"Developing next-generation technologies for high-temperature applications and their requirements."

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Applications for High Temperature Semiconductor and Other Electronics

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Acknowledgements

- I would like to acknowledge my co-authors:
  - Howard Chern
  - Xiaojuan Wang
  - Jennifer Hwu
  - And also others at InnoSys Inc.

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Outline

- Motivation
- High Temperature Electronics Applications
- High Temperature Electronics Technology Candidates & Qualifications
- Fundamental and Engineering Issues
- Some Device Performance and Results
- Conclusions and Recommendations

Motivation

Electronics for

- High-temperature
- High-power
- High-frequency applications

- Smart sensors: automobile engine, jet engine, and well-logging...
- Jet engine testing
- Supersonic aircraft technology
- Space exploration and satellite technology
- Telecommunications

Applications for High Temperature Electronics

- Applications for high temperature electronics include:
  - automobile
  - aeronautical
  - geothermal
  - deep well drilling
  - nuclear
  - space
  - aerospace electronics and optoelectronics
  - ground and space communications
  - industrial controllers
  - distributed control systems
  - high power microwave circuits
  - high temperature stable sensors
  - harsh temperature environment systems
  - accelerated reliability testing of electronics
  - fuel combustion
  - high temperature processes

Applications for High Temperature Electronics (cont.)

- The economic benefits of using distributed control systems is well understood.
- However, to realize distributed controls for applications including commercial and military automobile and aerospace engine systems will require high temperature analog, digital and sensor technology.
- Instrumentation for high temperature and harsh environments need to localize 'intelligence' to obtain increased accuracy and resolution, reduce weight and system response time, and to increase reliability and efficiency.

Distributed Control Blocks

- The distributed control building blocks are:
  - input sensing
  - signal amplification, conditioning and processing
  - actuator activation and control.
- The major high temperature components needed to realize high temperature distributed control systems are:
  - microprocessors and microcontrollers (SOI or GaAs)
  - pressure, temperature, vibration, speed, and light/optical sensors
  - relay, solenoid, motor drivers, etc. (SiC, GaN, others)
  - data transmission links.

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Distributed Control Blocks (cont.)

- Over 50% of electronic failures are due to high temperature.
- High temperature electronics will result in more reliable systems and will also eliminate or reduce the need for active or passive cooling of these systems which will further reduce the system weight and complexity.

Examples of Projected Future Operating Temperature Ranges

- Commercial automobiles
  - passenger compartment: -40 to 85°C
  - engine compartment: -40 to 165°C
  - wheel mounted systems: -40 to 250°C
- Oil and gas wells require electronics that operate at 225°C and above.
- Geothermal applications will have a need for electronics that can operate at 300°C and above.
- Aerospace will need electronics that can operate to 250°C to ~ 550°C for applications ranging from braking systems to mounted avionics electronic controls to engine control and monitoring and smart composite skins.
- Most consumer applications will require electronics that operate in the range of 200°C maximum.

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Some of the Rules of the Game

- Cannot beat the laws of physics
- Need to understand, abide by and work within the laws of physics, chemistry, metallurgy, etc.
- Need to separate and delineate fundamental limitations from engineering issues

The High Temperature Arena

- For high temperature electronics there are certainly no shortage of potential candidates:
  - Si (as long as the temperature is not too high or extreme)
  - SOI -- subject of other talks here (up to ~ 250 to 300 ^{o}C)
  - Conventional III-V -- i.e., GaAs-based, InP-based (~ 400 to 500 ^{o}C)
  - SiC -- subject of other talks here (300 to 600+ ^{o}C depending...)
  - SiGe (Possibly in certain applications)
  - Nitride III-V -- i.e., GaN-based (300 to 600+ ^{o}C depending...)
  - Diamond
  - Another potential candidate
    - Thermionic-based vacuum microelectronics

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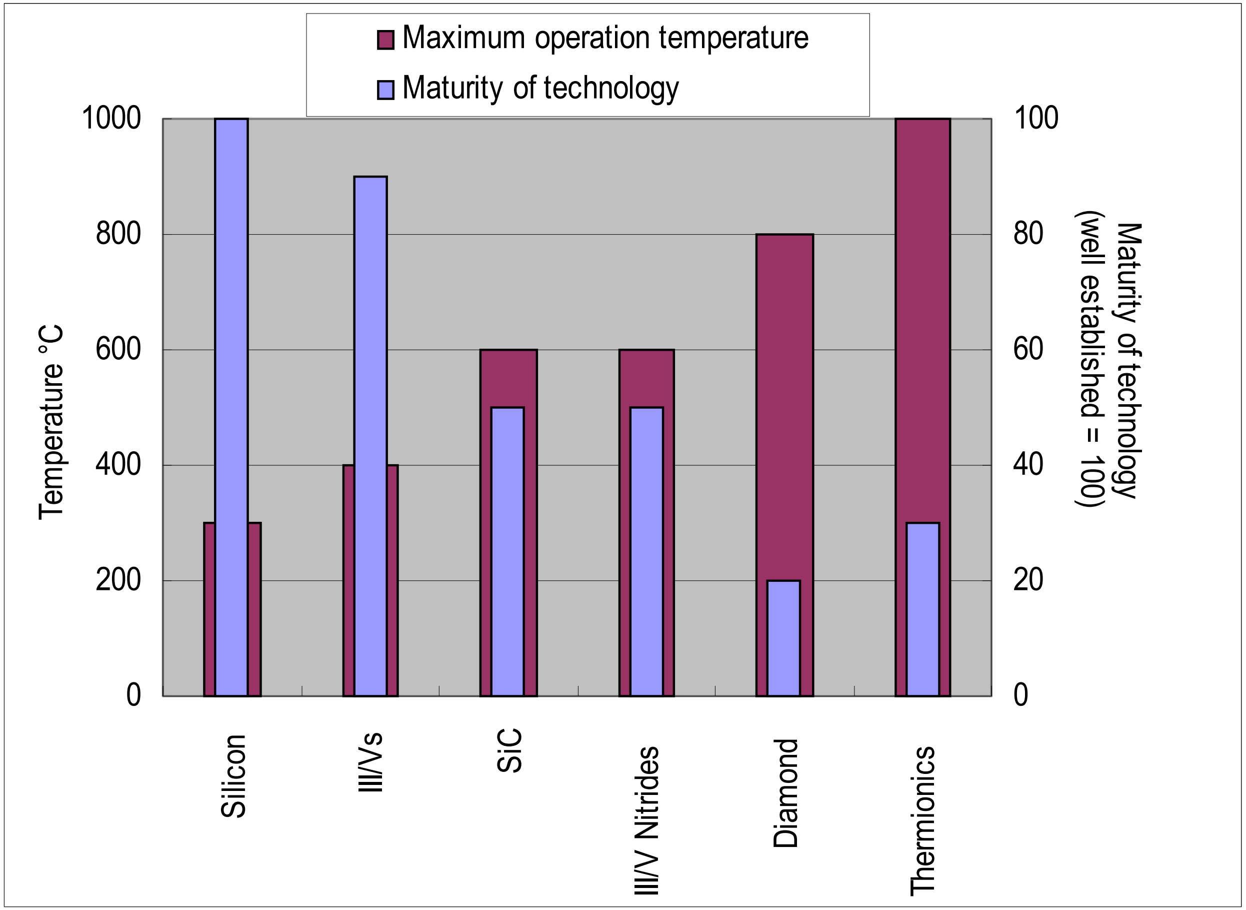
Maturity and Maximum Operation Temperature of Device Technologies



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Pecking Order

- Each material system and choice has its inherent advantages and disadvantages
- Like most things in life, maturity has much to offer
- Si is mature
- GaAs is fairly mature
- SiGe is well on its way to becoming mature
- SOI is also well on its way to becoming mature
- SOI, among other things, exploits the reduced volume/area for unwanted generation of thermal carriers. One of the main commercial interests is the inherent lower parasitic capacitance of SOI compared to conventional Si.
- Vacuum microelectronic thermionic devices, although not as mature compared to the above, potentially has much to offer in high temperature applications.

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Possible High Temperature Device Technologies

- Many possible devices:
- MOSFETs (metal oxide semiconductor field effect transistors) MISFETs (metal insulator semiconductor field effect transistors)
- IGFETs (insulated gate field effect transistors)
- JFETs ([pn] junction field effect transistors)
- MESFETs (metal emitter semiconductor field effect transistors)
- HEMTs (high electron mobility transistors)
- MODFETs (modulation doped field effect transistors)
- BJTs (bipolar junction field effect transistors)
- HBTs (heterojunction field effect transistors)
- SITs (static induction transistors)
- Thermionic triodes, pentodes, traveling wave tubes...
- and the list goes on...

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Some Considerations in High Temperature Electronics Selection

- As with most things in life, maturity has much to offer → Si and GaAs.
- The rest, well, they are not mature enough yet except in certain types of devices and applications for which commercial markets and applications exist, e.g.:
  - SiC: rectifiers, power transistors.
  - GaN: LEDs.
  - SOI: SSI to VLSI of analog, digital, data processing to 250 to 300 ^{o}C.
- In general, material quality and perfection has much to offer → again Si and GaAs with SiGe and SOI moving into this category.
- Intrinsic carrier concentration and other figures of merit.
- Defects whether electrical, mechanical, material, or some subset of these and other types are, in general, not good and usually become 'less good' as the operation temperature increases.

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Some Considerations in High Temperature Electronics Selection (cont.)

- The challenges are significant.
- Basically all wide bandgap systems have certain fundamentals in common including mobility decreasing as temperature increases.
- Energy Bandgap (E_g) is a very important figure of merit.
- For example, E_g plays a major and intimate role in intrinsic carrier concentration and bond strength of semiconductor materials.
- With all semiconductors n_i and n_i^2 play a significant fundamental role on the upper temperature limit of semiconductor devices.

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Change of Semiconductor Properties at Elevated Temperatures

- Effects influencing the electrical properties
  - Intrinsic carrier concentration increases

$$n_i = \sqrt{N_c N_v} e^{-E_g / 2kT}$$

  - Bandgap decreases

Eg(T)= Eg(0) - $\alpha T^2/(T+\beta)$; a ~ 5E-4, B ~ 200 to 800

  - Carrier mobility decreases
  - Fermi potential decreases
  - Reduction of depletion region
  - Minority carrier lifetime changes
  - Effective mass changes

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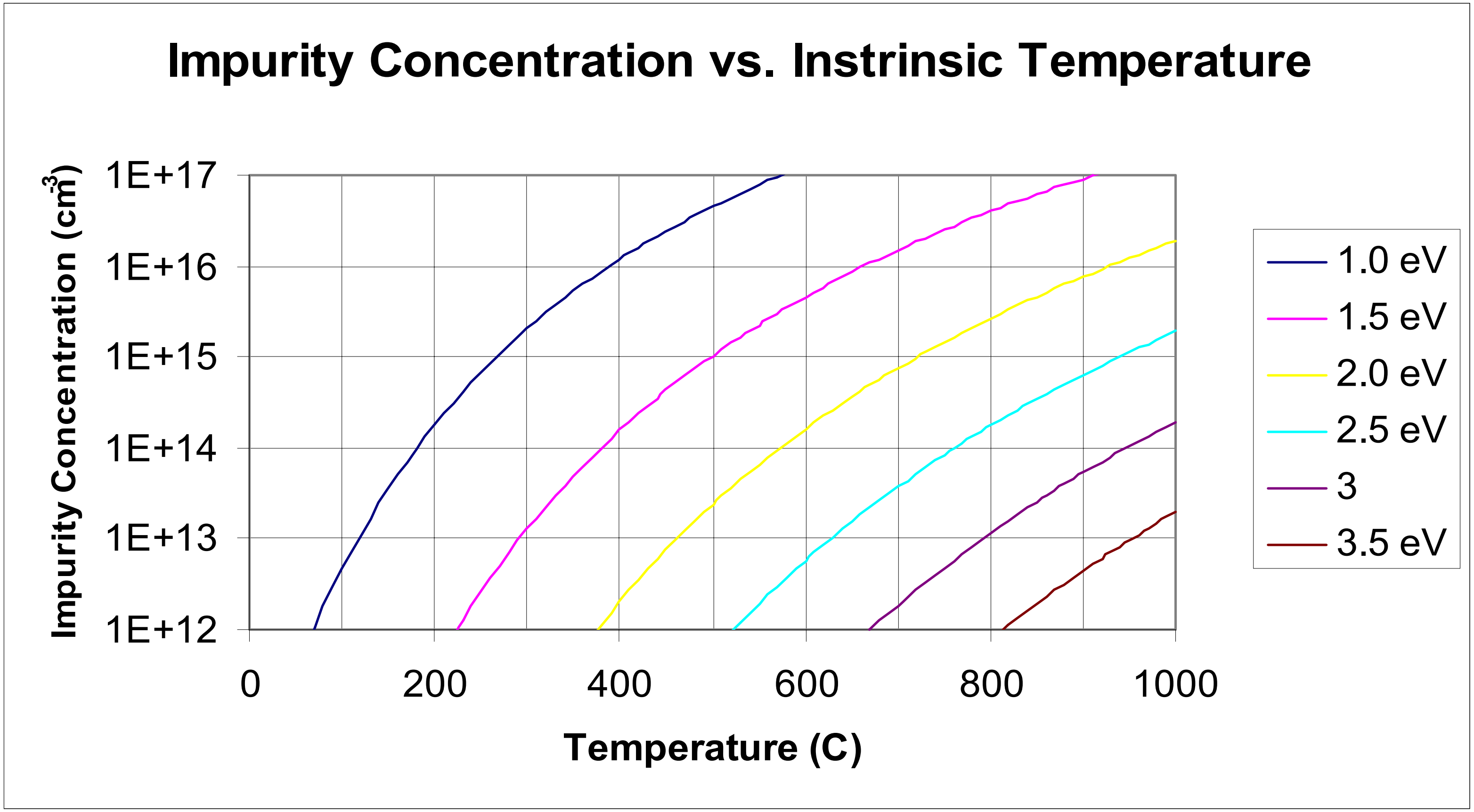
Impurity Concentration vs. Intrinsic Temperature



