IntelliEPI: Outline

Company Information Update
  • Facility and Products
  • Capabilities and in-situ monitoring technology

Selected Product Highlights
  • pHEMT, iHEMT, and mHEMT
  • HBT Activities (InP-based HBT, HBT w/ GaAaSb base)
  • PIN, QWIP, and Sb-based SLS

Quality Management System

Summary
IntelliEPI: The Company

- A Texas semiconductor manufacturing company located in Richardson, TX, since January 1999.
- Founded by Dr. Yung-Chung Kao (TI), Dr. Paul Pinsukanjana (UCSB/JPL), Randy Thomason (TI), and Kevin Vargason (TI), combining experiences in electronics and optoelectronics. In 2001, Dr. J.M. Kuo (Lucent) and Dr. H.J. Zhu (Paul Drude Inst) joined.
- A venture capital funded company

IntelliEPI provides GaAs (up to 6in) and InP (up to 4in) MBE PHEMT and HBT epitaxial wafers to RF MMIC and wireless wafer fabs for communications applications. We also provide optoelectronics products (PIN, QWIPs, and lasers) and various III-V based industrial and energy-related products.
IntelliEPI: Technical Experience

Technical team has combined experience over 100 years in industrial III-V MBE operation (GaAs and InP)

Yung-Chung Kao, Ph.D.EE, UCLA, ‘87; Texas Instrument, ‘87-’98; IET, ‘99-date
• 27 years in III-V related business. 25 years in MBE. Head of TI’s MBE Lab. 89-96.
• 12 US patents and over 100 technical publications related to III-V materials, devices.

Paul Pinsukanjana, Ph.D.Phys., UCSB, ‘94; EPI (Veeco), ‘96-’97; JPL, ’97-’99; IET, ‘99-
• 15 years in III-V electronics and optoelectronics: MBE growth, processing, and characterization. Hold 3 patents on in-situ real-time sensor technology for MBE.

Jenn-Ming Kuo, Ph.D.EE, Rutgers U., ‘87; AT&T/Lucent Bell Labs, ‘86-’01; IET, ‘01-
• 27 Years in III-V epitaxial growth by MBE and gas source MBE. 22 years experience in R&D of III-V electronic and opto-electronic device, MBE growth, and device processing.
• 9 US patents and 128 technical publications related to MBE growth and III-V devices.

Randy Thomason, Texas Instrument, ’82-’96; TriQuint Semi., ’96-’98; IET, ’99-
• 25 years in MBE operation, modification, facility maintenance, and construction

Kevin Vargason, Texas Instrument, ’90-’98; IET, ’99-
• 17 years in semiconductor characterization, MBE production, and failure analysis

H.J. Zhu, Ph.D. Phys., Fudan U., China, ‘96; Paul Drude Institute ’98-’01; IET,’01-
• 16 years in III-V electronics and opto-based MBE growth, 10 years in production MBE
IntelliEPI: Facility at Richardson, Texas

Current facility since January 2002: 1250 E. Collins, Richardson, TX (Dallas suburb)

- 23,000 ft² (production: 13,000 ft²; Office: 10,000 ft²)
- Set up to host 8 production MBE systems
- Clean room for post growth testing and LAD processing
- 30 full time employees
MBE Facility at IntelliEPI's Facility in Richardson, Texas

- **8 MBE reactors:**
  - 1 Riber 7000 (7x6”, 14x4”)
  - 3 Riber 6000 (4x6”, 9x4”, 15x3”)
  - 3 Riber 49, 1 VG V100 (4x4”, 5x3”)

- **Dedicated operation and cleaning facilities designed to handle phosphorous for all MBE systems**
IntelliEPI: Multi-Wafer Production MBE Platen Design

Capacity for production reactors

Riber7000: 7x6”
14x4”
25x3”

Riber6000: 4x6”
9x4”
15x3”

Riber 49: 4x4”
3x5”
11x2”

Experienced with product transition:

- Development to production on multi-wafer MBE systems
- Reactor & substrate size scaling: mainly support from 2” to 6” size substrates (1” and 8” are also supported)
Post-growth Characterization Capability

• **Class 100 clean room:**
  (2000 ft²)

• **Characterization tools:**
  – X-ray diffraction
  – PL mapping
  – Surface particle scan
  – Hall measurement
  – Contactless resistivity mapping
  – Electro-chemical CV profiling
  – White light reflection spectrometer
  – Electrical CV profiling
  – Mercury probe CV
IntelliEPI: III-V Compound Semiconductor Product Matrix

