Briefing To Industry

Wide Bandgap Semiconductor Materials: Status / Issues

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Presentation Overview

- **History Lesson**
  - **Using GaAs as a model**
  - **What have we learned? How to proceed?**
- **Where are we now? *General* Technical Issues**
  - **Substrates**
    - **Semi-insulating SiC**
    - **Conducting SiC**
    - **Alternate Substrates**
  - **Wide Bandgap Epitaxy**
    - **SiC**
    - **GaN/Nitrides**

Why the History Lesson?

Those who forget the past are condemned to repeat it

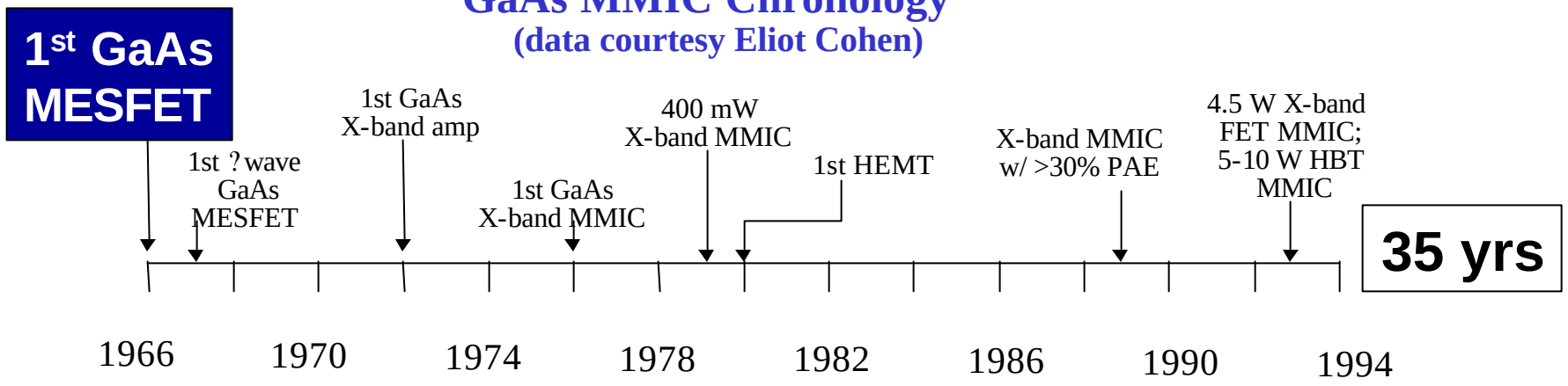
- George Santayana (1863 - 1952)
The Life of Reason, Volume 1, 1905

- **Many similar challenges to GaAs**
- **Many of the same faces!**
- **Don’t have the time, or funding for unnecessary iterations**

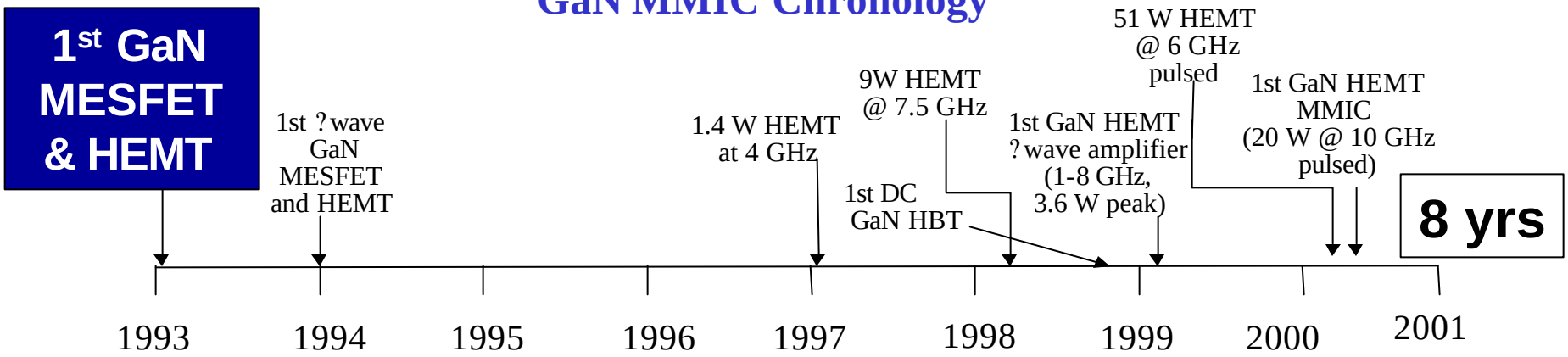
GaAs as a Model?

Chronology of GaAs and GaN

GaAs MMIC Chronology
(data courtesy Eliot Cohen)



GaN MMIC Chronology



Chronology of GaAs and GaN RF Device Development. DARPA GaAs MMIC program started in 1985 (20 years after first transistor demo) with established GaAs material and committed Defense Contractors.

GaAs as a Model?

GaAs Then vs GaN Now

There are no show-stoppers yet, but there is a hard road ahead.

GaAs (circa 1990)

- **Mature Materials Technology**
- **Material Well Characterized**
- **Well defined operating parameters**
- **Processing Maturing**

GaN (2001)

- **Viable Substrate?**
- **No Standard Epi**
- **Immature Processing**
- **No Standard Operating Conditions**
- **No agreement on testing procedures**
- **Unclear how small signal Performance relates to large**
- **Device performance is time dependent**

(chart courtesy Harry Dietrich NRL)

GaAs as a Model for WBG?

GaAs (1980) vs GaN (2000)

- **GaAs (circa 1980, Pre-DARPA MMIC)**
  - No SS alternative above 4 GHz
  - Native substrate. Numerous GaAs Crystal growers (TI, Rockwell, MA-Com, Westinghouse, etc.) creating a fledgling GaAs materials industry.
  - Defense industry committed to military and commercial use of GaAs RF products (TI, Raytheon, TRW, Westinghouse, ITT, TriQuint, Varian, Hughes Aircraft, MA-Com, GE, Rockwell)

A Thundering Stampede

- **GaN (circa 2001)**
  - Any compelling need for GaN RF?
  - No native substrate. Viable foreign substrate (semi-insulating SiC) of useful thermal, crystalline, and electrical characteristics. Limited availability.
  - Until very recently, only very limited interest from defense industry - this has been an area of research for universities and small businesses (commercial applications driven).