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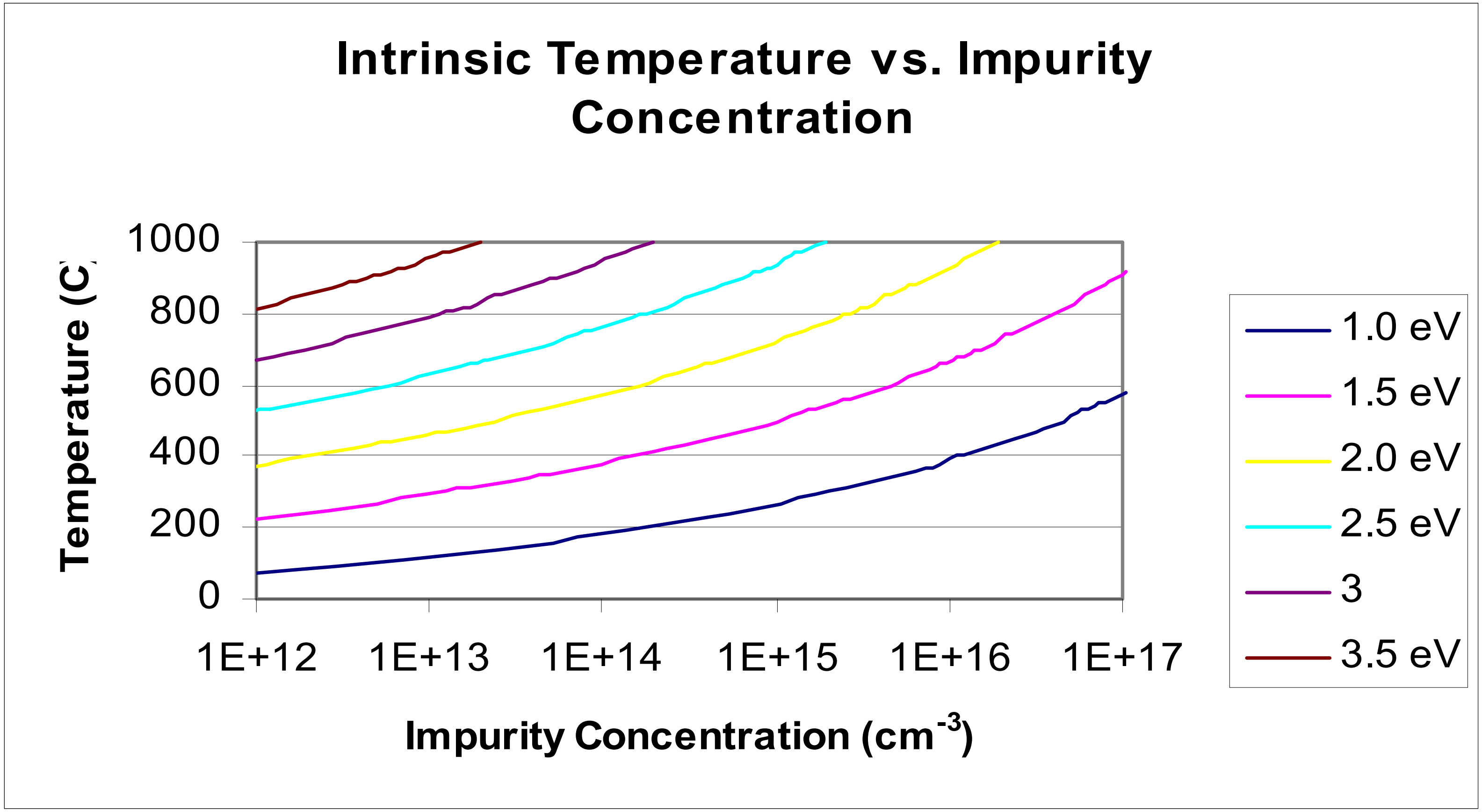
Intrinsic Temperature vs. Impurity Concentration



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Important Figures of Merit to Consider

Material	Maximum operation temperature (k)	$(E_b \times V_{d,s}/\pi)^2$ $(W\Omega s^{-2})$ (Johnson)	Ratio to Si	$\sigma_\tau \times (V_{d,s}/\varepsilon_r)$ ($Wcm^{-1/2}$ $s^{-1/2}$) (KEYES)	Ratio to Si
Si	600	9.0×10^{23}	1	1.4×10^{3}	1
GaAs	750+	6.3×10^{24}	7	6.2×10^{2}	0.46
GaN	800	2.5×10^{26}	282	2.4×10^{3}	1.76
α-SiC (6H)	900	6.3×10^{26}	695	7.1×10^{3}	5.12
β-SiC (3C)	1200	1.0×10^{27}	1138	8.0×10^{3}	5.8
Diamond	1500	7.4×10^{27}	8206	4.4×10^{4}	32.2

- Johnsons figure of merit:
  - Set by breakdown voltage and electron saturation velocity
  - Suitable for discrete power and high frequency devices
- Keyes figure of merit:
  - Determined by thermal conductivity and electron saturation velocity
  - Suitable for integrated power and high frequency devices

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Let's Get Real…

- In terms of high temperature electronics and operation: It ain't as easy as one would like it to be.
- In general, really high speed at high temperature is probably not very realistic.
- Never underestimate the materials issues including inter-connects and intermetallics -- really need to understand this.
- System budget (most certainly not just monetary).
- Problems with parasitic issues at high temperature -- parasitics are nasty and complex -- best not to underestimate them.
- Most things (e.g. materials, devices) leak at high temperatures.
- RC time constant (etc.) issues at high temperatures.
- Phonons have their own agenda-- better to work with them than against them.

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Let's Continue To Get Real... (it will take some time and effort to accomplish...)

- TCE issues are a real pain at extreme temperatures.
- Stress/strain are also a pain and don't usually improve with T.
- A whole host of exponential issues with high temperatures.
- Most/all of the commercial world could care less and try to avoid (like the plague) high temperature issues and operation.
- Low temperature has a lot going for it in terms of technology choices and options especially compared to high temperature.
- There are problems with contacts (Ohmic or otherwise) operating at high temperatures for prolonged periods of time.
- InnoSys is looking at PAs from sub-GHz to very high frequencies:
  - Real PAs are not made from/with SOI or SiGe.
  - Si PAs (e.g., LDMOS) need lots and lots of cooling.
  - In general, PA cost is of paramount concern.

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The Downside of High Temperature Operation

- Barring/excluding effects such as thermally generated emission from traps and V_t shifts for FETs this implies that the 'useful' current decreases with temperature.
- Also, in general, thermally induced breakdown voltages decrease with temperature.
- Thus, the controlled power (current-voltage product) decreases with temperature.
- **Self heating** is an issue for power electronics – this should not be underestimated nor can it be overstated.
- Most people do not like and try to avoid input current drive in circuits even at high temperatures - however with high temperature semiconductor electronics input current is usually 'there' (that is, a given) -- like it or not.

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A Partial List of the Issues

- Device versus circuit issues
- Device modeling issues
- Circuit topology issues
- Monolithic versus hybrid (in general, hybrid wins for high temperature applications).
- Voltage supply values
- Self-heating
- Heat dissipation and distribution
- Defects, traps

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Some of the Effects of High Temperature Device Operation

- Change of threshold voltage
- Increase of subthreshold current
- Reduction of transconductance
- Reduction of on/off current ratios
- Leakage current problems
- Potential Latchup problems

Degradation Effects in Semiconductor Materials Including Contact and Systems

- Dopant diffusion
  - Movement of Junctions
- Defect migration
  - Induces vacancy assisted diffusion
  - Short circuits
- Interdiffusion of heterointerfaces
  - Modifies band discontinuities
- Strain relaxation (especially in strained quantum wall layers)
- In diffusion from the ambient
- Degradation effects related to thermal mismatch
- Some of the above are not as prevalent in WBG materials

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Effects of Increasing the Operation Temperature

pn-Diodes

- Reverse junction leakage:
  - Increases exponentially with temperature
  - Generation currents dominate at room temperature
  - Diffusion currents dominate at high temperatures
  - Causes problem in:
    - Isolation properties of bulk MOSFETs (well to substrate leakage)
    - Protection circuits may affect device performance
- Forward voltage drop:
  - Decreases with increasing temperature
  - Increases with increasing bandgap
    - Power dissipation problems in wide bandgap diodes

Effects of Increasing the Operation Temperature (Cont.)

FETs

- Mobility decreases T^{-n} n ~ 1 to 2 (sometimes larger)
- Leakage currents increase exponentially
- Transconductane, g_m, generally decreases but does depend on parameters such as V_t.
- Output conductance eventually increases exponentially

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Effects of Increasing the Operation Temperature (Cont.)

BJTs and, to a Large Extent, HBTs

- V_{be} decreases as T increases (2 mV/^{o}C for Si BJT, similar behavior for SiC and SiGe).
- Mobility decreases results in increased base and collector resistances.
- Currents increase exponentially with T.
- β (= h_{fe} = I_c/I_b current gain) increases as T^m (m~ 1 to 2).

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Effects of Increasing the Operation Temperature (Cont.)

Circuits

- Analog
  - Amplifier gain-bandwidth (GBW) product decreases
  - Amplifier input offset voltages increase
  - Switched capacitors become leaky
  - Input currents and voltages increase
- Digital
  - Noise margins decrease
  - Switching speed decrease
  - Logic swings decrease
  - Noise margins decrease
  - Current sinking/sourcing capability decreases
  - Latch up happens
  - Digital
- Memory
  - Charge leakage increases; retention time decreases; power increases

Primary High/Extreme Temperature Active Devices

- Silicon semiconductors and technologies
  - CMOS on:
    - Bulk material
    - Epitaxial material
    - SOI
  - Bipolar transistors on SOI-material
- Wide bandgap semiconductors
  - III/V compounds together with the corresponding heterostructures FETs and HEMTs/MODFETs Both Discrete devices and Ics.
  - III/V nitrides HEMTs/MODFETs
  - SIC BJTs; MOSFETs limited to 300 to 350 ^{o}C operation (oxide issues at high temperature similar to SOI), possibly JFETs and MESFETs sometime down the road. Discrete devices.
  - Diamond Only very slow p-type FETs to date -- much work to be done...
- Vacuum microelectronics devices
  - Compatible with Si, SOI, III-Vs, other substrates, thin film technology, etc.
  - Based on thermionic emission and extremely well suited for extreme electronics

Silicon and Si-Based High Temperature Electronics

- Main problem: relatively small band gap, therefore low intrinsic temperature at which the doping is overcome by thermal carriers
- Bipolar Transistors:
  - Thermally induced breakdown
  - decrease of 2 mV/^{o}C in V_{be} (forward input voltage)
  - SiGe-HBTs probably promising in certain applications
- MOSFET Technologies
  - Bulk CMOS with special compensation structures
  - CMOS on epitaxial layers
  - SOI and associated variants and techniques (The real contender)

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Realized High Temperature Silicon Devices

- Analog devices
  - Operational amplifiers
  - Current and voltage sources
  - Sensor electronics (e.g. magnetic field, pressure etc.)
- Digital devices
  - ASICs
  - A/D converters
  - EEPROMs
  - Microcontrollers
  - Pulse generators
  - Caveat: need a voltage (bandgap?) reference

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Wide Bandgap Systems for High Temperature Applications

- The use of any wide bandgap semiconductor material system really depends on what the end goal is.

- Need to understand the intimate requirements of the application including trade-offs, cost, performance, limitations, expectations, realistic needs, system integration, etc.

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GaAs-Based Devices

- Intrinsic temperature is higher than silicon → principally capable for operation temperatures > 400°C (essentially up to 500°C and possibly a little higher)
- Well established standard foundry technologies are available
  - Limited modification of existing processes
  - Relatively very mature technology
- Exploit existing GaAs VLSI capability
- Typical material parameters open up additional possibilities and fields of applications
  - Ternary and quarternary heterostructure technologies
    - Bandgap engineering
    - Many degrees of freedom for device optimization
    - Many wide bandgap material possiblilities
  - High electron mobility
  - Direct bandgap → optoelectronic devices
  - Semi-insulating/semi-isolating substrates

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GaAs High Temperature Operation

- Numerous foundries available requiring relatively few process modifications.
- Adapt GaAs VLSI for use at high temperatures (e.g. ASICs and FPGAs).
- There are many, many methods and techniques that can be applied to GaAs-based electronics and we have applied a number of these to enhance and maintain functionality of, for example, GaAs FETs at high temperatures.
- These methods and techniques can be considered as modifications to standard GaAs foundry operations.
- Ways to control thermal runaway breakdown with the high temperature electronic technique. For example, we have demonstrated this with:
  - Microwave enhancement at high temperatures.
  - Inverter operation at high temperature.
  - Op amps
- Developing detailed device modeling -- both physical and CAD based.

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High Temperature GaAs Technologies

- Existing technologies can be optimized with respect to high temperature requirements
  - Metallizations
  - Passivation techniques
  - Appropriate incorporation of additional epilayers
  - On chip isolation
  - Leakage current reduction
  - High temperature electronic techniques
- Device technologies
  - Depletion and enhancement MESFETs
    - Performance demonstrated up to 500^{o}C
  - HEMTs
    - Even better -- many structures and types to choose from
  - JFETs
    - Including heterojunction JFETs -- also very promsing
  - HBTs
    - Especially InGaP/GaAs type HBTs seem to be attractive for high temperature applications

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Material Parameters of AlGaAs/GaAs and AlGaN/GaN for High-Temperature Applications

- Low thermal generation rates
- High breakdown fields
- High peak and saturation velocity
- Chemical inertness
- Fairly high thermal conductivity

Metric	AlGaAs/GaAs	AlGaN/GaN
Max. N_{Sheet} (cm^{-2})	$2\text{-}3 \times 10^{12}$	$1\text{-}5 \times 10^{13}$
Breakdown Field (V/cm)	4×10^5	33×10^5
2 D Electron Mobility (cm^2/Vs)	8500	2000
Saturated Electron Velocity (cm/s)	1.0×10^7	2.2×10^7
Thermal Con-ductivity (W/cmK)	0.53	1.3

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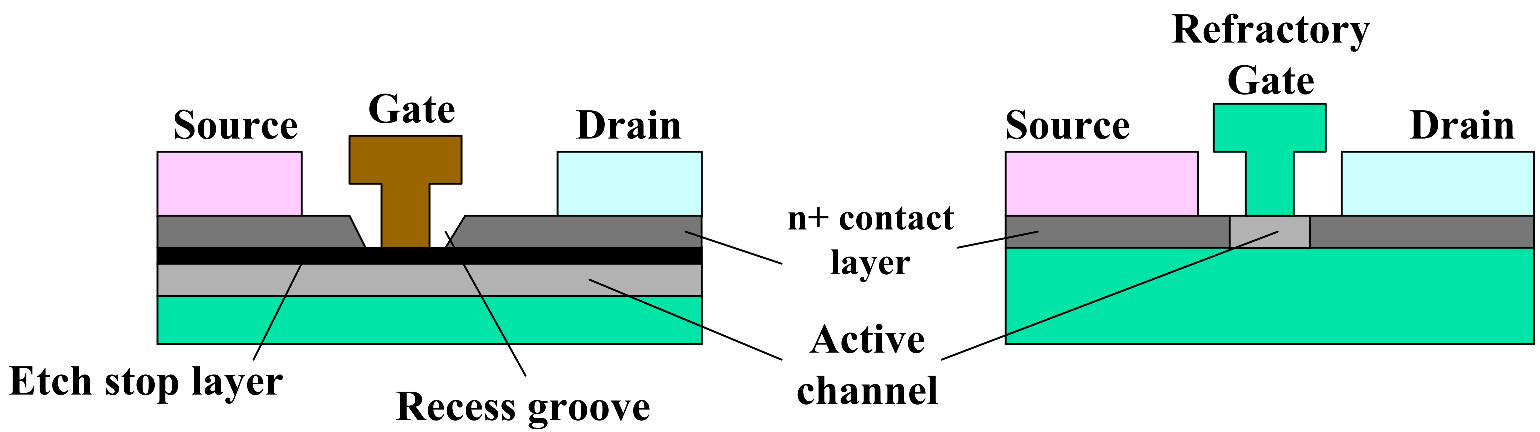
Simplified Example High Temperature MESFETs and HEMTs



Recessed gate FET:

- Epilayer wafers are needed
- High temperature source gate and drain contacts
- Etch stop layers for better control of recess

Self aligned gate structure

- Source/Drain contact regions defined by ion implantation
- Annealing of implantation damage requires refractory gate contacts
- Substrate wafers can be used

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Metallizations to III/V Semiconductors

- Electrically highly conductive metals (Al, Au, Ag, Cu) readily react with many III/V-semiconductors or show significant diffusion behavior.
- Many metallization schemes usually form multiple intermetallic components with III/V-semiconductors, reactions may be difficult to predict.
- Improper designed metallizations suffer from group V (e.g., As, P) loss at elevated temperatures.
- Need diffusion barriers are absolutely necessary for reliable device applications.

