Breakdown in Millimeter-Wave Power InP HEMTs: a Comparison with PHEMTs

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Abstract

In spite of their superior transport characteristics, InP HEMTs deliver lower output power than GaAs PHEMTs in the millimeter-wave regime. However, the superior power-added efficiency of InP HEMTs when compared with PHEMTs, makes this technology attractive for many applications. The reason for the lower power output of InP HEMTs is their relatively small off- and on-state breakdown voltage. This talk reviews the state of knowledge regarding the physics of BV in InP HEMTs placing it in contrast with PHEMTs. It also discusses strategies for improving BV and the power output of InP HEMTs.

I. Introduction

The use of InAlAs/InGaAs HEMTs (or InP HEMTs, for short) in low-noise applications is well established. Their suitability for millimeter-wave power amplification is still a matter of debate. At this time, PHEMTs exhibit higher power output than InP HEMTs across the entire frequency spectrum. (Fig. 1). However, due to their better frequency response, InP HEMTs exhibit substantially enhanced power-added efficiency over GaAs PHEMTs at 94 GHz. This makes InP power HEMT technology attractive for many applications and warrants its continuous development.

The reason for the relative inferior power performance of InP HEMTs is that: *i)* for a given maximum current, InP HEMTs exhibit an off-state breakdown voltage (BV_{off}) about 2-3 V lower than PHEMTs (Fig. 2), and *ii)* for a given BV_{off}, InP HEMTs have significantly worse on-state breakdown voltage (BV_{on}) than PHEMTs (see below). This paper reviews current understanding of the physics of BV in InP HEMTs and puts it in contrast with PHEMTs. Options for BV improvement in InP HEMTs are discussed.

II. Breakdown voltage characterization

Understanding the physics of BV, particularly in InP HEMTs, has been hampered by three problems: the definition of BV, the measurement of BV, and the difficulty in obtaining systematic measurements of BV on a single device. Recently, these difficulties have been resolved through the development of new characterization techniques that establish an unambiguous definition for BV and that can be performed repeatedly under different conditions (such as temperature) on a single device. The *drain-current injection technique*, Fig. 3, is a three-terminal measurement that defines BV_{off} as the condition that results in $-I_G = I_D$ for a predetermined current criteria, typically 1 mA/mm [1]. The *gate-current extraction technique* is also a three-terminal measurement that defines BV_{on} as the *locus* of constant I_G (also typically -1 mA/mm) with the device turned on, Fig. 4 [2]. A feature of these two techniques is that BV_{on} converges to BV_{off} as the device is turned off.

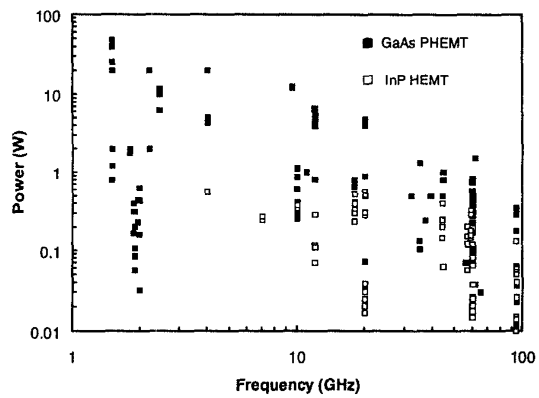

Figure 1: Reported output power versus frequency for InP HEMTs and GaAs PHEMTS.

III. Physics of breakdown

In well designed and manufactured devices, there are basically two physical mechanisms that can dominate the physics of breakdown in HEMTs: *i)* impact ionization (II) of channel electrons, and *ii)* tunneling or thermionic-field emission (TFE) of gate electrons. In PHEMTs, it is possible to separate these two paths through the temperature dependence of BV (Fig. 5). As Fig. 5 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 $x = 0.53$ [3]. In InP HEMTs, both BV_{off} and BV_{on} exhibit a negative TC (Fig. 5) [3]. It is possible however to unambigously determine the dominant mechanism responsible for BV in InP HEMTs by means of a sidegate test structure that monitors hole generation due to channel II [2]. This has established that similarly to PHEMTs, BV_{off} is generally TFE dominated while BV_{on} is II-dominated.

