Stable AlGaN/GaN high electron mobility transistors with tungsten nitride gate metallisation

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An AlGaN/GaN high electron mobility transistor (HEMT) with tungsten nitride (WN_x) Schottky gate fabricated on a sapphire substrate is presented. Gate forward current stress was chosen to evaluate the stability of the Schottky gate. After stress, this WN_x HEMT remains stable, while the conventional Ni/Au HEMT shows performance degradation and failure. The maximum output power density from this device is 5 W/mm at 2 GHz. A combination of these findings indicates the robust performance of this WN_x material and its potential as a Schottky gate for AlGaN/GaN HEMTs.

Introduction: AlGaN/GaN high electron mobility transistors (HEMTs) with high breakdown voltage and high channel carrier concentration are capable of delivering high power at radio frequencies [1–3]. Biasing the device at a high voltage or high channel current is a requirement for high-power operations, and inevitably causes large electric fields and high temperatures on the device itself. Previous studies have investigated degradation mechanisms related to those two factors [4–7]. While electric fields could introduce defects due to the piezoelectric nature of the GaN material system, the effects of the current and self-heating extend beyond the epitaxy layer because the temperature increases in the channel might lead to reaction of the metal contacts with the underlying semiconductors.

Another source of degradation in AlGaN/GaN HEMTs when used for RF power applications is the forward conduction current of the gate. This phenomenon occurs when the device is pushed into saturation under a large RF input signal. The current can cause changes in the characteristics of Schottky contacts and devices. Researchers do not know the exact mechanism of degradation, but the high current-induced temperature that damages the contacts may be a contributing factor [4, 6]. To reduce the forward conduction current, one study used a MISFET structure that inserts a thin insulator under the gate [8].

In this Letter, we propose a different approach to minimise possible reactions between the gate electrode and AlGaN layer using a thermally stable tungsten nitride thin film as the gate material. Based on our previous study on nitrogen-rich tungsten nitride Schottky diodes that demonstrate a high Schottky barrier height and good thermal stability [9], this Letter presents a WN_x gated HEMT device with no sign of degradation from gate forward current stress and which delivers excellent power performance.

Experiment: The AlGaN/GaN heterostructures in this study consist of a 3.5 μm-thick undoped GaN buffer on a sapphire substrate, followed by a 29 nm layer of $Al_{0.26}Ga_{0.74}N$. The mobility and sheet carrier concentrations are 900 $cm^2/V\,s$ and $1.0 \times 10^{13}\ cm^{-2}$, respectively. The device was isolated by mesa etching using a Cl_2/Ar gas mixture in an induced coupled plasma (ICP) etcher. Ti/Al/Ni/Au metal layers were evaporated and subsequently annealed in an N_2 atmosphere at 800°C to form ohmic contacts. The wafer was then split in half and two different Schottky gate schemes of WN_x/Au and Ni/Au metal stacks were deposited on separate pieces. The nitrogen-rich WN_x/Au metal stacks were deposited as described in [9]. The resulting WN_x layer was 100 nm thick. A 300 nm Au film was then deposited on top of the WN_x film by electron beam evaporation to reduce the gate resistance. AlGaN/GaN HEMTs with Ni/Au gate metal were also fabricated for comparison using electron beam evaporation. These two types of devices were passivated using 100 nm plasma-enhanced chemical vapour deposition (PECVD) silicon nitride. The pad connections of these devices were formed by electrochemical-plated 2 μm-thick gold with air bridges. The devices had a gate length of 1 μm, gate width of 100 μm (2 × 50 μm) and a source-to-drain distance of 5 μm.

The DC characteristics of the AlGaN/GaN HEMTs were measured using an Agilent E5270B. The gate current stress was applied by increasing the gate voltage by 0.5 V every 30 min, which effectively forward-biased the gate electrode. The maximum gate current density used was 1 A/mm, which was limited by the equipment capability. Between the increase of the gate voltage, the gate leakage current I_{Goff} was extracted to monitor the degradation at the conditions (I_G at $V_{ds} = 0.1$ V, $V_{gs} = -5$ V) as described in [6]. Microwave power was measured on-wafer using a Focus load-pull system at 2 GHz.

