Remarkable Breakdown Voltage on AlN/AlGaN/AlN double heterostructure

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***Abstract*— Ultra wide band gap (UWBG) materials such as AlN are part of a class of materials that have a larger band gap than conventional wide band gap (WBG) materials such as GaN, allowing higher operating voltages. In this work we present the fabrication and DC / high voltage characterizations of AlN/AlGaN/AlN double heterostructure that are regrown by metalorganic chemical vapor deposition on AlN/sapphire. A buffer breakdown about 1100V with low leakage current for a spacing below 2µm is reported, which corresponds to a breakdown field about 6 MV/cm. Furthermore, transistors have been successfully fabricated on this heterostructure with low leakage current and low on-resistance. A breakdown voltage of 4.5kV with an off-state leakage current below 0.1 µA/mm have been indeed achieved. These results that AlGaN-channel HEMTs are promising for high power, high temperature future applications.**

Keywords— AlGaN channel; High-Electron-Mobility Transistor (HEMT); Ultra-Wide Band Gap, AlN

I. Introduction

GaN-based HEMTs and SiC power semiconductors are the material of choice for high power applications owing to their superior breakdown voltage (about 10 times) over their Si competitors. Today, the WBG-based electronics are maturing rapidly and have found large-scale market adoption in electric vehicles, power supplies, and photovoltaic (PV) inverters. However, ultra-wide band gap materials such as AlN (6.2 eV) and related Al-rich AlGaN channel could allow for further improvement, especially in terms of voltage and temperature operations [1-7]. In addition, the use of an AlN back barrier [8-10] would enable to both increase the electron confinement in the transistor channel and enhance the thermal dissipation. It has already been demonstrated that for extremely high temperature electronics, the properties of Al-rich transistors are already showing favorable comparisons to conventional WBG materials [11]. Nevertheless, very high voltage operation is still plagued by the material quality and the ability to implement high Al content above 50% into the channel. The premise of voltage enhancement with AlGaN channels needs validation.

In this work, we demonstrate, state-of-the-art 3-terminal breakdown voltage (BV) for AlGaN channel HEMTs with multiple kilovolts.

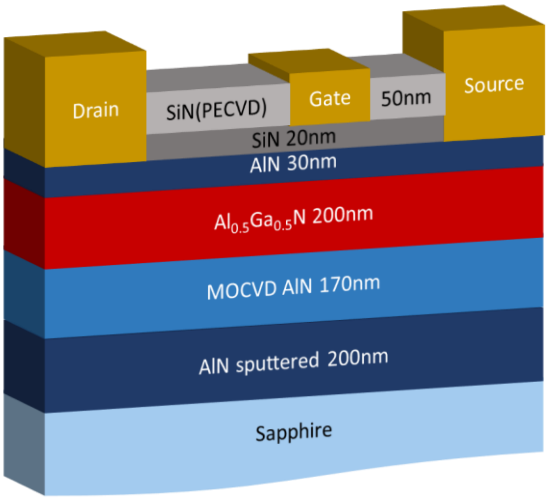

Fig. 1 : *Schematic cross section of the AlN/AlGaN/AlN HEMTs*

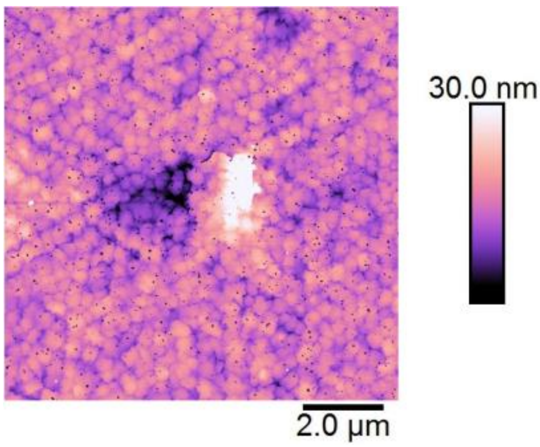

Fig. 2 : *Schematic cross section of the AlN/AlGaN/AlN HEMTs*

II. Material Description and Device Fabrication

Fig. 1 shows a cross-sectional drawing of the fabricated AlGaN channel HEMT. An AlN film with 200 nm thickness was grown on c-plane sapphire substrates by sputtering followed by annealing at 1700°C for 3h. Epitaxial layers, consisting of a 170-nm-thick AlN buffer, a 200-nm-thick $Al_{0.5}Ga_{0.5}N$ channel, and a 30-nm-thick AlN barrier capped with a 20-nm thick SiN layer, were grown by metal–organic vapour phase epitaxy. All the layers were unintentionally doped. Fig. 2 shows an AFM image of the as grown structure, where the surface mirrors dislocation mediated island growth induced by screw type threading dislocations. This reflects the large room for improvement in terms of material quality. Source/drain ohmic contacts were obtained by etching the SiN cap as well as part of the AlN barrier with a deposition of a Ti/Al/Ni/Au metal stack annealed at 875°C.

