

Article

Investigation of ON-State Breakdown Mechanism in AlGaIn/GaN HEMTs with AlGaIn Back Barrier

Yuchen Li ^{1,2} , Sen Huang ^{1,2,*} , Xinhua Wang ^{1,2}, Qimeng Jiang ¹ and Xinyu Liu ^{1,2}

¹ R&D Center of High-Frequency & High-Voltage Device and Integrated Technology, Institute of Microelectronics of Chinese Academy of Sciences, Beijing 100029, China; liyuchen@ime.ac.cn (Y.L.); wangxinhua@ime.ac.cn (X.W.); jiangqimeng@ime.ac.cn (Q.J.); xylu@ime.ac.cn (X.L.)

² University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: huangsen@ime.ac.cn

Abstract: The temperature-dependent ON-state breakdown BV_{ON} loci of AlGaIn/GaN high-electron-mobility transistors (HEMTs) with an AlGaIn back barrier were investigated using the gate current extraction technique. The impact ionization of acceptor-like traps was revealed to be responsible for the ON-state breakdown in HEMTs as a 2D electron gas (2DEG) channel is marginally turned on. The characteristic electric field E_i of impact ionization was extracted, exhibiting a U-shaped temperature dependence from 40 to -30 °C, with minimum E_i occurring at -10 °C. The impurity scattering effect of acceptor-like traps in AlGaIn/GaN heterostructures is suggested to be responsible for the negative temperature dependence of BV_{ON} and E_i below -10 °C.

Keywords: gallium nitride; HEMT; electric breakdown; ON-state breakdown



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1. Introduction

GaN-based high-electron-mobility transistors (HEMTs) are especially attractive for next-generation RF/microwave power amplifiers and power switching applications, as a result of their high breakdown electric field and polarization-induced high-mobility, as well as high-density 2D electron gas (2DEG) at the AlGaIn/GaN hetero-interface [1–4]. Intensive efforts have been dedicated to the mechanism of the three-terminal OFF-state breakdown BV_{OFF} characteristics that determine the power range of GaN-based power devices [5–8]. However, limited works have reported on the investigation of the ON-state breakdown BV_{ON} mechanism in AlGaIn/GaN HEMTs, although the high power state of high current and high voltage is typically an intermediate state for both RF power amplifiers in large-signal operation and power switches in the switching process of turn-ON and turn-OFF [9–11]. Moreover, the ON-state breakdown mechanism is also beneficial to the definition and design of the safe operation area (SOA) in GaN-based power devices. In addition, to improve the 2DEG confinement and breakdown characteristics of GaN-based HEMTs, a low-Al-composition AlGaIn back barrier is commonly introduced in the epitaxial structure of AlGaIn/GaN heterostructures [12–14], while its influence on the trapping behavior deserves further exploration.

To determine BV_{ON} , the typical approach is to increase the drain voltage of the devices, for a given gate bias, until a significant rise in the drain current is observed [15]. Although such a characterization method is precise, it is destructive and not suitable for breakdown mechanism study, which usually requires reproducible measurements [16,17]. In this regard, Somerville et al. developed a gate current extraction technique and applied it to study the ON-state breakdown of InAlAs/InGaAs HEMTs [18]. Such a non-destructive method is rarely used for the characterization of GaN-based HEMTs' ON-state breakdown except for GaN MESFETs [19].

In this work, the ON-state breakdown loci of AlGaN/GaN HEMTs with an AlGaN back barrier were studied with the gate current extraction technique, and the impact ionization of acceptor-like traps was observed within the temperature range from 40 to -30 °C. The characteristic electric field E_i of impact ionization of traps was extracted, exhibiting a U-shaped temperature dependence, and the underlying physical mechanism was investigated.

