Substrates and Epitaxy in III-V Manufacturing

Robert Yanka

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Overview

• Substrate Manufacturing Overview
• Metal-Organic Chemical Vapor Deposition (MOCVD) Basics
• Molecular Beam Epitaxy (MBE) Basics
• Epiwafer Characterization
• RFMD Epiwafer Production Overview
Substrate Manufacturing Overview
Process Flow of GaAs Substrate Production

Single Crystal Growth
Cylindrical Grinding
Slicing
Edge Rounding
Laser Marking
Polishing
Characterization & Inspection
Substrates – Boule Growth Techniques

Czochralski (Cz) Growth

Horizontal Bridgman (HB) Growth
Substrates – LEC vs. Vertical Boat

Liquid Encapsulated Czochralski (LEC)  \[ \text{B}_2\text{O}_3 \]

Vertical Boat

Temperature Profile

Melting Point
Substrate – VB vs. VGF

Vertical Boat vs. Vertical Gradient Freeze

Longer Ingot vs. Shorter Ingot

Furnace Moves

Fixed Furnace

Temperature Gradient Moves

VB

VGF
Substrates – Grinding and Slicing

As sliced Wafers

Wire Saw

Seed/Tail Removed

Remaining Ingot Ground Into Cylinder with Indication Flat

As sliced Wafers
Substrates – Edge Beveling and Polishing

Edge Beveling

Laser Marking

Double-Side Polishing
Substrates – Inspection and Characterization

Surface Inspection

Substrate Flatness
Substrates – Inspection and Characterization

• Etch Pit Decoration (KOH)
  – Chemical etch used to determine dislocation density

• Electrical Characterization
  – Hall and non-contact resistivity measurements are performed on the seed and tail to determine the electrical characteristics of the boule
MOCVD Basics
Epitaxial Crystal Growth

• Epitaxy
  – is derived from the Greek word meaning “ordered upon”
  – Epitaxy is the growth of thin single crystals of one material on the crystal face of the same (homoepitaxy) or another (heteroepitaxy) material, such that the two materials have a defined, relative structural orientation

• Two main Rules of epitaxy
  – *Matching of Symmetry between the substrate and the epilayer*
  – *Misfit between lattice constants of substrate and epilayer should be minimal*

• Examples of Epitaxy:-
  – GaAs on GaAs (Homoepitaxy) (misfit value = 0)
  – AlGaAs on GaAs (Heteroepitaxy) (misfit value > 0)
  – InGaAs on GaAs (Heteroepitaxy) (misfit value >> 0)
Metal Organic Chemical Vapor Deposition

• First documented in 1963 by Harold Manasevit for silicon on sapphire at Rockwell Corporation

• Manasevit grew GaAs on sapphire in 1968

• Growth involves the transport of metal-organic and hydride precursors to heated substrates where they pyrolyze, leaving the growth species on the substrate surface

• Also referred to as (LP-, AP-) OMCVD, MOVPE, OMVPE
Metal Organic Chemical Vapor Deposition

• MOCVD is capable of high growth rates, making it the most widely used technique for the manufacture of optical devices such as LED’s

• At lower growth rates, MOCVD can produce abrupt interfaces, allowing it’s application to RF devices such as HBT’s and FET’s
Metal Organic Chemical Vapor Deposition

- Source materials for MOCVD are extremely hazardous, requiring rigorous monitoring and handling procedures
  - Metal-organics are toxic and pyrophoric
  - Hydrides are highly toxic
  - Hydrogen carrier gas is explosive

- Maintenance cycles driven by coating of reaction chamber
  - Requires relatively frequent cleaning to remove material from system components and reduce particulates in the chamber
  - System downtime is on the order of hours
MOCVD – System Block Diagram

gas blending unit

reactor with heated susceptor

control unit

vacuum system

scrubbing system
MOCVD – System Photograph

- Reactor + heater
- Gas mixing system
- Vacuum pump (inside)
- Scrubbing system
- Computer (not shown)
MOCVD – Flow Control

• Mass Flow Controller (MFC)
  – A portion of the gas flow passes through a tube incorporating two temperature sensors
  – A temperature difference results that is proportional to the mass flow through the controller
MOCVD – Sources

MO Bubbler
Carrier gas (H₂) flowing through the bubbler picks up MO vapor from the liquid

Typical MOCVD Sources
Group III: Tri-methyl gallium, Tri-methyl aluminum, Tri-methyl indium
Group V: Arsine, Phosphine, Ammonia, Tertiary-butyl arsenic (TBAs), Tertiary-butyl phosphine (TBP)
Dopants: Carbon-tetrabromide, Disilane, Di-methyl zinc
MOCVD - Growth Dynamics

