**The Impact of AlxGa1-xN Back Barrier in AlGaN/GaN High Electron Mobility Transistors (HEMTs) on 6-inch MCZ Si Substrate**

H.Y. Wang1, H.C. Chiu1\*, C.H. Liu1, C.R. Huang1, C. W. Chiu1, W.C. Hsu2, C.M. Liu2, C.Y. Chuang2, J.Z. Liu2, Y.L. Huang2

1Department of Electronics Engineering, Chang Gung University, Taiwan, R.O.C.

2Innovation technology research center, GlobalWafers Co., Ltd., Taiwan, R.O.C.

**TEL: +886-3-2118800 # 3645 Email:** [**hcchiu@mail.cgu.edu.tw**](mailto:hcchiu@mail.cgu.edu.tw)

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## **Abstract**

**In this study, AlGaN back barriers (B.B.) with different Al mole fractions and thicknesses were used in AlGaN/GaN high electron mobility transistors (HEMTs) to improve device performance. Relative to thickness, a proper Al mole fraction (Al0.08GaN) of the B.B. more strongly affected the device’ Ion/Ioff ratio. It exhibited a low leakage current and high Ion/Ioff ratio of approximately 106. Relative to B.B. mole fraction, B.B. thickness more greatly affected the devices’ horizontal breakdown voltage (760V) and LFN characteristics. Increasing the Al mole fraction and the thickness of the B.B. more strongly affected the dynamic RON. The current gain cut-off frequency (fT) and maximum stable gain cut-off frequency (fmax) were 5.2 GHz and 10.5 GHz, respectively, for the Al0.08GaN B.B. device.**

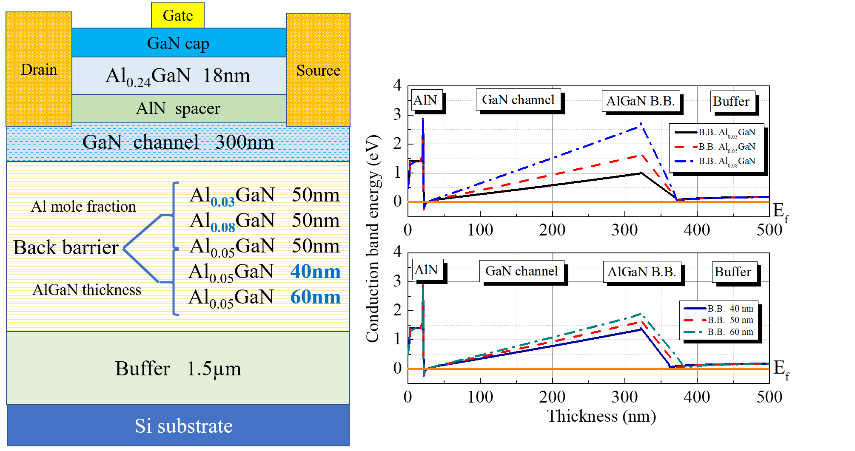
## Introduction

GaN exhibits high thermal conductivity, high saturation drift velocity benefits, and wide band gap energy. It is widely used to develop high-temperature, high-frequency, and high-power devices [1], [2]. Until recently, the epitaxy quality of GaN on silicon substrate was important to the production of such devices. The lattice mismatch between the GaN material and Si substrate has caused high-density dislocation and defects in GaN epi structure. High-concentration carbon (C) or iron (Fe) doping allows a high breakdown voltage, but it affects crystal quality and forms deep-level traps. Dynamic capture processes of these deep traps which are below the GaN conduction band, may be uncontrol with the switching gate[3], resulting in a dynamic on-resistance (RON). Moreover, surface defects on the AlGaN barrier also capture electrons, which cannot be released during switching, causing a higher dynamic RON [4].

Fig. 1. (a) Cross-section of AlGaN/GaN with AlGaN back barrier HEMT on Si substrate. (b) one-dimensional Poisson simulation.

One effective solution to the aforementioned problems is the use of an AlGaN B.B. layer. Presumably, the embedded gradient driving force from Al composition and strain can bend back the dislocation in the lateral direction [5], [6]. The use of a B.B. structure is an alternative solution for reducing the short-channel effects without additional top-barrier scaling. B.B. structures have been successfully applied to AlGaN/GaN HEMTs, and they have resulted in significant performance improvements [7]–[9]. Furthermore, an AlGaN back barrier can improve two-dimensional electron gas (2DEG) confinement and prevent penetration by electrons [10]. This study investigated the effect of AlGaN B.B. thickness (tB.B.) and Al mole fraction.