A simple physics-based model has been recently developed for tunneling/TFE-limited BV_{off} [4,5]. This model has allowed the identification of the Schottky

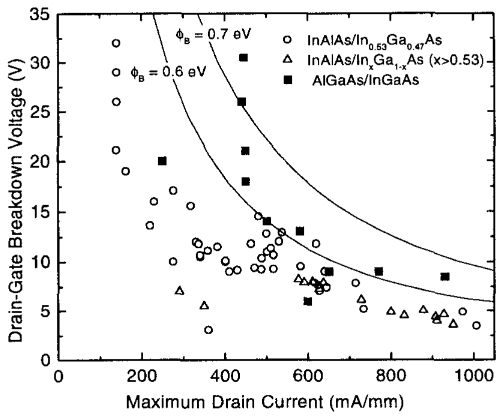

Figure 2: Reported off-state breakdown voltage vs. maximum current for InP HEMTs and PHEMTs.

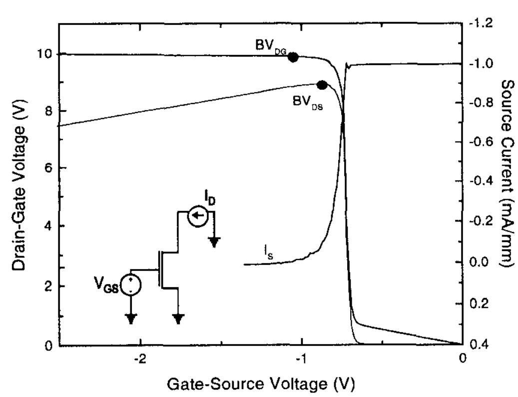

Figure 3: Illustration of *drain-current injection technique* to measure BV_{off} in a typical InP HEMT.

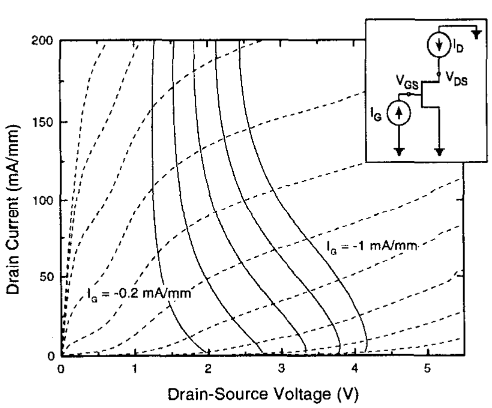

Figure 4: Illustration of *gate-current extraction technique* to measure BV_{on} in a typical InP HEMT.

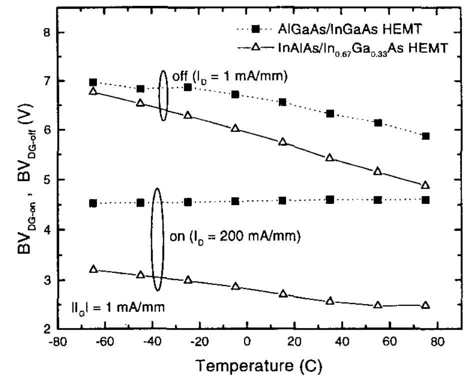

Figure 5: Temperature dependence of BV_{off} and BV_{on} in a typical power PHEMT and a typical strained-channel power InP HEMT.

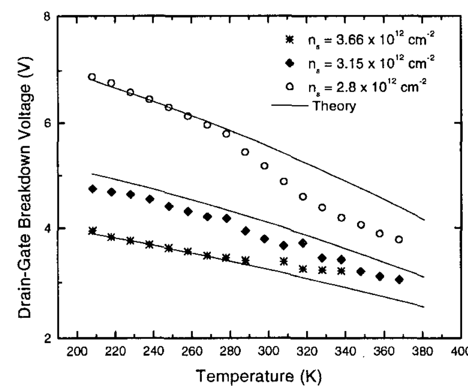

Figure 6: Experimental and modeled BV_{off} versus temperature in InP HEMTs for different values of n_s.

