

GaN HEMT and MMICs at Chalmers • - Challenges for microwave GaN HEMTs

NIKLAS RORSMAN

2020-01-16



Chalmers GaN HEMT activities

- 20 years of GaN HEMT research
- Industrial collaborations
 - Saab, Ericsson, UMS AG, SweGaN,....
- Early demonstration of GaN MMICs
- Activities
 - Material, device design, processing, small- and large-signal characterization, modelling, MMIC-processing (microstrip)

<https://saabgroup.com/media/stories/stories-listing/2015-3/leading-the-way-with-gallium-nitride-technology/>



to products for delivery in

defence and aviation industries, for the extended Giraffe surface radar. Saab is world leading in active radar and electronic warfare", Defence Systems.

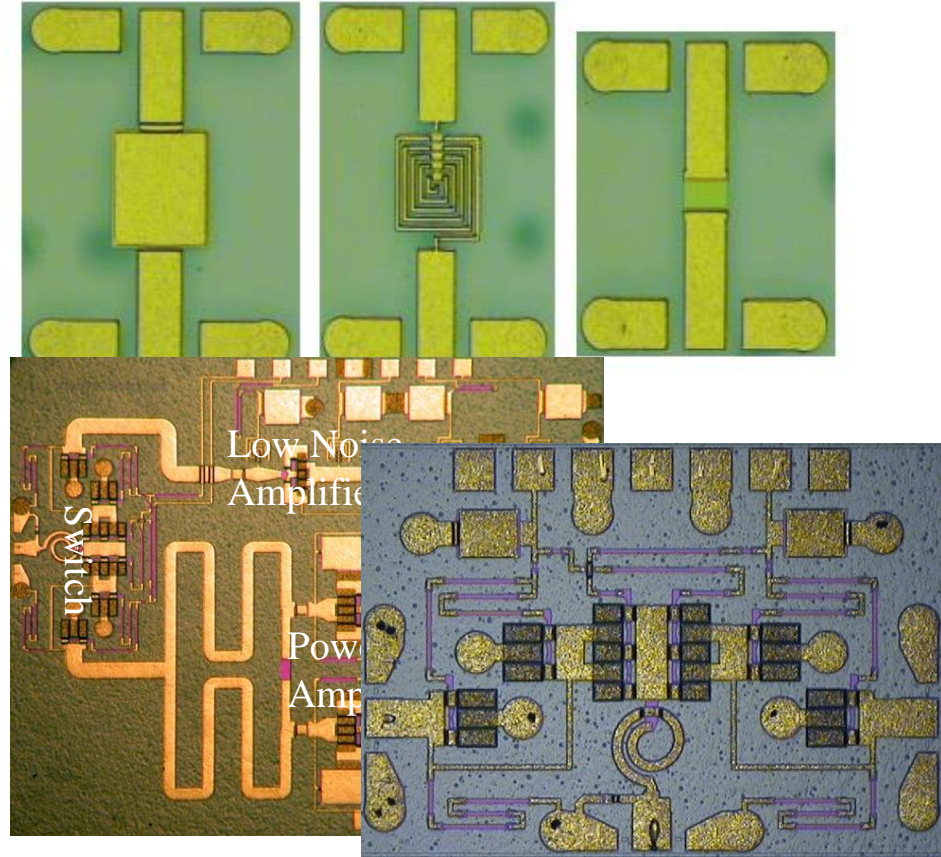
ment. Areas of use include LED-lights, microwave applications in the military of Saab's extended surface radar family, higher output power and is a more robust and higher reliability.

Saab will be one of the first to take this technology to the market, with Giraffe 4A set to be delivered in 2016.

Saab has been working with GaN for a number of years, with Chalmers university of technology and the Swedish Defence Materiel Administration (FMV) as important contributors in the long-term development of GaN. Saab is also participating in research programmes in the European Union.

Microstrip WBG MMIC Process

- All processes performed in-house
 - 15 mask layers
 - Combination of Laser writer/EBL/Contact lithography
- Chalmers WBG Design-kit (ver 2.11)
 - New design-kit available (Compatible with ADS 2017 and later versions)
- Processed on 3" or 4" epi wafers
- MIM-cap: SiN 200pF/mm², $V_{BD} > 150$ V
- Resistors: TaN 42Ω/□, TiN 10 Ω/□, semiconductor resistor (200-300 Ω/□)
- Inductors
- Transmission lines
- Via holes
- Examples of demonstrator circuits
 - Integrated GaN X-band Transceiver
 - Single pole, double throw (SPDT) switches
 -

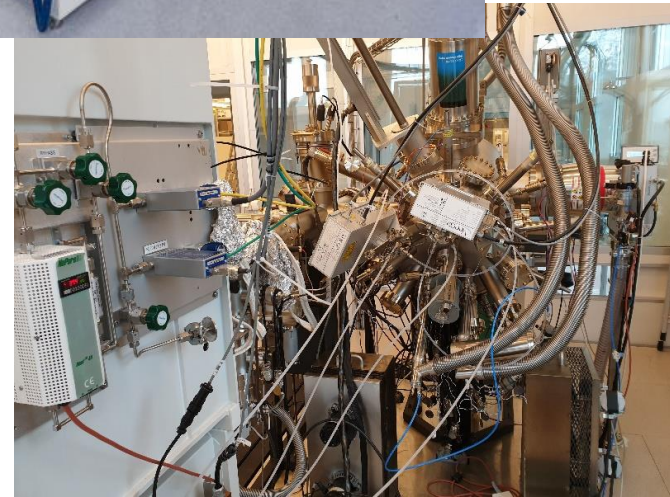


Current Chalmers goals

- High frequency (>100 GHz), low dispersion HEMTs and integrated circuits for wireless communication and sensor systems
 - Utilize advances in GaN HEMT technology to demonstrate power amplification at D-band