<table>
<thead>
<tr>
<th>Applications</th>
<th>RF and microwave</th>
<th>High Speed Digital</th>
<th>Optoelectronics</th>
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<tbody>
<tr>
<td>RF components in handsets</td>
<td></td>
<td>OC768-40Gbps network</td>
<td>Fiber optic network light</td>
</tr>
<tr>
<td>Automotive radar</td>
<td></td>
<td>OC192-10Gbps network</td>
<td>sources and Photo-detectors</td>
</tr>
<tr>
<td>Defense related</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Red in Production mode)</td>
<td>GaAs pHEMT</td>
<td>InP SHBT/DHBT</td>
<td>GaAs PIN/APD</td>
</tr>
<tr>
<td></td>
<td>GaAs mHEMT</td>
<td>InP HEMT</td>
<td>InP PIN/APD</td>
</tr>
<tr>
<td></td>
<td>InP HEMT</td>
<td>GaAs mHEMT</td>
<td>QMIP</td>
</tr>
<tr>
<td></td>
<td>InP HBT</td>
<td>GaAsSb DHBT</td>
<td>Diode laser</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Modulator</td>
</tr>
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</table>
IntelliEPI: Thickness Uniformity Across Platen for 7x6’’ MBE

• Thickness variation across platen < 1% across 7X6” platen configuration

• Si doping GaAs layer uniformity by contactless resistivity mapping:
  – 6” wafer doping variation < 1%
  – Difference from center wafer to outside wafer < 0.5%
CBr4 Carbon Doping of P-type InGaAs

Sheet resistance measurement using Lehighton shows the resistivity across 4" wafer grown from a 4x4 MBE system. The epi layer is a 350 nm thick InGaAs doped at 4e19 cm-3.

Statistical Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Number of Test Points</td>
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<tr>
<td>Average Value</td>
<td>73.8482</td>
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<td>Maximum Value</td>
<td>74.1416</td>
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<tr>
<td>Minimum Value</td>
<td>73.521</td>
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<td>Sample Spread (%)</td>
<td>0.84</td>
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<tr>
<td>Std Dev Value</td>
<td>0.1379</td>
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<tr>
<td>Wafer Uniformity Value</td>
<td>0.19</td>
</tr>
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</table>

Intelligent Epitaxy Technology, Inc.
Production MBE Operation Improvement by In Situ Sensors

- Run-to-run reproducibility:
  - Maintaining critical specification ranges
  - Verification of growth process details (condition and layers)

- Limitations of ex-situ characterization:
  - Slow post-growth feedback
  - Additional wafer handling and cost
  - Limited information about growth condition profile vs. epi-depth

- New product development:
  - Faster development cycle time
  - Improved performance for more demanding specifications

- Bad run detection/correction/termination:
  - Loss of wafers: very expensive for larger systems and for InP
  - Wasted machine time, materials, & operating expenses
Overview of IntelliEPI in-situ Sensor Technologies

- **Substrate temperature**
  - Pyrometry
  - Absorption Band-Edge Spectroscopy (ABES): band-gap dependence on temp

- **Materials composition**
  - Optical-based Flux Monitor (OFM): atomic absorption of group III fluxes

- **Growth rate**
  - Optical Reflectometry
  - Pyrometric Interferometry

ABES light source: Light pipe, or Heater filament

Optical Pyrometer

Optical Reflectometry

OFM setup

Absorption Band-Edge Spectroscopy, Pyrometer, and Laser Reflection.
PHEMT In-situ Composition Monitoring with OFM

- **Direct composition monitoring for each critical layer**

- **In-situ composition monitoring for key layers:**
  - InGaAs Channel: Accurate x-ray measurement
  - AlGaAs Gate: X-ray represents average of SL and Gate
  - InGaP Etch Stop: Very thin layer limits x-ray accuracy

PHEMT Structure

<table>
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<tr>
<th>Layer</th>
<th>Note</th>
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<tr>
<td>n+ GaAs Cap</td>
<td>Cap</td>
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<tr>
<td>n InGaP Etch Stop</td>
<td>Etch Stop</td>
</tr>
<tr>
<td>n AlGaAs Gate</td>
<td>Gate</td>
</tr>
<tr>
<td>AlGaAs Spacer</td>
<td>Spacer</td>
</tr>
<tr>
<td>InGaAs Channel</td>
<td>Channel</td>
</tr>
<tr>
<td>AlGaAs Spacer</td>
<td>Spacer</td>
</tr>
<tr>
<td>AlGaAs</td>
<td></td>
</tr>
<tr>
<td>GaAs SL</td>
<td></td>
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<tr>
<td>AlGaAs</td>
<td></td>
</tr>
<tr>
<td>GaAs Buffer</td>
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</tr>
<tr>
<td>GaAs Substrate</td>
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</tr>
</tbody>
</table>

