MACOM™

Partners from RF to Light

GaN Technology for High Frequency Applications

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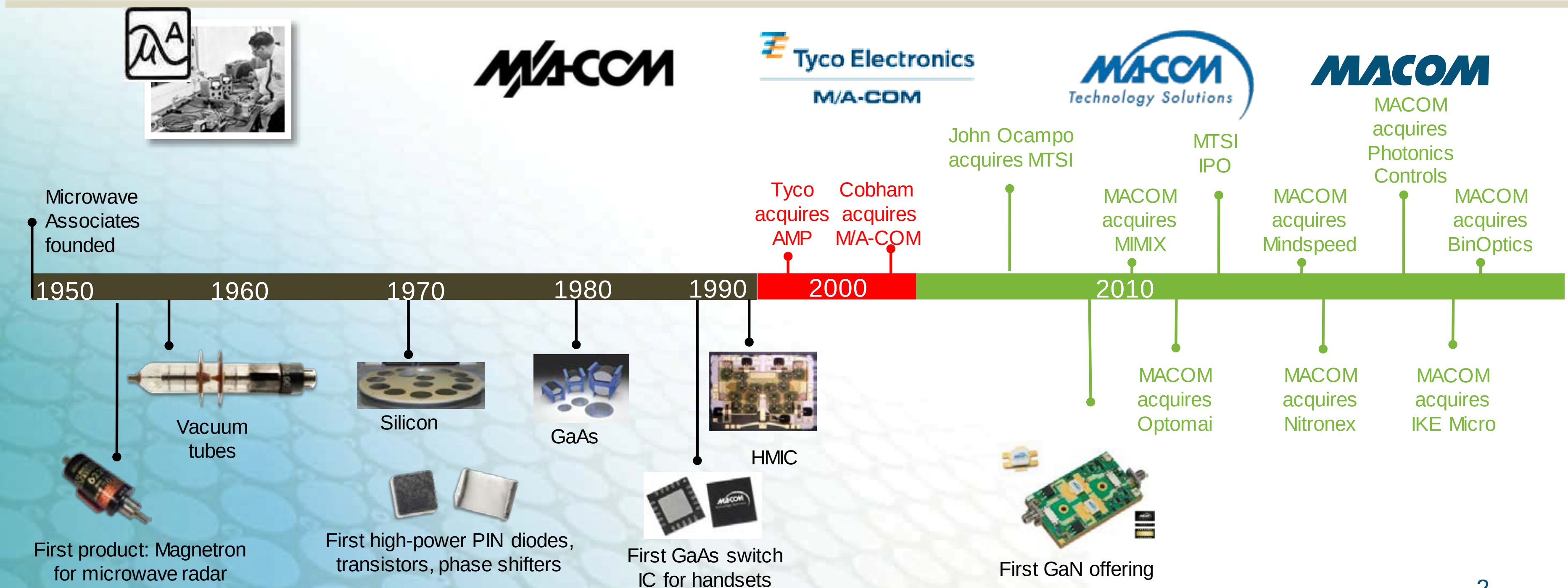
GaN Technology for High Frequency Applications

- Agenda
  - Brief MACOM History
  - Winning in the Marketplace
  - Why GaN
  - GaN HEMT Structure
  - High Frequency/High Power Applications
  - GaN/SiC vs GaN/Si
  - GaN vs Alternate Technologies
  - GaN Challenges
    - Design
    - Process
    - Reliability
  - Future Directions
  - Summary

MACOM Company Overview

Provider of High-Performance Analog RF, µW, mmW and Photonic Solutions

- Headquartered in Lowell Massachusetts
- 27 offices worldwide, 1061 employees
- $418 million of FY 2014 revenue
- Strong Patent and IP Position
- 6,000+ customers worldwide
- Global, multi-channel sales strategy
- 3,000+ products across 40 product lines
- 60 years of RF & Microwave History



Technology Portfolio

	Radar	Military Comms	Wireless	Optical	Wired Broadband
					
GaAs	Low noise, high frequency	Low noise, high frequency	Low noise, high frequency, high linearity	High voltage, low power, high linearity	High linearity
GaN	High frequency, power, efficiency	High frequency, power, efficiency	High frequency, power, efficiency		High linearity, efficiency
Si	High Peak Power	High power, high linearity			
InP				High speed, high voltage, low power	
SiPh	High integration, high power, high performance			High integration, high linearity, high performance	
SiGe	Low noise, high frequency, high integration		Low noise, high frequency, high integration	High speed, low noise, high integration	High integration
CMOS		High integration		High speed, low noise, high integration	High integration

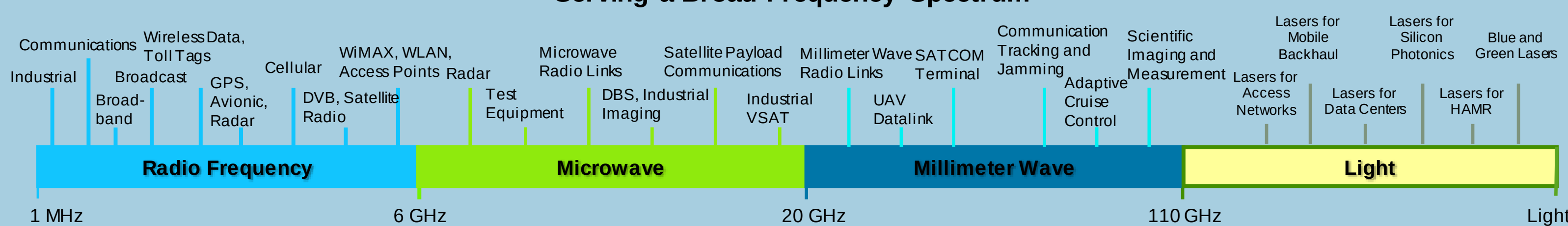
Broad Array of Specialized Products

- ***High speed analog RF, µW, mmW and photonic engineering competencies***
- ***Long product lifecycles***

Diverse Array of Products and Form Factors

Power Pallets & Transistors	Integrated Circuits	Diodes, Switch Limiters, Switches	Passive Components	Crosspoint Switches	Multi-Chip Modules	Photonics

Serving a Broad Frequency Spectrum



…from RF to Light

The Market Sets the Price

Market	Typical Device	Price Point
Aerospace and Defense	Broadband, High Efficiency, MMIC HPA • 10 – 100 W • 28/48 V operation	$2.00 – $5.00/Watt
CATV	Low Frequency, Broadband, High Linearity	$0.5 – $1.00
Infrastructure	Discrete Power Transistors	$0.15 – $0.30/Watt

- The lowest cost solution ***always*** wins in the marketplace
- So …. If Silicon can do …. Silicon will win ….
- So …. If Silicon can't & GaAs can …. GaAs will win ….
- GaN needs to provide unique solutions & provide compelling value to win