A few stray cats

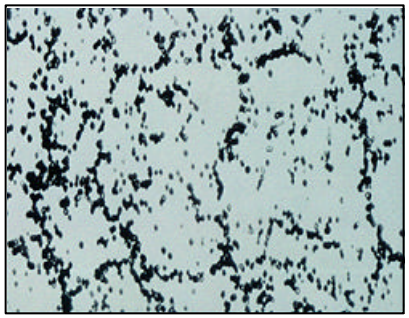
There are many lessons from GaAs which can be applied to WBG Mat'ls, however, there are also several problems unique to WBG Mat'ls

Lessons Learned

Transition of Semiconductors…

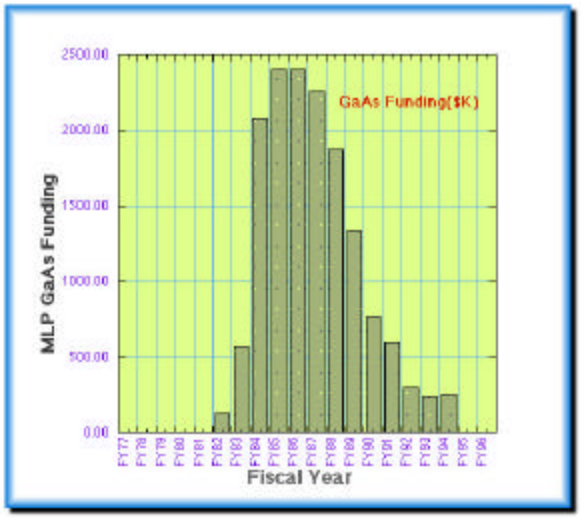
GaAs - Pre FY80 Status

- Wafers Under 2”
- Horizontal Bridgeman Growth
- Unoptimized Growth Processes
- High Impurities, High Defects
- Cr-Doped Semi-Insulating



GaAs Development Program

- LEC Growth Techniques
- Optimize/Automate Growth
- The EL2 Defect - Undoped S. I. GaAs
- Improve Purity/Reduce Defects
- Matl’s Device Correlation Studies
- Indium-Doped Dislocation Free GaAs



GaAs - Title III

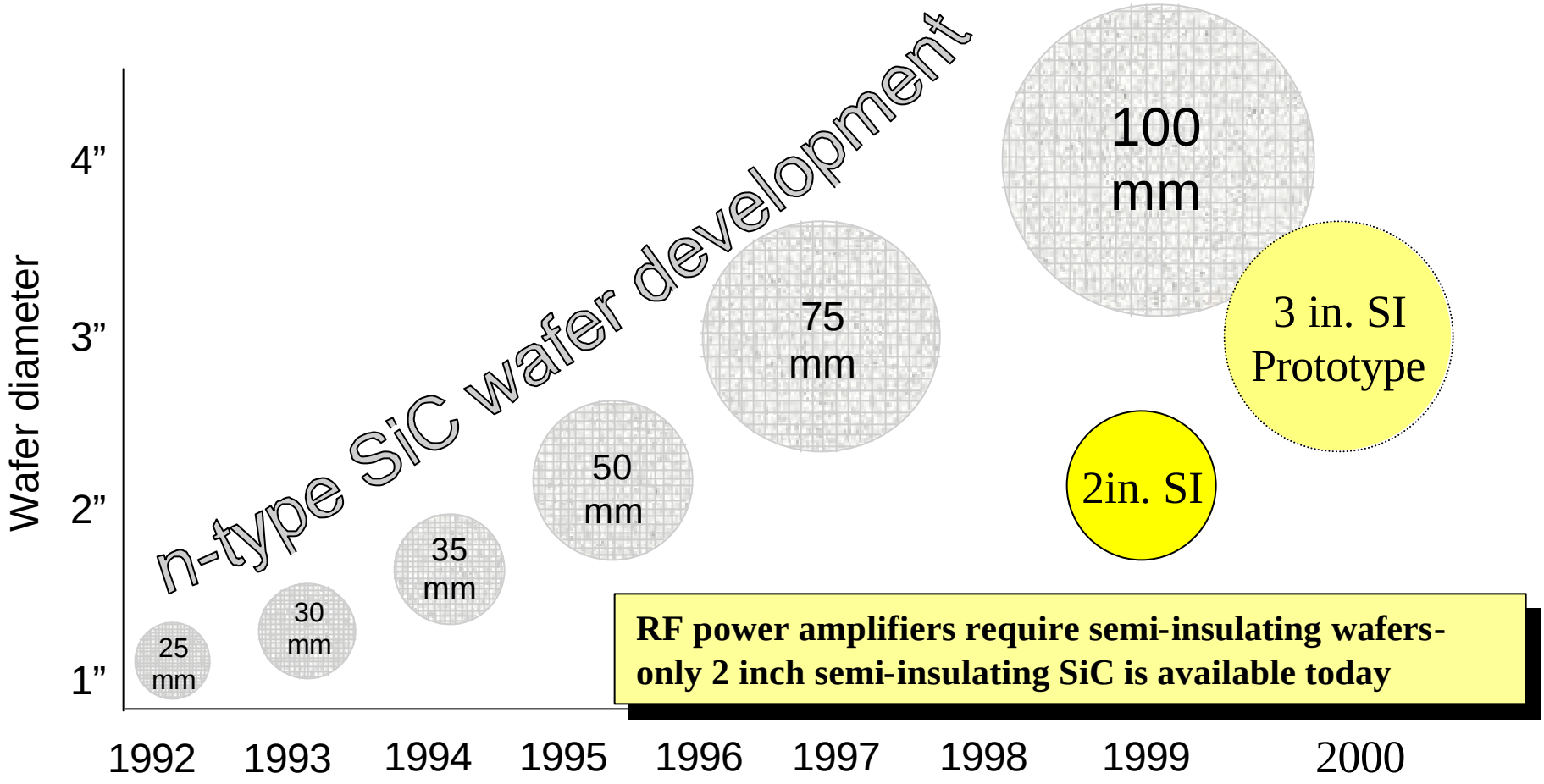
- Late 1990’s
- VGF Growth
- 6-Inch Wafers
- $23.1M in Title III
- Transition to Production

Status / Issues: Substrates

- **Where are we now?**
  - **Consider both RF and Power Applications**
  - **Substrates**
    - **Semi-insulating SiC (RF)**
    - **Conducting SiC (Power)**
    - **“Alternate” Substrates**
      - **Bulk GaN (Homoepitaxy)**
      - **Other Bulk (GaN, AlN, Lithium Gallate…)**

Historical increases in n-type SiC wafers: Semi-insulating wafers lag behind

Note: SiC active devices require 4H, GaN-on-SiC can employ 4H or 6H SiC



RF power amplifiers require semi-insulating wafers- only 2 inch semi-insulating SiC is available today

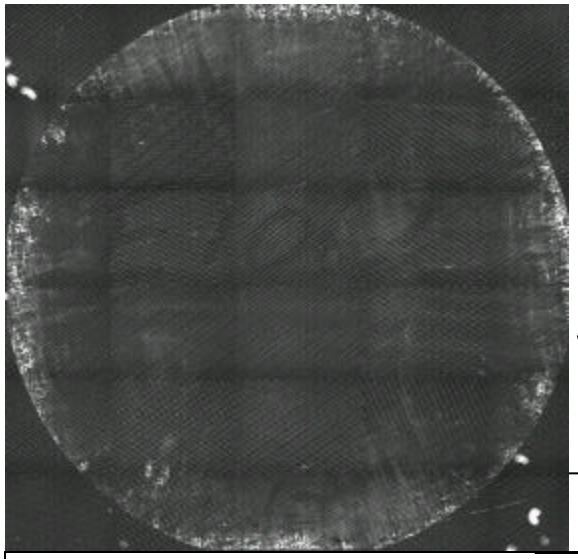
Status / Issues: Substrates

- **Semi-insulating SiC: Two primary approaches to obtaining appropriate electronic properties**
  - Vanadium doping
    - Reasonably well understood
    - Issues with yield, device performance
  - Others (high purity? co-doping?)
    - Mechanisms not understood
    - Must be studied, and ultimately, controlled
- **Diameter:** Large (75mm – 100mm) Diameter required for device development efforts

