Ultra-scaled GaN HEMTs with AlN barrier

Huili (Grace) Xing[1*], Edward Beam[5], Yu Cao[2], David Deen[3], Tian Fang[1], Faiza Faria[1], Patrick Fay[1], Satyaki Ganguly[1], Xiang Gao[4], Jia Guo[1], Shiping Guo[4], Zongyang Hu[1], Prem Kumar[1], Oleg Laboutin[2], Guowang Li[1], Wayne Johnson[2], Andrew Ketterson[5], Paul Saunier[5], Michael Schuette[5], Berardi SensaleRodriguez[1], Gregory Snider[1], Jai Verma[1], Ronghua Wang[1], Yuanzheng Yue[1], Tom Zimmermann[1], Debdeep Jena[1*]

[1]Electrical Engineering Department, University of Notre Dame, IN 46556 USA. [2]Kopin Corporation, Taunton, MA 02780 USA [3]Now at SVT associates, MN USA. [4]IQE RF LLC. Somerset, NJ 08873 USA. [5]Triquint Semiconductor, Inc., Richardson, TX 75080 USA
E-mail address: hxing@nd.edu, djena@nd.edu

As GaN-based high electron mobility transistors (HEMTs) are scaled down for higher speed operation, electrostatic control of the device as well as the ohmic contacts need to be extremely carefully engineered. Without going to FINFET or nanowire – like designs for ultimate electrostatic control, the most attractive device structure for the conventional planar single-gate layout is a 2-dimensional electron gas (2DEG) sufficiently confined in a quantum-well with both the top and back barriers made of wider bandgap materials than the channel. This paradigm of heterostructure design has been successfully applied in GaAs and InAs channel HEMTs in the past 30 years, especially in pseudomorphic HEMTs (pHEMTs) where a narrow bandgap channel with a higher carrier mobility is compressively strained between lattice-matched top and bottom barriers. For GaN HEMTs, this implies the most suitable structure for ultrascaled devices is AlN/InN/AlN. However, this structure is nearly impossible to grow owing to the large lattice mismatch between InN and AlN. Another attractive choice is AlN/GaN/AlN. But, high quality AlN substrates or templates with low trap densities are not yet readily available. Given the constraints of available high quality heterostructures at present, AlN/GaN-channel, $Al_{x>0.5}GaN$/AlN/GaN-channel and (nearly) lattice-matched-InAlN/AlN/GaN-channel/AlGaN HEMTs have been investigated by various groups including our own. A thin layer of AlN (~ 1 nm) between the barrier and channel is necessary in these structures to suppress alloy scattering that is much higher in GaN family than GaAs and InAs material systems. In this paper, an overview is presented on the progress made by our team on ultra-scaled GaN HEMTs with AlN barrier.

AlN barrier was considered as an insulator in a GaN MISFET similar to SiO_2/Si for the first time by Kawai et al [1]. With the polarization effects and carrier transport properties in GaN better understood, sub-1nm AlN was employed as an interlayer inserted between AlGaN and GaN to improve low field mobility in HEMTs [2]. Majority of the AlN/GaN HEMT heterostructures reported in the literature were grown by molecular beam epitaxy (MBE) [3-6] since MBE enables growth of high quality epitaxy at lower temperatures than metalorganic chemical vapor deposition (MOCVD) and low growth temperature helps manage the high strain built up in such heterostructures with large lattice-match and/or thermal expansion mismatch with substrates. More recently, MOCVD grown AlN/GaN HEMTs were also reported by using an in-situ SiN cap to keep AlN from cracking [7]. Studies from various groups showed very different 2DEG density dependence on the AlN barrier thickness though the structures were all nominally unintentionally doped thus the polarization charges and surface states dictate n_s. For instance, for an AlN thickness of ~ 3 nm, some [3,5-6] observed $n_s > 2\times10^{13}$ cm^{-2} with mobility $u >$ 1000 cm^2/Vs while some [4,7] observed $n_s<1\times10^{13}$ cm^{-2} with mobility $u <$ 1000 cm^2/Vs. This indicates the polarization effect, being the strongest in AlN/GaN, is very sensitive to the growth conditions as well as how the surface is terminated. One of the possible culprits is thought to be incorporation of oxygen occupying the nitrogen site [8] since Al tends to bond to O – a well-known phenomenon in all Al-containing semiconductor materials. However, further systematic studies are necessary to understand the role of O and H in Al(GaIn)N.

For D-mode HEMTs, we have investigated both AlN (<5nm)/GaN [6, 9-11], $Al_{0.75}GaN$/AlN/GaN [12] and (nearly) lattice-matched InAl(Ga)N(≤10nm)/AlN/GaN HEMTs [13-15, 19] with non-recess etched gate since recess-etch generally degrades the 2DEG mobility when the remaining barrier thickness is within 5-10 nm. Work function engineering was demonstrated to shift HEMT V_{th} commensurate with the gate metal work function difference. Drain output current density $I_{dmax} > 2$ A/mm, extrinsic $g_m > 920$ mS/mm, $V_{br} > 50$ V and $f_t > 220$ GHz have been demonstrated. DC-RF dispersion characterized by pulsed I-V measurements is < 10%, the lowest ever reported among all GaN-HEMTs with $f_t > 200$ GHz to date thanks to the novel passivation scheme developed in our laboratory: dielectric-free passivation (DFP).