Semiconductor Material Properties

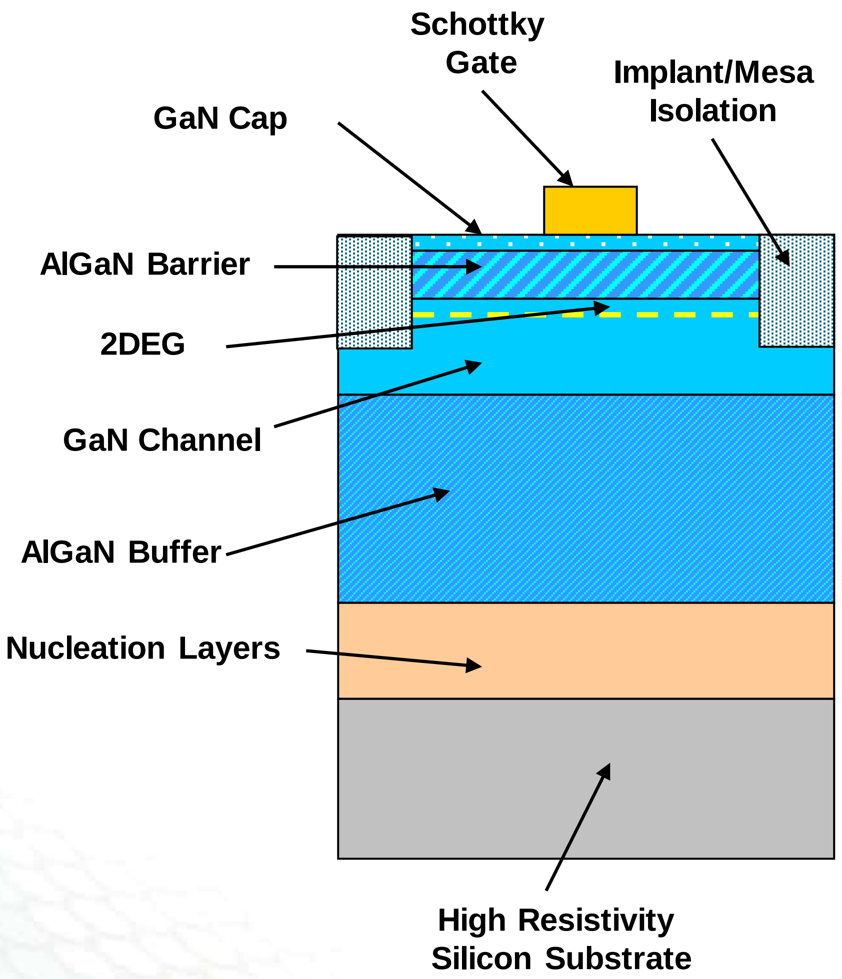
Why Gallium Nitride

- High Breakdown Field
  - 10x Si or GaAs
  - Smaller Devices
  - Higher Impedances
  - Lower Intrinsic Capacitances
- Low Dielectric Constant
  - 50% of Si or GaAs
  - Reduced Intrinsic Junction Capacitances
- High Power Density
  - 2-10x GaAs or Si
  - Smaller Devices
  - Higher Impedances
  - Good Thermal Conductivity
- Best Power Device Figure of Merit
- Increased Frequency Response
  - Smaller Devices
  - Lower Capacitances
  - Reduced Matching Loss
  - High Saturation Velocity
  - High f_{max}
- Highest Johnson Figure of Merit

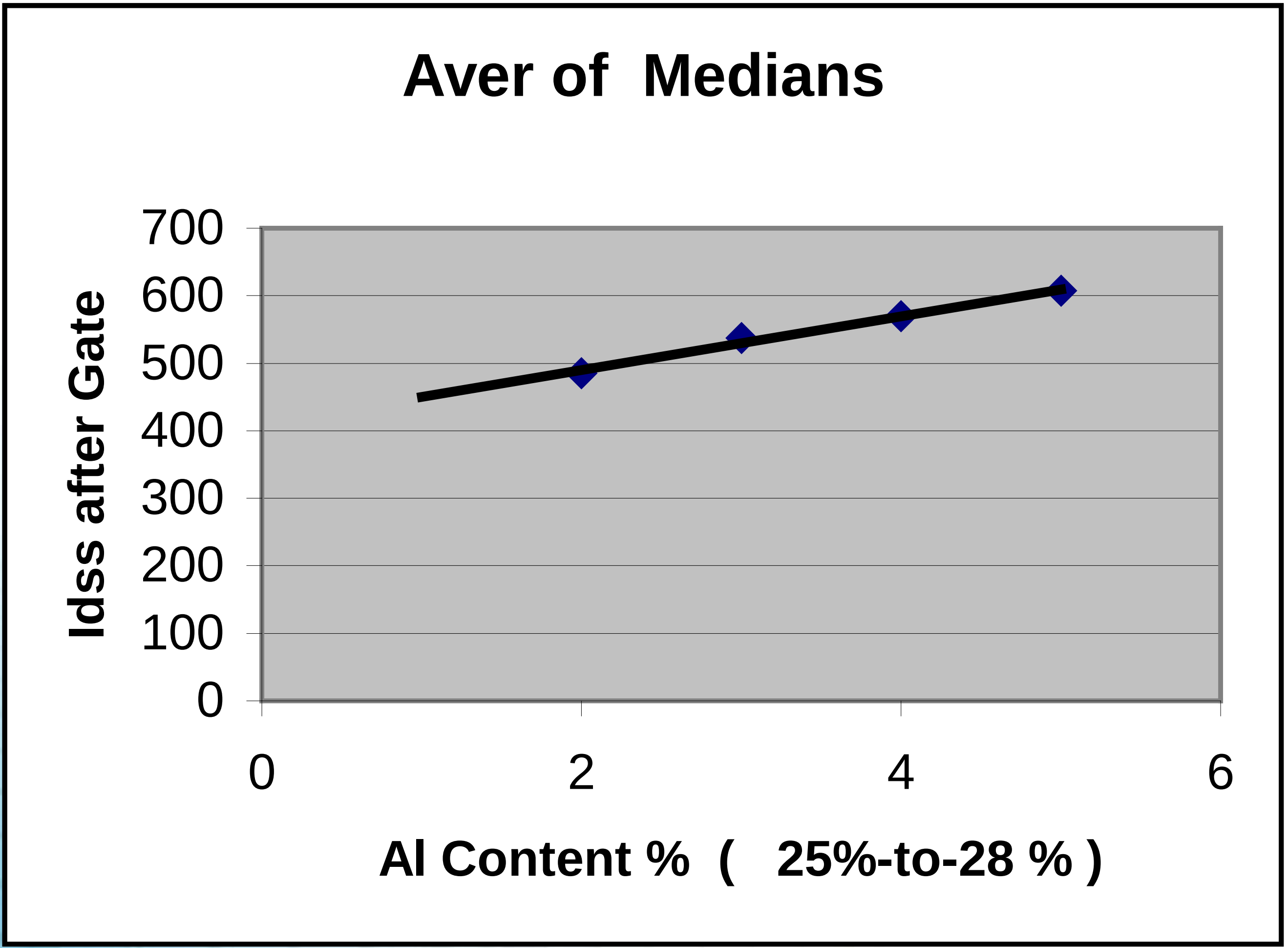
Property	Si	GaAs	SiC	GaN
Band Gap (eV)	1.1	1.4	3.2	3.4
Breakdown Electric Field (V/cm)	$3x10^5$	$4-5x10^5$	$2-4x10^6$	$4x10^6$
Electron Mobility (cm^2/Vs)	1100	6000	370	1350
Power Device Figure of Merit ($\mu_n * E_c^3$)	1	20	675	3000
Saturation Velocity (cm/s)	$1.0x10^7$	$2.0x10^7$	$2.0x10^7$	$2.7x10^7$
Johnson Figure of Merit ($(E_c * v_{sat})/2\pi$)	1	2.7	20	27.5
Dielectric Constant	11.8	12.9 (static) 10.9 (high freq)	9.7 (static) 6.7 (high freq)	9.5 (static) 5.3 (high freq)
Thermal Conductivity (W/cm C)	1.5	0.5	3.7	1.3
Expansion Coefficient	$3.6x10^{-6}$	$6.0x10^{-6}$	$2.4x10^{-6}$	$3.2x10^{-6}$
FET Technology	LDMOS	HFET	MESFET	HFET
Power Density (W/mm)	0.8	1-1.5	4	7

