Experimental and Qualitative Investigation of Abnormal Gate Leakage Currents in Pseudomorphic HEMTs

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ABSTRACT : We report abnormal gate leakage currents in GaAs-based PHEMTs with L_g= 0.2μm. Abnormal positive and negative humps in the gate current (I_G) and the negative differential resistance (NDR) in the drain current have been investigated and physical models are provided. Experimental verification has been also provided for the abnormal I_G which occurs under high drain bias (V_{DS}>2.3V) and forward gate bias (0.2<V_{GS}<0.6) due to the formation of hybrid excited states across the InGaAs channel and AlGaAs donor layer. These results will provide an interpretation of the abnormal positive humps in I_G caused by resonant-tunneling and the NDR of the drain current due to a field-assisted tunneling real-space transfer by hot channel electrons.

I. INTRODUCTION

Scaling of the gate length to the deep sub-micrometer range is one of best ways to achieve the highest possible transconductance (g_m) and cut-off frequencies (f_T, f_{max}). However, the gate leakage characteristics and breakdown effects of the devices limit the design and process technology. Therefore, it is essential that further improvement of high reliability, good noise performance, and excellent stability of electrical characteristics are required for reliable operation of pseudomorphic high electron mobility transistors (PHEMTs). In this paper, we have investigated the abnormal electrical characteristics of the gate leakage current which is a crucial factor for implementing reliable and high performance MMICs.

II. ANALYSIS OF THE ABNORMAL GATE LEAKAGE CURRENT

The mechanisms of this gate leakage current (I_G) consist of impact ionization, thermionic emission (TE), resonant tunneling (RT), and field-assisted tunneling real-space transfer (FTRST). Previous works have been generally focused on the hot-electron effect (HE) due to the impact-ionization and no indication has been given on the possible analysis of the APH of I_G [1]. Based on the RT and the FTRST, we investigated more thorough description of physical models for the abnormal I_G observed in the PHEMTs.

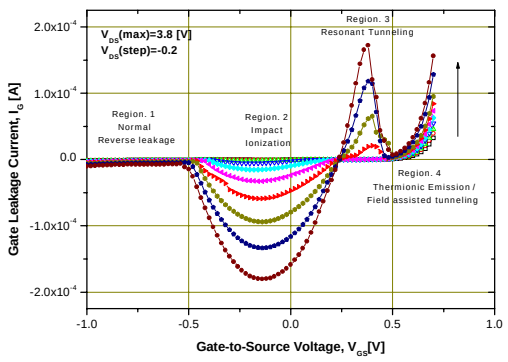


Fig. 1. The abnormal gate leakage currents divided by four regions.

In the experiment, we employed commercial PHEMTs for ultra-sensitive low noise amplifiers up to 12GHz. Electrical characteristics were observed to be I_{DSS}=30mA and g_{mo}=55mS. Typical values of NF_{min} and associated gain at 12GHz, reported on the datasheets, are 0.5 dB and 12 dB, respectively, at V_{DS} =1.5V and V_{GS}=0V. Abnormal gate leakage characteristics are measured and shown in Fig.1 as a function of V_{GS} for different drain voltage V_{DS} at room temperature. Based on the related physical mechanisms, abnormal I_G has been modeled as four different regions as follows;

Region 1: In this region as shown in Fig.1, the generation current with the impact ionization in the depletion region under the gate is a dominant current mechanism. I_G in this region is the same as that in the reverse biased diodes and predominantly determined by the Schottky barrier height and depletion width under large reverse.

Region 2: In this region as shown Fig.1, a bell-shaped negative hump in I_G is observed in the device under test. Such behavior has been known to be due to hot electrons (HE) caused by the impact-ionization. In this region, I_G is proportional to the $\alpha_n \cdot L_{eff}$ product and I_D where α_n: the impact-ionization coefficient, L_{eff} : the effective length of the channel for impact ionization; $|I_G| = I_D \alpha_n \cdot L_{eff} \cong I_D \cdot L_{eff} \exp(1/\varepsilon)$ where ε : longitudinal electric field in the L_{eff}. When the electric field in the L_{eff} region increases, an energetic electron by impact ionization may provide a valence band electrons with sufficient energy to leap into the conduction band, leaving a hole behind. The generated electron-hole pairs are split and accelerated by the electric field at the L_{eff} region. But while the electrons easily reach the nearby drain, some of holes flowing toward the source may overcome the valence band discontinuity, experiencing real-space transfer (RST) into the barrier layer, and collected by the gate electrode to form I_G.

Region 3: For a possible explanation of the abnormal positive hump (APH) in the Region 3, as shown in Fig.1, we incorporate the concept of RT into the HE to obtain APH generation in PHEMTs at room temperature. RT is a quantum mechanical concept that manifests itself in particles tunneling through a sequence of classically forbidden regions sandwiching a classically allowed region. The forbidden region must be thin enough so that particles can tunnel through it and the allowed region should be thick enough to allow the existence of eigen-energy states [2]. These conditions are correlated with metal-AlGaAs-InGaAs structure in PHEMTs when the V_{GS} is biased between pinch-off voltage and forward-conduction onset-voltage. The RT in PHEMTs can occur when enough hot-electrons caused by impact ionization is excited to two-dimensional (2D) quantized states in the channel and hybridized with 2D quantized states in the AlGaAs donor layer. We focus on the simultaneous condition of enough hot-electrons occupation on 2D quantized states in the channel and hybridization between the lowest quantized AlGaAs level and the first and second quantized levels in InGaAs layer. The hybridization of quantized energy levels in AlGaAs and InGaAs layers is a sensitive function of the gate voltage while the hot-electron occupation on quantized states is controlled by the drain voltage V_{DS}. The energy band diagrams in metal-AlGaAs-InGaAs structure are illustrated in

