Ultra-thin Body GaN-on-Insulator nFETs and pFETs: Towards III-Nitride Complementary Logic

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Ultra-thin body (UTB) devices with tight electrostatic and quantum confinement of charge carriers have been well developed in highly scaled silicon CMOS technology. For adopting such advanced methods, III-nitrides can benefit immensely from epitaxial AlN as the substrate platform, in contrast to conventional GaN-based substrate platform. With its large polarization charge, wide bandgap and large band offsets, AlN induces the maximal carrier densities while providing the best confinement for nitride channels of all compositions. Such devices stand also to benefit from the symmetry of electronic polarization: high density *hole gases* can be generated in much the same way as the high density 2DEG in GaN HEMTs, thus enabling p-channel FETs on the same material platform in a logical manner. The AlN/GaN heterojunctions where mobile carriers are located are epitaxial, and excellent transport properties are expected as opposed to the rougher oxide-semiconductor interfaces. Furthermore, AlN is an excellent electrical insulator but simultaneously an excellent thermal conductor, which makes it highly attractive to act as back-barrier and to lower junction temperatures in high power devices by efficient heat dissipation. There have been reports on relaxed GaN n-channel FETs (nFETs) on AlN [1, 2] and III-nitride based p-channel field effect transistors (pFETs) [3, 4]. All the prior work uses relaxed GaN as the channel, and strained GaN channels on AlN have not been explored before. In this work we demonstrate UTB GaN nFETs [5] and pFETs on AlN grown by molecular beam epitaxy (MBE) as the first step towards complementary logic and high power applications.

Fig.1 shows the schematic heterostructures and band diagrams of (a) conventional AlN/GaN HEMTs, (b) AlN/GaN/AlN nFETs and (c) GaN/AlN pFETs. The wide bandgap AlN serves as back barrier. The nFETs consist of strained GaN channels sandwiched in strain-free AlN barriers, and pFETs are derived from nFETs by simply removing the top AlN barrier. At this stage, Mg doping is used in the channel for holes, a step that can be dispensed of in the future.

High-resolution X-ray diffraction measurements on the nFET sample shown in Fig.2 (a) clearly show the strained GaN channel peak, and the inset AFM image shows smooth surface morphology. Abrupt binary GaN/AlN heterojunction of the pFET sample is observed in Z-contrast scanning TEM image in Fig.2 (b). The schematic device structure is shown in Fig.3 for (a) nFETs and (b) pFETs. MBE regrowth of heavily Si-doped n^+-GaN has been used for ohmic contacts for nFETs. The pFET employ Schottky gates of Ni/Au directly deposited on the p-type GaN channel without annealing. In the pFET heterostructure, we measure by Hall effect mobile hole gas density of $\sim 5 \times 10^{13}$ cm^{-2}, enable by polarization. This is the highest hole gas density measured in *all* semiconductor heterostructures to date.

Complementary device performance of a 2.1-μm-long nFET and a 2.4-μm-long pFET is shown in Fig. 4. In these preliminary demonstrations, the nFETs show ~3 order of magnitude of current modulation, but due to leakage at Schottky gate and high hole density, the pFET is not completely pinched off at $V_{GS} = +2$ V as shown in Fig.4 (a). The transfer characteristics are shown in (b) linear scale and (c) semi-log scale. The capacitance-voltage (C-V) curves measured at 1 MHz are shown in Fig. 5. For nFET heterostructures a circular Schottky diode is measured while for pFET heterostructures the gate-to-source capacitor of a 2.6-μm-long pFET is used. This first demonstration of polarization-induced complementary FET behavior, in spite of its current shortcomings, paves the way for vast improvement by scaling and gate stack advances. Temperature dependent family IVs of a 2.6-μm-long pFET are plotted in Fig. 5 for (a) T = 77 K, (b) T = 300 K and (c) T = 400 K. The drain is biased up to 50 V with L_{sd} = 5.2 μm. The drive current and transconductance increase as temperature is lowered, as signatures of polarization-induced p-type doping.

In conclusion, we report novel complementary UTB strained GaN nFETs and pFETs on an AlN substrate platform. The symmetry of polarization fields is exploited to create high-density mobile electron and hole gases in strained channels on the same substrate. Low hole mobilities lead to asymmetric device characteristics, a problem that can be addressed effectively by exploiting the epitaxial strain. The device results provide promising ways for scaling in vertical direction (i.e. perpendicular to channel direction) for III-nitride heterostructures, and a compelling case for complementary logic applications.

