AlGaN/GaN HEMTs and HBTs

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PART I

AlGaN/GaN HEMTs

Materials Properties Comparison

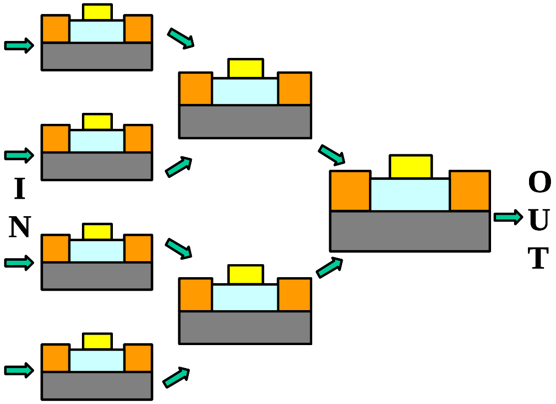
Material	μ	ε	Eg	BFOM Ratio	JFM Ratio	Tmax
Si	1300	11.4	1.1	1.0	1.0	300 C
GaAs	5000	13.1	1.4	9.6	3.5	300 C
SiC	260	9.7	2.9	3.1	60	600 C
GaN	1500	9.5	3.4	24.6	80	700 C

BFOM = Baliga's figure of merit for power transistor performance [$K*\mu*Ec^3$]
JFM = Johnson's figure of merit for power transistor performance
(Breakdown, electron velocity product) [$Eb*Vbr/2\pi$]

Advantages of WBG Devices

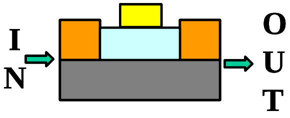
Need	Enabling Feature	Performance Advantage
High Power/Unit Width	Wide Bandgap, High Field	Compact, Ease of Matching
High Voltage Operation	High Breakdown Field	Eliminate/Reduce Step Down
High Linearity	HEMT Topology	Optimum Band Allocation
High Frequency	High Electron Velocity	Bandwidth, μ-Wave/mm-Wave
High Efficiency	High Operating Voltage	Power Saving, Reduced Cooling
Low Noise	High gain, high velocity	High dynamic range receivers
High Temperature Operation	Wide Bandgap	Rugged, Reliable, Reduced Cooling
Thermal Management	SiC Substrate	High power devices with reduced cooling needs
Technology Leverage	Direct Bandgap: Enabler for Lighting	Driving Force for Technology: Low Cost

Example of Advantage of WBG Devices



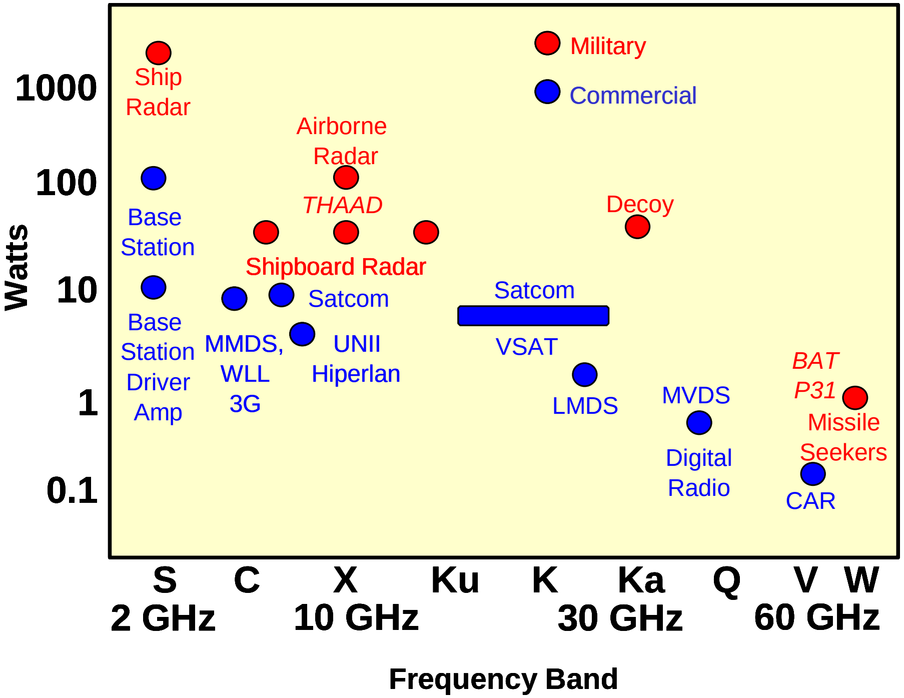
GaAs High Power
Amplifier Module

- 10-x power density (> 10 W/mm)
- 10-x reduction in power-combining
- Improved efficiency (> 60 %)
- Improved reliability
- Compact size
- Superior Performance at reduced cost

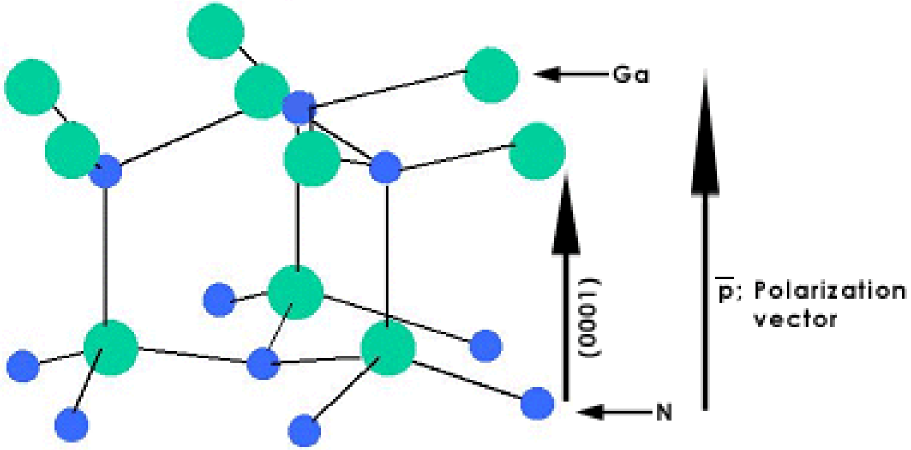


Equivalent
High Power
GaN Amplifier
Module

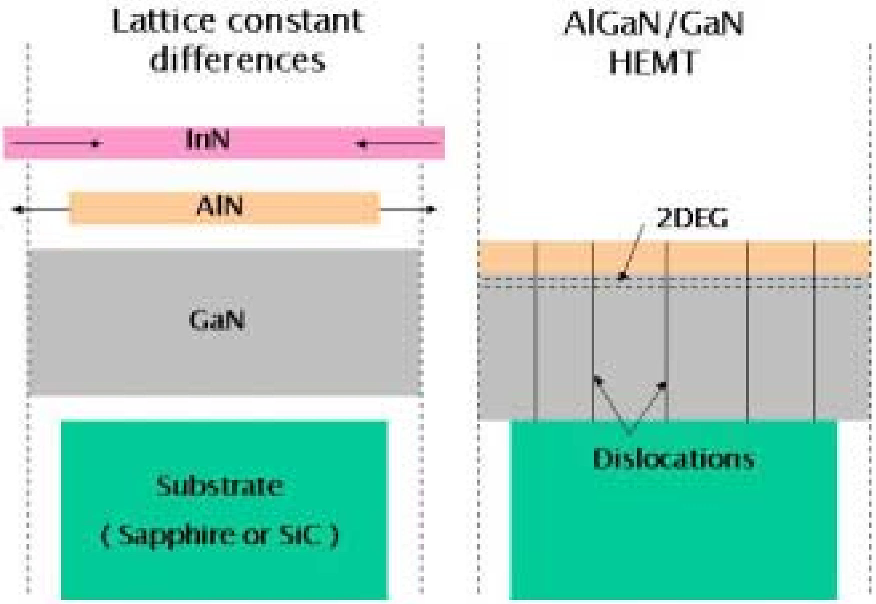
Application Space

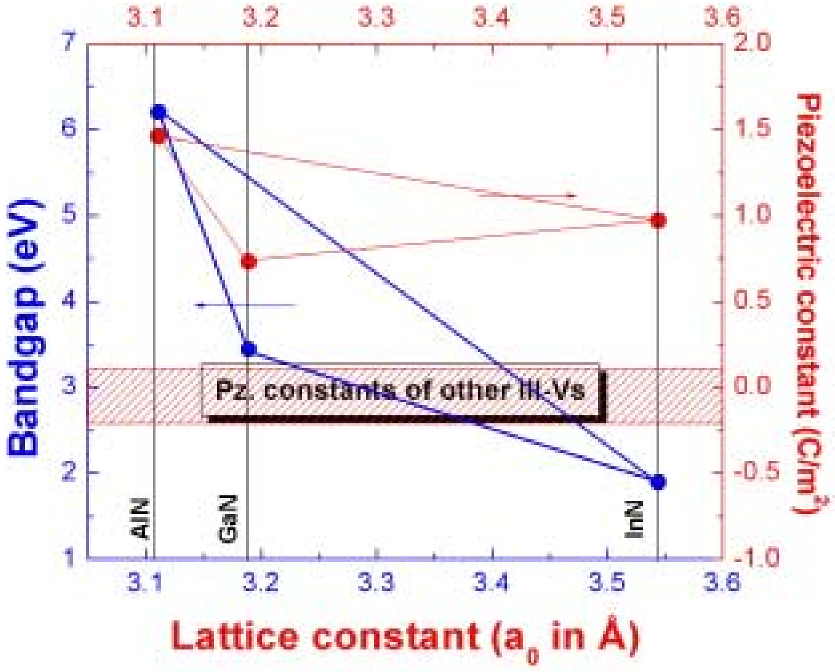


Ball and Stick Diagram of the GaN Crystal



Polarization World





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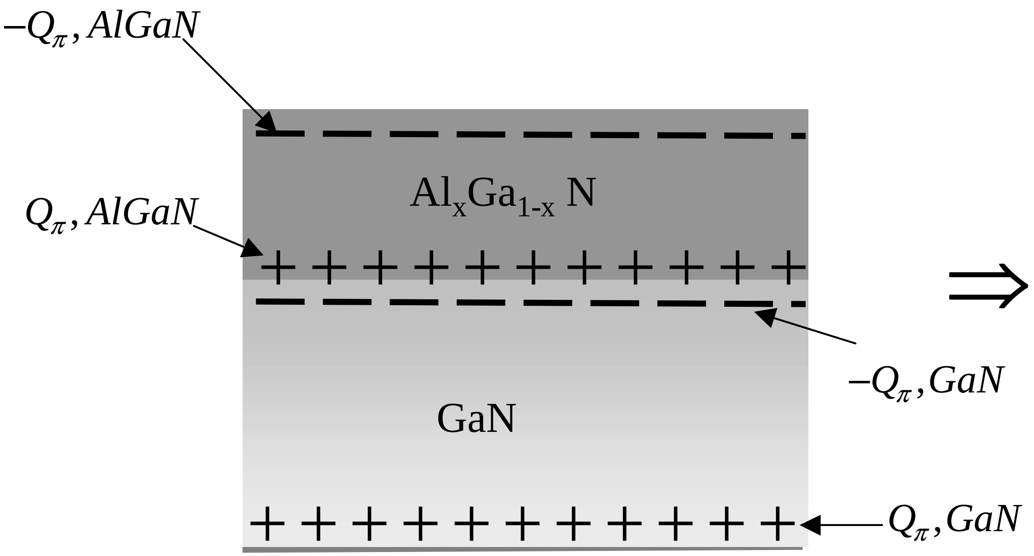
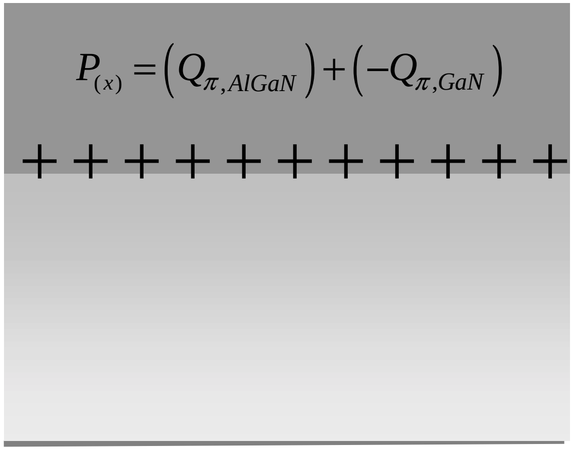
How does the electron gas form in AlGaN/GaN structures? - A

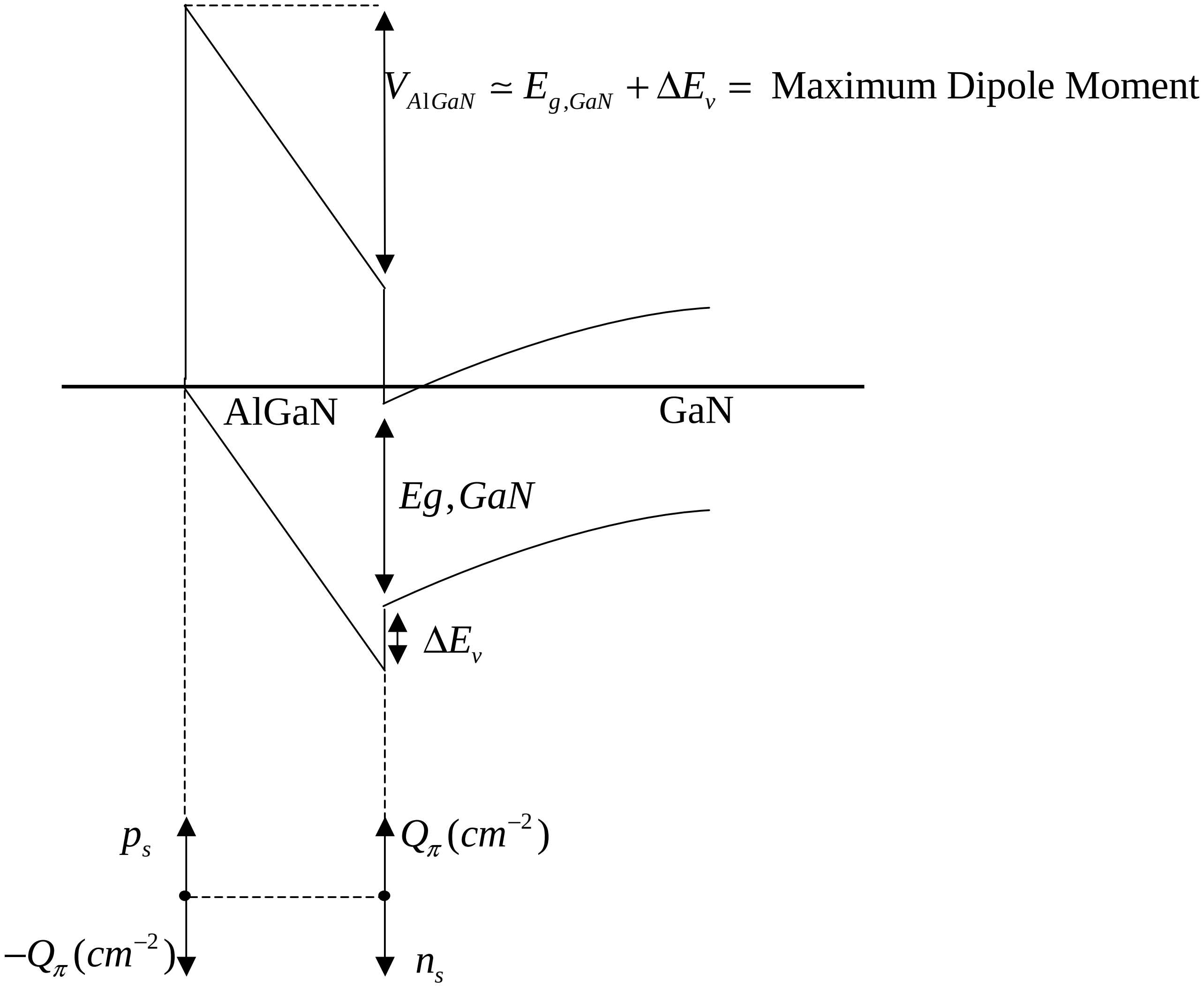


$\Rightarrow$

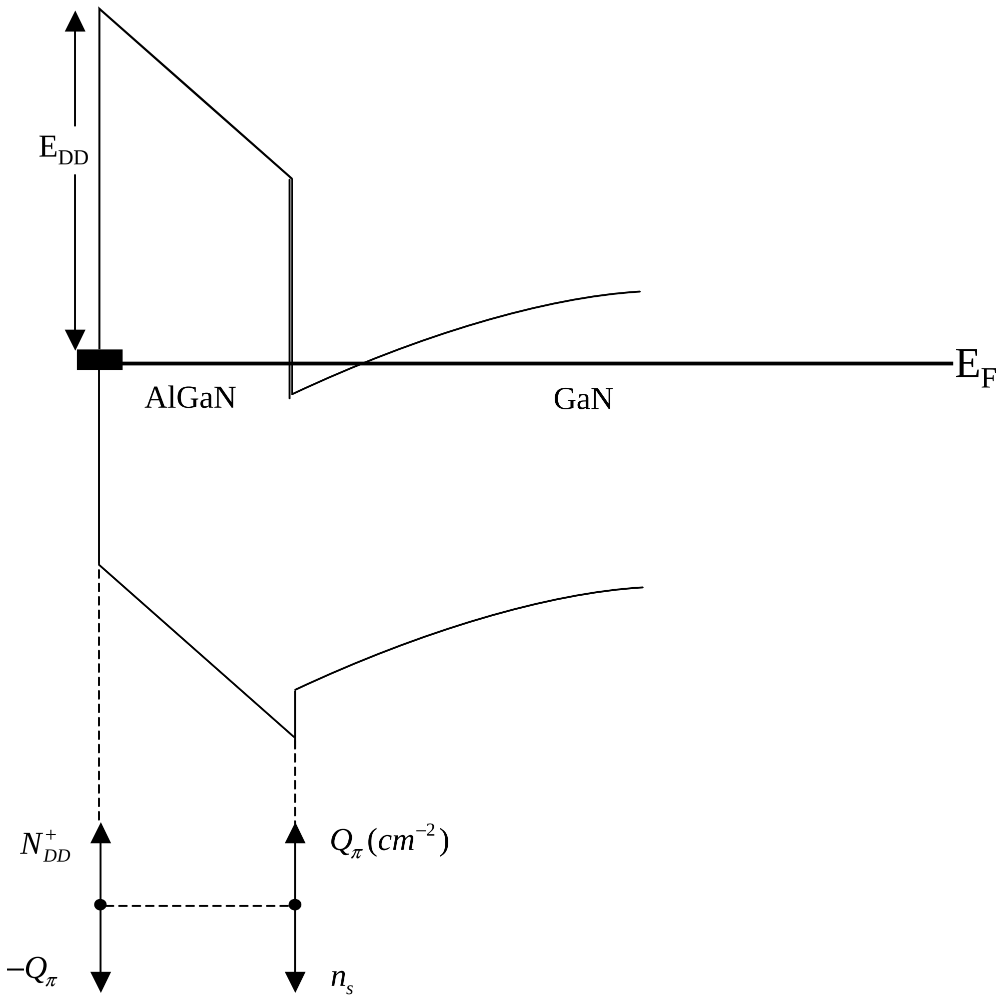


Q_π includes the contribution of spontaneous and piezo-electric contributions

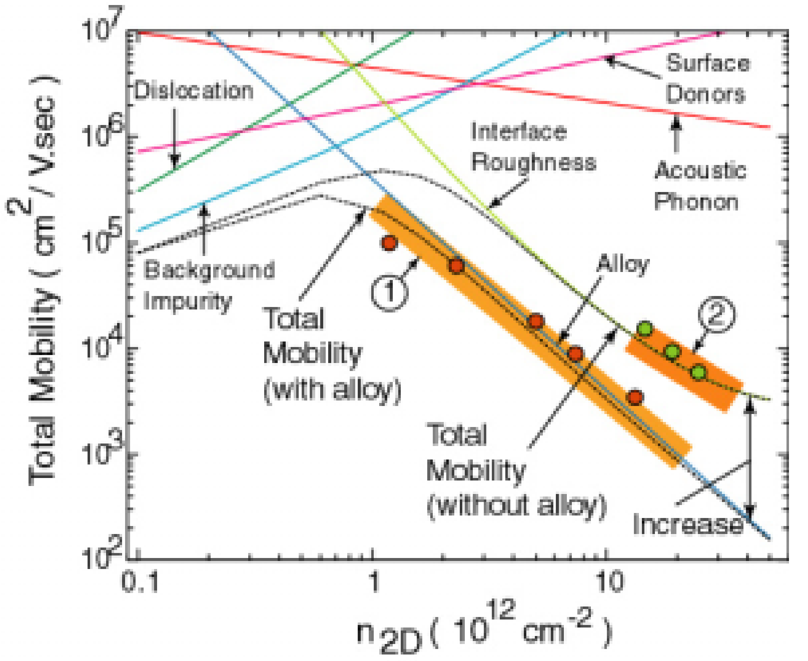
How does the electron gas form in AlGaN/GaN structures? - C

