Gallium Nitride Based HEMT Devices

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Outline

- Introduction
- Device Structure and Materials Issues
  - Structure and origin of 2DEG
  - Key elements to determine the performance
  - Ways to improve the device
- Fabrication and Performance
- Concluding Remarks

Introduction

<u>Current FET issues</u>: high power; high temperature; high frequency

<u>GaN materials</u>: wide band gap; high saturation velocity; high breakdown electron field; high sheet carrier density

Reference: R. J. Trew, SiC and GaN Transistors, Proc. IEEE 90 (2002) 1032-1047.

Introduction

Advantages of GaN

Some of the commercial and military markets that can be targeted by GaN

Reference: U.K. Mishra; AlGaN/GaN HEMTs: An overview of device operation and applications

Development of AlGaN/GaN HEMT devices

- The first AlGaN/GaN HEMT was introduced byAsif Khan in 1994.

Lg=0.25_m; I_{dss}=60mA/mm; g_m=27mS/mm; no microwave power density has been reported.

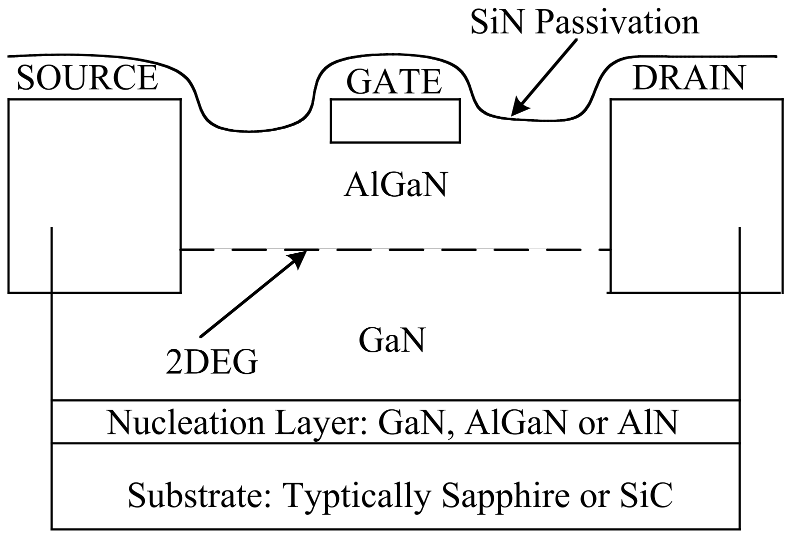
- Cornell; Cree; UCSB
- I_{dss}=1A/mm; g_m=270mS/mm;

power density~11W/mm; sheet carrier density~10^{13}/cm^2

Reference: M. Aslf Khan, J. N. Kuznia, et al, Appl. Phys. Lett., 65(9):1121

U.K. Mishra, AlGaN/GaN HEMTs: An overview of device operation and applications

Structure of Basic AlGaN/GaN HEMTs



- Even without intentionally doping the barrier layer, AlGaN/GaN can have high charge carrier density at the interface to form 2DEG, which is 10 times higher than that of conventional GaAs systems.
- This high density of 2-dimensional free electron gas is due to the piezoelectric and spontaneous polarization of GaN and AlGaN layers.

Reference: U.K. Mishra, AlGaN/GaN HEMTs: An overview of device operation and applications

2DEG in AlGaN/GaN HEMTs

- Polar nature of GaN and AlGaN
- Spontaneous polarization and piezoelectric polarization induce a net positive charge at the interface of AlGaN and GaN.
- The charge distribution is then composed of the polarization dipole $\pm Q$ and an opposing dipole comprising of a surface hole gas (ps) and a 2DEG at the hetero-interface

Reference: O. Ambacher, et al, J. Appl. Phys., 85 (6), 1999: 3222

U. K. Mishra, IEEE Lester Eastman Conference on High Performance Devices (2002: Newark, Delaware): P9

To acquire high power of the HEMT devices---Key issues

- high sheet charge density which needs maximized spontaneous and piezoelectric polarization
- electron mobility which requires the minimization of scattering centers due to dislocations
- electron velocity, demanding an reduced effective gate length
- low leakage in buffer, demanding highly resistive epilayers with low defect density
- breakdown voltage, requiring high quality material, proper device design and proper surface passivation
- thermal conductivity, necessary to remove the heat generated by devices

Reference: H. Xing, et al, J. Phys: Condens. Matter 13 (2002) 7139

To acquire high power of the HEMT devices---Key issues

- Optimize growth condition for high quality of GaN and AlGaN films

GaN was grown on MOCVD(~11W/mm), MBE (~8W/mm).