Gallium Nitride
High Electron Mobility Transistor

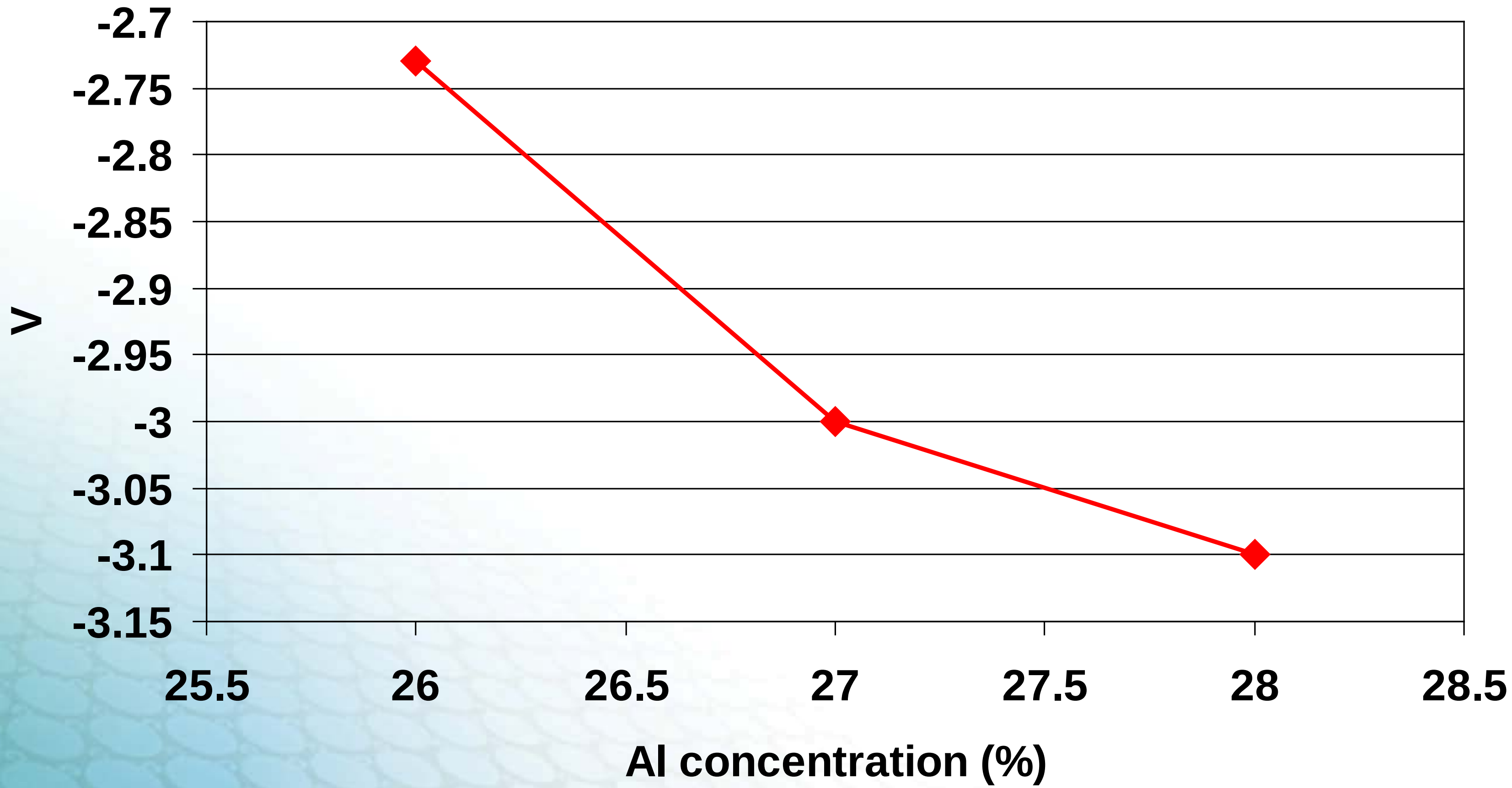
- GaN HEMT Structure
  - High Resistivity Substrate – Sapphire, SiC, Silicon
  - Nucleation Layers
  - AlGaN Buffer
  - GaN Channel
  - AlGaN Barrier
  - GaN Cap Layer – Oxidation of AlGaN
- GaN HEMT Operation
  - Gate Control – Schottky Diode MESFET
  - Active Layers Undoped
  - Channel Conduction
    - 2 Dimensional Electron Gas
    - AlGaN/GaN Band Gap Difference
    - AlGaN/GaN Lattice Mismatch/Strain
    - Piezoelectric Induced Charge
  - 2DEG Layer in GaN Channel at AlGaN/GaN Interface
  - Drain Current – Function of Al Fraction in AlGaN & Thickness of Barrier Layer



Idss vs Al % in AlGaN

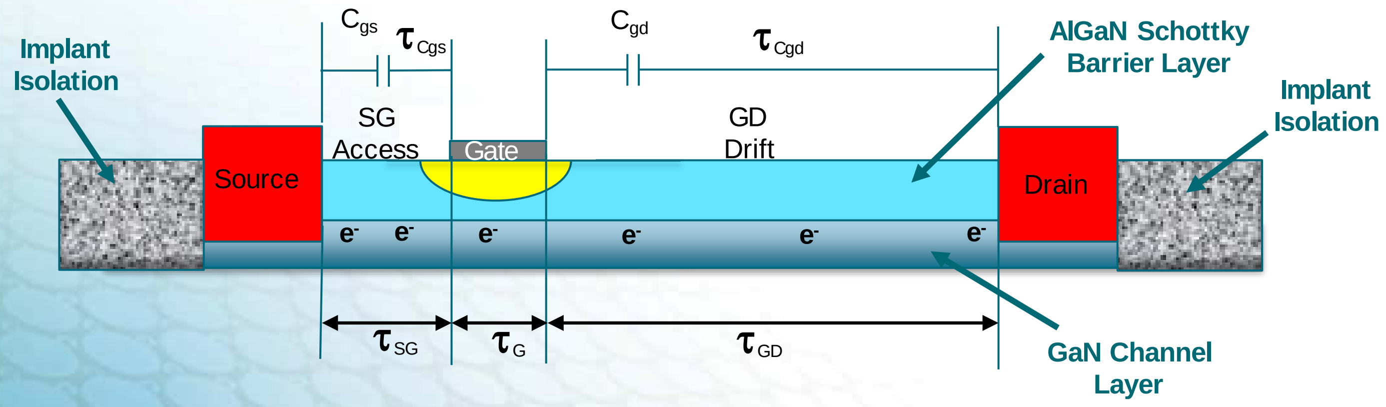


Vp vs Al % in AlGaN



GaN High Power/Frequency Advantages

- High Breakdown Field Strength
  - Enables High Drain Operating Voltages (>50 volts)
  - 10x Reduction GD Spacing while Supporting High Peak Fields
- Smaller SD Spacings => Higher Frequency Operation
  - 1st Order Analysis
  - Trapping/Dispersion Effects Not Considered
  - Phase Shifts/Delays Not Included
  - Time Delay for an Electron to Transit from Source to Drain
  - Frequency Capability/RF Gain Direct Function of Transit Delay



$$\tau_{SD} = \tau_{SG} + \tau_{Cgs} + \tau_{G} + \tau_{Cgd} + \tau_{GD}$$

$$f_T = 1/(2\pi\tau_{SD})$$

$$RF_{gain} \approx f_T/f$$

GaN High Power/Frequency Advantages

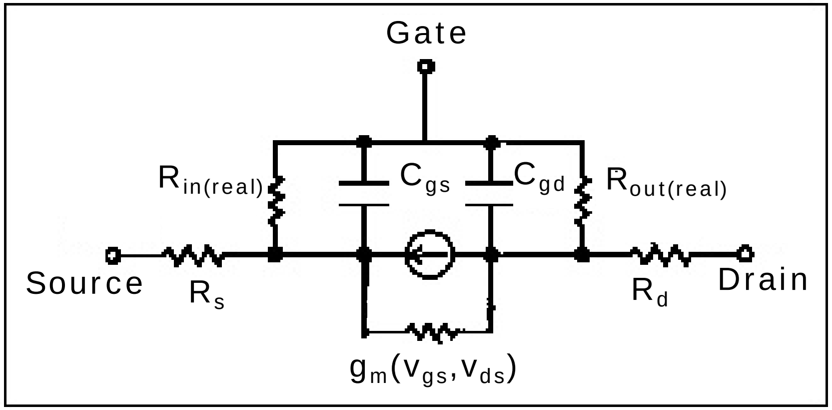
- Higher Device Impedances

$$P = \frac{V^2}{R} \quad \text{Ohms Law}$$

$$V_{rms} = V_{p\text{-}p}/(2^*\sqrt{2}) \quad V_{p\text{-}p} = 2V_{dd}$$

$$R_{o(real)} = V_{dd}^2/2P_o$$

  - Outside World is 50Ω
  - Transformation Elements ARE NOT Lossless – Have a Finite Q
  - Higher Real Impedance => Reduced Impedance Transformation/Fewer Elements
- Low Dielectric Constant
  - Low Intrinsic Terminal Capacitances
  - C_{gs}/C_{gd} in Parallel with $R_{in(real)}/R_{out(real)}$ – Parasitic Transformation Lowers Impedances
  - C_{ds} is Feedback Element – Improved Device Stability



GaN/SiC vs GaN/Si

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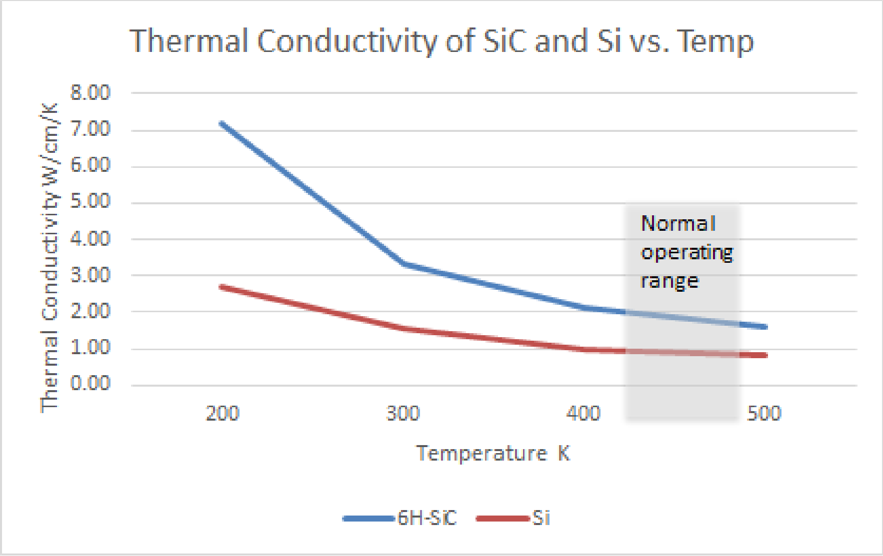
- High Frequency Power Devices
  - GaN is GaN!!
  - GaN has Excellent Saturated Electron Velocity - 2.7×10^7 cm/s
  - Highest Among Standard Semiconductor Materials
- Thermal Conductivity
  - GaN approximately the same as Silicon
  - GaN approximately one third of SiC and Copper
  - Improved Thermal Conductivity of SiC Substrate
  - Everything Else Being Equal – GaN/SiC WILL Outperform GaN/Si

