhancing the Schottky barrier height of the gate. Continuous experimentation with wide bandgap insulators, alternate gate metals, and novel interface treatments is required. Reliability is a key concern in any new scheme. In spite of a great of deal of research, devices with demonstrated power operation at frequencies at or above 60 GHz use InAlAs as insulator. This would suggest that there is room for improvement.

Increasing BV_{on} demands management of impact ionization. Composite channels, compositionally-graded channels and quantized channels have all been investigated towards this goal, although long lasting benefit has not been obtained. Composite InGaAs/InP channels, for example, have only been used in power devices at frequencies below 20 GHz (Shealy et al. (5)). Cap recess engineering should also be an effective approach for improving BV_{on}. Single symmetric recess is the norm in millimeter-wave power devices. Experiments indicate, however, that an asymmetric recess with a longer extension on the drain side of the device should improve the breakdown voltage and largely preserve the gain (Ballegeer et al. (6)). Double recess should also bring substantial benefits (Hur et al. (7)). Although physical understanding is not complete at this time, an additional avenue with potential for improvement of BV_{on} is the effective draining of impact ionized holes by means of a p-type body contact on the source side of the device (Suemitsu et al.

(8)). If similarity between the kink effect in InP HEMTs and SOI MOSFETs can serve as guide, suppression of the kink effect should result in a significant improvement in BV_{on}.

The reliability of power InP HEMTs is rarely discussed in open forums. Several concerns have been reported: burnout, Hydrogen sensitivity, and drain-resistance degradation, among others. In GaAs PHEMTs, device burnout appears to be of a thermal nature as it seems to follow a constant power locus. In contrast, InP HEMTs seem to suffer from premature burnout. There is also evidence that burnout is related to BV_{on} and impact ionization (Rohdin, et al. (9)). In fact, burnout seems to follow a constant impact ionization locus. The reason for this is not understood at this time. A fundamental difference between PHEMTs and InP HEMTs that might bear some relevance is the sign of the temperature coefficient of the impact ionization rate which is negative for the former but positive for the later.

The characteristics of InP HEMTs have been reported to be sensitive to Hydrogen poisoning (Chao et al. (10)). H_2 appears to be released from the walls of the module package and over time, it shifts the device characteristics. This is a particularly acute problem in millimeter-wave InP HEMTs where high performance dictates a thin passivating layer and a mushroom-shape gate. Under the umbrella of the mushroom, the nitride layer is rather thin and its encapsulating properties are somehow compromised. The detailed physical origin of H_2 poisoning is not understood. Hydrogen is known to compensate donors, but it has also been reported to react with Ti, to introduce disorder at the InAlAs surface, and even to change the Schottky barrier height of metals on GaAs. A device level solution to this problem does not exist.

Under operation, the characteristics of InP HEMTs have been observed to degrade. LaCombe et al. (11) have reported degradation in the source resistance, transconductance, and current in 0.1 um InP HEMTs under high temperature DC life test. Wakita et al. (12) have reported drain-resistance degradation under continuous bias at room temperature. They have correlated the increase in R_d with impact ionization in the channel. It has also been postulated that hot electrons might degrade the semiconductor surface (Menozzi et al. (13)). On the other hand, residual Fluorine from the process is also attributed to drift throught the device, compensate donors and increase parasitic resistance (Sasaki et al. (14)). These and other reliability concerns will have to be solved before InP HEMTs gets deployed in millimeter-wave systems.

Finally, establishing low-cost manufacturing is a major challenge for InP HEMTs. Low-cost manufacturing basically hinges on high-yield processing of large wafers. Besides reducing wafer breakage, in order to achieve high yields, identifying the physical sources of parametric yield loss is of primary importance. At TRW's 3-inch 0.1 um InP HEMT fabrication line, Elliott et al. (15) identified MBE and gate as the most critical nodes in HEMT manufacturing. In remarkable agreement with these results, Krupenin et al. (16), using a Principal Component Analysis, have recently identified Si-doping non-uniformities during MBE and the location of the gate with respect to the source ohmic contact as the two leading causes of variance in a 0.1 um 3-inch HEMT wafer from Sanders' R&D line.

