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ABSTRACT

The rapidly increasing power demand, downsizing of power electronics and material specific limitation of silicon has led to development of AlGaN/GaN heterostructures. Commercial GaN power devices are best available for radio frequency (RF) and high voltage switching applications. Emerging $Al_xGa_{1-x}N$ channel based heterostructures are promising to enhance the limits of next generation high voltage GaN power switching devices. In this work, we report on the study of electrical performance of AlGaN channel HEMTs-on-Silicon using various Al content. The fabricated devices exhibited outstanding buffer breakdown electric field above 2.5 MV/cm considering the submicron thin heterostructures grown on silicon substrate. Furthermore, we also experimentally demonstrate high temperature operation of fabricated AlGaN channel HEMTs.

1. Introduction

In the last decade, wide bandgap (WBG) materials such as GaN and SiC have been a game changer in semiconductor fabrication offering even faster, powerful and compact devices with respect to conventional silicon (Si) based devices. Compared to Si (0.3 MV/cm), GaN has approximately 11 × higher electric field strength (3.4 MV/cm) which is crucial for power devices [1]. In addition, the availability of polarization induced two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures made GaN channel HEMTs, a promising technology for high power and high frequency switching applications. Nowadays, GaN HEMTs with high switching frequency, reduced losses and high operational temperature are commercially available for voltages and currents up to 650V and 150A, respectively [2]. To enable multiple kilovolts operation of lateral transistors, ultra-wide bandgap (UWBG) materials (E_g >3.4 eV) are attractive since the blocking voltage capabilities scale with the material bandgap. UWBG such as AlGaN, AlN, diamond, β-Ga_2O_3 show promising material properties that can revolutionize the development of next generation of power electronics. Doping diamond and β-Ga_2O_3 based transistors still need to be controlled, as this drastically affects the overall breakdown strength of the material. On the other hand, $Al_xGa_{1-x}N$ gives control over Al composition offering a bandgap range up to 6eV, therefore critically improving the electric breakdown strength [3]. Furthermore, properties of spontaneous and piezoelectric polarization can be exploited, which enables the development of heterostructures aiming for superior breakdown voltage and low on-state resistance [4]. One of the major challenge for fabrication of AlGaN channel HEMTs is to optimize source-drain ohmic contacts to achieve high current density especially when using higher Al mole fraction in the channel [5]. The first AlGaN channel HEMTs were reported in 2008 by Nanjo et al., with AlGaN channel composed of 20% Al and 40% into the barrier layer yielding a maximum drain current of 130 mA/mm at a gate voltage $V_{GS} = +2V$ using sapphire substrate [6]. They later developed AlGaN channel HEMTs-on-sapphire with remarkable breakdown voltage of 1650V for 10 μm gate-drain spacing (L_{GD}) [7]. $Al_{0.86}Ga_{0.14}N/Al_{0.51}Ga_{0.49}N$ HEMT grown on freestanding AlN substrate demonstrated by Tokuda et al. in 2010, have shown breakdown voltage of 1800 V for $L_{GD} = 15\mu m$ with a maximum drain current density of 25.2 mA/mm [8]. In 2011, Hashimoto et al. demonstrated high 2DEG carrier concentration of 2.48×10^{13} cm^{-2} in $Al_{0.89}Ga_{0.11}N/Al_{0.51}Ga_{0.49}N$ HEMT

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fabricated on sapphire and AlN substrate [9]. AlN/$Al_{0.85}Ga_{0.15}N$ HEMT-on-sapphire were developed in 2016 by *Baca et al.*, showing low gate leakage and resulting in high I_{on}/I_{off} current ratio greater than 10^7 together with a breakdown voltage of 800V [10]. Performance of $Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N$ HEMT-on-sapphire substrate characterized over −50 °C to 200 °C temperature range is shown by *Baca et al.* in 2017, thus proving the benefit in terms of temperature stability [11]. In 2019, Douglas et al. illustrated enhancement-mode $Al_{0.45}Ga_{0.55}N/Al_{0.30}Ga_{0.70}N$ HEMTs with a p-$Al_{0.30}Ga_{0.70}N$ gate with a threshold voltage of +0.3 V for a gate length of 3 μm [12]. *Razzak et al.* showed design of compositionally graded drain-source contacts for $Al_{0.75}Ga_{0.25}N$ channel HEMTs-on-AlN, exhibiting maximum drain current density of 635 mA/mm with low contact resistance of 3.3×10^{-5} Ω cm^2 [13]. In 2021, *Abid et al.* demonstrated AlN/$Al_{0.50}Ga_{0.50}N$ HEMTs-on-sapphire with n+ GaN regrowth drain-source contacts combining a breakdown voltage of more than 4400V and a maximum drain current density of 100 mA/mm with a buffer breakdown field as high as 5 MV/cm [14]. Many researchers showed various techniques and approaches to fabricate state-of-the-art AlGaN channel HEMTs mainly on sapphire or bulk AlN substrate [15,16]. However, very few attempts have been realized on large diameter (up to 8 in.), cost-effective silicon substrate [17]. In this study, we demonstrate AlGaN channel HEMTs-on-silicon with two different structures using high Al composition into the barrier and channel layers and analyze their DC and high voltage characteristics, as well as high-temperature operation up to 600 K. To the best of our knowledge, this is the first report on high Al-content (> 50%) AlGaN channel HEMTs grown on silicon substrate.

