

Leakage current degradation in lattice-matched $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ Schottky barrier diodes

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A comparative study is performed on the difference of degradation behaviors between $\text{Al}_{0.27}\text{Ga}_{0.73}\text{N}/\text{GaN}$ and lattice-matched $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ Schottky barrier diodes (SBDs). The results indicate that, the degradation of InAlN/GaN SBDs exhibits absolutely lower “critical voltage” and more serious deterioration than that of AlGaIn/GaN SBDs in step-stress experiments. By fitting the experimental data with various transport models and testing the dislocation density using cathode-luminescence microscope, a model associating with traps is proposed to address the current degradation behaviors in InAlN/GaN SBDs, which emphasizes that the enhanced Fowler-Nordheim tunneling process due to a thinner triangular barrier after stress is mainly responsible for degradation.

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1. Introduction

In recent years, GaN-based high electron mobility transistors (HEMTs) have emerged as the most promising candidates for microwave and high temperature/high power application [1-3], due to their excellent physical properties such as high electron saturation velocity, good thermal stability and high breakdown field. In particular, several breakthrough performances about GaN-based HEMTs have been demonstrated [4-5]. Despite impressive progress has been made, the commercial application of the devices is seriously limited by the reliability of operating under high reverse bias. It has been reported that high reverse gate voltage can cause permanent increase of leakage current in AlGaIn/GaN HEMTs [6]. Therefore, it is essential to understand the current degradation mechanism completely for further improving the reliability of GaN-based devices. Since the last decade, various instructive phenomenological models, such as the inverse piezoelectric effect, the hot electrons effect and the defect generation and percolation process, have been proposed to explain the degradation [7-9]. But so far, the degradation process of leakage current still remains unclear and needs to be in-deeply investigated.

To investigate the leakage current degradation mechanism in GaN-based HEMTs, in this work circular Schottky contact structures were fabricated on HEMT epi-wafer, which have the same electrical properties with the Schottky gate of a standard device. Based on step-stress experiments and current transport analysis, the difference of leakage current degradation behaviors between AlGaIn/GaN and lattice-matched InAlN/GaN

SBDs was compared. A model associating with traps was developed to explain the obvious leakage current degradation in InAlN/GaN SBDs. This model points out that the generation of the donor-like traps induced by Fowler-Nordheim (FN) tunneling can effectively increase the electric field over the InAlN barrier, which could increase current by enhancing the tunneling component.

2. Experimental

Fig. 1 shows the cross-sectional schematic of the fabricated AlGaIn/GaN and lattice-matched InAlN/GaN Schottky contact structure. The GaN epiwafers ($\sim 3 \mu\text{m}$) of AlGaIn/GaN and InAlN/GaN SBDs used here are both grown by metal-organic chemical vapor deposition on *c*-plane sapphire substrates. The AlGaIn/GaN epi-heterojunction includes a $3 \mu\text{m}$ GaN layer, an 18 nm $\text{i-Al}_{0.27}\text{Ga}_{0.73}\text{N}$ barrier layer and a 2 nm GaN cap layer. The InAlN/GaN epi-heterojunction includes a $3 \mu\text{m}$ GaN layer, a 2 nm AlN spacer, an 18 nm $\text{i-In}_{0.17}\text{Al}_{0.83}\text{N}$ barrier layer and a 2 nm GaN cap layer. The electrode structure consists of $100 \mu\text{m}$ circular Schottky dots separated radially by $20 \mu\text{m}$ from the Ohmic contacts. Pt/Au (50/300 nm) (Ni/Au for AlGaIn/GaN SBDs) Schottky contact was patterned by the standard lithography and lift-off technique. Ohmic contact was formed by annealing a Ti/Al/Ti/Au (30/120/50/100 nm) metal stack using rapid thermal annealing in N_2 at $870 \text{ }^\circ\text{C}$ for about 30 s. Finally, a 150-nm-thick SiN (SiO_2 for AlGaIn/GaN SBDs) passivation layer was deposited by plasma-enhanced chemical vapor deposition. A Keithley 4200 SCS

semiconductor parameter analyzer was used to provide the stress voltages and measure the currents after stresses.