The Curtice Equation

$$I = Beta(V_{gs} - V_t)^2 \times (1 + \lambda) Tanh(\alpha V_{ds})$$

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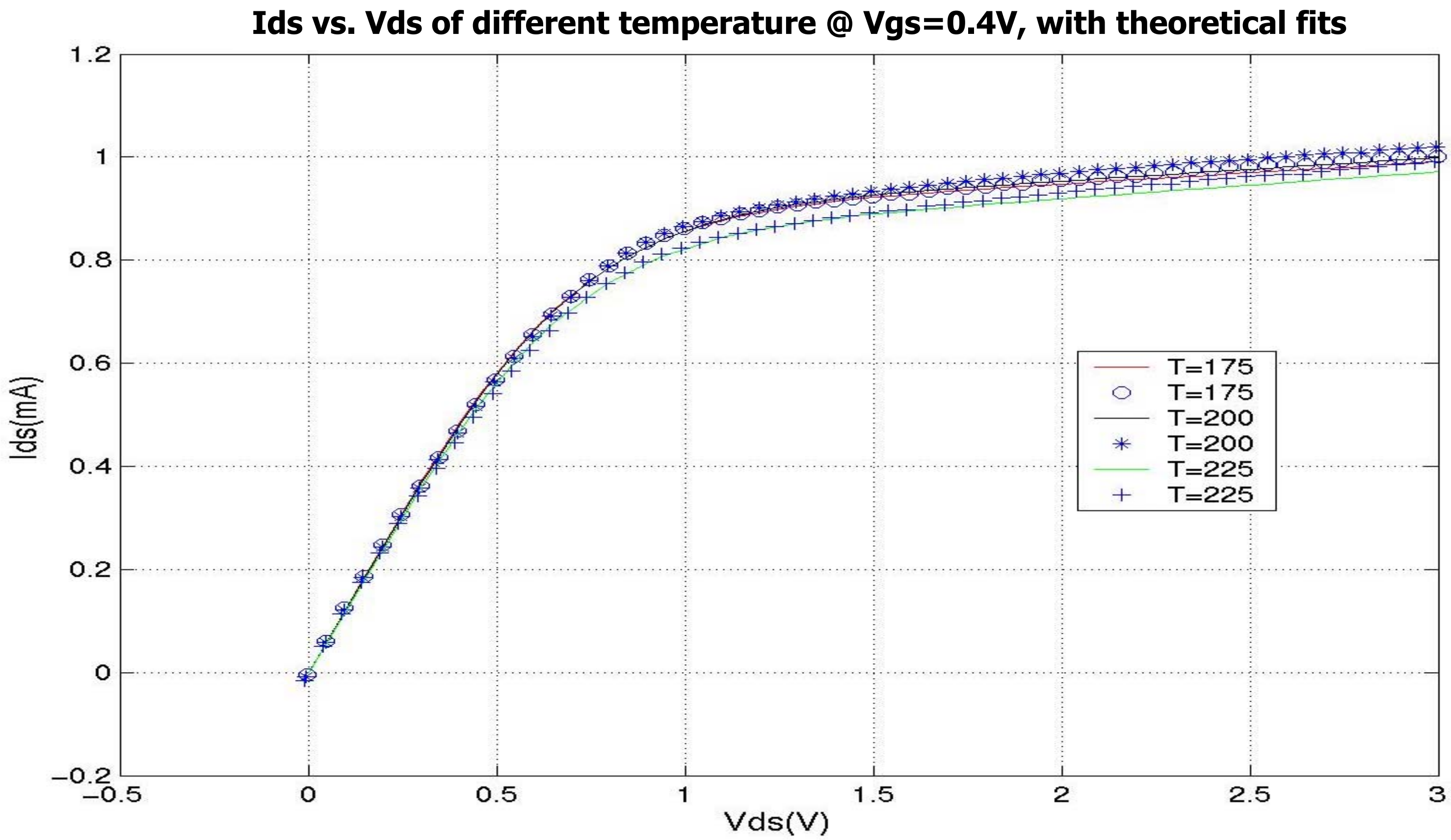
Measured and Simulated (using modified Curtice Model) Ids vs. Vds Curves



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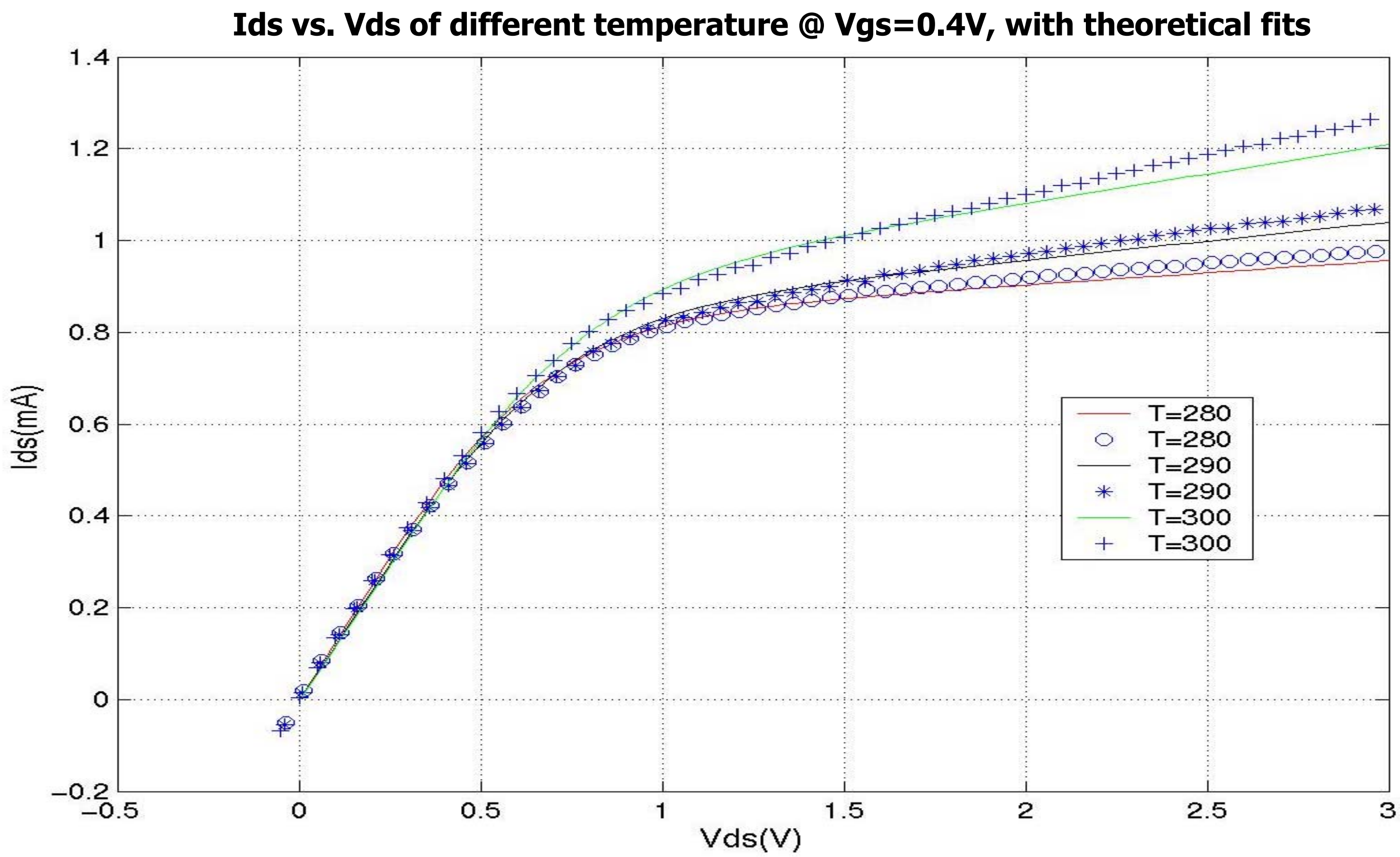
Measured and Simulated (using modified Curtice Model) Ids vs. Vds Curves



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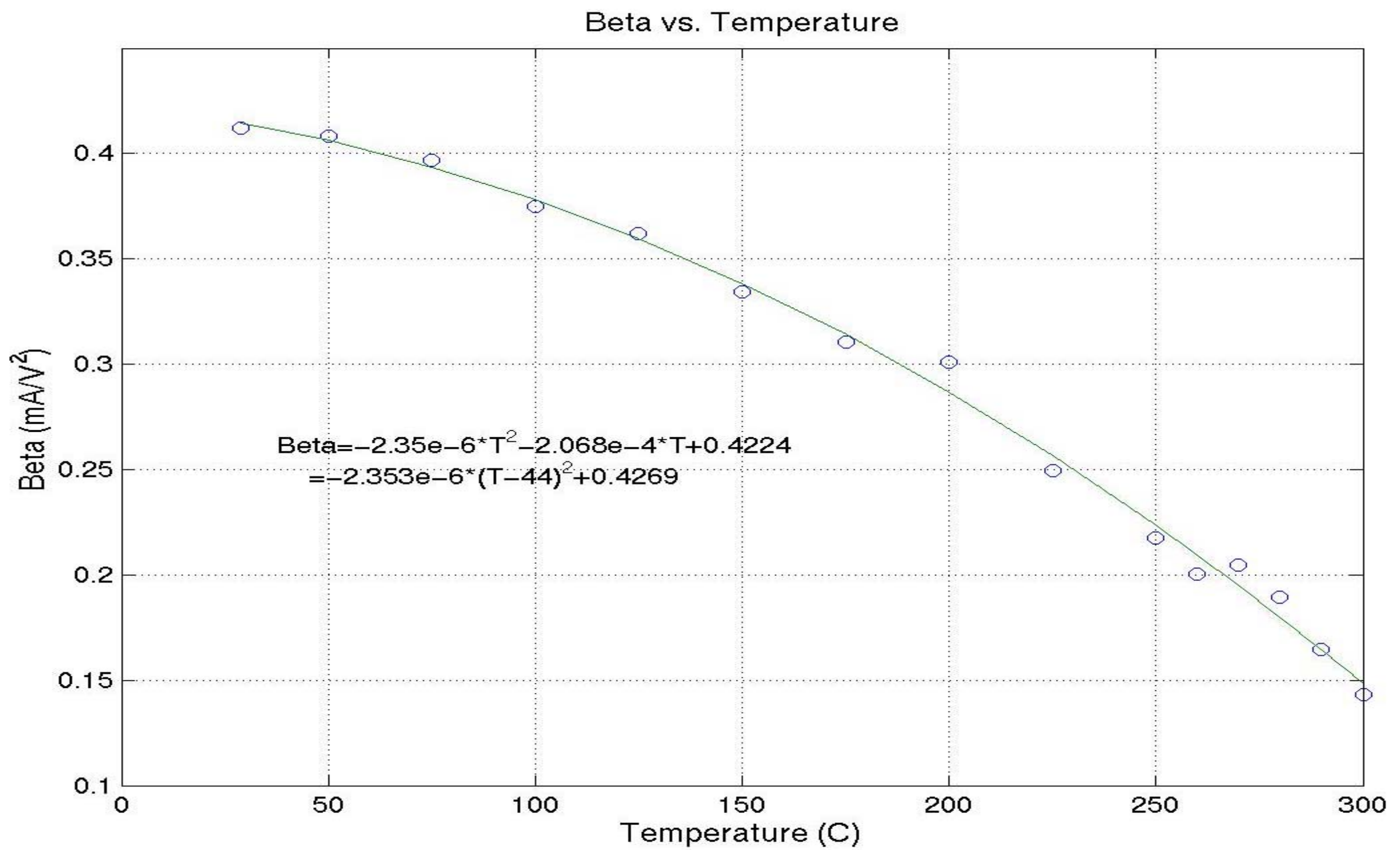
Beta (β) vs. Temperature (^oC)