2. Device Fabrication

The GaN-on-SiC HEMT wafer used in this work was grown by MOCVD on a 2-inch SiC substrate. The epitaxial layer structure was GaN cap (~ 2 nm)/barrier- $\text{Al}_{0.21}\text{Ga}_{0.79}\text{N}$ (~ 25 nm)/interlayer-AlN (~ 1 nm)/channel-GaN (~ 50 nm)/buffer- $\text{Al}_{0.04}\text{Ga}_{0.96}\text{N}$ ($1\text{ }\mu\text{m}$)/buffer—GaN ($1\text{ }\mu\text{m}$)/nucleation-AlN (~ 100 nm). Note that the $1\text{ }\mu\text{m}$ $\text{Al}_{0.04}\text{Ga}_{0.96}\text{N}$ back barrier was used to realize a better 2DEG confinement. The sheet density of the 2DEG, as determined by capacitance–voltage measurement, was $7.2 \times 10^{13}\text{ cm}^{-2}$. The typical 2DEG sheet resistance at room temperature, as determined by the transfer length method, was about $325\text{ }\Omega/\text{sq}$. The contact resistivity was $0.8\text{ }\Omega\cdot\text{mm}$, and the specific contact resistivity was $1.22 \times 10^{-6}\text{ }\Omega\cdot\text{cm}^{-2}$.

The fabrication of the AlGaN/GaN HEMTs was started with ohmic contacts formed by an alloyed Ti/Al/Ni/Au metal stack. Then, a 120 nm SiN_x was grown at $300\text{ }^\circ\text{C}$ by PECVD to passivate the surface. After that, device isolation was achieved by multiple-energy nitrogen ion implantation. A $0.35\text{-}\mu\text{m}$ gate was defined by E-beam lithography, and Ni/Au Schottky gate deposition was applied after dry etching through the PECVD- SiN_x layer. The gate width, gate–source, and gate–drain separations were $8 \times 100\text{ }\mu\text{m}$ (multi-finger), $1.25\text{ }\mu\text{m}$, and $2.4\text{ }\mu\text{m}$, respectively.

The fabricated HEMTs featured a typical threshold voltage V_{TH} of -3.3 V and an extrinsic peak transconductance of 274 mS/mm at $20\text{ }^\circ\text{C}$ at V_{DS} of 10 V . The OFF-state breakdown voltage was determined to be $\sim 76\text{ V}$ at a drain leakage current of 0.1 mA/mm . As shown in Figure 1a, the output characteristics show a climbing step on I_{DS} after the device is turned ON, which exhibits as kink behavior. This is probably caused by acceptor-like traps located in the vicinity of the 2DEG channel [20]. The traps are charged at low drain bias, partially depleting the 2DEG in the channel. Then, as the V_{DS} increases, these charged traps may be discharged, caused by hot electrons under high drain bias, resulting in an increasing I_{DS} . This phenomenon can also be observed from the transfer characterizations of the device. As shown in Figure 1b, the gate leakage current I_G may increase when the gate voltage changes from -4 to -3 V as a result of the traps' discharge. Owing to the back barrier effect of the AlGaN buffer, the peak E -field on the drain side of the gate edge will be significantly enhanced, contributing to the effective acceleration of channel electrons. The traps will be discharged by these high-energy electrons through hot electrons [21]. The impact-ionization-induced detrapping behavior was also confirmed by the appearance of bell-shaped features in the gate leakage current at $V_{DS} > 6\text{ V}$, as the device is turned ON during transfer characterizations (Figure 1b). The impact ionization would induce electron–hole pairs with holes captured by the gate electrodes [22,23]. Meanwhile, the impact-ionization-induced detrapping behavior also causes a negative shift of V_{TH} , as shown in Figure 1b.