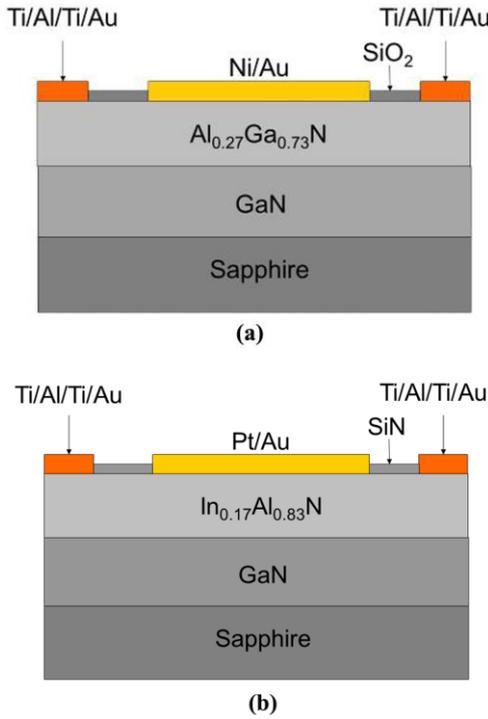


Fig. 1. Cross-section schematic of the fabricated (a) AlGaIn/GaN SBDs and (b) lattice-matched InAlN/GaN SBDs (color online)

3. Results and discussion

Firstly, step-stress experiments were carried out to study the current degradation behaviors in AlGaIn/GaN SBDs and lattice-matched InAlN/GaN SBDs, respectively [6,9]. The reverse gate voltage of AlGaIn/GaN SBDs increases from 40 V to 120 V in steps of 20 V, while the voltage of InAlN/GaN SBDs increases from 6 V to 14 V in steps of 2 V. The period for each bias-stress is 1000 s and 30 s, during which the gate currents are simultaneously measured. Fig. 2 illustrates the final results of step-stress experiments. It can be obviously found that three similar degradation behaviors occur in both AlGaIn/GaN SBDs and lattice-matched InAlN/GaN SBDs. Depending on the value of applied voltage, three different behaviors can be observed. (1) At low voltage levels, the leakage current shows a recoverable decrease accompanied by small noise during the stress time. (2) Before the failure occurs, the leakage current becomes noisy. (3) When a “critical voltage” is reached, the leakage current shows an irreversible increase accompanied by large noise. The “critical voltage” of degradation in AlGaIn/GaN SBDs is about 80 V (see Fig. 2(a)), while for lattice-matched InAlN/GaN SBDs, the “critical voltage” is only about 10 V (see Fig. 2(b)). In addition, the leakage of AlGaIn/GaN SBDs degrades about 16.34 %, while the leakage of

AlGaIn/GaN Schottky diodes degrades about 265.63%. In general, the degradation of InAlN/GaN SBDs exhibits absolutely lower “critical voltage” and more serious deterioration than that of AlGaIn/GaN SBDs in step-stress experiments.

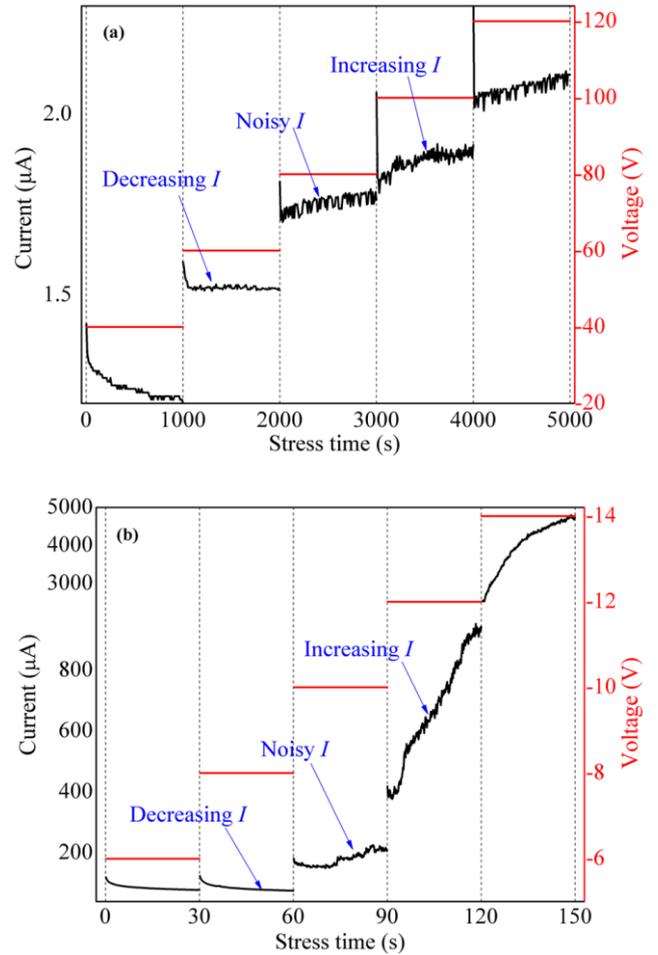


Fig. 2. Step-stress experiments of (a) AlGaIn/GaN SBDs and (b) lattice-matched InAlN/GaN SBDs (color online)

