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

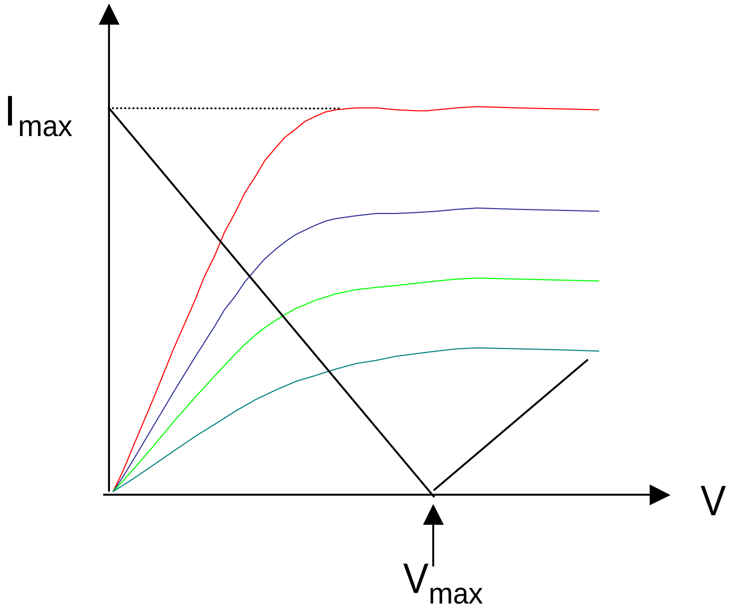
BFOM = Baliga's figure of merit for power transistor performance [$K*\mu*Ec^3$]
JFM = Johnson's figure of merit for power transistor performance
(Breakdown, electron velocity product) [$Eb*Vbr/2\pi$]

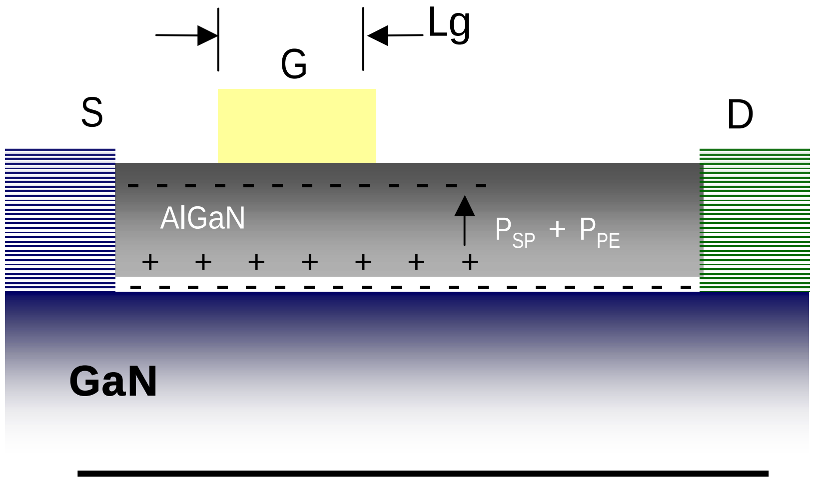
Advantages of WBG Devices

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

DC Device Level Issues (HEMTs)

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



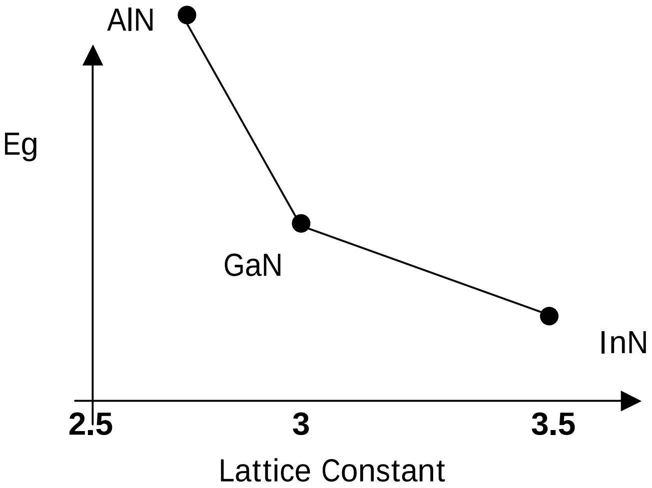


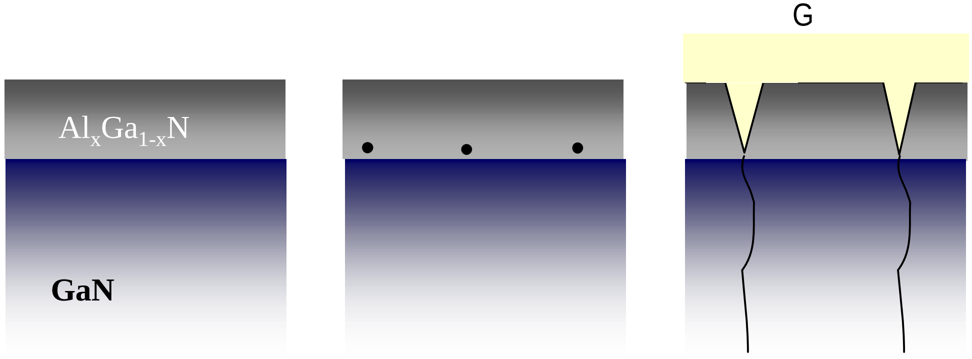
$$P_{max} = \frac{1}{8} V_{max} \cdot I_{max}$$

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

- 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

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



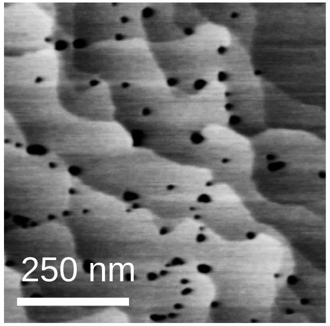


Pseudomorphic

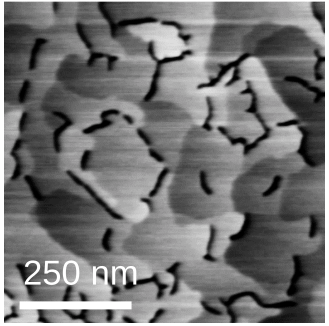
Relaxed with Misfit

Morphology Mediated
By Dislocaton

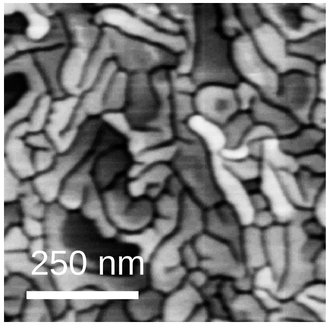
x_{Al} = 0.2



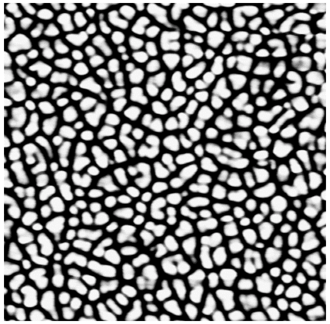
x_{Al} = 0.4



x_{Al} = 0.6



x_{HC}= 0.3



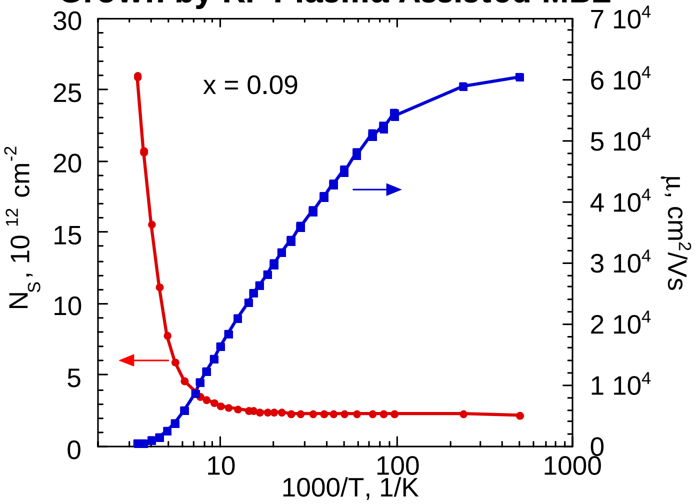
relaxed

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

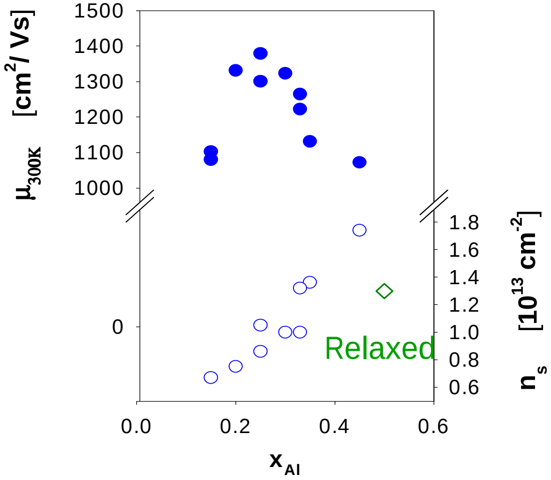
Issues With Increasing Mobility

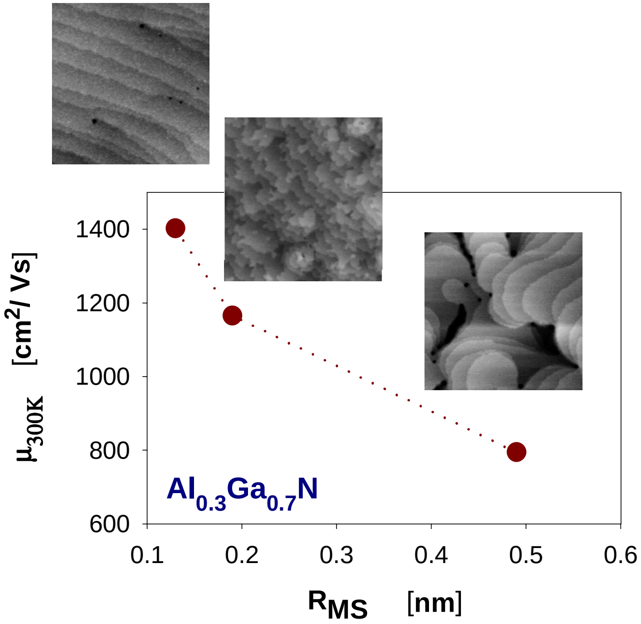
INCREASING Al MOLE FRACTION DECREASES MOBILITY

High Mobility AlGaN/GaN Structures Grown by RF Plasma Assisted MBE

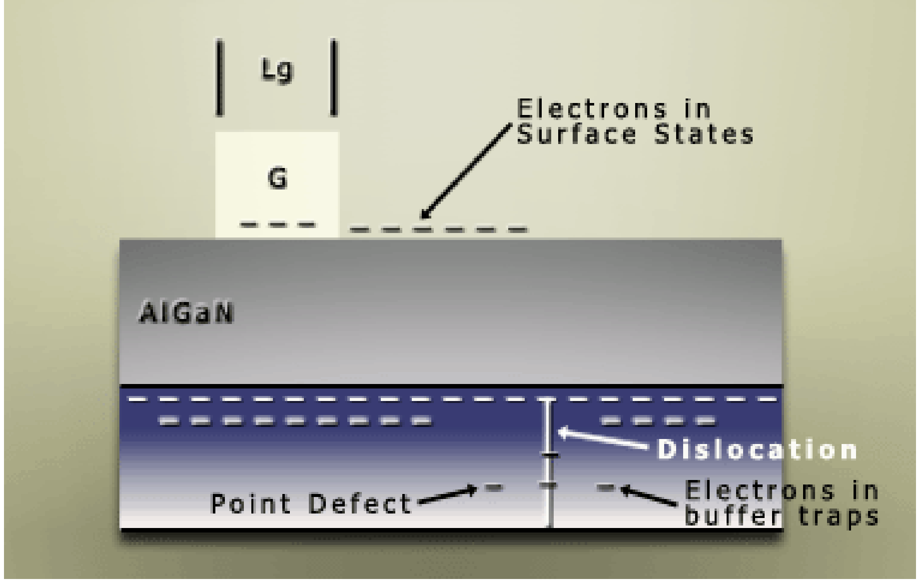


Mobility v. Al Fraction Plot

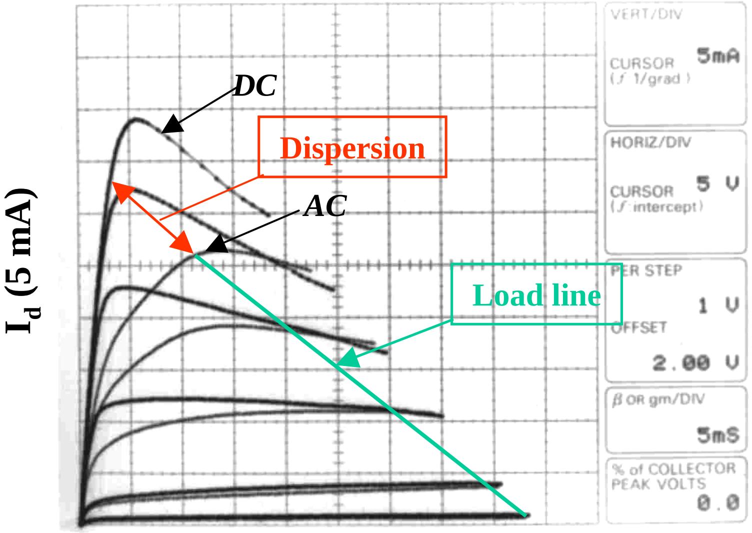




Minimizing Gate Length Extension



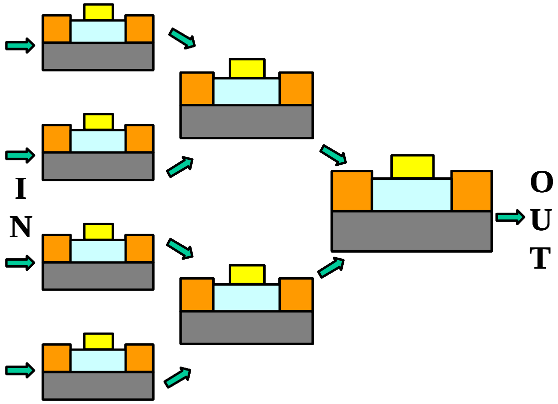
ELECTRONS IN SURFACE STATES AND/OR BUFFER TRAPS DEPLETE THE CHANNEL CAUSING GATE LENGTH EXTENSION



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

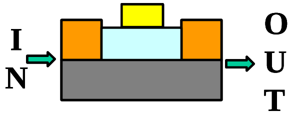
WHY DO THESE TRAPS ARISE?