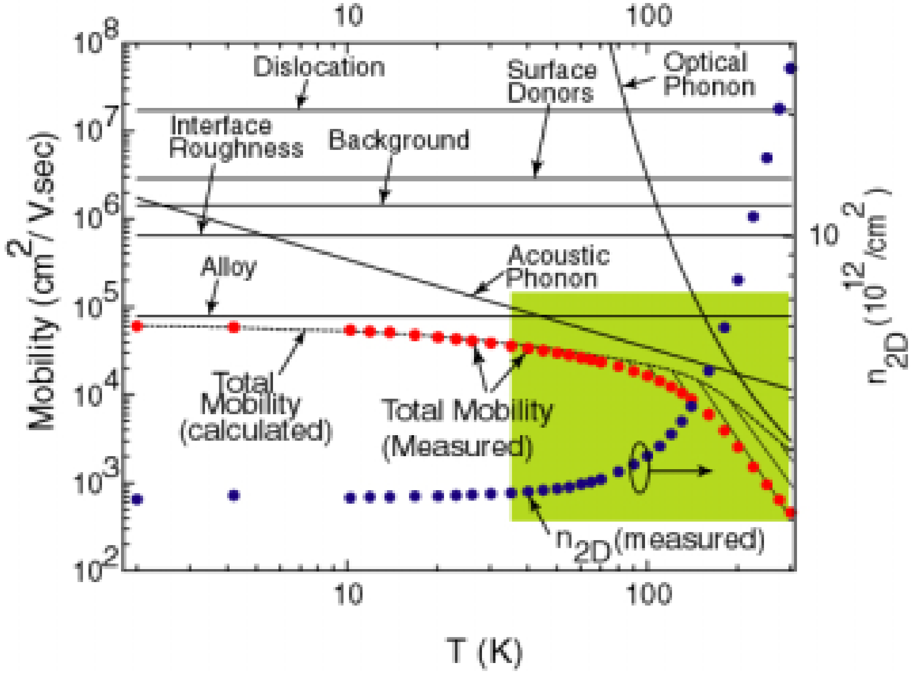


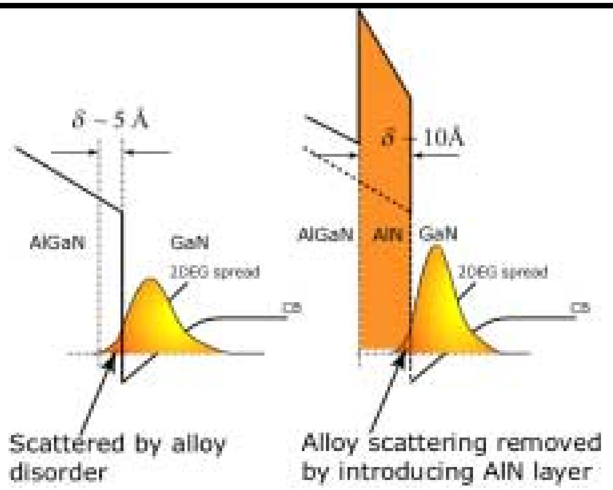
How does the electron gas form in AlGaN/GaN structures? - D



Application of AlGaN/GaN 2DEG transport studies

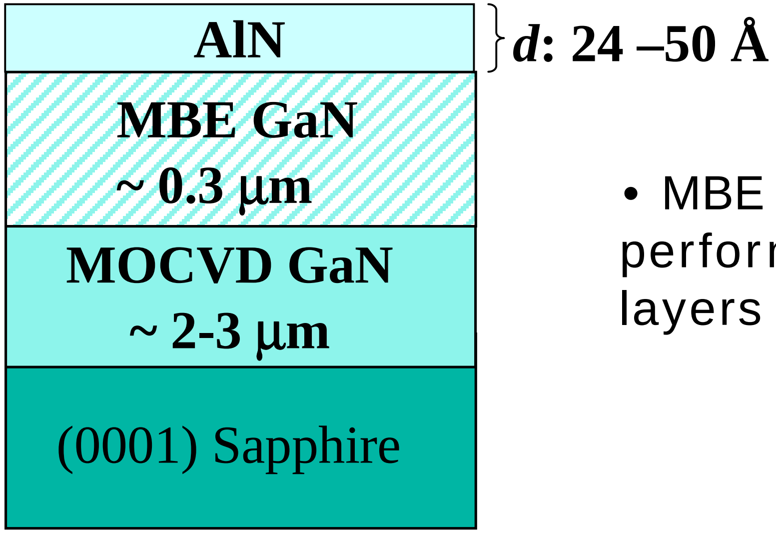






- High density 2DEG mobility limited by alloy scattering.
- Introduce thin AlN interlayer – remove alloy scattering by pushing 2DEG wavefunction out of the alloy region.
- Very useful result for attaining high conductivity 2DEG channels for HEMTs.

RF Plasma-Assisted Molecular Beam Epitaxy of AlN/GaN Heterostructures



AlN

MBE GaN
~ 0.3 µm

MOCVD GaN
~ 2-3 µm

(0001) Sapphire

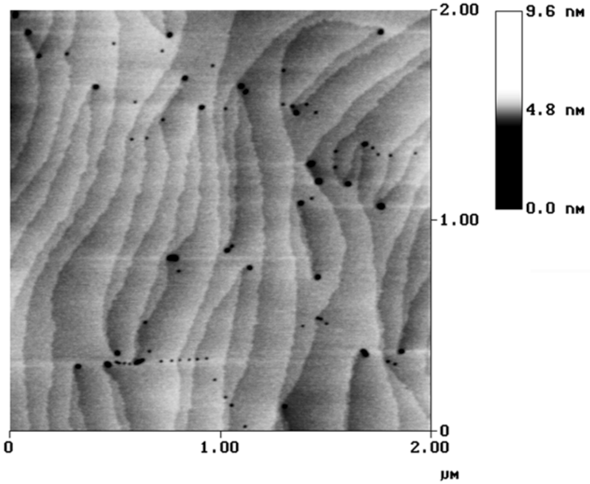
***d*: 24 –50 Å**

- MBE growth of AlN/GaN structures is performedon GaN "templates" – thick GaN layers grown by MOCVD on (0001) sapphire

- Templates of two types are employed:
  (a) unintentionally doped GaN
    (dislocation density: ~ 5x10^8 – 10^9 cm^{-2})
  (b) semi-insulating GaN
    (dislocation density: ~ 10^{10} cm^{-2})

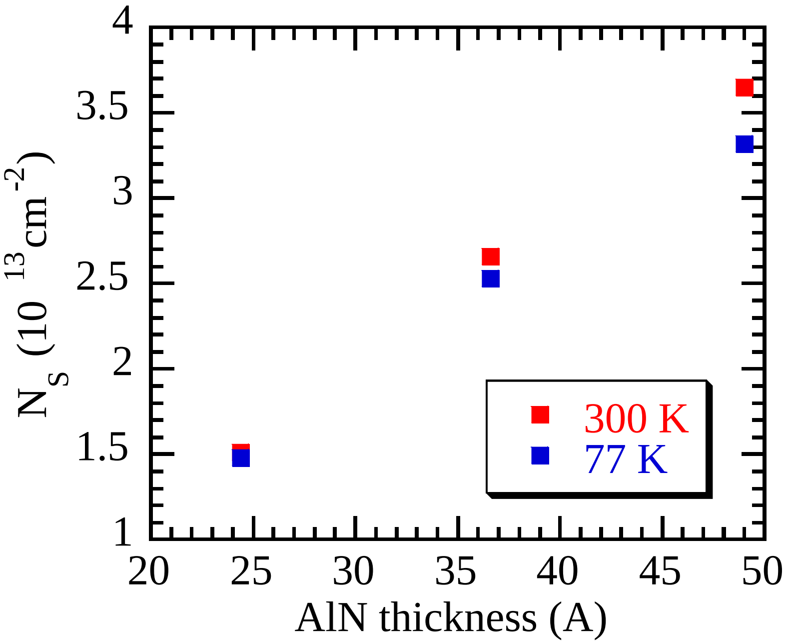
- Ga-stable growth (III/V flux ratio > 1)

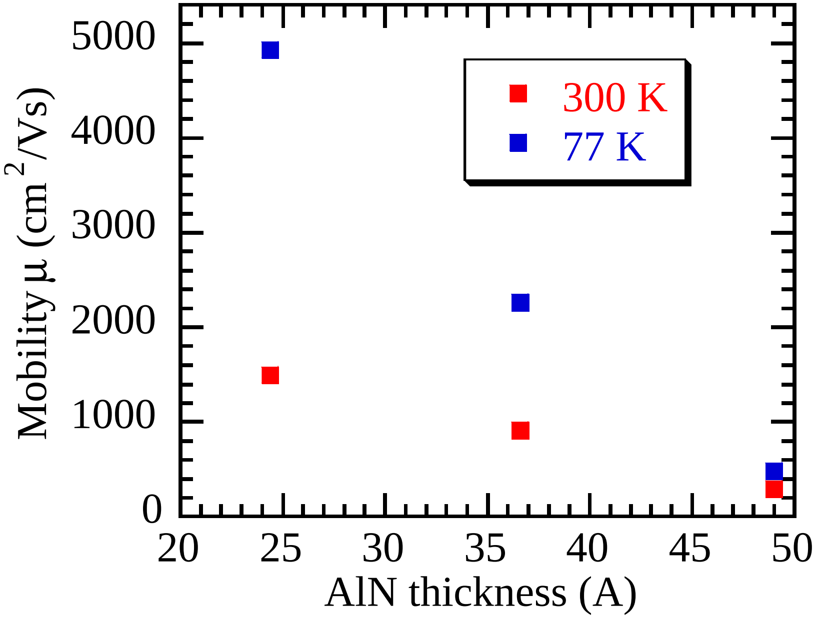
- T_S ~ 740 °C



AFM image of type (a) GaN template

AlN/GaN Structures Grown on Semi-Insulating GaN Templates

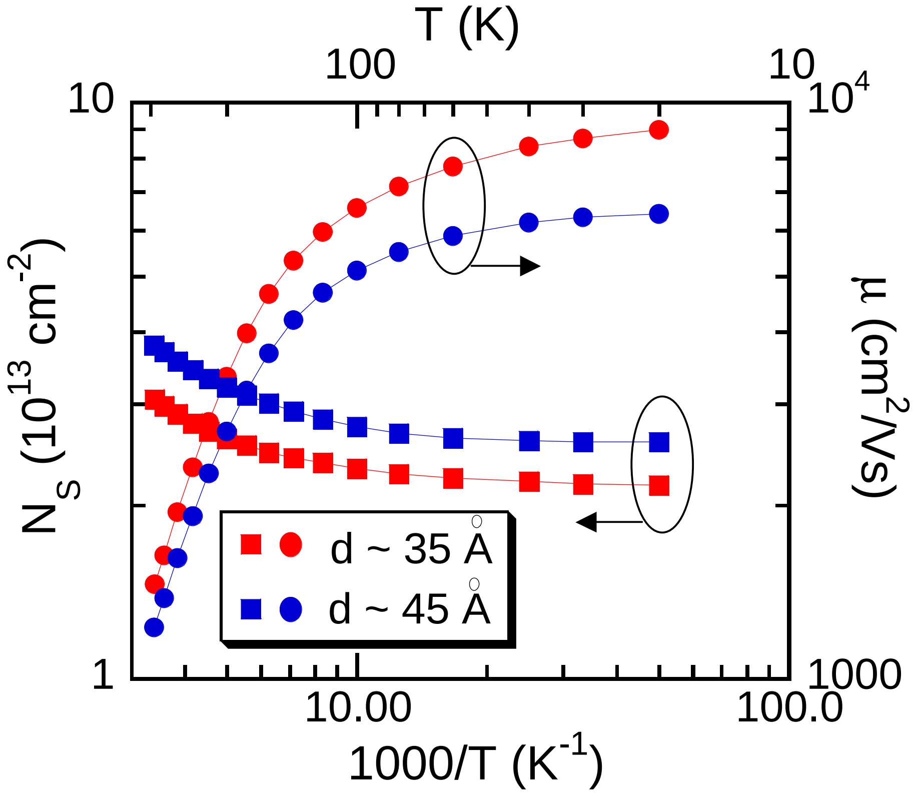




- 2DEG sheet density reaches the value of 3.65×10^{13} cm^{-2} in the AlN/GaN structure with a 49 Å barrier

- Both room-temperature and 77 K electron mobility decrease drastically as AlN barrier width increases

AlN/GaN Structures Grown on Unintentionally Doped GaN Templates



AlN ~ 35 Å

μ(300 K) = 1460 cm^2/Vs

$N_{2DEG} \approx N_S$(20 K) = $2.2 \times 10^{13} cm^{-2}$

AlN ~ 45 Å

μ(300 K) = 1230 cm^2/Vs

$N_{2DEG} \approx N_S$(20 K) = $2.7 \times 10^{13} cm^{-2}$

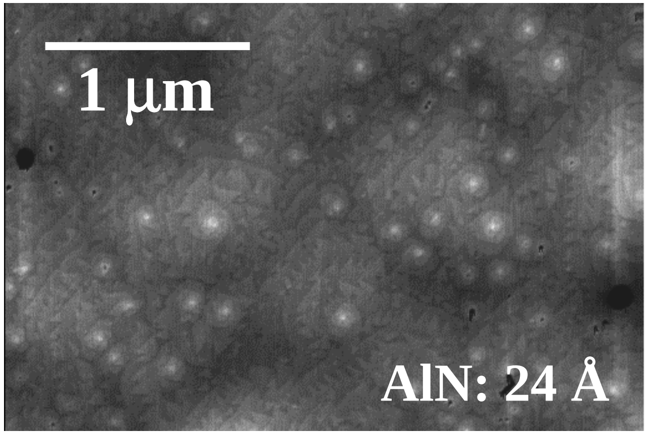
Pessimistic estimate of the
2DEG sheet resistance at 300 K:
$R_{\square} < 200\ \Omega/\square$

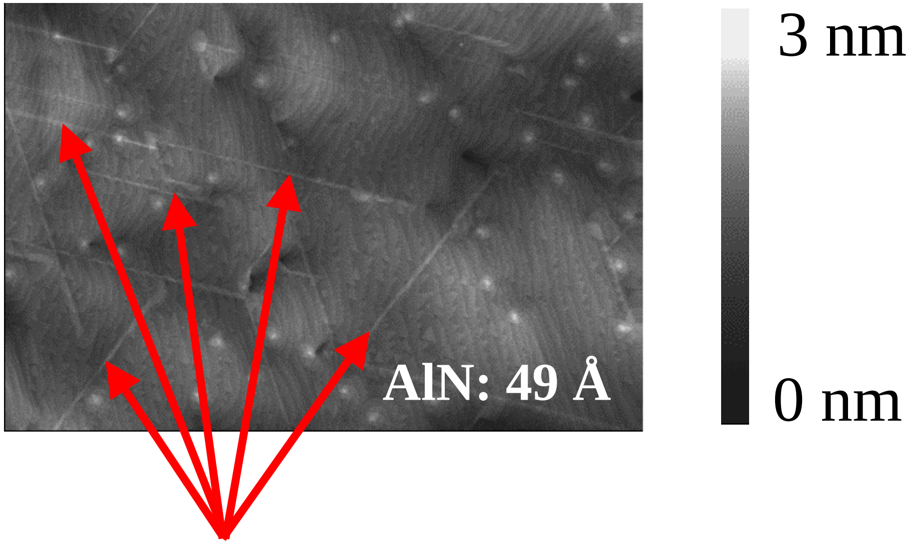
AlN ~ 50 Å

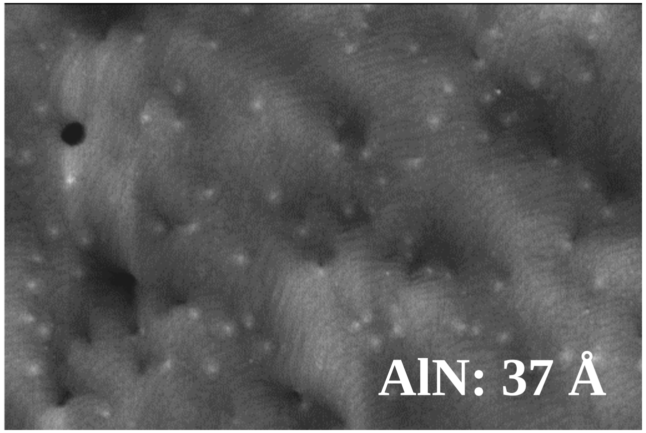
μ(300 K) = 330 cm^2/Vs; N_S(300 K) = $5.6 \times 10^{13} cm^{-2}$