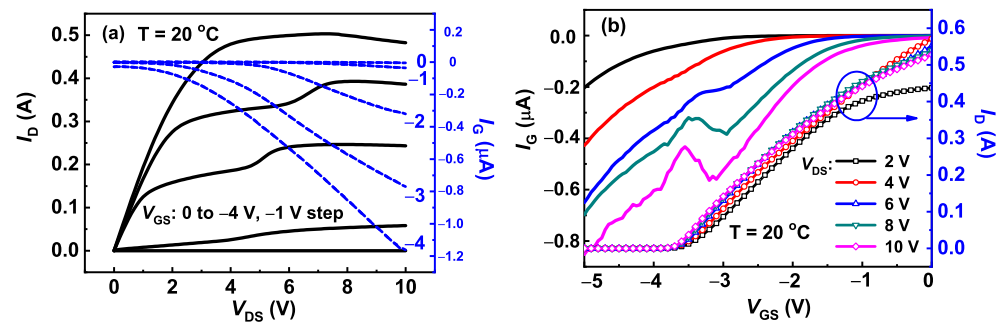


Figure 1. Room-temperature ($\sim 20^\circ\text{C}$) output (a) and I_G - V_{GS} (b) characteristics of the fabricated HEMTs with $L_G/L_{GS}/L_{GD}/W_G = 0.35/1.25/2.4/800\ \mu\text{m}$.

3. ON-State Breakdown and Impact Ionization

The ON-state breakdown loci (BV_{ON}) of the fabricated device were measured by the gate current extraction technique, as shown in Figure 2a. The gate current I_G was held constant at different predefined values ($-1/-2/-3\ \mu\text{A}/\text{mm}$), and I_D was ramped from $-I_G$ (OFF-state) to 100 mA (ON-state). The corresponding drain-source (V_{DS}) and gate-source voltages (V_{GS}) were monitored and shown in Figure 2a,b, respectively. At I_G of $-1\ \mu\text{A}/\text{mm}$, the monitored V_{DS} increased rapidly with I_D in the OFF-state as V_{GS} was below V_{TH} . The gate leakage current in this region was expected to be dominated by electrons injected from the gate into the channel through thermionic field emission and tunneling, and the increase of the V_{GS} was driven by the increase of the drain current to turn on the channel gradually [23]. Once V_{GS} increased above V_{TH} and turned the device ON, lower drain bias voltage was enough to sustain the drain current, until an upsurge of I_D featuring infinite conductance was observed.

The abrupt increase of I_D in the ON-state breakdown locus of $I_G = -1\ \mu\text{A}/\text{mm}$ (Figure 2a) implies that impact ionization takes place near the drain-side gate edge in AlGaIn/GaN HEMTs [16,18–24]. A large amount of holes can thus be generated in this high-field region, and some of them are collected by the gate electrode, contributing a new leakage current component I_{hole} , which makes a dominant contribution to I_G in the infinite conductance region (I_D versus V_{DS}) [16]. By increasing the magnitude of I_G to -2 and $-3\ \mu\text{A}/\text{mm}$, a higher maximum OFF-state V_{DS} can be reached, as a higher electric field is required to inject electrons to sustain a higher $|I_G|$ [18,19]. However, the maximum ON-state V_{DS} of both $I_G = -2$ and $-3\ \mu\text{A}/\text{mm}$ is close to the OFF-state breakdown voltage of the device ($\sim 76\ \text{V}$), and the burnout of the devices occurred after such measurements, probably due to the high power density they suffered. From this point of view, a safe I_G of $-1\ \mu\text{A}/\text{mm}$ was used to perform reproducible temperature-dependent measurements, through which the ON-state breakdown mechanism can be investigated. On the other hand, the monitored V_{GS} of $I_G = -2$ and $-3\ \mu\text{A}/\text{mm}$ exhibited significant negative shift as compared with that of $I_G = -1\ \mu\text{A}/\text{mm}$, as shown in Figure 2b. This was likely caused by drain-induced barrier lowering (DIBL) at high drain bias [25].

To verify the impact ionization characteristics in AlGaIn/GaN HEMTs, the temperature-dependent ON-state breakdown loci of the fabricated devices were performed from 40 to -30°C , as shown in Figure 3. It shows a rapid degradation of the device's BV_{ON} properties both at a high and a low temperature, where the high temperature BV_{ON} degradation has been reported as the cause of the impact-ionization-induced hot electrons [10], and the degradation at a low temperature is considered as a result of the carrier mobility decrease. For all the measured temperature, the BV_{ON} loci exhibited similar features except for the different minimum value of BV_{ON} ($BV_{ON,min}$). It decreased from 9.3 to $6.8\ \text{V}$ from 40 to -10°C and then reversed to increase to $8.4\ \text{V}$ as the temperature further decreased to -30°C . Note that a further increase of I_D over the infinite conductance region made the BV_{ON} loci bend forward to a higher V_{DS} again. This was due to the reduction of the peak electric field in the gate-drain region (roughly proportional to V_{DG}) and consequently of

the impact ionization rate, as V_{GS} increased further with I_D . To maintain a constant I_G , a higher V_{DS} was required again [23]. Moreover, the forward bending of BV_{ON} loci became more evident at a higher temperature, since the impact ionization features a negative temperature coefficient.