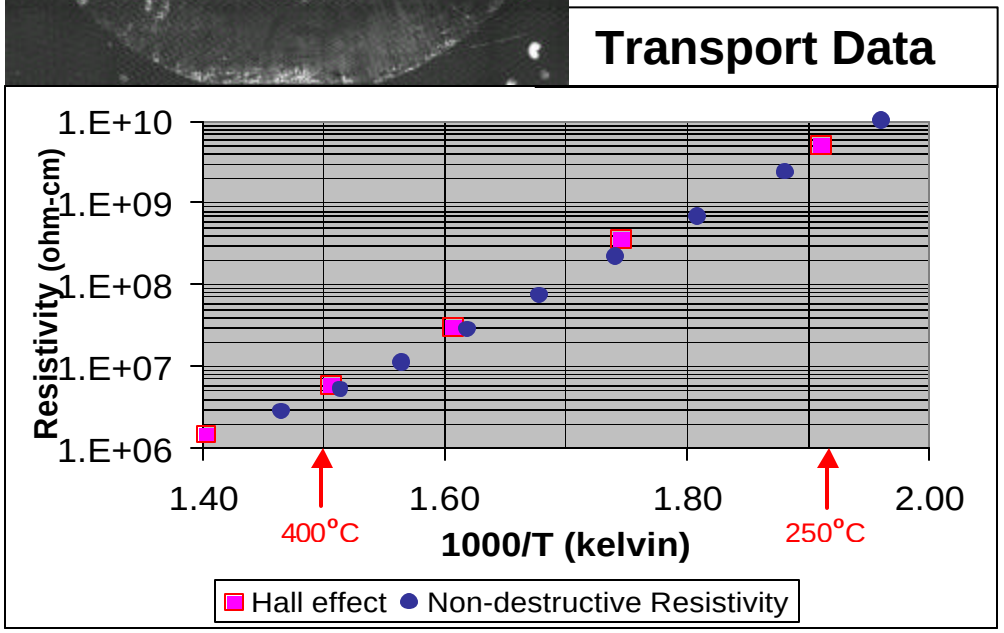
Semi-Insulating SiC Substrates

Issues in addition to dopants

- Micropipe reduction
- Structural issues
  - Polytypes
  - Crystalline quality
- Measurement of HIGH TEMPERATURE resistivity
  - Non-destructive techniques desirable
- Surface preparation
  - Polishing may not be same as for conducting



Cross polarized image of 50.8 mm Semi-insulating wafer



Semi-Insulating SiC substrates: Status and issues

- **Semi-Insulating Properties:** Current materials are not optimal for RF devices: Need to be stable, predictable, uniform.
  Solutions: Optimized doping schemes, high purity, find "EL2-like" defect level, physics-based studies

- **Defects:** Micropipes, dislocations and crystalline defects
  Solutions: Optimized growth processes, studies of defect generation mechanisms, novel growth techniques

- **Surface finish:** High density of scratches and subsurface damage
  Solutions: High temperature H-etch; chemical mechanical polish; correlation to epi and devices needed

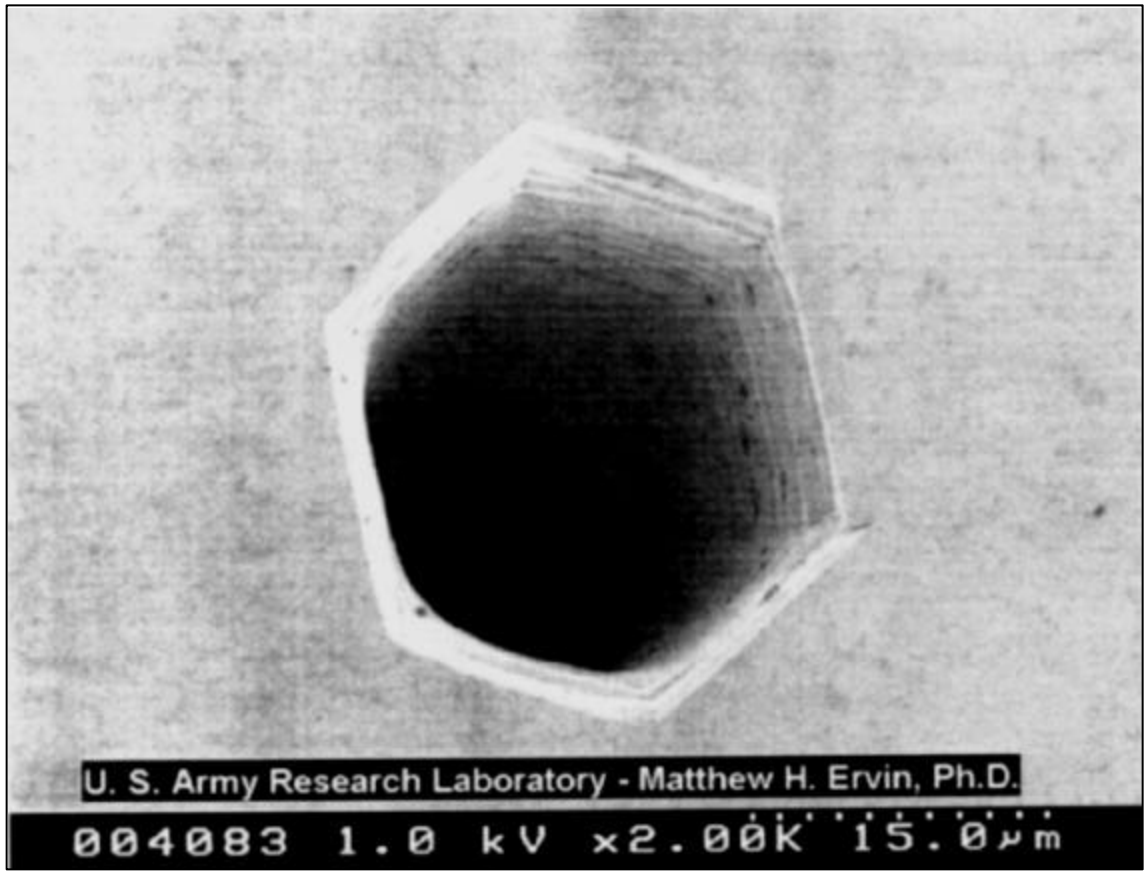
Greatest challenge: Stabilizing semi-insulating properties to assure reproducible, uniform, high yield growth processes. Optimizing materials for best RF Performance/Reliability