- Source molecules mixed into a carrier gas (hydrogen) with mid-stream velocity V
- Friction reduces gas velocity to near zero at surfaces
- Sources must diffuse through the near stagnant boundary layer above substrate
- Precursor decomposition
- Surface adsorption & diffusion incorporation and growth
- Growth rate depends upon pressure, flow rate and temperature
MOCVD – Growth Regimes

A. Desorption / Gas Phase Limited Growth

B. Mass Transport Limited Growth (Diffusion through boundary layer).

C. Surface Kinetic Limited Growth

Growth rate ~ temperature independent in mass transport limited regime

MOCVD – Growth Rate Control

Growth Rate: The Mass Transport Limited Regime

![Graph showing growth rate vs. TMGa source flow](image-url)
MOCVD – In-situ Monitoring

- Pyrometry
  - Substrate temperature measurement
  - Multi-wavelength for emissivity correction

- Reflectometry
  - Growth rate and ternary composition data
  - Wafer curvature measurement

![Graphs showing R/R_sapphire vs. time for Transparent Film and Absorbing Film](image)
MBE Basics
Molecular Beam Epitaxy

• Molecular Beam Epitaxy was developed by Alfred Cho and John Arthur in 1970 at Bell Labs

• Originally applied to the growth of GaAs lasers

• Growth involves the evaporation of high purity elemental sources in an ultra-high vacuum environment

• The resulting “molecular beams” impinge heated substrates producing epitaxial growth
Molecular Beam Epitaxy

• MBE typically utilizes slower growth rates (~1µm/hr) resulting in high quality, atomically abrupt interfaces. This is an advantage for superlattice and/or quantum well based applications.

• Relatively simple growth kinetics and precise layer control have made MBE a popular technique for investigating novel devices structures in R&D. However, MBE is also widely used in the manufacture of pHEMT’s and HBT’s.

• MBE source materials are relatively safe, as they are low vapor pressure solids at room temperature
Molecular Beam Epitaxy

- Maintenance cycles are driven by the need to replenish sources

- Ultra-high vacuum environment requires extensive cleaning and baking of the system
  - Maintenance cycles require several weeks to complete

- Campaign lengths between cleaning can range from six to nine months
Wafers are introduced from atmosphere into the load lock.

Next they move into the prep chamber for outgassing.

Finally, they are transferred into the deposition chamber for growth.
MBE - System Photograph

Prep/Transfer Chamber  Depo Chamber  Cryo Pumps

Load Locks  Source Flange

Veeco Gen2000
MBE – System Schematic

Cryopanel maintains low impurity background in the depo chamber.

Substrate rotation improves uniformity.
MBE – Effusion Cell

Typically used for Group III’s and Dopants
Ga, In, Al Be, Si

Cell stability plays a major role in product variability
MBE – Valved Cracker

Group V’s consumed at a high rate due to the flux requirements

Temperature ramps are impractical for the large material loads required

Valved cells provide flux control at a constant temperature

Valve controls flow between sublimator and cracking zone
MBE – Growth Dynamics

Surface adsorption and disassociation of Group V dimers

Arriving Group III atoms react on the surface forming the compound

Substrate temperature must be sufficient to promote layer-by-layer growth

High vapor pressure Group V’s require high flux to stabilize the surface

Growth only when Group III present

Growth rate proportional to Group III flux at optimized growth temperature
MBE – Growth Rate

- Growth rate proportional to Group III flux
  - Follows Arrhenius relationship
  - Doping is controlled in the same manner as growth rate

\[ y = -14.782x + 5.2548 \]
\[ R^2 = 0.9998 \]
MBE – In-situ Monitoring

- Ion gauge for measuring source material flux
- Reflection High Energy Electron Diffraction (RHEED) for growth rate and structural information
- Optical pyrometry for substrate temperature
- Band edge thermometry for substrate temperature
- Laser reflectometry for growth rate
- Atomic absorption flux monitoring
Epiwafer Characterization
Epiwafer Characterization

• Characterization Categories
  – Surface morphology
  – Electrical properties
  – Structural properties

• Destructive vs. Non-Destructive

• Product Wafers vs. Process Monitors
Epiwafer Characterization – Surface Morphology

Surface roughness, particulates, growth defects, scratches
Typically non-destructive

• Visual Inspection
  – Looking for gross defects such as haze, scratches, large particles

• Automated Inspection
  – Commercial tools such as Tencor’s SurfScan or Candela
  – Provides wafers maps for haze, point defects and scratches