In the last few years, there has been a great deal of interest in developing a manufacturable process for InAlAs/InGaAs HEMTs on GaAs wafers (metamorphic HEMTs or MHEMTs). The primary motivation for this is cost - while InP manufacturing deals with 3-inch wafers, GaAs is already at 6 inch. Also, for the same wafer diameter a GaAs wafer is about five times cheaper than an InP one. Successful demonstrations of InAlAs/InGaAs HEMTs devices and circuits on GaAs have been reported by Higuchi et al. (17) and Rohdin et al. (18). The main thrust of this work has been the development of a thin buffer layer that accommodates the mistmatch between GaAs and InP and that contains a minimum amount of threading dislocations. Otherwise, the device structure on top of the buffer layer is similar to those on InP substrates.

Perhaps the most exciting potential outcome of an MHEMT technology is not to simply substitute an InP substrate by a GaAs one, but to exploit the new opportunities for device design that such a new technology would engender (Chertouk et al. (19)). For example, for power applications, an AlGaAs gate insulator is more desirable than the conventional InAlAs. P-based materials offer the promise of an Al-free gate insulator. Selecting a lattice constant half way between GaAs and InP for the active device would allow the design of a layer structure with stress-compensation between the InGaAs channel and an AlGaAs insulator. The use of an InAs mole fraction somehow below $x=0.53$ could be instrumental in reversing the sign of the temperature coefficient of impact ionization in the InGaAs channel. Stress engineering of the channel perhaps can be used to relax the severe trade-off that exists today between electron velocity and bandgap in the InGaAs channel.

In some way, if the metamorphic technology is demonstrated to be reliable, a convergence of HEMT technology is likely to eventually take place. It is conceivable that in the near future, device designers will be able to specify channel and insulator compositions over a much broader range than what is available today and have their devices fabricated in the same fab by a single process. This could have important economic significance because as the millimeter-wave regime opens up for commercial use, there will be a great need for devices designed to different circuit and system specifications. Working with a single manufacturing organization using a single set of design tools and layout rules would be cost-effective and highly attractive to circuit designers.

CONCLUSIONS

While the power potential of InP HEMTs in the millimeter-wave regime is yet to be fully exploited, their future in these applications looks bright. Recent developments in the understanding of the physics of breakdown coupled with technological improvements in the breakdown voltage hold excellent promise for power performance enhancements. Before this technology gets inserted into millimeter-wave systems, substantial progress in reliability and manufacturing will have to be demonstrated.

ACKNOWLEDGMENTS

Over the last few years, research on power InP HEMTs at MIT has been funded by JSEP, MAFET, Lockheed Martin, Hewlett Packard, NTT, TI and NSF. The authors are particularly indebted to P. C. Chao, George Duh, Takatomo Enoki, Katerina Hur, Yasunobu Ishii, Hans Rohdin, Paul Saunier, and Alan Swanson for enriching discussions.

REFERENCES

1. G. Meneghesso A. Mion, A. Neviani, m. Matloubian, J. Brown, M. Hafizi, T. Liu, C. Canali, M. Pavesi, M. Manfredi, and E. Zanoni, 1996 Int. Electron Dev. Meet., p. 43.

2. M. H. Somerville, R. Blanchard, J. A. del Alamo, G. Duh, and P. C. Chao, 1997 Int. Electron Dev. Meet., p. 553.

3. M. H. Somerville and J. A. del Alamo, 1996 Int. Electron Dev. Meet., p. 35.

4. C. S. Putnam, M. H.Somerville, J. A. del Alamo, P. C. Chao, and K. G. Duh, 1997 Int. Conf. on InP and Rel. Mat., p. 197.

5. J. B. Shealy, M. Matloubian, T. Liu, R. Virk, J. Pusl, and C. Ngo, 1997 IEEE Microw. and Guided Wave Lett. 7, p. 261.

6. D. G. Ballegeer, I. Adesida, C. Caneau, and R. Bhat, 1994 Int. Conf. on InP and Rel. Mat., p. 331.

7. K. Y. Hur, R. A. McTaggart, B. W. LeBlanc, W. E. Hoke, P. J. Lemonias, A. B. Miller, T. E. Kazior, and L. M. Aucoin, 1995 GaAs IC Symp., p. 101.