μ(77 K) = 660 cm^2/Vs; N_S(77 K) = $3.6 \times 10^{13} cm^{-2}$

Atomic Force Microscopy of AlN/GaN Heterostructures







Cracks in AlN layer

Tensile strain relaxation process begins at *d* ~ 49 Å

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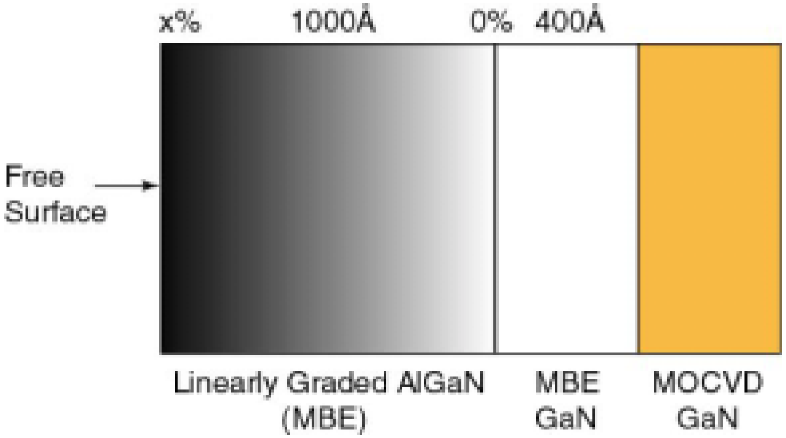
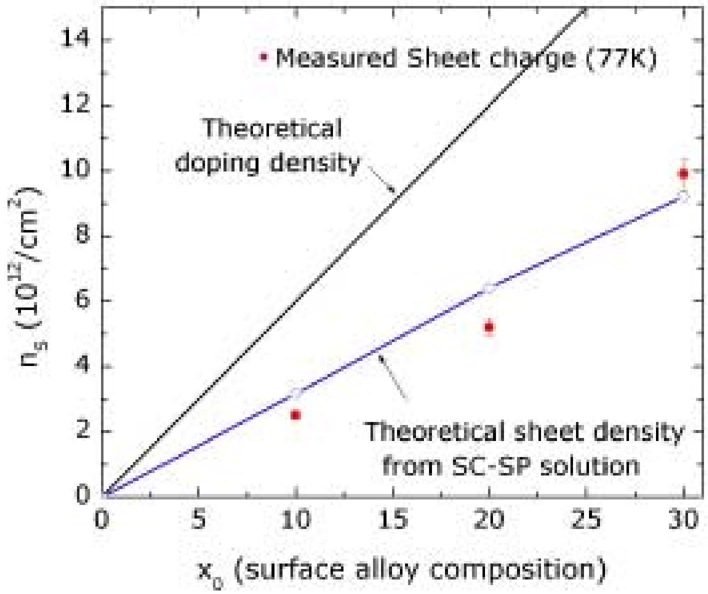
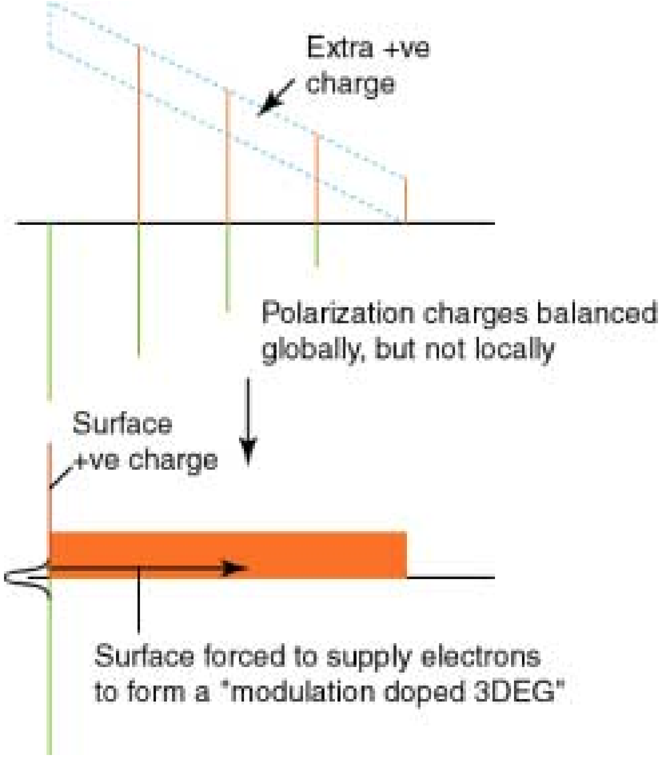
Polarization doping – concept and demonstration

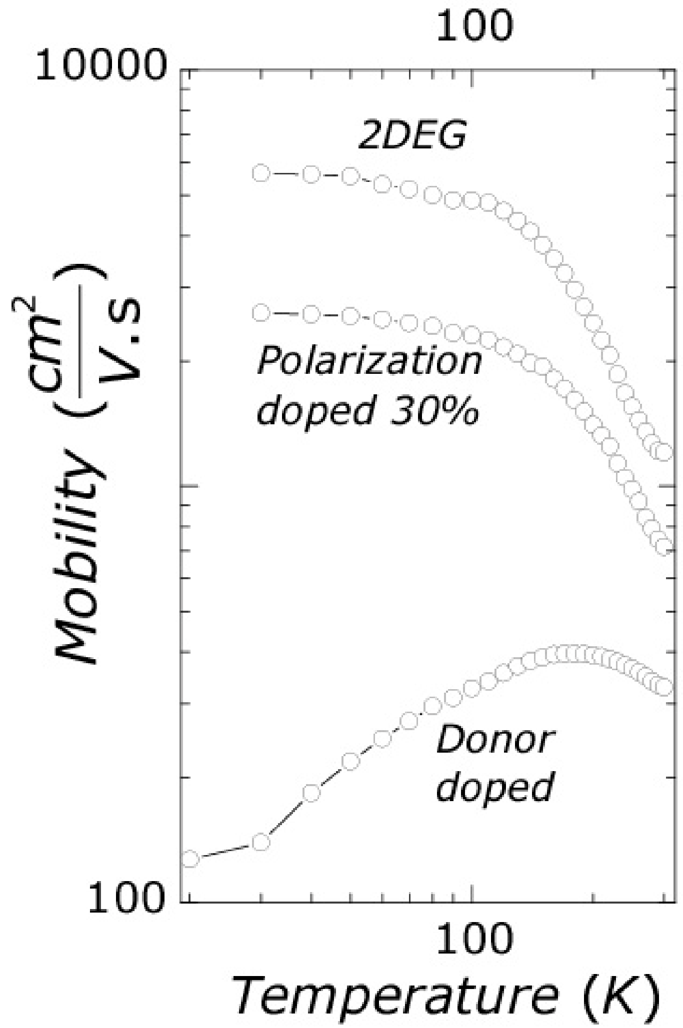


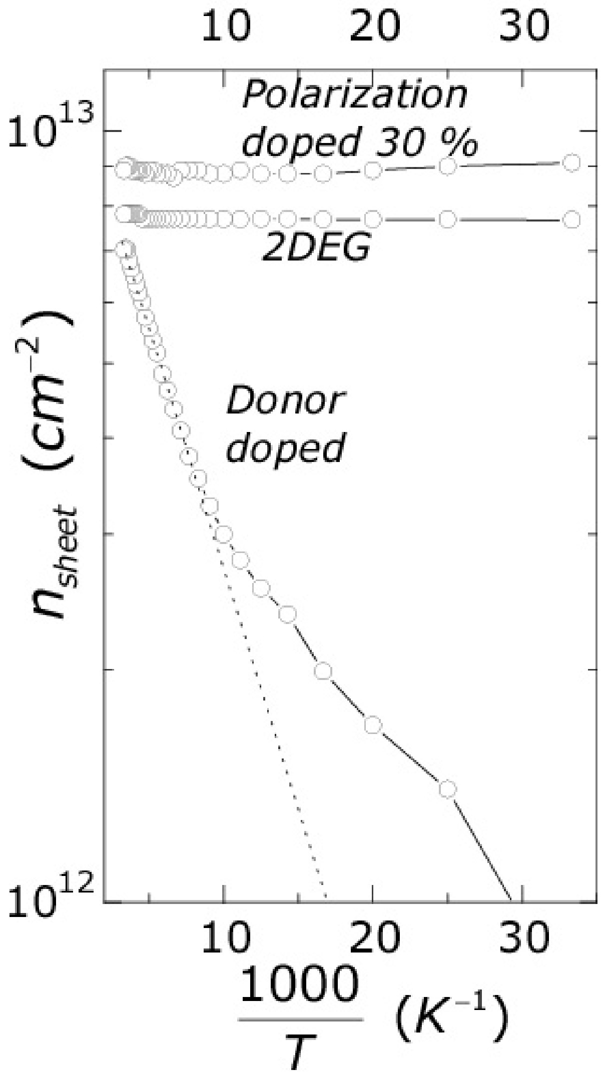




- 3D electron slab by Polarization doping demonstrated.
- Carrier density verified by self –consistent Schrodinger – Poisson calculations.
- How do transport properties of the 3DES compare to the donor doped and 2DEG counterparts ?

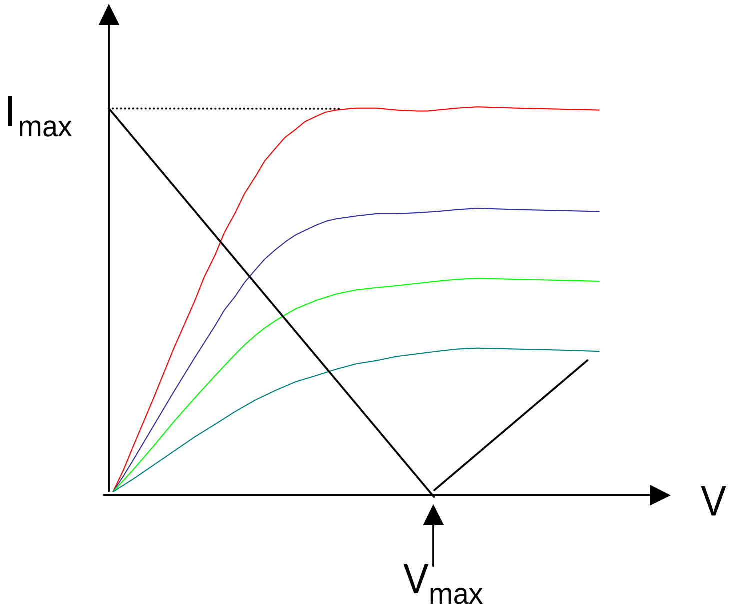
Comparison of transport properties

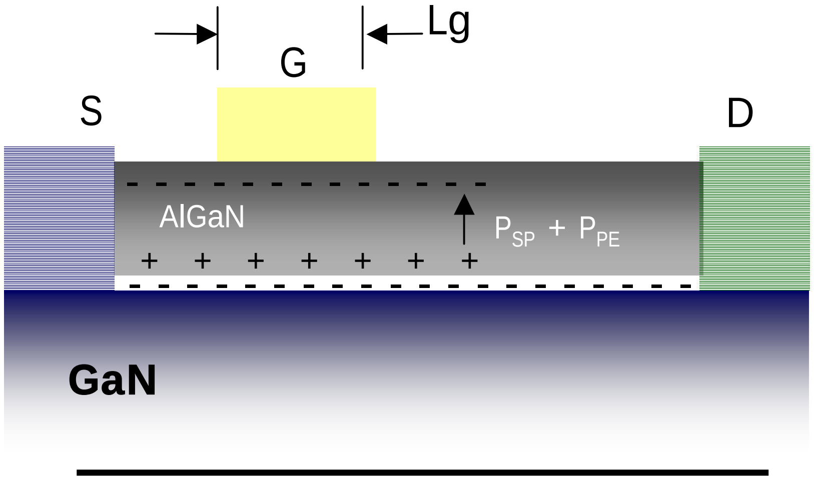




DC Device Level Issues (HEMTs)

If it ain’t good @ DC it ain’t goin’ to be good @ RF



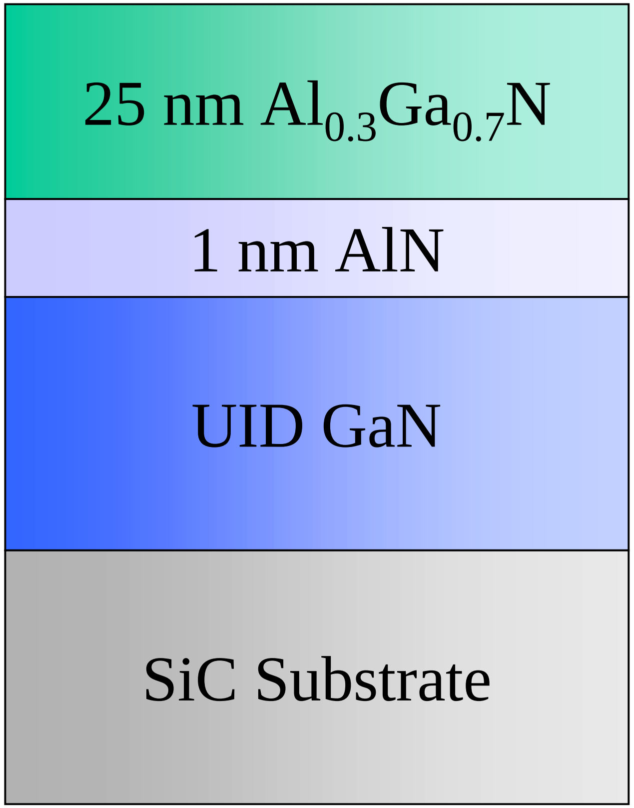


$$P_{max} = \frac{1}{8} V_{max} \cdot I_{max}$$

$$I = V \cdot n_S \cdot \upsilon$$

• Maximize I	⇒	Maximize n_S, ν
• Maximize n_S	⇒ ⇒	Maximize P_{SP}, P_{PE} Maximize Al mole fraction without strain relaxation
• Mazimize ν	⇒ ⇒	Minimize effective gate length Minimize Lg and gate length extension
• Maximize μ	⇒ ⇒	Minimize dislocations Smooth interface

AlGaN/AlN/GaN Heterostructure



25 nm $Al_{0.3}Ga_{0.7}N$

1 nm AlN

UID GaN

SiC Substrate

+ High charge
+ High mobility

Hall Data:

- Conventional $Al_{0.3}Ga_{0.7}N$/GaN HEMT
  $n_s = 1.2 \times 10^{13}$ cm^{-2}
  $\mu = 1200$ cm^2/V/s
- $Al_{0.3}Ga_{0.7}N$/AlN/GaN HEMT
  $n_s = 1.65 \times 10^{13}$ cm^{-2}
  $\mu = 1716$ cm^2/V/s

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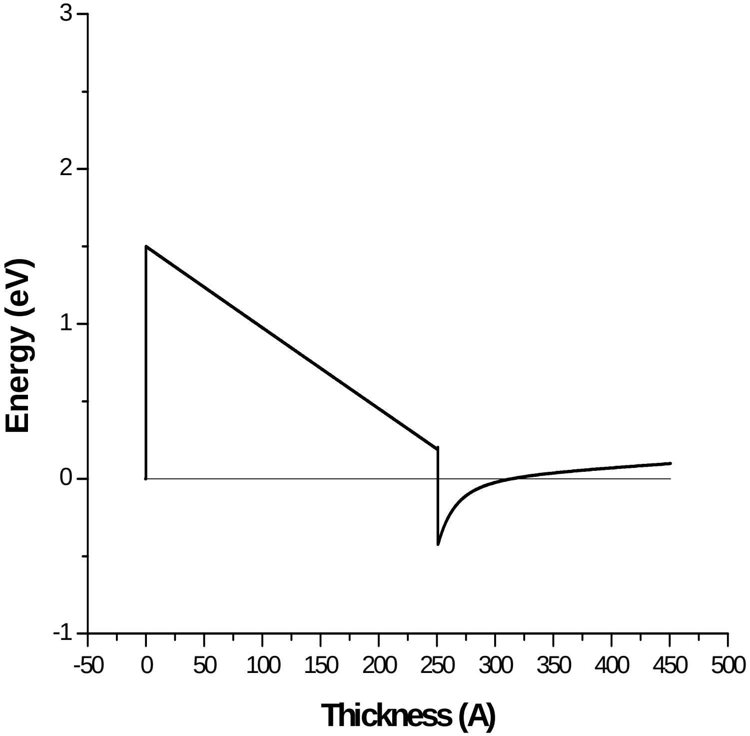
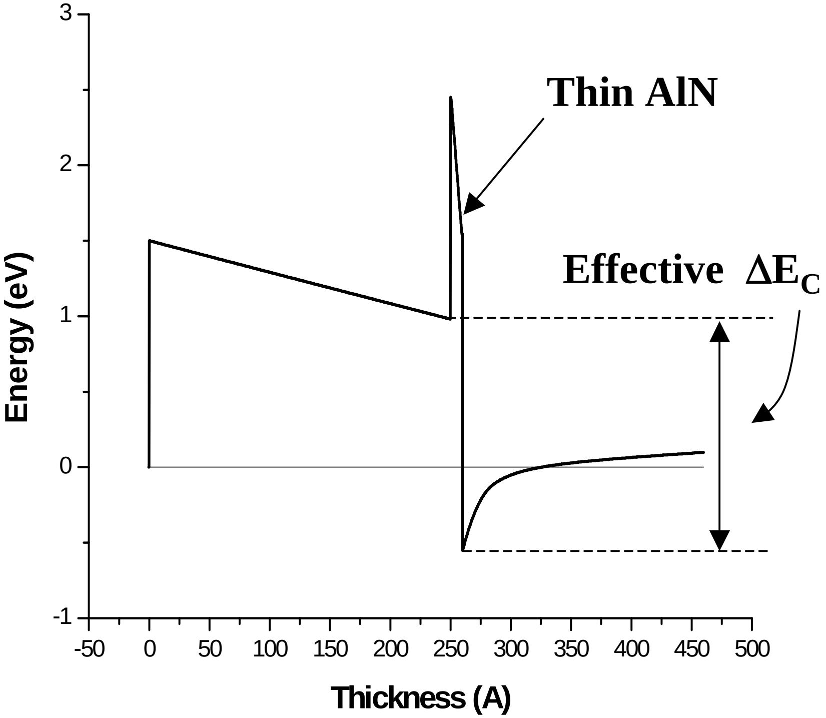
Band Diagram of AlGaN/AlN/GaN HEMT