Example of Advantage of WBG Devices



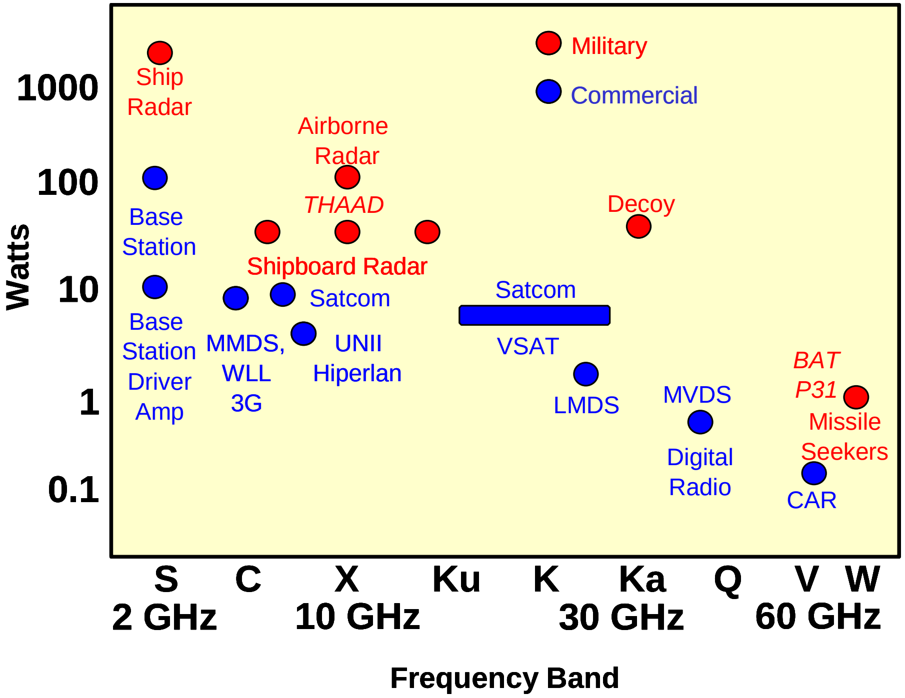
GaAs High Power
Amplifier Module

- 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

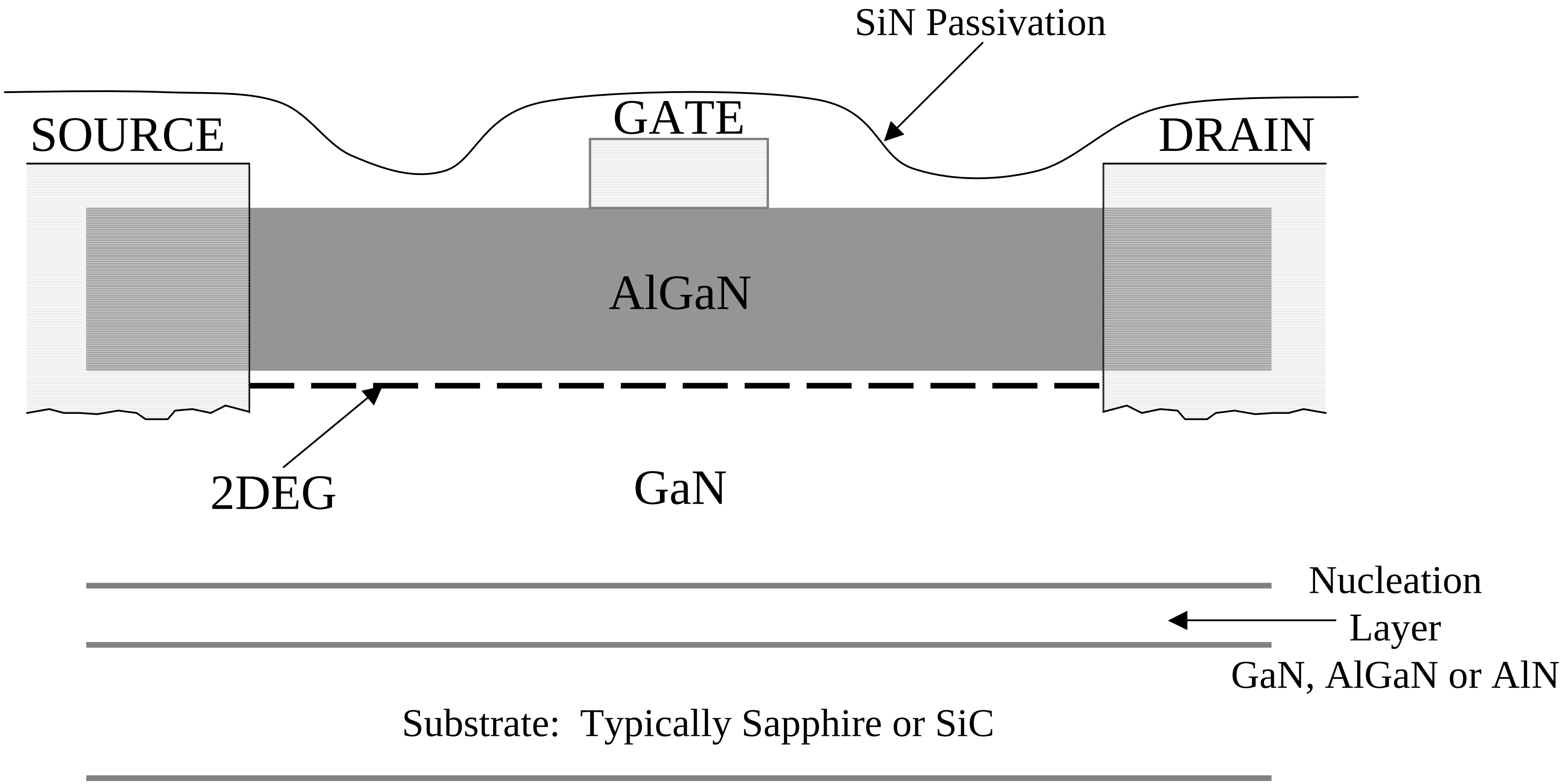


Equivalent
High Power
GaN Amplifier
Module

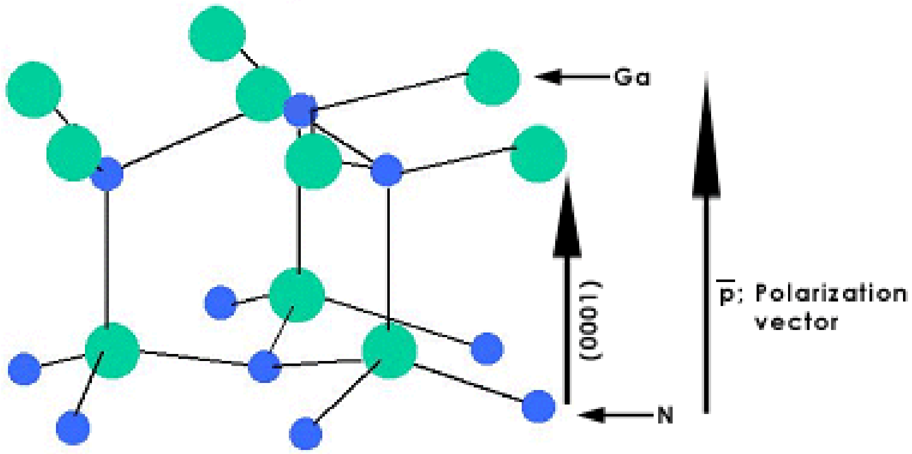
Application Space



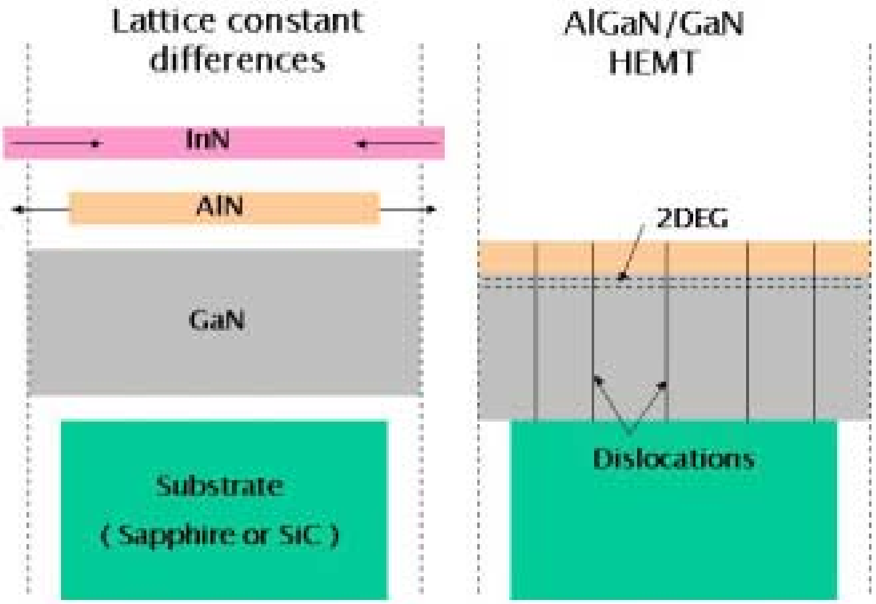
Schematic of Device Structure

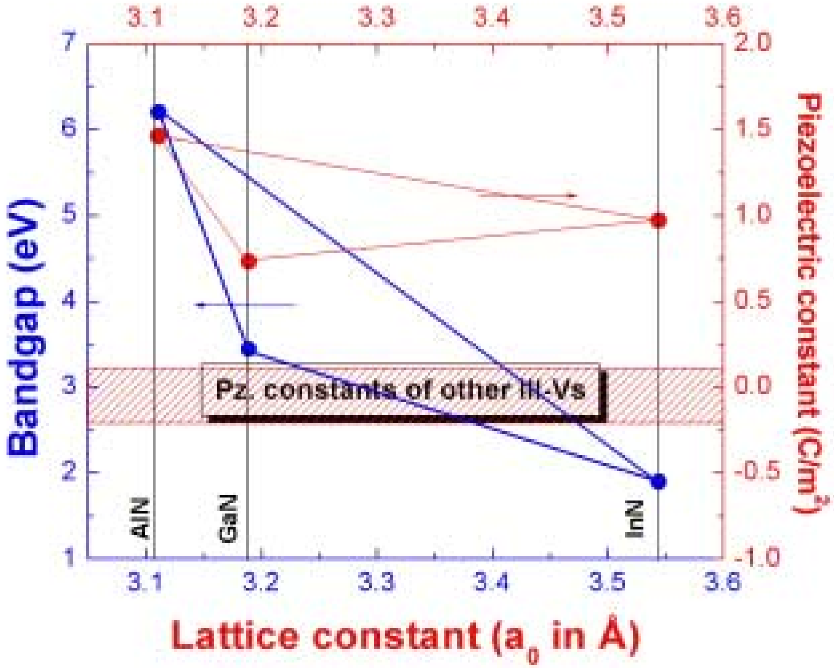


Ball and Stick Diagram of the GaN Crystal

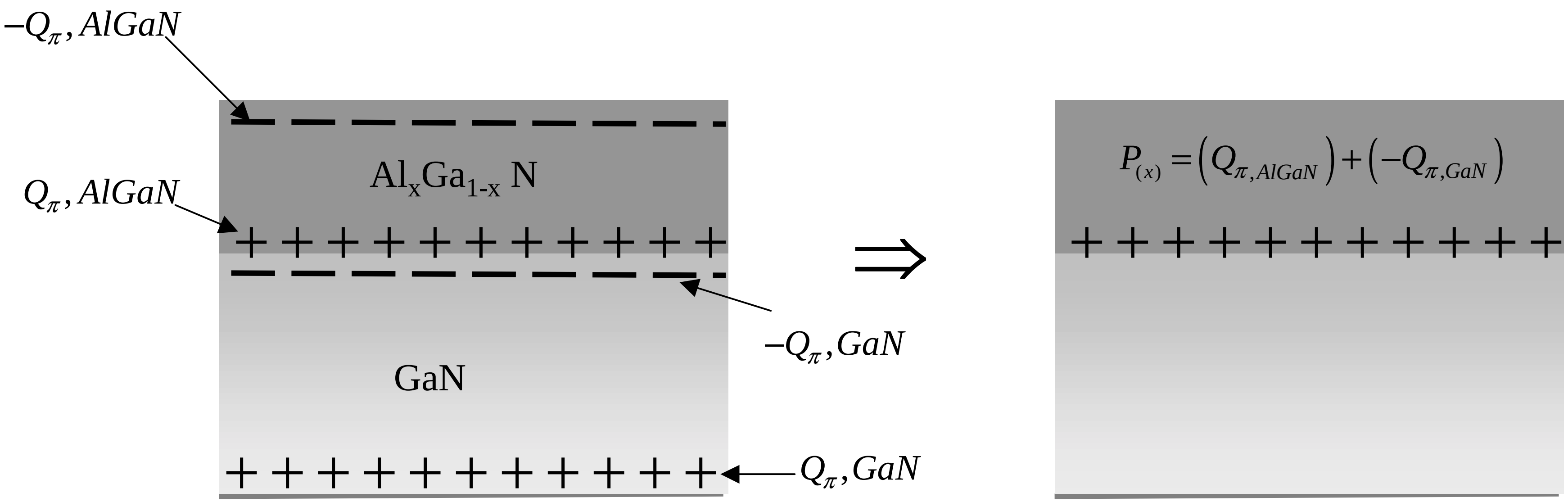


Polarization World



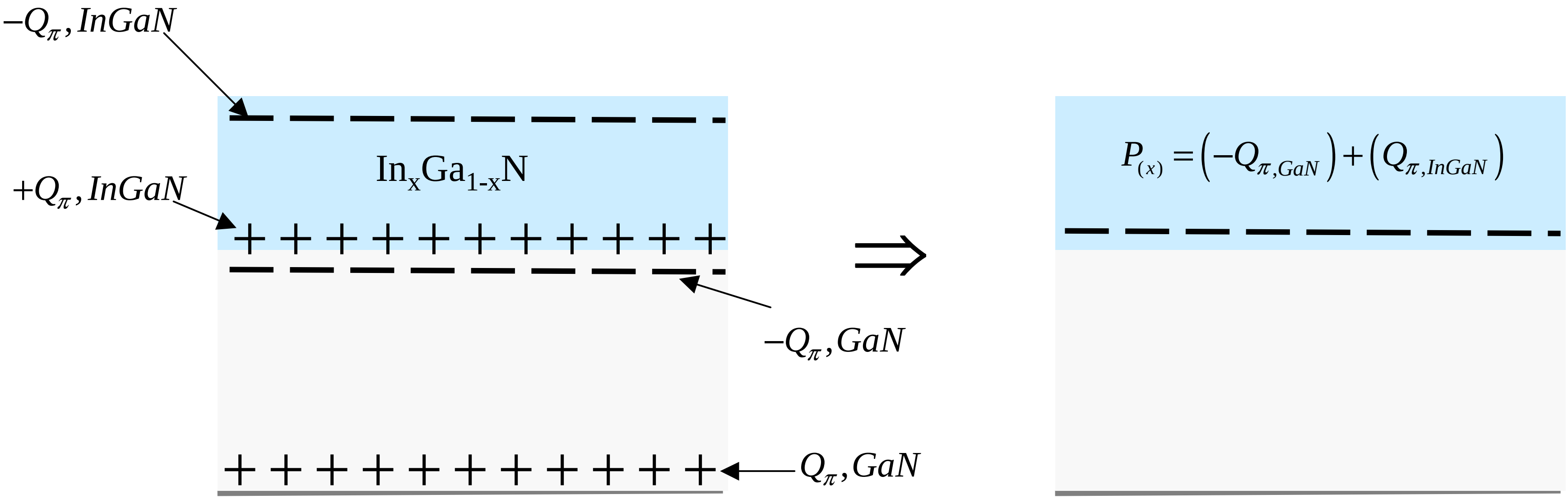