• Optical Microscopy
  – Standard and phase-contrast
  – Usually for diagnostic purposes, to indentify the type of defects
Epiwafer Characterization – Electrical Properties

Doping levels, doping uniformity, doping depth profile
  Carrier concentration, mobility, sheet resistance
Destructive or non-destructive depending upon technique

• Electro-chemical CV Profiling
  – Usually referred to as Polaron from the commercial system
  – Provides a carrier concentration depth profile but is destructive

• Hall Measurement
  – Provides average carrier concentration and mobility over a sample
  – Typically destructive (non-destructive approaches exist)

• Non-contact Sheet Resistance
  – Provides non-destructive sheet resistance mapping
Epiwafer Characterization – Structural Properties

Layer thickness, composition, uniformity and crystal quality
Techniques are typically non-destructive

• Surface Profilometry
  – Simple step height measurement for thickness / growth rate

• X-ray Diffraction / Reflection
  – Layer thickness and composition mapping
  – Defect density estimates

• Photoluminescence
  – Optical technique for probing bandgap
  – Provides composition mapping and material quality data
RFMD Epiwafer Production Overview
RFMD MBE Operations

• Nearly 100% of AlGaAs HBT and pHEMT starts are from MBE systems in Greensboro, NC

• Minimal number of device structures
  – Easily more MBE systems than SKU’s
  – Allows an MBE tool to produce a single SKU for weeks or months

• Heavy focus on production metrics
  – System uptime, throughput and yield
  – Manpower efficiency
  – Reproducibility across different types of MBE systems
  – Wafer uniformity and run-to-run reproducibility
RFMD MBE Operations

- MBE Operation’s production fleet consists of 14 – 7x6” MBE systems
  - Veeco GEN2000
  - Riber MBE 7000

- Three additional system are dedicated to process development
  - Riber MBE 6000
  - VG V100

- Development work is also carried out on production tools
  - Facilitates transition of new processes into production
RFMD MBE Operations – 24/7 Utilization

• Production technicians in a 12 hour day shift maintain 24 hours of production on MBE systems
  – Documentation, training and discipline become critical to effective shift passdowns

• Leverage automation on production MBE systems to reduce manpower demands

• Dual load locks allow continuous operation (complimentary operation)
RFMD MBE Operations – System Management

Original Source Load Quantities

Known Consumption Rate per Epiwafer Run

Number of Runs Since Last Reload

MBE System Estimated Uptime

- Ga1
- Ga2
- Ga3
- Ga4
- As1
- As2
- As3

Weeks
RFMD MBE Operations – Maintenance Cycle

- Maintenance activities are tracked to provide feedback for minimizing system turn-around times
RFMD MBE Operations – Epi Characterization

• Epiwafer characterization data is monitored using online process control charts

• Daily check of SPC data provides feedback to alert Production technicians and engineers of any need for process adjustments

• Appropriate process adjustments are calculated with standardized tools
  – Input characterization data from recent runs
  – Input MBE process parameters from same runs
  – Outputs include setpoint correction
RFMD MBE Operations – HBT “Quick Turn”

• Periodic sampling from every MBE tool growing HBT’s

• Essential for determining if device parameters are on target

• Additional information on doping levels of individual layers can eliminate the need for dedicated calibration runs
  – Base sheet resistance
  – Emitter sheet resistance
  – BVebo

• Process adjustments calculated with standardized tools
RFMD MBE Operations – Fab Data

• MBE process engineers monitor online trend charts
  – Contact resistance
  – Doping levels and breakdown voltages
  – Current gain (HBT)
  – Turn-on voltage (HBT or pHEMT)

• Sampling of recent production epiwafers keeps in-process test data current (Modified FIFO)

• MBE process engineers held accountable for MBE related wafer fab yield loss
  – Wafer fab corrective action reports automatically assigned
  – MBE engineer may scrap additional wafers from epiwafer inventory
  – Create a culture in which MBE personnel realize wafer fab scrap is more costly to business than epiwafer scrap
RFMD MBE Operations – Continuous Improvement

- Ongoing efforts to improve yield and reduce variation
  - MBE epiwafer yield
  - Wafer fab line yield
  - Final product test yield

- Pareto analysis of scrap causes during monthly and quarterly reviews. (MBE yield and fab yield)

- Common databases provides traceability from GaAs substrates through MBE and fab processing
  - Invaluable in determining correlations between MBE process parameters, epiwafer characterization and device performance
  - Identify sources of variation that can be reduced to achieve specific goals in product performance or yield
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