Si - delta

**2009/2010**

Intelligent Epitaxy Technology, Inc.
30-nm D-Mode & E-Mode $\text{In}_{0.7}\text{Ga}_{0.3}\text{As/InP}$ HEMT

D-mode InP HEMT on InP
- $G_m = 1.4 \, \text{S/mm}$
- $f_T = 547 \, \text{GHz}$
- $f_{max} = 400 \, \text{GHz}$

E-mode InP HEMT on InP
- $G_m = 2.2 \, \text{S/mm}$
- $f_T = 550 \, \text{GHz}$
- $f_{max} = 350 \, \text{GHz}$
MHEMT: Temperature and Group III flux control

- MHEMT: InP-performance on GaAs substrate.
- Critical growth parameters: substrate temperature, and growth rates.
- Room temp mobility 11,000 cm²/V·sec, ns~3.9e12 cm².
E-Mode In$_{0.7}$Ga$_{0.3}$As/InP HEMT and mHEMT on GaAs

Strain-relaxed InP mHEMT on GaAs
- $G_m = 1.7$ S/mm
- $f_T = 500$ GHz
- $f_{max} = 320$ GHz

InP HEMT on InP
- $G_m = 2.2$ S/mm
- $f_T = 550$ GHz
- $f_{max} = 350$ GHz
IntelliEPI: InP SHBT/DHBT Status

**Strong Customer Base Facilitates Fast Structure Optimization**
- US and Japan foundries and companies
- Both C and Be doped SHBTs and DHBTs
- HBT-PIN and HBT-Opto structure integration

**In-House Large Area Device (LAD) Fabrication Capability**
- Fast turn around (~8 hours)
- Correlation with customers device characteristics
- CV measurements for device fine tune
- Correlation with in-house in situ growth database

**Developed GaAsSb-base HBT under DARPA TFAST Program**
- GaAsSb-base up to $1\times10^{20}$ cm$^{-3}$ carbon doping
**IntelliEPI: InP-HBT Experience Highlights**

**Pohang University of Science and Technology (POSTECH): InP-HBT results**
- $F_{\text{max}} = 689$ GHz (Postech/IntelliEPI, IEDM, San Francisco, December 2004)

**University of Illinois, Urbana Champaign: InP-HBT results**

**IntelliEPI provides volume InP-based HBTs to US and Japan InP IC foundries**
- High level of integration VIP-1 SHBT: ~5000 transistors inside 3 mm square die
- 100% transistor yield for VIP-2 DHBT: over 450 GHz $F_t$ and $F_{\text{max}}$ (DARPA – TFAST)
InP/InGaAs SHBT with High Base doping DC Characteristics

<table>
<thead>
<tr>
<th>Layer</th>
<th>comment</th>
<th>Material</th>
<th>Thickness (Å)</th>
<th>Dopant</th>
<th>Level (cm³)</th>
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<tr>
<td>7</td>
<td>InGaAs:Si</td>
<td>In(x)Ga(1-x)As</td>
<td>500</td>
<td>Si</td>
<td>2.00E+19</td>
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<td>6</td>
<td>InP:Si</td>
<td>InP</td>
<td>500</td>
<td>Si</td>
<td>1.0E+19</td>
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<td>5</td>
<td>InP:Si</td>
<td>InP</td>
<td>500</td>
<td>Si</td>
<td>5.0E+17</td>
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<tr>
<td>4</td>
<td>InGaAs :C</td>
<td>In(x)Ga(1-x)As</td>
<td>400</td>
<td>C</td>
<td>8.0E+19</td>
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<tr>
<td>3</td>
<td>InGaAs :Si</td>
<td>In(x)Ga(1-x)As</td>
<td>2,000</td>
<td>Si</td>
<td>2.0E+16</td>
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<td>2</td>
<td>InP:Si</td>
<td>InP</td>
<td>100</td>
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<td>1</td>
<td>InGaAs :Si</td>
<td>In(x)Ga(1-x)As</td>
<td>4,000</td>
<td>Si</td>
<td>2.00E+19</td>
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Substrate InP

- **Current Gain**
  - 24 @ 10A/cm²
  - 25 @ 100A/cm²
  - 26 @ 1kA/cm²

- **Base Rbs (TLM)**
  - 406 Ohm/sq

- **Current cross-over**
  - < 1.0E-9 A

- **Von @ 5A/cm²**
  - 542 mV

Gain vs Current Density

Gummel Plots
100% Transistor Yield attained!