How does the electron gas form in AlGaN/GaN structures? - A



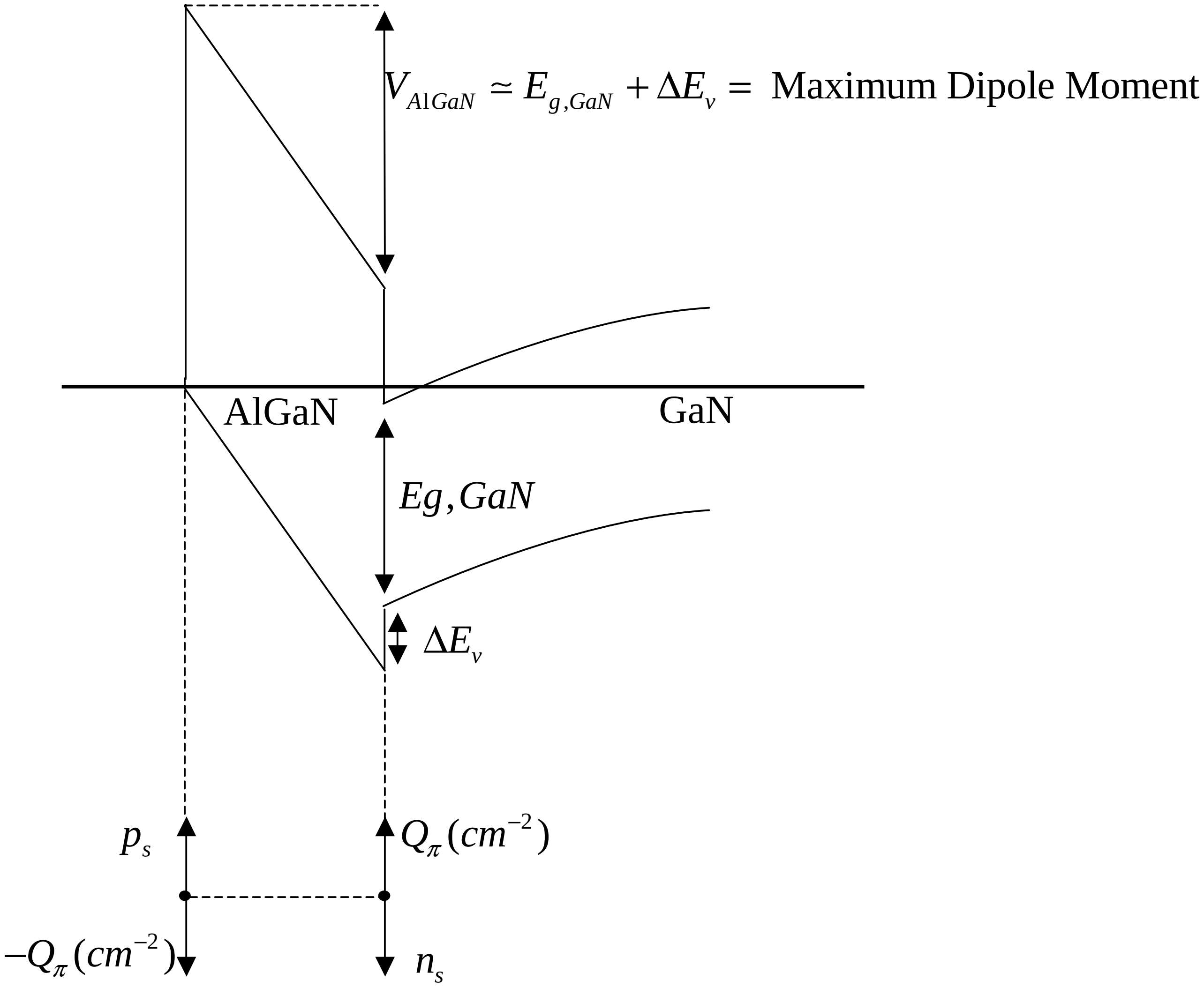
Q_π includes the contribution of spontaneous and piezo-electric contributions

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



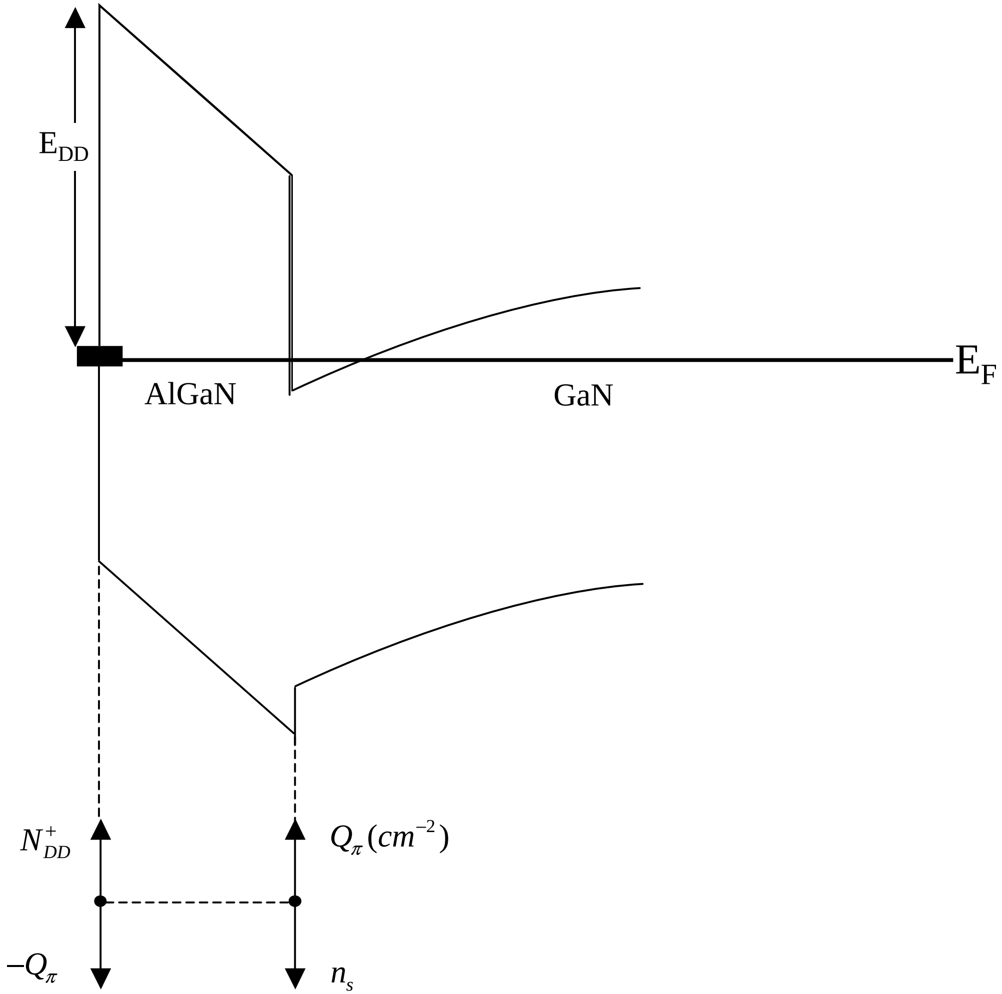
Q_π includes the contribution of spontaneous and piezo-electric contributions

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

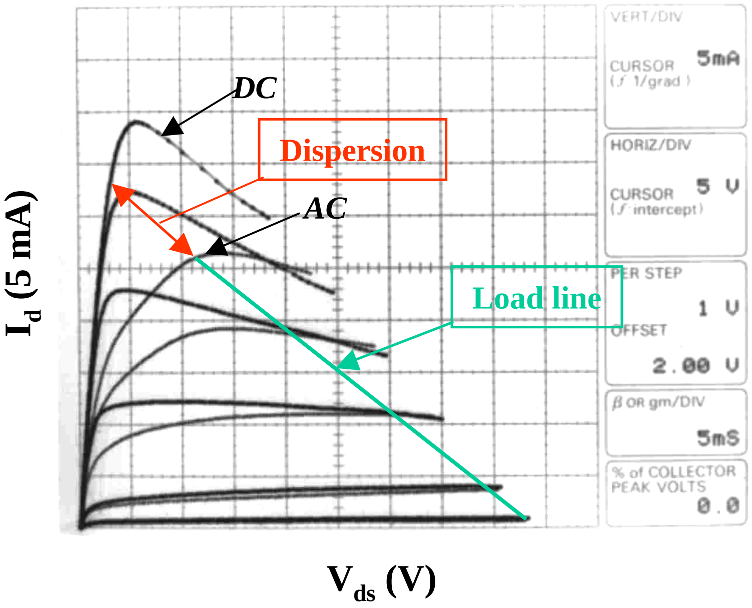


$$V_{AlGaN} \simeq E_{g,GaN} + \Delta E_v = \text{Maximum Dipole Moment}$$

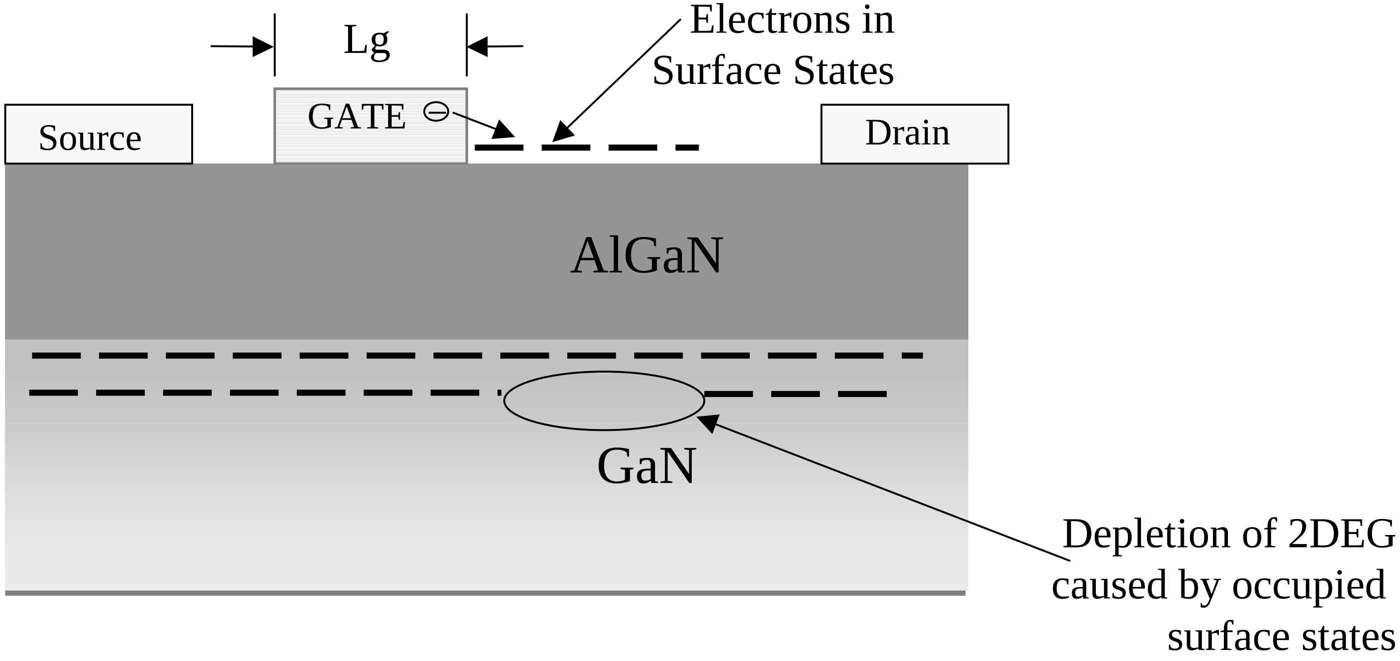
How does the electron gas form in AlGaN/GaN structures? - D



