Student Paper

Ultra-scaled AlN/GaN Enhancement-& Depletion-mode Nanoribbon HEMTs

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Due to its high electron density (> 1x 10^{13} cm^{-2}) and high electron mobility (> 1000 cm^2/V.s), AlN/GaN high-electron mobility transistors (HEMTs) present themselves as attractive candidates for high power and high speed applications. In order to continue increasing their high frequency performance, gate length (L_g) needs to be scaled downed below 30 nm. According to Jessen et al. [1], the aspect ratio of gate length (L_g) to barrier thickness (t_g) for AlGaN/GaN HEMT without back barriers should be greater than 15 to avoid the short channel effects. For ultrascaled HEMTs, the barrier thickness includes the thickness of Al(GaIn)N and a possible gate dielectric. To maintain this ratio with a reasonable two-dimensional electron gas (2DEG) channel and low gate leakage, the gate length will be limited to be ~ 75 nm assuming a 2 nm AlN and a 3 nm gate dielectric. In this paper, a 3-dimensional nano-ribbon AlN/GaN HEMT structure is studied by simulations in comparison with experiments as a candidate for mitigating the short channel effects. By reducing the ribbon width, the device threshold voltage can also be continuously tuned from depletion mode to enhancement mode.

Shown in Fig 1 are the device structure schematic and the nano-ribbon channel cross-section under the gate in the Synopsys TCAD simulation. The structure consists of a 2.3 nm AlN barrier with a 150 nm GaN (N_D ~ 1x10^{13} cm^{-3}) on top of 2 um semi-insulating GaN substrate. The gate length is 50 nm and the separation between gate to source/drain is 100 nm. Three ribbon widths have been simulated: 20, 35, and 50 nm, and the ribbon depth was fixed at 170 nm. Because of the polarization effect, a 2DEG of 1.3x10^{13} cm^{-2} is induced at the AlN/GaN interface in contact with air. Low field mobility is chosen to be 1350 cm^2/Vs as determined in the Hall effect measurement in samples with the same layer structure grown by molecular beam epitaxy (MBE) at the University of Notre Dame [2]. In this simulation, hydrodynamic model is used for electron transport. A conventional AlGaN/GaN HEMT is also simulated with the same physical models and a good agreement is achieved with the experimental results [3].

The transfer characteristics of simulated 2D planar HEMTs and 3D nanoribbon HEMTs are shown in Fig. 2 (left). A near ideal subthreshold slope of 70 mV/decade was observed for the 2D HEMT with 250 nm gate length, consistent with one of the best values of ~ 64 mV/decade reported from experimental observations [4]. The subthreshold slope increased to 192 mV/decade as the gate length reduced to 50 nm, which indicates existence of short channel effects. For 3D nanoribbon devices, subthreshold slopes of 68 mV/decade and 62 mV/decade were extracted for 50 nm and 500 nm gate length HEMTs, respectively. If normalized to the 50 nm top gate width (i.e. the ribbon width) a simulated DC-output current density of ~1200 mA/mm could be obtained in nanoribbon HEMTs with a 50 nm gate length, shown in Fig. 2 (right).

By controlling the ribbon width, pinch off voltage shift was achieved in simulations. This same trend has been also observed in the experiment results [5, 6], as shown in Fig. 3. The necessary ribbon width for enhancement mode operation was found to be different between the experimental and simulation results. This discrepancy could be potentially contributed to the following factors: (1) strain modification in the ribbon due to edge strain relaxation as well as from the device processing, (2) surface depletion of ribbon side walls due to plasma damage, and (3) interface traps at the oxide/nitride interfaces and etc. The encouraging current density of up to 500 mA/mm and a subthreshold slope of 80 mV/decade have been experimentally measured in the AlN/GaN nanoribbon devices [5], suggesting an interesting platform for alleviating short channel effects in III- V nitride based HEMTs as well as achieving E-mode operation.

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References

[1] G. H. Jessen, R. Fitch, J. Gillespie, G. Via, A. Crespo, D. Langley, D. Denninghoff, M. Trejo, Jr., and E. Heller. *IEEE transactions on electron devices*, vol.54, no. 10, pp. page 2589/s, 2007.

[2]Yu Cao and Debdeep Jena. *Applied Physics letter*, vol.90, no.18, 2007.

[3]A. Chini, R. coffie, G. Meneghesso, E. Zanoni, D. Buttari, S. Heikman, S. Keller and U.K. Mishra. *Electronics letters*, vol.39, no.7, pp. page 625, 2003.