Growth of GaN HEMT structures

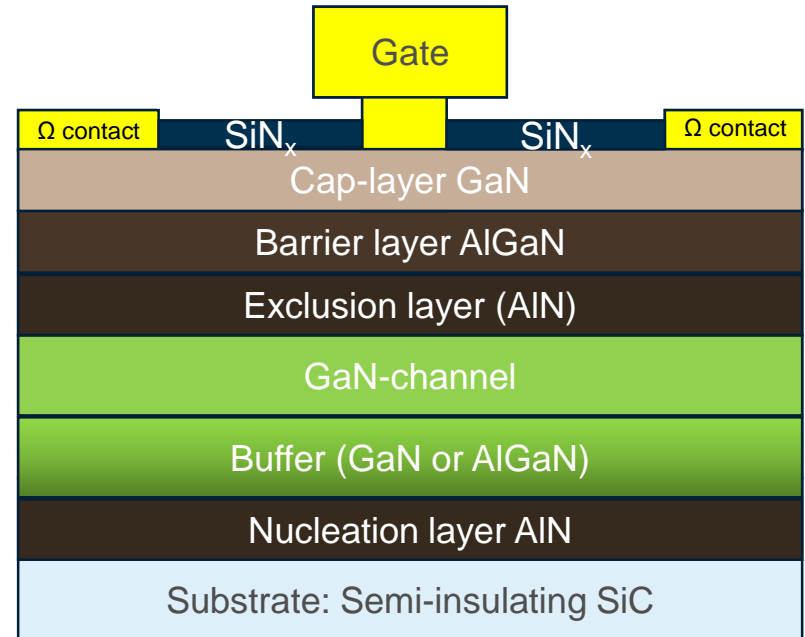
- GaN HEMT epiwafers generally grown by **Metal-Organic Chemical Vapor Deposition (MOCVD)**
 - Elements supplied by precursors in carrier gas
 - High crystal quality
 - High throughput
- An alternative method is **Plasma Assisted Molecular Beam Epitaxy (PA-MBE)**
 - No carrier gases or precursors, combined with ultra-high vacuum, result in higher purity
 - Decreased need for compensational doping
 - p-doping
 - Low throughput
 - Lower growth temperature
 - Allows for growth of In-containing HEMT structures
 - PA-MBE is a complementary growth method for exploring the intrinsic limitations of GaN electronics



CHALLENGES FOR GaN HEMT TECHNOLOGIES

- Electron trapping effects
 - Surface trapping
 - Passivation
 - Buffer trapping
 - Deep level doping
 - Back-barrier
- High frequency optimization
 - Ohmic contacts
 - Electron transport properties

The anatomy of GaN HEMTs



Downscaling for high frequency optimization

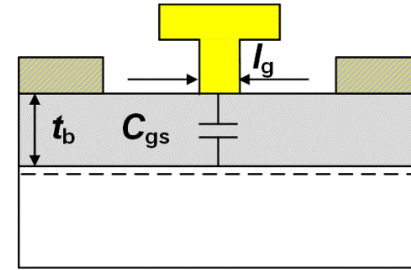
$$f_T \approx \frac{g_m}{2\pi C_{gs}} = \frac{v}{2\pi l_g}$$

$$f_{max} \approx \frac{f_T}{2\sqrt{(R_i + R_g + R_s)g_{ds} + 2\pi f_T C_{gd} R_g}}$$

$$C_{gs} \sim \frac{\epsilon}{t_B} l_g$$

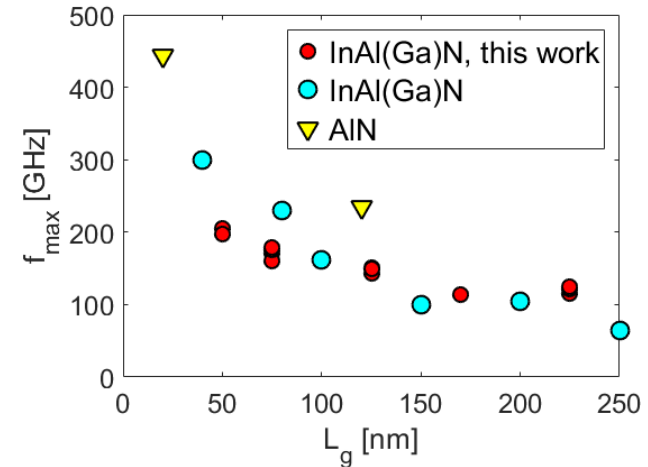
$$g_{ds} \sim \frac{q\mu n_s(t_B)}{l_g}$$

$$g_m \sim \frac{\epsilon}{t_B} v$$



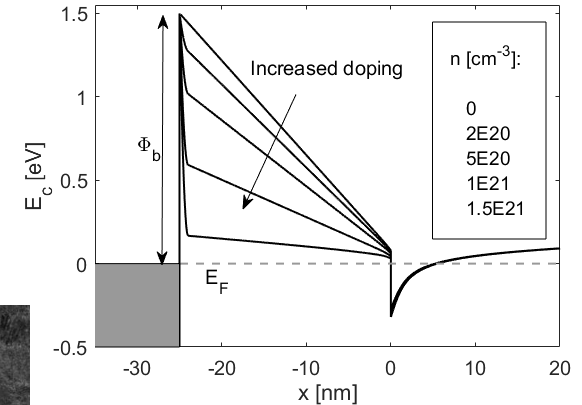
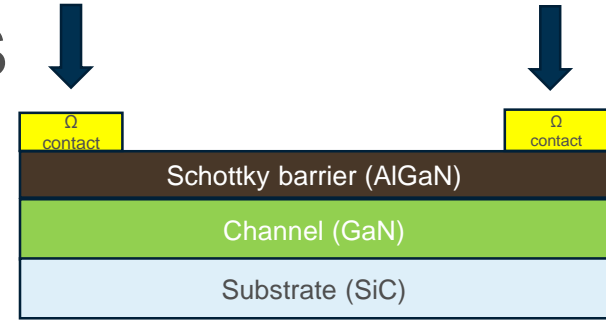
High frequency optimization

- Down-scaling the gate length (C_{gs})
- Down-scaling the barrier thickness (g_{ds} , g_m)
- Improve the electron confinement (g_{ds})
- Improve electron transport properties (g_m , f_T)
- Decreasing R_s (R_c , μ)

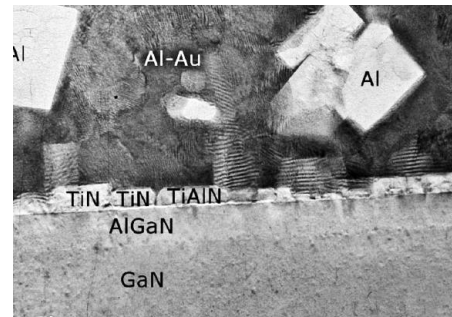


Decreasing R_s : Ohmic contacts

- Ohmic contacts on (Al)GaN are challenging due to the large bandgap
 - Large spread in reported values of R_c in the literature.
- Ohmic contacts are formed by creating a heavily doped region beneath the contact which promotes tunneling via band-bending
- Ohmic contacts conventionally based on Ti/Al/Ni/Au
 - Ti + N = TiN (detected by e.g. TEM or XRD)
 - N vacancies equivalent to n-doping
 - Annealed at high temperature ($>800^\circ\text{C}$)
 - Purple plague (AuAl alloy) formed
 - May affect sheet resistance