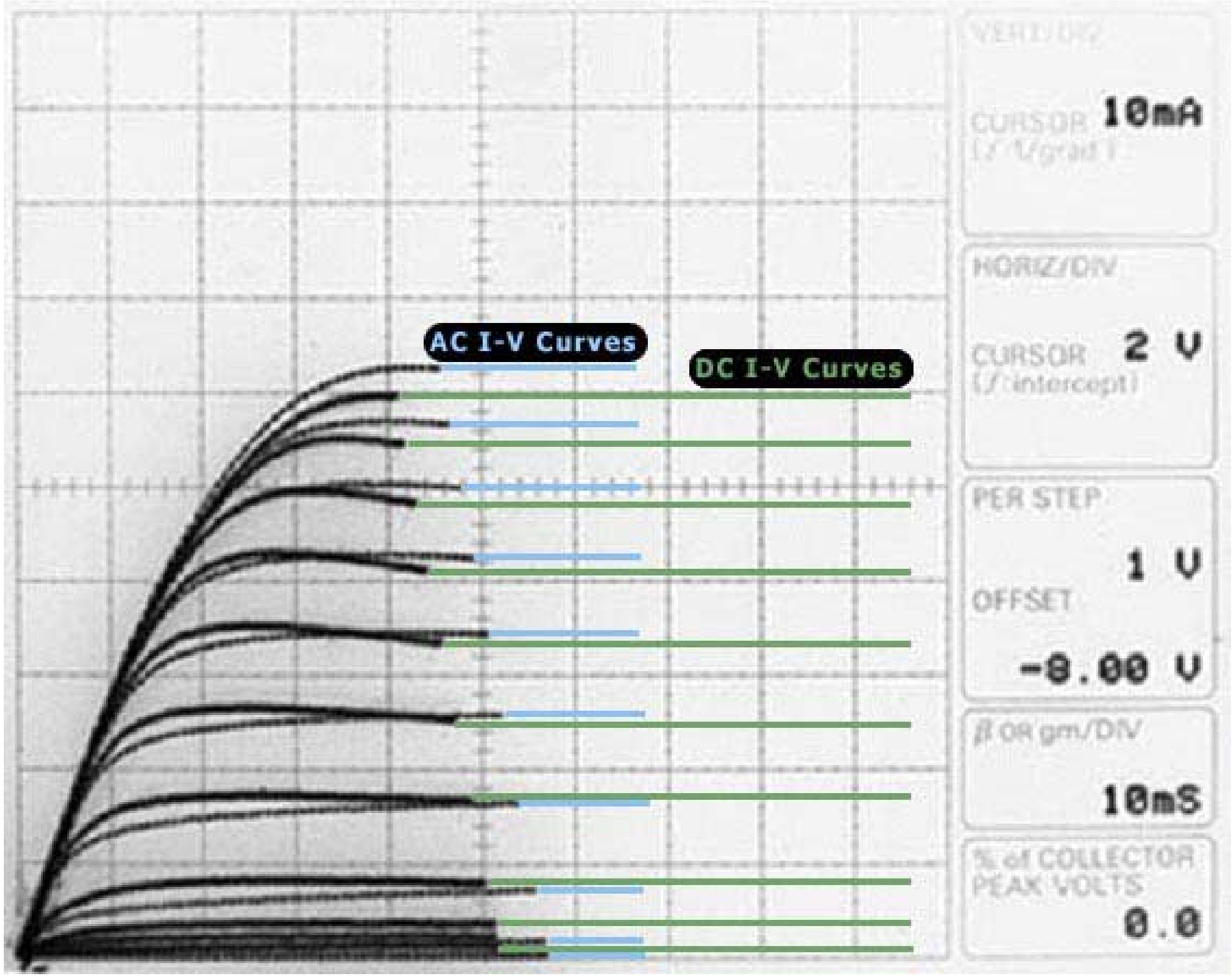
Dispersion in AlGaN/Ga HEMTs



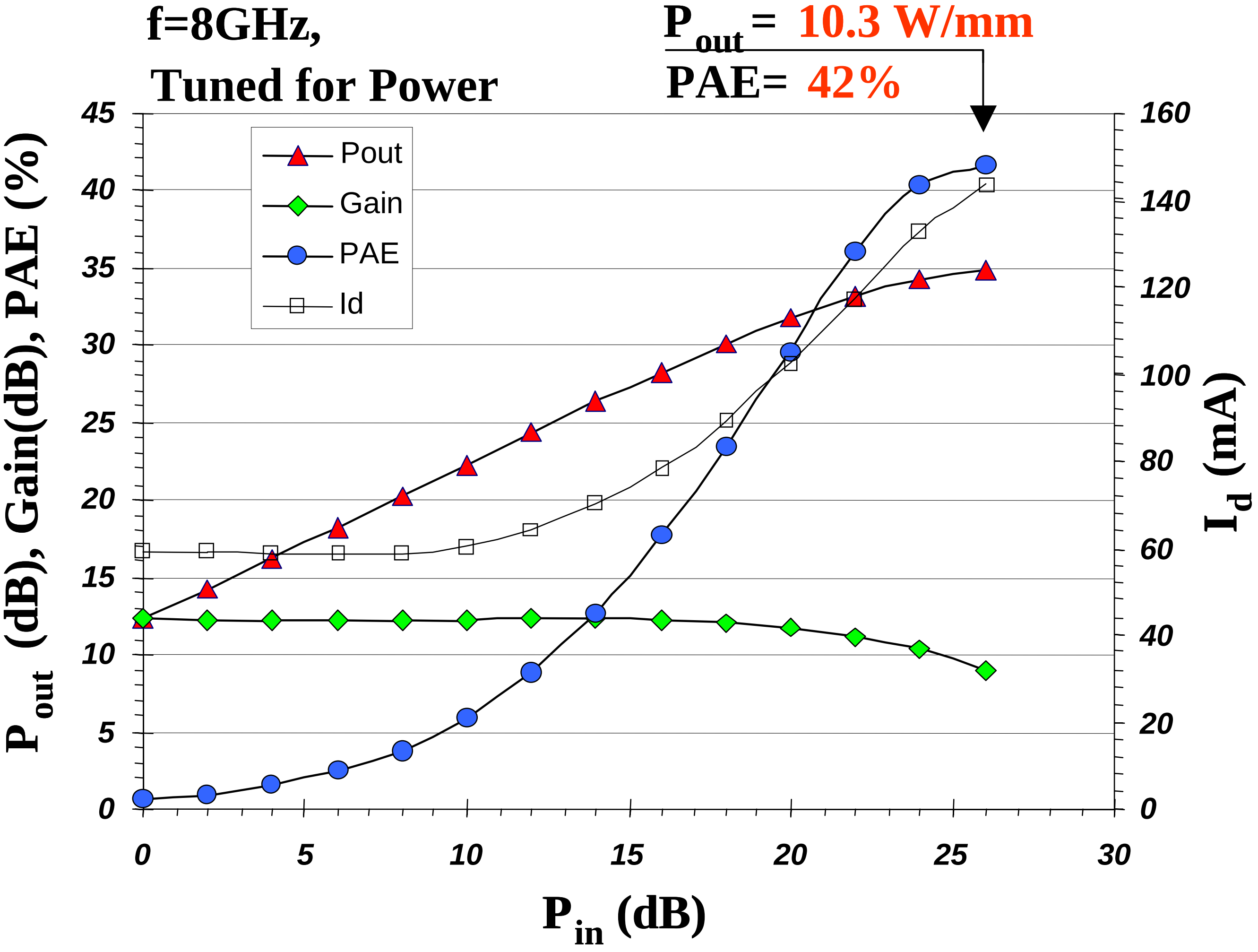
VERT/DIV
CURSOR (∫ 1/grad) 5mA
HORIZ/DIV
CURSOR (∫ intercept) 5 V
PER STEP 1 V
OFFSET 2.00 V
β OR gm/DIV 5mS
% of COLLECTOR PEAK VOLTS 0.0


Lg
Electrons in
Surface States
GATE
⊖
Source
Drain
AlGaN
GaN
Depletion of 2DEG
caused by occupied
surface states

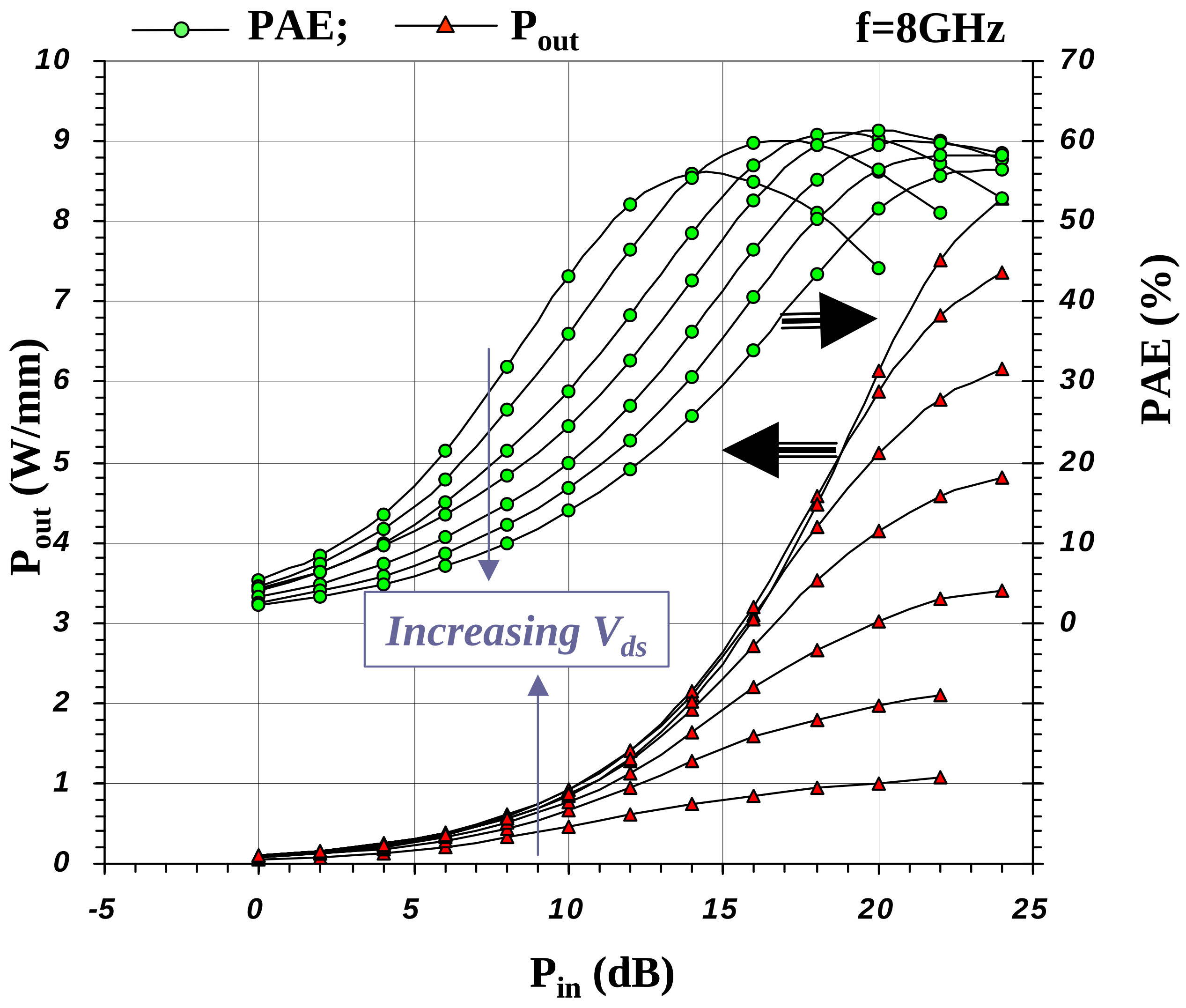
Performance of Passivated AlGaN/GaN HEMT on Sapphire



Performance of AlGaN/GaN HEMT on SiC (CLC)

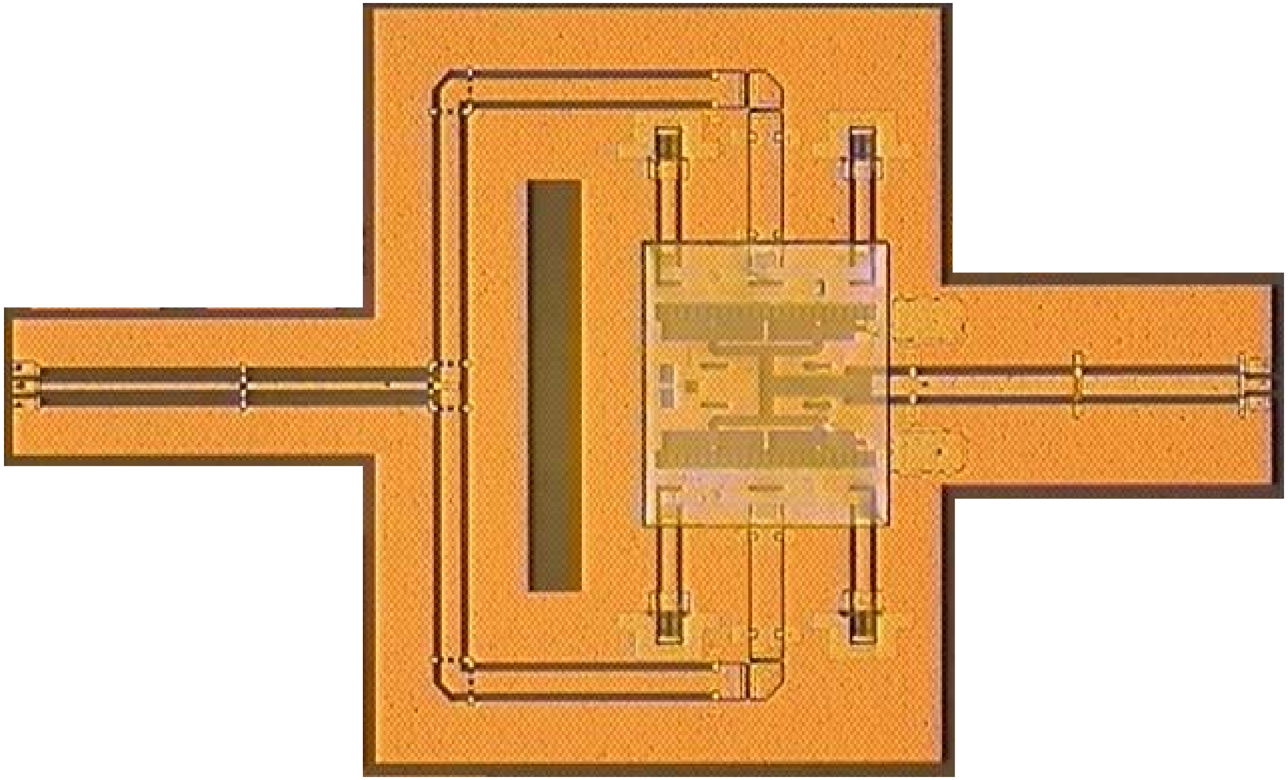


Drain Bias Dependence of Rf Power (CLC)



