Electroluminescence - Comprehensive Characterization of HB-LED Epi Wafers

May 1st, 2014

Atomic Force Microscopy
3D Optical Microscopy
Tribology
Automated AFM
Stylus Profilometry
Mechanical Testing, Nanoindentation

Innovation with Integrity
Agenda

- Industry Problem - Current MOCVD Epi Wafer Metrology Methods are Limited
- Industry Solution – Reliable, Fast Electro-Luminescence
- LumiMap – Bruker’s New Electro-Luminescence Technology
- How it Works
- LumiMap’s Unique Features
- Customer Data
- Production Solution and Range of Use
- Validation and Summary
- Questions
About the Presenter

Hugh Palmer is the Senior Product Line Marketing Manager at Bruker Nano Surfaces in Tucson, Arizona. He has an undergraduate degree in Chemical Engineering from BYU and a Master’s degree from Thunderbird in International Business. Hugh has worked in product management for 15 years, 6 of which were in China as a regional product manager.

Hugh can be contacted at:
Hugh.Palmer@Bruker-nano.com
**Bruker:** the leading provider of high-performance scientific instruments and solutions for life science, diagnostic and applied markets.

**KEY FIGURES**
- Founded in 1960
- $1.79B revenue
- ~6,700 employees
- ~82% of revenues outside of the US
- ~Direct sales organizations in 33 countries
- ~1,000 R&D professionals with strong track record of innovation
Bruker Stylus and Optical Metrology
SOM - World Leading Surface Metrology

• History of QA/QC solutions for industry
  • Semiconductor
    100+ Installed base multi-chip module inspection at board level
  • Data Storage
    500+ Installed base slider metrology
  • Electronics and Industrial
    1000+ Installed base
  • Worldwide
    10,000+ Installed base

• Manufacturing Excellence
  • Lean, six sigma-based process
  • 100+ systems/quarter capacity
  • Rapid production ramp capability

New Facility - Tucson, Arizona, USA
Opened December 2011
Industry Problem
Current Epi Wafer Metrology Methods are Limited

MOCVD is a Critical Process for Device Performance and NEEDS Better Metrology that can Correlate to final device

The SSL Manufacturing Roadmap stated that there remains a strong need to develop in-line characterization of the epitaxial wafers for rapid feedback to the manufacturing process.

*Rapid, accurate and reliable Metrology at the Epi Wafer Stage can guide MOCVD reactor process tuning, which in turn will improve yields and reduce scrap*
Industry Problem
Current Epi Wafer Metrology Methods are Limited

Photoluminescence (PL) Mapping
- Laser Excitation vs Electrical Excitation
- Relative Spectral Data Only
- Provides No Electrical Feedback

Indium Dot Metrology  “n-Dot” is embedded in contact location
- Limited Accuracy
- Labor Intensive
- Operator Dependent
- Time consuming
- Destructive in test region
- Limited wafer coverage
- Does not correlate to device level
Industry Problem
Current Epi Wafer Metrology Methods are Limited

- If an MOCVD quality excursion is not caught at the Epi stage, it will likely not be realized until after significant process expenses
- A scrap event left undetected for 3-7 days could result in hundreds of wafers scrapped and hundreds of thousands of dollars

Yield is the single highest contributor to Epi Cost!

- Variations in LED color, brightness and electrical performance result in yield loss and end of line binning

Undetected process shifts result in COSTLY scrap events!

<table>
<thead>
<tr>
<th>Substrate Processing</th>
<th>MOCVD (Epitaxy)</th>
<th>Post MOCVD to Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 6% of total wafer cost</td>
<td>- 6% of total wafer cost</td>
<td>- 88% of total costs</td>
</tr>
</tbody>
</table>

Current Quality Checks
- PL Mapper
- Indium Dot
- Wait until Chip on Wafer

Epi Wafer
3-7 days processing
LED Die Processing
Chip on Wafer
Early warning of Chip/Device level performance

Electro-Luminescence LumiMap
Most Comprehensive Metrology!
Integrates all Epi-Wafer Electrical and Spectral Testing in ONE System
- Peak Wavelength
- Center Wavelength
- Centroid Wavelength
- Forward Voltage
- Reverse Current
- Efficiency
- Peak Intensity
- Integrated Intensity
- Spectral Width

First System with Vf Accuracy Good Enough to Correlate with Chip Level Test!
LumiMap
Electro-Luminescence Mapping

Device Level Quality Control at the Epi-Wafer Stage!