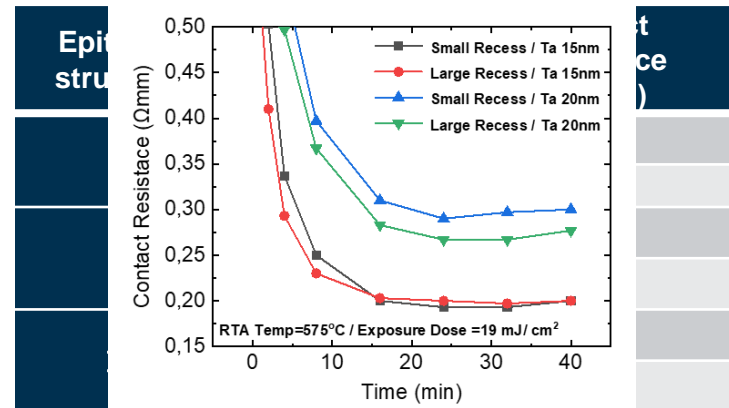
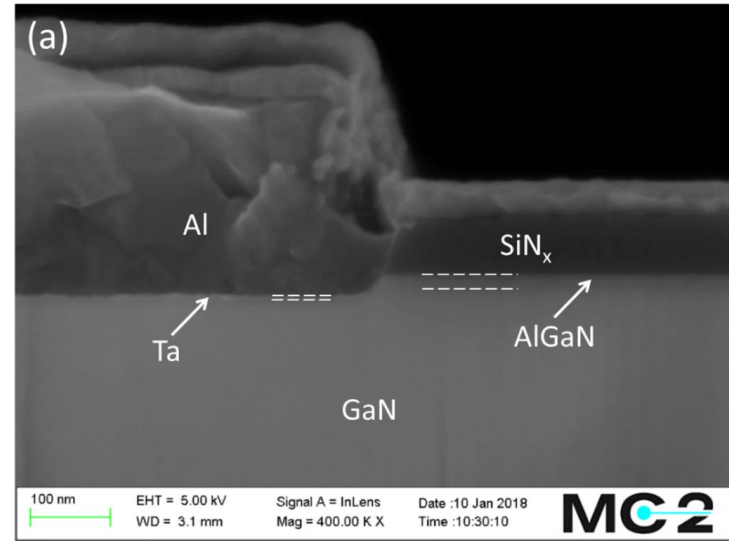


Simulated E_c of an AlGaN/GaN structure for increasing surface doping levels.



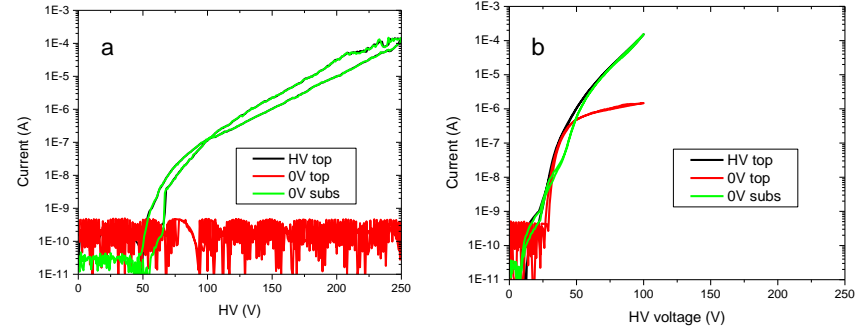
Recessed, Ta-based Ohmic contacts

- Ta-based (Ta/Al/Ta)
 - Low anneal temperature (550C)
 - Au free
 - Better edge acuity
 - Alignment marks for e-beam often defined in the ohmic-layer
 - Critical for downscaling
- More advanced epi-structures with AlN exclusion layer or high Al content in the barrier generally requires ohmic recess.
- Deeply recessed Ta-based ohmic contacts posses a wide process window
 - Versatile process
 - Etch depth
 - Anneal temperature and duration
 - Critical parameters
 - Angle of recess
 - Metal coverage

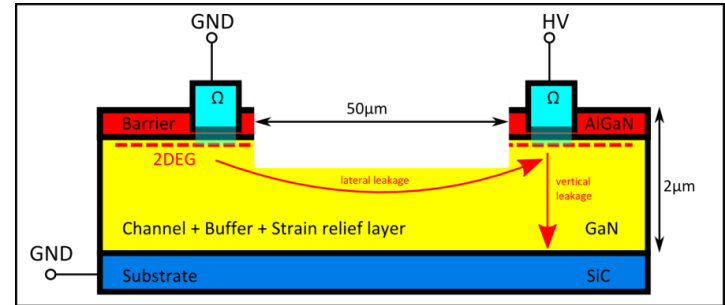


Impact of ohmic process on vertical currents in AlGaN/GaN-on-SiC HEMTs

- Low and high anneal temperature ohmic metal processes for GaN-based transistors have been tested for buffer leakage.
- Improvements in maximum achievable voltage for the low temperature process.
- Higher power will be achievable with such a contact compared to the conventional process.
- Collaboration with Bristol University and IQE Europe

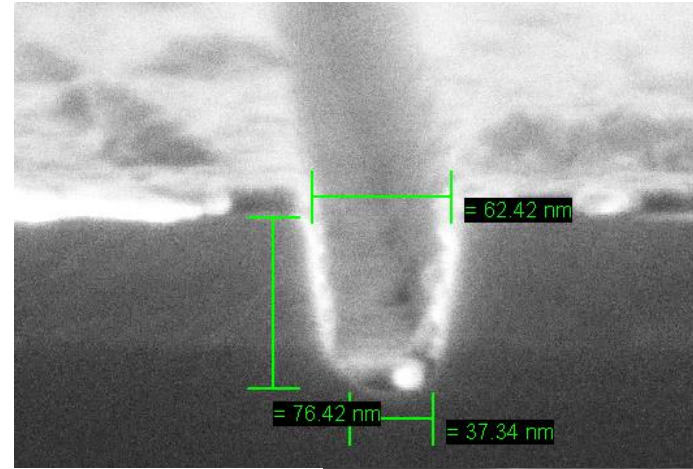


Absolute vertical and lateral leakage for Ta (a) and Ti (b) based contacts.



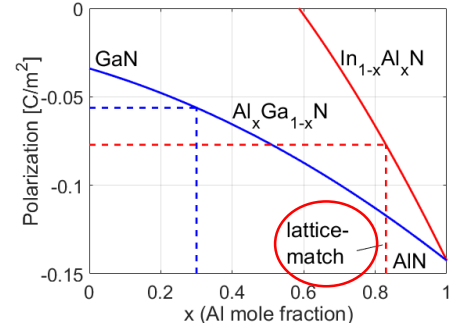
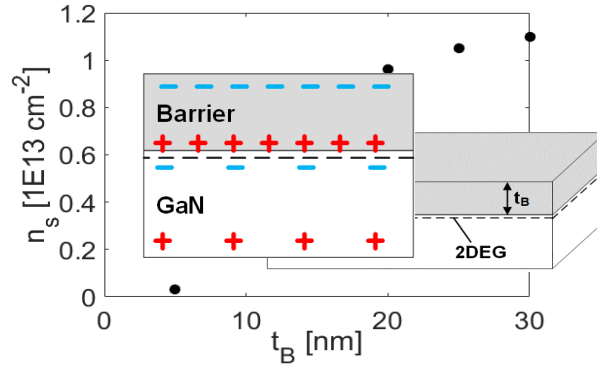
Down-scaling the gate length

- Gate length scaling required for +100 GHz applications
- Reliable definition of gate lengths down to 30 nm
 - One EBL-step to create a recess in SiNx, effectively defining the gate length
 - One additional EBL-step to form a T-(mushroom-) gate
 - Two EBL-steps required?



