Top-Down AlN/GaN Enhancement- & Depletion-mode Nanoribbon HEMTs

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III-V Nitride HEMTs are currently being intensively investigated for both depletion- and enhancement mode operation at high powers and high frequencies. Among the various methods that can render the polarization-doped HEMTs enhancement-mode, the least investigated are those that exploit 3-D nanoscale geometrical electrostatic effects. Recently, bottom-up grown GaN nanowire MISFETs have shown respectable depletion-mode device performance [1]. However, the handling of isolated nanowires is technologically challenging. Here, we demonstrate that by combining conventional epitaxially grown AlN/GaN HEMT structures with top-down nanoribbon fabrication, both E-mode and D-mode HEMTs with high performance can be realized in a facile manner, and allow integration on the same substrates. In addition to the ease of realizing E-mode and D-mode devices, these top-down nanoribbon HEMTs also take advantage of the superior electrostatics of wrap-gates and quasi-1D charge transport for high performance.

The AlN/GaN HEMT structures used here are grown by Molecular Beam Epitaxy. The polarization-induced 2DEGs exhibit densities in the $\sim10^{13}/\mathrm{cm}^2$ range, and RT mobilities close to $\sim1300\ \mathrm{cm}^2/\mathrm{Vs}$. Thin nanoribbons (see Figure 1) are fabricated by E-Beam Lithography and etching after the Ohmic contact formation. By controlling the nanoribbon-width w_y, and by using a high-k-oxide/Ni/Au gate metal stack wrapped around the top and the side-walls of the nanoribbon, the conducting channel can either be present for wide channels, or absent due to sidewall depletion in narrow channels (Fig 1). Thus, by lithographic adjustment of the ribbon-widths we realize enhancement- and depletion-mode operation, enabling the integration of ED-mode logic on a single chip.

The inset in Fig. 2 (left) shows a SEM picture of 50 nm deep etched nanoribbons between the source and drain contacts. DC measurements on an AlN/GaN nanoribbon HFET with a 3 μm long gate and w_y~70 nm show a maximum output current density of ~ 500 mA/mm (Fig. 3 left) and a positive threshold voltage of $V_{th} = +0.3$ V in the transfer-characteristics (Fig. 2 left). A subthreshold-slope of 80 mV/decade was measured on a 2 μm gate device indicating superior gate electrostatics and promise for digital logic-circuits. DC-output current densities of ~ 1000 mA/mm of a depletion-mode AlN/GaN HFET with a 2 μm long gate and w_y>200 nm integrated on the same wafer were demonstrated (Fig. 3 right). Thus, the sidewall-depletion of nanoribbons is highly effective in forming both E-and D-mode HEMTs.

In addition to the device characteristics presented, the top-down AlN/GaN nanoribbon HEMTs also exhibit high on/off ratios ($>10^4$), which makes them highly attractive for digital operation at high temperatures. The geometry of the devices allows for array structures for increasing the current drive and possible vertical stacking of the polarization-induced channels. Further device optimization in the geometry and reduction of the access- and contact-resistance of the top-down nanoribbon HEMT structures will enable the design of the first integrated AlN/GaN nanoribbon HEMT logic devices.

[1] S. Vandenbrouck, K. Madjour, D. Theron, Y. Dong, Y. Li, C. M. Leiber, and C. Gaquiere, "12 GHz f_{max} GaN/AlN/AlGaN Nanowire MISFET", IEEE EDL, 30(4), p. 322, 2009.

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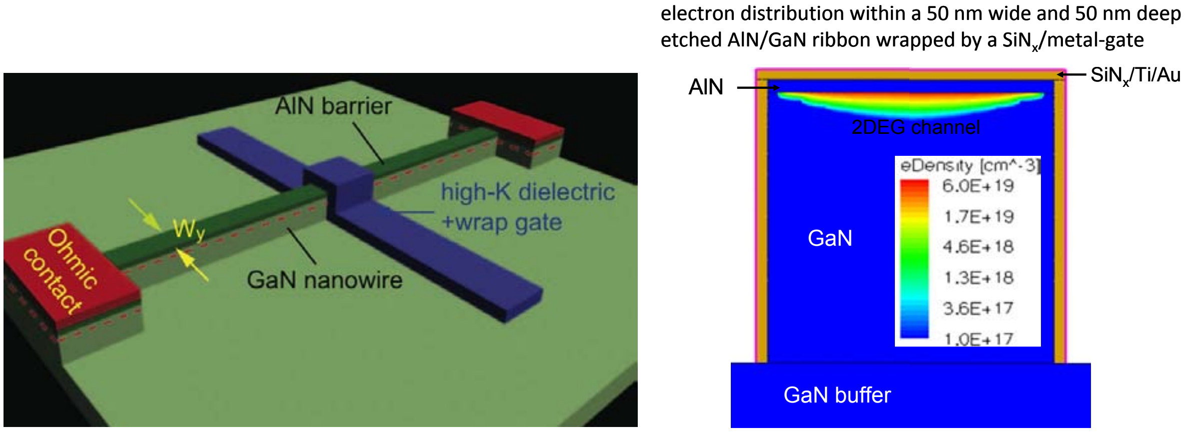