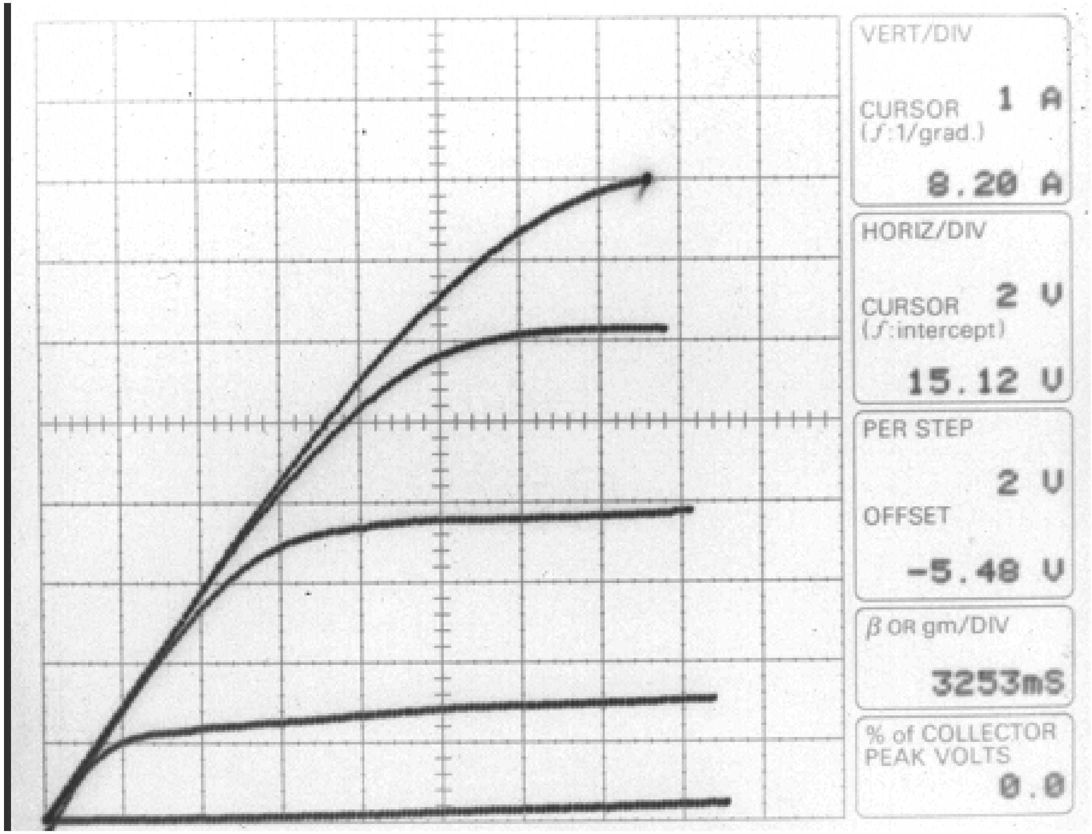
UCSB

Flip-chip AlGaN/GaN HEMT for Thermal Management



I-V Curves from 8mm-wide HEMT

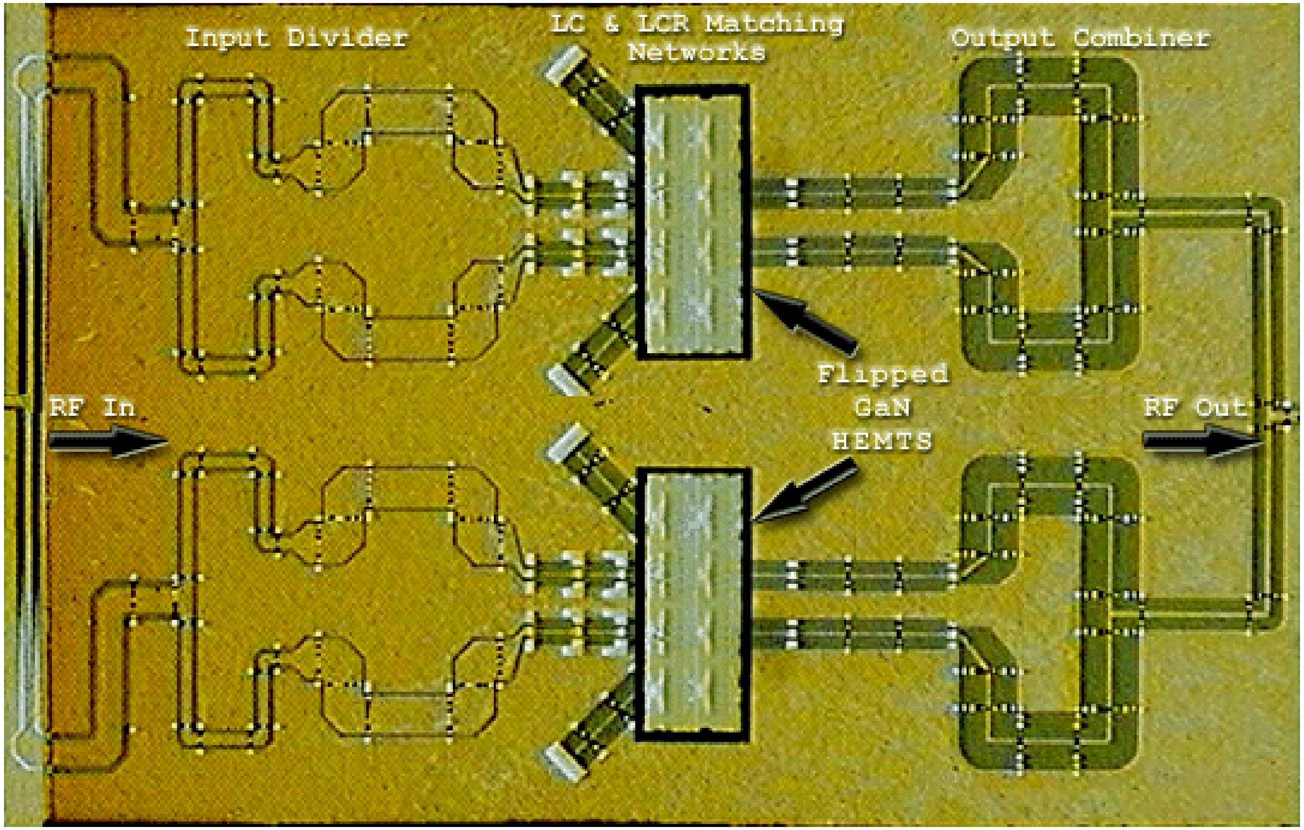
V_g start: +2V, Step: -2 V



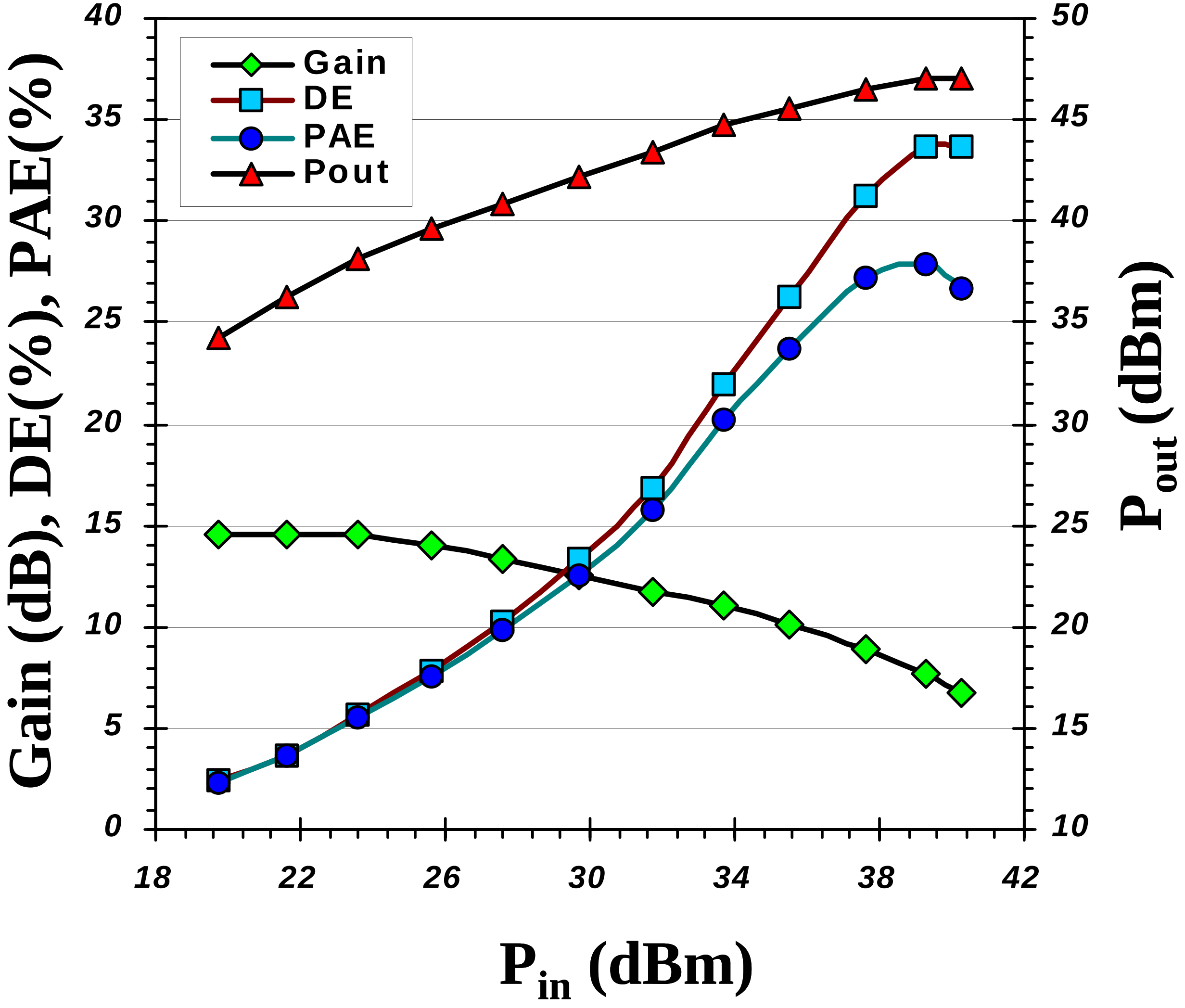
I_d (A/divsion)

V_{ds} (V/divsion)

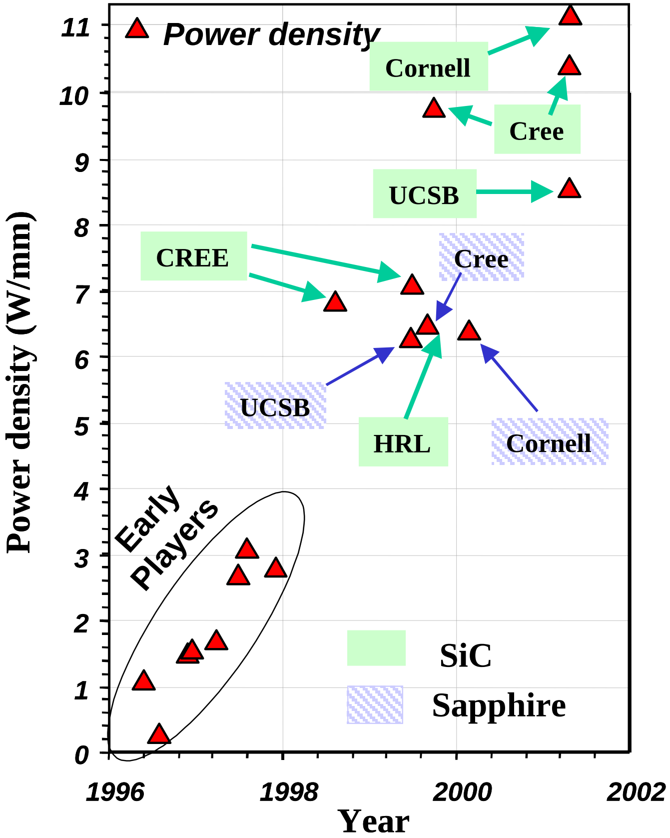
Low Flip-chip Wide Bandwidth Amplifier

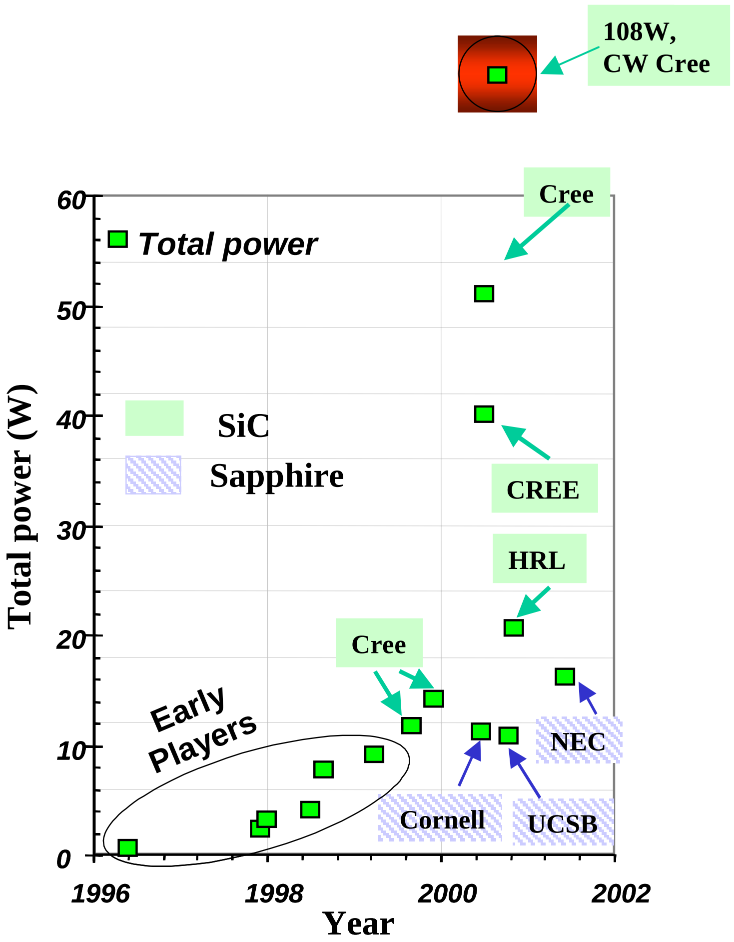


Pulse Power Performance of mm-flipped Device



Power Performance vs. Year





- Includes <u>ALL LEADING</u> players in the field
- CREE = <u>Cree Lighting</u> + <u>Cree-Durham</u>