250 Å Al$_{0.3}$GaN/GaN HEMT



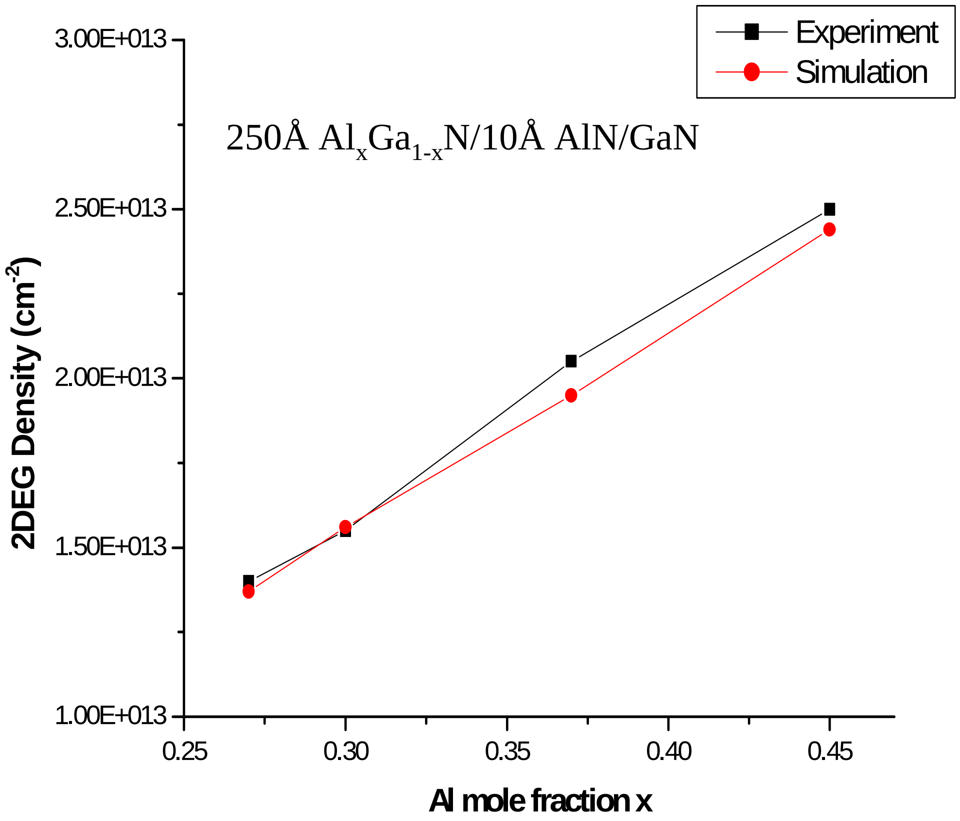
- $n_s = 1.35 \times 10^{13}$ cm^{-2}

250 Å Al$_{0.3}$GaN/ 10 Å AlN/GaN HEMT



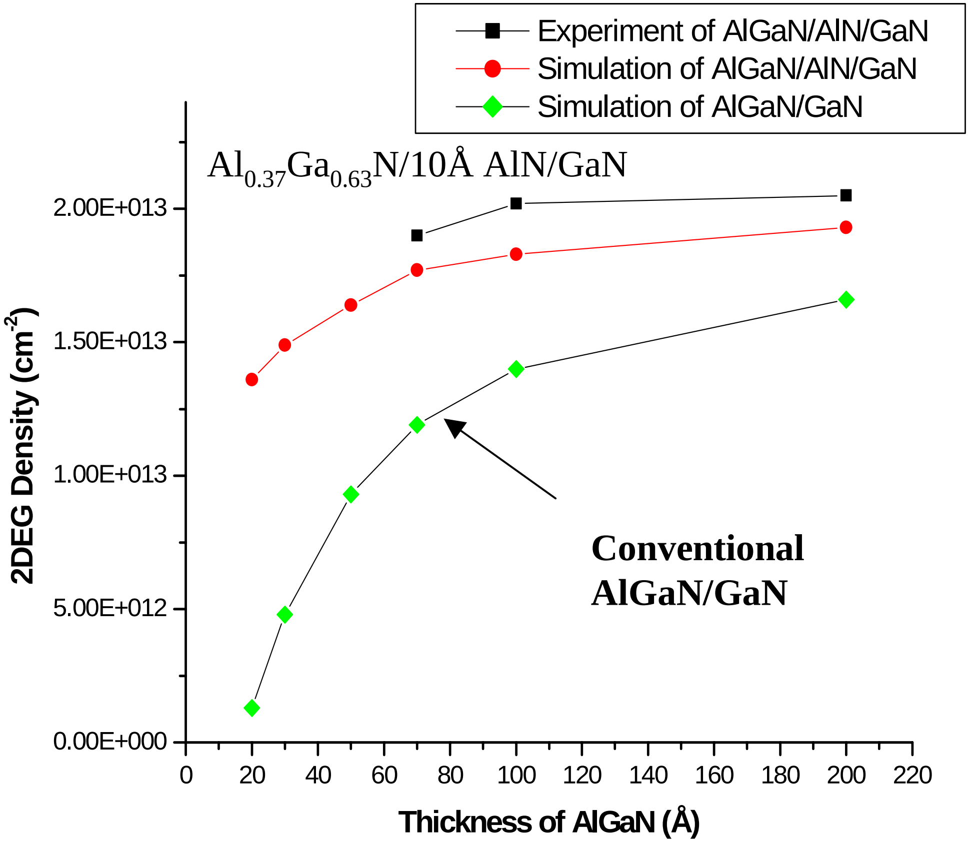
- Higher charge: $n_s = 1.56 \times 10^{13}$ cm^{-2} due to higher effective ΔE_C
- Higher mobility due to the removal of alloy disorder scattering

Sheet charge density vs. Al mole fraction



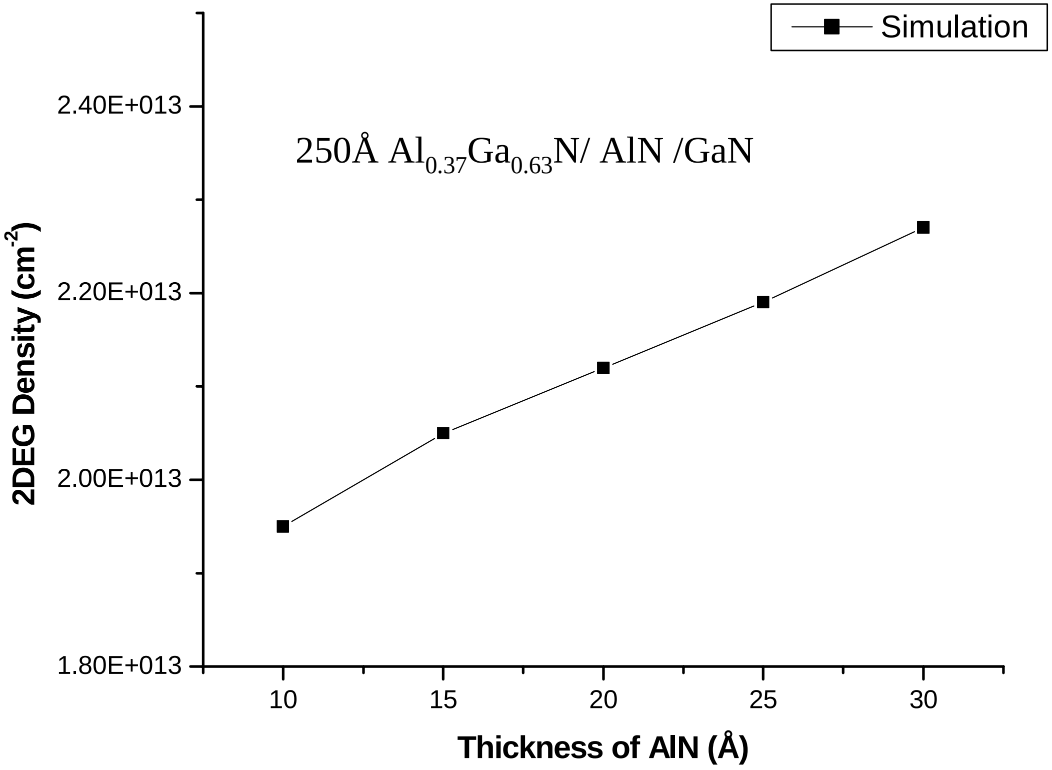
- Strongly dependent on the Al mole fraction

Sheet charge density vs. AlGaN thickness



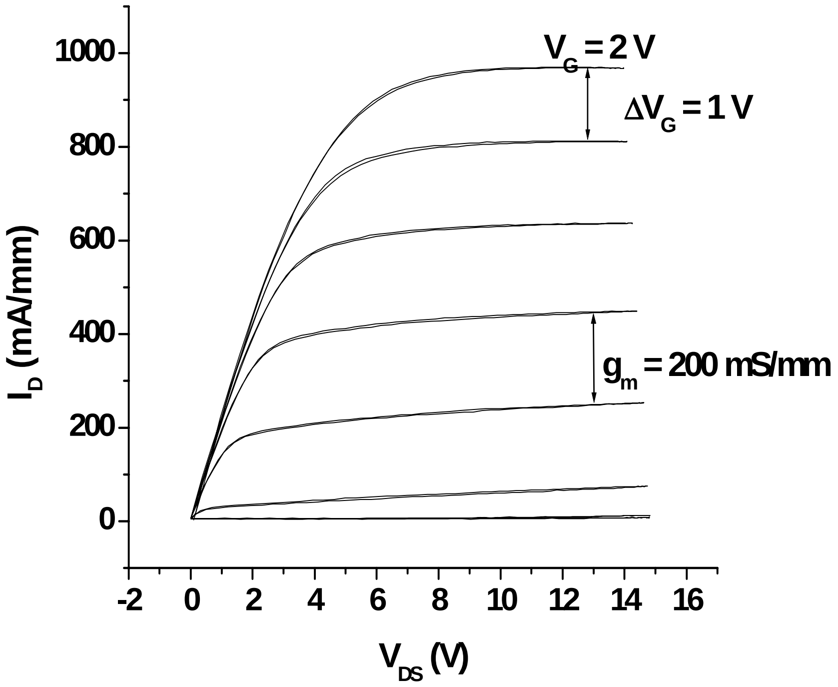
- Weak function of AlGaN thickness
- Faster saturation than conventional AlGaN/GaN HEMT

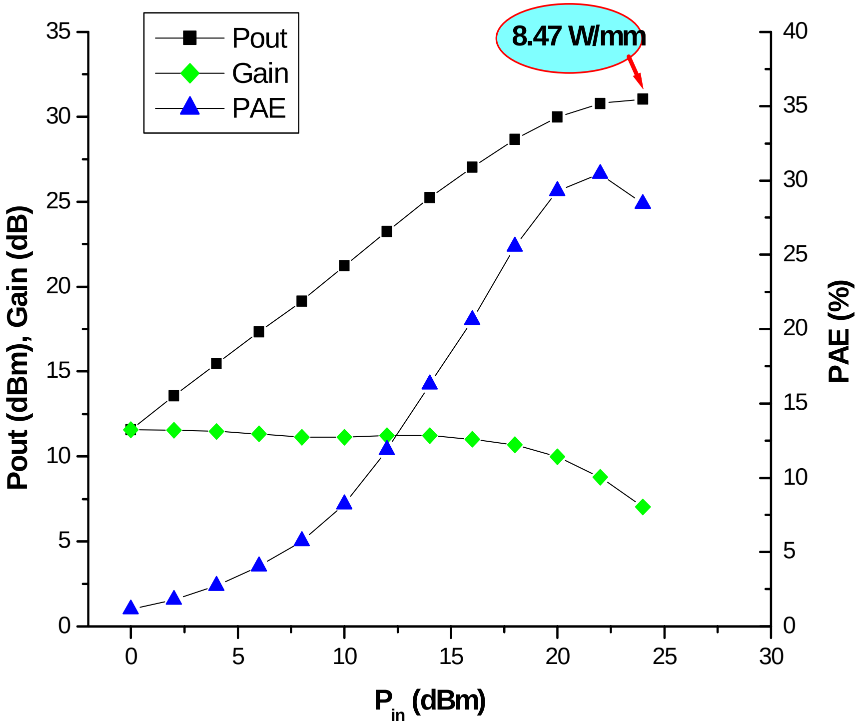
Sheet charge density vs. AlN thickness



- 2DEG increases when AlN is thicker

Device Performance of AlGaN/AlN/GaN HEMT

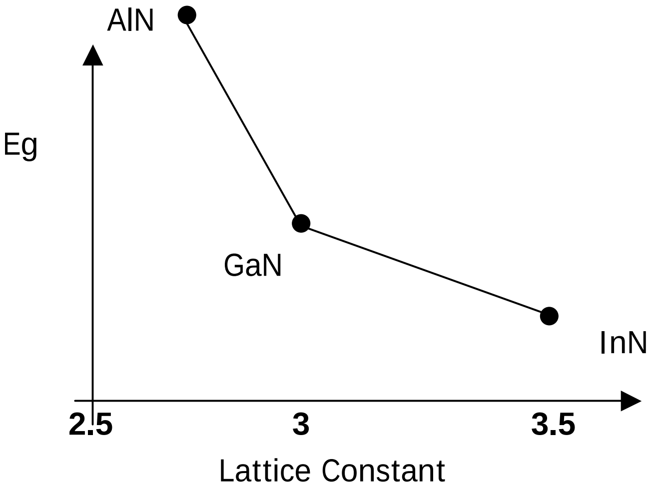


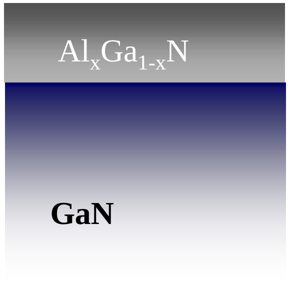


- I_{max} = 950 mA/mm
- g_m = 200 mS/mm

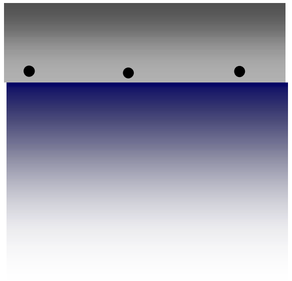
- 8.47 W/mm with a PAE of 28% @ 8GHz
- Bias: class AB at 45 V × 160 mA/mm
- Gate dimension: $0.7 \times 150\ \mu m^2$

Issues With Mazimizing Al Mole Fraction in $Al_xGa_{1-x}N$

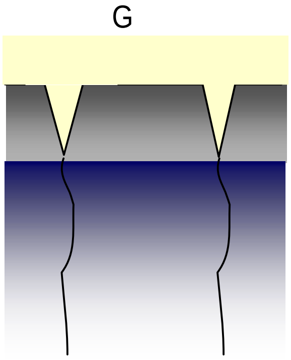




Pseudomorphic

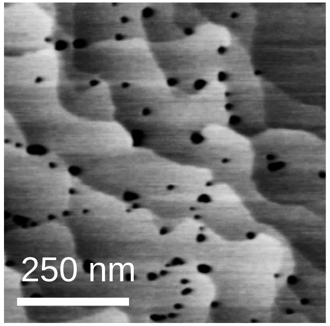


Relaxed with Misfit

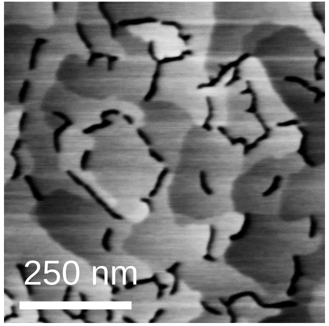


Morphology Mediated
By Dislocaton

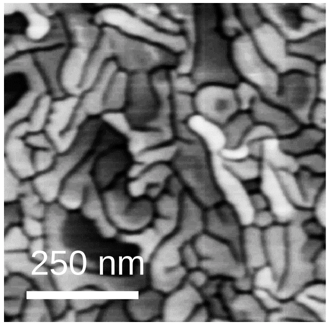
x_{Al} = 0.2



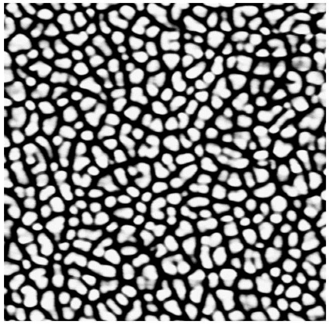
x_{Al} = 0.4



x_{Al} = 0.6



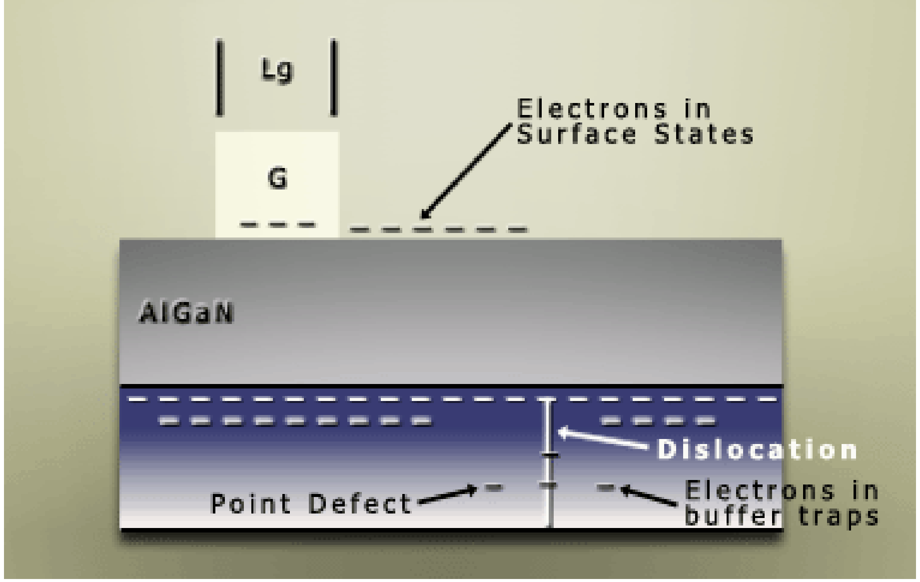
x_{HC}= 0.3



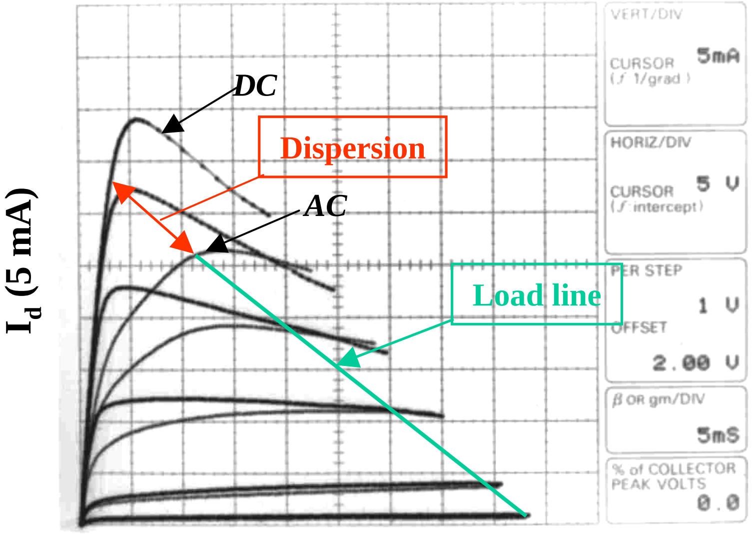
relaxed

DISLOCATIONS LEAD TO PREMATURE RELAXATION OF AlGaN AND A POTENTIAL RELIABILITY PROBLEM BECAUSE OF THE METALLIZED PITS

Minimizing Gate Length Extension



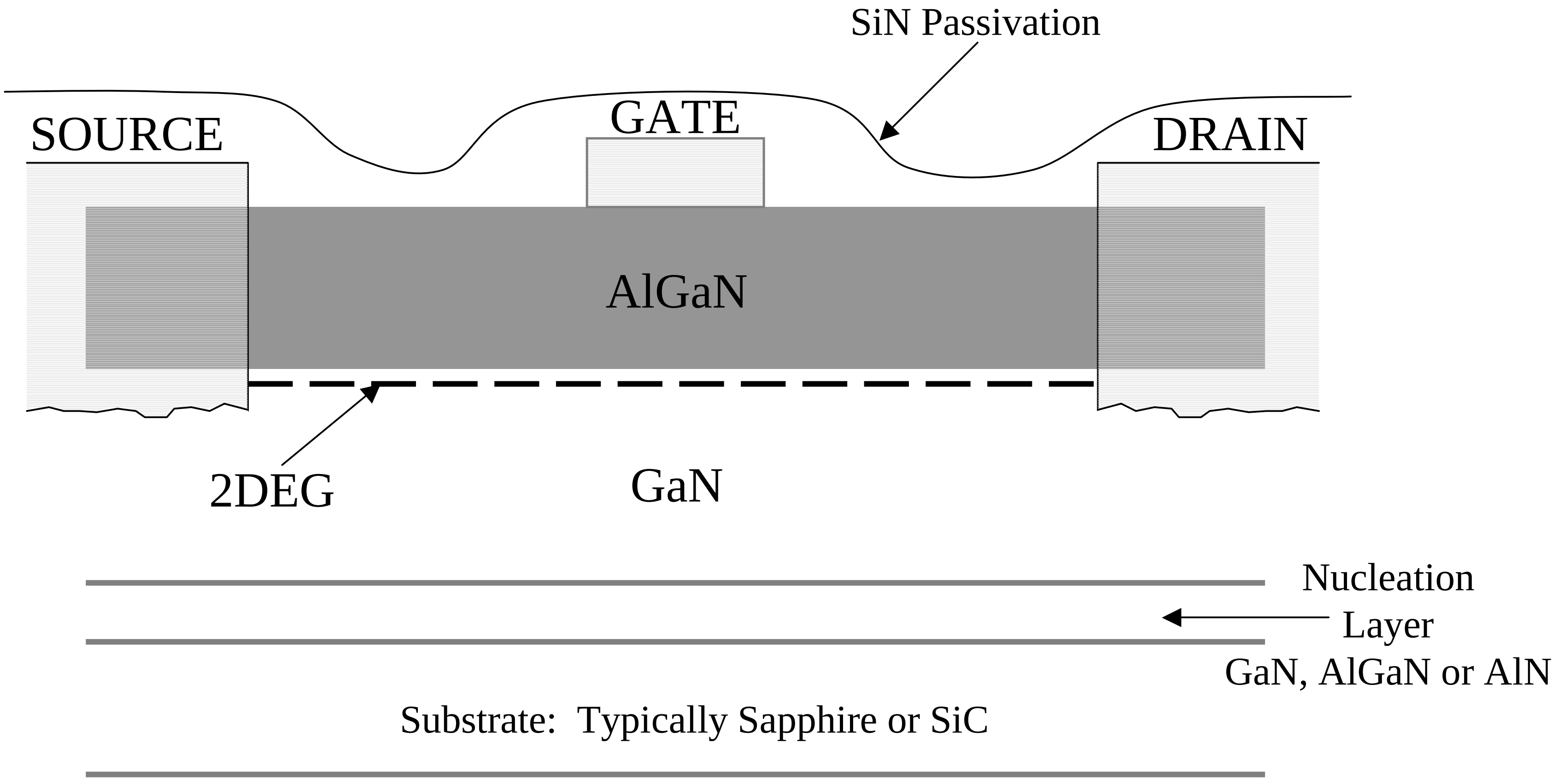
ELECTRONS IN SURFACE STATES AND/OR BUFFER TRAPS DEPLETE THE CHANNEL CAUSING GATE LENGTH EXTENSION