- **Immediate Epi Quality Feedback**
  - No Pre Inspection Wafer Preparation
  - No Post Inspection Wafer Clean
  - Non Destructive

- **Most Accurate Technology**
  - Operator Independent
  - Repeatable / Reproducible
  - With-in Wafer Uniformity Mapping

- **High Throughput / Cycle Time**
  - User defined multiple point inspection
  - Less than 1min/wafer (seconds per location)
LumiMap Improves Yields and Reduces Production Costs

- **Improves Yields** by providing rapid, accurate and reliable within-wafer uniformity mapping that can guide MOCVD reactor process tuning
- **Minimizes End of Line Binning** by providing accurate, correlatable data at the wafer level
- **Reduces MOCVD Scrap** by providing early warning of process shifts
- **Improves MOCVD Reactor Uptime** by providing immediate re-qualification data when tools are down
- **Reduces Fab Ramp Time** by providing fast, reliable data during reactor tuning or process development
- **Reduces Expenses** for fabs that outsource device level testing
LumiMap
How it Works

• A wafer friendly Conducting Probe (P contact) touches the top surface of the wafer
• A unique Wafer Edge Contact (N contact) completes the circuit allowing a controlled current to flow through the Epi active layer causing it to emit light
• Advanced Software accurately displays and maps all electrical and optical data
• Motorized Programmable Stage for automated, user-defined, multiple point inspection
• Advanced IV Curve Modeling for accurate and repeatable electrical measurements
LumiMap
Bruker’s Electrical Probe – Heart of our Technology!

- Patent Pending Electrical Probe
  - Real Electrical Excitation vs Laser Excitation
  - Repeatable and Reproducible over time
  - Non-Contaminating
  - Long Life Time (> 40,000 touches)

Probes Technology is Critical for Production/QA/QC

### Performance Spec on Sapphire

<table>
<thead>
<tr>
<th></th>
<th>Repeatability</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD%</td>
<td></td>
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</tr>
<tr>
<td>Peak Int</td>
<td>1.0%</td>
<td>1.5%</td>
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<tr>
<td>Centroid Wave</td>
<td>0.5nm</td>
<td>0.5nm</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>0.5nm</td>
<td>0.5nm</td>
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<tr>
<td>VF</td>
<td>1.0%</td>
<td>3.0%</td>
</tr>
<tr>
<td>IR(-20V)</td>
<td>1.0%</td>
<td>3.0%</td>
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</tbody>
</table>

Repeatability: 25 measurements in same location; Reproducibility: 9 locations; 1 wafer reloaded 25 times Measurements taken at 100mA max current
Advanced IV Curve Modeling

Patent Pending

- IV curve from wafer level (LumiMap) and Chip Level will be inherently different due to contact techniques.

- Advanced IV Curve Model will provide Vf correction that accounts for these inherent differences resulting in greater accuracy and better correlation.
LumiMap Vf Correlation to Chip Level Data
Sample Range <0.15V
LumiMap Current at 170mA

\[ \sigma_{W-C}^2 = \sigma_W^2 + \sigma_C^2 \]
\[ \sigma_{C-W} = 0.0442 \]

Standard Error is only 0.044V
LumiMap Vf Correlation to Chip Level Data

- 7 points per wafer, 16 wafers.
- Vf well correlated at low current with $R^2$ of 0.8162.
LumiMap IR Correlation to Chip Level VR

- 7 points per wafer, 16 wafers
  - Bruker Ir correlates well with chip-level Vr.
  - Different sensitivity for Ir at -10V vs -15V
LumiMap Intensity correlates well with Chip Level Flux data

$R^2 = 0.7474$
LumiMap Wavelength Correlation to Chip

Each point is an average over full wafer.
LumiMap Vf Sensitivity
Detecting Process shift of 0.1V!