2. Device fabrication and characterization

Submicron AlGaN / AlGaN heterostructures were grown by molecular beam epitaxy (MBE) on Si (111) substrate using a single 200 nm thin AlN nucleation layer as shown in Fig. 1 along with a 1 nm *in-situ* GaN cap on top. In the given structures, $Al_xGa_{1-x}N$ channels are composed of 30% and 60% Al as shown in sample_A and sample_B respectively. Fig. 2 shows the surface morphology of AlGaN channel HEMTs by atomic force microscopy (AFM) images over a scan area of 2 μm × 2 μm. These scans derives a root-mean-square roughness of 0.29 nm for 30% AlGaN (a.) and 0.79 nm for 60% AlGaN (b.) Al composition in the AlGaN channel, respectively. The roughness increases as expected with the Al-content into the channel but remains below 1 nm in both cases reflecting a decent crystal quality. Fig. 2(c.) shows (002) X-Ray Diffraction (XRD) profile cover angles of 33–37° along the omega axis. We can see the shift in diffraction angle while moving from 30% to 60% AlGaN channel suggesting increment of compressive strain in the channel. However, interestingly the FWHM shows improvement in crystal quality while moving from 30% to 60% AlGaN channel, which can be supported by the reduction of lattice mismatch with the AlN nucleation.

Drain and source contacts were fabricated by partially etching the AlGaN barrier followed by e-beam evaporation of Ti/Al/Ni/Au metal stack with a 15 s wet etch in BOE solution prior to the metallization. Subsequently, optimum rapid thermal annealing (RTA) of these devices has been set to 875 °C. The gate-drain (L_{GD}) and gate-source spacing (L_{GS}) are (5 to 40) μm and 2.5 μm, respectively. 220 nm thick mesa isolation is achieved by ICP etching technique. Plasma enhanced chemical vapor deposition of 30 nm thick SiN aided to the passivation of the device surface while used as a gate dielectric. Finally, 220 nm Ni/Au metal stack is evaporated on top of SiN to fabricate gate electrodes with 3 μm gate lengths, yielding metal insulator semiconductor (MIS) - HEMTs.

3. Experimental results and discussion

Hall Effect and resistivity measurements were realized by Van der Pauw method. Electrical measurements were carried out using a Keysight N1268A Ultra High Voltage Expander Unit (UHVU) operating in conjunction with a Keysight B1505A Power Device Analyzer / Curve Tracer. The buffer breakdown measurements were carried out with the samples immersed in Fluorinert FC-40 to avoid arching in air. The samples were mounted on a thermal stage inside a cryostat for variable temperature measurements. Their DC measurements were performed with a Keithley 2612B Source Measure Unit in dark environment, with temperature range from 300 K to 600 K.

The output transfer characteristics of fabricated devices show fully functional MIS-HEMTs with low off-state leakage in both samples and on-state current in agreement with sheet resistances and related contact resistances (see Table I). The output characteristics are measured at a drain-source voltage (V_{DS}) of 4V for $L_{GD} = 5$ μm as shown in Fig. 3(a) and (b.). Considering sample_A, TLM measurements results in R_C of 4.3 Ω mm with I_{Dmax} up to 90 mA/mm as shown in Fig. 3(c) for V_{GS} from −10 V to +4 V. As the drain-source contacts to sample_B showed non-ohmic behavior, the I_{Dmax} was limited to 17 mA/mm as shown in Fig. 3(d), in agreement with reported results in the literature by other research groups [15,18]. Selective regrowth has been proven to solve this issue to a large extent [14] and local implantation could also be used when using high Al-content AlGaN channels.