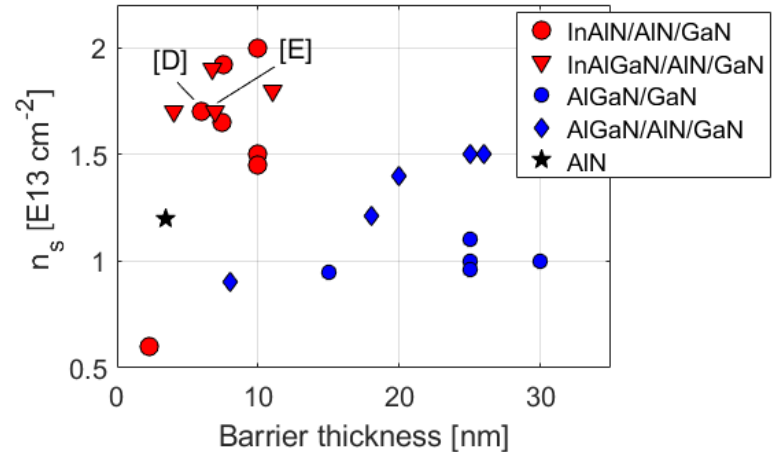
Down-scaling the barrier thickness: Barrier design

- $n_s \sim$ barrier thickness t_B
 - Scaling down the barrier thickness leads to a loss of electrons.
- $n_s \sim \vec{P}$
 - Polarization depends on composition
 - AlGaN
 - InAlN



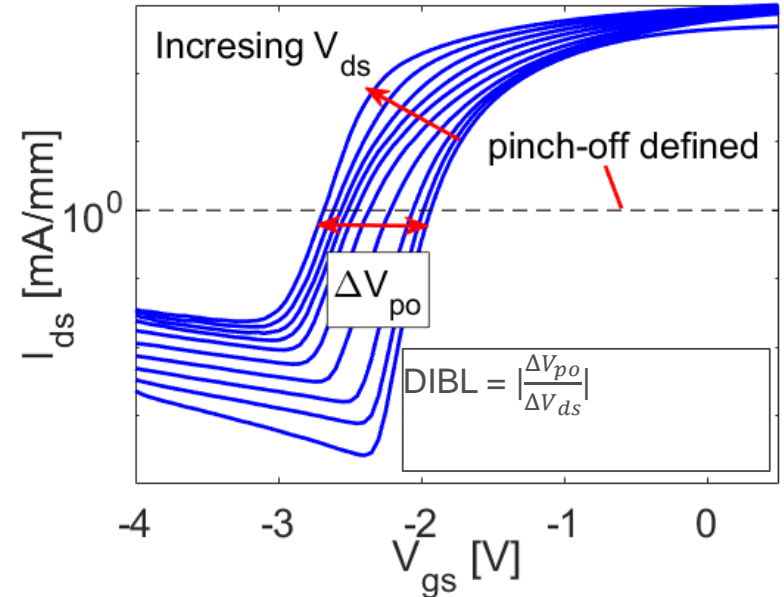
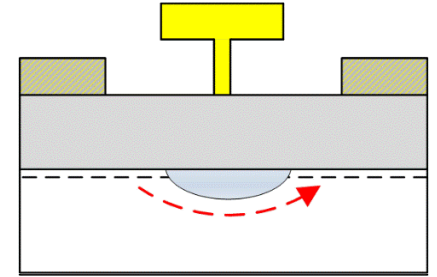
InAlN

- For a given thickness t_B , a lattice-matched InAlN barrier will generate more electrons than an AlGaN barrier.
- More challenging growth
 - Compositional control challenging (InAlGaN)
 - Ga can be incorporated



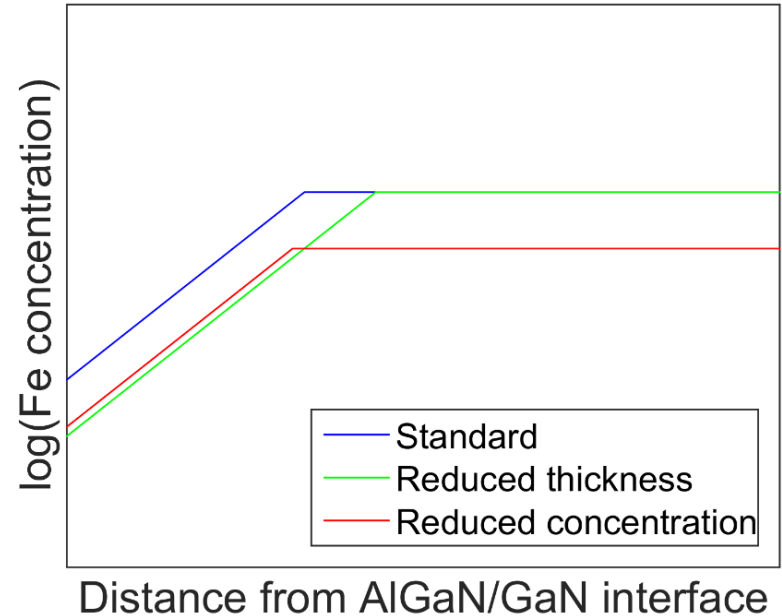
Improving the electron confinement

- Gate downscaling leads to short-channel effects (increased g_{ds} and decreased g_m)
 - Electron confinement in the channel important for
 - High frequency performance
 - High breakdown, low leakage
 - High P_{out}
 - High efficiency
 - High linearity
- Electron confinement/low buffer leakage achieved by
 - Doping of GaN buffer with a deep acceptor
 - AlGaN back-barrier