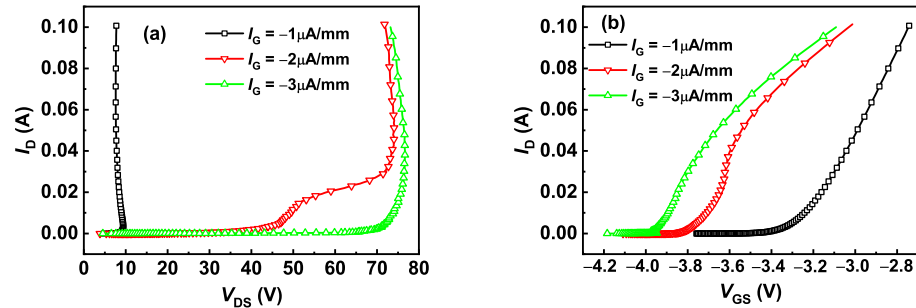


Figure 2. Room-temperature ($\sim 20^\circ\text{C}$) BV_{ON} loci of the $8 \times (0.35 \times 100) \mu\text{m}^2$ AlGaIn/GaN HEMTs. (a) V_{DS} versus I_D . (b) V_{GS} versus I_D . Different constant currents ($-1/-2/-3 \mu\text{A}/\text{mm}$) are extracted from the gate while I_D is swept from the OFF-state ($-I_G$) to the ON-state.

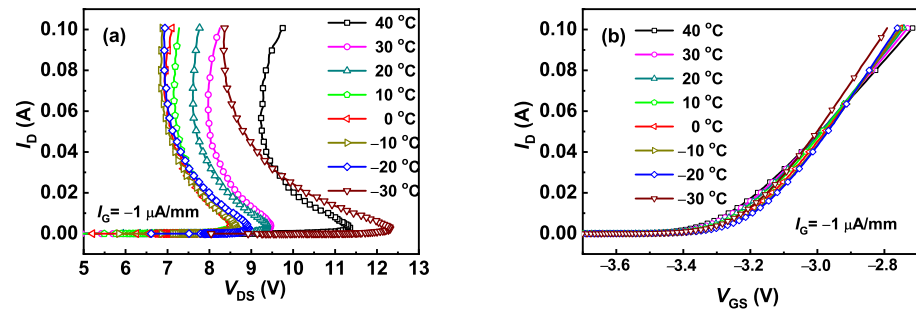


Figure 3. Temperature-dependent BV_{ON} loci of the $8 \times (0.35 \times 100) \mu\text{m}^2$ AlGaIn/GaN HEMTs. A constant current ($1 \mu\text{A}/\text{mm}$) is extracted from the gate while I_D is swept from the OFF-state ($-I_G$) to the ON-state. (a) V_{DS} versus I_D . (b) V_{GS} versus I_D .

The impact-ionization-induced hole current I_{Hole} can be expressed using a classical impact ionization model as follows [16]:

$$I_{hole} = \alpha_n(E) \cdot I_D \cdot L_{eff} = \alpha_0 \cdot e^{-E_i/E} \cdot I_D \cdot L_{eff} \quad (1)$$