Fig. 4 shows the buffer breakdown electric field behavior of the fabricated AlGaN channel HEMTs for various two-terminal contact spacing. The electrical measurements were performed with 100 × 100 μm mesa isolated contact patterns. The total stack thickness of 650 nm was considered assuming the electric field distribution behavior to be

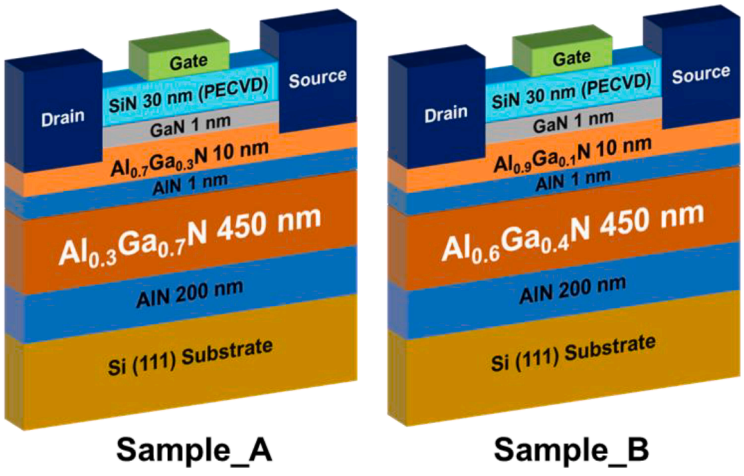


Fig. 1. Schematic illustration of AlGaN channel HEMTs with different Al composition.