All sites over 300 GHz $F_t$ and $F_{\text{max}}$ (DHBT)

All sites functional and operational at high speed

RF measurements for 337595 w03
for RFM0 device on all 37 die across 4” wafer
GaAsSb composition uniformity is within ±0.1 atomic percent across 4x4” platen.
**InAlAs/GaAsSb/InP DHBT DC characteristics**

**InAlAs emitter GaAsSb DHBT (Improved E-B junction)**

**Current Gain**
- 34.3 @ 10A/cm²,
- 36.6 @ 100A/cm²,
- 38.1 @ 1kA/cm²

**Base Rbs (TLM)**
- 885.9 Ohm/sq

**Current cross-over**
- < 1.0E-9 A

**nc = 1.10; nb = 1.29**

<table>
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<tr>
<th>Layer</th>
<th>Comment</th>
<th>Material</th>
<th>x</th>
<th>Thick. (Å)</th>
<th>Dop. Level (Å/cm³)</th>
<th>Type</th>
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<td>8</td>
<td>Emitter cap</td>
<td>In(x)Ga(1-x)As</td>
<td>0.532</td>
<td>1,000</td>
<td>Si 3.0E+19</td>
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<td>7</td>
<td>Emitter cap</td>
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<td>N+</td>
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<tr>
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<td>300</td>
<td>Si 5.0E+17</td>
<td>N</td>
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<td>5</td>
<td>Emitter</td>
<td>In(x)Al(1-x)As</td>
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<td>4</td>
<td>Base</td>
<td>GaAs(1-x)Sb(x)</td>
<td>0.513</td>
<td>400</td>
<td>C 4.5E+19</td>
<td>P+</td>
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<td>0.532</td>
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<td>Substrate</td>
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</tr>
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</table>

**I-V Characteristics, 50x50 um²**

**Vce (V)** vs **Ic (A)**

**Vbe (V)** vs **Current (A)**

![Graphs showing I-V characteristics and Vbe-Vce curves](image-url)
IntelliEPI's optimized MBE PIN advantages:

- Nearly depleted at 0V bias
- Background doping level better than MOCVD
- Intrinsic InGaAs mobility from $10 - 12 \times 10^3$ cm$^2$/V·sec
Intelligent Epitaxy Technology, Inc.

High Speed InGaAs/InP PIN Photodetector from MBE

• Average 3 dB bandwidth of ~ 4.6 GHz @ –2V
• Dark current well below 1 nA @ –2V

Data Courtesy of VITESSE

75 µm Diameter Active Area

Intelligent Epitaxy Technology, Inc.
IntelliEPI: QWIP Production Experience

• **Stability of growth rate during long repeated structure as indicated by narrow x-ray peaks**
• **Excellent interface and materials quality as indicated by sharp x-ray peaks**
• **0.5% thickness uniformity across 6 inch diameter wafer based on x-ray**
• **Achieved 100% pixel yield with 320x256 format FPA**

8.6 µm thermal image taken with large format 640x512 QWIP FPA IntelliEPI. Die size ~16x13 mm².
IntelliEPI: Device Data for QWIP FPA

- Normalized Spectra
- Blackbody Responsivity
- Photoresponse (mV/degree) @ 25 C
- NETD (mK) for 25°C Scene Temperature

- 320x256 and 640x512 formats
- LWIR band, 8.6-mm peak wavelength
- Optical response uniformity ≈ 2%
- Average NEDT less than 25 mK at F/4
- Operability greater than 99.8%

Data Courtesy of QmagiQ

Intelligent Epitaxy Technology, Inc.
IntelliEPI: Dual-color QWIP

- 2-color per pixel in 320x256 format
- Dual-band for MWIR and LWIR
- Epi materials on 6” GaAs

Data Courtesy of QmagiQ
**IntelliEPI:** InAs/GaSb SLS Growth for LWMR Applications

- QmagIQ design InAs / binary GaSb SL for long wavelength (LW) IR detection
- SL FWHM < 30 arc sec, SL0 peak mismatch < 16 arc sec
- Thickness uniformity from center to inner ring within $\pm 1\%$

![X-ray data across 2” Platen](image)

- Wafer Tech
- IntelliEPI polished
- Galaxy
IntelliEPI: Quality Management System

Lehighton-Average Resistance by Wafer

CPK ~ 4.7

SPC chart of contactless sheet resistivity mapping during PHEMT production

- ISO9001:2000 certified since March 2007
- Utilize SPC for volume production tracking/control
IntelliEPI: Summary

IntelliEPI’s real-time sensors monitor growth and maintain reproducible conditions

• Non-invasive; early identification of problems during run: immediate feedback
• Yield improvement, fast product development and delivery

IntelliEPI developed advanced MBE growth technology and materials

• High volume GaAs product such as PHEMTs for handset switch applications
• High performance InP based HBTs and PINs for fiber optical applications

IntelliEPI provides 100% customer satisfaction guaranty