8. T. Suemitsu, T. Enoki, and Y. Ishii, 1995 Electron.Lett. 31, p. 758.

9. H. Rohdin, C.-Y. Su, N. Moll, A. Wakita, A. Nagy, V. Robbins, and M. Kauffman, 1997 Int. Conf. on InP and Rel. Mat., p. 357.

10. P. C. Chao, M. Y. Kao, K. Nordheden, and A. W. Swanson, 1994 IEEE Electron Dev. Lett. 15, p. 151.

11. D. J. LaCombe, W. W. Hu, and F. R. Bardley, 1993 Int. Rel. Phys. Symp., p.364.

12. A. S. Wakita, H. Rohdin, C.-Y. Su, N. Moll, A. Nagy, V. M. Robbins, 1997 Int. Conf. on InP and Rel. Mat., p. 376.

13. R. Menozzi, M. Borgarino, Y. Baeyens, M. Van Hove, and F. Fantini, 1997 IEEE Microw. and Guided Wave Lett. 7, p. 3.

14. H. Sasaki, K. Yajima, N. Yoshida, O. Ishihara, and S. Mitsui, 1995 Int. Conf. on InP and Rel. Mat., p. 745.

15. J. Elliott, L. Tran, R. Lai, T. Block, J. Cowles, D. Tran, W. Jones, Y. C. Chen, A. Oki, and D. Streit, 1997 Int. Conf. on InP and Rel. Mat., p. 501.

16. S. Krupenin, R. R. Blanchard, M. H. Somerville, J. A. del Alamo, K. G. Duh, and P. C. Chao, this Symposium.

17. K. Higuchi, M. Kudo, M. Mori, and T. Mishima, 1994 Int. Electron Dev. Meet., p. 891.

18. H. Rohdin, A. Nagy, V. Robbins, C.-Y. Su, C. Madden, A. Wakita, J. Raggio, and J. Seeger, 1995 Int. Conf. on InP and Rel. Mat., p. 73.

19. M. Chertouk, H. Heiss, D. Xu, S. Kraus, W. Klein, G. Bohm, G. Trankle, and G. Weimann, 1995 Int. Conf. on InP and Rel. Mat., p. 737.

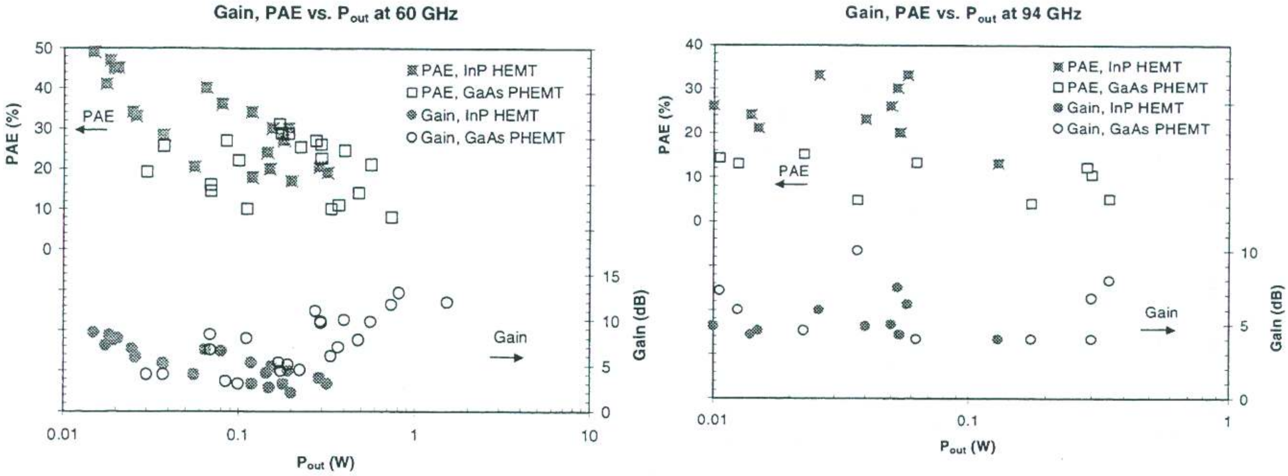

Fig. 1 - Gain and power-added efficiency vs. output power for InP HEMTs and GaAs PHEMTs at 60 GHz (left) and 94 GHz (right).