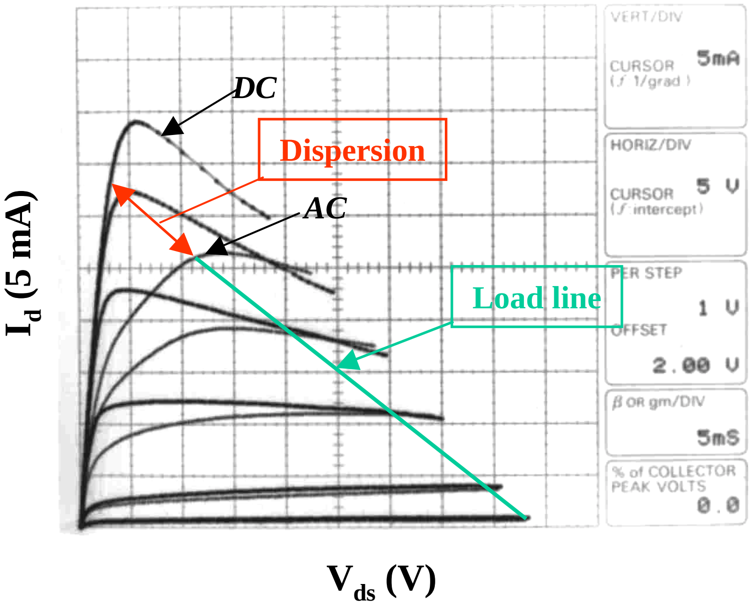
SEVERE CONSEQUENCE: DISPERSION BETWEEN SMALL SIGNAL AND LARGE SIGNAL BEHAVIOR BECAUSE OF THE LARGE TRAP TIME CONSTANTS

WHY DO THESE TRAPS ARISE?

Schematic of Device Structure



Dispersion in AlGaN/Ga HEMTs



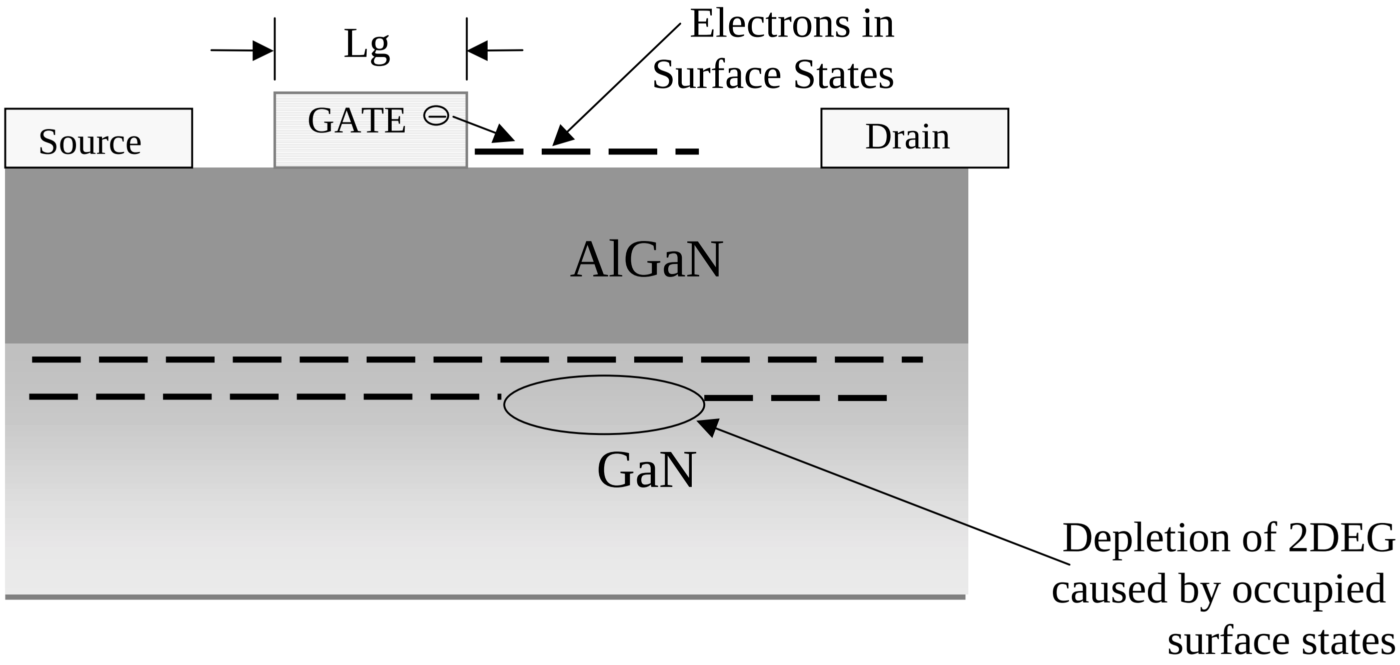
VERT/DIV
CURSOR (∫ 1/grad) 5mA

HORIZ/DIV
CURSOR (∫ intercept) 5 V

PER STEP 1 V
OFFSET 2.00 V

β OR gm/DIV 5mS

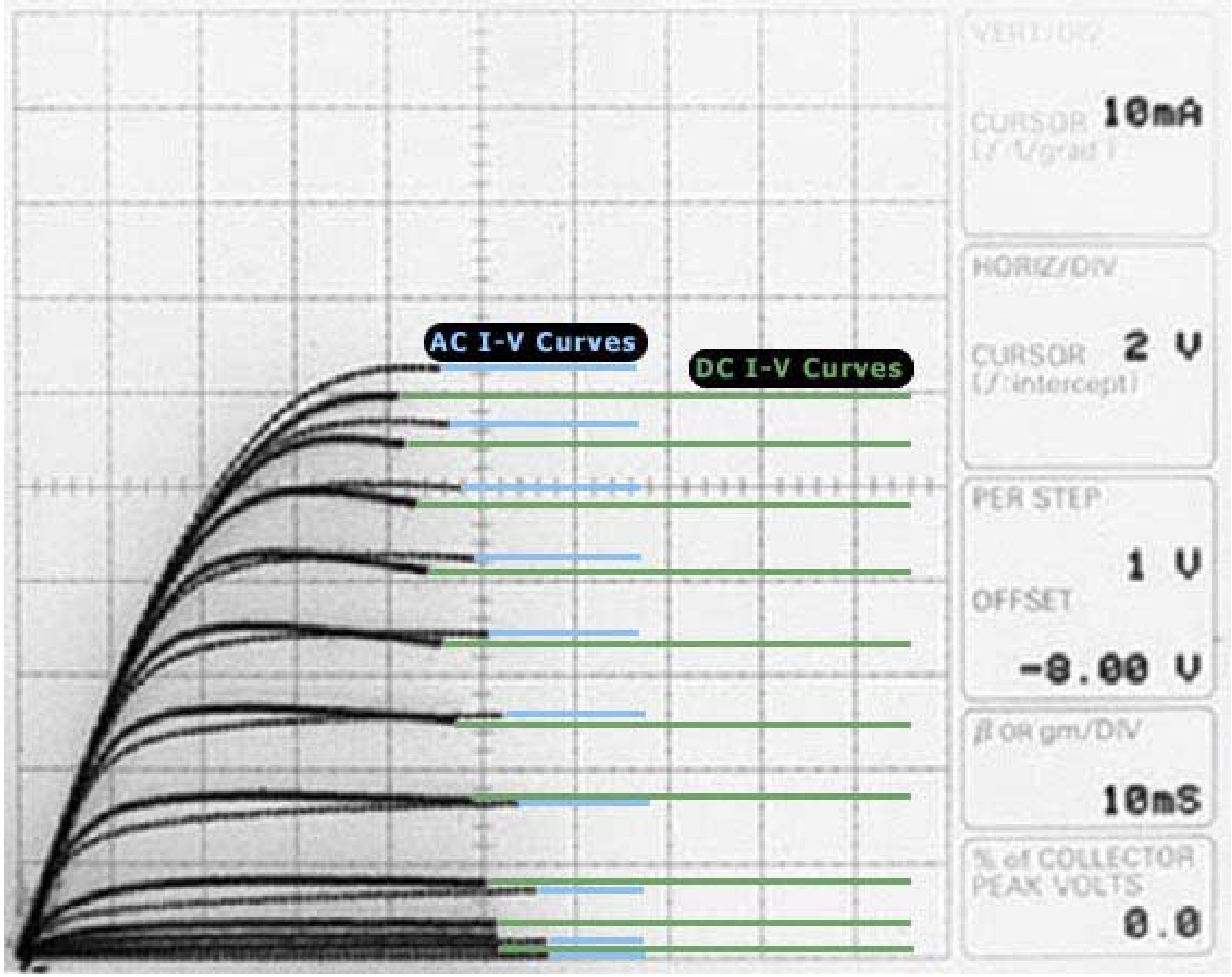
% of COLLECTOR PEAK VOLTS 0.0



Electrons in Surface States

Depletion of 2DEG caused by occupied surface states

Performance of Passivated AlGaN/GaN HEMT on Sapphire



VERT/DIV
CURSOR (/ 1/grad) 10mA

HORIZ/DIV
CURSOR (/ intercept) 2 V

PER STEP 1 V
OFFSET -8.00 V

β OR gm/DIV 10mS

% of COLLECTOR PEAK VOLTS 0.0

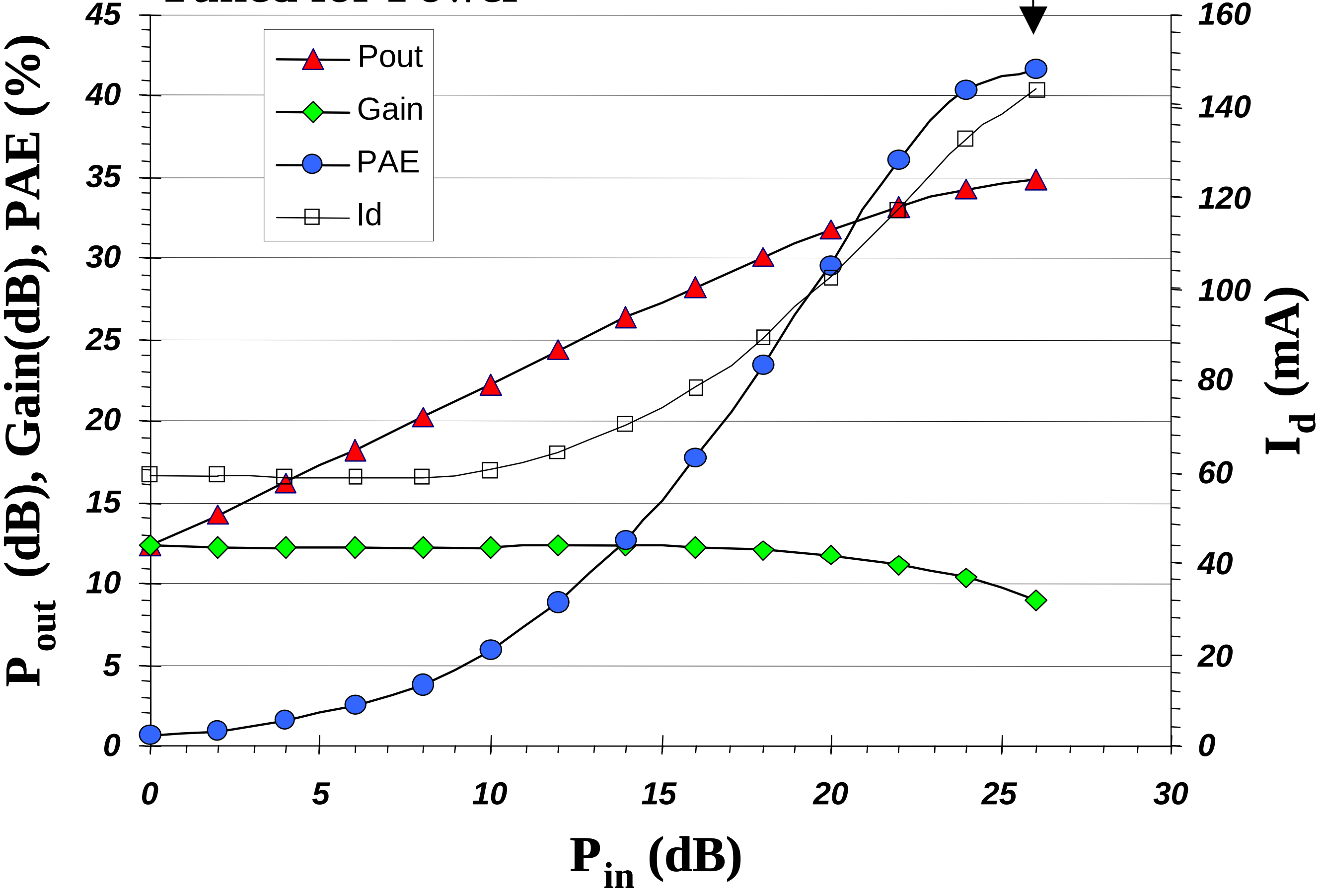
Performance of AlGaN/GaN HEMT on SiC (CLC)

