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Investigation of Breakdown Characteristics in High-voltage GaN-HEMTs

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Abstract

The breakdown mechanism of high-voltage GaN-HEMTs was investigated using the experimental I-V characteristics and two dimensional device simulation results. Especially in the vicinity of breakdown voltage, we clarify that breakdown characteristics are determined by the positive feedback of five steps, which are (1) impact ionization by substrate leakage current, (2) hole accumulation under the gate (3) gate potential barrier lowering, (4) increase of source leakage current and (5) enhancement of the impact ionization at the drain electrode edge.

1. Introduction

The GaN HEMTs can realize high power density operation with low power loss in power electronics system because of high carrier mobility in two-dimensional electron gas (2DEG) and high breakdown voltage due to large critical electric field [1]. Although the GaN on Si has high cost performance due to large wafer diameter and ULSI process manufacturing line, the material parameters would be influenced by high defect density of hetero-epitaxy. Especially, the off-state leakage current and breakdown voltage are strongly affected by the material parameters. The breakdown characteristics has been studied using experimental and simulation results by other groups [2]-[4]. In this paper we focus on the physical behavior of high-voltage GaN-HEMTs especially in the vicinity of breakdown voltage and clarify the breakdown mechanism.

2. Breakdown mechanisms

High-voltage GaN-HEMTs were fabricated using heterostructure grown on a Si-substrate and the drain leakage current was composed of three different leakage current paths as shown in Fig. 1. The Si substrate was connected to the source electrode as a role of the backside field plate.

Experimental I-V characteristics showed the breakdown at Vds = 840 V as shown in Fig. 2. The gate tunneling current (Gate Current) through the MIS-gate insulator was dominant at Vds of less than 600V. On the other hand, the vertical leakage from the substrate through the epitaxial layer (Substrate Current) became dominant at Vds of over 600V. Although the bulk and buffer leakage (Source Current) was small for almost all ranges of Vds, the current was rapidly increasing in the vicinity of breakdown voltage.

To clarify the breakdown mechanism, we reproduced experimental results using Sentaurus TCAD simulation as shown in Fig. 3. The figure also shows the model parameter dependency of each leakage current and breakdown voltage. The key models and parameters are mentioned in the figure. The final fitting parameters might be guides for improvement of actual device performances by comparing with values of appropriate references. For example, breakdown voltage lowering is estimated from the final value of impact ionization rate fitting parameter b (0.8 times the size of a default value [3], and that means the impact ionization is stronger for the same electric field value). That may indicate quality of GaN crystalline of the device is a little poor. Although most of the tendencies were reproduced, the discrepancies in the substrate and drain current at high Vds between the experiment and simulation results might be due to band-to-band tunneling mechanism as mentioned in the paper [4].

Fig. 4 (a) shows simulation results of the contribution of electrons and holes with respect to the substrate current and maximum values of the electric field in GaN layer. The results show the holes, which are generated by the impact ionization due to increase in vertical electric field, begin to increase at Vds = 500V and the source current also begins to increase at the same time. The peak point of the electric field in the device changes with Vds as shown in Fig. 4 (b). The breakdown steps are as follows. Firstly, the electric field under the drain electrode edge becomes more dominant at high Vds than that under the gate electrode and field plates, and the impact ionization is induced at the drain electrode edge as shown in Fig. 4 (c). The electron current flowing through the bottom of the depletion layer under the gate electrode (Source Current) is increased at high Vds as shown in Fig. 4 (d), because the gate potential barrier is lowered by electric shielding due to the flow of holes into the layer under the gate as shown in Fig. 4 (e). As a result, the impact ionization is enhanced further, and the positive feedback occurs in the worst case. These breakdown behaviors are summarized in Fig. 5. In conclusion, breakdown mechanism in the vicinity of breakdown voltage is characterized by the positive feedback, which composed with the impact ionization and the gate potential barrier lowering due to the hole accumulation.

References

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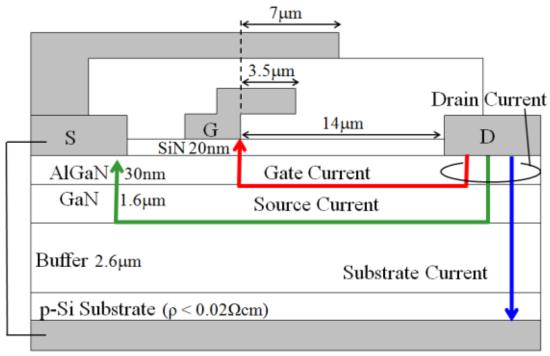

Fig. 1 Cross-sectional structure of fabricated GaN-HEMT.

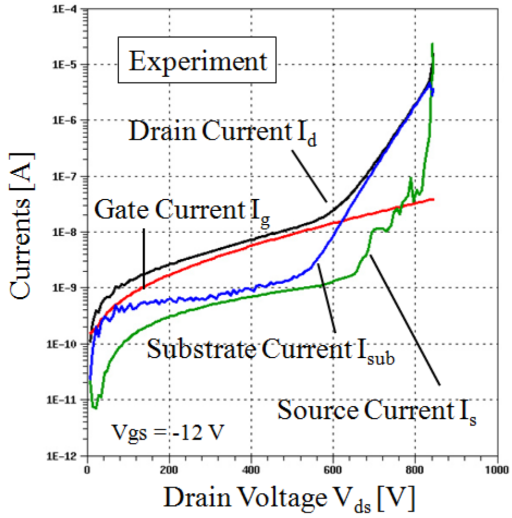

Fig. 2 Measured breakdown I-V characteristics.