To explore the reason for different current degradation behaviors, the reverse I - V characteristics before and after stress were measured in AlGaIn/GaN SBDs and lattice-matched InAlN/GaN SBDs, respectively (shown in Fig. 3). It can be seen from Fig. 3 that the leakage current obviously increases with the increasing stress time. It must be noticed that the leakage current of AlGaIn/GaN SBDs is completely saturated at 2.5 V due to the fully depletion of 2DEG with the external applied voltage. While for InAlN/GaN SBDs, the current continuously increases with increasing reverse voltage. To achieve a better understanding on the current transport process, the experimental data were carefully fitted by various transport models [10]. Consequently, the low-field currents of both AlGaIn/GaN SBDs and InAlN/GaN SBDs show good agreement with the Frenkel-Poole (FP) emission

mechanism [11], however, the high-field currents of InAlN/GaN SBDs are mainly the FN tunneling current [12] (see the red solid line in Fig. 3(b)). The expressions of FP emission is:

$$I_{FP} \propto F \exp\left[-\frac{q(\phi_B - b\sqrt{F})}{kT}\right], \quad (1)$$

where F is the average electric field strength, $q\phi_B$ is the zero-field emission barrier height, and β is the FP emission coefficient, k is Boltzmann's constant and T is the absolute temperature. The expressions of FN tunneling is:

$$I_{FN} \propto F^2 \exp\left(-\frac{B}{F}\right), \quad (2)$$

where B is FN tunneling coefficient.

Fig. 3 indicates that FN tunneling process is non-negligible for the serious degradation of InAlN/GaN SBDs.

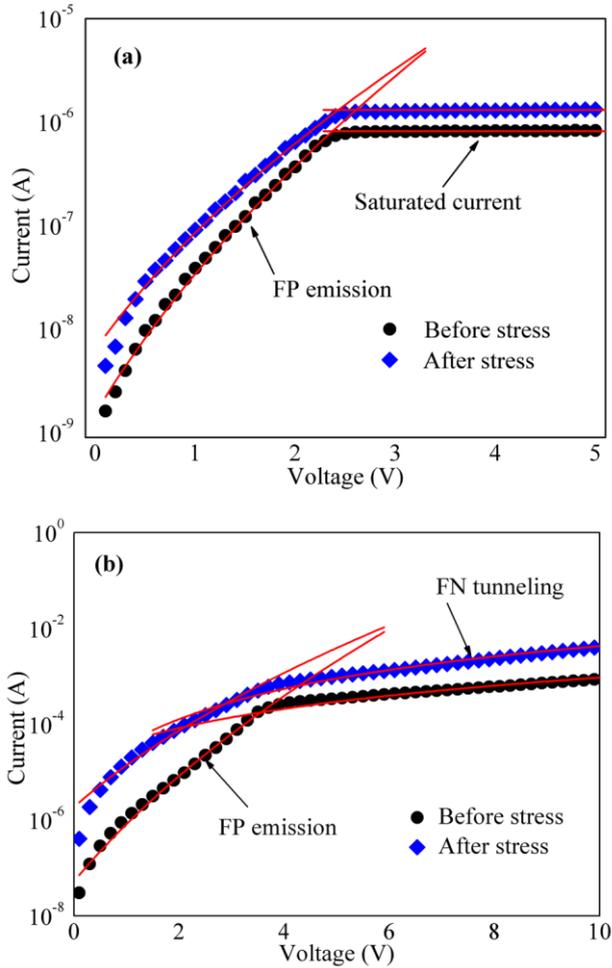


Fig. 3. Reverse I - V characteristics of (a) AlGaIn/GaN SBDs and (b) lattice-matched InAlN/GaN SBDs measured before and after stress (color online)

Next, the reason for the different high-field current mechanism between AlGaIn/GaN SBDs and InAlN/GaN SBDs was explained based on the dislocations analysis. Fig. 4 illustrates the dislocations of barrier layer tested by cathodoluminescence (CL) microscope. It is estimated that the dislocation density of AlGaIn and InAlN barrier layer is about $5 \times 10^8 \text{ cm}^{-2}$ and $1.2 \times 10^9 \text{ cm}^{-2}$, respectively. Therefore, we have reason to believe that the higher dislocation density is mainly responsible for the formation of FN tunneling current in InAlN/GaN SBDs.