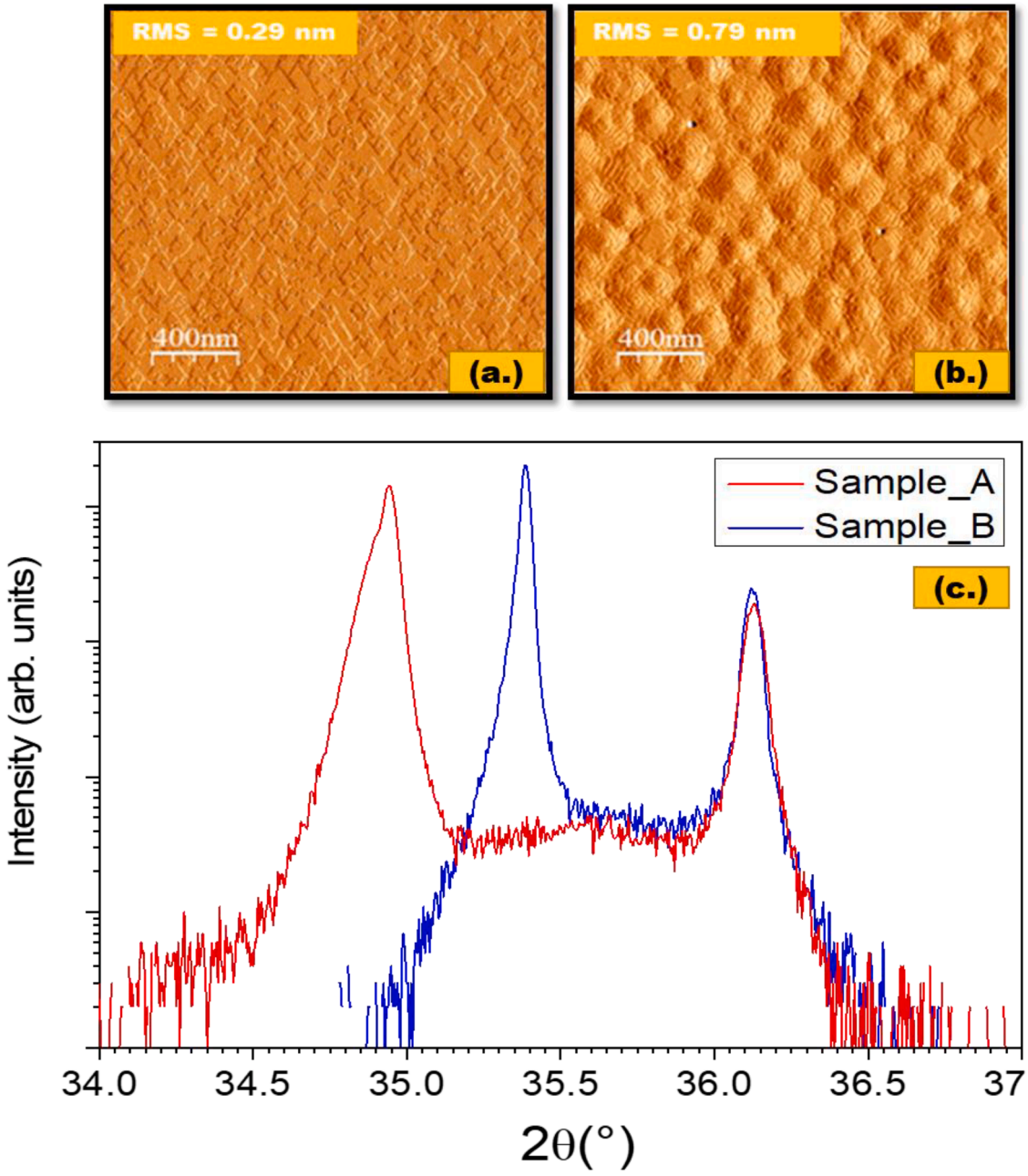


Fig. 2. AFM scans for heterostructures with (a.)30% AlGaN channel, (b.) 60%AlGaN channel and (c.) XRD 2θ-ω scans for AlGaN channel HEMTs.

Table I
Hall Effect measurements of AlGaN channel MIS-HEMTs.

Samples	Sheet Resistance [kΩ/□]	Electron Mobility [cm^2/V.s]	2DEG Concentration [1/cm^2]
Sample_A	1.8	323	1.1×10^{13}
Sample_B	7.3	137	6.3×10^{12}

consistent for small lateral contact spacing. We observe a drastic increase of the buffer breakdown field from 0.8 MV/cm to 2.54 MV/cm while changing the Al content from 30% to 60% into the $Al_XGa_{1-X}N$ channel for a contact spacing of 1μm. In all cases, the buffer breakdown voltage saturation is limited by the electron injection into the silicon substrate. However, this saturation is observed for 30% AlGaN channel transistors at 3μm contact spacing. As vertical breakdown voltage measurements in these thin heterostructures grown on silicon are consistently below 100 V in both cases, we attributed the large lateral 2-terminal breakdown voltage improvement to the wider 60% AlGaN bandgap as compared to 30% AlGaN. Thus, higher Al content into the AlGaN channel enables to benefit from significant breakdown field down to submicron gate-drain spacing. This is an attractive property in view of reducing the device dimensions for lateral power switching HEMTs.

The blocking voltage advantage with higher Al content into the channel is also reflected at the transistor level. Indeed, Fig. 5 (a.) depicts the off-state 3-terminal breakdown voltage at $V_{GS} = -12$ V for transistors with a gate-drain spacing of 5μm. The Al-rich AlGaN channel HEMTs showed excellent voltage handling compared to 30% AlGaN channel considering the submicron thick heterostructures. In particular, a significant drop of leakage current and related increase of the blocking voltage is observed while increasing the Al content. This is confirmed for different gate-drain spacing as shown in Fig. 5 (b.) and attributed to the wider bandgap of Al-rich AlGaN channels. It can be pointed out that the