As expected from previous work on AlGaN channel, high contact resistances are observed. Si implantation or highly doped regrowth layer would be needed to achieve low contact resistances. Device isolation has been performed by mesa etching. A 2DEG charge density of 1.9×10^{13} cm^{-2} with an electron mobility of 145 cm^2/V.s has been measured on Van der Pauw patterns. Ni/Au MIS gates were deposited on top of the SiN cap layer.

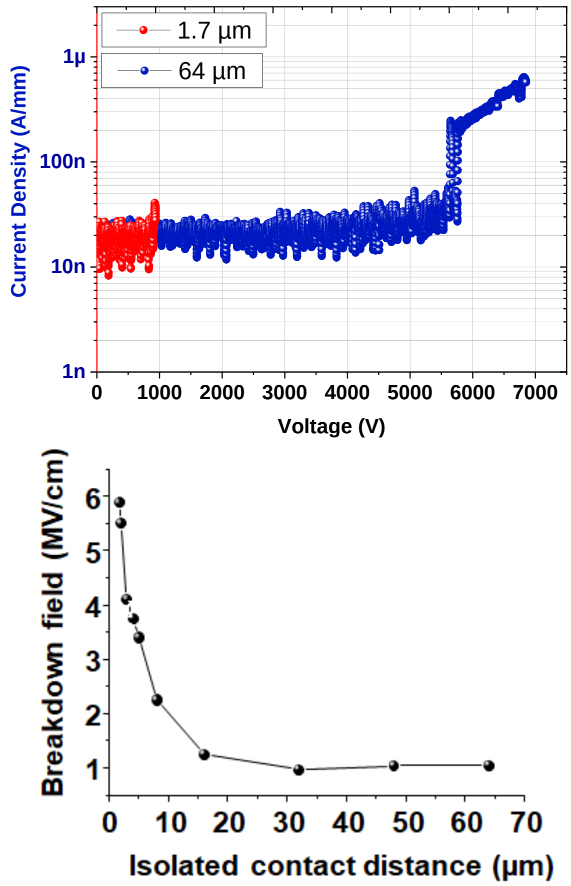

Fig. 3 : *Buffer BV and breakdown field for various contact distances of AlN/AlGaN/AlN HEMTs*

III. Results and Discussion

Buffer BV on isolated contacts for various distances appears in Fig. 3. It can be noticed that the buffer breakdown reaches about 1000V with low leakage current for a spacing as low as 1.7 µm, which corresponds to a remarkable breakdown field close to 6 MV/cm. For larger spacing, significant lateral buffer BV up to 7 kV has been measured, using a Keysight B1505A with N1268A Ultra High Voltage Expander. It can be pointed out that the BV drop for larger contact distances is mainly limited by the sapphire substrate, which has about 0.5 MV/cm breakdown strength.