Status / Issues: Substrates

- **Conducting SiC**
  - **Defect reduction efforts still required**
    - 30-50 micropipes/cm^2 available
    - Surface preparation still an issue
  - **Diameter:** For LARGE FOOTPRINT DEVICES must have large diameter wafers
    - 75mm – 100 mm

Defects in Silicon Carbide

SiC Micropipe



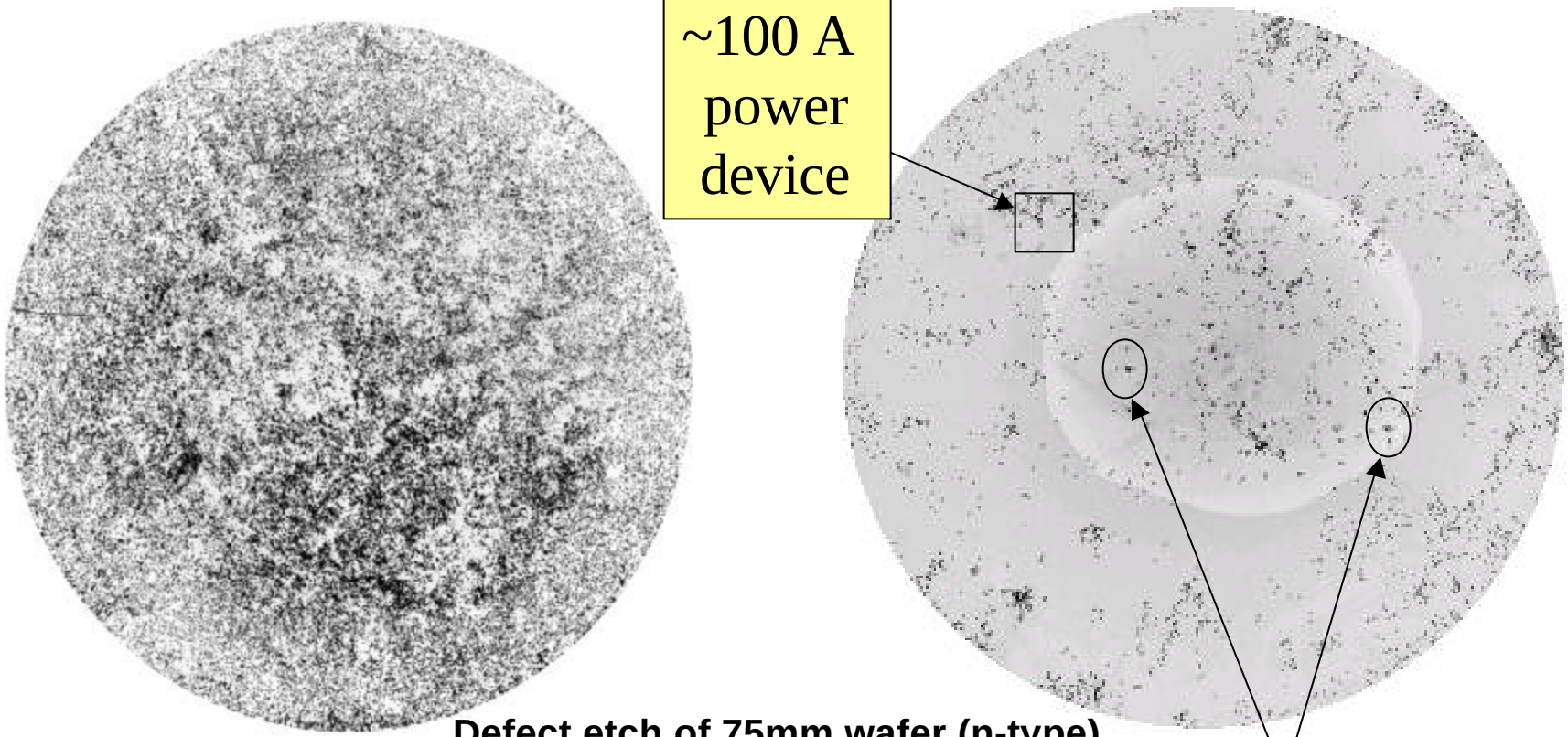
- Major defect in SiC
- Formed during crystal growth
- Cause poor yield, poor quality epitaxy
- Are ‘device killers’
- Significant process improvements have reduced defects, but these are still an issue.

Micropipe Density in 75 mm n-type 4H-SiC

Circa 1998
pipes = 600cm^{-2}

Current status (2001)
pipes = 60 cm^{-2}

~100 A power device



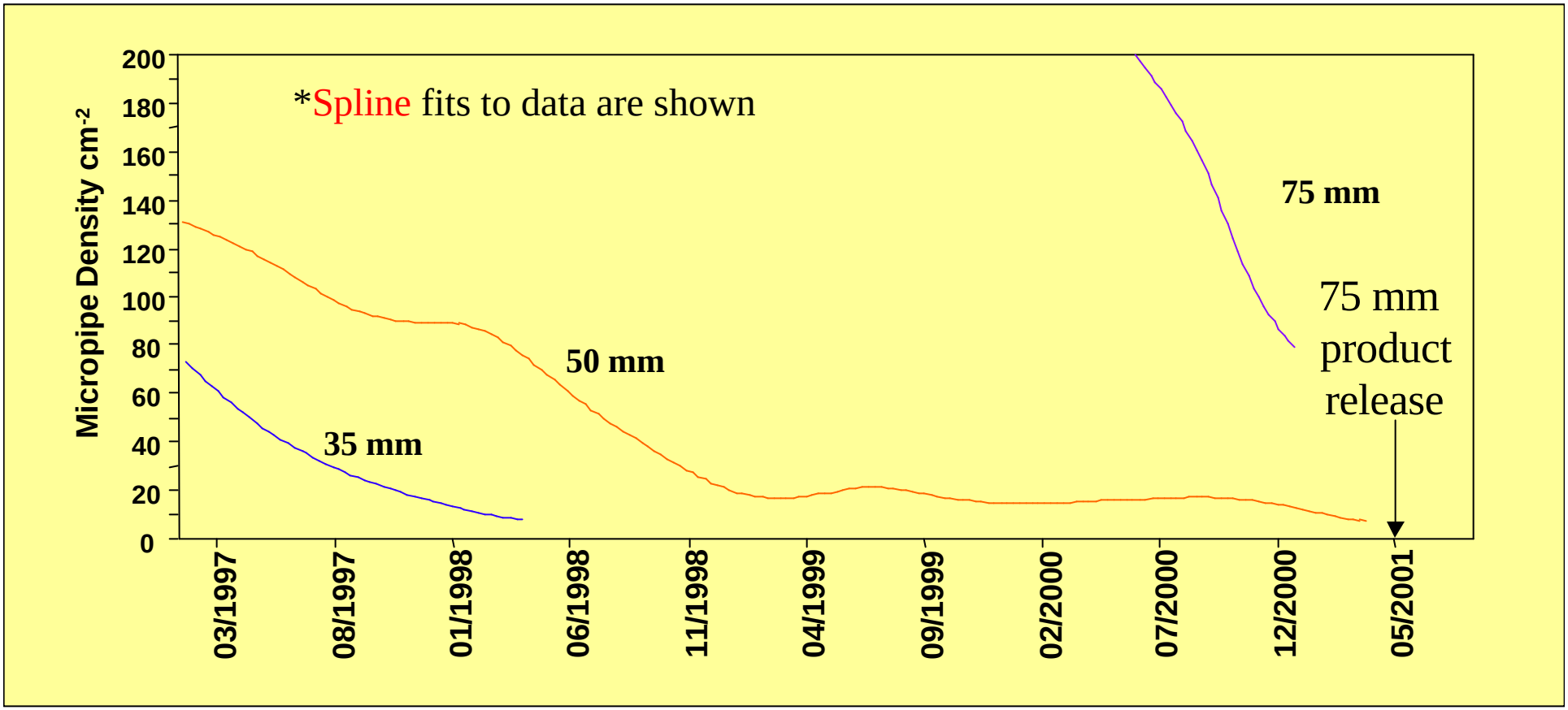
Defect etch of 75mm wafer (n-type)