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}, and predicts well the temperature evolution of BV_{off} of InP power HEMTs (Fig. 6). The model also explains the superior values of BV_{off} observed in PHEMTs when compared with InP HEMTs (Fig. 2) - they arise from the $\sim$ 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 minor importance for BV_{off}. At high current values, the substantial body of data summarized in Fig. 2 is largely consistent with this conclusion.

While an entirely physics-based model of BV_{on} is yet to be developed, a simple phenomenological model for II coupled with the TFE model has been shown to give good agreement with BV_{on} in InP HEMTs (Fig. 7) [2]. This model illuminates the shifting relative im-

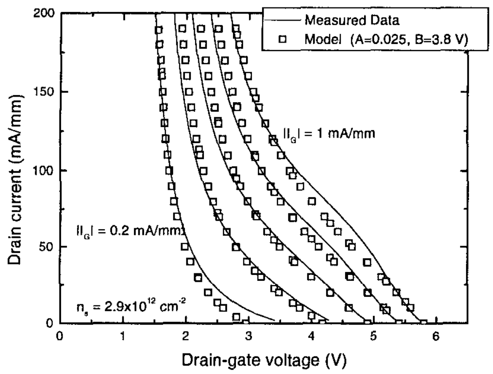

Figure 7: Experimental and modeled BV_{on} contours in an InP HEMT for different I_G criteria.

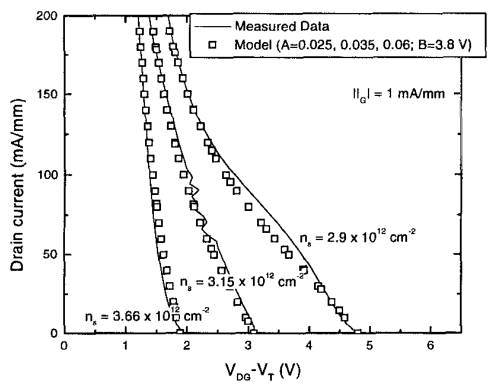

Figure 8: Experimental and modeled BV_{on} contours for InP HEMTs with different values of n_s.

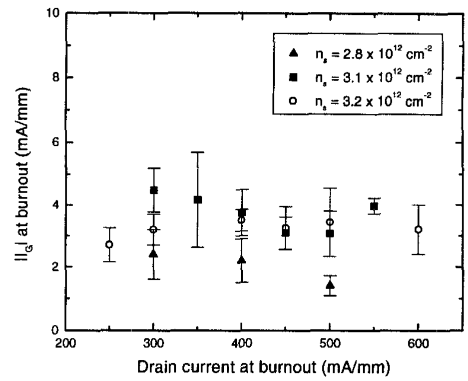

Figure 9: Gate current vs. drain current at burnout for InP HEMTs with different values of n_s.

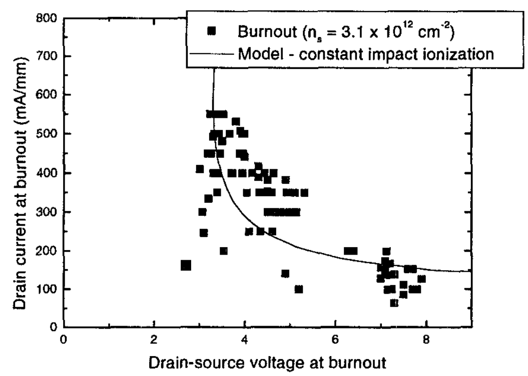

Figure 10: Comparison of measured burnout points and modeled contour of constant impact ionization in 0.1 μm InP power HEMTs.

portance of II and TFE at breakdown as the device is turned on. 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 (Fig. 8). 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 (Fig. 8). While a similar mechanism occurs in PHEMTs, the lower II rate results in a relatively smaller BV degradation when the device is turned on. Furthermore, in PHEMTs, the effect is suppressed at higher operating temperatures, while in InP devices, the negative TC of II makes the mechanism more prominent. This is clearly undesirable from a power perspective.