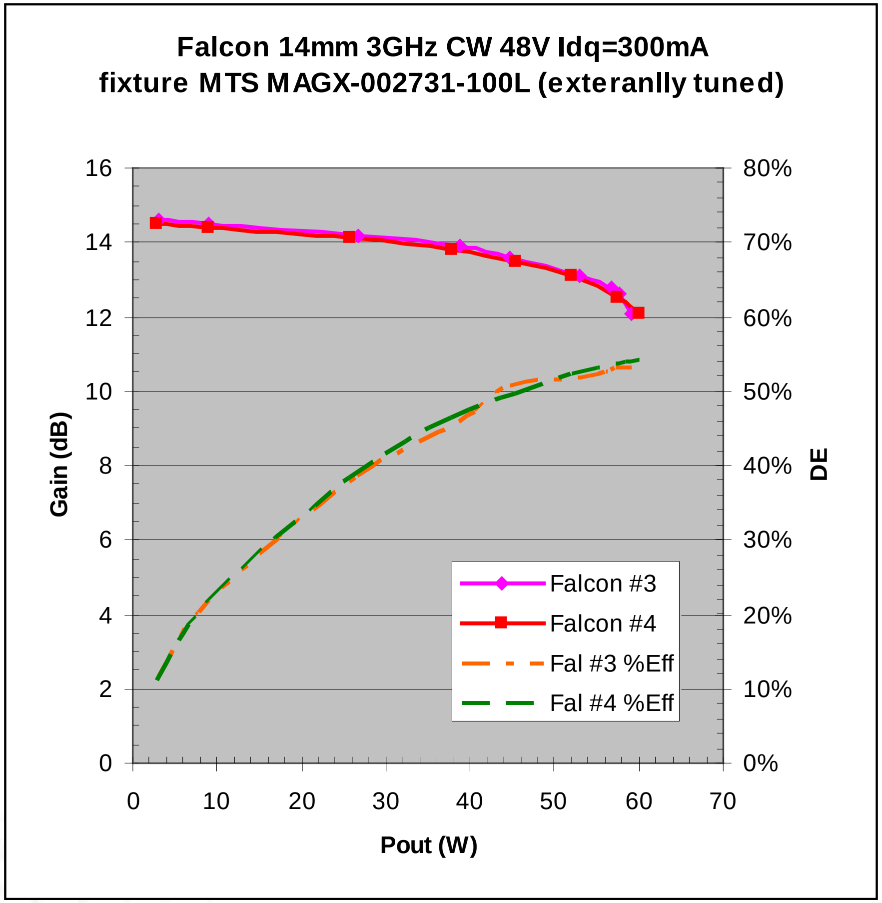


- Everything Isn't Equal
  - Difference in Thermal Response Not as Great as it Would Seem
  - Thermal Conductivity for SiC & Silicon Asymptote at Elevated Temperature
  - GaN Operating Temperature - 200°C to 220°C
  - 3:1 Factor Reduces to <2:1 at Temperatures >150°C
  - Thermal Difference Can be Overcome by Improved Thermal Design

Comparison: GaN/Si to GaN/SiC

- GaN on Silicon
  - Condition: Freq = 3GHz, Vds = 48V, Idq = 300mA
  - P_{1dB} = 60W (CW) min
  - G_{1dB} = 15dB
  - Eff_{1dB} = 60%
- GaN on SiC
  - Condition: Freq = 3GHz, Vds = 48V, Idq = 300mA
  - P_{3dB} = 60W (CW)
  - G_{3dB} = 12dB
  - Eff_{3dB} = ~55%

48 V GaN/Si Showing Comparable Performance (or Superior) as Compared to GaN/SiC



GaN-on-Silicon Performance

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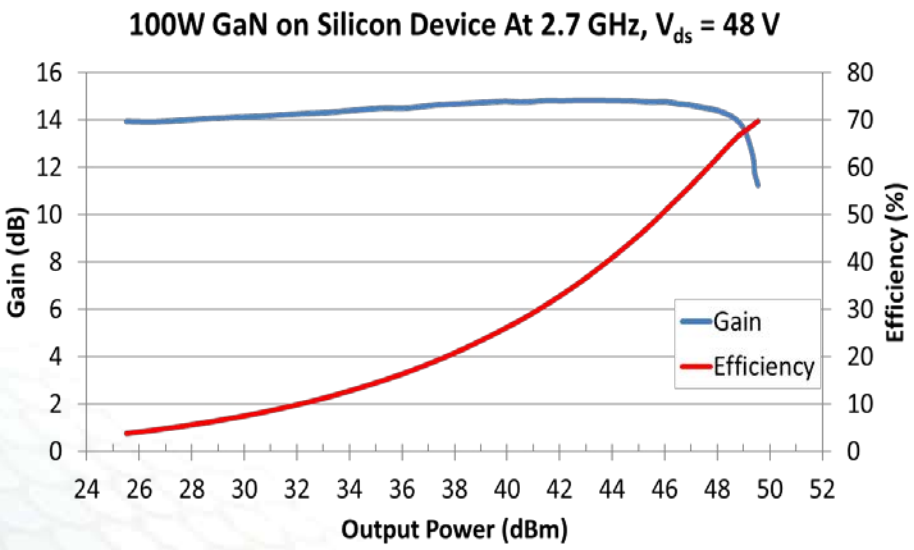
GaN/Si Matches GaN/SiC Performance

- Epitaxial Structure
- Epitaxial Growth Conditions
- Device Processing
- Goal: Minimize total parasitic interfacial charge
  - High Resistivity Silicon Substrate (>100 ohm-cm; preferably >10,000 ohm-cm)
  - Peak interfacial charge $<10^{17}cm^{-3}$

0.5 µm gate length at 2 GHz	GaN/Si	GaN/SiC
Power Density (W/mm)	7	7
Gain (dB)	17.5	15
Efficiency (%)	>70	>65



GaN/Si Has Achieved The Performance Required To Enable Wide Adoption

GaN/SiC vs GaN/Si
Substrate Materials Technology Drives Cost

Device Technology	Substrate Technology	Substrate Maturity	Size	Industry Volume	$/in^2
GaN on SiC	SI-SiC	Low	3" - 6"	1 X	1 X
GaN on Si	Silicon	High	4" – 12"	10^6 X	10^{-3} – 10^{-4} X

- Cost Structure
  - SiC Substrate Material Generation – 150 μm/hr at >2200°C
  - SiC Substrate Production Dominated by One Supplier
  - Silicon Substrate Material – 3 in/hr (76,200 μm/hr) at ≈1400°C
  - Silicon Substrates – Many Suppliers/Very Competitive Market
  - Substrate Cost/Area is Factor of >1000x - Si:SiC
  - GaN Epitaxial Growth Differences Immaterial
  - Substrate Cost Dominates GaN Epitaxial Material
- Effect on Thermal Design
  - Improve Device Thermal Resistance on Silicon Substrate
  - Thermal Resistance Sets the Reliable Device Operating Junction Temperature
  - Spread Heat Generating Areas => Larger Die
  - Die Size Increase ≈20%
  - Enabled by Lower Cost of Silicon Substrate