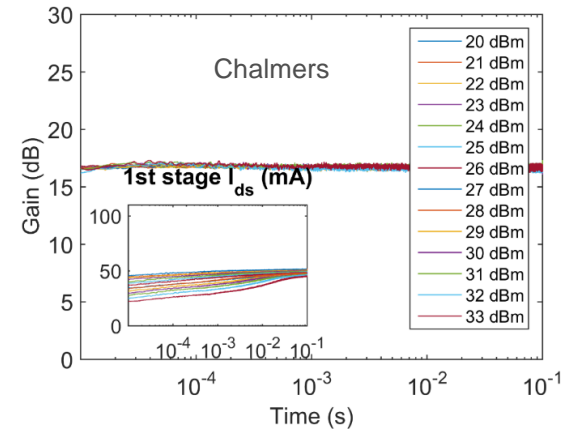
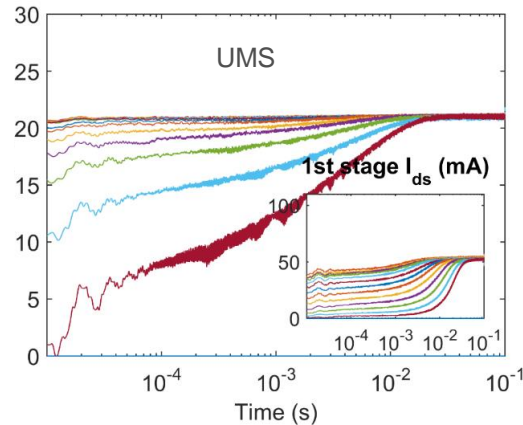
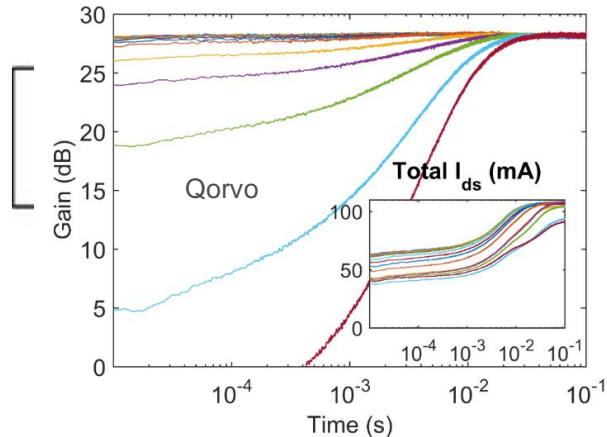
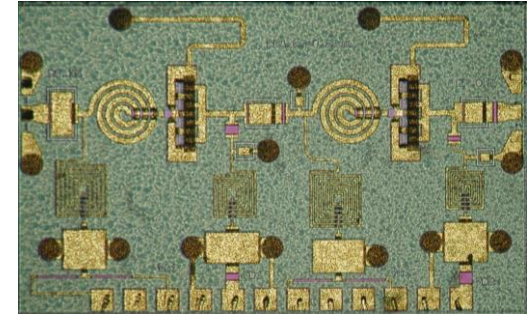
Doping of GaN buffer with a deep acceptor

- High resistive GaN buffer generally achieved with Fe-doping
 - Excellent breakdown, very low leakage
- However....
 - Doping complicated due to memory effects (exponential decay)
 - Fe in or near the channel causes unwanted trapping effects



Transient gain measurements of GaN-based LNAs with Fe-doped and undoped buffers

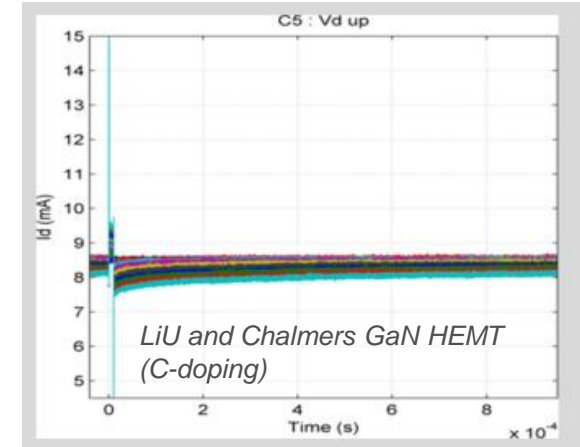
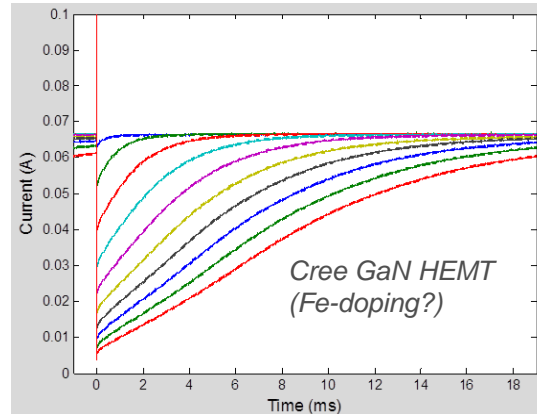
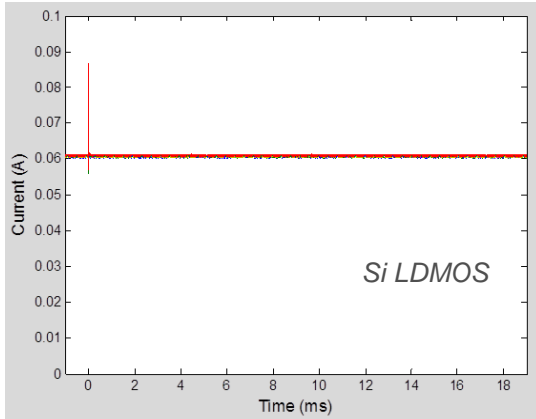
- Radar receivers need to be operational immediately after high P_{in} pulse
- Gain recovery after a pulse (with varying power level) on the input
- Large gain, drain current drop for ~ 20 ms after the pulse for LNAs with Fe-doped buffer (commercial LNAs)
- Chalmers process without Fe buffer: no effects on the gain, smaller drain current drop



Trapping in buffers with different buffer doping

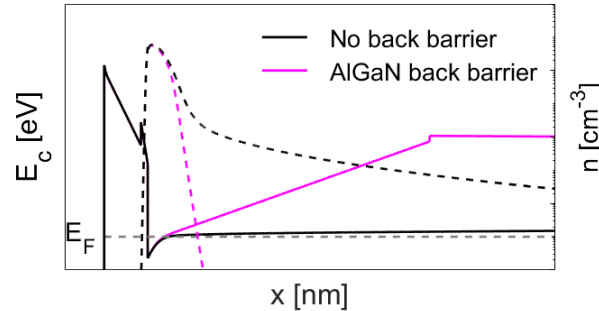
Different semiconductor technologies are compared by mimicking power amplifier operation with modulated signals by pulsing the drain voltage from a quiescent point of 20 V to higher values for 1 μ s. The current response after the pulse is monitored.