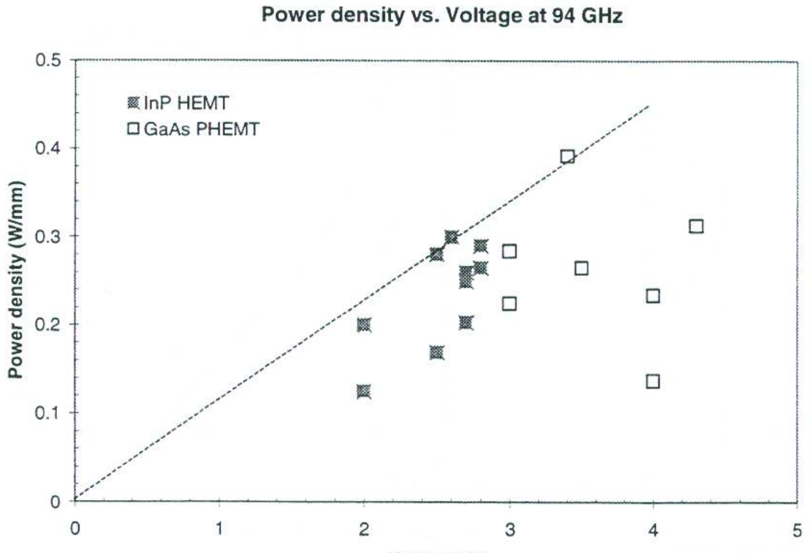

Fig. 2 - Power density vs. DC Voltage for InP HEMTs and GaAs PHEMTs at 94 GHz.

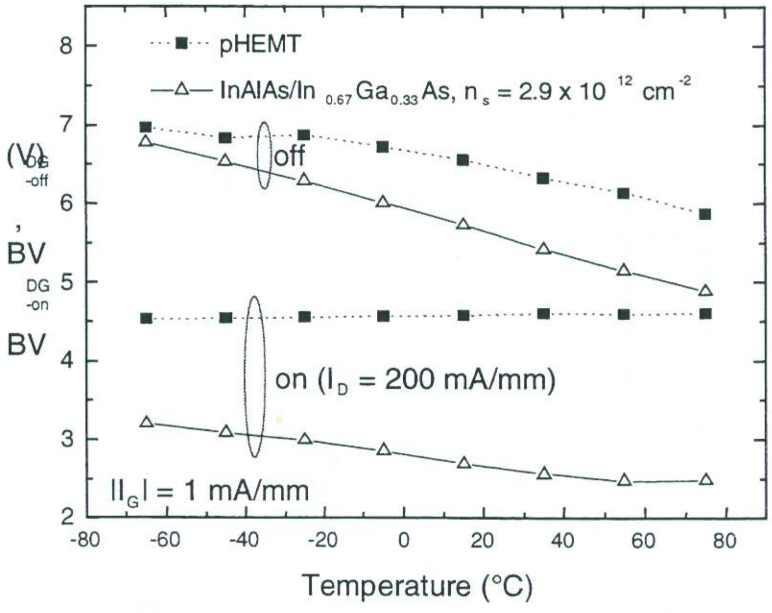

Fig. 3 - BV_{on} and BV_{off} vs. temperature for a typical power InP HEMT and a GaAs PHEMT.