Silicon Carbide World

Silicon World

GaN High Frequency Power Performance Alternate Technologies Comparison

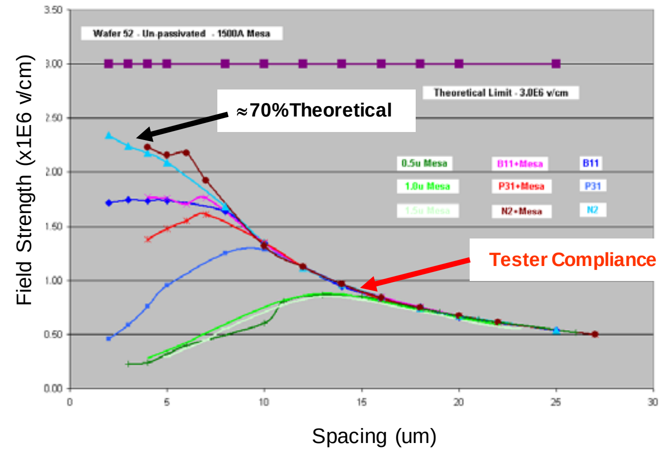
Technology	Power Capability	Gate Length	Drain Voltage	Frequency Response
	(w/mm)	(µm)	(v)	(GHz)
MSAG (Ion Implanted/Epitaxial GaAs FET)	0.5	0.4	8.0	20.0
HVMSAG (GCFP/SCFP, Ion Implanted/Epitaxial GaAs FET)	0.9-1.3	0.5	24.0	6.0
Power pHEMT	1.0-1.3	0.3	9.0	20.0
High Voltage PHEMT	1.9	0.5	24.0	10.0
mmW pHEMT	0.5	0.20	6.0	40.0
Silicon LDMOS	0.8	0.6	50.0	2.5
GaN on Si	2.5-3.5	0.5	28.0	10.0
GaN on Si	3.5-5.5	0.5	50.0	10.0
GaN on SiC	4.8-5.2	1.0	28.0	10.0
GaN on SiC	6.5-10	0.5	50.0	10.0

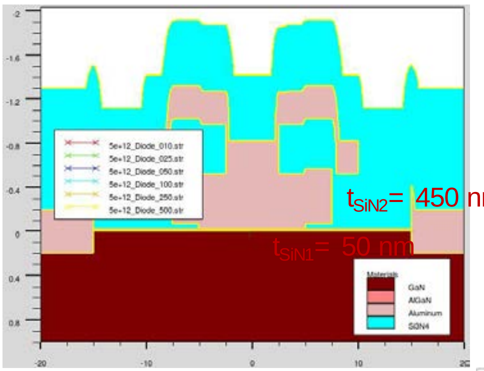
GaN HEMT Issues/Challenges

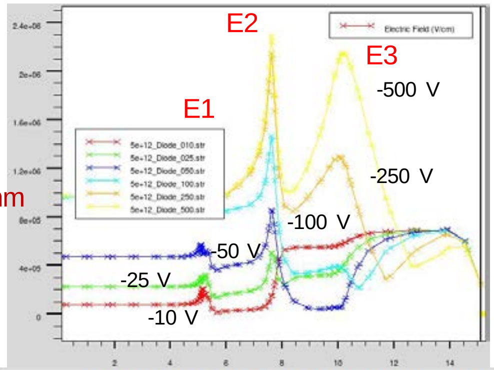
- Design
  - Device Breakdown/Leakage
  - GaN Epitaxy
    - Defects/Bulk Traps
    - Schottky Barrier Layer Design
  - Epitaxial Buffer Thickness
  - Surface Traps
  - Dispersion
  - Passivation
  - SD/Gate Leakage
    - Gate Metal Stack-Up/Thermal Cycle
    - Fowler-Nordheim Tunneling

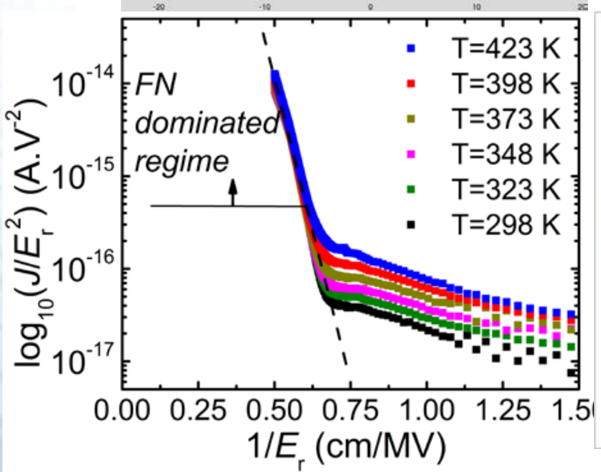
$$J_{FN} = AE_r^{\ 2} \exp(-\frac{B}{E_r})$$

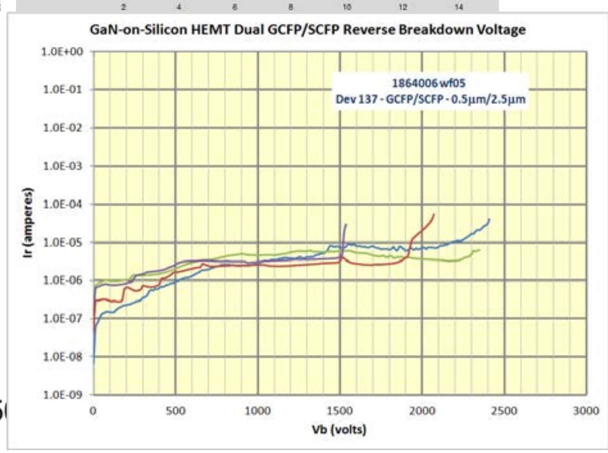
  - Peak Field Management/ Field Plate Design
  - Thermal Layout





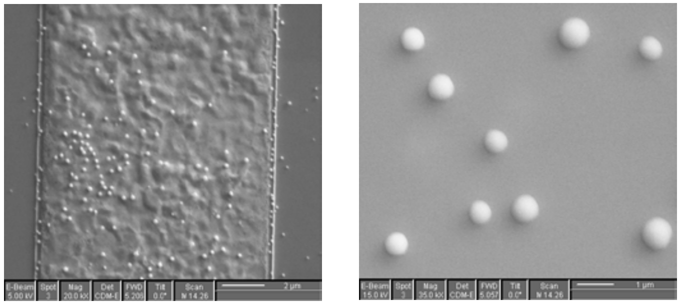




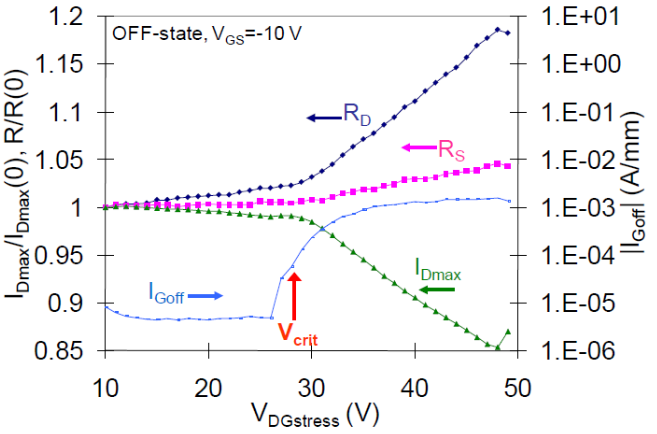


GaN HEMT Issues/Challenges

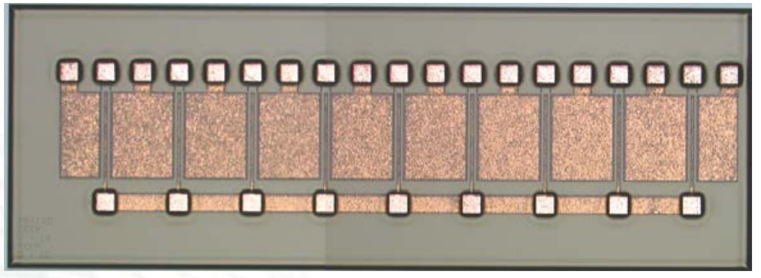
- Process
  - GaN Coherency
    - Nitrogen Sublimation from Surface
    - GaN Ohmic Metal – Ti/Al/Ni/Au
    - Thermal Cycle >800C
  - Gate Leakage/Stability
    - Gate Metal Stack-Up
    - Ni/Au; Ni/Pd/Au; Ni/Pt/Au; NiO/Ni//Au
    - GaN Surface States/Passivation
  - Bulk/Surface Traps - Dispersion
  - Source Vias
  - MOSFET/High Frequency GaN/Si Integration
    - Large Diameter Wafers – 150mm/200mm
    - Al or Cu Interconnect Metallization
    - Contact Resistance/Gold Free Ohmics
    - Ti/Al/W; Ta/Al/Ta; Si/Ti/Si/Al/Mo
    - Dielectric Crossovers
    - Source Vias
    - Wafer Thinning – 50um to100um