### EXPERIMENTAL PROCEDURES



An AlGaN/GaN HEMT with AlGaN B.B. structures were grown using the MOCVD method on MCZ-Si substrate. The MCZ-Si substrate means high resistivity magnetic Czochralski silicon (MCZ-Si). Magnetic Czochralski grown silicon (MCZ) is a promising material relatively to other traditional CZ and float zone (FZ) Si materials for high energy physics applications such as the radiation hardness (RH) of the protons.[11] Fig. 1(a) illustrates the cross-section of the fabricated device and the corresponding epitaxial structure. Fig. 1(b) illustrates the one-dimensional Schrödinger–Poisson simulation for the conditions of the AlGaN back barrier. The simulation estimated a 2DEG confinement potential that was higher than the bandgap energy of GaN. The device with a 1-µm gate length had a drain-to-source distance of 4 µm. The device structure had a 1.5-µm GaN buffer. The AlGaN B.B. were of different Al mole fractions (3%, 5%, and 8%) and thicknesses (40 nm, 50 nm, and 60 nm); the barrier additionally comprised 300-nm GaN, 1-nm AlN, an 18-nm Al0.24GaN barrier, and a 2-nm GaN cap. During device fabrication, the active region was protected by a photoresist, and the mesa isolation region was removed in a reactive ion etching chamber using BCl3 + Cl2 mixed-gas plasma. Ohmic contacts were prepared using electron beam evaporation involving a multilayered Ti/Al/Ni/Au (30 nm/125 nm/50 nm/200 nm) sequence, which was followed by rapid thermal annealing at 850°C for 30 s in a nitrogen-rich environment. After ohmic formation, the Ni/Au (15/330 nm) gate metal was evaporated.

### RESULTS AND DISCUSSION

We used Agilent 4142B to measure the devices’ Drain to source current (IDS) at different gate voltage (VGS) characteristics. Fig. 2 presents the effect of the AlGaN B.B. on the devices’ Ion/Ioff ratio. The measured VGS ranged from −6 to 2 V. The off-state channel leakage current of the B.B. Al0.08GaN HEMTs had an Ion/Ioff ratio of approximately 1.2 × 106. Because of the high barrier height, an improvement in leakage current was observed for AlGaN B.B. devices with a high Al mole fraction. The subthreshold swing slope (S.S.) was also affected by the AlGaN B.B. The S.S. values of the Al0.08GaN B.B. device and 60-nm B.B. device were 0.30 V/dec and 0.33 V/dec, respectively. Relative to thickness, Al mole fraction more greatly affected S.S. characteristics. Apparently, the increase of the S.S. is means that transistors requires exploiting carrier transport mechanisms and electrostriction in conjunction with piezoelectricity was reduced [12-14].



Fig. 2. The measured IDS–VGS at VDS = 10 V of devices.

Fig. 3 presents the effect of the AlGaN B.B. on devices’ RON and drain to source current (IDS). The measured VGS was 2 V, and the drain voltage (VDS) ranged from 0 to 10 V. The B.B. increased the 2DEG level from the Fermi level, and the AlGaN B.B. affected maximum IDS. The Al0.08GaN B.B. device and 60-nm AlGaN B.B. device had IDS values of 542 mA/mm and 532 mA/mm, respectively. The RON values of the Al0.08GaN B.B. device and 60-nm AlGaN B.B. device were 8.04 and 8.89 mΩ/mm, respectively.

Fig. 4 presents the horizontal breakdown characteristics of the different AlGaN B.B. devices. The results were obtained using Angilent B1505. The measurement pattern distance was 40 μm. Al0.08GaN B.B. had a higher breakdown voltage of 740 V, and the 60-nm AlGaN thickness breakdown voltage was 762 V. Relative to mole fraction, thickness more greatly affected the horizontal breakdown voltage characteristics of the back barrier structure

Fig. 3. The measured IDS–VDS at VGS = 2 V of devices.



Fig. 4. The horizontal breakdown characteristics of devices.