Micropipe: open core dislocation propagating through entire wafer

Reducing the micropipe density represents a critical challenge in going from < 5 Amp devices to >100 Amps

Micropipe Reduction vs Diameter

High initial micropipe density for each new wafer diameter is reduced through process optimization.



SiC Conducting Substrates: Status and issues

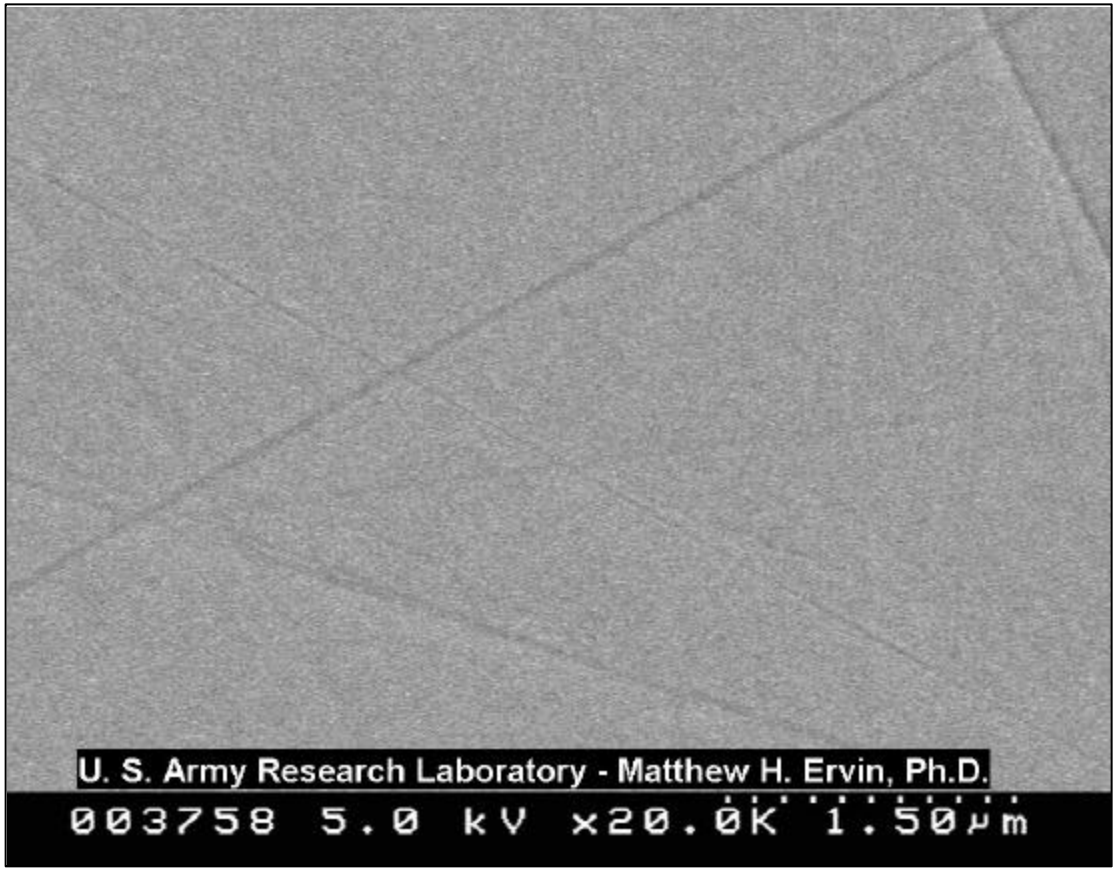
- **Micropipes:** Commercial products < 30 cm^{-2}, 3 inch 4H n-type product release, cost still high due to low yield
  Solutions: Purity, thermal process control while maintaining stability of other materials properties

- **Dislocations:** >$10^4 cm^{-2}$ impact reverse leakage
  Solutions: Lower growth temperature, increase wafer diameter to reduce thermal gradients during growth.

- **Surface finish:** High density of scratches and subsurface damage
  Solutions: High temperature H-etch; chemical mechanical polish; correlation to epi and devices needed

Greatest challenge: optimizing growth conditions and wafering for growth and processing of large wafers (>3”) *without degrading other properties*

SiC Substrate – Surface Damage



- Polishing damage
- Wafering damage
- Cause poor yield, poor quality epitaxy
- Both surface, and subsurface effects
- Must improve surface preparation with processes suitable for high volume processing

Status / Issues: Substrates

- **Alternate Substrate Approaches**
  - **Bulk Nitrides**
  - **Other Bulk**
- **Looking for candidate materials that can improve:**
  - **Epitaxy quality – reduced dislocations, better crystallinity**
  - **Device design parameters**
  - **Affordability**
  - **Availability**
  - **Thermal management**

Nitride Substrates

Comparison of Substrates for GaN Epitaxy

Substrate	Sapphire (Al_20_3)	6H SiC	ZnO AlN	LAO, LGO $Li[Al(Ga)]O_2$	GaN
Lattice Mismatch (a-axis)	14%	3%	~2%	1.4%, 0.18%	0%
Crystal Structure	Hexagonal (Spiral Structure)	Hexagonal (Polytype)	Hexagonal (Perfect Wurtzite)	Tetragonal, Orthorhombic	Hexagonal (Perfect Wurtzite)

Best Compromise?
Isomorphic to GaN

Ideal!

Bulk Nitride Substrates

- Substrates
  - Recent demonstrations / sales of ‘freestanding’ GaN substrates is promising
  - Development of AlN also showing progress
- Continued development of ‘higher volume’ processes desired, with a focus on large diameter
- KEY DEVELOPMENT AREAS:
  - Must start producing RF devices with these materials
  - Characterize materials and device performance
  - Evaluate impact of thermal conductivity

“Other” Substrates for Nitrides

- Substrates – other candidate materials
  - Lithium Gallate, and related compounds
  - Zinc Oxide
- Continued development of ‘higher volume’ processes desired, with a focus on large diameter
- Assess role: Actual substrate or template (removed)
- KEY DEVELOPMENT AREAS:
  - Must start producing RF devices with these materials
  - Characterize materials and device performance
  - Evaluate thermal performance

Bulk Nitride & Alternate Substrates: Status and issues

- **Diameter:** Viable substrate processes must concentrate on production of large diameter (>3”) material
  Solutions: Novel approaches to materials growth should be considered.