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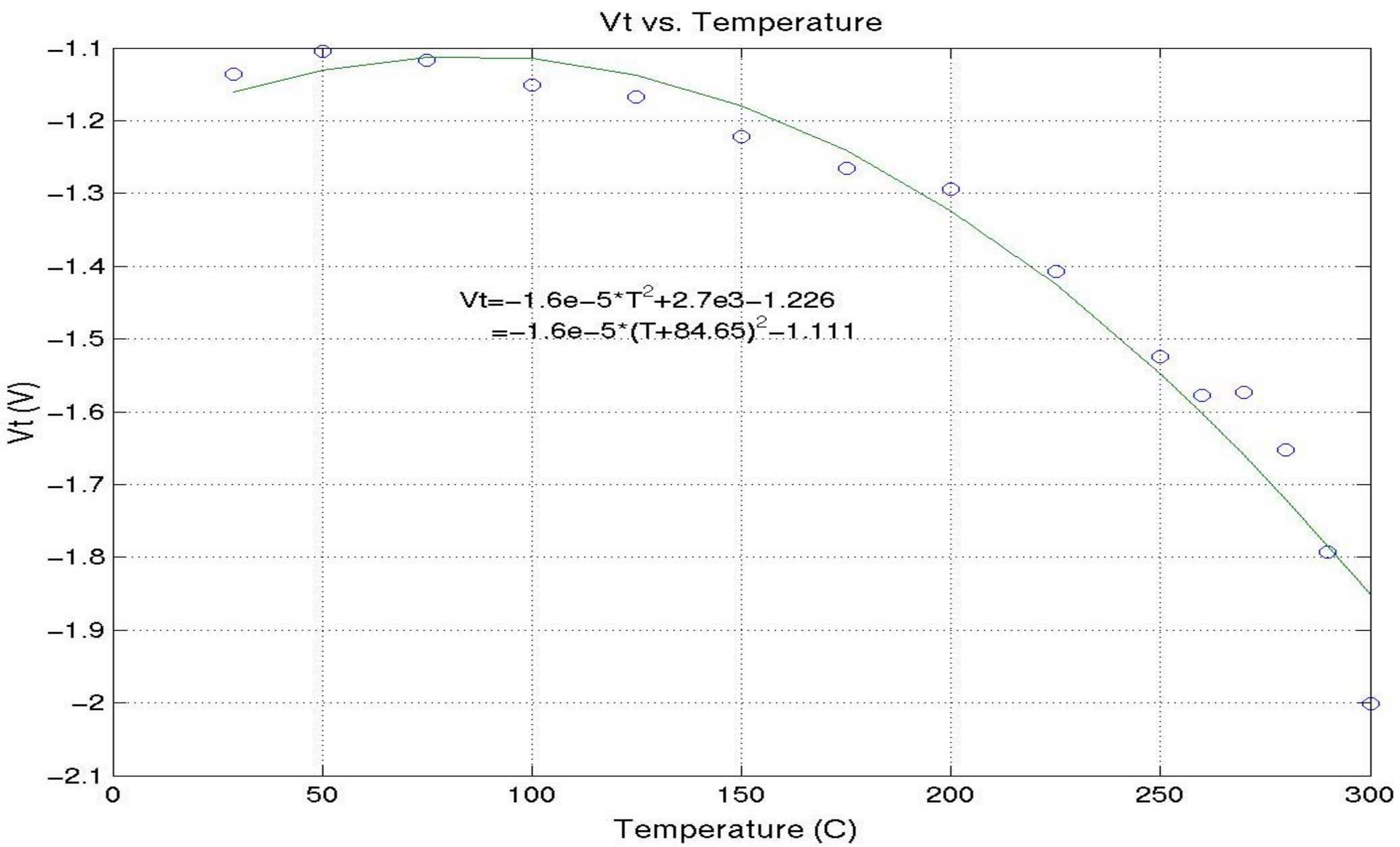
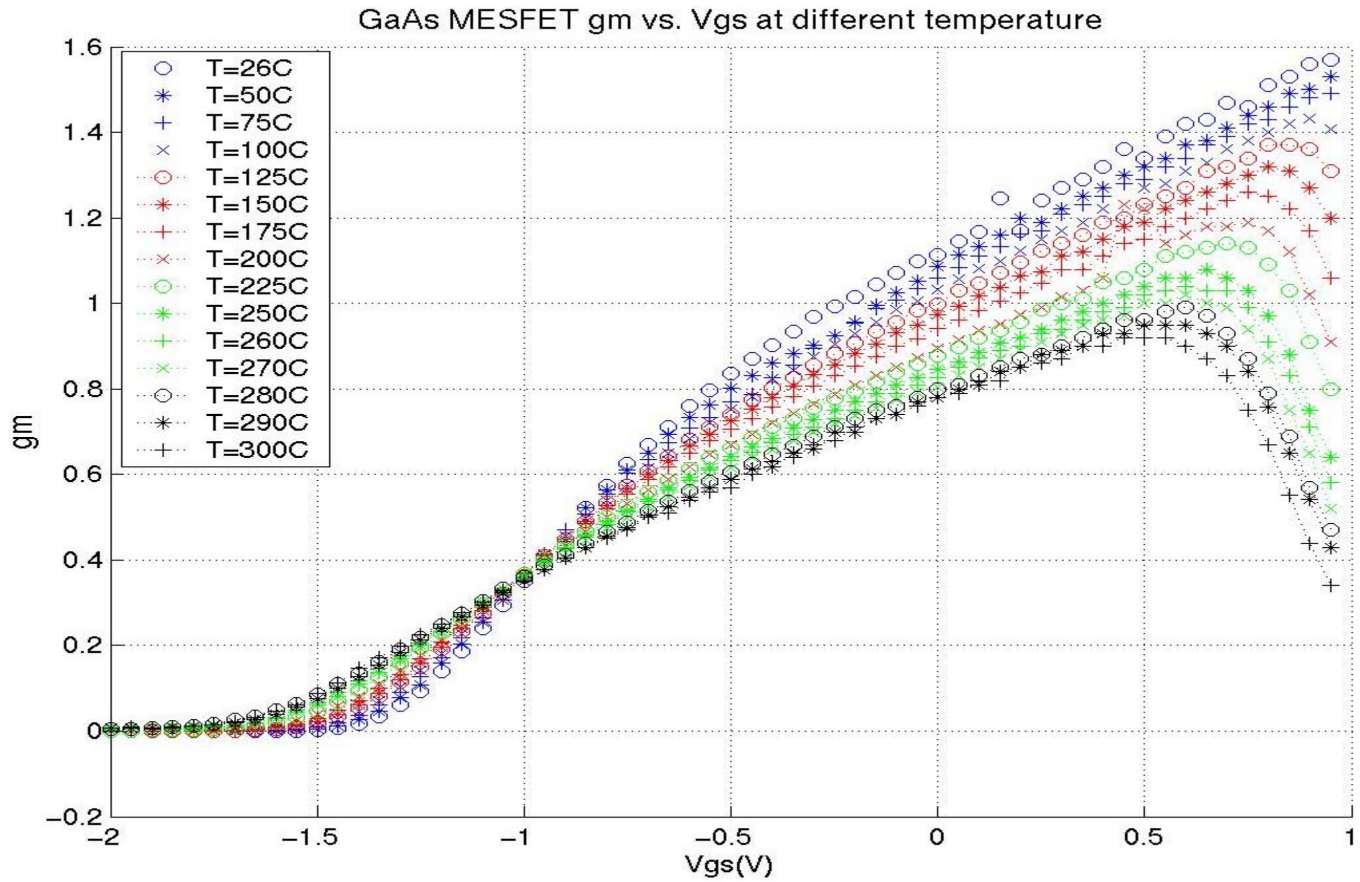
V_t vs. Temperature (^oC)



g_m vs. Temperature for a GaAs MESFET



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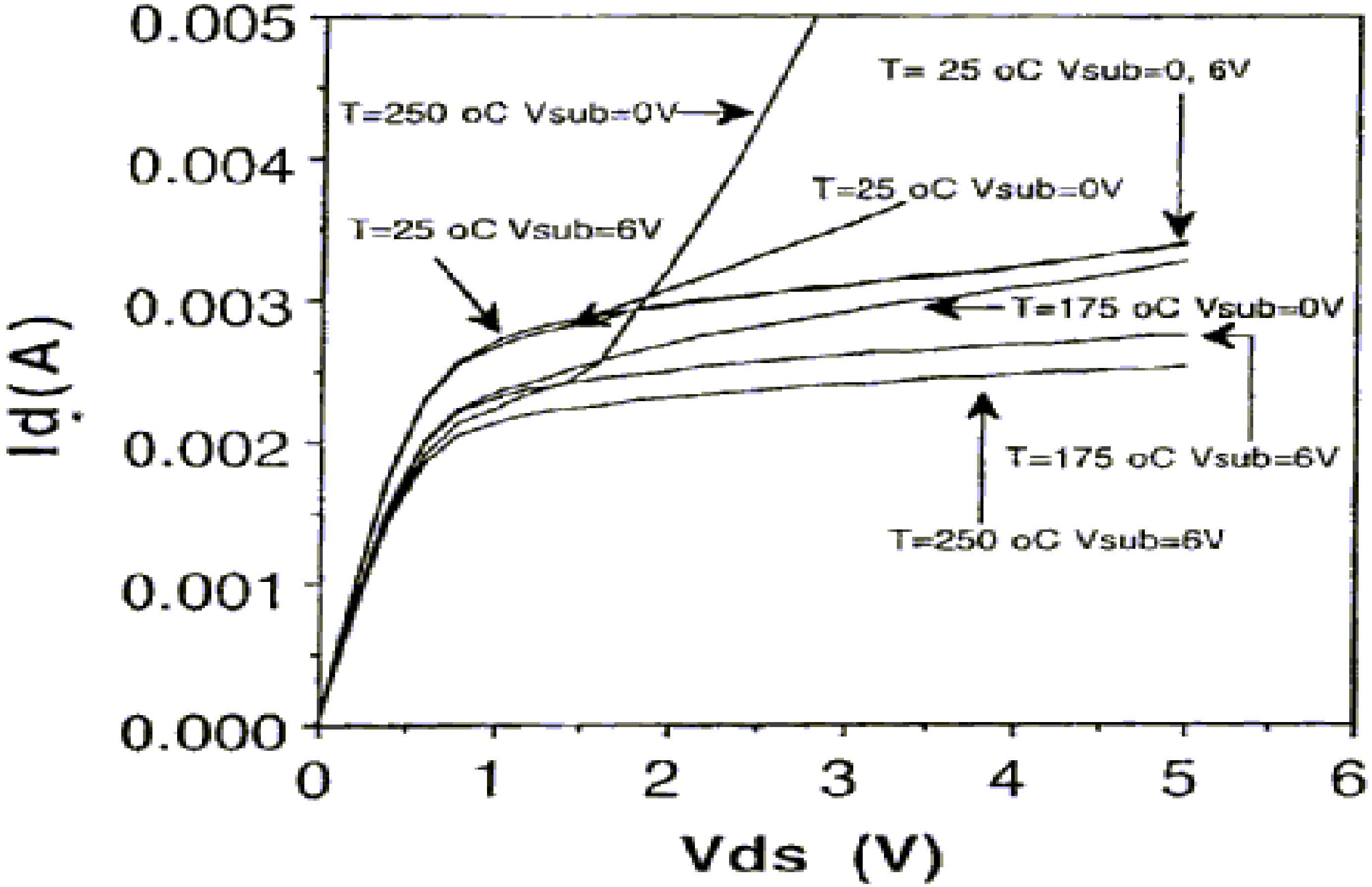
Reduction of Thermal Leakage Current using the HTET



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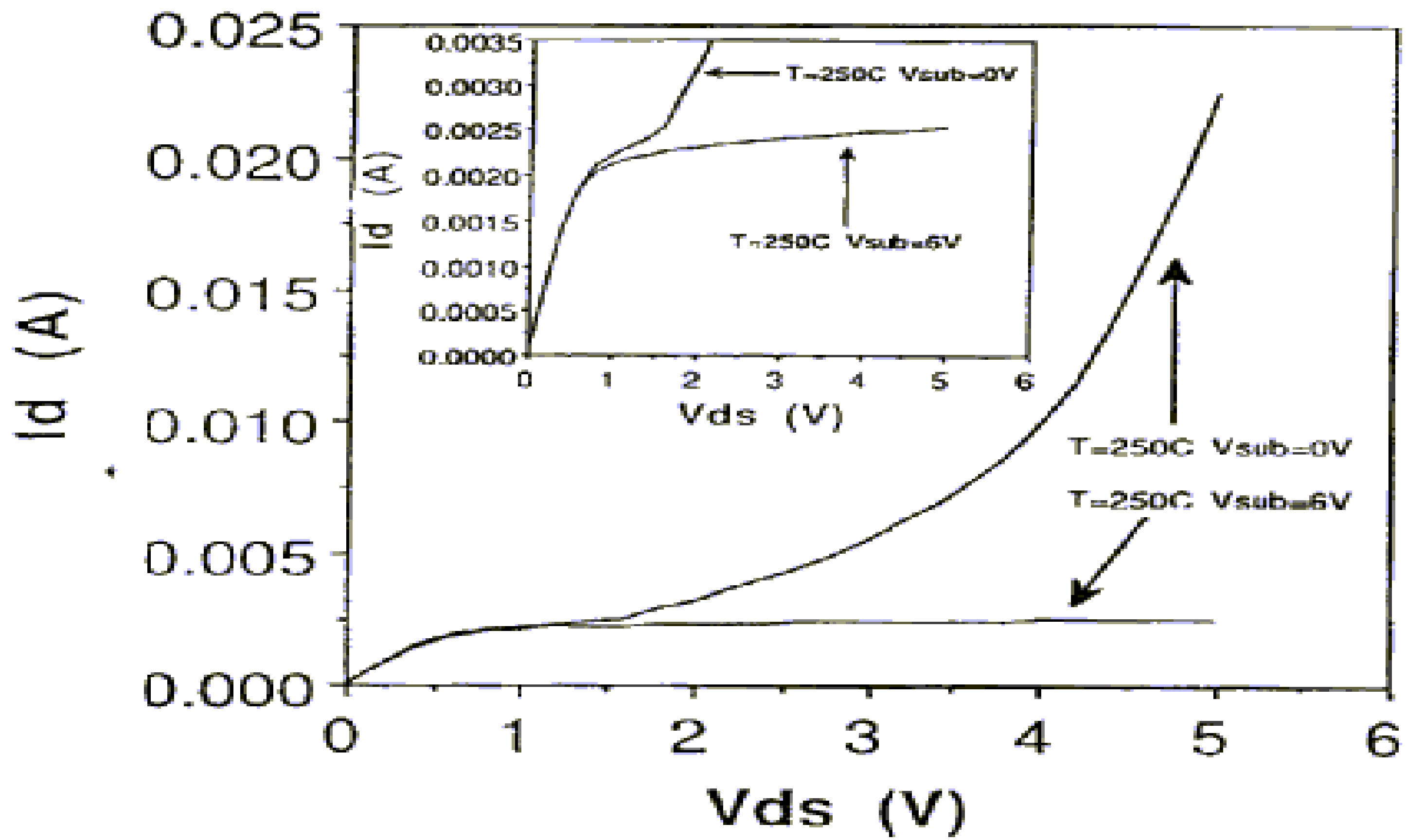
GaAs MESFET at 250 ^oC with and without HTET



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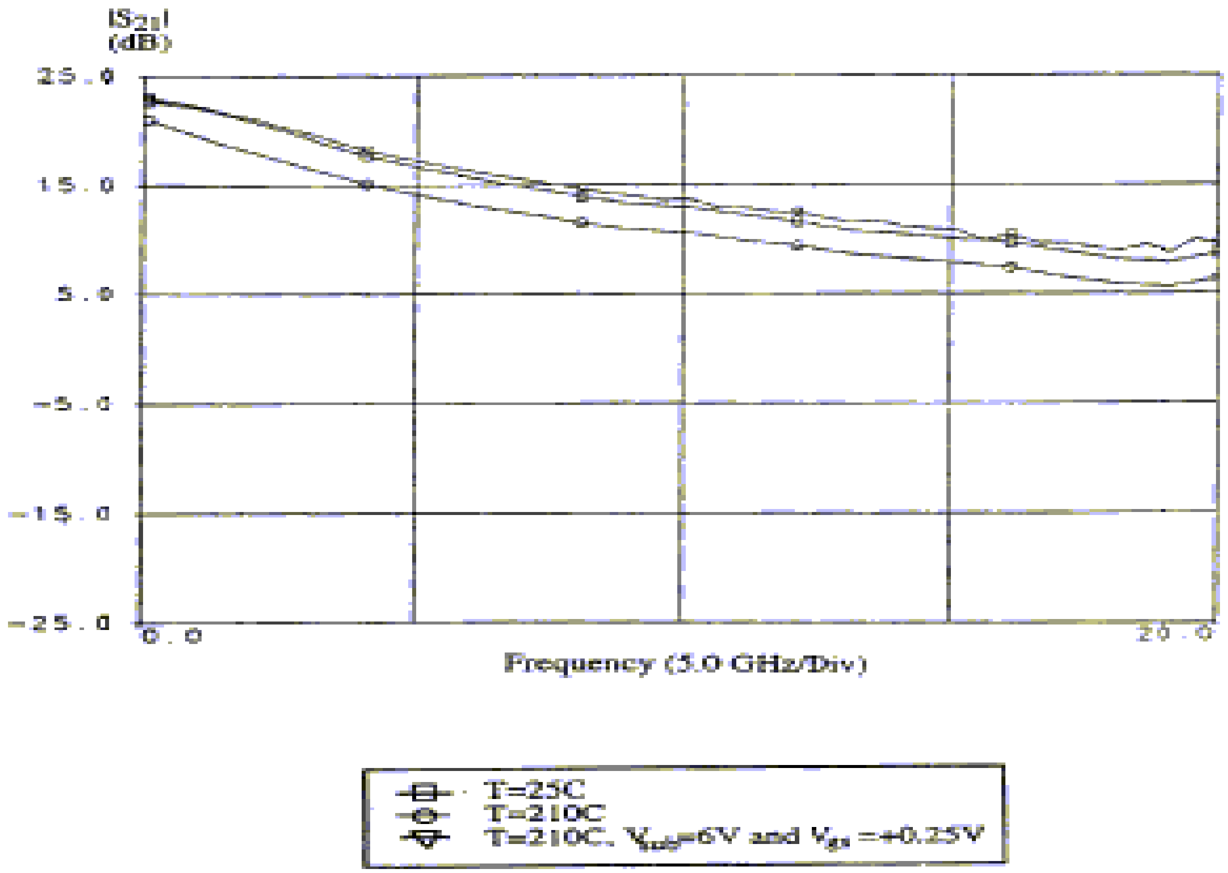
High Frequency Performance Enhancement using the HTET