- Carbon-doping is an interesting alternative to Fe
- Carbon doping method and profile still to be optimized
- Carbon-doping offers well-controlled doping profiles with two alternative methods:
 - by tuning the MOCVD growth parameters (temperature, pressure, and precursor flow), to control incorporation of carbon from precursors
 - may compromise GaN crystal quality
- or by adding a carbon precursor
 - maintains crystal quality

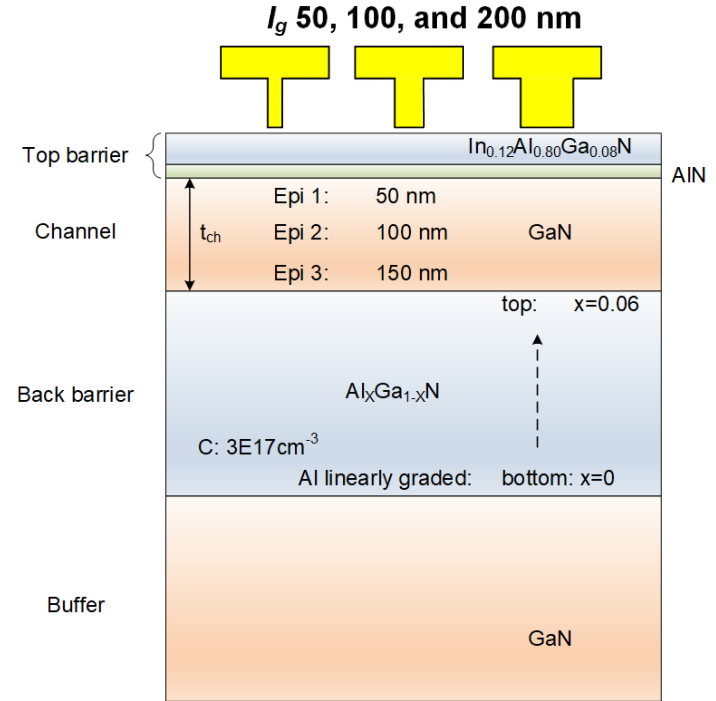


Optimization of channel layer thickness in InAlN-based HEMTs with AlGaN back barriers

- Minimizing the short channel effects with an AlGaN-back-barrier
- Back-barrier improves electron confinement and decreases short channel effects



- Effect of deep-level doping in the back-barrier still needs to be considered



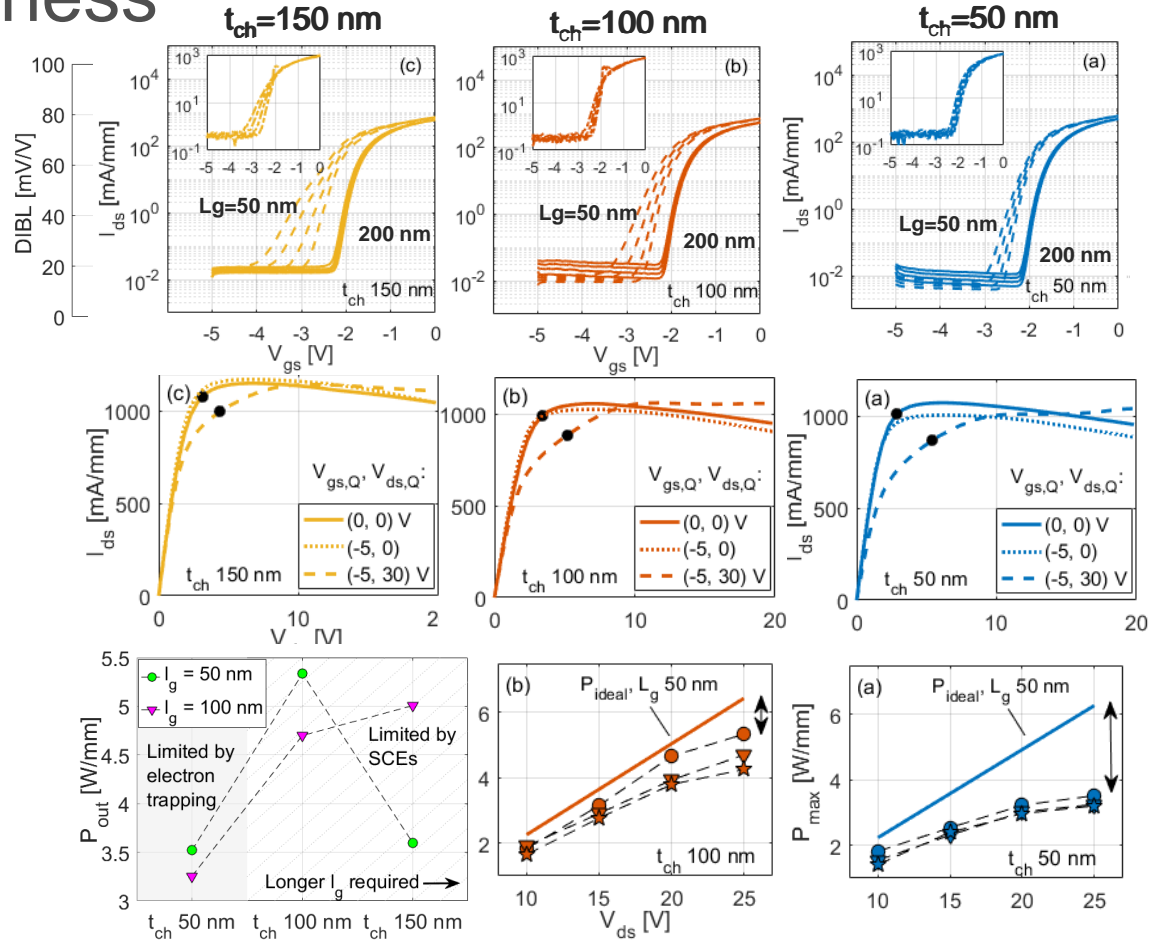
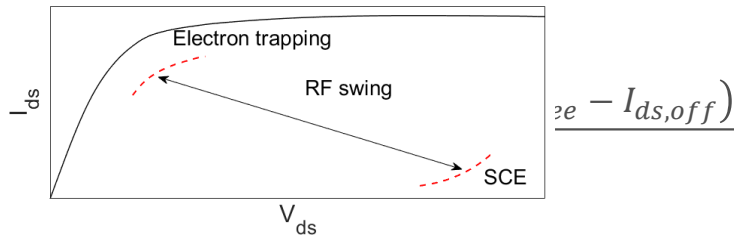
Effect of channel thickness

DC: Thicker channel layer causes short channel effects (SCE) for very short gate-lengths




Pulsed IV: Thinner channel layer results in larger dispersion (increased dynamic R_{on})