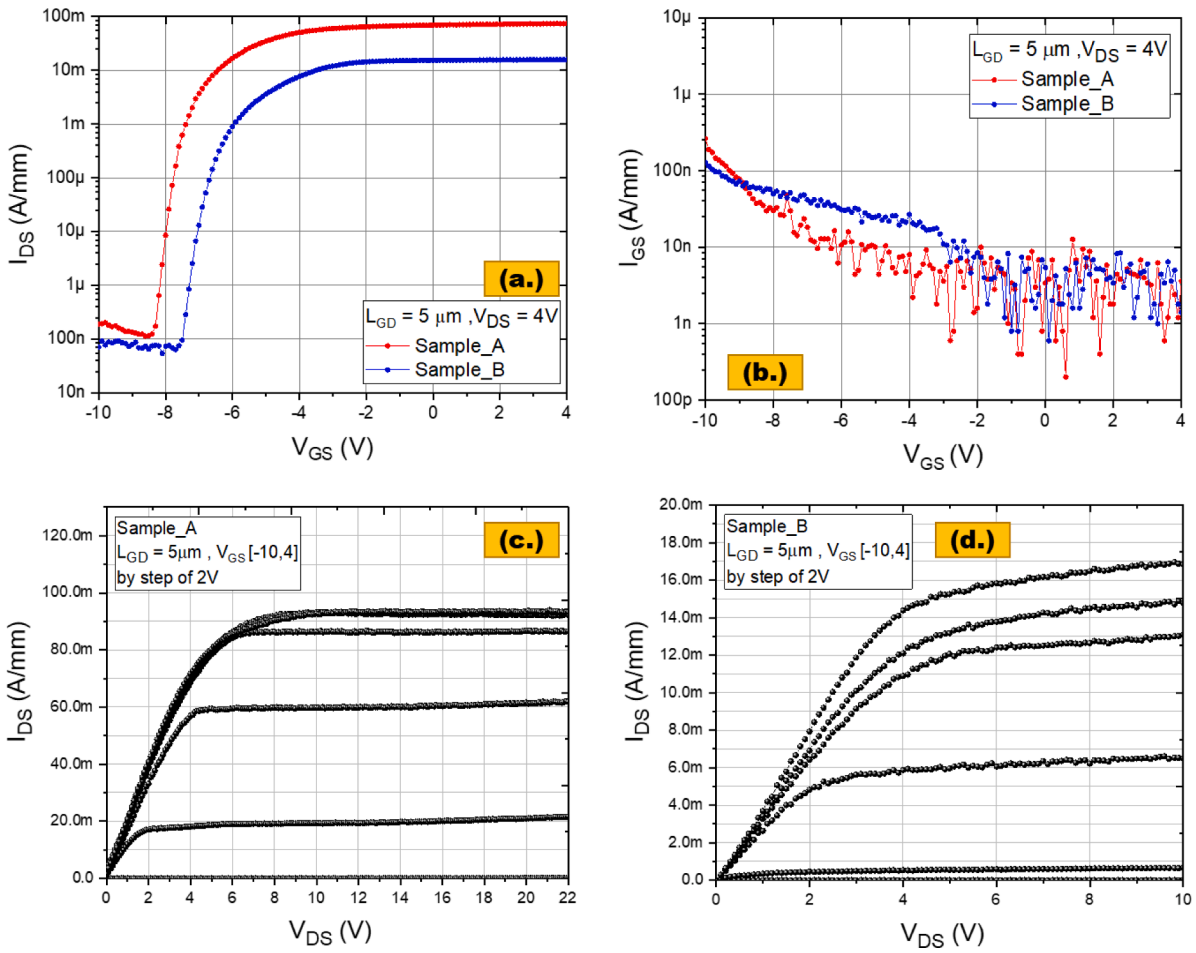


Fig. 3. (a.) AlGaN channel HEMT transfer characteristics at V_{DS} = 4V (b.) I_g-V_g characteristics (c.) Id-Vd characteristics of Sample_A (d.) Id-Vd characteristics of Sample_B for 5 µm gate-drain spacing.

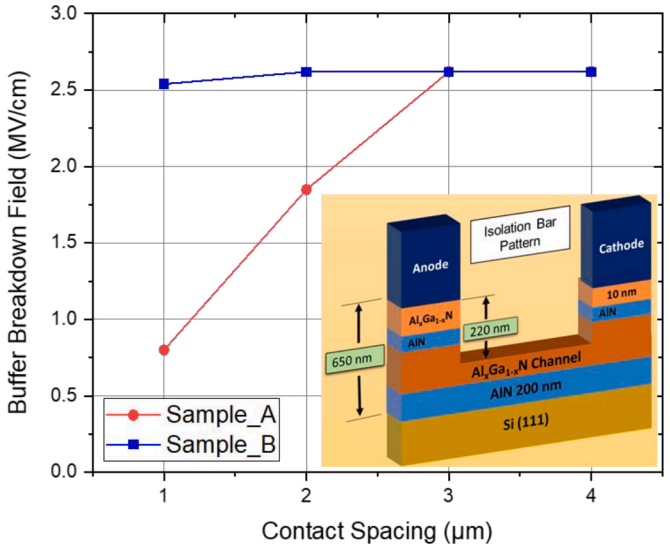


Fig. 4. Two-terminal buffer breakdown field as a function of contact spacing.

breakdown voltage is limited to less than 200V since the structure total thickness is well below 1 µm, which prevails the electron injection at the AlN/Si interface. This limitation can be mitigated by inserting Al-rich AlGaN buffer layers to eventually improve the electric field distribution inside the structure resulting in multiple kilovolts blocking voltages.