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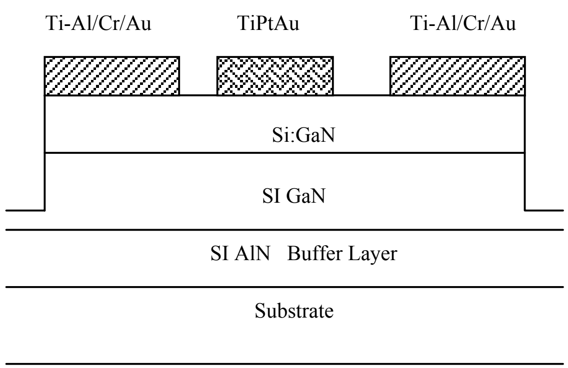
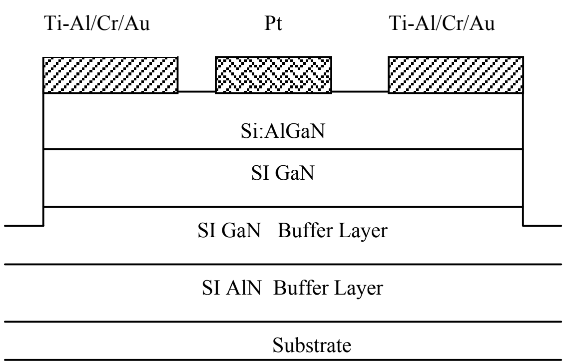
Typical Structures of GaN-MOSFET & AlGaN/GaN-MODFET

- Cross-section of a representative GaN-MESFET



- Cross-section of a representative AlGaN/GaN-MODFET



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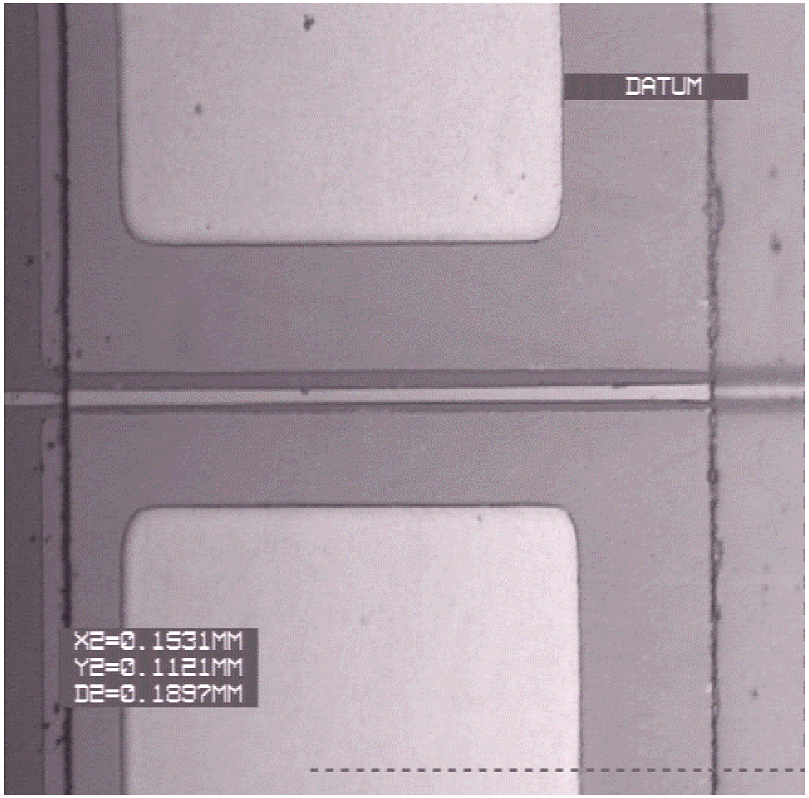
Photograph of an AlGaN/GaN-MODFET

- Pt gate (SBH~1.0 eV)
- Gate length = 2 μm
- Device width = 100 - 200 μm
- Si_3N_4 Passivation



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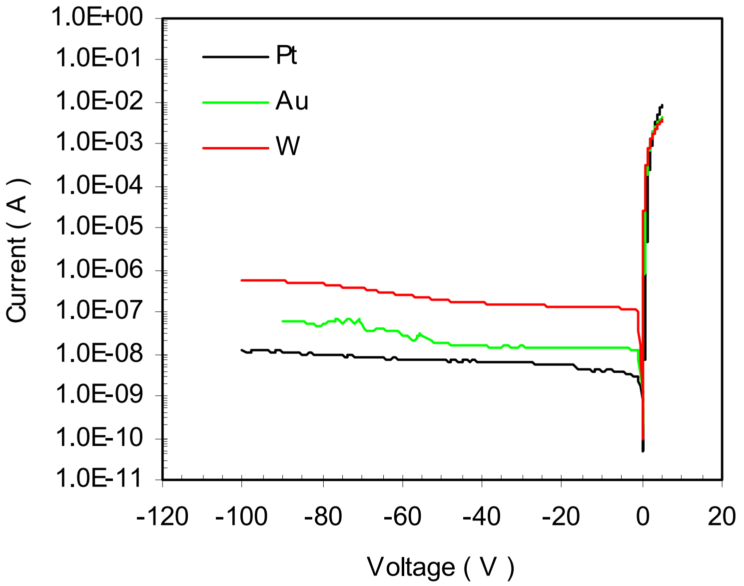
Schottky Contacts to n-type $Al_{0.3}Ga_{0.7}N$

- W - SBH = 0.63 eV
- Au - SBH = 0.86 eV
- Pt - SBH = 0.97 eV

- Dimension = 210 x 210 μm^2

 SBH = Schottky Barrier Height



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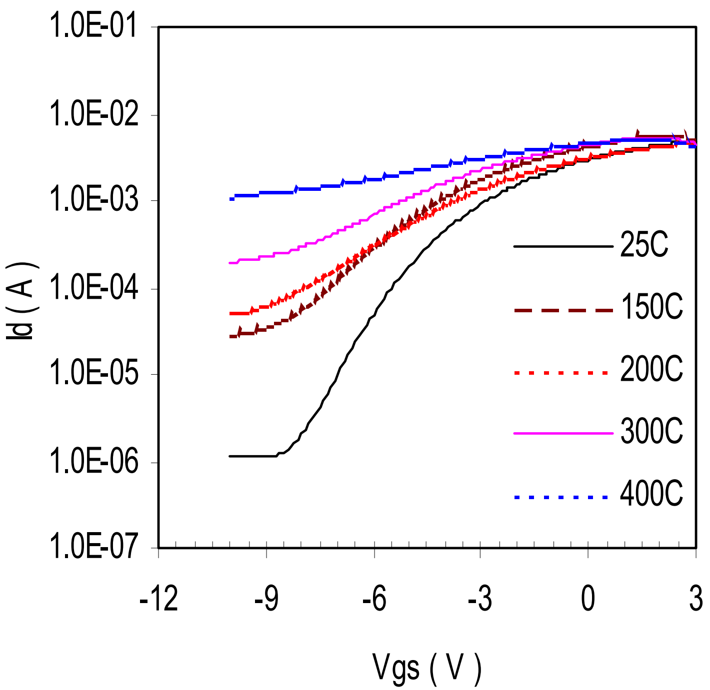
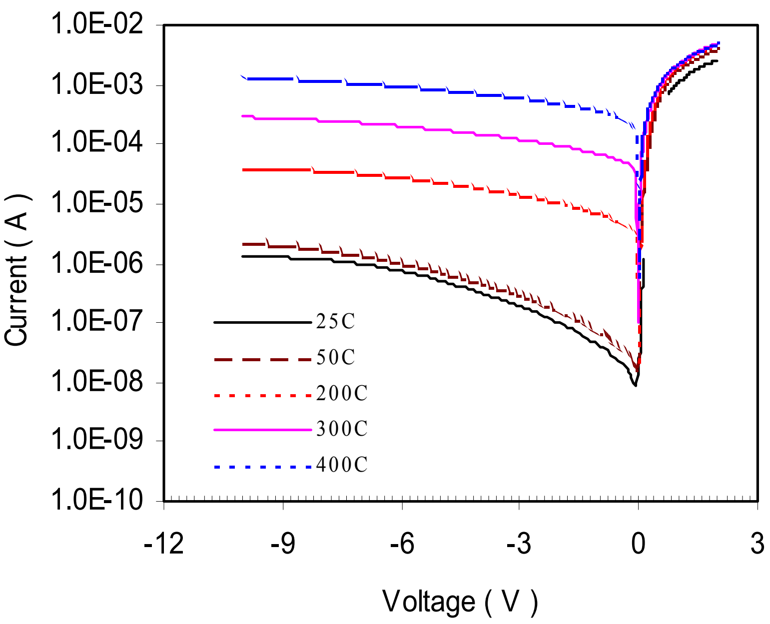
Device Performance of GaN-MESFETs at Different Temperatures (Not great at High Temperatures)





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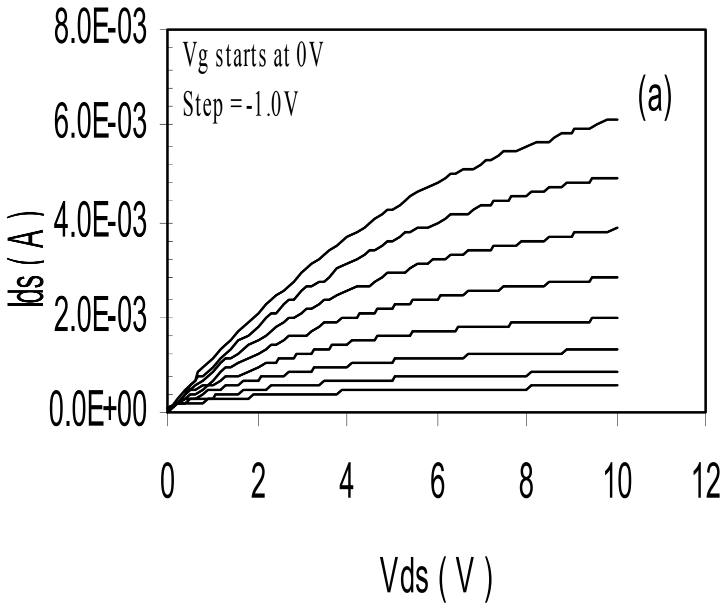
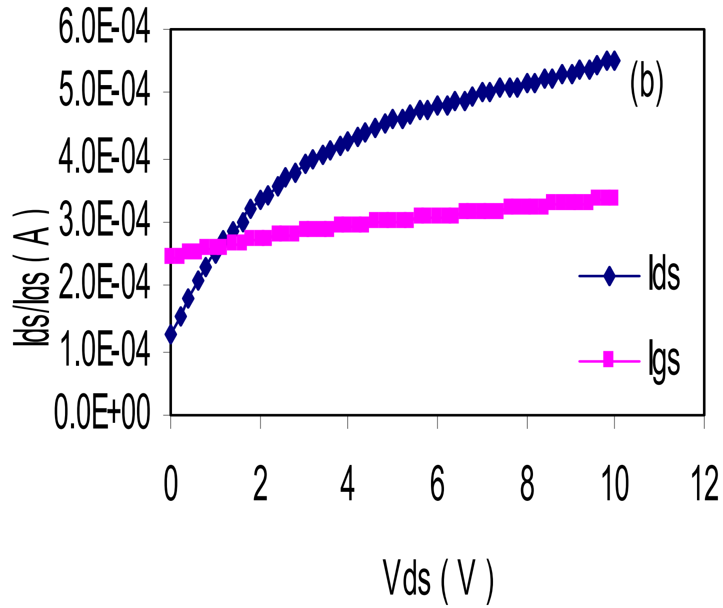
Current-Voltage Characteristics at 300°C for a Representative GaN-MESFET





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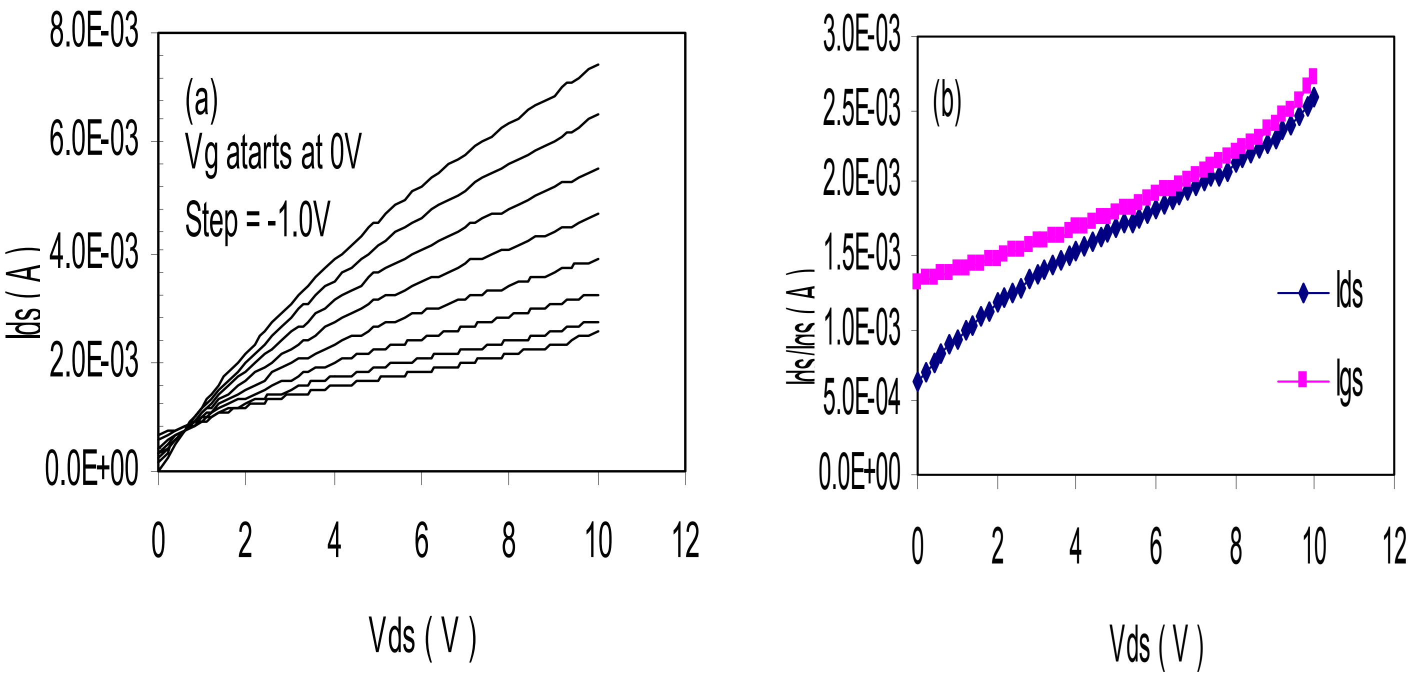
Current-Voltage Characteristics at 400°C for a Representative GaN-MESFET (Not Great at 400°C)