f=8GHz,

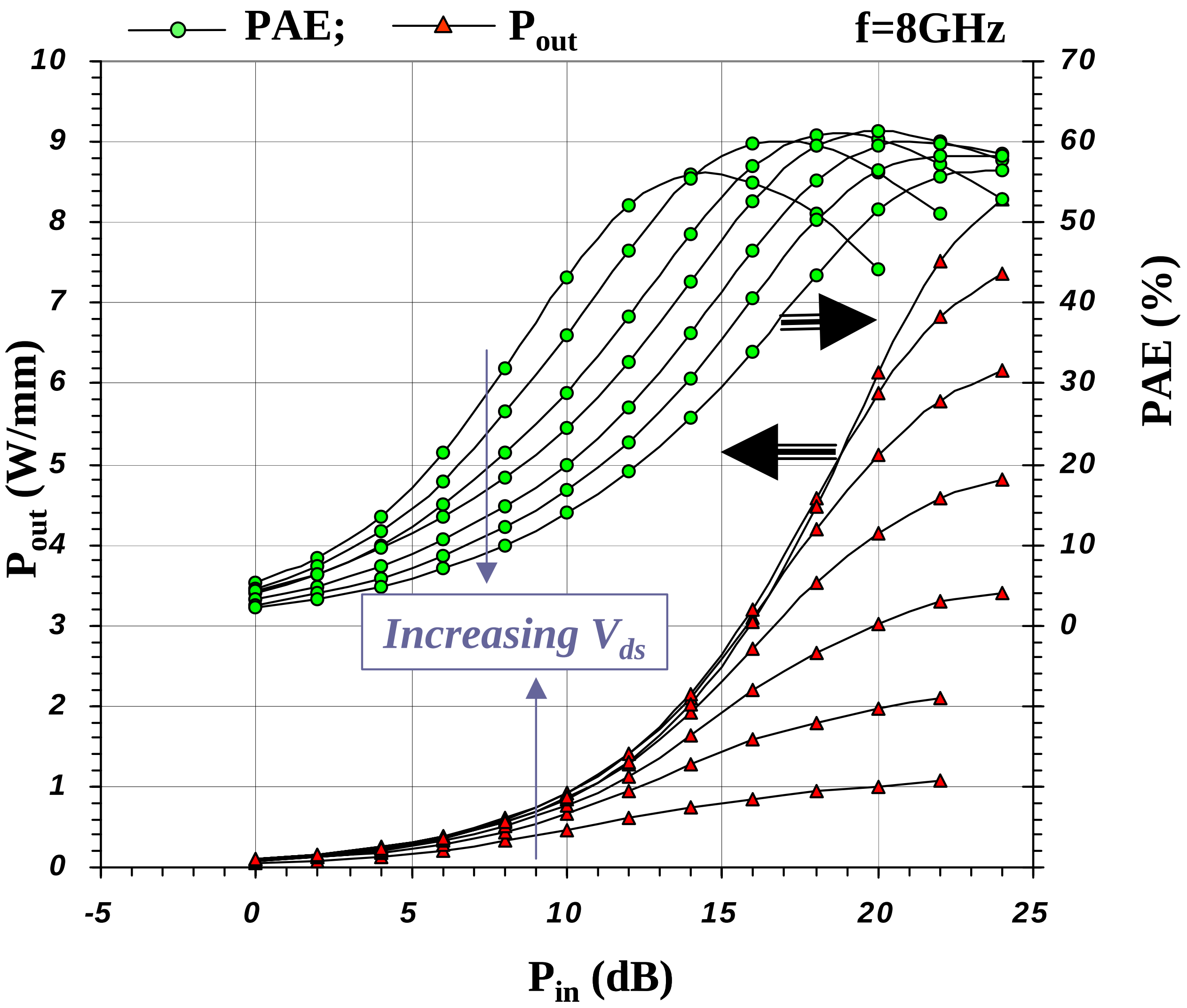
Tuned for Power

P_{out}= 10.3 W/mm

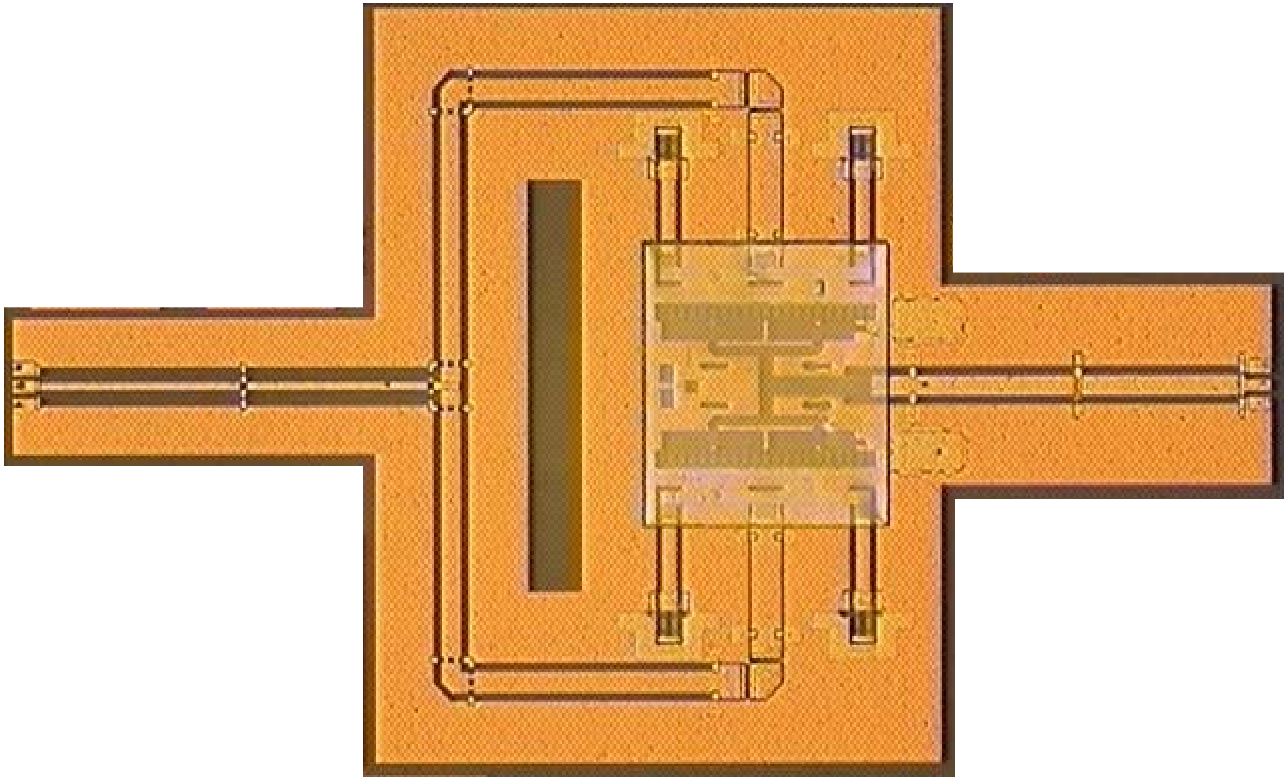
PAE= 42%



Drain Bias Dependence of Rf Power (CLC)

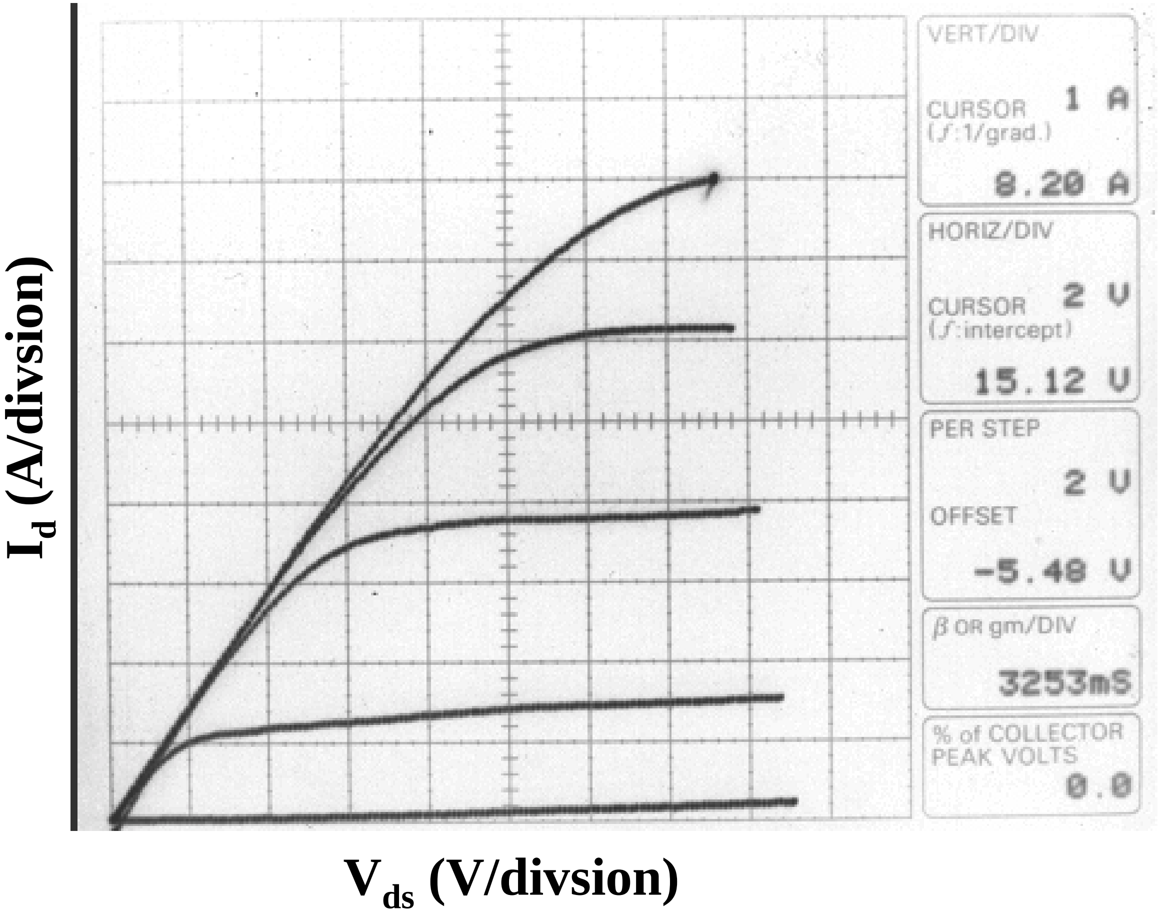


Flip-chip AlGaN/GaN HEMT for Thermal Management



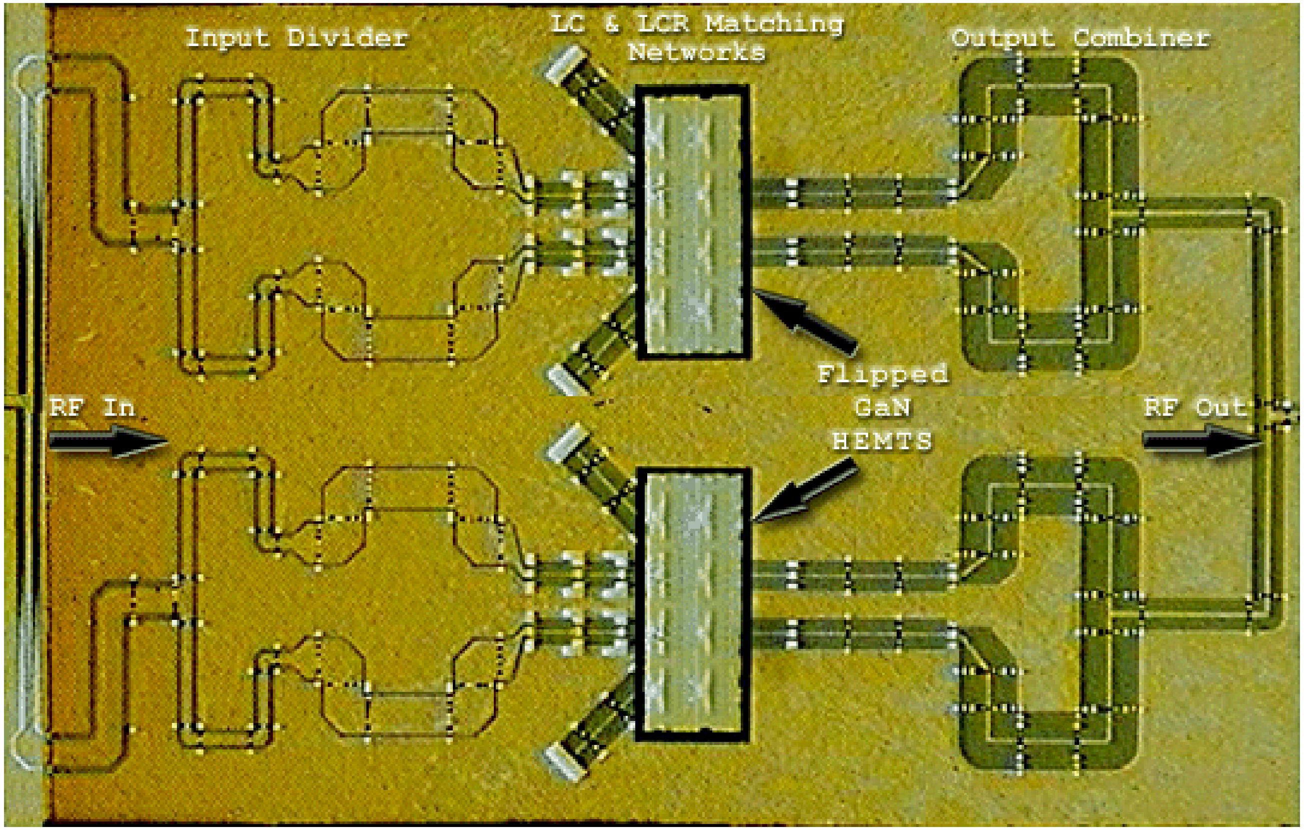
I-V Curves from 8mm-wide HEMT

V_g start: +2V, Step: -2 V

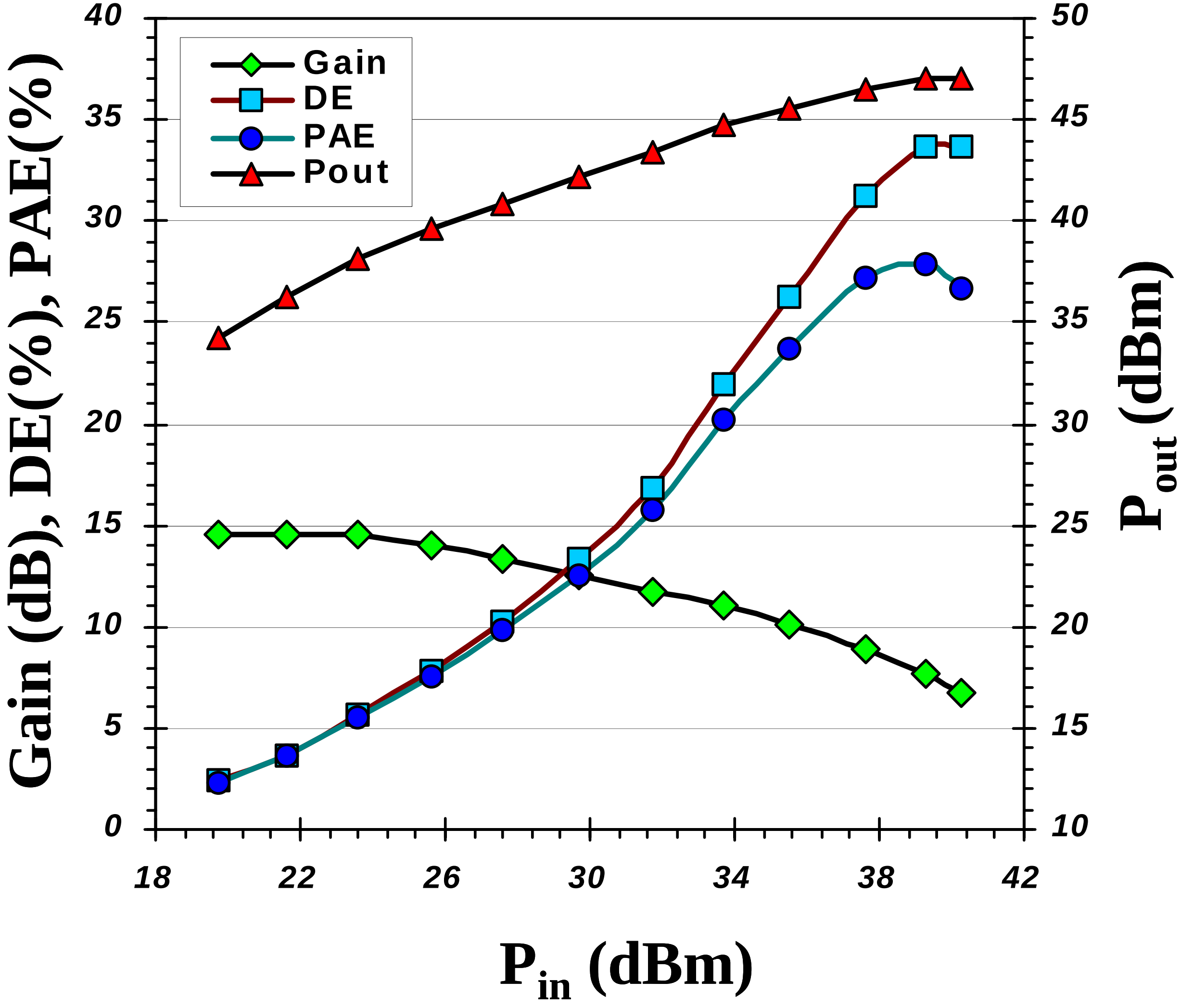


UCSB

Low Flip-chip Wide Bandwidth Amplifier

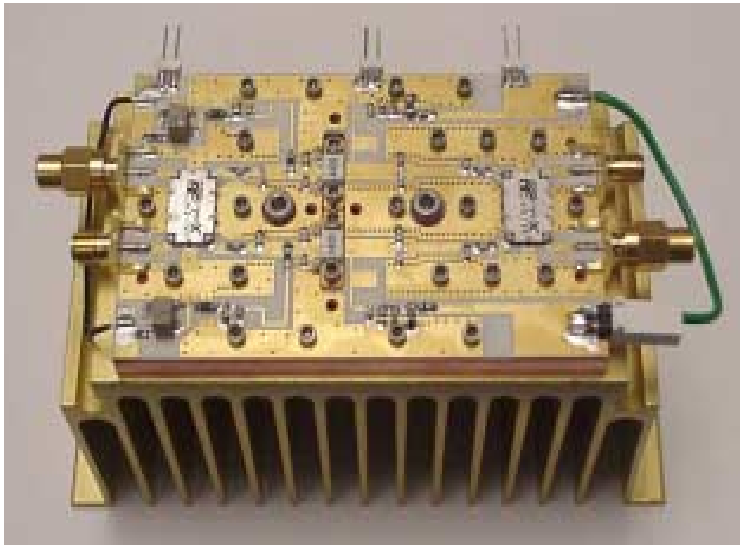


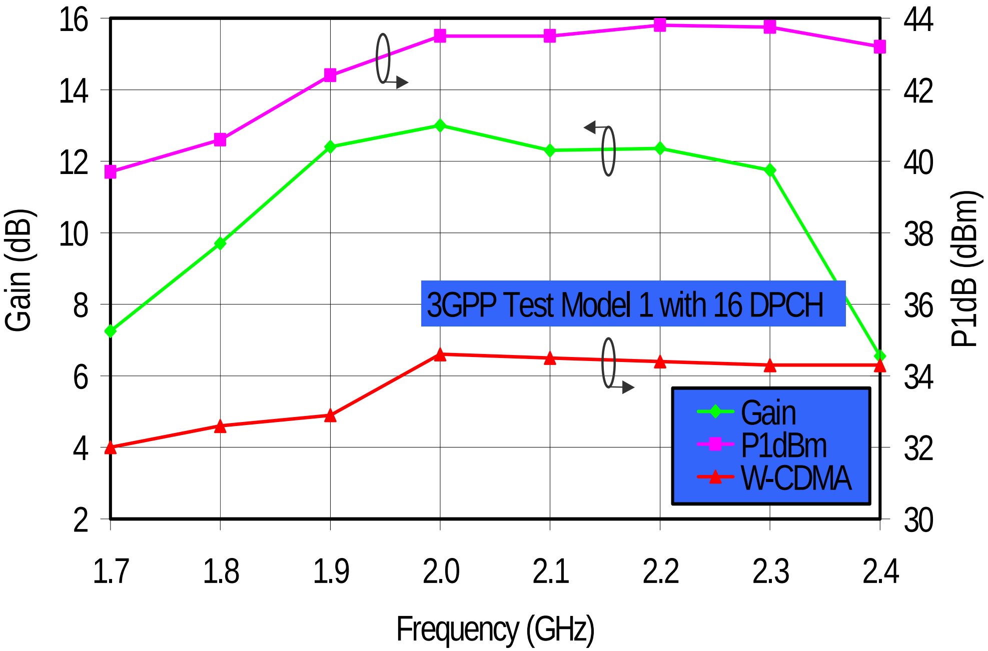
Pulse Power Performance of mm-flipped Device



CREE, Inc.