where $\alpha_n(E)$ is the impact ionization rate, L_{eff} is the characteristic length of high-field region with its upper bound given by L_{GD} , E_i is the characteristic electric field, and α_0 is a temperature-dependent coefficient reported by Baliga [26]. As L_{eff} increased, the average electric field and I_D became lower, resulting in a higher BV_{ON} of the device. However, this would lead to other problems such as the rising ON-state resistance of the device in turn, which calls for further research. Assuming that the total gate current I_G is dominated by I_{hole} in the infinite conductance region, all the measured BV_{ON} loci were simulated with Equation (1), and some of them are shown in Figure 4a. The deviation between the measured and simulated ones in the ON-state region was probably a result of hot-electron-induced de-trapping of acceptor-like traps [6]. This also needs more precise calculation on the parameters especially as the temperature becomes lower. For example, the impact ionization rate $\alpha_n(E)$ may be taken as a temperature-dependent parameter, which may be set as $\alpha_n = 2.82 \times 10^6 - 6.34 \times 10^3 T$ [26], and the effective gate length L_{eff} may also change at various temperatures as the electron velocity distribution may be different, influenced by carrier mobility. The de-trapping process results in a negative shift of V_{TH} and, thus, increases of I_D .

The effective gate length L_{eff} of the fabricated device was determined to be $0.49 \mu\text{m}$ by the formula of $L_G + 5.1 \times t_{barrier}$ from [25] and was consistent with the simulation results,

as shown in Figure 4b. The electron velocity distribution was simulated under the ON-state breakdown measurement condition ($I_D = 100$ mA/mm, $V_{DS} = 7.5$ V, $V_{GS} = -2.8$ V). As the result of drain bias, the electrons gradually accelerated under the effect of the electric field and led to a higher velocity on the drain side. The characteristic electric field E_i was extracted and plotted with temperature in Figure 4c. It featured a U-shaped temperature-dependent behavior, with minimum E_i occurring at -10 °C. The monotonic increase of E_i with temperature above -10 °C is a typical behavior of impact ionization [26], while its increasing with decreasing temperature below -10 °C suggests that other scattering mechanisms featuring a negative temperature-dependent behavior come into play. The extracted E_i s were at 20 °C and 2.5 MV/cm.

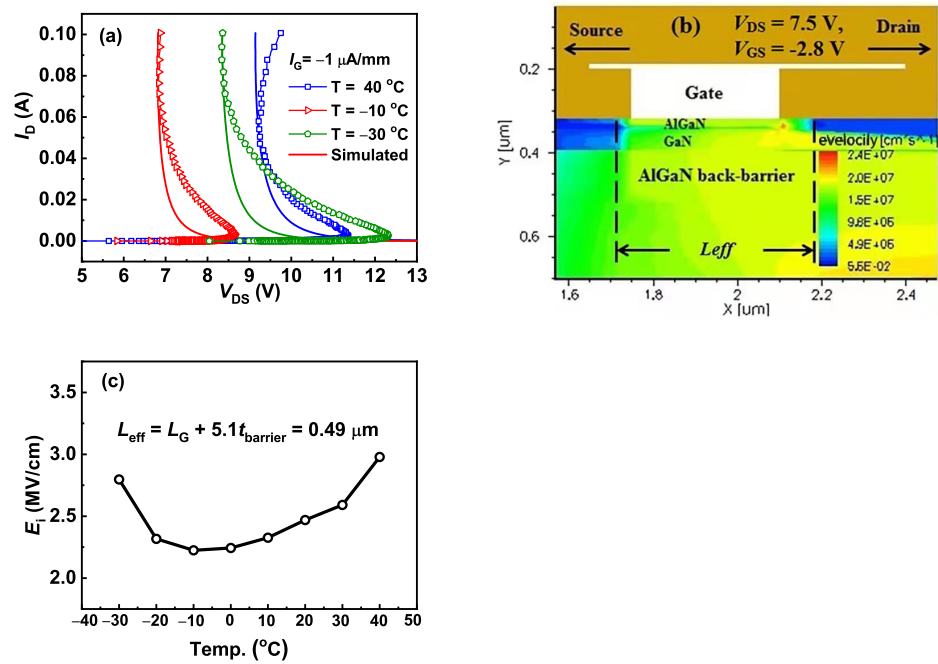


Figure 4. (a) Impact ionization modeling of the measured BV_{ON} loci for the fabricated AlGaIn/GaN HEMTs. (b) Value of effective gate length obtained by simulation in condition of ON-state breakdown measurement at $V_{DS} = 7.5$ V and $V_{GS} = -2.8$ V. (c) Evolution of the extracted E_i with temperature.