Ga Nodules after Ohmic Metal RTA Cycle



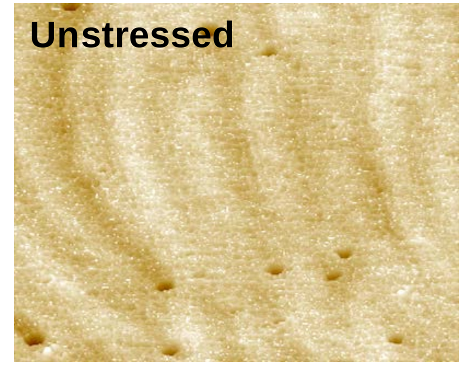
Gate Schottky Diode Degradation

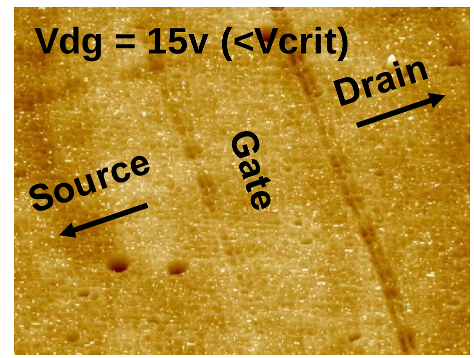


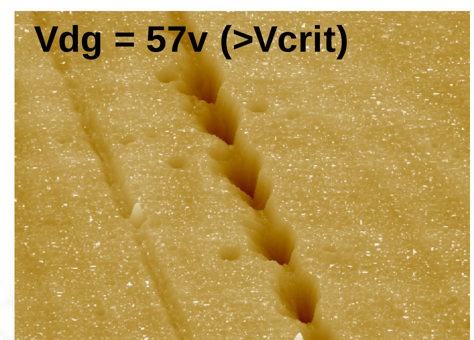
20mm Gate Periphery Gold Free GaN/Si – 200mm Si CMOS Fab

GaN HEMT Issues/Limitations

- Reliability
  - Electrical & Structural Degradation
  - Independent of Substrate
  - Gate Leakage
  - Current Collapse
  - Reverse Piezoelectric Effect
  - Mechanical Pit Formation
    - Ig Increase - Temperature Dependence
    - Id Degradation - Driven by High Field – Primarily at Drain Side of Gate
    - Coalesce Into Continuous Line/Crack
  - RF Power Degradation
  - Field Controlled/Field Plate Design Critical







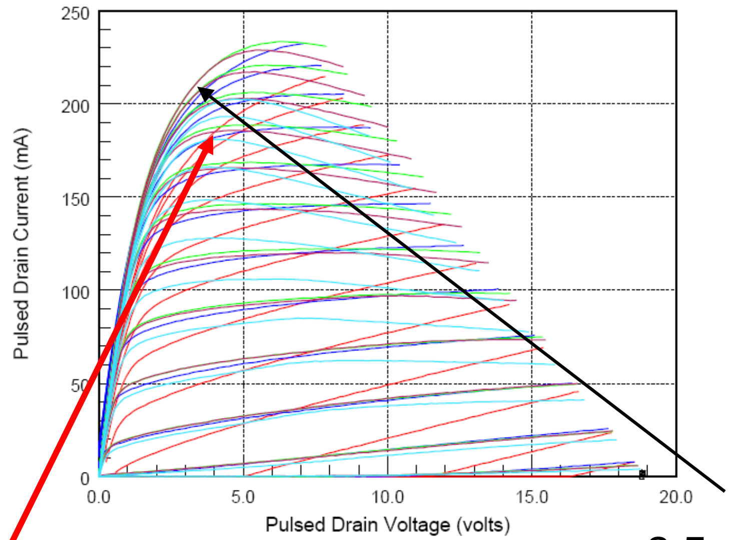
Makaram, APL 2010

GaN HEMT Issues/Limitations

Reliability

Pulsed IV Characteristics
Current Collapse

- 200µ FET
- 20 volt Load Line
- 1.15 A/mm
- 300ns, 1µs, 10µs, 80µs, 1ms Pulse Widths

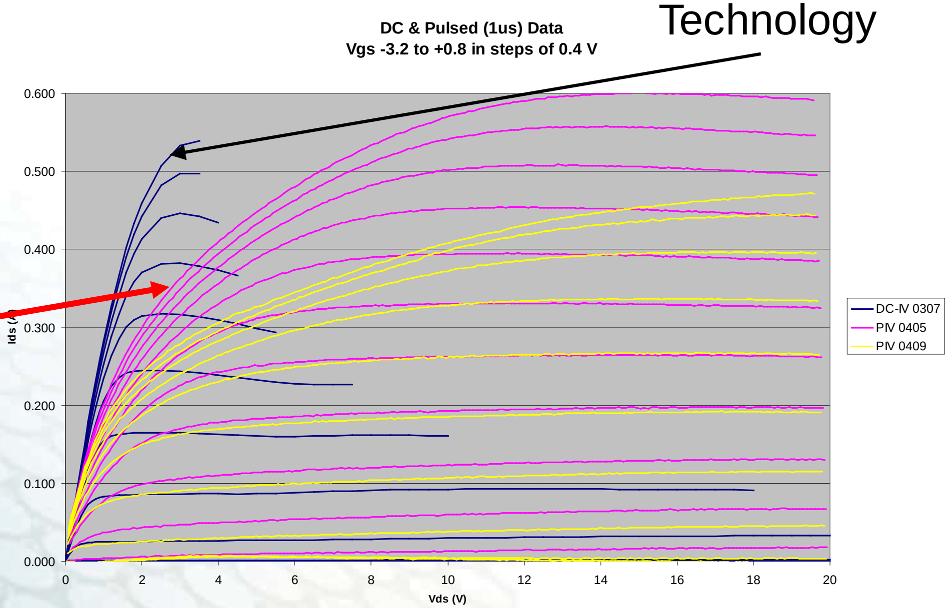


3.5v Knee Voltage

GaN is a High Voltage Technology

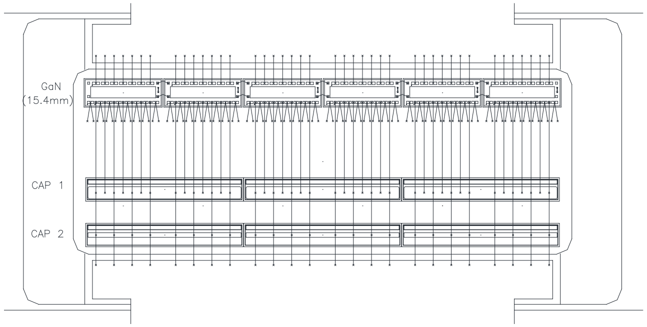
- Minimal Current Dispersion

- Severe Current Collapse

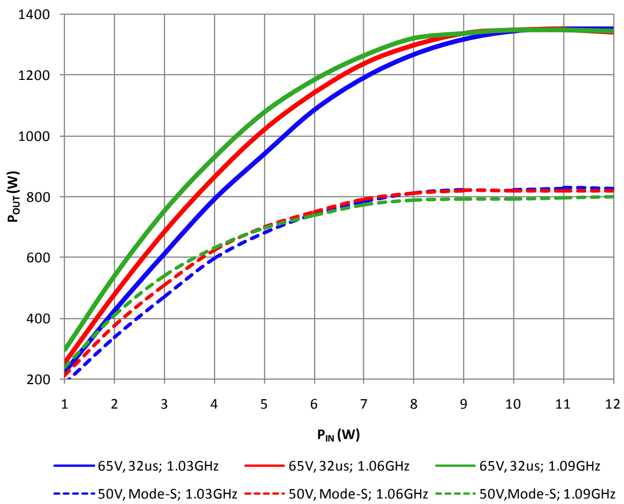


GaN Future Directions

- Future is NOW
- Higher Power
  - >1kW
  - Increased Operating Voltages
  - Modular Integration

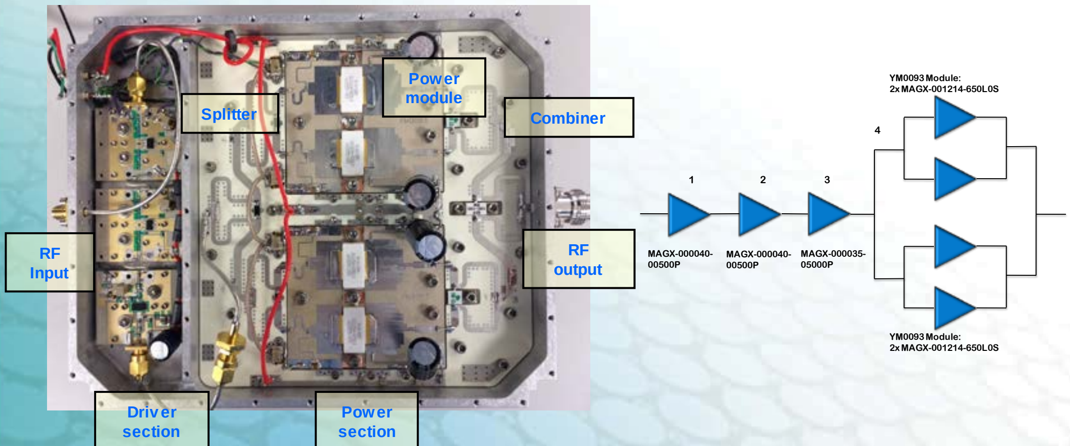


GaN/SiC - 650 mm of Gate Periphery



Pout vs Pin Characteristic

MACOM MAGX-001090-1K1L00, 1.1kW GaN/SiC Power Transistor



MACOM 2kW L-Band Amplifier, 4 Stage Lineup.