To analyze the trapping and detrapping phenomena in AlGaN/GaN with AlGaN B.B. HEMTs, low-frequency noise spectra were measured at various gate bias voltages. The gate leakage current flowed to the drain, and the noise in the source current was measured and minimized [15]. To locate the source of noise in the channel area, the normalized current spectral density *S*I/I2 at 100 Hz was plotted against the effective gate-to-source voltage (VGN)of AlGaN B.B. HEMTs, where VGN was set as VGS–Vth (Fig. 5). The results indicated that in the Al0.08GaN B.B. device, SI/I2 increased the VGS−1 and VGS−3regions; the range of increase was much larger than that for the 60-nm AlGaN B.B. device, which is consistent with a previous study [16]. These results demonstrate that the thickness of the AlGaN B.B. more effectively reduces the ungated channel resistance noise of devices.



Fig. 5. The measured low-frequency noise of devices.



The dynamic RON test was performed using an AMCAD AM241 pulsed system. The dynamic RON characteristics were also measured from different quiescent bias points at VGS = 1 V to investigate the effect of off-state drain bias stress on dynamic RON and current (Fig. 6). The reference bias was set at (VGSQ, VDSQ) = (0 V, 0 V)—VDSQ is the quiescent drain bias—and did not induce any relevant trapping. The devices were switched with a 5-μs pulse width and 500-μs pulse period. VDSQ was swept from 0 to 30 V at 10 V increments, and the quiescent gate bias was swept to −6 V.

The dynamic RON ratio (RON, D/RON, Q) for the Al0.08GaN B.B. device slightly increased to 1.48 when the drain bias stress increased to 30 V because of high electron injection into the buffer trap states from the drain electrode; the ratio for the 60-nm AlGaN B.B. device increased to 1.38 at the off-state drain bias stress of 30 V. These results demonstrate that the Al mole fraction more effectively mitigates the buffer trapping phenomenon.

Fig. 6. The dynamic Ron of devices

To experimentally measure the surface temperature distribution in the devices, an infrared (IR) thermographic system with micro-Raman spectroscopy was adopted, and the IR radiation of the device was detected using an IRM P384G detector. The surface temperature map values were obtained from the IR radiation intensity, which was determined following emissivity calibration performed for the B.B. devices at the current of 60 mA for 30 s. As presented in Fig. 7(a), the Al0.08GaN B.B. device and 60-nm AlGaN B.B. device had peak surface temperatures of 33.95°C and 32.69°C, respectively. The results indicated that the Al mole fraction caused thermal issues. In addition, the surface temperature distribution was not uniform, which decreased reliability due to the presence of hot spots. Fig. 7(b) shows the thermal resistance of the devices. The Al0.08GaN B.B. device had a thermal resistance of 6.211 °C/W, and the 40-nm B.B. device had a lower thermal resistance of approximately 2.01 °C/W.

Fig. 7. (a) The peak surface temperature of the device, and (b) the thermal resistance of the devices.

To determine the effect of a B.B. on RF performance, the microwave S-parameters of both devices were evaluated using a common source configuration and a PNA network analyzer in conjunction with Cascade direct probes. The measurement frequency range of the S-parameters was 100 MHz to 50 GHz at the operating condition of VDS = 10 V. Based on the optimal RF operation of both devices, the VGS values were defined at the appearance of their peak gm. As presented in Fig. 8, the Al0.08GaN B.B. device exhibited a higher current gain cut-off frequency (fT = 6 GHz). The results indicated that increasing the Al mole fraction can improve 2DEG confinement. This increase affected carrier concentration and the current gain cut-off frequency. The maximum stable gain cut-off frequency (fmax) was 10.4 GHz for the B.B. 60-nm device when thermal equilibrium was reached.



Fig. 8. The current gain frequency (FT) and power gain frequency (Fmax) of devices.

### CONCLUSION

This paper compared various thicknesses and mole concentrations of AlGaN B.B. in AlGaN/GaN HEMTs. The IDS–VGS result demonstrated that the use of Al0.08GaN B.B. improved the device’s Ion/Ioff ratio. The horizontal breakdown characteristics demonstrated that AlGaN thickness more strongly affected the breakdown voltage than mole concentration did. Increasing the Al mole fraction and thickness of the B.B. affected dynamic RON. The Al mole fraction of B.B. also affected the RF characteristics of devices. Increasing the Al mole fraction potentially improves 2DEG confinement.

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Acronyms

GaN: Gallium Nitride

HEMT: High Electron Mobility Transistor