It has recently been suggested that InP HEMTs suffer from premature burnout [6] associated with II in the channel [2,6]. This is evident in the fact that devices with different n_s values burnout at constant I_G regardless of I_D, as shown in Fig. 9 [2]. The burnout locus in the output characteristics matches a constant II criteria (Fig. 10) [6]. This is unlike PHEMTs in which burnout appears to be of a thermal nature and follows a constant power locus (Fig. 11) [7]. While this dramatic difference is not yet understood, the higher II rate of the InAs-rich InGaAs channel and perhaps its positive TC are behind it.

IV. Options for BV improvement

Improving millimeter-wave power performance of InP HEMTs demands enhancement of their voltage handling capability, that is, increasing BV_{on} and BV_{off}. For a given recess design, BV_{off} can only be meaningfully improved by enhancing the Schottky barrier height of the gate. Wide bandgap insulators, alternate gate metals and novel interface treatments have been explored with some success. However, power devices operating above 60 GHz have yet to incorporate many of these new features.

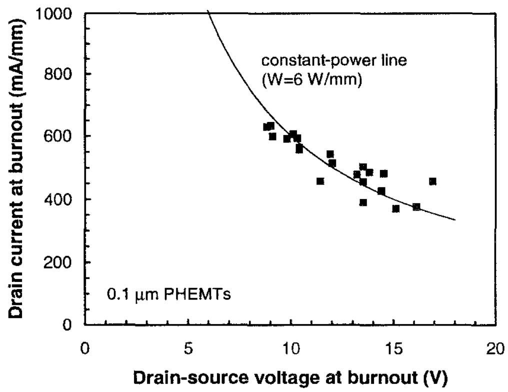

Figure 11: Comparison of measured burnout points and modeled contour of constant power in 0.1 μm GaAs power PHEMTs [7].

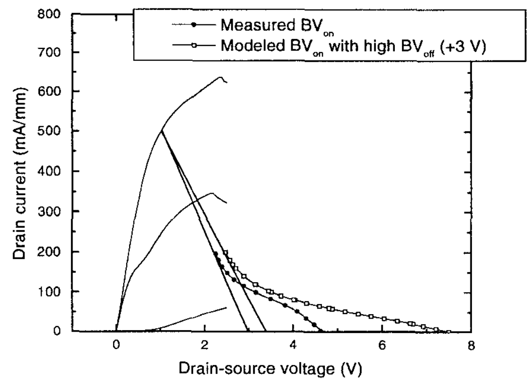

Figure 12: Change in BV_{on} and maximum power load line produced by an increase in ϕ_B that results in an enhancement of $3\,V$ in BV_{off}.

Furthermore, improving BV_{off} alone is not enough. Due to the high channel II rate, BV_{on} constitutes the power bottleneck for many device designs. 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 3 V, the change in BV_{on} would be minimal and the output power would not change significantly (Fig. 12).

On the contrary, for InP HEMTs, significant improvements in power density can only be obtained by adequate management of impact ionization, particularly given its positive TC. Composite channels, compositionally-graded channels and quantized channels have all been investigated towards this goal, although long lasting benefit has not been obtained. Cap recess engineering should also be an effective approach for improving BV_{on}. Experiments indicate, for example, that an asymmetric recess should improve BV and largely preserve the gain [8], as should double recess designs [9]. Although physical understanding is still insufficient, a potential avenue to improve BV_{on} might be the effective draining of impact-ionized holes by means of a p-type body contact on the source side of the device [10]. 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}.

V. Conclusions

In comparison with GaAs PHEMTs, InP HEMTs are characterized by a small gate Schottky barrier height, resulting in a reduced off-state breakdown voltage. Additionally, InP HEMTs suffer from an enhanced impact ionization rate in the channel yielding a small on-state breakdown voltage. Perhaps more importantly, the II rate of InP HEMTs has a positive thermal coefficient. Future improvements in the breakdown voltage of InP HEMTs will require careful management of impact ionization in the channel.

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