The temperature output characteristics of 30% AlGaN channel HEMTs showed good temperature performance with increase in off-state leakage current of 170 nA/mm at 300 K to more than 2 µA/mm at 600 K as shown in Fig. 6 (a.). The 60% AlGaN channel HEMTs showed off-state leakage characteristics with current density up to 500nA/mm at 600K with I_{on}/I_{off} ratio $> 10^5$, (Fig. 6 (b.)) demonstrating excellent high temperature operation. Fig. 7(a.) quantifies the change in maximum drain current density for the various AlGaN channel HEMTs while increasing the temperature from 300 K to 600 K. The drop in I_{DSmax} is about 6% while increasing the temperature from 300 K to 600 K for 30% AlGaN channel HEMTs. The off-state leakage current density evolution from 300K to 600K shows about one-fold increase in leakage current density for both AlGaN channel HEMTs portraying its superior thermal stability on silicon substrate. The already reported high temperature operation benefit from AlGaN channel HEMTs is thus further verified when grown on silicon substrate.

3. Conclusion

In summary, we have demonstrated fully functional AlGaN/AlGaN MIS-HEMTs on silicon substrate with 0.3 and 0.6 Al mole fraction into the channel. AlGaN channel devices showed remarkable buffer breakdown field > 2.5 MV/cm, which is almost 8 × higher than critical electric field of silicon. A key finding of this study is the possibility to achieve high buffer breakdown field whilst significantly reducing the device dimensions down to submicron gate-drain distances. These results show the promise of moving beyond conventional GaN devices to develop highly scaled components that can operate in high voltage

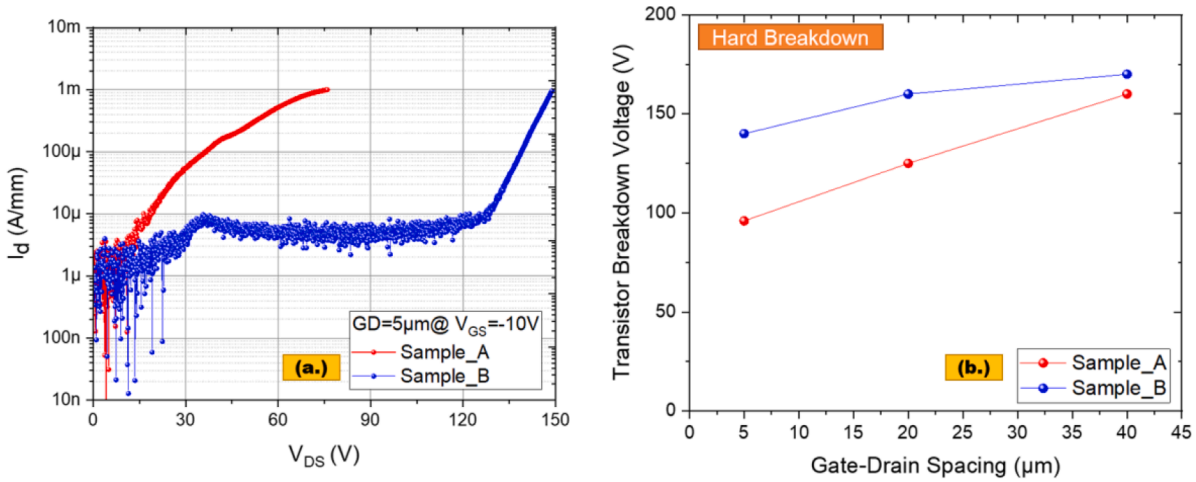


Fig. 5. (a.) Off-state 3-terminal breakdown voltage for transistors at $V_{GS} = -10$ V with a gate-drain spacing of 5 μm, (b.) for various gate-drain spacing.