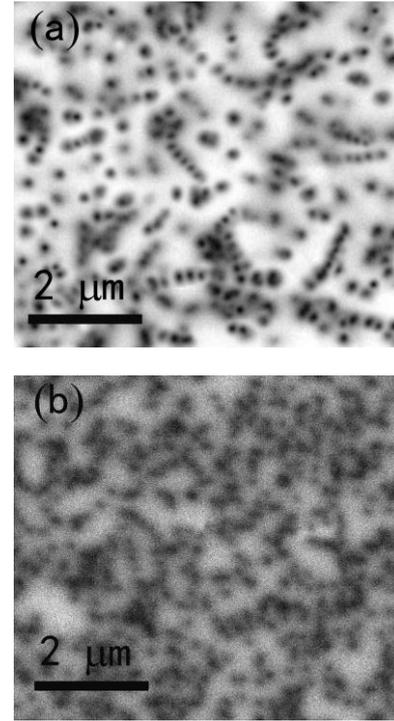


Fig. 4. CL results of (a) AlGaIn and (b) InAlN barrier layer

Based on the experimental evidence collected above, a model associating with donor-like traps is developed to explain the obvious degradation of InAlN/GaN SBDs. Fig. 5 schematically illustrates the leakage current degradation process in InAlN/GaN SBDs. At low fields, the electrons from the surface donor states can be readily emitted to the continuous electrical states through linear dislocations with a reduced barrier height. While at higher fields, the current of AlGaIn/GaN SBDs is saturated due to good barrier material quality, only a small amount of traps are generated by high field [13], leading to the slightly increase of FP emission current. However, the current of InAlN/GaN SBDs at high field flows by means of FN tunneling due to the formation of a triangular barrier. When a constant and strong electric field is applied on the device, the energetic electrons induced by high electric field can cause significant Joule heating effect and give rise to the generation of the donor-like traps in the GaN buffer near InAlN barrier layer. These positively charged

states would effectively increase the electric field over the InAlN barrier, enhancing the FN tunneling process by inducing a thinner surface barrier layer. Therefore, we think that the enhanced FN tunneling process should be mainly responsible for the serious degradation in InAlN/GaN SBDs.

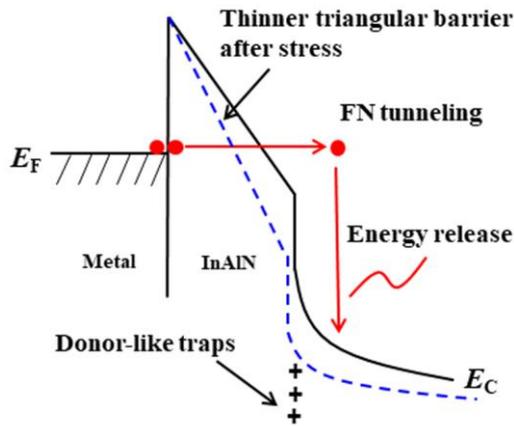


Fig. 5. The proposed FN tunneling degradation model for InAlN/GaN SBDs (color online)

Finally, a critical problem must be discussed is which kind of the donor-like traps may be generated during the stress. Based on numerous reported theoretical studies, we believe that N vacancy and their Frenkel pairs may be mainly responsible for the leakage current degradation [14]. Some experimental observations point out that the metastable donor-like traps exist in the vicinity of dislocations, which could cause the high leakage current and low effective Schottky barrier height at the metal/semiconductor interface. Therefore, it is most likely that the donor-like traps generated in the degraded devices are the N vacancy and/or the involved complex. More experimental measurements and in-depth analysis will be performed to confirm the presence of these interface trap states in the future work. To restrain the degradation, we suggest that it is essential to reduce the defect density in the Schottky barrier layer and modulate the electric field distribution around the gate electrode.

4. Conclusion

In summary, the leakage current degradation mechanisms in AlGaIn/GaN SBDs and lattice-matched InAlN/GaN SBDs were investigated. By validating the leakage current transmission mechanisms, an alternative FN tunneling model was proposed to interpret the degradation behaviors of leakage current. Experimental evidence collected in this work suggests that the enhanced FN tunneling process induced by the generation of donor-like traps in InAlN barrier layer should be mainly responsible for the degradation. This model has certain significance for understanding the current transmission

and degradation behaviors of the other GaN devices.

Acknowledgements

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Reference

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