Blind Test to see if LumiMap can distinguish between two wafers with Vf differing 0.1V

10x10 grid with space of 3mm, total 100 point map
**LumiMap Vf and IR Repeatability**

**20 Runs**

LumiMap Electrical Performance is Repeatable and Stable

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**VF Before and After Correction**

- **Red** line: VF(130mA)
- **Blue** line: VFC

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**IR (5V / 20V)**

- **Red** line: IR(5V)
- **Blue** line: IR(20V)
LumiMap Spectral Repeatability
20 Runs

Integrity / Wavelength / Spectral Width

Parameters (log scale)

Test Number (20 runs, 6 parameters)

Intensity / Wavelength / Spectral Width

I INT \( \sigma = 2455 \) (0.44%)

INT \( \sigma = 147 \) (0.50%)

WP \( \sigma = 0.042 \) nm

WC \( \sigma = 0.012 \) nm

WD \( \sigma = 0.013 \) nm

FWHM \( \sigma = 0.022 \) nm
Long Term Stability
(5 Days, 2 Test/Day, 8 Hours Apart)

**VF Long Term Stability**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
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<tbody>
<tr>
<td>1</td>
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</table>

**Intensity Long Term Stability**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
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<tbody>
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<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>W4</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF(0.1)</td>
<td>0.009</td>
<td>0.014</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>INT</td>
<td>304 (1.2%)</td>
<td>145 (0.7%)</td>
<td>283 (1.0%)</td>
<td>242 (1.2%)</td>
</tr>
</tbody>
</table>
LumiMap
Production Solution

Designed for the Production Environment

• Small Footprint
• Powerful analytical software provides device level SPC capability at the Epi Wafer Stage
• Intuitive Operator Friendly Interface
• Automated Stage for User Defined Multiple Point Inspection (up to 1000 locations)
• Robust Design is Easy to Maintain
• Low Cost of Ownership
• Automated Measurements for Repeatability over time