Fig. 1. Schematic of a nanoribbon HEMT with ribbon-width w_y between of source- and drain-contacts wrapped by a gate with gate-oxide (l.), Simulation of electron density distribution in a 50 nm wide AlN/GaN ribbon wrapped by SiN_x/metal gate showing depletion of the conducting channel from the sidewall gates (r.)

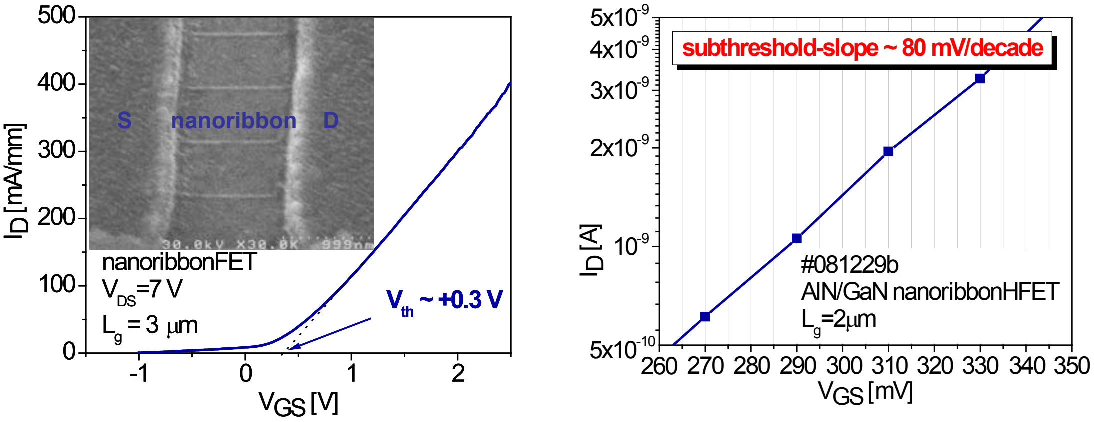

Fig. 2. Transfer-characteristics of an enhancement-mode nanoribbon device with 3 μm gate-length and +0.3 V threshold-voltage (l.), inset: SEM of 50 nm deep etched AlN/GaN ribbons between source and drain contacts (l.), best subthreshold-slope of 80 mV/decade was measured for a nanoribbon device with 2 μm gate-length (r.)

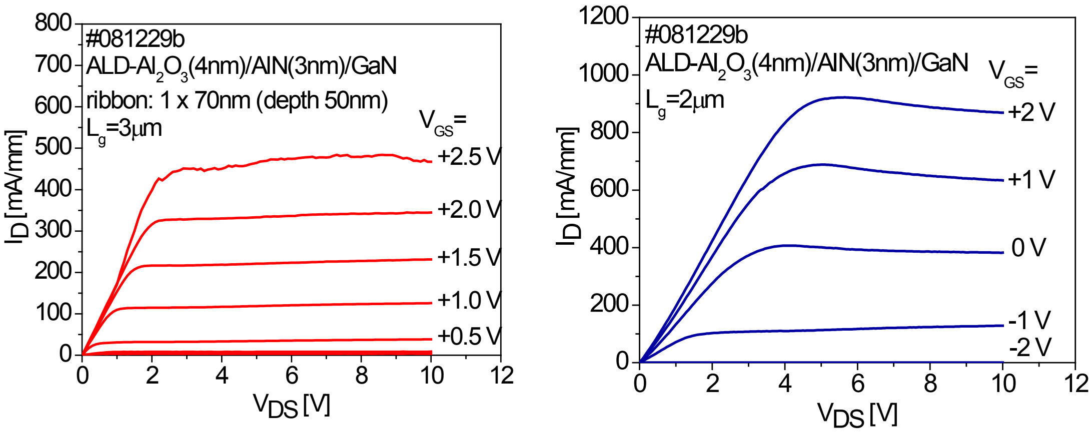

Fig. 3. DC-output characteristics of an enhancement-mode AlN/GaN nanoribbonHFET with a 3 μm long gate (l.), DC-output characteristics of a depletion-mode AlN/GaN HFET with 2 μm long gate integrated on the same wafer like E-mode nanoribbon device (r.)