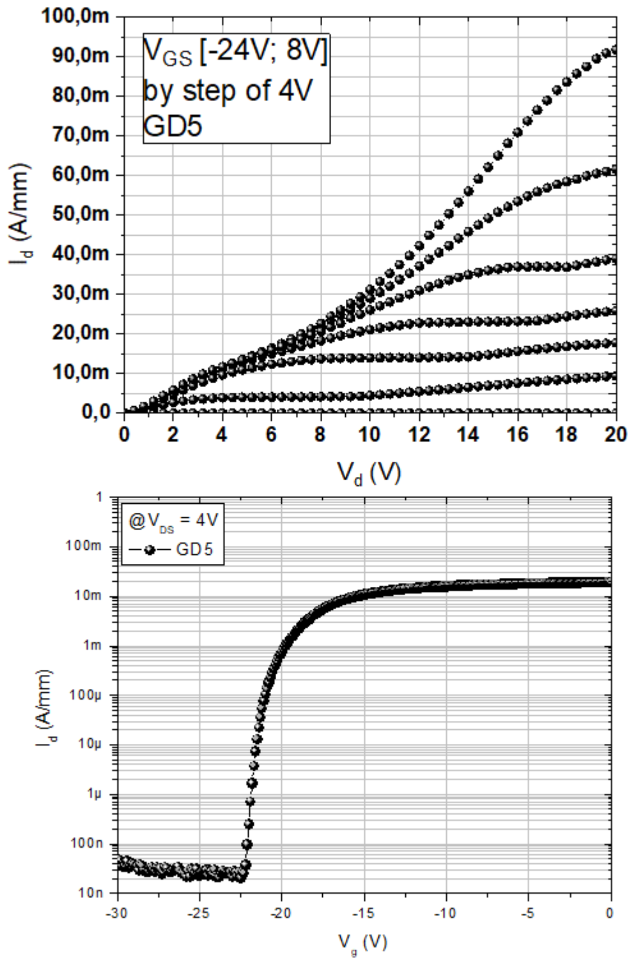

Fig. 4 : *Output characteristics and transfer characteristics for a gate-drain distance of 5µm of AlN/AlGaN/AlN HEMTs*

DC characteristics show fully functional devices (Fig 4). Although the ohmic contacts are quite poor, a maximum current density above 90 mA/mm with an off-state leakage current around 20 nA/mm has been obtained on devices with gate width/length = 50µm/1.5µm and gate-to-drain spacing (L_{GD}) of 5 µm (yielding an I_{ON}/I_{OFF} ratio close to 10^6). Strong pinch-off and no punch-through effects are observed owing to the efficient AlN back barrier. Low leakage current is obtained without the use of field plates confirming that tunneling mechanisms are not present in Al-rich transistors. In general, Al-rich transistors are less prone to gate leakage than

AlGaN/GaN HEMTs. The corresponding specific on-resistance R_{ON} ranges from 5.5 to 9.5 mΩ.cm^2 for the various transistor designs. Finally, Fig 5 show the 3-terminal BV as a function of the transistor gate-drain distance measured at V_{GS} = -25 V. Despite the rather high defect density, a record BV of 4500V with an off-state leakage current below 0.1 µA/mm is achieved for AlGaN-based channel HEMTs. It can be noticed that low gate-drain of 5 µm yields a breakdown field of 3.5 MV/cm, which is well-beyond that of SiC and GaN devices.

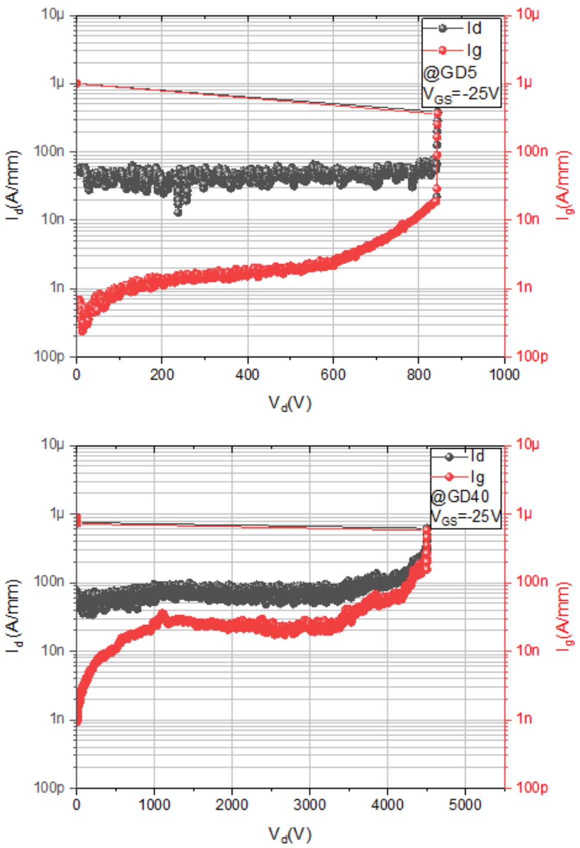

Fig. 5: *3-terminal off-state BV for various GD distances of AlN/AlGaN/AlN HEMTs*

IV. Conclusions

In summary, Al-rich AlGaN channel combined with AlN material offers great potential as the material of choice for the next generation of transistors for power switching applications. We have shown the possibility to operate at high voltage using an AlN/AlGaN/AlN heterostructure with 50% Al content into the channel. This resulted in an increase in the critical electric field as compared to more standard GAN HEMTs. Further study of the breakdown mechanisms may offer insight toward increasing breakdown fields in Al-rich transistors.

Although epitaxial growth efforts have mainly been conducted on sapphire substrates, AlN may be the long-term best substrate for Al-rich transistors, in spite of its immaturity. Its advantages include a better thermal conductivity and a better crystalline quality due to near lattice-matched growth conditions for $Al_xGa_{1-x}N$ with large x.

Acknowledgment

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