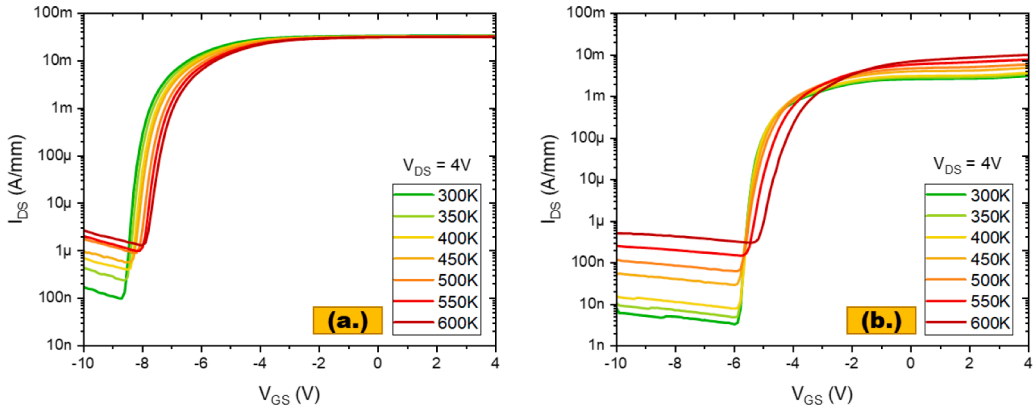


Fig. 6. Temperature DC Characteristics for (a.)30% AlGaN channel and (b.)60% AlGaN channel.

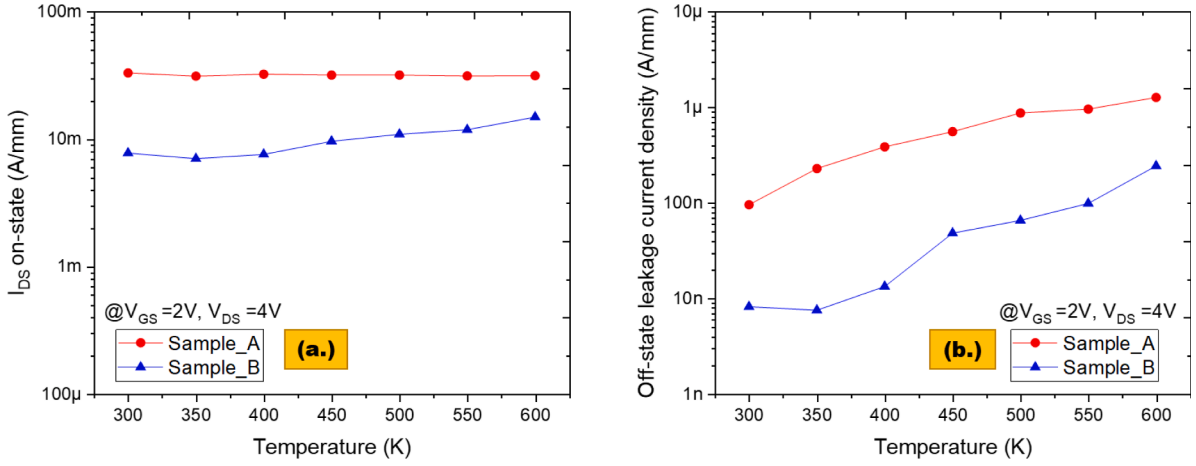


Fig. 7. (a.) Change in maximum drain current density from 300 K to 600 K temperature operation for various AlGaN channel HEMTs. (b.) off-state leakage current density vs temperature for the various AlGaN channel HEMTs on Si.

range. Furthermore, the temperature DC characteristics show superior thermal stability in Al-rich AlGaN channel devices, paving the way for developing extreme power electronics suitable for harsh environment on silicon substrate as shown in costly GaN and AlN bulk substrates. The main challenge will be the reduction of ohmic contacts to Al-rich $Al_xGa_{1-x}N$ channel in order to ensure power devices with high breakdown voltage and low on-state resistances. The implementation of thick Al-rich buffer layers can be employed to produce multiple kilovolts AlGaN channel HEMTs on large silicon substrate wafers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

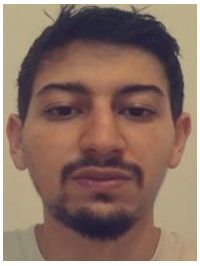
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Farid Medjdoub is a CNRS senior scientist and leads a research team WIND focused on wide bandgap material and devices at IEMN in France. He received his Ph.D. in Electrical engineering from the University of Lille in 2004. Then, he moved to the University of Ulm in Germany as a research associate before joining IMEC as a senior scientist in 2008. Multiple state-of-the-art results have been realized in the frame of his work. Among others, world record thermal stability up to 1000 °C for a field effect transistor, best combination of cut-off frequency / breakdown voltage or highest lateral GaN-on-silicon breakdown voltage using a local substrate removal have been achieved.