To reveal the physical mechanism of the anomalous temperature dependence of the BV_{ON} loci, as well as E_i below -10 °C, variable-temperature output characteristics were measured at V_{GS} of -3 V from 40 to -30 °C, as shown in Figure 5a. The 2DEG mobility at different biases was extracted using the output equation in the saturation region [27]:

$$I_D = \frac{W}{2L} \cdot \mu \cdot C_{barrier} \cdot (V_{GS} - V_{TH})^2 \quad (2)$$

where W is the gate width, L is the gate length, μ is the carrier mobility, and $C_{barrier} = 344$ nF/cm² is the AlGaIn barrier capacitance obtained by capacitance–voltage (C–V) measurements. The effect of V_{DS} on the V_{TH} shift, e.g., ~ 0.2 V negative shift as V_{DS} increased from 5 to 10 V (figures not shown), was also considered in the mobility extraction.

The extracted mobility exhibited a slight decrease below -10 °C for the case of $V_{DS} = 2, 3$, and 4 V, which is believed to be the result of the impurity scattering effect induced by the aforementioned acceptor-like traps. Acceptor-like states are capable of trapping free carriers, which will perform as impurity scattering centers as a result [28]. Since the impurity scattering will become gradually violent as the temperature decreases [29], it will show degradation on the carrier mobility at a low temperature, as shown in Figure 5b. Therefore, a higher V_{DS} corresponding to a higher E_i is required to compensate the increased impurity scattering, as shown in Figure 4b. However, once the traps are discharged to be neutral at high drain bias, e.g., $V_{DS} = 10$ V, the impurity scattering will become weak,

and the temperature dependence of the mobility changes to a phonon-scattering dominated behavior (Figure 5b). As the BV_{ON} properties will be degraded at a high temperature by impact ionization [10,26], E_i may rise further as a result of its mobility-dependent properties.

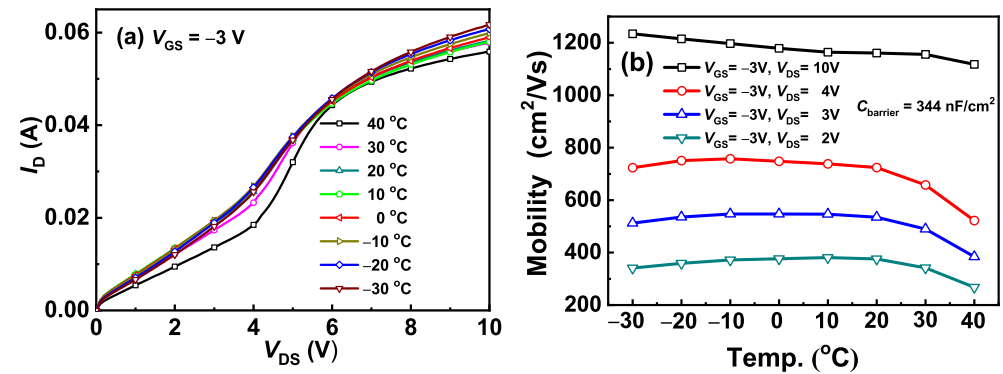


Figure 5. Temperature-dependent I-V characteristics (a) and extracted carrier mobility (b) of the fabricated AlGaIn/GaN HEMTs at various drain biases.

4. Conclusions

In summary, the temperature-dependent ON-state breakdown loci of AlGaIn/GaN HEMTs with an AlGaIn back barrier were experimentally demonstrated. With the gate current extraction technique, the impact ionization of acceptor-like traps was observed as the 2DEG channel was marginally turned on. The characteristic electric field E_i was extracted, exhibiting a U-shaped temperature dependence from 40 to −30 °C. The anomalous temperature dependence of the BV_{ON} loci and E_i below −10 °C was attributed to the impurity scattering effect of acceptor-like traps in AlGaIn/GaN heterostructures, which also correlated with the observed kink effect.

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