20-Watt Broadband SiC MESFET Amplifier

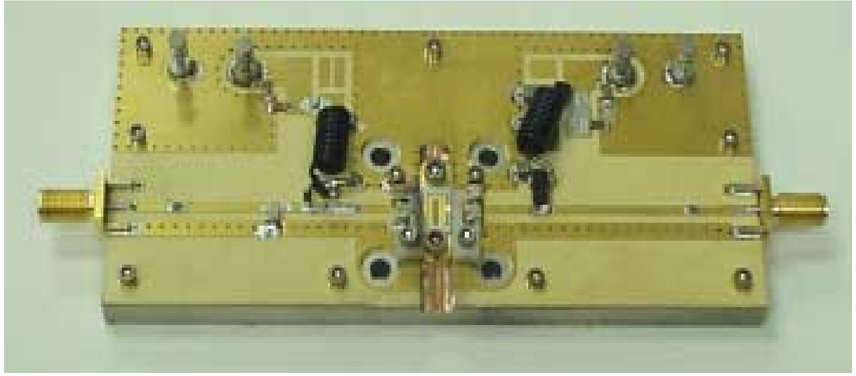




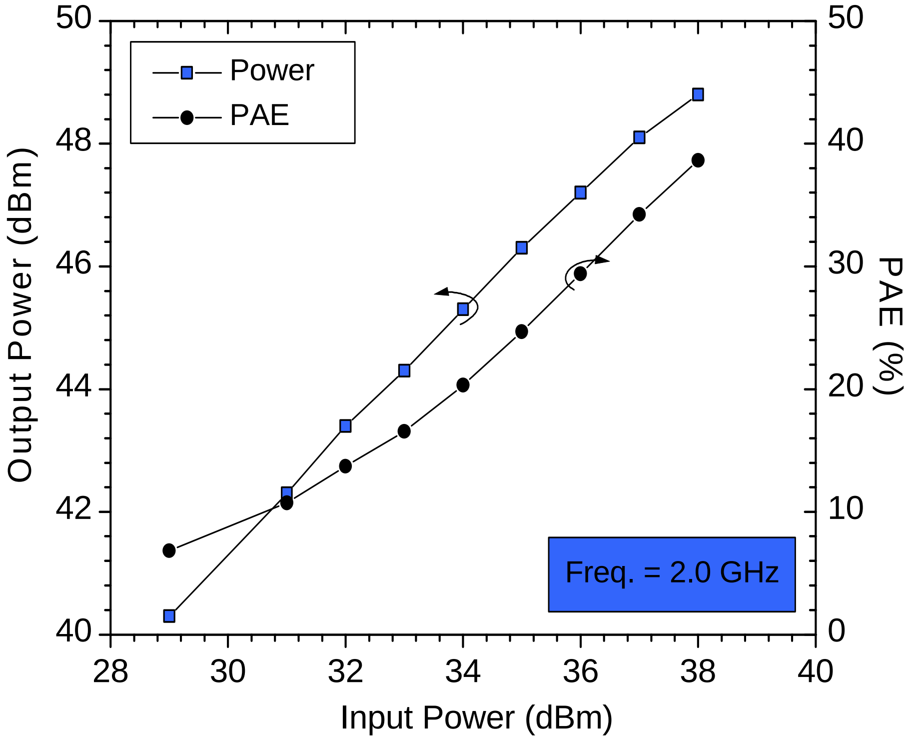
Balanced amplifier with Cree's 10-Watt commercial FETs, CRF22010

- 22 W at P_{1dB} across a 400 MHz band
- Advantage of wide bandgap transistors: power-bandwidth product greatly exceeding Si LDMOS

75-Watt SiC MESFET Amplifier

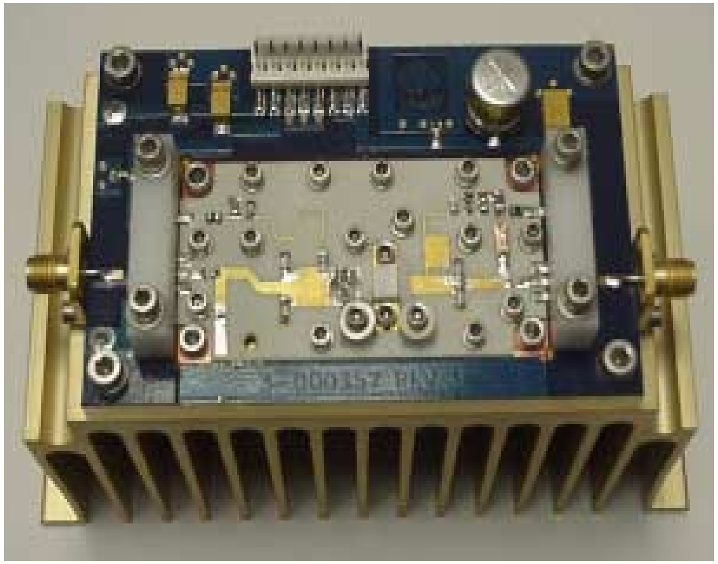


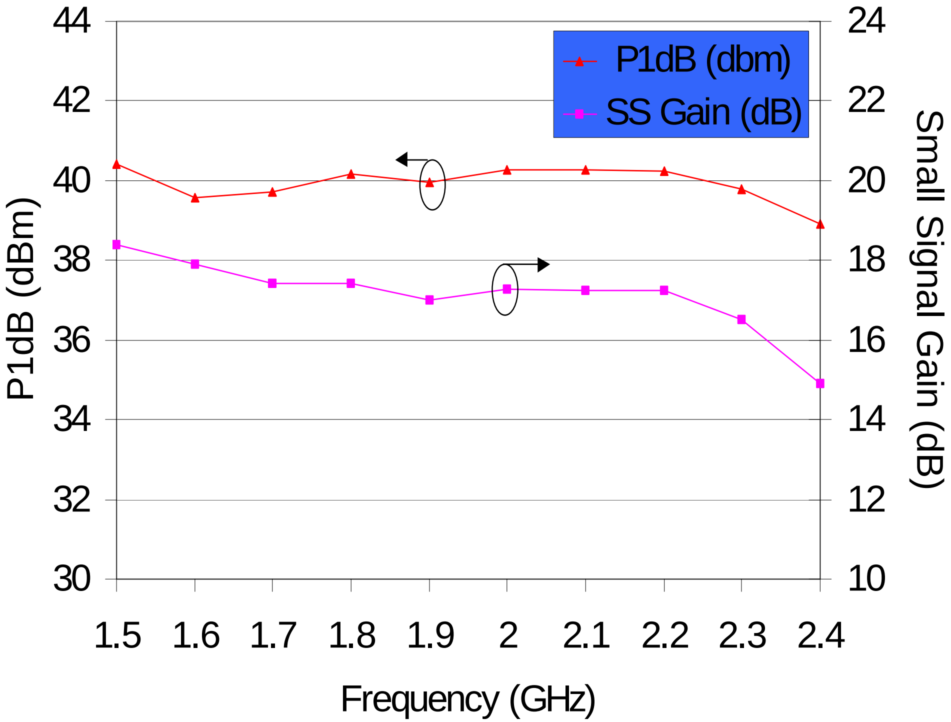
2 GHz test fixture for 60 W MESFET development



- 75 W CW, 11 dB gain demonstrated from a single SiC MESFET
- Currently being optimized for a 60-Watt Class A MESFET product, targeted for release by the end of the year

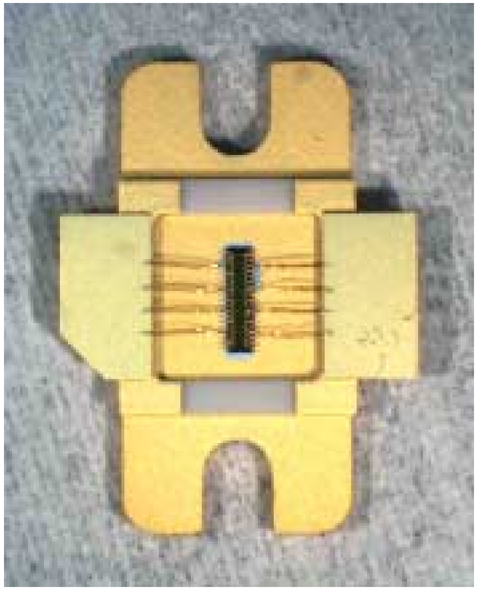
10-Watt Broadband GaN HEMT Amplifier



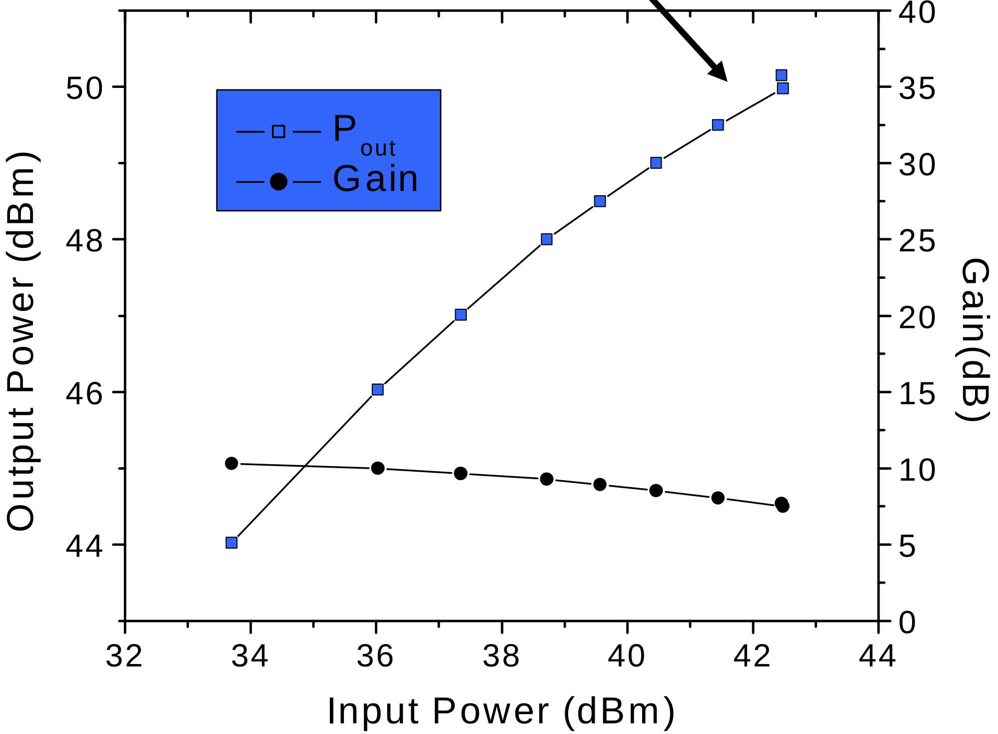


- 11 W at P_{1dB} across the 1.8 - 2.2 GHz band
- 17 dB gain with only ±0.15 dB ripple

Demonstration of 100W CW GaN HEMT



- Freq. = 2 GHz
- V_{DS} = 52V
- Peak Drain Eff. = 54%
- 108 W achieved at P_{3dB}



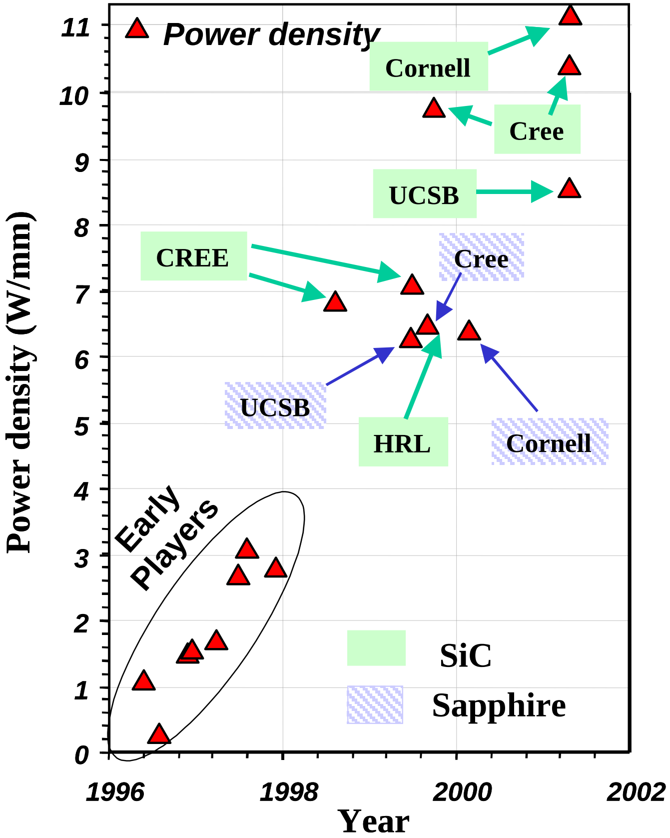
103W @ 2.6 dB compression

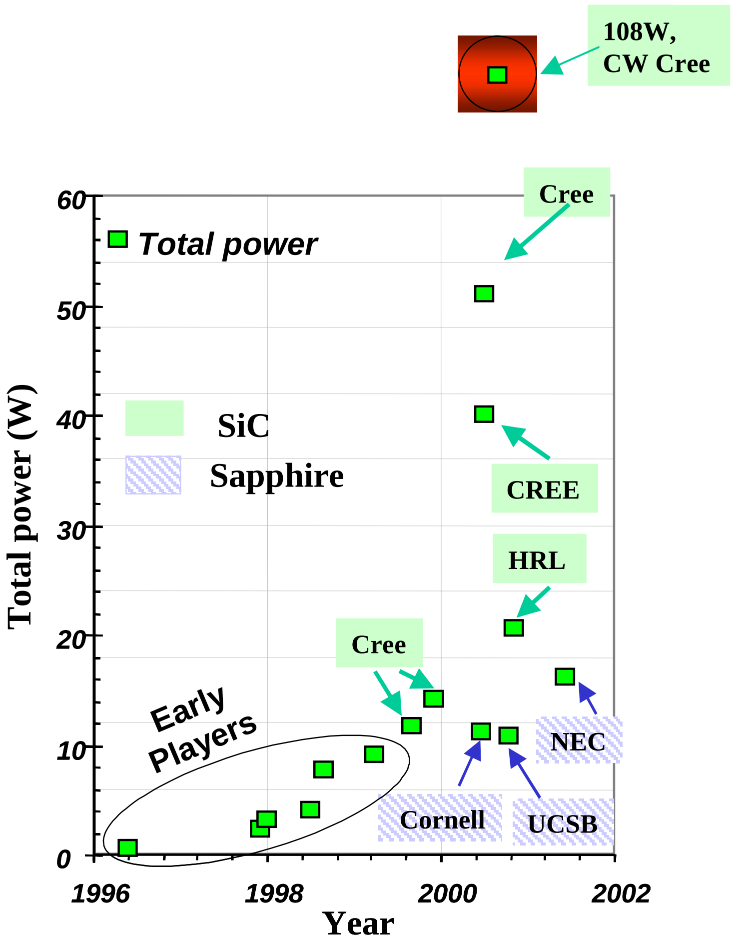
Sponsored by Tom Jenkins,
DUS&T/AFRL

Summary of Technology Status

- Commercially-available SiC MESFETs
  - 22 W broadband amplifier demonstrates power-bandwidth advantage of this technology
  - 60 W Class A MESFET targeted for release by end of year
- GaN HEMTS on SiC Substrates
  - excellent broadband and high power performance demonstrated
  - emphasis of development is now on reproducibility and reliability
- SiC-based MMIC process developed for both technologies
- 3-inch SI substrates will enable cost-competitive manufacturing

Power Performance vs. Year





- Includes ALL LEADING players in the field
- CREE = Cree Lighting + Cree-Durham

Part II

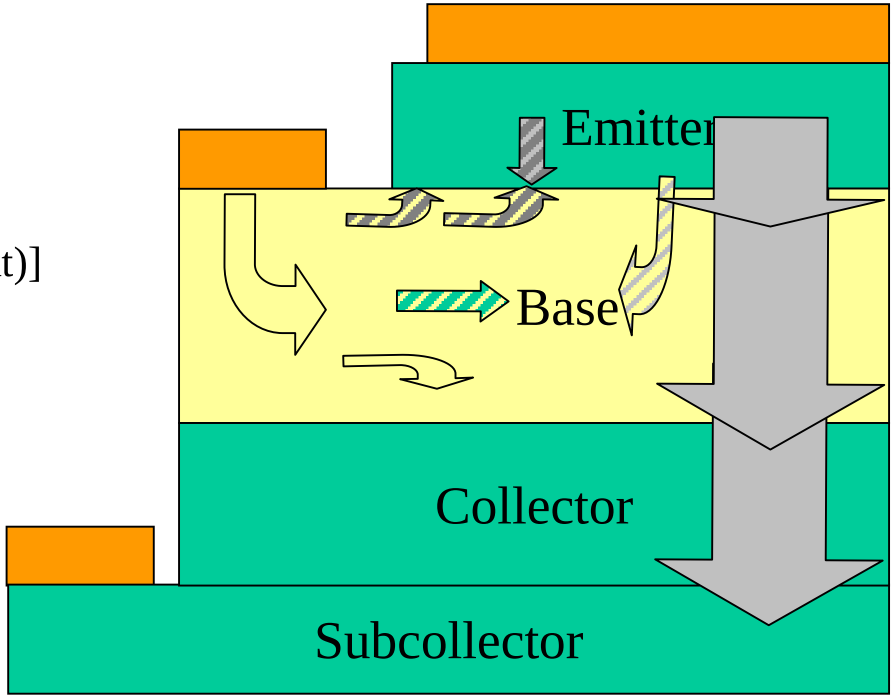
High Voltage Operation (> 330 V) of AlGaN/GaN HBTs

UCSB

Bipolar transistor key issues

- Injection
  - $\gamma \Rightarrow 1$
  - $n \Rightarrow 1$

    $[I = I_0 \exp(qv/nkt)]$



Transport

-- $\alpha \Rightarrow 1$

Collection

- $C_{bc} \Rightarrow 0$
- $v \Rightarrow v_{sat}$ **[2 x 10^7 cm/s]** *(Kolnik et. al.)*
- $V_{br} \Rightarrow E_{crit} W_C$ **[E_{crit} ~ 2 MV/cm]** (*Bhapkar and Shur*.)

Output Conductance

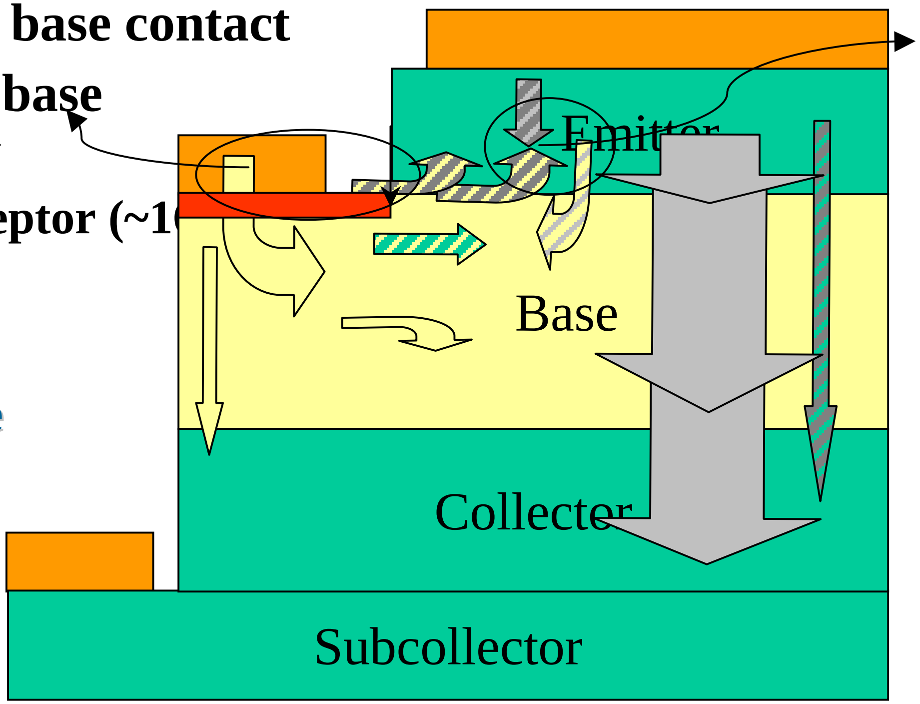
- $\Delta I_C/\Delta V_{CE} \Rightarrow 0$

  $(\Delta W_B/\Delta V_{CE} \Rightarrow 0)$

Hurdles with GaN bipolar transistors

- Lack of low damage etch to reveal base
  - Leaky E/B junction
  - Bad base contact
  - No etch stop
- High R_B
  - Poor p-GaN base contact
  - Low p-GaN base conductivity
    - Deep acceptor (~1

- Hard to control junction placement in MOCVD due to memory effect of p-dopant Mg