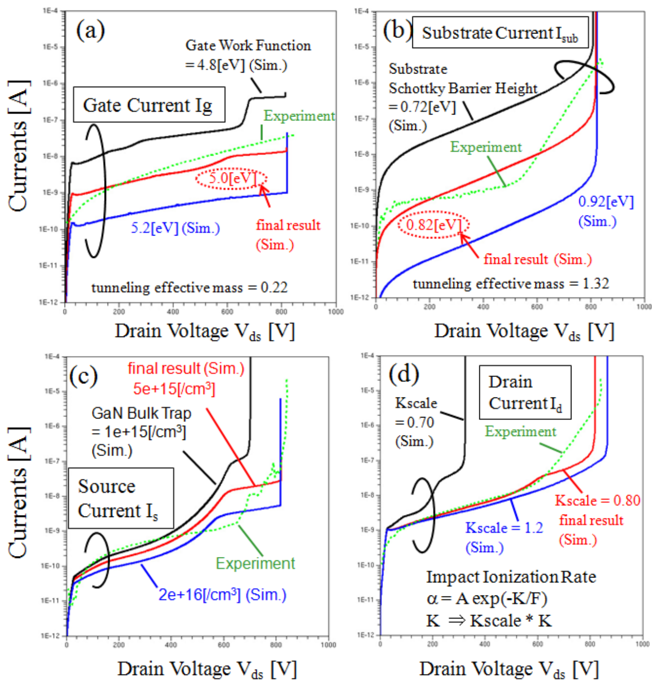

Fig. 3 Reproduced breakdown I-V characteristics by device simulation and measured I-V characteristics for each current component. With respect to the parameter values in impact ionization coefficient expression, see Ref [3].

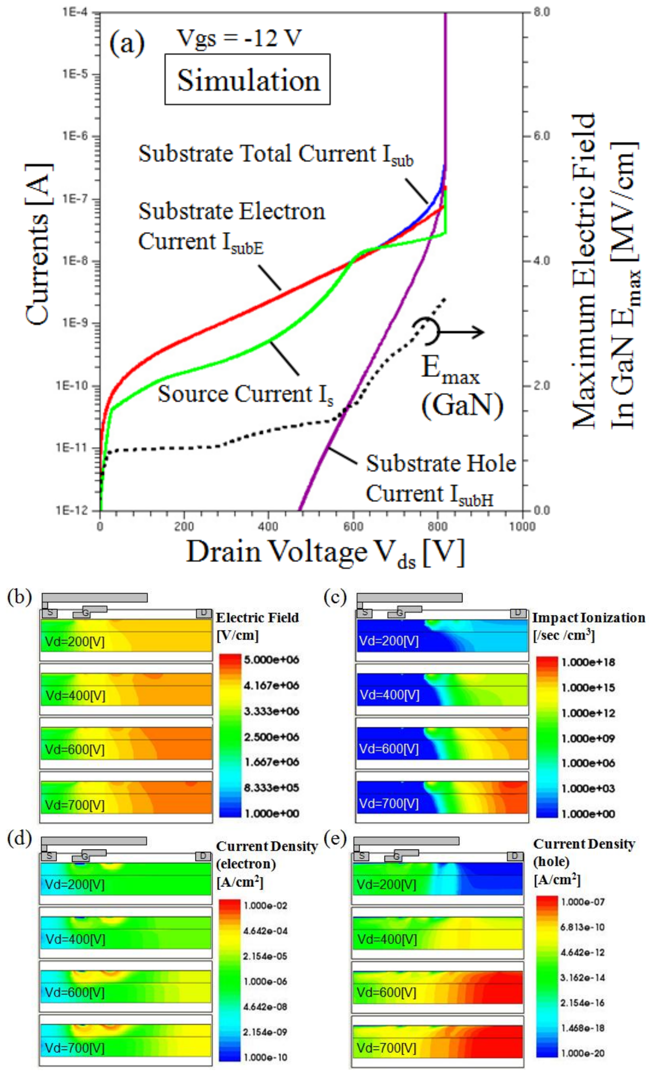

Fig. 4 Simulation results of (a) the contribution of electrons and holes with respect to the substrate current and maximum values of the electric field in GaN layer and (b) distributions of electric field, (c) impact ionization, (d) electron current density and (e) hole current density.

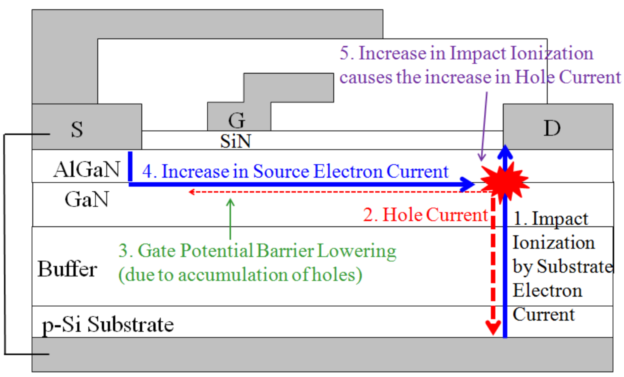

Fig. 5 Schematic diagram of the positive feedback that leads a rapid increase in the currents in the vicinity of breakdown voltage.