Results: The DC gate current stress test was carried out by forward-biasing the gate contact. This method creates both electrical and thermal stress in the vicinity of the gate. Fig. 1 compares the results of two different gate metal schemes. This Figure shows that the Ni/Au contacts are not stable at stress currents above 0.9 A/mm, and the gate leakage current exhibits a drastic increase. This degradation during gate forward stress is consistent with previous studies [4, 6]. The Ni/Au HEMTs failed after 9 h as a result of this stress current. As for the WN_x/Au HEMTs, the device remained stable and exhibited no appreciable change in the gate leakage current after 24 h of the stress test. Fig. 2 compares the device characteristics before and after the stress, and there is no observable device degradation. These WN_x/Au HEMTs have a saturation current of 585 mA/mm, maximum transconductance of 180 mS/mm, and an off-state breakdown of more than 100 V after stress.

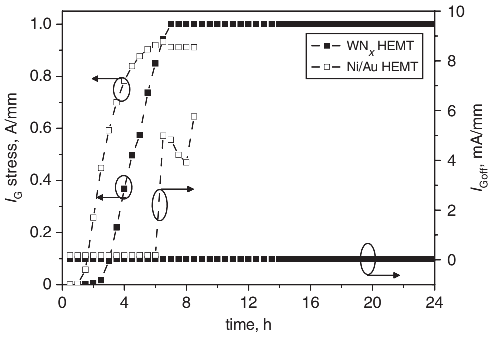

Fig. 1 *Dependence of gate stress current and monitored gate leakage current on stress time for Ni/Au HEMTs and WN_x/Au HEMTs*

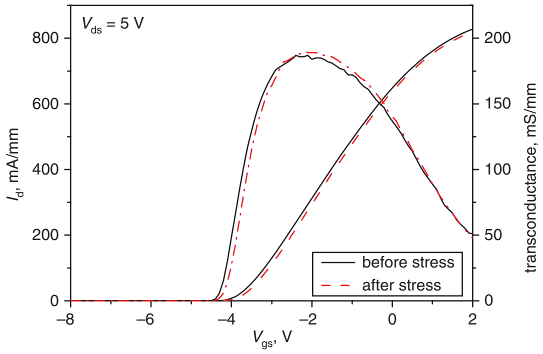

Fig. 2 *Comparison of DC characteristics of WN_x/Au HEMTs before and after gate forward current stress*

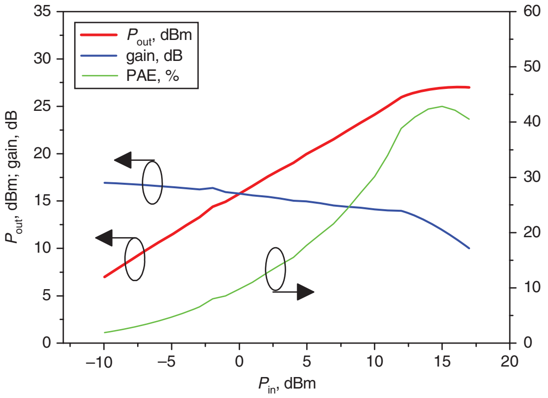

Fig. 3 *Power performance of 2 × 50 μm WN_x-gated AlGaN/GaN HEMT at 2 GHz, biased at drain voltage of 40 V*

Maximum output power density 5 W/mm, power added efficiency (PAE) 43%

The load-pull measurement results of the WN_x-gated AlGaN/GaN HEMTs are shown in Fig. 3. These devices were biased under class

AB conditions with a drain voltage of 40 V and a quiescent current density of 100 mA/mm. Their maximum output power density is 5 W/mm and the power added efficiency (PAE) is 43 %. These results indicate the feasibility of using a WN_x contact metallisation scheme in AlGaN/GaN HEMTs for high power microwave applications.

Conclusions: This Letter presents an AlGaN/GaN HEMT with nitrogen-rich tungsten nitride gate metallisation. Forward gate current stress was carried out on the device for 24 h, with no apparent change in gate leakage current after stress. This device has a maximum output power density of 5 W/mm and a PAE of 43% at 2 GHz. Results imply that the WN_x/Au Schottky gate contact on AlGaN/GaN heterostructures is stable and can serve as an alternative scheme for the gate metallisation of AlGaN/GaN HEMTs.

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