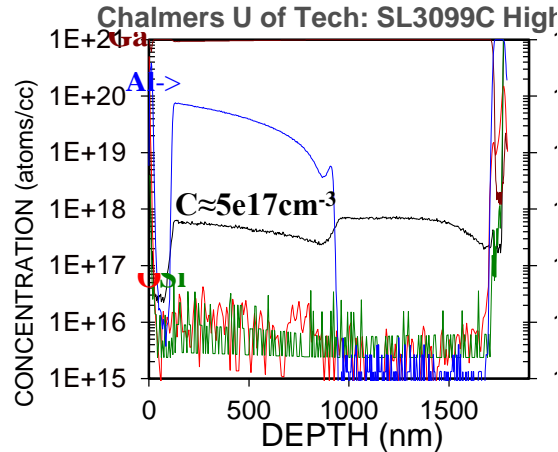
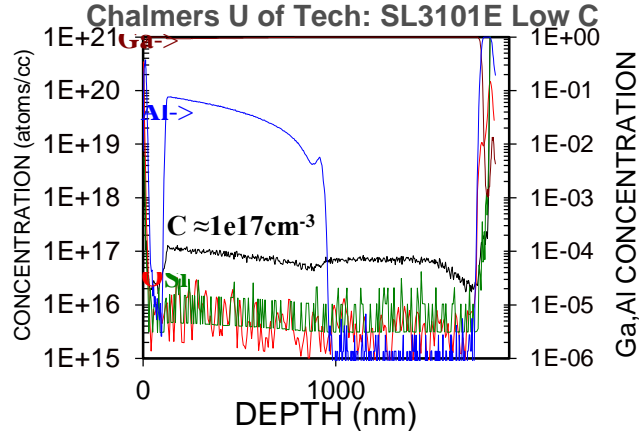
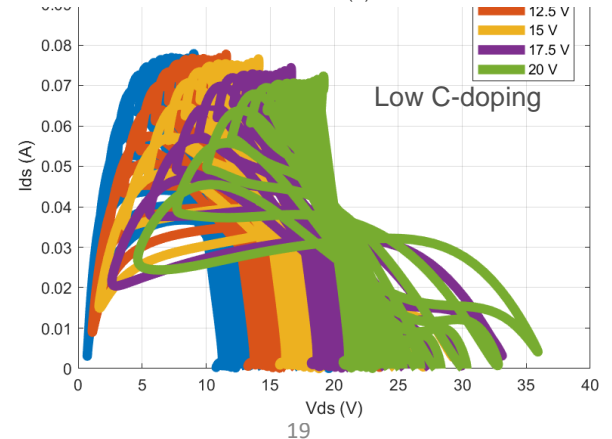
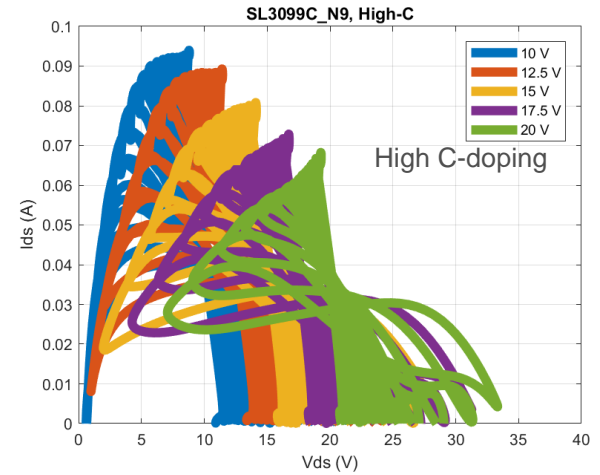
Large-signal (Power sweep @30 GHz): Output power limited by

- SCE for thicker channels
- Knee walk-out for thinner channels



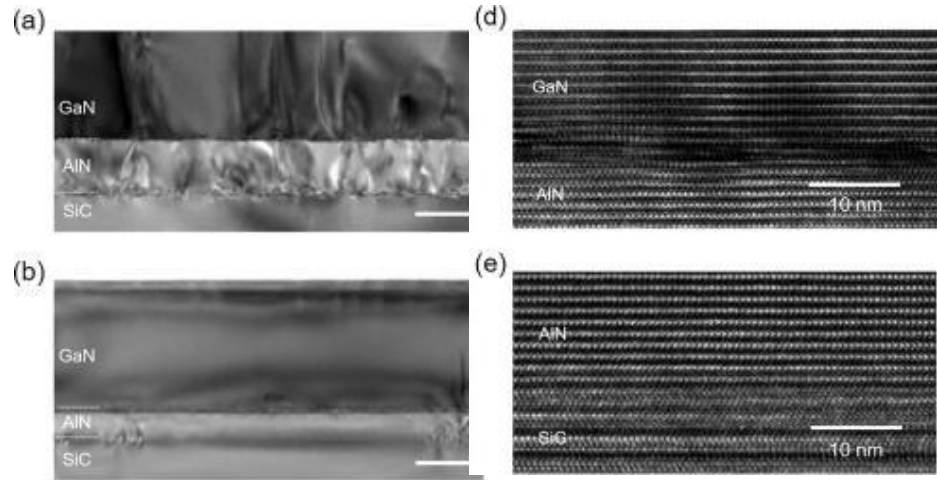
Impact of C-doping level in the back-barrier

- Three different C-doping levels in back-barrier
- Back-barrier doping affects HEMT performance
 - DC: Higher C-doping shows smaller short channel effect 
 - Pulsed IV: Higher C-doping shows larger current collapse 
 - Power sweep: Higher C-doping has lower Pout and PAE due to trapping effects 



“A GaN–SiC hybrid material for high-frequency and power electronics” (Appl. Phys. Lett. 113, 041605 (2018); doi: 10.1063/1.5042049)

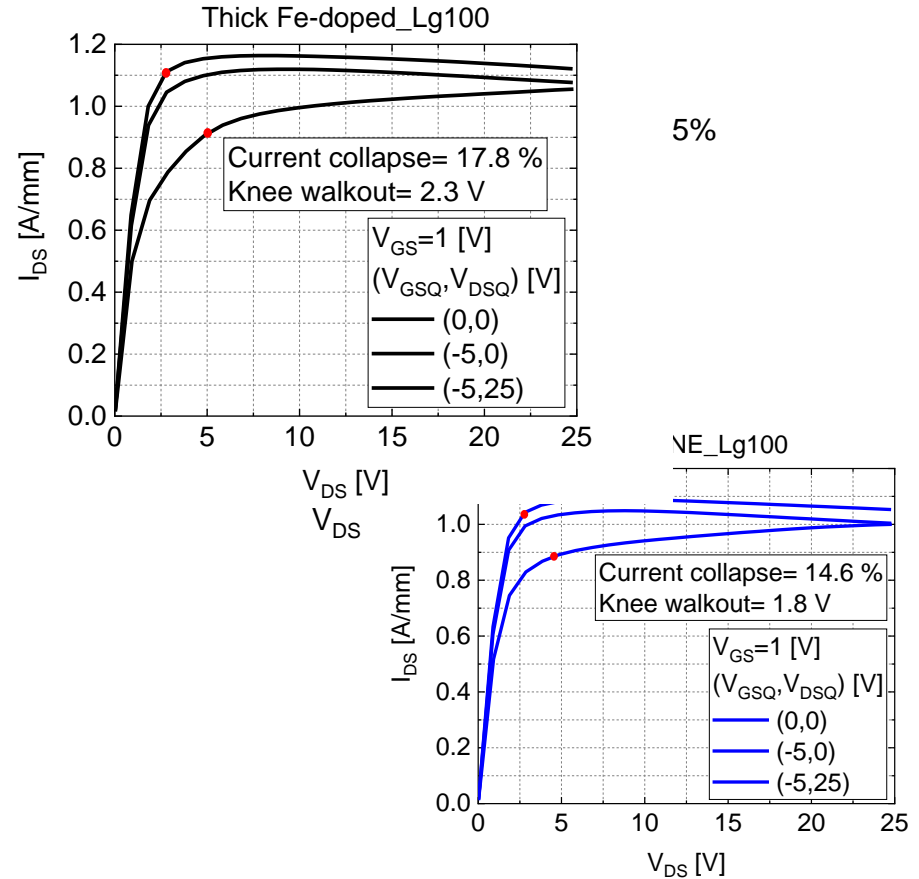
- Collaboration with Linköping University and SweGaN AB
- The lattice mismatch (3.5%) between GaN and SiC substrates can be accommodated without triggering extended defects over large areas using a grain-boundary-free AlN nucleation layer (NL)
- Buffer thickness decreased from ≈ 2 to 0.2–0.3 μm
- Preliminary measurements indicate enhanced breakdown voltage in GaN HEMTs



Cross-sectional TEM images at the GaN/AlN/SiC interface using (a) a conventional AlN NL and (b) the optimized NL. (d) High-resolution image at the interface of GaN/optimized AlN NL. (e) High-resolution image at the interface of optimized AlN NL/SiC.