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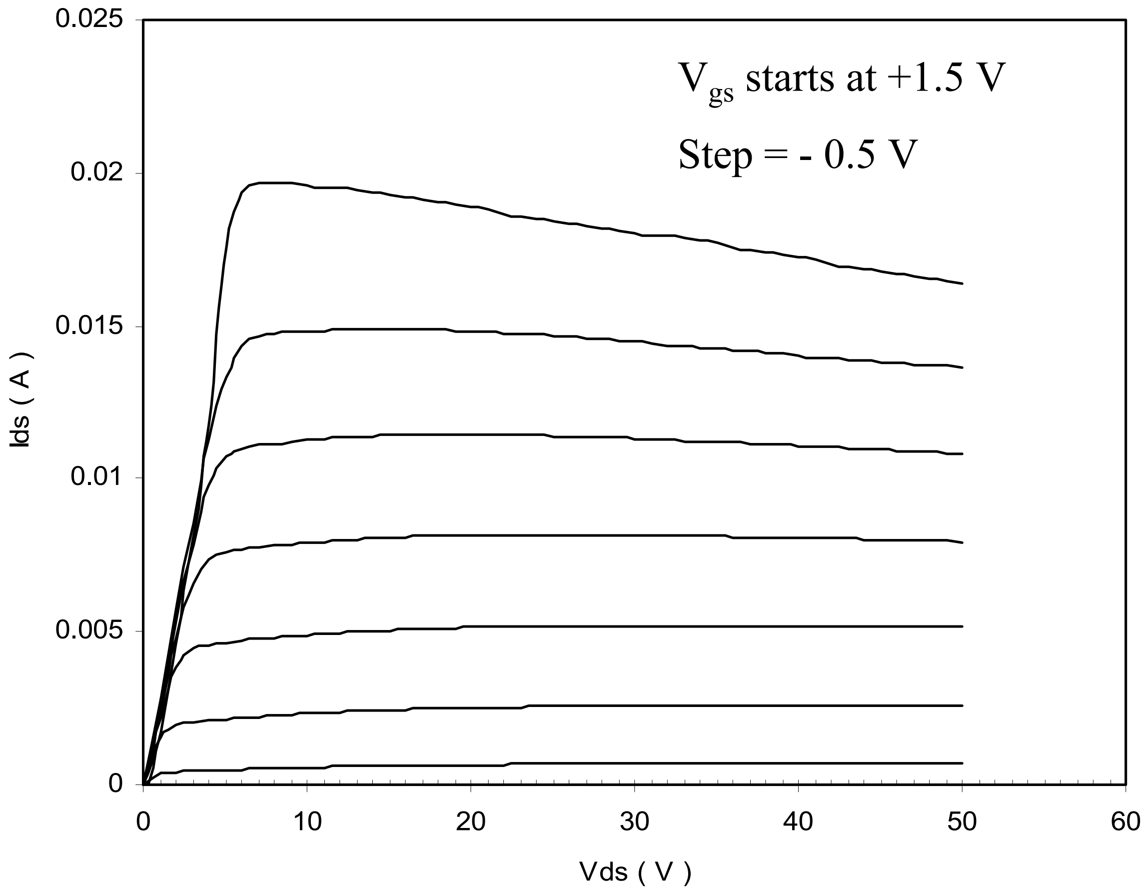
I_d-V_{ds} Characteristics at 35°C for a Representative GaN-MODFET

Self Heating Evident at Higher Current/Power



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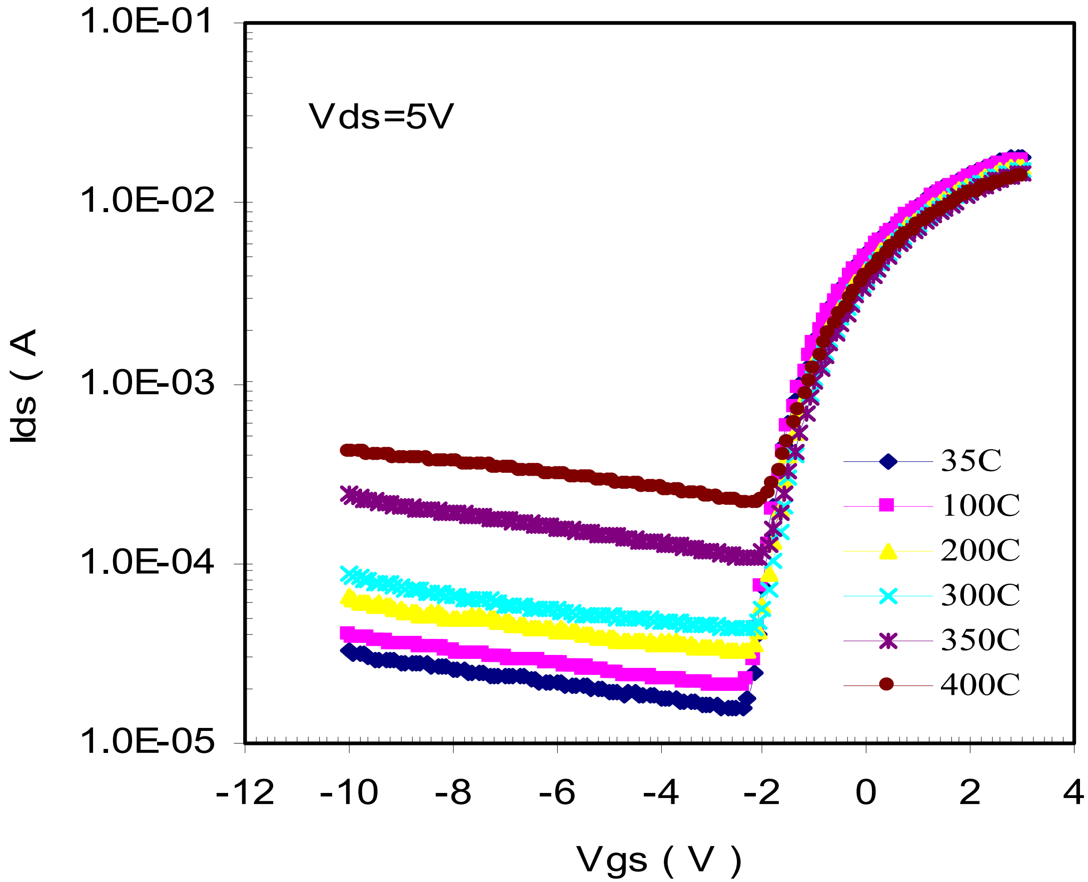
I_{ds}-V_{gs} Characteristics for a Representative GaN-MODFET at Temperatures Between 35°C and 400°C (Suitable for Extreme Environments)



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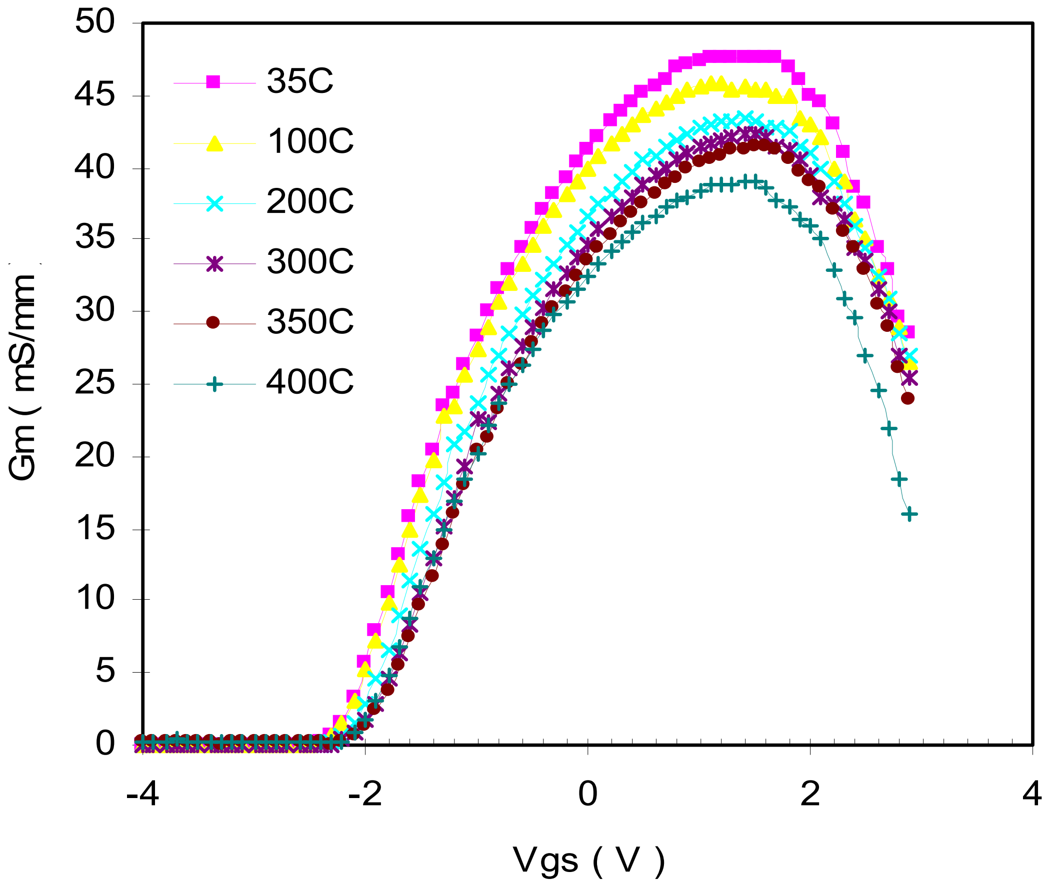
Transconductance for a Representative GaN-MODFET at Temperatures Between 35°C and 400°C



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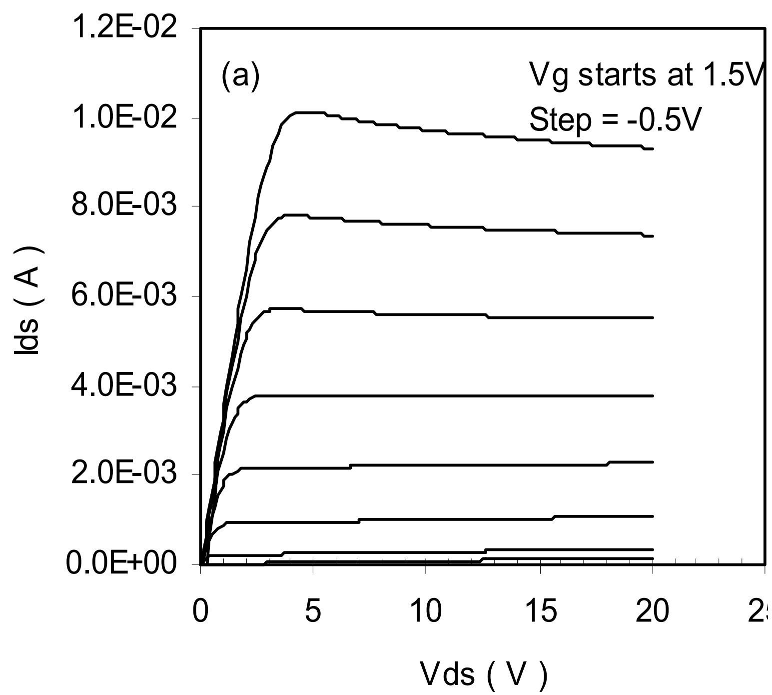
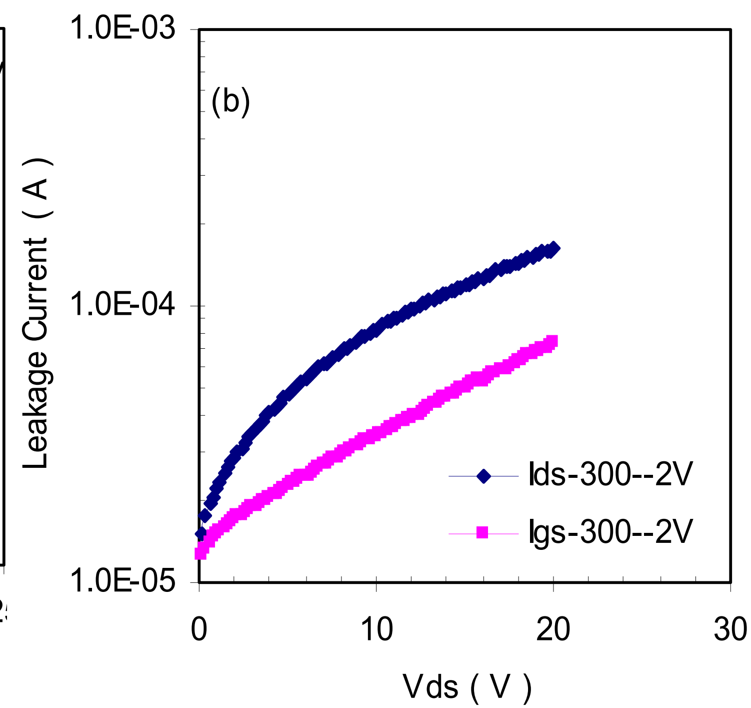
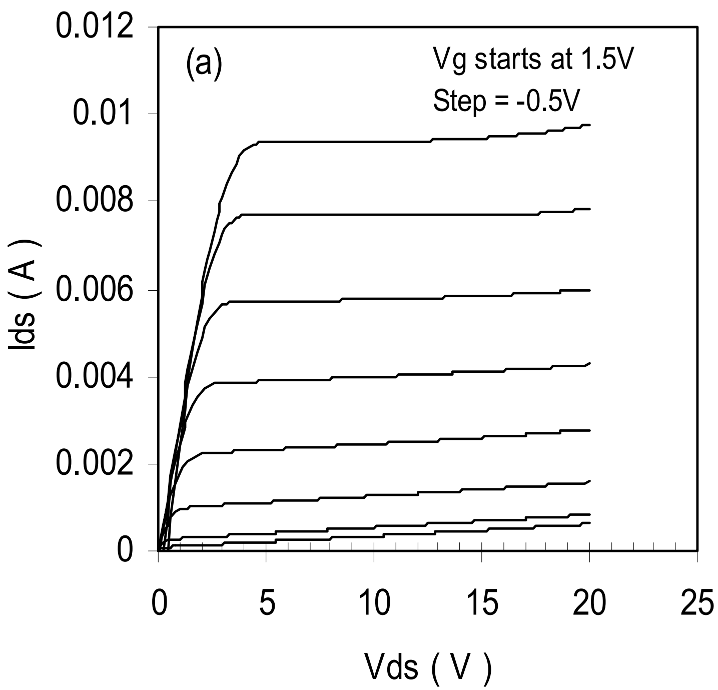
Current-Voltage Characteristics at 300°C for a Representative AlGaN/GaN-MODFET (Self Heating Observed at Higher Currents)