[4] Jinwook W. Chung, John C. Roberts, Edwin L. Piner, and Tomas Palacios. *IEEE Electron Device Letters*, vol.29, no.11, page 1196, November 2008.

[5]Tom Zimmermann, Yu Cao, Jia Guo, Xiangning Luo, Debdeep Jena and Huili （Grace） Xing. *Device Research Conferenece*, 2009.

[6] Takahiro Tamura, Junji Kotani, Seiya Kasai and Tamotsu Hashizume. *Applied Physics Express*, vol.1, 2008.

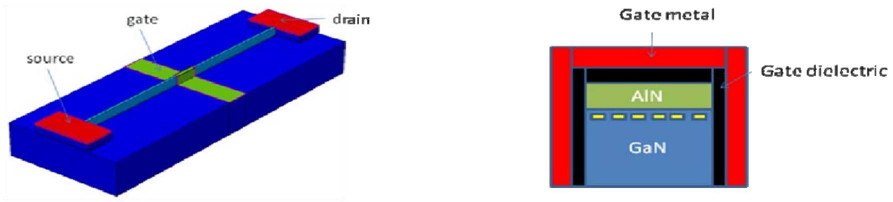

Fig 1 (Left) Schematic of a nanoribbon HEMT, (Right) cross section of the nanoribbon structure

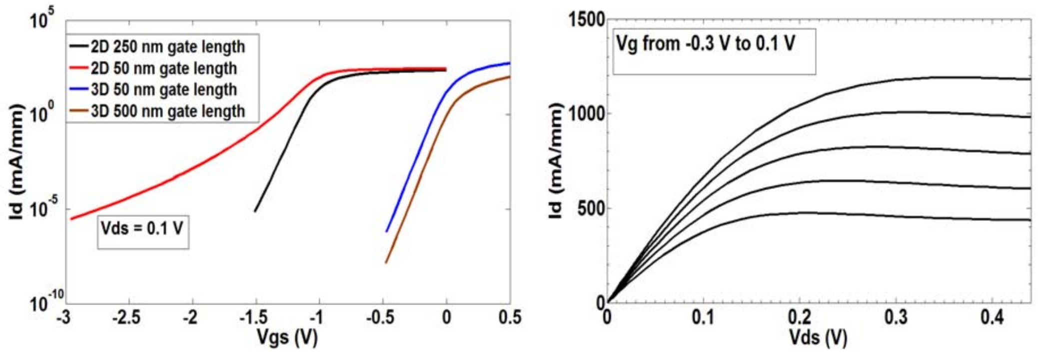

Fig. 2. (Left) Simulated transfer characteristics of 2D planar HEMTs with 50 nm and 250 nm gate length and 3D nanoribbon HEMTs with 50 nm and 500 nm gate length, (right) simulated I-V characteristics of a depletion-mode AlN/GaN HEMT with a 50 nm gate length and a 50 nm ribbon width.

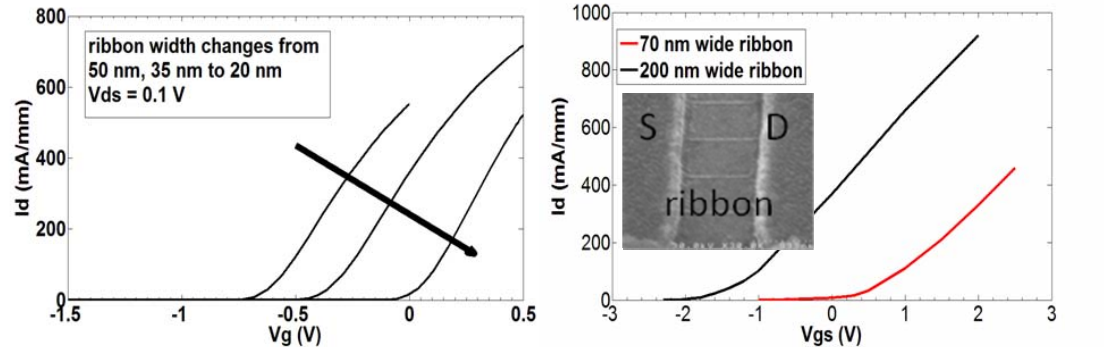

Fig. 3. (Left) Simulation results of the transfer-characteristics of nanoribbon HEMTs with different ribbon widths, (Right) experimental results of transfer-characteristics of 70 nm and 200 nm wide ribbon HEMTs with + 0.3 V and -1.6 V threshold voltages, respectively. Inset: SEM of AlN/GaN ribbons between source and drain contacts