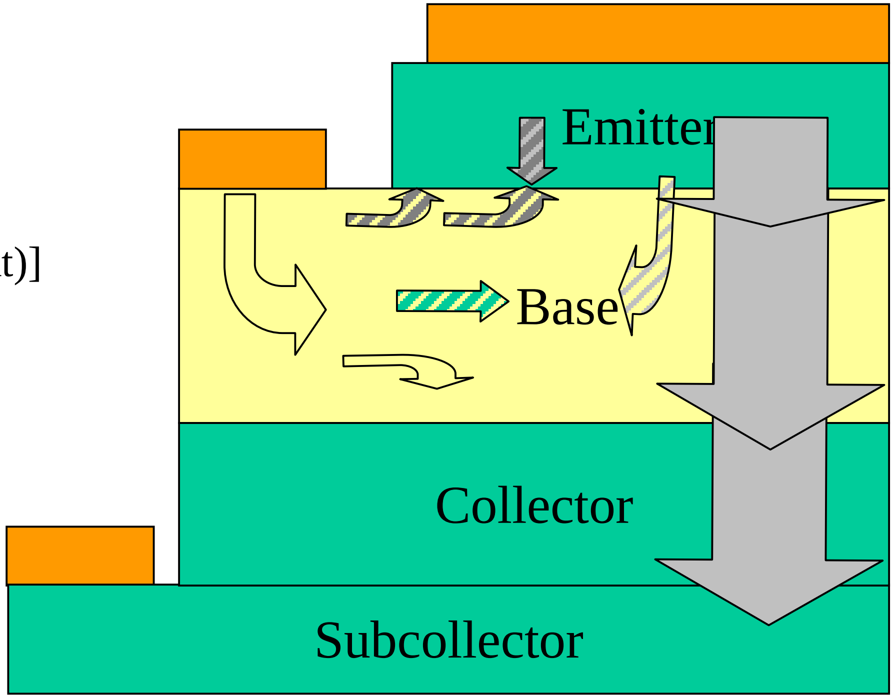
Part II

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

UCSB Bipolar transistor key issues

- Injection
  - γ ⇨ 1
  - n ⇨ 1

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



Transport

-- α ⇨ 1

Collection

–C_{bc} ⇨ **0**

– v ⇨ v_{sat} **[2 x 10^7 cm/s]** *(Kolnik et. al.)*

–V_{br} ⇨ $E_{crit} W_C$ **[E_{crit} ~ 2 MV/cm]** (*Bhapkar and Shur*.)

Output Conductance

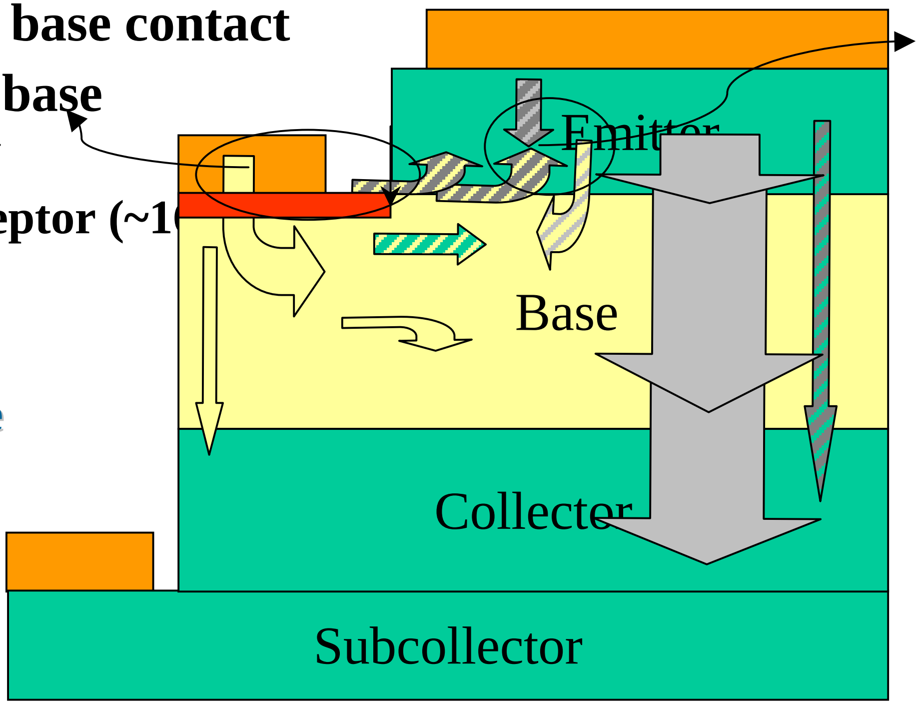
– $\Delta I_C/\Delta V_{CE}$ ⇨ **0**

($\Delta W_B/\Delta V_{CE}$ ⇨ 0)

UCSB 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**



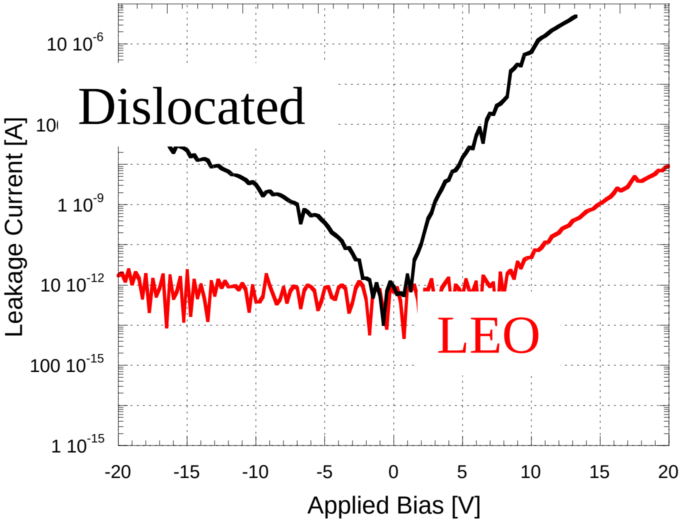
Low minority carrier lifetime

Dislocation causes leakage

Surface leakage due to etch damage

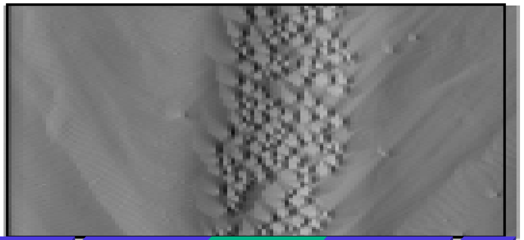
Demonstration of dislocation enhanced leakage

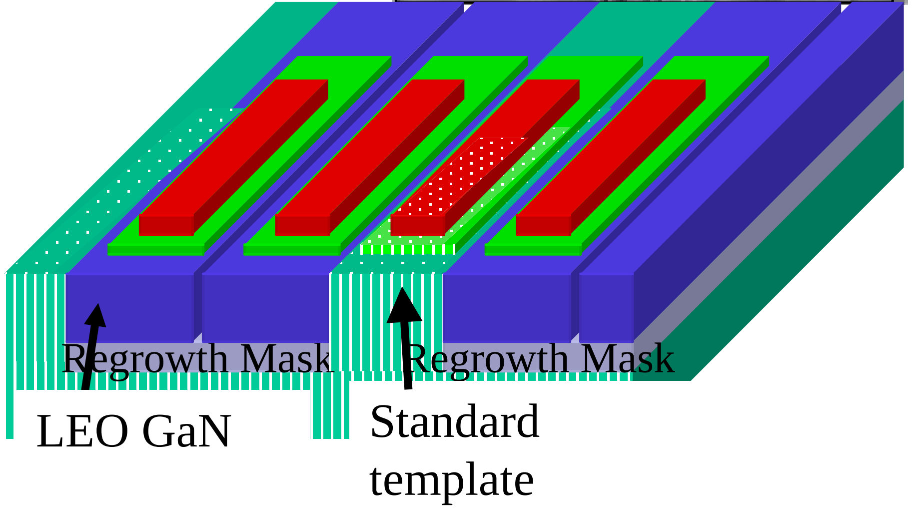
LEO used to investigate leakage of devices without dislocations. (Lee McCarthy et al.)



Leakage from Collector to Emitter,
Wing vs Window

AFM scan of wing vs Window on LEO GaN





Results: LEO device demonstrated

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

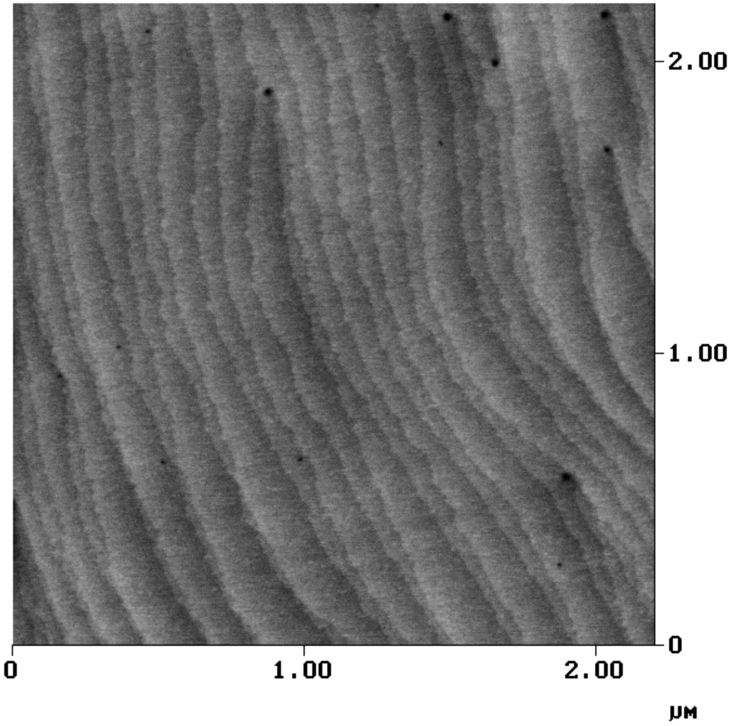
Explanation

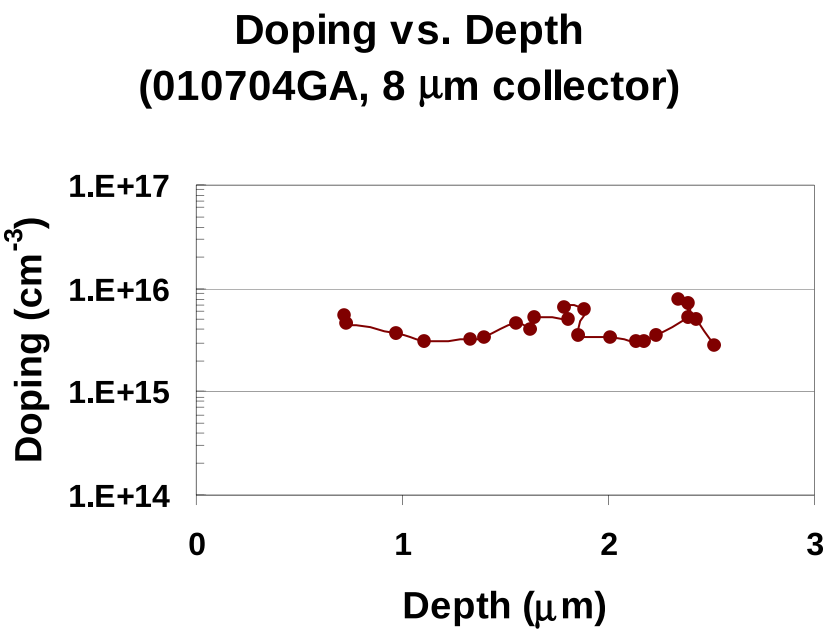
- Thick substrate sufficiently reduces dislocations to prevent C/E short in window region
- Gain (τ_e) not currently limited by dislocation density

Strategy: Thick Collector

- Decent dislocation density
  - High quality MOCVD templates achieved

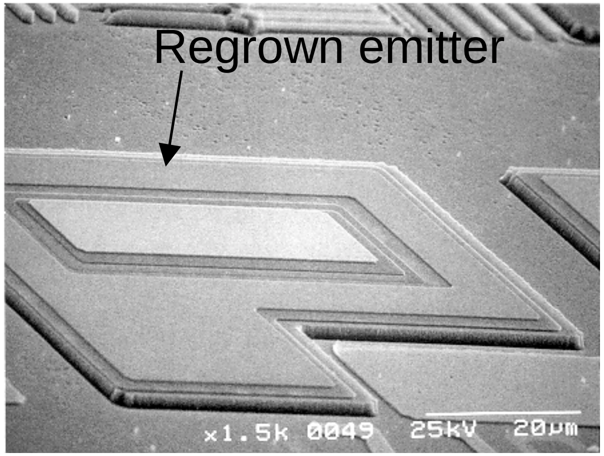
    Dislocation density ~ 5e8 cm^{-2}
- Low background doping
  - $N_D < 1e16\ cm^{-3}$ (Assuming uniform doping N_D and $E_{critical}$ = 2 MV/cm, requires 10 µm to achieve 1 KV breakdown voltage.)