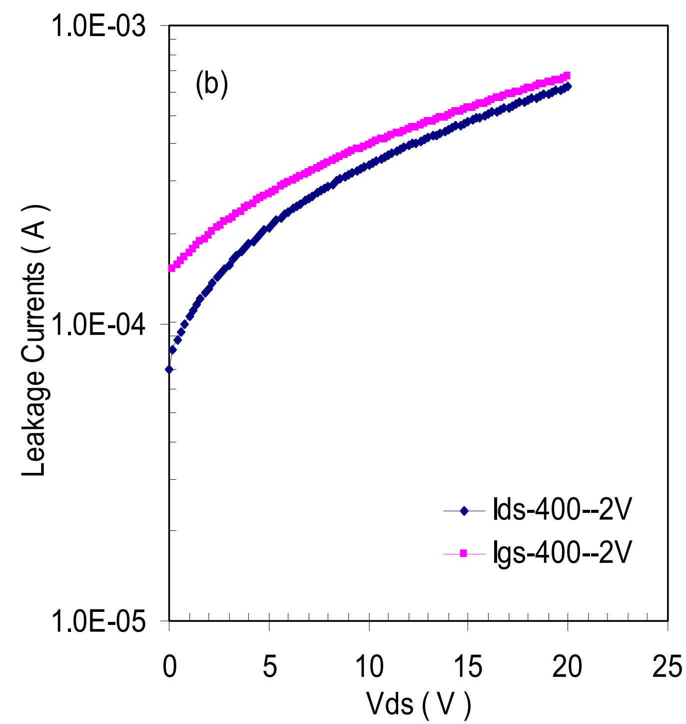




Current-Voltage Characteristics at 400°C for a Representative AlGaN/GaN-MODFET

(Still Doing Great - Slight Thermal Current Generation and a Little Lower Vds Breakdown)





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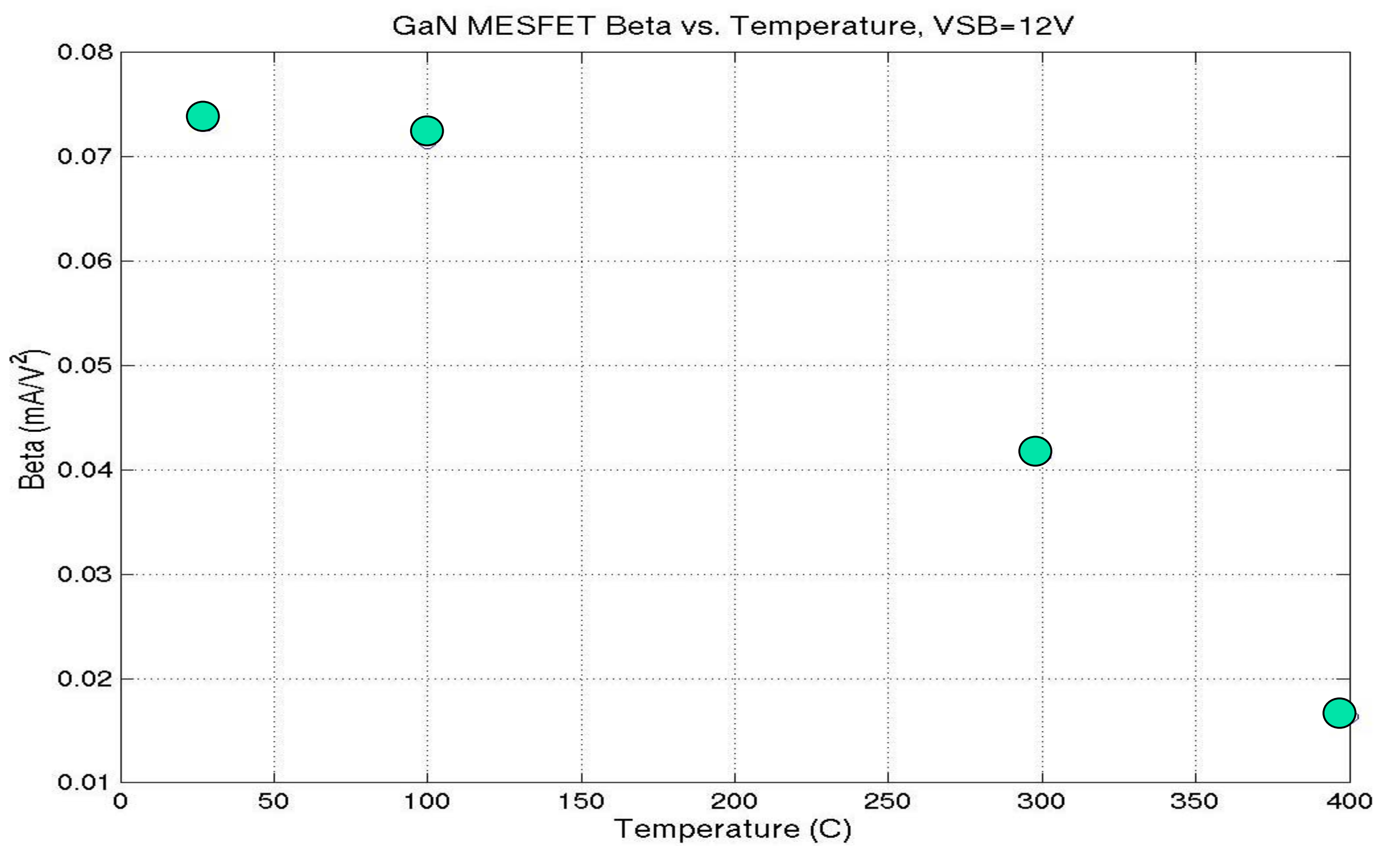
GaN MESFET
Beta (β) vs. Temperature



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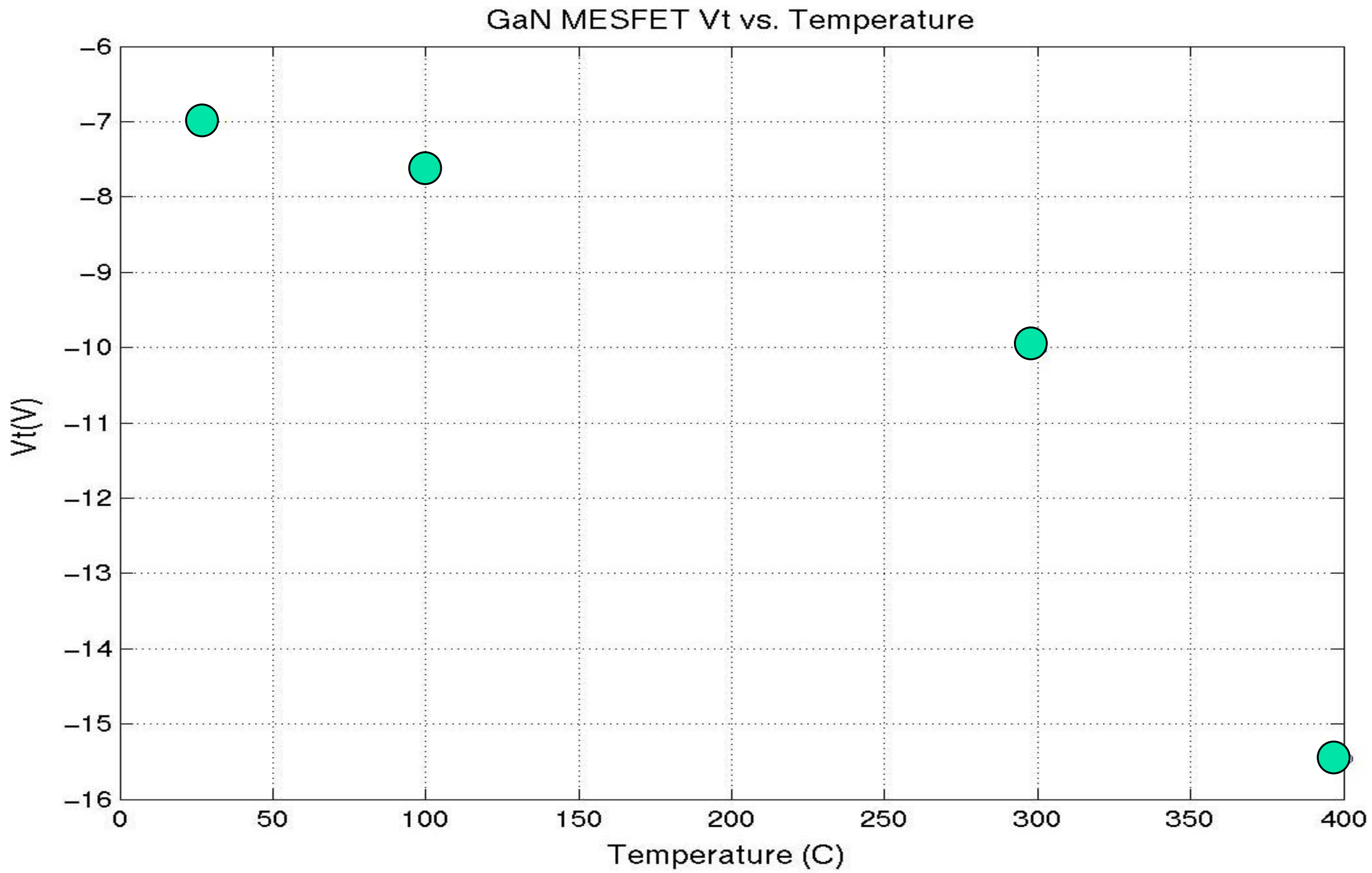
GaN MESFET
V_t vs. Temperature



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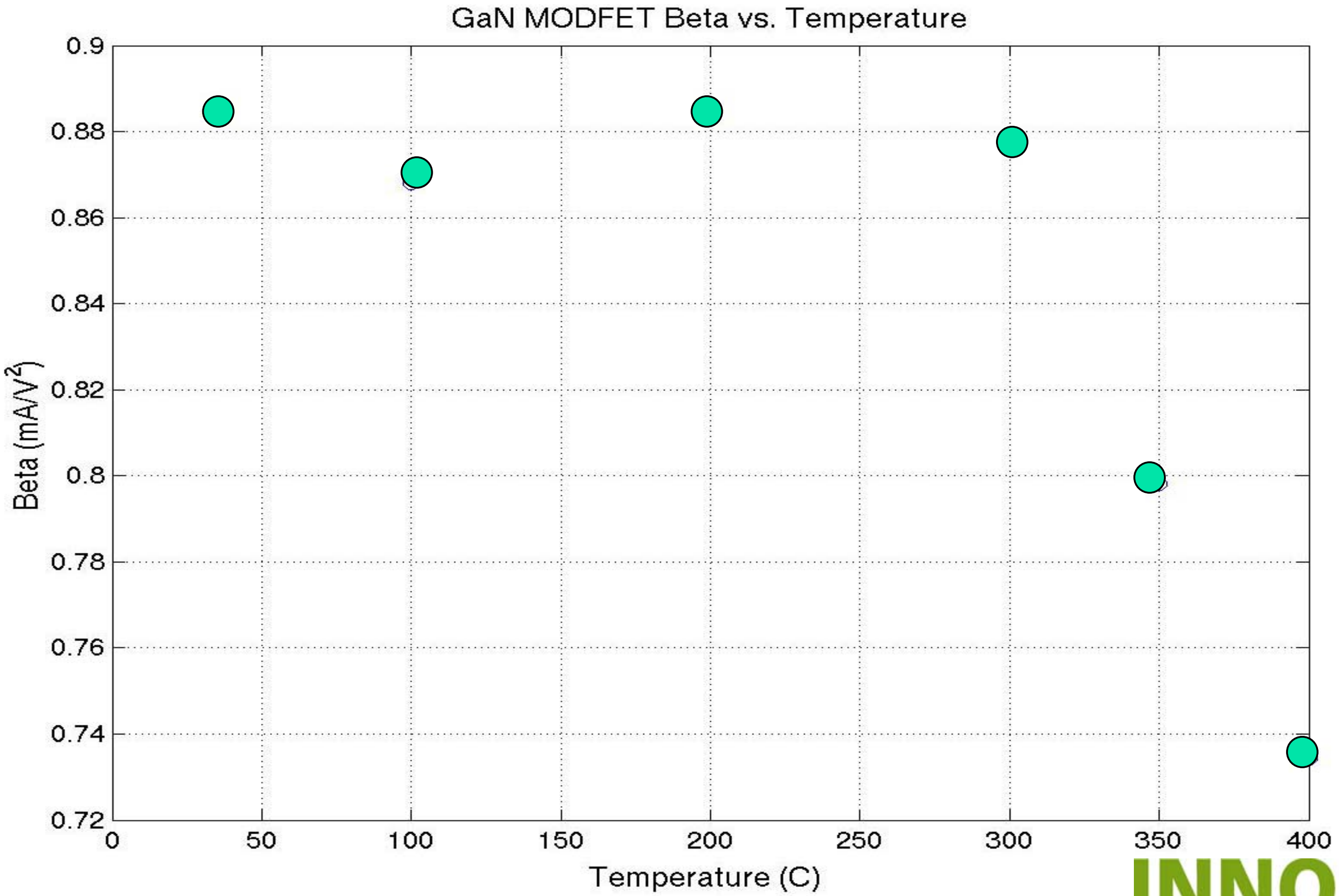
GaN MODFET Beta (β) vs. Temperature



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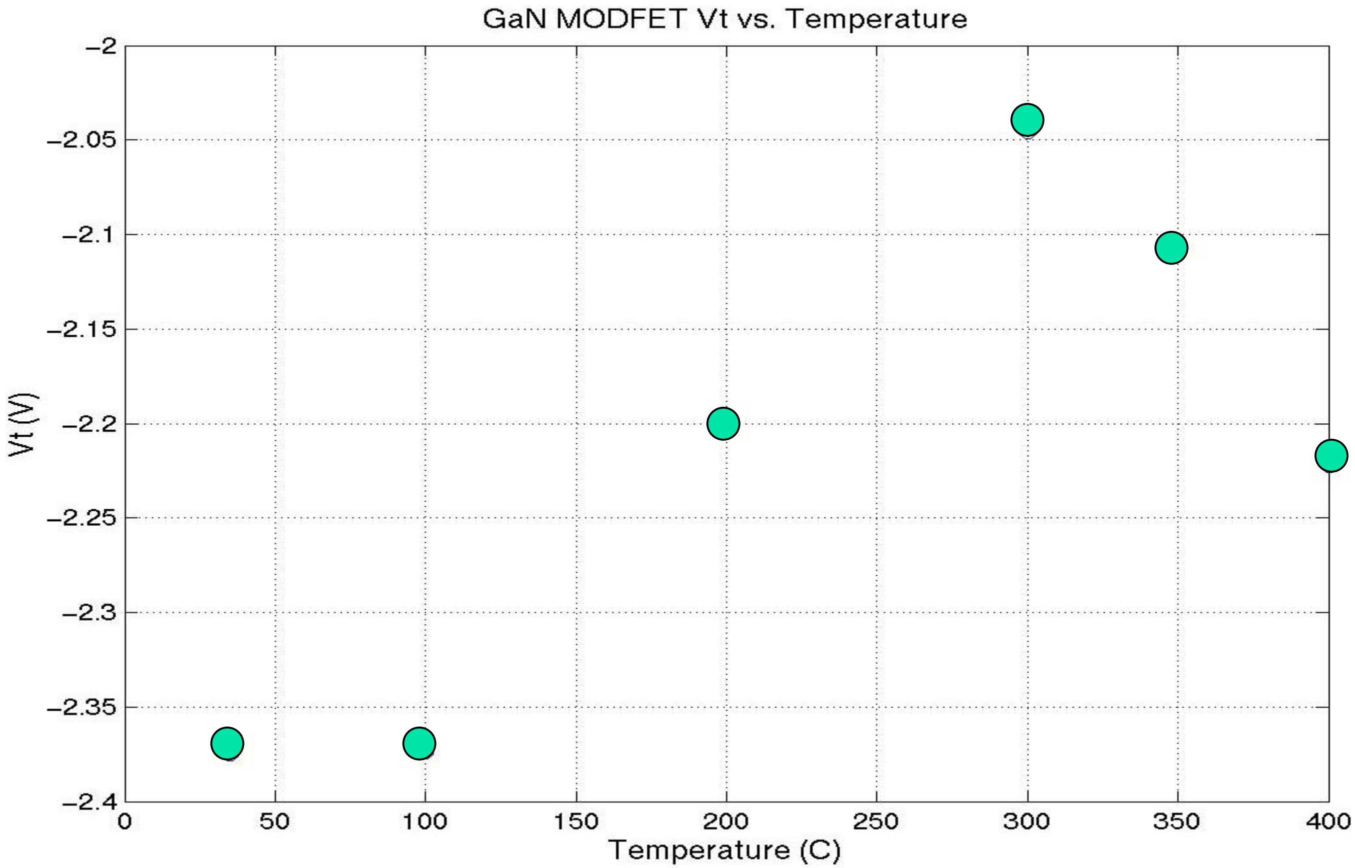
GaN MODFET
V_t vs. Temperature