GaN Future Directions

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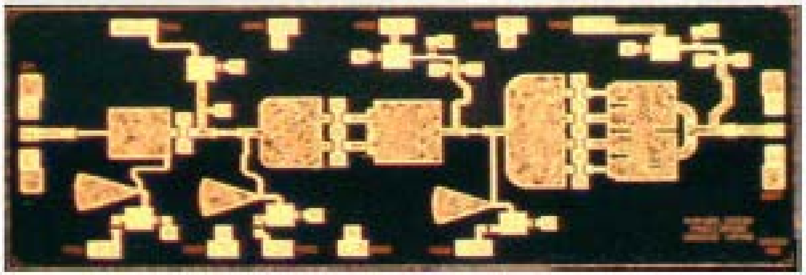
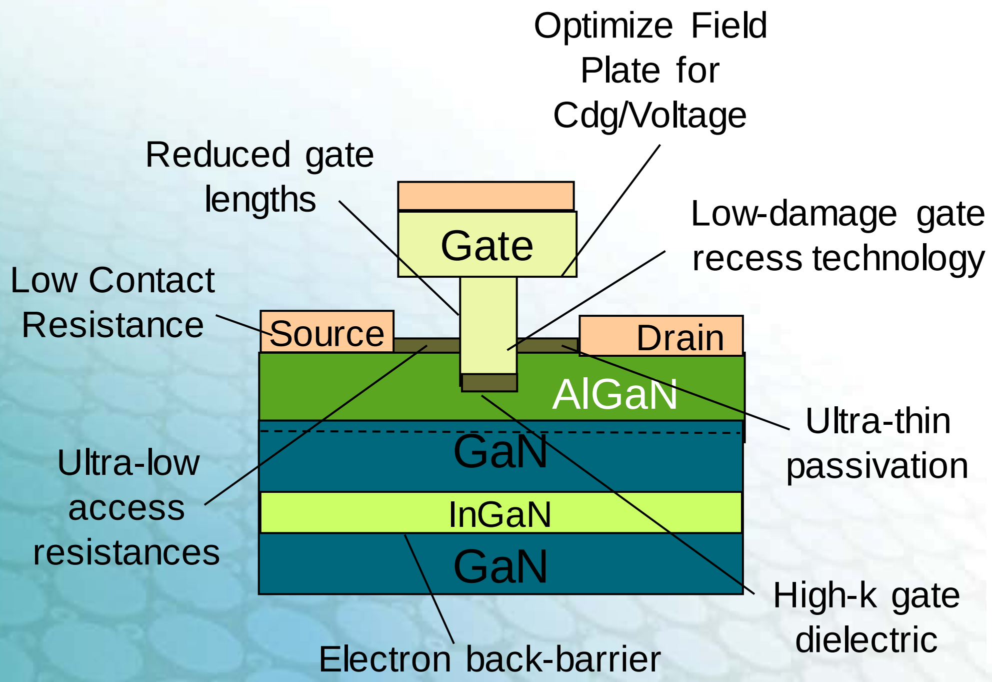
- Pushing to Higher Frequencies
  - Ka Band (26.5-40 GHz)
  - E- Band (60-90 GHz)
  - W-Band (75-110 GHz)
  - TeraHertz Operation

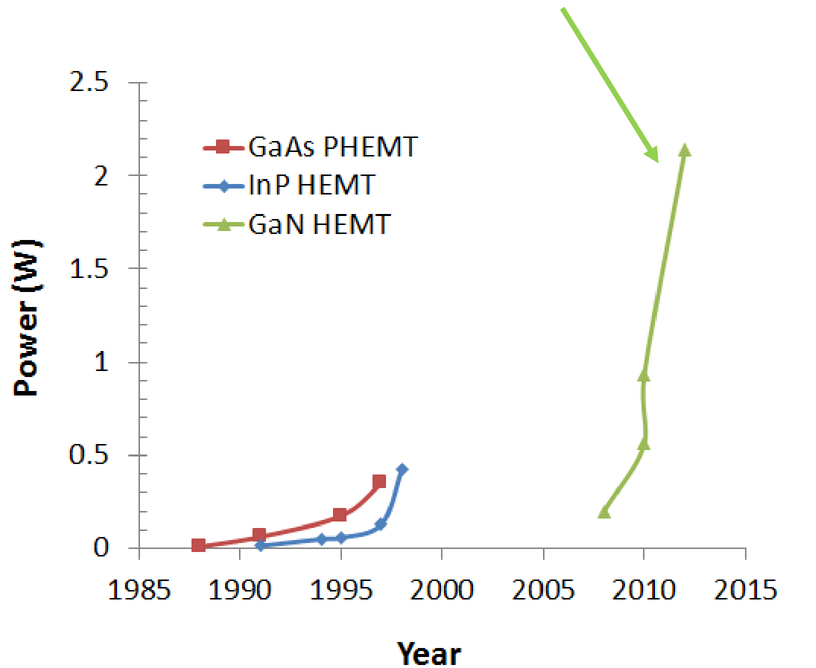
94-95 GHz MMIC PA



Micovic, MTT-S 2010



Micovic, MTT-S 2012

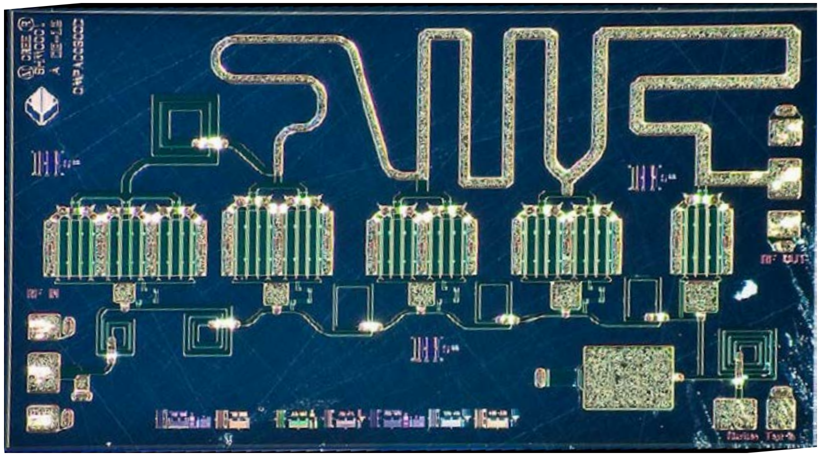


GaN Future Directions

MACOM

- GaN MMICs
  - Multi-Stage Amplifiers
  - Mixers
  - High Power Switches
  - Receivers
    - Common Leg Circuit
      - Phase Shifter
      - Attenuator
      - SPDT Switches
    - LNA
    - Gain Blocks
  - Transmit/Receive on a Chip
    - Multi-Stage Amplifiers
    - Receivers
    - Switches
    - Limiters
    - Filters