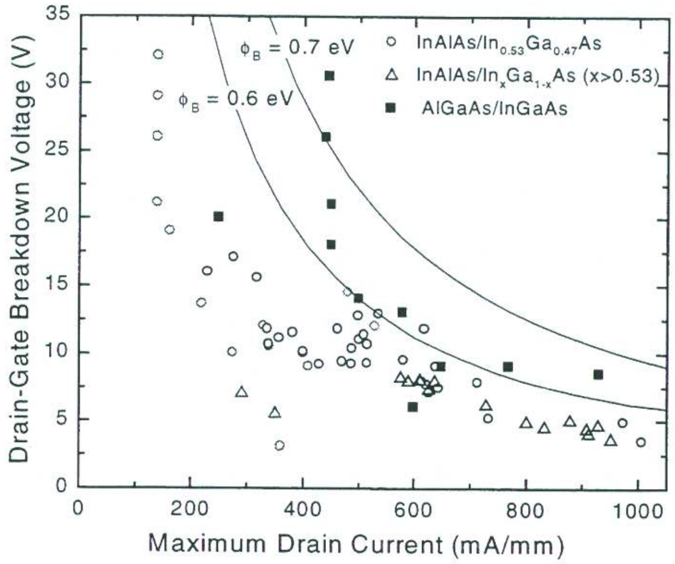

Fig. 4. – BV_{off} vs. maximum drain current for InP HEMTs and GaAs PHEMTs.

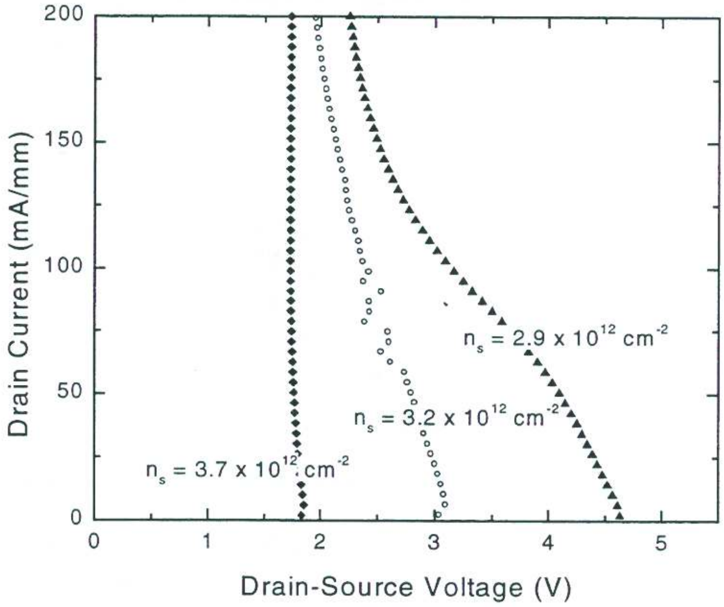

Fig. 5 - Locus of BV_{on} of three InP HEMTs with different sheet-carrier concentrations.

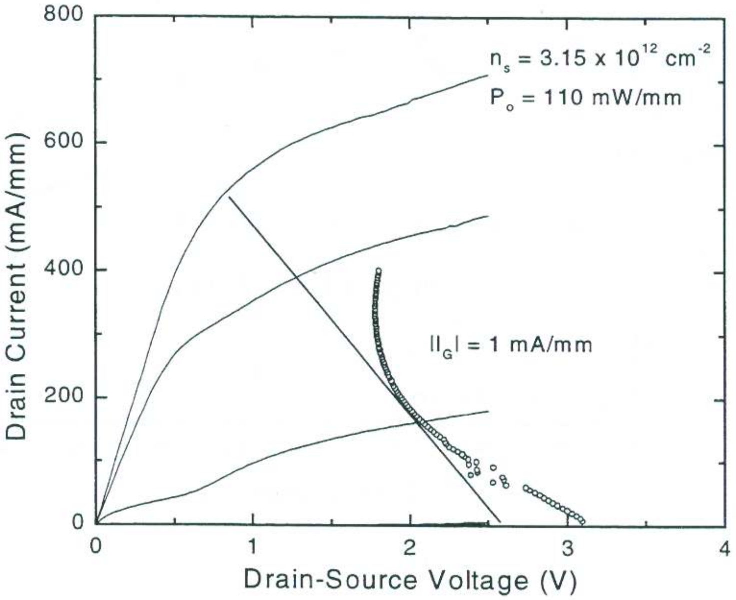

Fig. 6 – Output characteristics and locus of BV_{on} of an InP HEMT indicating that BV_{on}, as opposed to BV_{off}, is largely the bottleneck for power density in this device.