Replaces the Indium Dot Test
LumiMap Range of Use

**Wavelength Range (300nm – 850nm)**

**Range of Substrates** (special wafer holder for fragile substrates)
- Sapphire
- Silicon
- SiC
- GaN
- GaP
- GaAs

**Ultraviolet wafers**
- Wavelengths < 400nm
- Often backside emitting (GaN absorbs wavelengths <360nm)

**Red LED**
- Special wafer chuck for fragile substrates

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength [nm]</th>
<th>Voltage drop [ΔV]</th>
<th>Semiconductor material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared</td>
<td>λ &gt; 700</td>
<td>ΔV &lt; 1.63</td>
<td>Gallium arsenide (GaAs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aluminium gallium arsenide (AlGaAs)</td>
</tr>
<tr>
<td>Red</td>
<td>610 &lt; λ &lt; 760</td>
<td>1.63 &lt; ΔV &lt; 2.03</td>
<td>Aluminium gallium arsenide (AlGaAs)</td>
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<td>Gallium arsenide phosphide (GaAsP)</td>
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<td></td>
<td>Aluminium gallium indium phosphide (AlGaInP)</td>
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<td></td>
<td>Gallium(III) phosphide (GaP)</td>
</tr>
<tr>
<td>Orange</td>
<td>590 &lt; λ &lt; 610</td>
<td>2.03 &lt; ΔV &lt; 2.10</td>
<td>Gallium arsenide phosphide (GaAsP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aluminium gallium indium phosphide (AlGaInP)</td>
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<td></td>
<td></td>
<td>Gallium(III) phosphide (GaP)</td>
</tr>
<tr>
<td>Yellow</td>
<td>570 &lt; λ &lt; 690</td>
<td>2.10 &lt; ΔV &lt; 2.18</td>
<td>Gallium arsenide phosphide (GaAsP)</td>
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<tr>
<td></td>
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<td></td>
<td>Aluminium gallium indium phosphide (AlGaInP)</td>
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<tr>
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<td></td>
<td></td>
<td>Gallium(III) phosphide (GaP)</td>
</tr>
<tr>
<td>Green</td>
<td>500 &lt; λ &lt; 570</td>
<td>1.97 &lt; ΔV &lt; 4.0</td>
<td>Traditional green:</td>
</tr>
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<td></td>
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<td>Gallium(III) phosphide (GaP)</td>
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<td>Aluminium gallium indium phosphide (AlGaInP)</td>
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<td>Aluminium gallium phosphide (AlGaP)</td>
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<td>Pure green:</td>
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<td>Indium gallium nitride (InGaN)</td>
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<td></td>
<td></td>
<td></td>
<td>Gallium(III) nitride (GaN)</td>
</tr>
<tr>
<td>Blue</td>
<td>450 &lt; λ &lt; 500</td>
<td>2.48 &lt; ΔV &lt; 3.7</td>
<td>Zinc selenide (ZnSe)</td>
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<td></td>
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<td></td>
<td>Indium gallium nitride (InGaN)</td>
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<td></td>
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<td></td>
<td>Silicon carbide (SiC) as substrate</td>
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<td></td>
<td></td>
<td></td>
<td>Silicon (Si) as substrate—under development</td>
</tr>
<tr>
<td>Violet</td>
<td>400 &lt; λ &lt; 450</td>
<td>2.76 &lt; ΔV &lt; 4.0</td>
<td>Indium gallium nitride (InGaN)</td>
</tr>
<tr>
<td>Purple</td>
<td>multiple types</td>
<td>2.48 &lt; ΔV &lt; 3.7</td>
<td>Dual blue/red LEDs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>blue with red phosphor—white with purple plastic</td>
</tr>
<tr>
<td>Ultraviolet λ &lt; 400</td>
<td>3.1 &lt; ΔV &lt; 4.4</td>
<td></td>
<td>Diamond (236 nm)[90]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Boron nitride (215 nm)[57][58]</td>
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<td></td>
<td>Aluminium nitride (AlN) (210 nm)[99]</td>
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<td></td>
<td></td>
<td>Aluminium gallium nitride (AlGaN)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Aluminium gallium indium nitride (AlGaInN)—down to 210 nm[70]</td>
</tr>
</tbody>
</table>
LumiMap
New Product Validated in Production!

- Tool Development Together with Three Industry Leading Manufacturers Over 6 months
- Solid Feedback from world’s leading production facilities
  - Good correlation of all parameters to flash test and chip level test
  - Hardware is robust
  - Easy to Maintain
  - Fast turn around time to data

“LumiMap provides more accurate and reliable electrical and optical epi wafer measurements than the traditional indium dot method.” Executive VP, CTO of a Leading Production Facility

“A reliable electro-luminescence quality check immediately after MOCVD will help us further improve Epi wafer yield and reduce costs.”
Questions?
Thank-You!

For More Information Please Contact:
Bruker Nano (productinfo@bruker-nano.com)
Typically p-layer resistance is much higher than n-layer resistance.
Current Density Estimation

Contact area:
\[ A = \alpha \pi 0.85^2 \text{ mm}^2 \quad (\alpha < 1) \]
\[ = 0.023\alpha \text{ cm}^2 \]
Assume \( \alpha = 0.5 \)

Probe diameter 1.7mm

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Current Density (A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>75</td>
</tr>
<tr>
<td>170</td>
<td>14</td>
</tr>
<tr>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td>0.002</td>
<td>0.17</td>
</tr>
</tbody>
</table>
IV Curve Modeling and Vf Correction

Intra-wafer I-V Correction

- Corrected I-V
- Raw I-V

Current (mA)
VF (V)

Intra-wafer I-V Correction

Corrected I-V
- Raw I-V

Current (mA)
VF (V)

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