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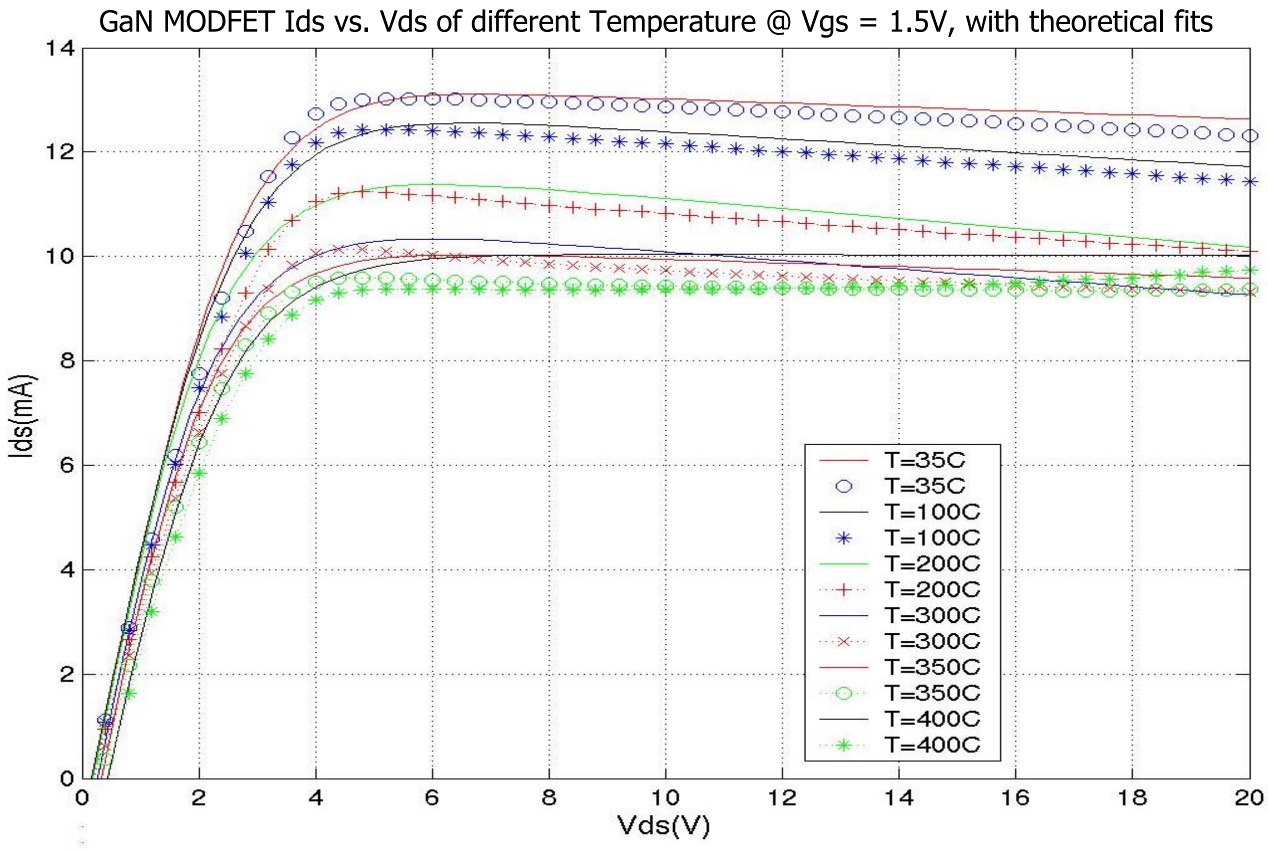
GaN MODFET Measured and Simulated Ids-Vds Curves



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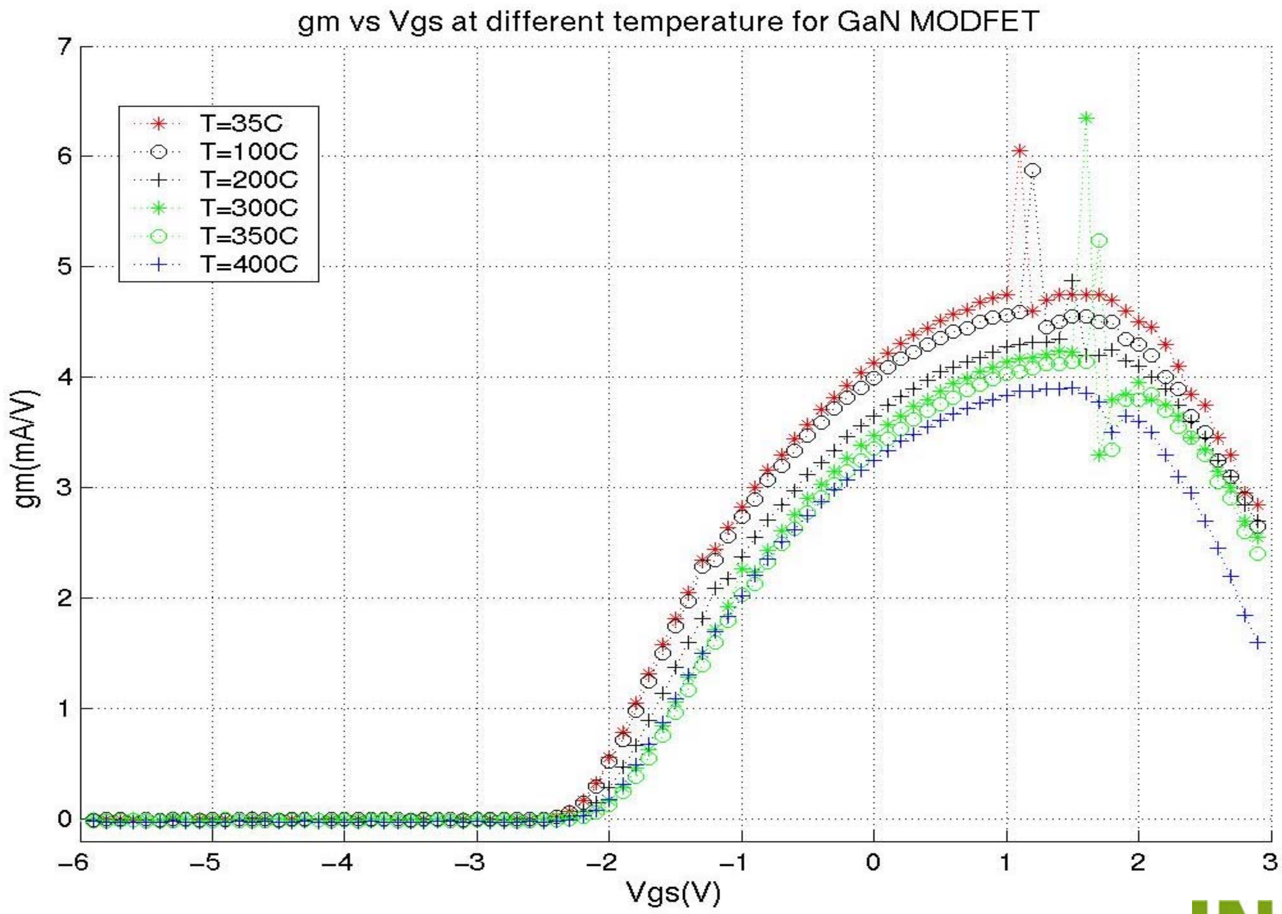
GaN MODFET
g_m vs. Temperature



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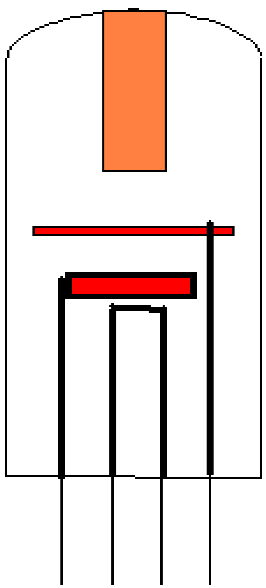
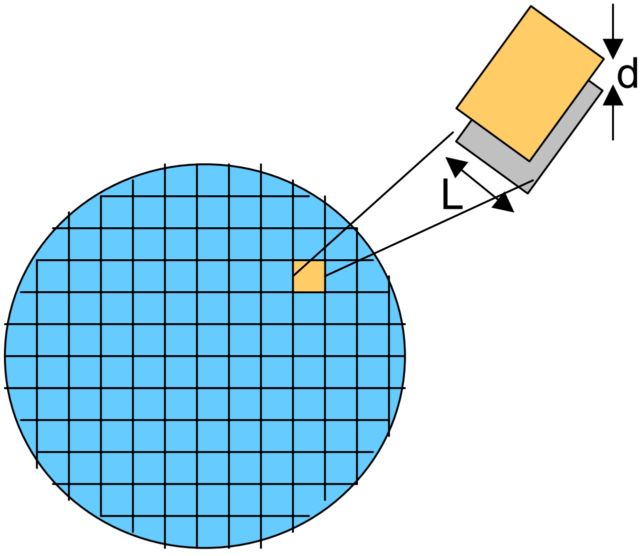
Solid-State Vacuum Device (SSVD) Technology

Conventional vacuum tube **+** Solid state technology





SSVD technology allows conventional vacuum tubes and millimeter-wave power modules (MMPMs) to have IC form factors, to be low-cost, and to utilize microelectronic design, process, and manufacturing technologies.

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Thermionic High Temperature Microelectronics

- Thermionic vacuum microelectronics are, by their very nature, high temperature electronics.
- We have been working on thermionic vacuum microelectronics for more than 10 years.
- We refer to thermionic vacuum microelectronics as SSVDs
- SSVDs can be fabricated on a number of substrates (e.g., Si, SiC, SOI, sapphire, alumina, etc.).
- SSVDs are compatible and can be integrated with most semiconductor device technologies (e.g., MOSFETs, BJTs, JFETs, diodes, MODFETs).
- SSVDs can be used as power devices (well into the GHz range) or as SSI or MSI integrated circuits.

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Thermionic High Temperature Microelectronics (continued)

- SSVDs can be made in many different sizes and shapes to suit the application.
- SSVDs can operate in ambients up to 700 to 800 ^{o}C and extended up to over 1000 ^{o}C (depending on packaging).
- SSVDs are compact and lightweight.
- Device parameters (e.g., gain, g_m, output resistance, etc.) are design parameters that can be chosen to match the application.
- SSVDs enjoy harsh environments.
- SSVDs are inherently radiation tolerant and should be very suited to space exploration applications.
- SSVDs should be well suited to address long haul (e.g., satellite to Earth) communciations.
- Can be utilized for thermal to energy converters.

Thermionic High Temperature Microelectronics (continued)

- The external environment is much tamer and friendly than the internal environment.
  - We are probably more brutal (not in terms of caustic environment) than any environment the SSVD will see.
- Lower Frequency SSVDs behaves like FETs and are accurately modeled and simulated (e.g. SPICE) as FETs.
- We would be very happy to have the SSVD be the heat sink and sink/pipe/channel the heat into the device.
- SSVDs can be very efficient overall.
- Where applicable, we test with/to the appropriate or modified MIL SPEC.
- Does quite well with thermal cycling.
- We are designing for reliability and robustness.

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Conclusions

- Silicon
  - By far, the most established technology -- use if possible!
  - World wide intensive activities toward different high temperature SOI technologies notably Honeywell's SOI line.
    - Capable for electronic device applications up to 250 to 300°C.
  - Foundries available.
- GaAs and III/V-Based
  - Established technologies -ways to adapt for extreme environment use.
  - Increased range of temperature to 400 to 500 °C
  - Particular material properties allow the combination of high temperature electronics with following application areas
    - Microwave and mm-wave electronics
    - Optoelectronics
  - Foundries available.
  - Improvement of semi-insulating buffers, stable ohmic contacts, and Schottky barrier heights is needed to optimize the high temperature operation.

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Conclusions (Cont.)

- III/V Nitrides
  - Very fertile field of research
  - World wide enormous increase of research activities triggered by the success in LEDs and related optical technologies.
  - High temperature electronic devices demonstrated
  - High frequency power applications.
  - Still at the research status.
  - Maximum operation temperature: 600 ^{o}C, depends on success in technology development.
  - Using wide band-gap semiconductors such as GaN reduces the substrate. leakage current at elevated temperatures.
  - For this potential to be realized, defect levels must be reduced.
- **SiC**
  - Power electronics up to 600 ^{o}C
  - Interesting also for certain high frequency power applications
  - Substrate material for III/V nitrides
  - SiC wafers are commercially available

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Conclusions (Cont.)

- Diamond
  - Unique physical properties
  - Suitable for very high power density devices
  - Sensors
  - Maximum estimated operation temperature: 800^{o}C
  - Still very much in the research stage
- Thermionic Vacuum Microelectronics
  - Very promising for extreme temperature applications up to 700 and 1000+ ^{o}C
  - Can be used for a number of extreme environment applications ranging from power conversion to SS/MSI ICs to RF transmission.
  - Can be integrated with other semiconductor process and device technologies.
  - Flexible in design and application.
  - Could work in collaboration with other technologies
  - Possibility of thermal to electrical power conversion using this technology coupled with high temperature battery storage.
  - Intended applications include harsh, extreme environment electronics and high frequency data transmission.

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Some Closing Recommendations

- There is no one superior dominant high temperature electronics technology that will meet the demands for all applications -- diversity is good and should be welcomed.
- In general, choose the most mature technology, all other things considered equal.
- Use hybrid approach combining two or more technologies: e.g., SOI for analog, logic and data processing and SiC for power discrete devices;
- GaAs for analog, logic and data processing and GaN for power discrete devices; and
- SOI for analog, logic and data processing and SSVD for power discrete devices and data transmission
- Seriously consider innovative hybrid approaches coupled with heat removal and or redistribution.

Finally…

He or she who does or tries to understand, know and learn the history of high temperature microelectronics failures and shortcomings may still be doomed to repeat and relive them.

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