- **Material Properties:** Semi-insulating for RF? Good thermal conductivity desired.
  Solutions: Dopant studies, high purity materials and processes

- **Scaleability:** Process should be amenable to large diameter, high volume production
  Solutions: ?

Greatest challenge: Developing growth processes that can be scaled to high volume semiconductor production.

Status / Issues: SiC Epitaxy

SiC Epitaxy Status –

- Reasonable growth rate – 2.5 ?m/hr
- Reasonable purity – RT mobility of 950 $cm^2/V?s$ in n-4H
- Reasonable background doping – 10^{14} cm^{-3}
- Reasonable doping control above 10^{15} cm^{-3} - ± 5%
- Reasonable thickness control - ± 2%
- > 50 ?m thick for high power devices

SiC Epitaxy

Limitations:

- Uniformity still an issue
  - Dopants
  - Thickness
- Scale growth processes up to 3” and 4” (not trivial!)
- Cleaner p-n junctions
- Better thick epitaxy capabilities
  - Strain / Cracking serious issue
- Improve crystalline (structural) quality

SiC Epitaxy: Status and issues

- **Uniformity:** Thickness and dopant uniformity still only ~5-10% across large wafers
  Solutions: Process design, process control, reactor optimization, new approaches to growth?

- **Strain / Cracking:** Gets worse with thickness and large diameter!
  Solutions: Lower growth temperature, optimize growth process, novel reactor design

- **Structural Quality:** Crystallinity & Structural imperfections
  Solutions: Better process control, higher reactor purity

Greatest challenge: Getting BETTER uniformity while increasing wafer diameter. Getting BETTER epitaxy while growing THICKER layers.

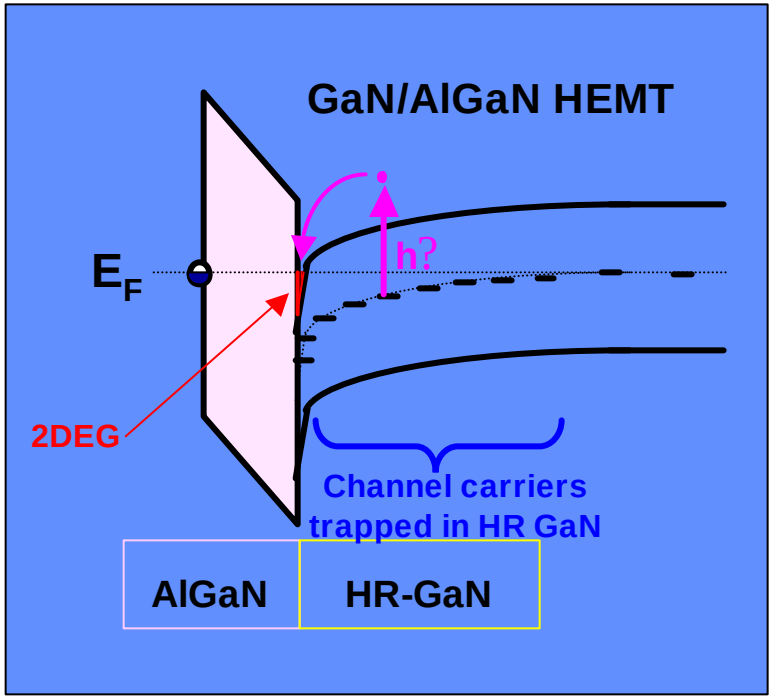
Status / Issues: GaN Epitaxy

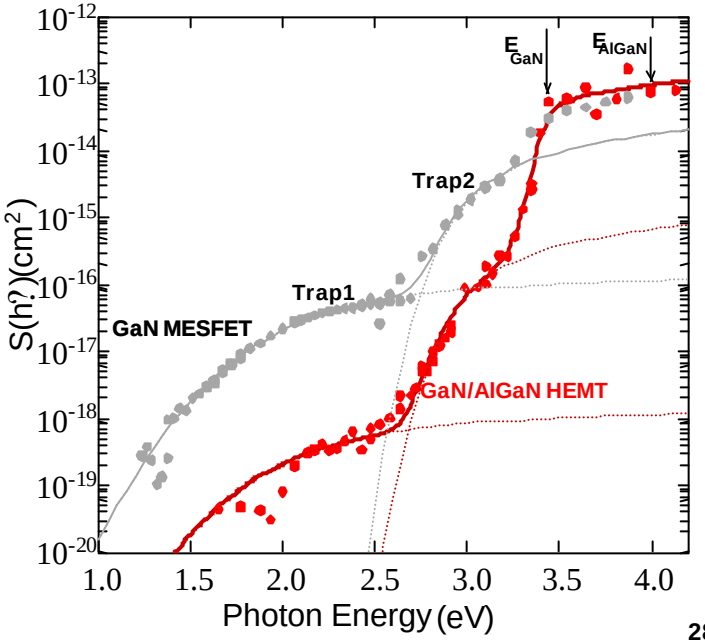
- GaN Epitaxy
  - Significant progress with both MOCVD and MBE growth
  - LEO and pendeo epitaxy - innovative growth methods
- Still Required:
  - Charging at interfaces, other surface traps
  - Determine the effects of defects in the substrates on crystal growth
  - Better understanding of how defects affect device properties
  - Better control of stoichiometry
  - P-type dopant: Something better than Mg for HBTs?

Traps in III-V Nitride Devices

Materials Defects Impact Performance!

- **Current Collapse (CC):**
  - 2DEG carriers lost to traps.
  - Limits FET output power.
- **Photoionization Spectroscopy (PS):**
  - Spectral dependence of carrier trapping
  - Signature of responsible traps
  - Measurement of trap characteristics.
- **PS measurements of HEMT structure:**
  - Spectral features present in HEMTs, MESFETs
  - Features independent of reactors / lab
- **Traps causing CC appear to be unique!**





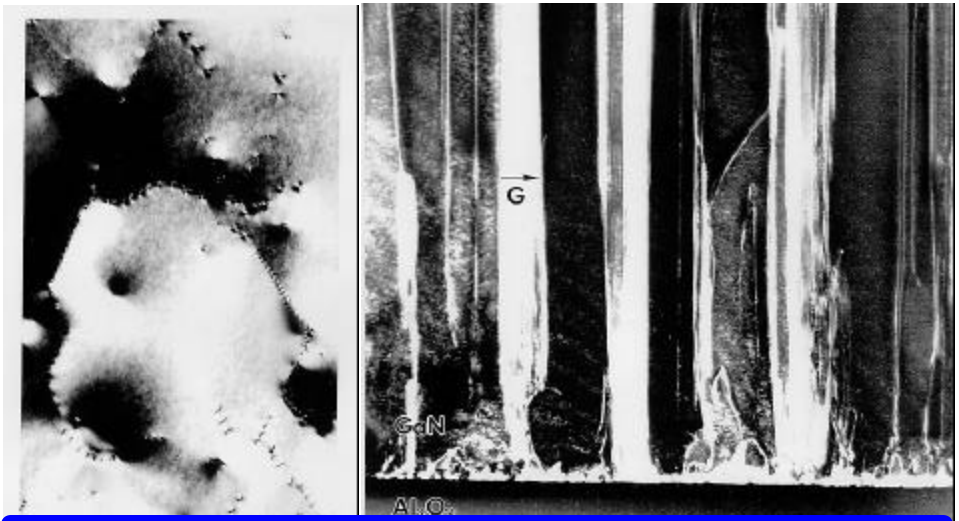
Comparison of MOCVD and MBE Growth of GaN