HEMTs on Quanfine-structures

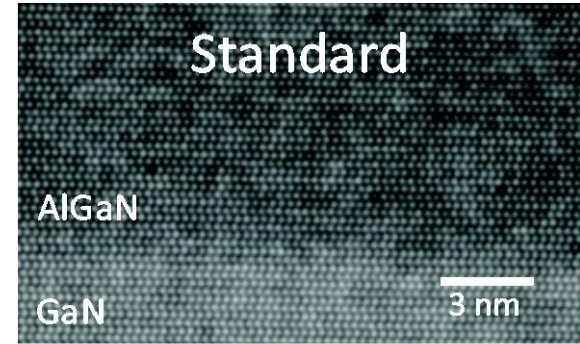
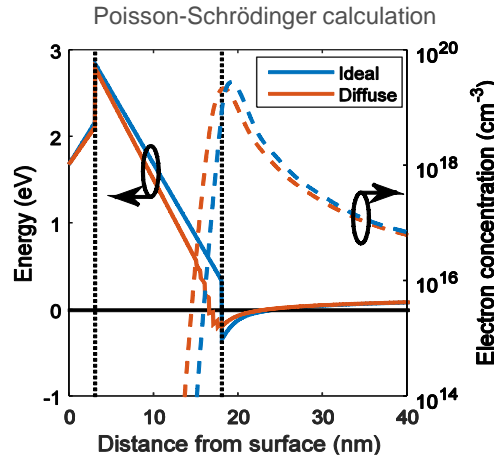
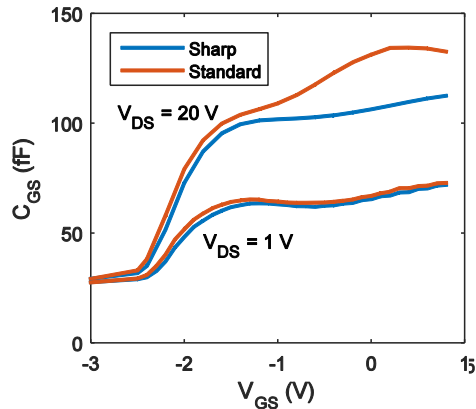
- ▶ SweGaN's optimized nucleation layer allows for a very thin buffer $\approx 0.2 \mu\text{m}$ (virtually no buffer)
 - GaN-buffer on SiC normally $\approx 2 \mu\text{m}$
 - Potentially better electron confinement and lower thermal resistance
- Quanfine-structures demonstrate similar performance as Cree's Fe-doped buffer
 - DC: Similar performance in
 - I_{ds}-V_{ds} and gm.
 - Short channel effects?
 - Pulsed IV: Smaller current slump in Quanfine
 - Power sweep: To be measured



Improve electron transport properties: Performance Enhancement of Microwave GaN HEMTs Using an Optimized AlGa_N/Ga_N Interface

TEM of the AlGa_N/Ga_N interface



- Very high mobility achieved with optimized AlGa_N/Ga_N interface (>2200cm²/Vs) (comparable with the best AlGa_N/AlN/Ga_N structures)

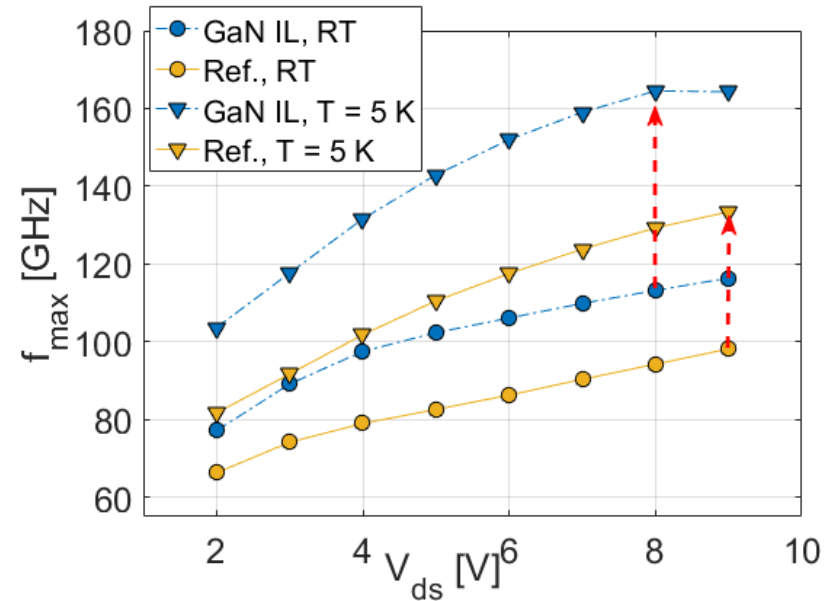


- The sharp interface also results in equally high mobility due to less electron penetration into the barrier

➔ Interface scattering dominant

Enhanced Mobility in InAlN/AlN/GaN HEMTs Using a GaN Interlayer

- HEMTs with InAl(Ga)N-barrier is an interesting alternative for downscaling
 - High electron density for thin barriers
- InAl(Ga)N/GaN HEMTs
 - Very low μ (~ 500 cm²/Vs)
- InAl(Ga)N/AlN/GaN HEMTs
 - $\mu \sim 1600$ cm²/Vs
- InAl(Ga)N/GaN/AlN/GaN HEMTs
 - $\mu \sim 1900$ cm²/Vs 
- 'Standard' AlGaN/AlN/GaN HEMTs
 - $\mu \sim 2000$ cm²/Vs
- Mobility vs. temperature indicate elimination of a scattering mechanism
 - Compositional variations in the InAlN causes local variations in n_s and subband energies intra-subband scattering 
 - Large increase in f_{\max} at cryogenic temperatures



SUMMARY

GaN HEMT is an exciting technology for higher frequency applications such as

- High power, high efficiency amplifiers
- Robust LNAs and switches

Due to its high bandgap and complicated material physics (polarization, growth methods), there is still much research for optimum high frequency and low dispersion performance



CHALMERS

UNIVERSITY OF TECHNOLOGY