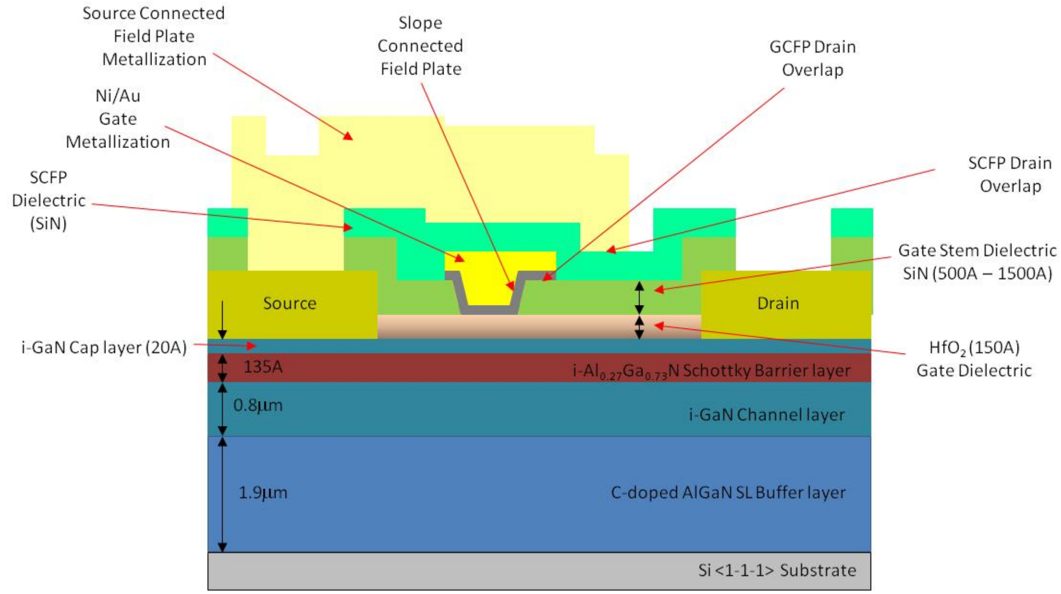
CREE - 20 MHz - 6.0 GHz, GaN MMIC, Power Amplifier



- Ultra Broad Band Multi-Stage Amplifier
- Gain - 18 dB
- Psat - 30 W
- Power Gain – 13.5 dB
- PAE – 33%
- Operation up to 50 V
- 50Ω Input & Output Match
- Die Size 0.157 x 0.094 x 0.004 inches

GaN Future Directions

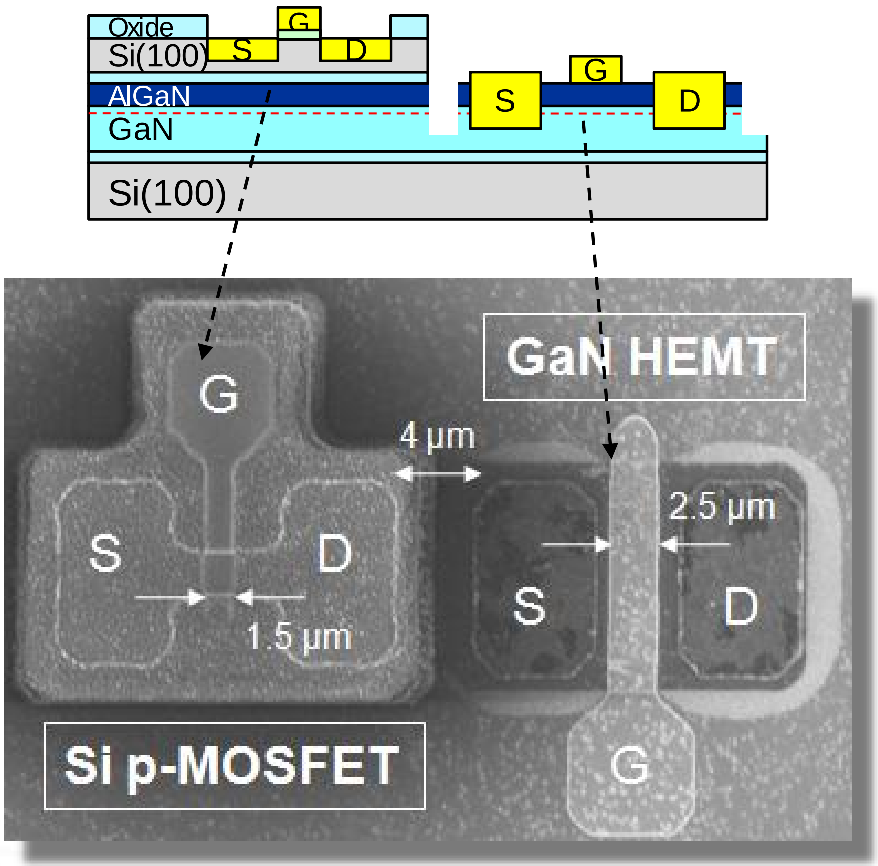
- GaN MISHEMTs
  - Turn to Mainstream Silicon
  - MISHEMT Formation
  - High-k Dielectrics Gate Dielectrics Have Successfully Reduced Gate Leakage
  - Traditional Silicon Gate Dielectrics Decrease the Gate Capacitance, Reducing Gate Modulation, and Transconductance



  - Si Industry has Successfully Adopted High-k Dielectrics for State-of-the-Art Silicon MOSFETs
  - Atomic Layer Deposition
  - Self Limiting Reactions of Various Pre-Cursors
  - Atomic Layer Control - Excellent Uniformity, Thickness Control and Reproducibility
  - Multi-Layer Films Readily Achievable – “Tune” the Fixed Film Charge
  - Large Variety of Dielectrics Possible Including High-k Films
  - Al_2O_3, HfO_2, La_2O_3, SiO_2, TiO_2, ZnO, ZrO_2, Ga_2O_3, Sc_2O_3, AlN, and HfN Available
  - Incorporating Field Plate Optimization

GaN Future Directions

- GaN/MOSFET Integration
  - Integration of III-V HEMTs and Si (100) MOSFETs
  - *High power digital-to-analog converters (DACs)*
  - On-wafer wireless transmitters
  - *Driver stages for on-wafer optoelectronics*
  - *Power amplifiers coupled to Si linearizer circuits*
  - *High speed (high power) differential amplifiers*
  - *Normally-off power transistors*
  - *New enhancement-mode power transistors*
  - *Buffer stages for ultra-low-power electronics*
  - *Power distribution network in Si electronics*



Summary

- Old Technologies NEVER Die (Always Find a Niche)
- New Technologies Always Take Longer to Implement Than Predictions
- **COST/Capability** is the Prime Driver
- Lowest Cost Solution that Delivers the Minimum Requirement **WINS**
- Gemanium Started it All - Before Everyone in this Room was Born
- Quickly Supplanted by Silicon
- Ge Still Alive Today – IR Sensors & SiGe BiCMOS ICs
- GaAs - Circa 1960
  - The Material of the Future (And Always Will Be – Silicon World)
  - Prediction Realized for μW and mmW Applications – 1980's (Cell Phones)
- New Semiconductor Materials (And Not So New)
  - SiGe – High Speed Digital
  - SiC – Power Switching
  - InP – Optical Lasers
  - HgCdTe – IR Detectors
  - GaN – LEDs, Power Switching, RF/μW/mmW
  - Ga_2O_3 – High Frequency
  - Groups II, III, IV, V, VI

Summary

- GaN
  - Newest Future Material
  - Needs to Find Unique Capability
  - Hetero-Epitaxy
  - Multiple Substrates

- Future is Already Here (At Least for Some Applications)

- High Brightness LEDs
  - **Already CLEAR WINNER**
  - Enormous Market - Commercial/Consumer
  - **Sapphire**, **SiC**, Silicon Substrates

Summary

- Smart Grid/Power Switching
  - <100kHz
  - Huge Market Potential – Just Emerging – Again Commercial Market Driven
  - Smart Electrical Grid
  - Electric Vehicles
  - Motor Controllers
  - Small Power Supplies
  - Lots of DOE Funding - Still has Technical Challenges
  - BV_{ds} = 600v to 20kv
  - Normally Off Device Required
  - Monolithic Inverters/Converters
- High Frequency
  - 1 MHz to 100 GHz
  - Good Market Potential (No Where Close to LEDs or Smart Grid)
  - Mixture of Commercial (Higher Volume) and Aerospace/Military (High Performance)
  - 5-G Base Stations/MilCom/Phased Array Radars/mmW
  - Clear Technical Successes
  - Number of Challenges Remain

Summary

MACOM

GaN – The REAL WIN

- Combine GaN Power & Frequency Capability with Digital Logic
- Opens a New World of Possibilities – All with Digital Control
  - High power digital-to-analog converters (DACs)
  - Combine Microprocessor with Monolithic Power Supply
  - On-wafer wireless transmitters
  - Driver stages for on-wafer optoelectronics
  - Power amplifiers coupled to Si linearizer circuits
  - High speed (high power) differential amplifiers
  - Normally-off power transistors
  - New enhancement-mode power transistors
  - Buffer stages for ultra-low-power electronics
  - Power distribution network in Si electronics