MOCVD	MBE
•Higher Growth Rate	•Lower Growth Rate
•Thicker GaN Buffer	•Thinner GaN Buffer
•Better GaN Quality	•Abrupt Heterojunctions
•Graded Junctions	•Improved Uniformity
•Poorer Uniformity	•Better Reproducibility
•Poorer Dopant Control	•Better Dopant Control

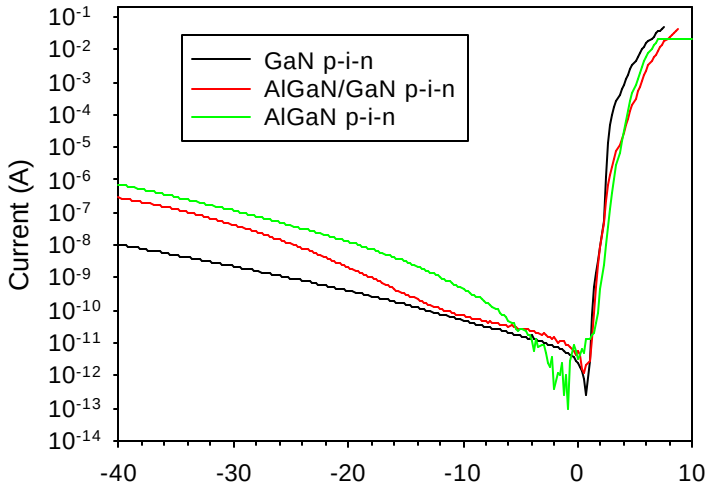
In addition, cost / producibility issues must be considered for future transition.

Traditional Epitaxial Growth of Nitrides

- **Lattice mismatch with hetero-substrates leads to defects**
  - **Causes dislocations to form during columnar growth**
- **Deleterious effects in devices from dislocations/point defects**
  - **Leakage currents, lower breakdown voltages, low carrier mobility, current collapse, higher thresholds, poor reliability, etc.**