SiC and sapphire are used as substrates.

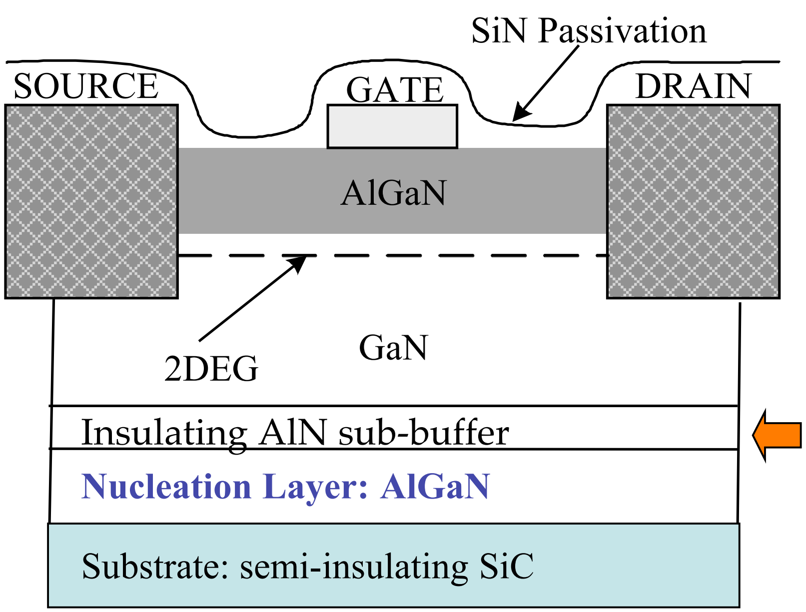
2-step growth (with nucleation layer) for GaN materials to reduce dislocation density and good quality.

To acquire high power of the HEMT devices---Key issues

- Sub-AlN buffer layer engineering (Cornell Univ.)

  If channel electrons are not well confined to the nitride structure, the fringing fields which penetrate the GaN buffer layer at pinch-off introduce significant substrate conduction at modest drain bias.

  This insulating AlN sub-buffer on the semi-insulating SiC substrate suppresses this parasitic conduction.



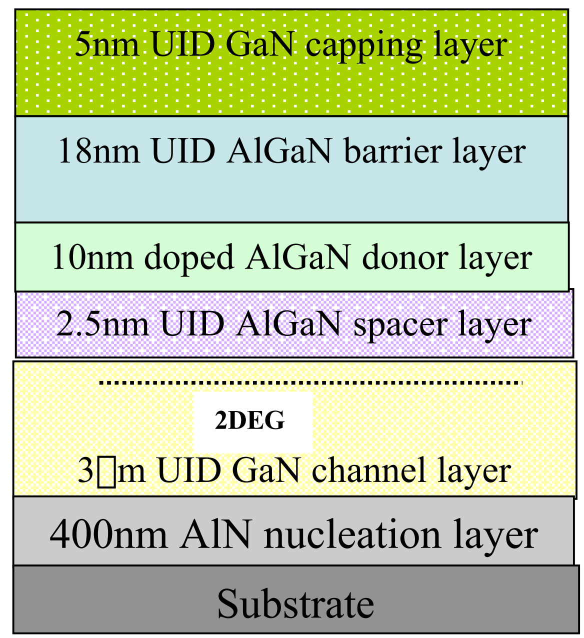
Power density~ 11.2 W/mm if AlN > 200nm

Sheet charge density~ 1.5_10^{13}cm^{-2}

Reference: J. R. Shealy, L.F. Eastman, et al, J. Phys.: Condens. Matter 14 (2002) 3499

To acquire high power of the HEMT devices---Key issues

- high Al-composition in $Al_xGa_{1-x}N$ alloy
  - increase the band discontinuity, which would improve the carrier confinement, and the stronger spontaneous polarization and the piezoelectric effects contribute to a higher sheet charge density in the channel. In addition, the higher band gap of the AlGaN layer promised a higher composite breakdown field.
  - The difficulty is grains and cracks will forms when high Al content.
  - Optimized Al-content -----35%