Fig.2. Large V_{DS} heats up the electrons in the channel and increases the occupation of hot-electrons on higher quantized energy states (Fig.2(a)). In addition, increasing V_{GS} (reducing V_{GD} at drain end), which is proportional to creating additional localized states in AlGaAs layer and increasing the quasi-Fermi level, has the hybridization between the lowest quantized level in the AlGaAs and the first quantized level in the InGaAs channel (Fig.2(b)). If we keep pushing V_{GS} up, the lowest quantized level in the AlGaAs crosses the second quantized level in the InGaAs so that they will form hybridization (Fig.2(c)). Then, electrons tunnel through the heterobarrier from the InGaAs channel to the AlGaAs layer. Continually on increasing V_{GS}, the occupation of electrons on the quantized level in AlGaAs layer may be reduced due to difference between the quasi-Fermi level and the conduction band edge (Fig.2(d)). Fig. 3 shows the measured dual humps in the abnormal gate current under hot-electron condition.

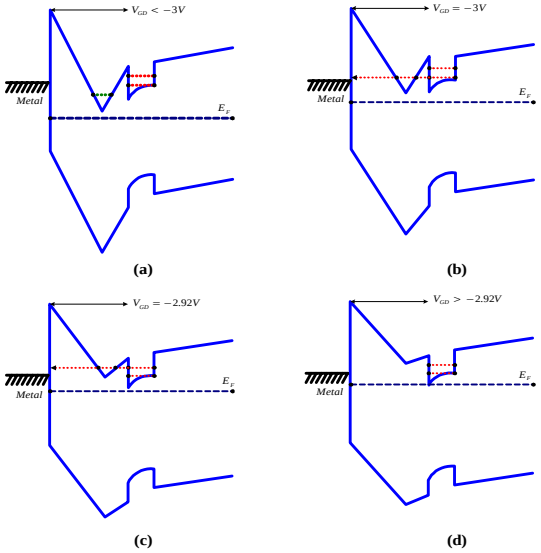


Fig. 2. Energy band diagram of resonant tunneling cross the first/second quantized InGaAs level

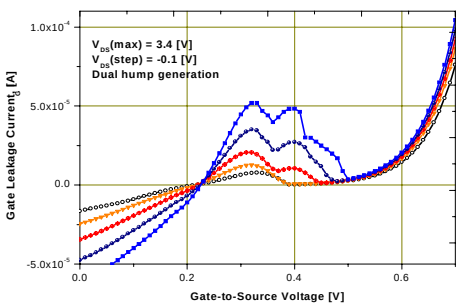
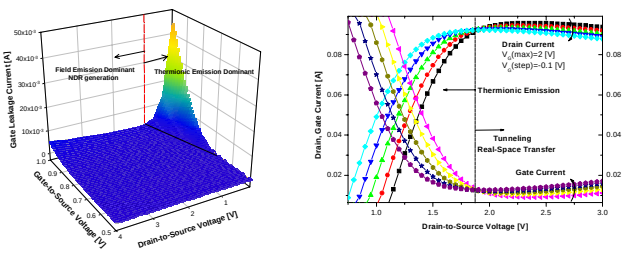


Fig. 3. Abnormal dual hump of gate leakage currents due to RT

Region 4 : Finally, in the fourth region, there are two physical mechanisms associated with the forward gate current. The forward conduction onset starts up at V_{GS}=0.7V with V_{DS}=0V when the gate-channel diodes are forward-biased. In this bias condition, the channel electron concentration increases and results in the elevated gate leakage by thermionic emission. As V_{DS} is raised, however, the quasi-Fermi level will be low at the drain end of channel with decreasing the gate leakage current by TE as shown Fig.4(a). When V_{DS} is higher than V_{GS}=0.7V, although the gate leakage current by TE shrinks down because the region biased below V_{GS}=0.7V by TE are extended along the quantum-well channel toward source from drain end, the gate leakage current starts up at the drain end of channel. Therefore, if V_{DS} continually is raised, the 2D electrons drift along the quantum-well channel from source toward drain and some of them acquire enough energy to be real-space transfer into AlGaAs layer through the undoped spacer layer by the field-assisted tunneling real-space transfer (FTRST). This behavior can be explained qualitatively by the RST mechanism through hot-carrier tunneling under high drain field. Then, the gate leakage current is increased again as shown Fig.4(a). With these considerations, the distinction between the forward conduction gate currents by TE and FTRST becomes more understandable. This increase of the gate leakage current is correlated to corresponding decrease in the drain current, resulting in the NDR as shown Fig. 4(b).



(a) (b)

Fig. 4. Forward Schottky gate leakage currents as function of V_{GS}, V_{DS}

III. Conclusion

We have explained physical mechanisms in the abnormal gate leakage current with experimental data and provided qualitative models for measured *I-V* characteristics in PHEMTs. Physical mechanisms for the gate leakage current in each region could be classified as normal reverse leakage, HE due to impact ionization, RT, and FTRST. Especially, we incorporated the concept of RT into the HE for explaining the abnormal positive humps in the gate current. We also provided a direct evidence of dual hump characteristics to confirm the RT mechanism. Incorporating the resonant tunneling, abnormal positive humps in the gate current caused by RT and the distinction between the forward conduction gate currents by TE and FTRST become more understandable.

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