Low minority carrier lifetime

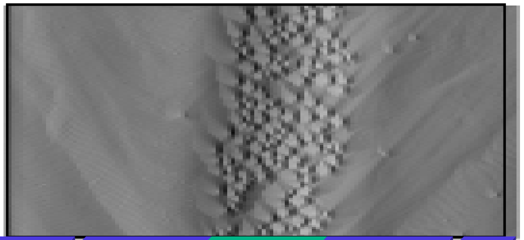
Dislocation causes leakage

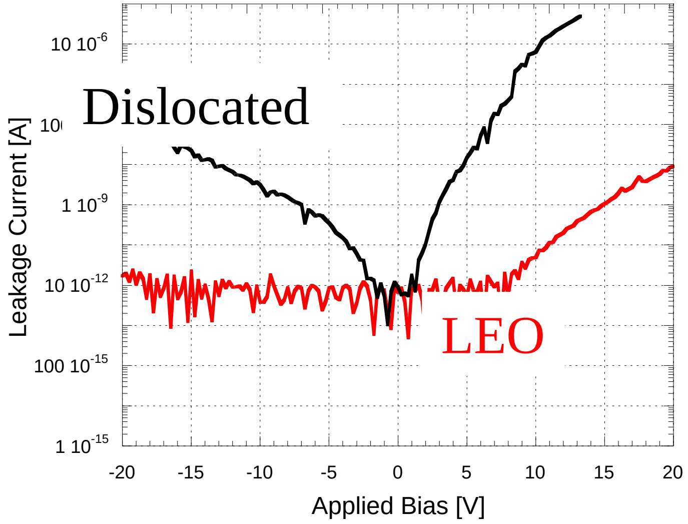
Surface leakage due to etch damage

Demonstration of dislocation enhanced leakage

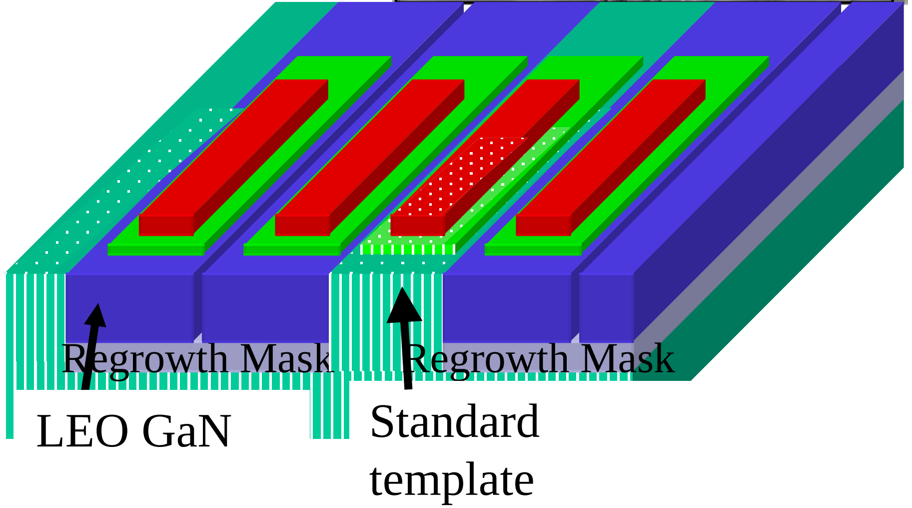
LEO used to investigate leakage of devices without dislocations. (Lee McCarthy et al.)

AFM scan of wing vs Window on LEO GaN





Leakage from Collector to Emitter, Wing vs Window



Results: LEO device demonstrated

- Reduction in Leakage
- Stable operation past 20V
- Gain unchanged
- Devices on dislocated material also functional

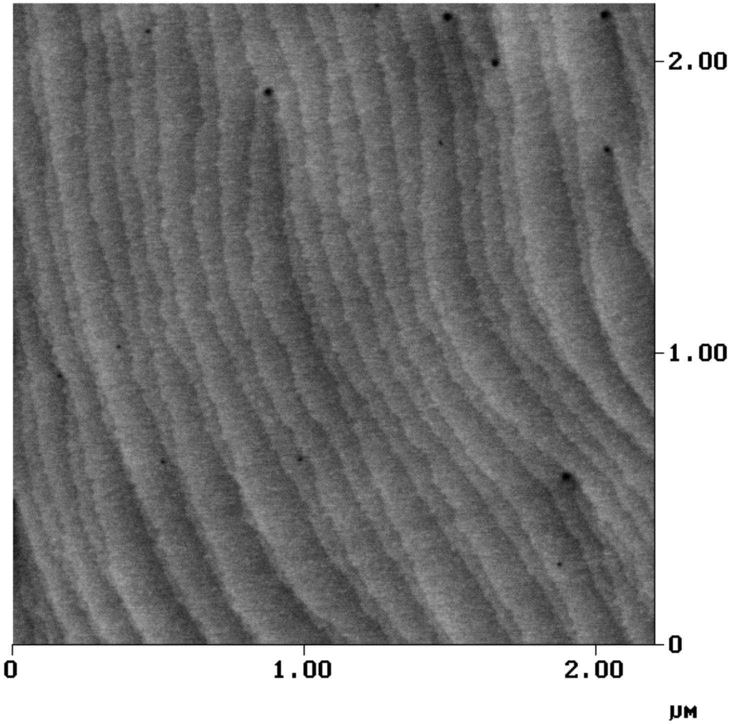
Explanation

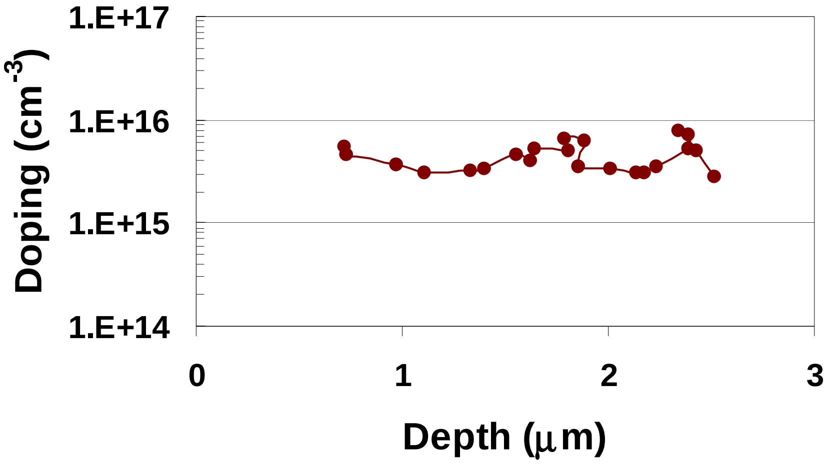
- Thick substrate sufficiently reduces dislocations to prevent C/E short in window region
- Gain (τ_e) not currently limited by dislocation density

Strategy: Thick Collector

- Decent dislocation density
  - High quality MOCVD templates achieved

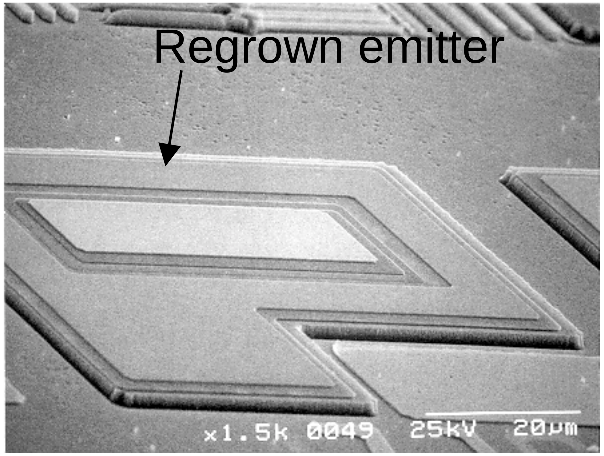
    Dislocation density ~ 5e8 cm^{-2}
- Low background doping
  - $N_D < 1e16$ cm^{-3} (Assuming uniform doping N_D and $E_{critical}$ = 2 MV/cm, requires 10 µm to achieve 1 KV breakdown voltage.)

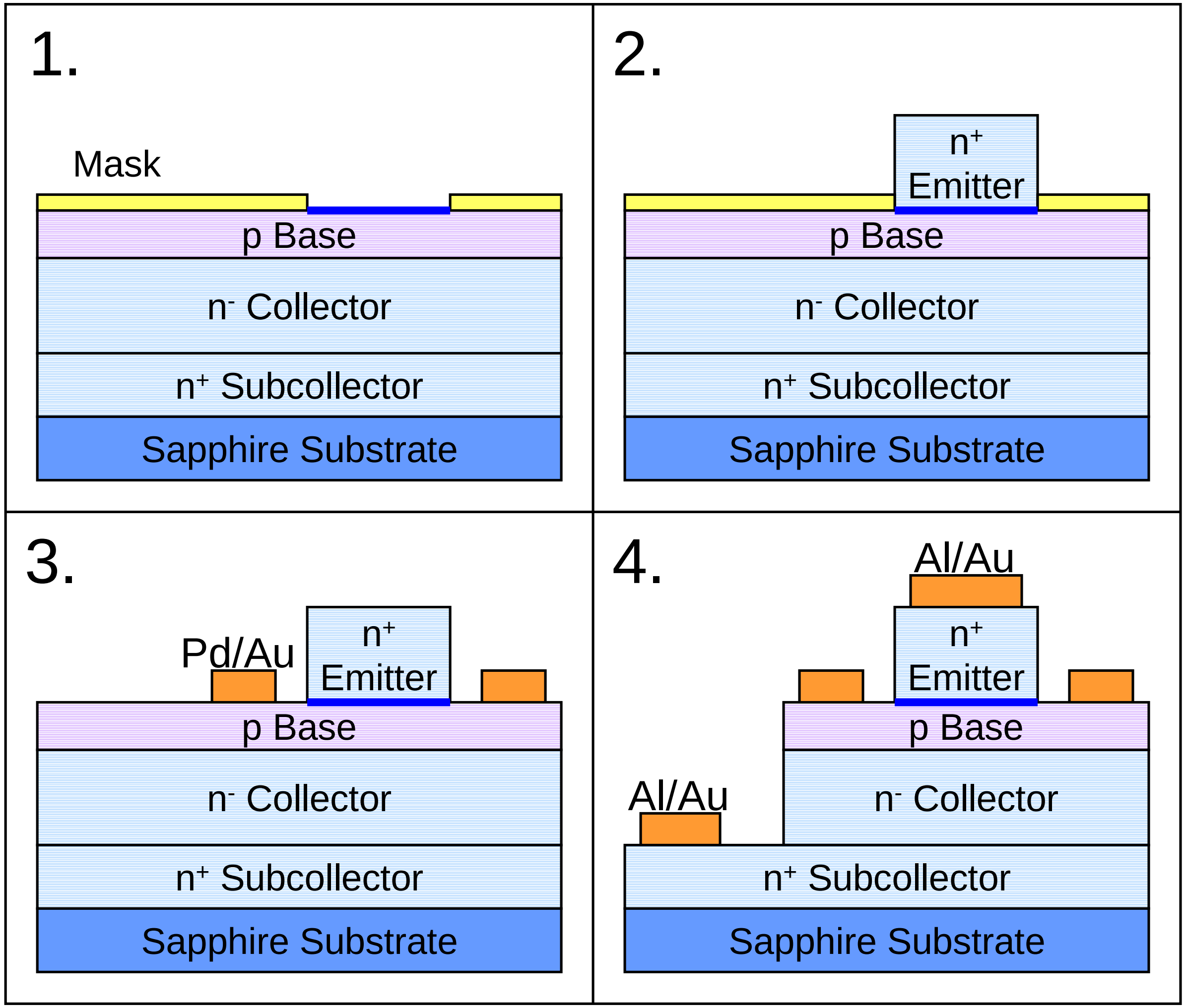



Doping vs. Depth (010704GA, 8 µm collector)

Emitter Regrowth Process Flow

- **Selectively grow MOCVD emitter on base-collector structures.**
  1. Pattern regrowth mask
  2. Regrow emitter layer by MOCVD
  3. Remove mask and contact base and etch to collector
  4. Contact collector, emitter





Device structure

- Utilization of uid GaN spacer and grading layer
  - HBTs with high emitter injection coefficiency
- Etch damage and current mask layout limits V_{br}

4 nm GaN:Si (1e18 cm^{-3}) contact

4 nm $Al_{0.05}$ GaN->GaN:Si (1e18 cm^{-3}) grading

105 nm $Al_{0.05}$ GaN:Si (1e18 cm^{-3}) emitter

8 nm GaN->$Al_{0.05}$ GaN (?3e18 cm^{-3}) grading

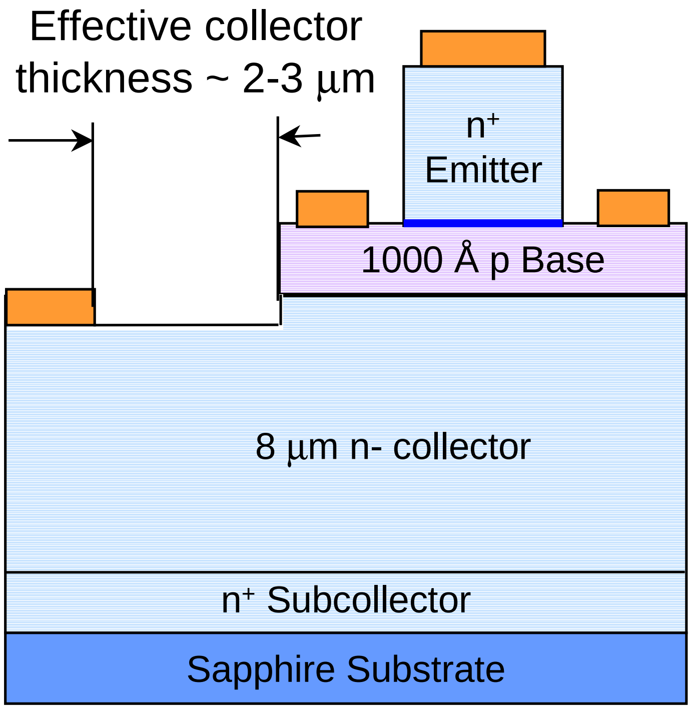
8 nm uid GaN spacer

100 nm GaN:Mg (2e19 cm^{-3}) base

8 μm uid GaN (4e15 cm^{-3}) collector

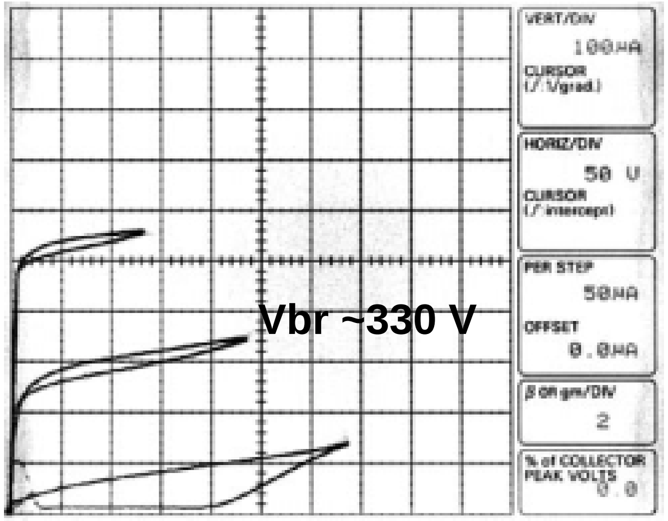
2 μm GaN:Si (1e18 cm^{-3}) subcollector

Sapphire

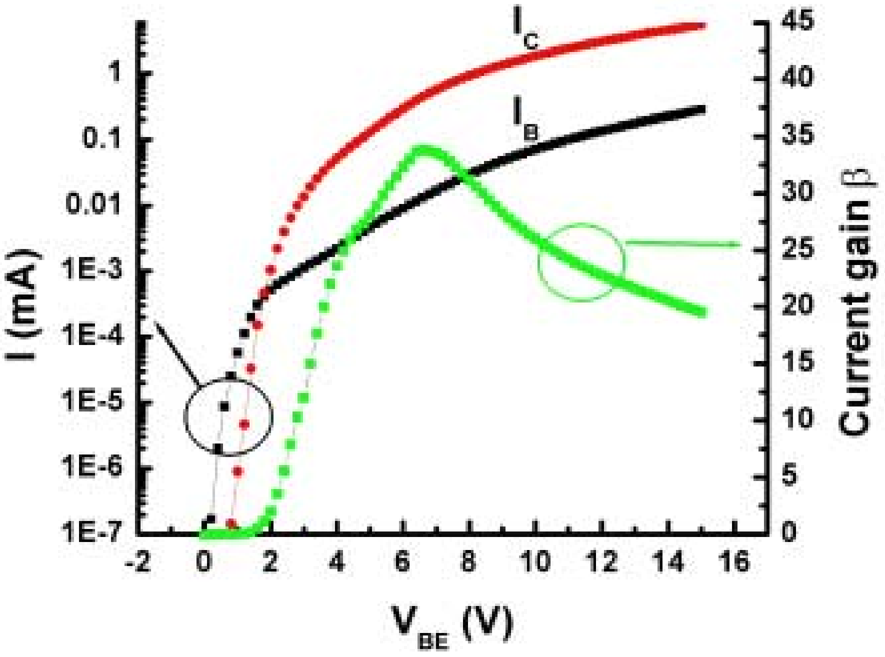


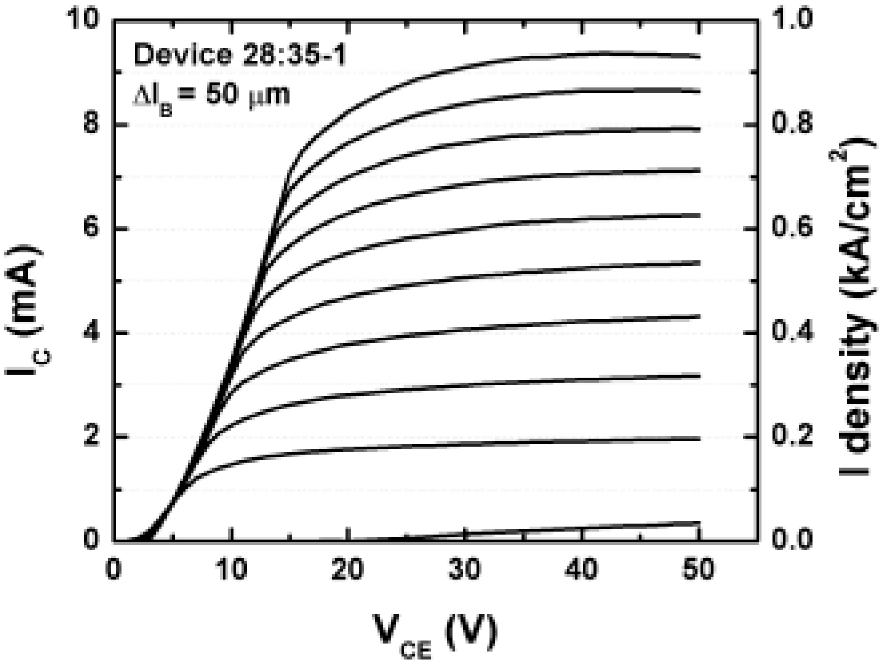
UCSB HBT with 8 mm GaN collector

- Current gain (β) > 20
- Common emitter operation > 300 V
- Non-passivated
- Base thickness 1000 Å
- $Al_{0.05}GaN$ emitter



Vbr ~330 V





Summary

- Conclusion
  - In selective emitter regrowth, a sharp Mg profile, ~ 40 nm/decade, enables the precise junction placement
  - Improvement of regrown-emitter/base diodes
  - Demonstration of high Vbr (> 300 V) with high β (DC common emitter operation up to 35)