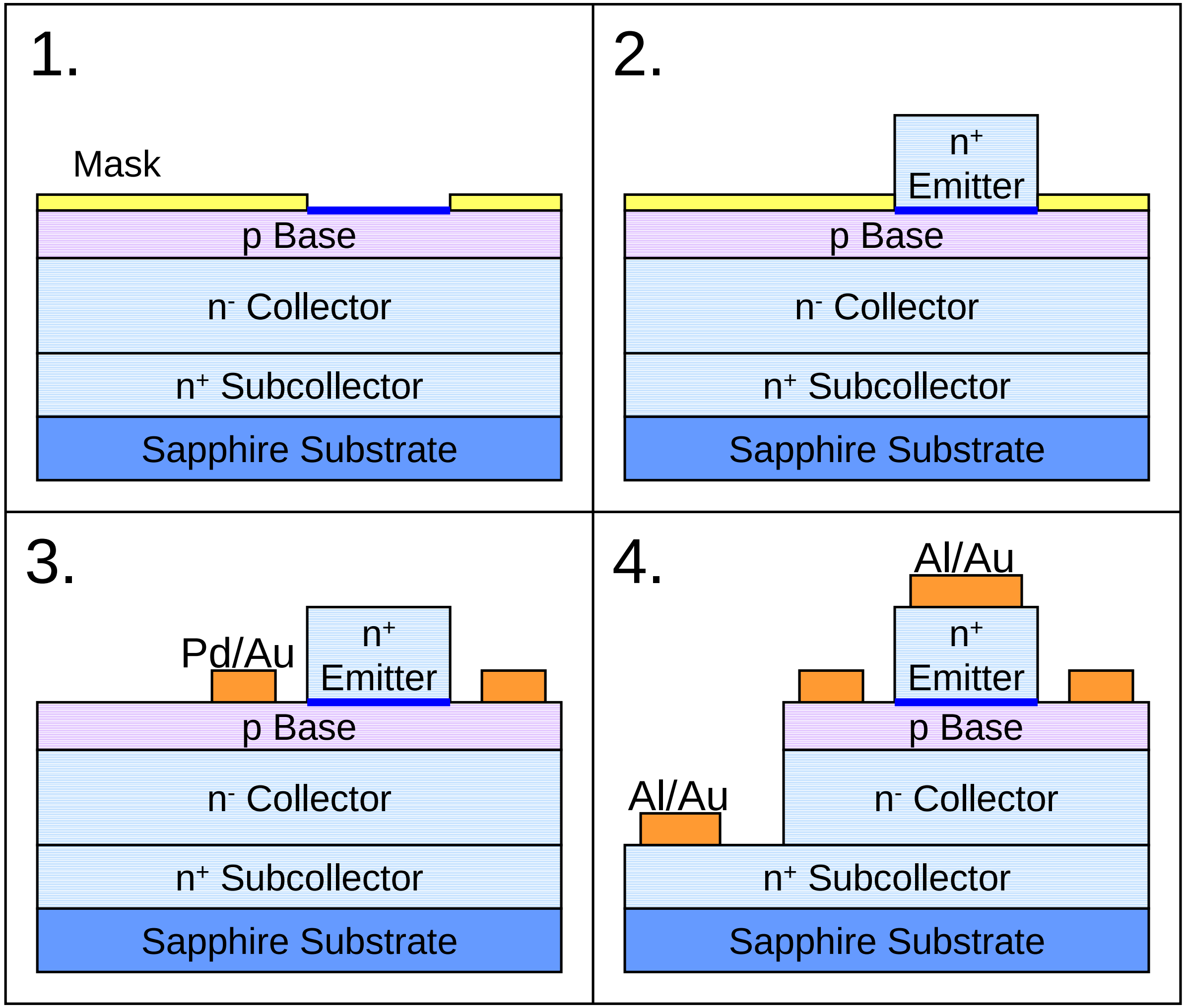




UCSB Emitter Regrowth Process Flow

- **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

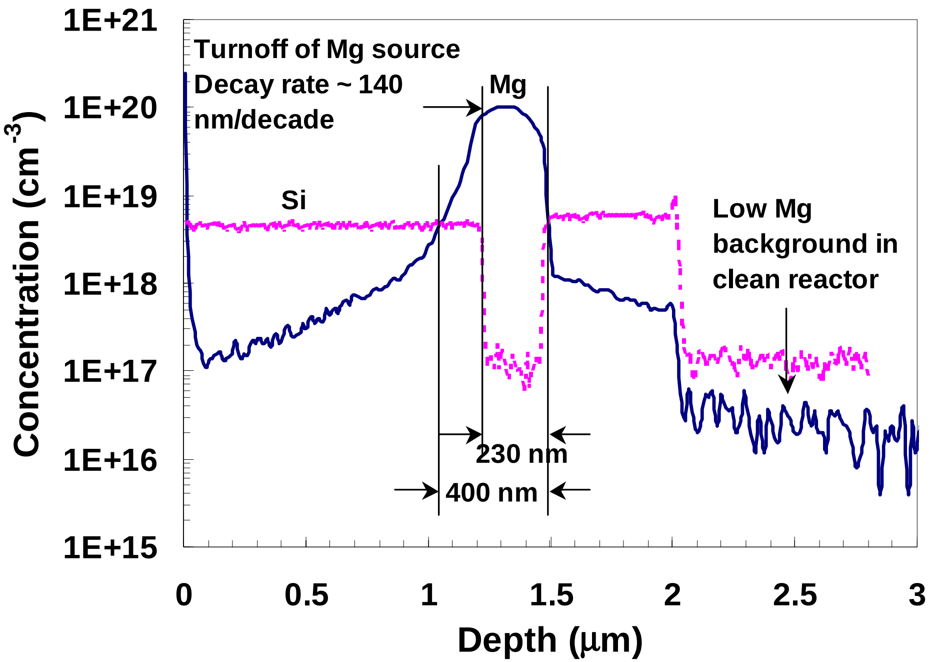




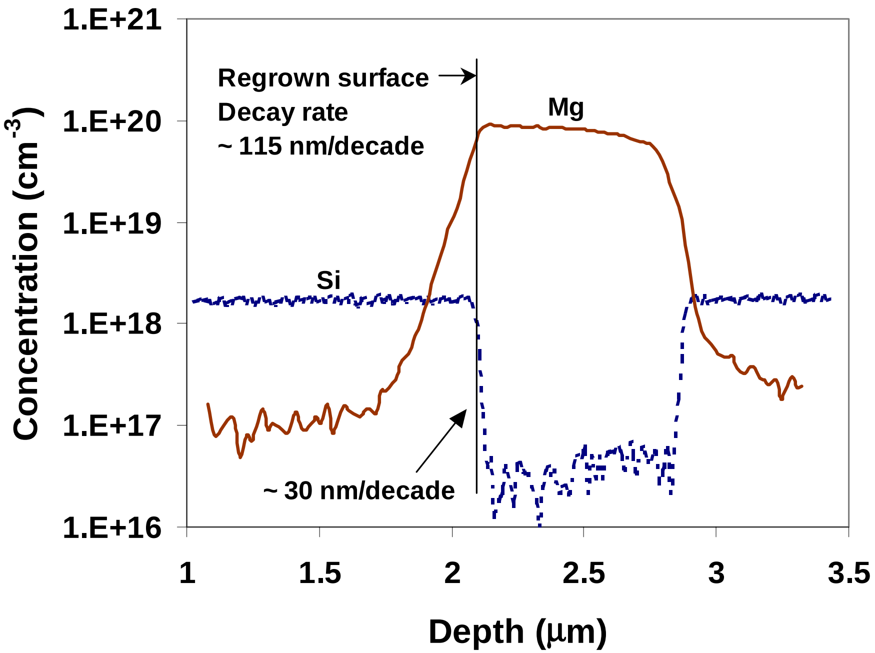
UCSB SIMS: Mg by MOCVD

Severe memory effect observed in non-interrupted MOCVD growth

Slow decay tail into GaN:Si regrown on as-grown GaN:Mg layer



Memory effect

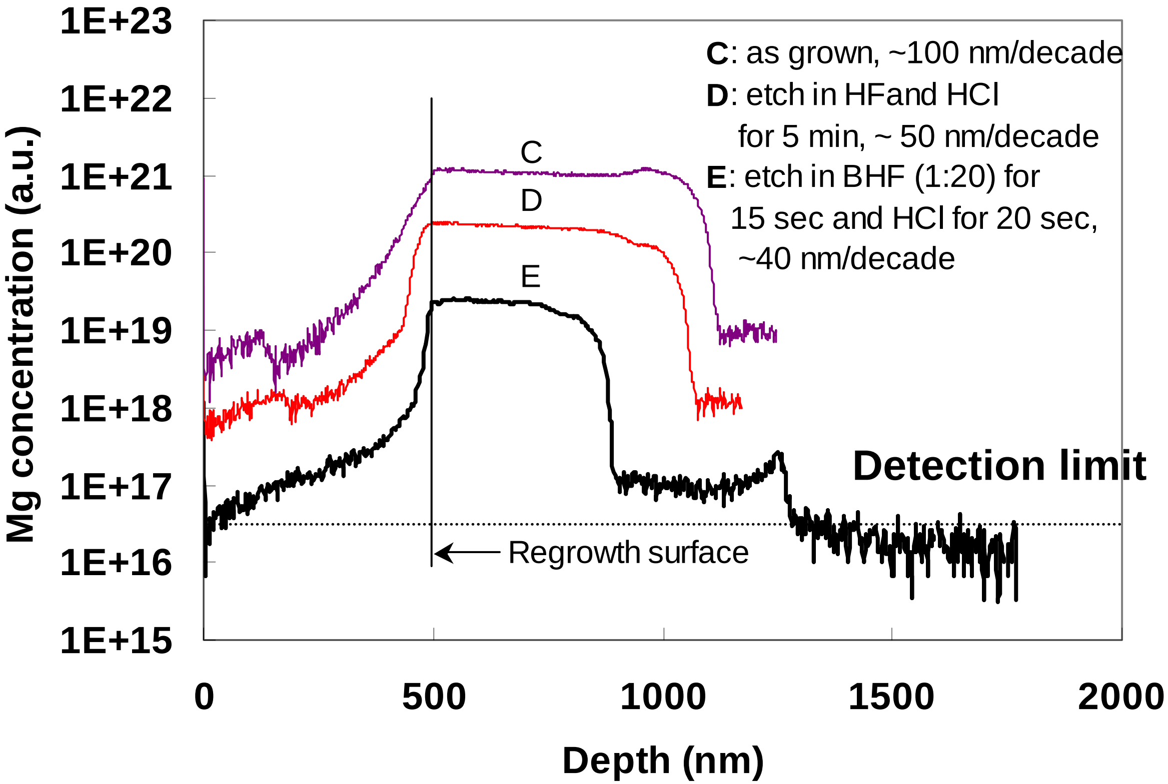


Slow decay tail in regrowth

UCSB

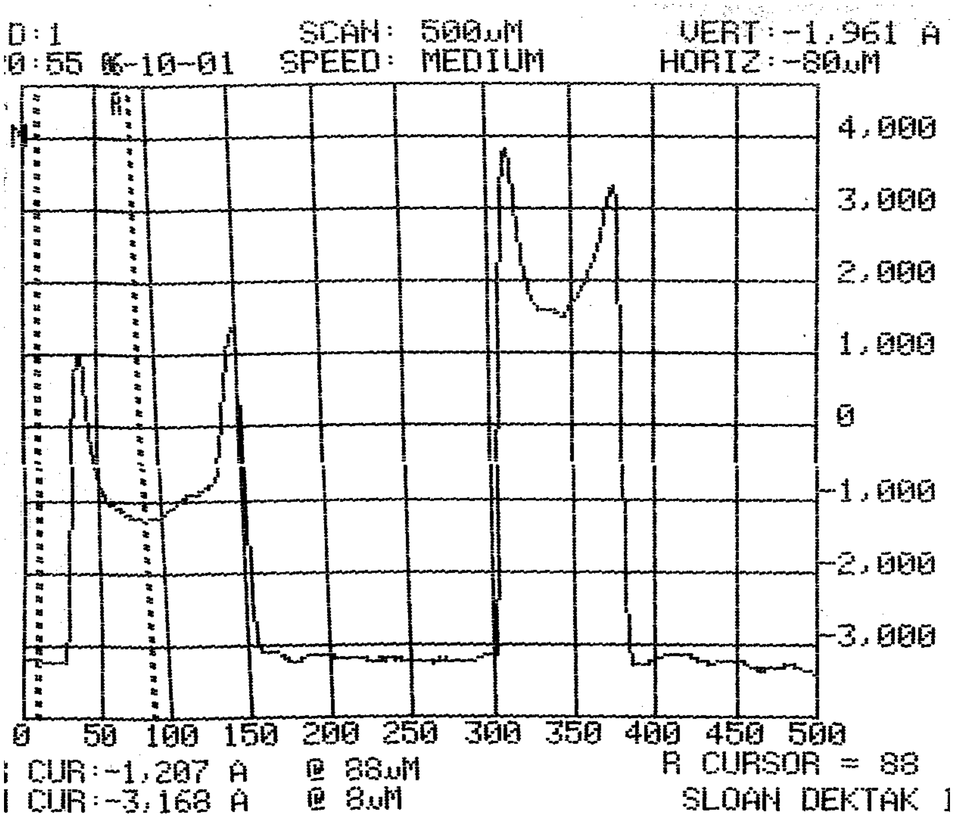
SIMS: regrowth with surface treatment

- Regrown in Mg-free reactor and all grown by MOCVD
- Presence of an excessive amount of Mg on the surface, which can be removed by acid etch
- Occurrence of Mg diffusion, ~ 40 nm/decade sharpness achieved

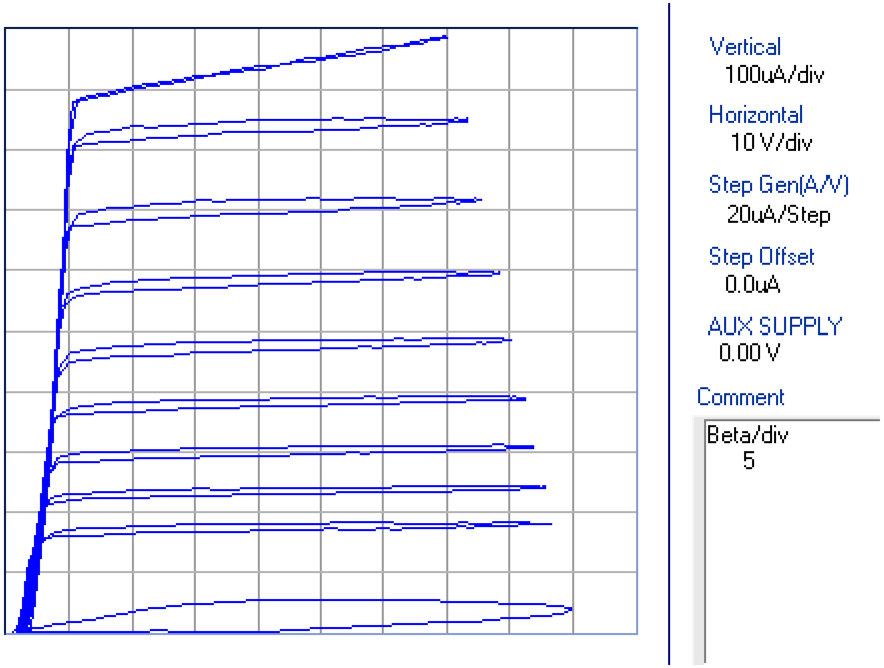


Selectively regrown n/p diodes

- Mask enhanced growth complicates the analysis
  - Regrowth rate depends on the mask layout, diode size etc
  - “Bunny ear” regrowth profile is often seen
  - Only the emitter edge is active in device operation due to highly resistive base layer
  - The junction quality depends on how the regrowth is initiated, e.g. Temp, P, flows, presence of Si and Al etc.