For E-mode HEMTs, we have investigated AlN(<1.5 nm)/GaN HEMTs with the AlN thickness being subcritical in terms of n_s formation [16] and lattice-matched InAlN/AlN/GaN HEMTs with a gate-recess process selectively stopped at 1-nm AlN [17,18]. I_{dmax} ~ 2 A/mm, extrinsic g_m > 800 mS/mm, V_{br} > 30 V and f_t > 180 GHz have been demonstrated. An impressive I_{on}/I_{off} ratio of 10^{12} was achieved, the highest ever reported in all GaN-based HEMTs.

The E/D-mode inverters based on both subcritical barrier AlN/GaN and gate-recessed InAlN/AlN/GaN HEMTs have been also reported [16,19]. With a 144 nm-gate length, 15.3 ps/stage delays was measured in the monolithically integrated E/D-mode 51-stage ring oscillators. Though in this first demonstration the bias of the transistors was not at peak f_t thus resulting in compromised ring speed, it suggested these E/D HEMTs are very promising for mixed-signal applications.

Finally, AlN/GaN/AlN HEMTs were for the first time grown on AlN/sapphire templates and subsequently processed [20]. To ensure there is a conducting channel, a GaN channel as thick as 10 nm was grown and the entire structure is unintentionally doped. The Hall effect measurement showed a carrier concentration of 1.66 x 10^{13} cm^{-2} with a mobility of 540 cm2/Vs. The devices showed a drain output current of 0.14 A/mm despite of an extraordinarily high contact resistance by alloying of > 3 ohm-mm.

Formation of reliably low contact resistances in AlN containing barrier HEMTs is indeed challenging. Generally speaking, the lowest contact resistance of alloyed contacts is 0.2 ohm-mm, which is also very sensitive to the annealing conditions thus difficult to reproduce. Regrowth contacts on metal-face GaN HEMTs have been demonstrated both by our team and HRL [16, 21-22] with a regrowth/2-DEG interface resistance on the order of 0.05 ohm-mm. These advances in low resistance contact formation will enable us to explore the intrinsic properties of AlN barrier GaN HEMTs, which are largely obscured by the high parasitics present in current devices.

[1] Kawai, H; et al. IEE Electron. Lett. 34(6), 592, 1998.
[2] Shen, L., et al. IEEE Electron Device Lett., 22(10), 457, 2001.
[3] Smorchkova, I.P.; et al. Appl. Phys. Lett., 77(24), 3998, 2000.
[4] Higashiwaki, M. et al. IEEE Electron Device Lett., 17(9), 719, 2006.
[5] Cao, Y., D. Jena et al. Appl. Phys. Lett. 90(18), 182112, 2007.
[6] Zimmermann ,T., D. Jena and H.G. Xing et al. IEEE Electron Device Lett. 29(7), 661, 2008.
[7] Medjdoub, F. et al. IEEE Electron Device Lett., on line, 2011.
[8] Higashiwaki, M. et al. Appl. Phys. Lett., 97, 222104, 2010.
[9] Zimmermann, T. D. Jena and H.G. Xing et al. Phys. Stat. Sol. (c) 5(6), 2030, 2008
[10] Zimmermann, T. D. Jena and H.G. Xing et al. Int. J. of High Speed Electr. and Systems. 19, 153, 2009.
[11] Deen D. D. Jena and H.G. Xing et al. Phys. Stat. Sol. (c), 5(6), 2047, 2008
[12] Li, G. D. Jena and H.G. Xing et al. IEEE Electron Device Lett., 31(9), 954, 2010
[13] Wang, R.; D. Jena and H.G. Xing et al. IEEE Electron Device Lett., 32(8), 2011
[14] Wang, R.; D. Jena and H.G. Xing et al. IEEE Electron Device Lett., on line, 2011
[16] Guo, J.; D. Jena and H.G. Xing et al. Phys. Stat. Sol.(a), on line, 2011
[17] Zimmermann ,T.; D. Jena and H.G. Xing et al. Phys. Stat. Sol. (a), on line, 2011.
[15] Wang, R.; D. Jena and H.G. Xing et al. IEEE Electron Device Lett., 31(12), 1383, 2010
[18] Wang, R.; D. Jena and H.G. Xing et al. IEEE Electron Device Lett., 32(3), 309, 2011
[19] Yong, T.; D. Jena and H.G. Xing et al. IEDM 2010
[20] Li, G. D. Jena and H.G. Xing et al. ISCS 2011
[21] Milosavljevic, I.; et al. IEEE Dev. Res. Conf. 2010.
[22] Guo, J.; D. Jena and H.G. Xing et al. WOCSEMMAD, Savannah, GA, USA, 2011.