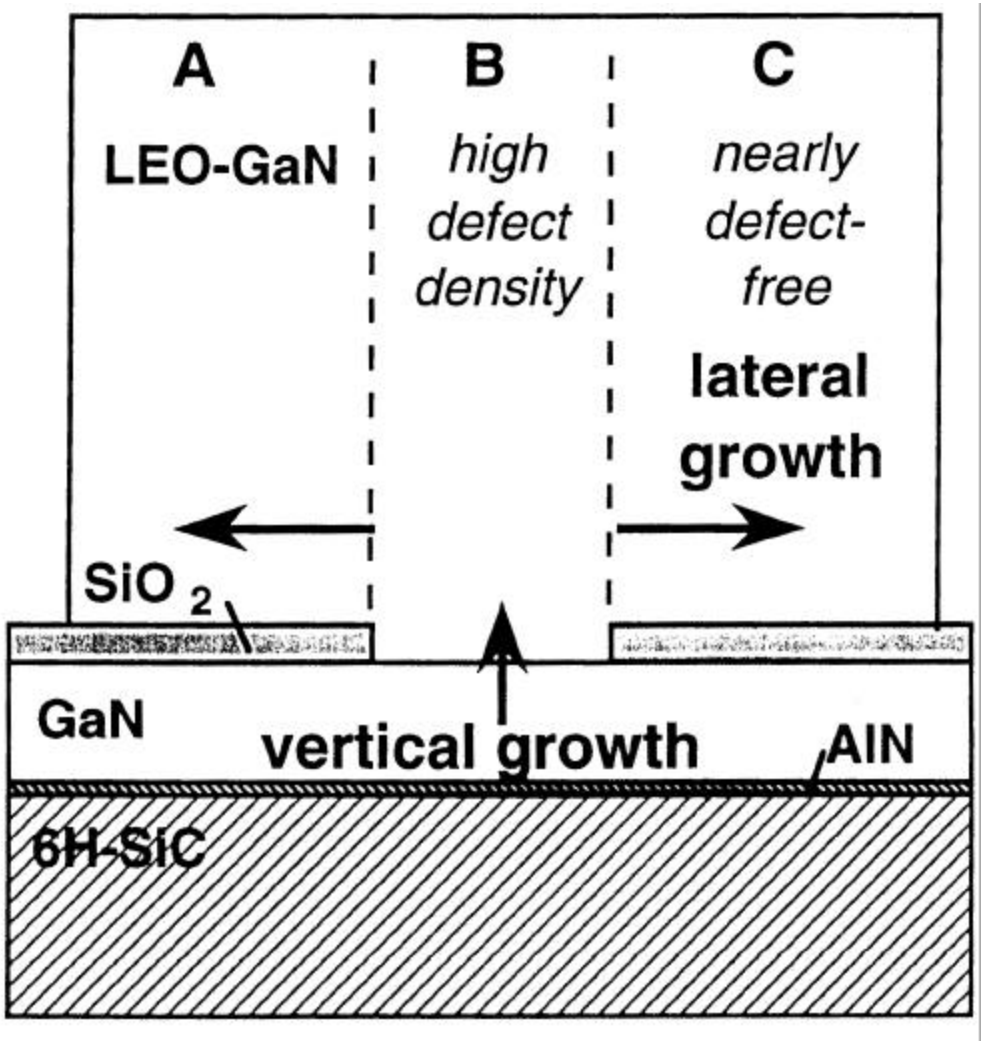


TEM Images of GaN on sapphire

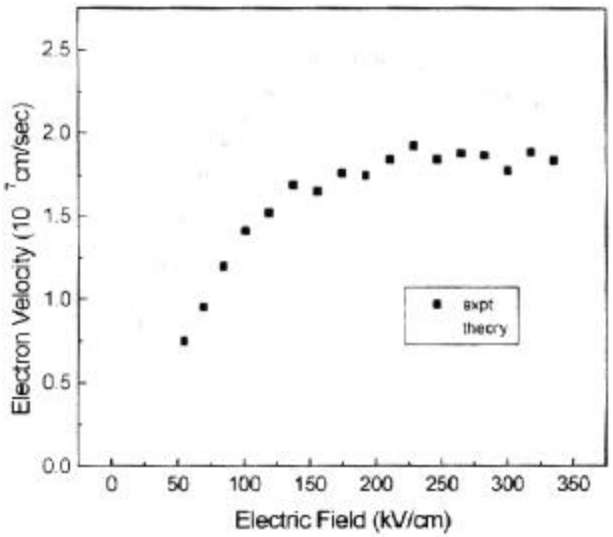


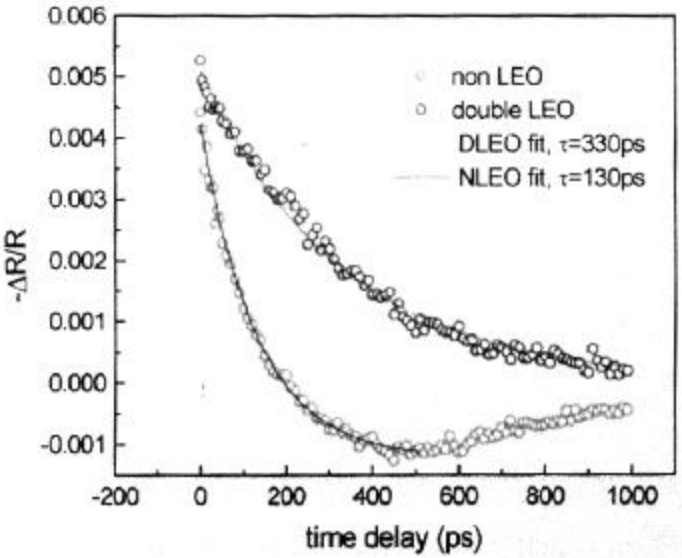
Leakage Currents in GaN p-i-n Diodes

Lateral Epitaxial Overgrowth (LEO) of GaN epitaxial layers



Longer Carrier Lifetimes in LEO GaN





Optical time-of-flight measurements employing femtosecond time-resolved electroabsorption techniques have enabled the first measurement of the electron velocity-field characteristic in **GaN p-i-n photodetectors**.

Applications
- high power, high frequency electronics
- high sensitivity solar blind APD detectors

Reduction of threading dislocations in lateral epitaxially overgrown (LEO) GaN lead to a three-fold enhancement of carrier lifetime.

Implications
- smaller reverse leakage currents for APD detectors
- higher detection sensitivity

LEO / Pendo Status

- **Improves material and device characteristics and reliability**
  - Increases carrier lifetime
  - Reduces diode leakage currents
  - Reduces gate leakage currents in HFET's
  - Greatly increases lifetime of blue emitting lasers.
- **Both are in exploratory phase for application to RF devices**
  - Interface effects / passivation must be well understood
  - Materials scale-up and affordability issues still TBD

GaN Epitaxy: Status and issues

- **Structural Quality:** Material quality limited by substrates and growth process parameters. Dislocations still too high.
  Solutions: Improved substrates, buffer layers, novel growth techniques

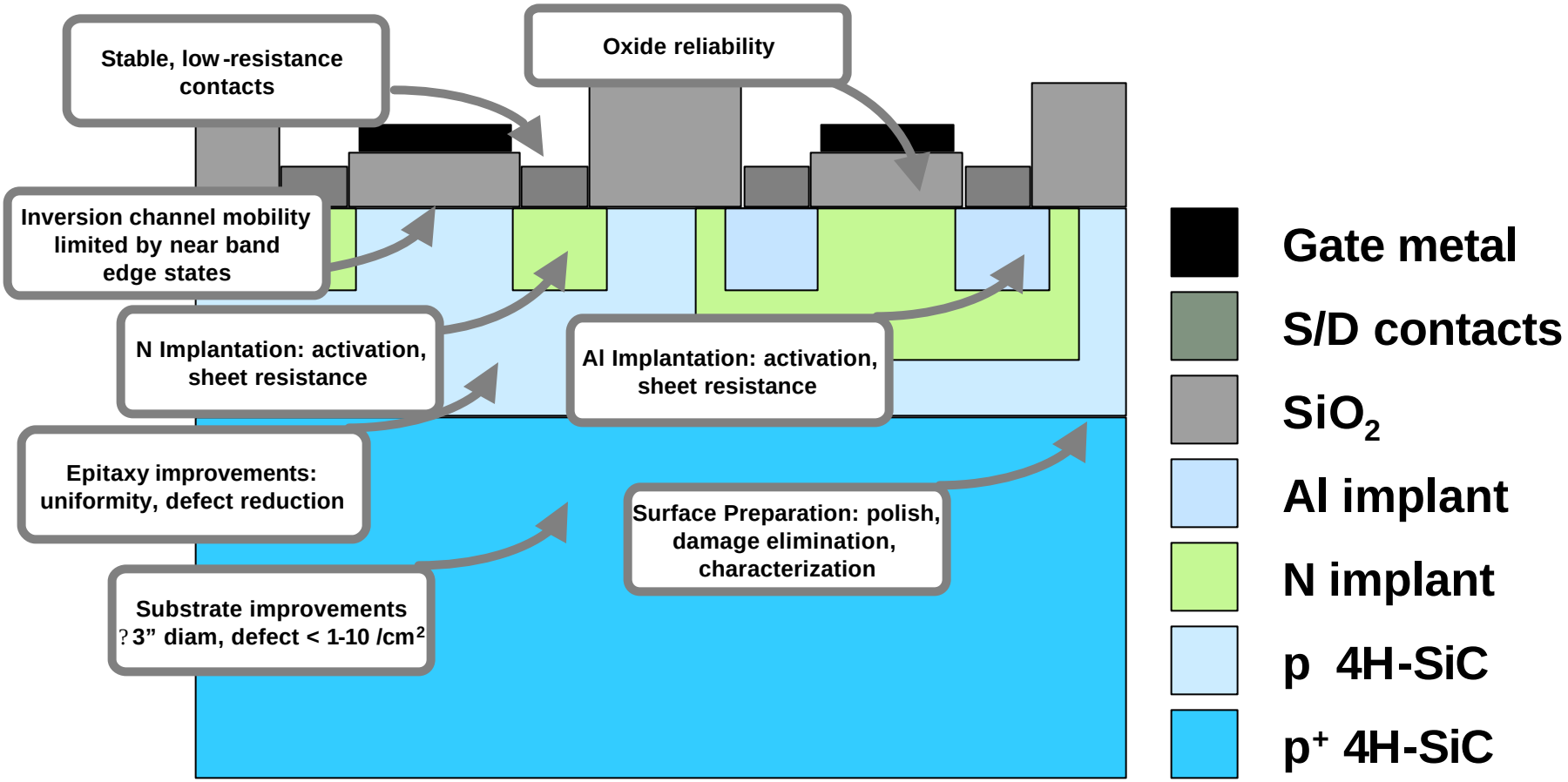
- **Interface effects:** Charging & trapping have impact on performance.
  Solutions: Understand physics of material / interfaces, improved passivation techniques.

- **P-type Dopants:** Development of HBT structures limited.
  Solutions: Alternate to Mg, improved activation approaches

Greatest challenge: Reduction of dislocations in material is critical. Continued materials improvements with scale up to 3" substrates (and 4") will be a challenge.

Wide Bandgap Materials Issues

More than just Substrates & Epitaxy…



SiC power MOSFET