“Bunny ear” regrowth profile of two different square diodes



Vertical
100uA/div

Horizontal
10 V/div

Step Gen(A/V)
20uA/Step

Step Offset
0.0uA

AUX SUPPLY
0.00 V

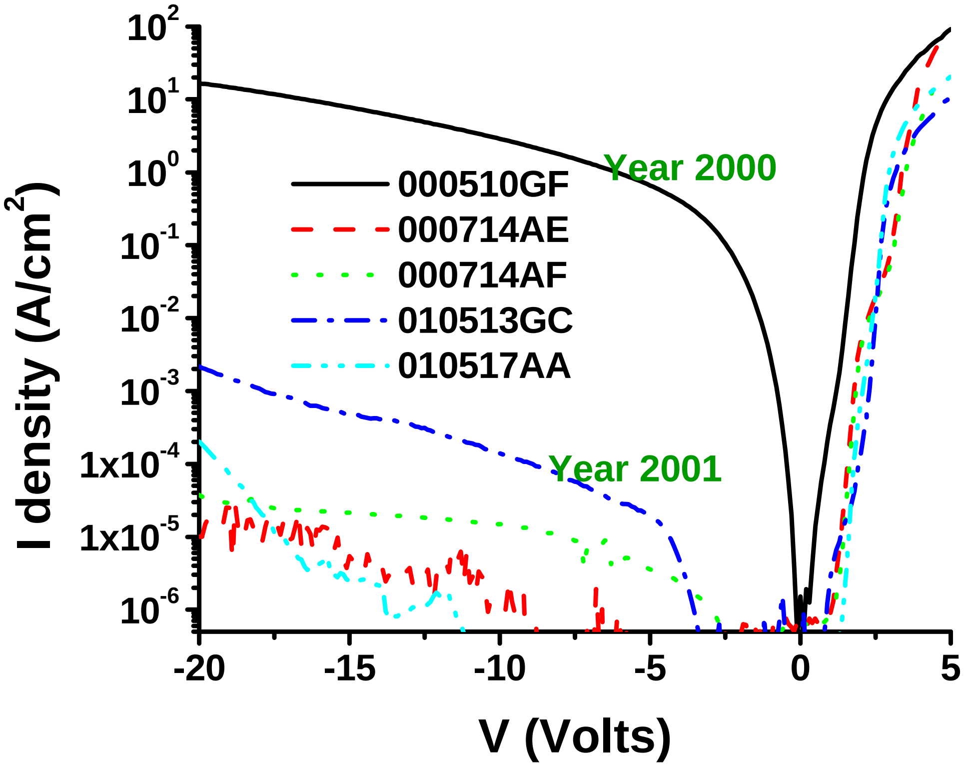
Comment

Beta/div
5

UCSB Regrown n/p Diodes Characteristics

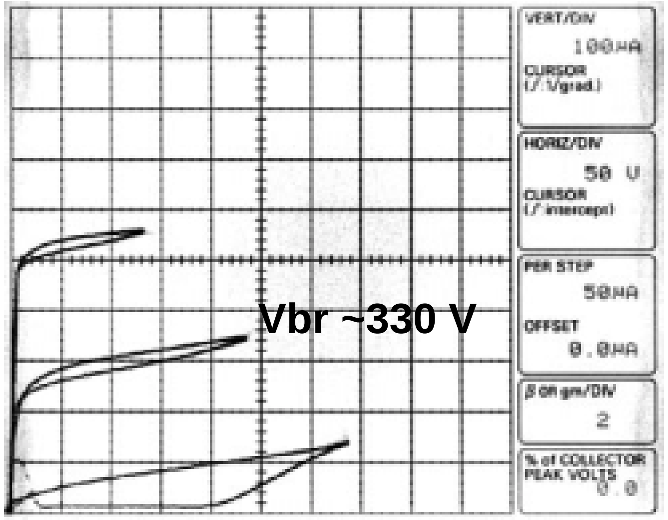
- Comparison of various structures regrown on 0.5 µm GaN:Mg

Run #	Layer structure	Growth Parameter	
		G.R. (nm/min)	Temp/Press (C/Torr)
0005 10GF	400 nm GaN:Si (4e18 cm^{-3})	~30	1140/760
0007 14AE	250 nm $Al_{0.06}$GaN:Si (1e18)	~30	1100/300
0007 14AF	x_{Al}~ 5% 250 nm AlGaN:Si (1e18) 75 nm GaN->AlGaN:Si (1e18)	~30	1100/300
0105 13GC	450 nm GaN:Si (1e18) 30 nm GaN	~40	1100/300
0105 17AA	x_{Al}~ 5% 30 nm GaN:Si 30 nm AlGaN->GaN:Si 730 nm AlGaN:Si 60 nm GaN->AlGaN 60 nm GaN	~60	1100/300

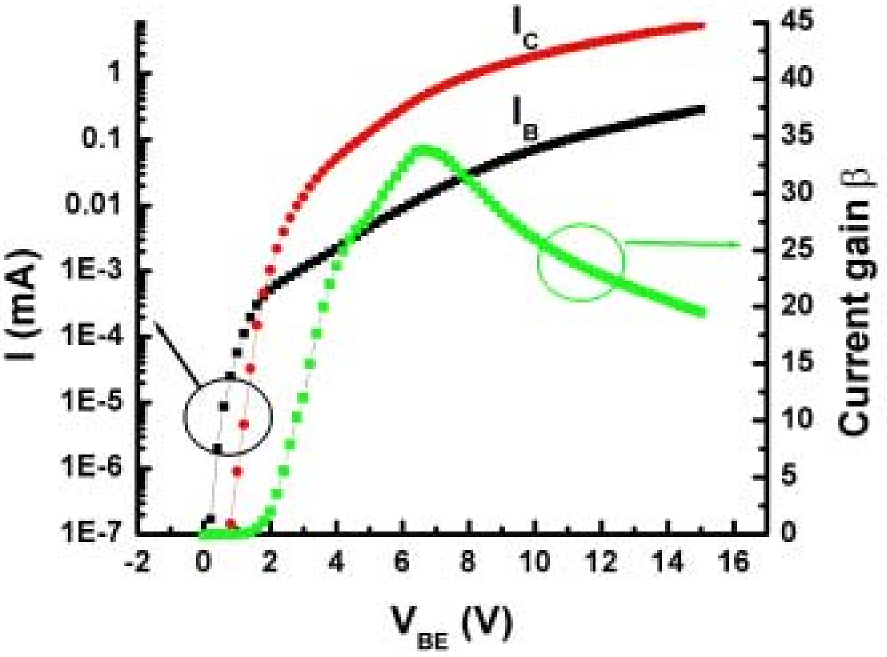


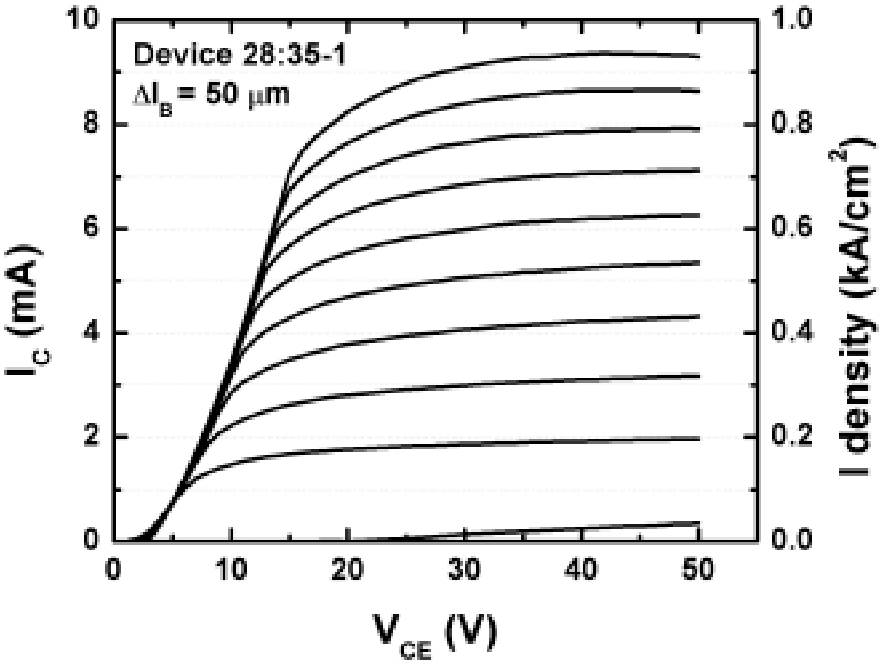
UCSB HBT with 8 mm GaN collector

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



Vbr ~330 V





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

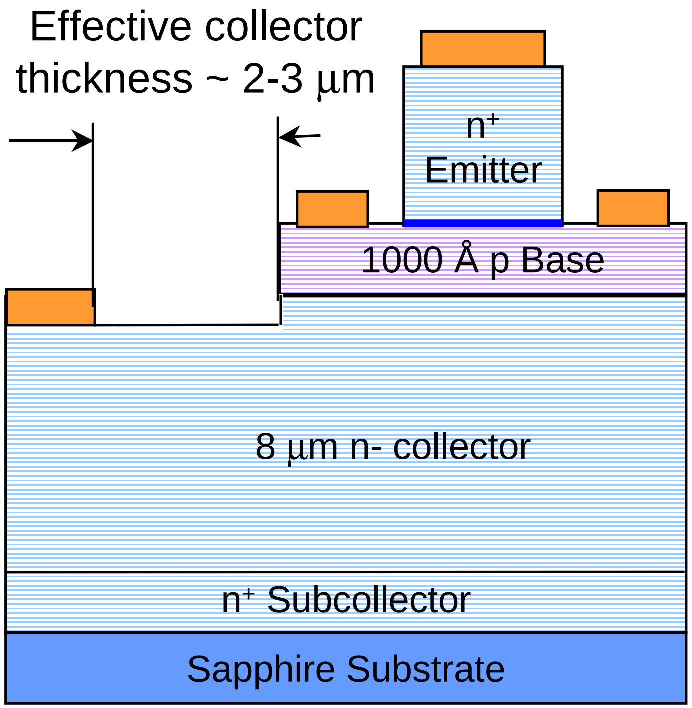
8 nm uid GaN spacer

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

8 µm uid GaN (4e15 cm^{-3}) collector

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

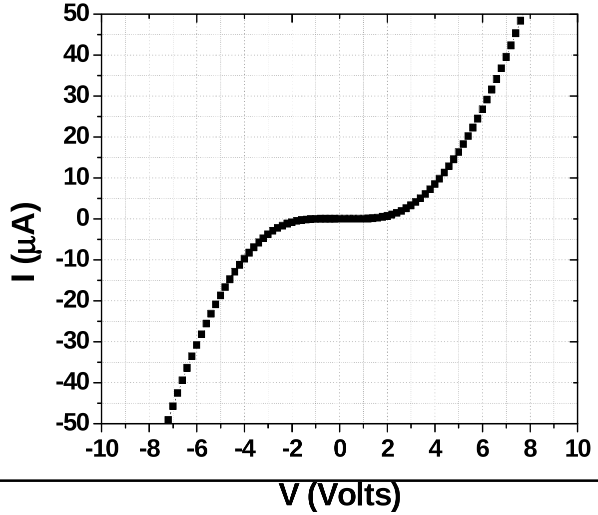
Sapphire

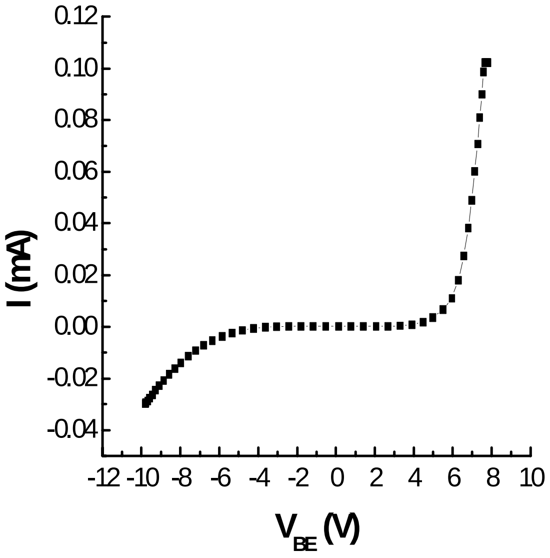


Effective collector thickness ~ 2-3 µm

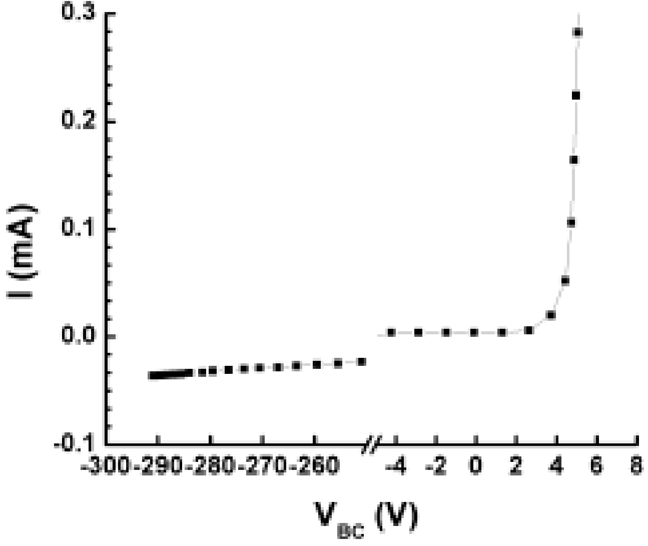
UCSB I-V Characteristics

- reasonable base contacts
- Improved B/E diodes
- Rectifying B/C diodes, Vbr > 300 V





Base-emitter diode



Base-collector diode

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)