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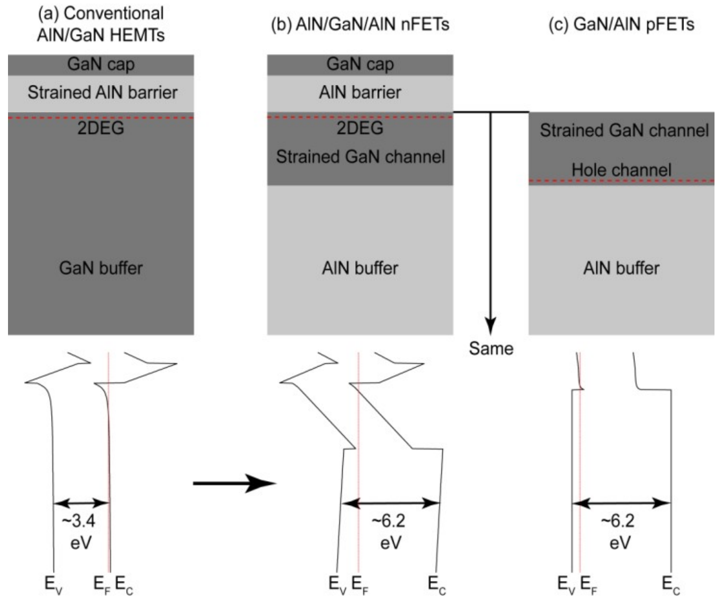

Fig.1 Schematic heterostructures and band diagrams of (a) conventional AlN/GaN HEMTs, (b) AlN/GaN/AlN nFETs and (c) GaN/AlN pFETs.

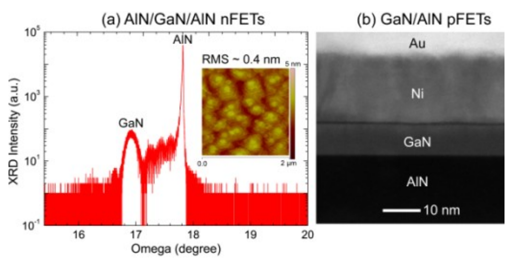

Fig.2 (a) High-resolution XRD and AFM (inset) scans on nFETs; (b) Z-contrast STEM image of pFETs under the gate.

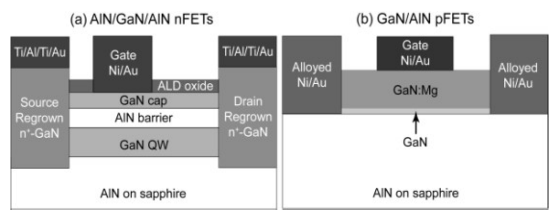

Fig.3 Schematic device structures of (a) nFETs and (b) pFETs.

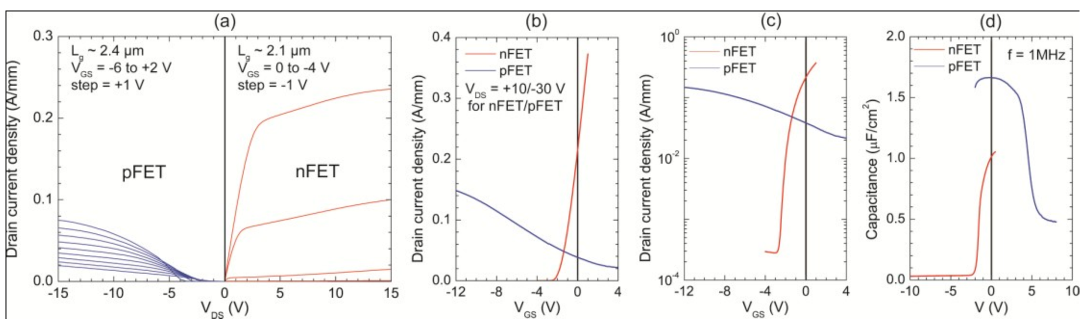

Fig.4 (a) Output characteristics; (b) linear plots of transfer curves; (c) semi-log plots of transfer curves; (d) C-V plots of a circular Schottky diode for n-channel, and gate-to-source capacitor of a pFET for p-channel.

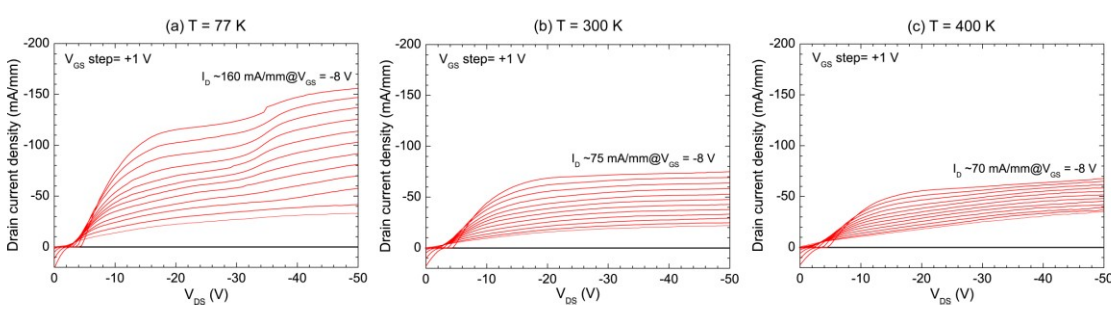

Fig.5 Output characteristics for a pFET with L_g = 2.6 μm at (a) T = 77 K, (b) T = 300 K and (c) T = 400 K.