CREE

Power density~ 9.8 W/mm on SiC;

~6.5W/mm on sapphire

Sheet charge density~ 1.2_10^{13}cm^{-2}

Reference: Y. F. Wu, D. Kapolnek, J. P. Ibbetson, P. Parikh, B. P. Keller, and U. K. Mishra, *IEEE Trans. Elect. Dev.* **48**, 586 (2001); H. Xing, et al, J. Phys: Condens. Matter 13 (2002) 7139

To acquire high power of the HEMT devices---Key issues

Other approaches:

- Short gate length: to increase the electron velocity close to saturation, the saturation current was 1.13A/mm, g_m=240mS/mm.
- Thermal management: Flip-Chip bonding of AlGaN/GaN HEMT-on-sapphire onto AlN substrates (UCSB)

- UCSB-----AlGaN/GaN HEMT on sapphire substrates

  Flip-chip bonding

  Al content is 35%

  2-step growth to grow high quality of semi-insulating GaN film

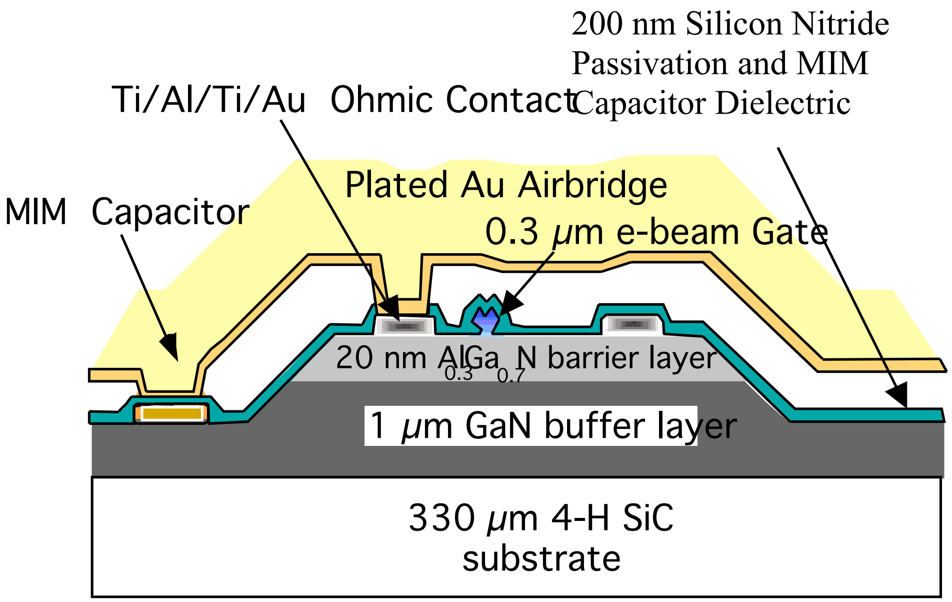
  Power density ~6.6W/mm (UCSB)

  Saturation current density: 1.2A/mm

  g_m=120mS/mm

Reference: S. Keller, Y. F. Wu, G. Parish, N. Ziang, J. J. Xu, B. P. Keller, S. P. DenBaars, and U. K. Mishra, *IEEE Trans. Elect. Dev.* **48**, 552 (2001); H. Xing, et al, J. Phys: Condens. Matter 13 (2002) 7139

Fabrication



Example from Cornell Univ.

- etched Mesa FETs and resistors
- Ti/Al/Ti/Au Ohmic Contacts
- 0.25 mm E-beam mushroom gates
- 20 nm PECVD Si_3N_4 Passivation/ capacitor dielectric
- Plated airbridges

Reference: Bruce M. Green

Concluding Remarks

- Achieved:

  1. High quality epi-layer with low defect density was prepared

  2. Techniques were developed to improve device performance

  3. Power density 11W/mm on SiC, and 6.6W/mm on sapphire

- remaining issues:

  1. Traps in the device: Electrons can be excited and captured in the traps between the gate and drain regions. The time constant for de-trapping is too long for these trapped electrons to follow the ac signal and hence they are not available for conduction in the on state. Thus limit the channel current and output power.

  2. The undoped GaN buffer layer introduces a significant output conductance from the short-channel effect, which introduces additional device heating during operation at large drain bias.

  3. The relative high cost and unanswered long-term reliability are still the issue for commercialization