Silicon Photonics - Challenges & Solutions for Wafer-Level Production Tests

Dr Choon Beng Sia

Dr Johnny Yap,
Ashesh Sasidharan, Robin Chen,
Soon Leng Tan, Guo Chang Man

June 2-5, 2019
Overview

• Why Huge Demands for Silicon Photonics?
• Why Wafer-Level Photonics Tests?
• What are the Photonics Test Challenges & Possible Solutions?
  1. How to Optimize Test Setup for Accurate & Repeatable Measurements?
     • How to couple light into a photonics chip (wafer-level)?
     • Optimizing Fiber Height and Incident Angle.
  2. How to Correlate Wafer-Level Test to Final Product test?
  3. How to Achieve Fully Automatic Wafer-Level Production Solution?
• Summary
Communication Network for 4th Industrial Revolution

- 5G (10Gbps)
- RF/mmW
- 100B Devices
- IoT, VR, AR, Telehealth etc
- Autonomous Vehicles
- Data Center
  - 100/400/800Gbps
  - Optical Interconnects

Source: Keysight
The Need for High Performance Network & Data Centers

Big Data Analytics

Artificial Intelligence

Genomics Revolution

Financial Acceleration

Cyber Security

Video Transcoding

Dr Choon Beng Sia

Facebook Invests US$1B HyperScale Data Center in Singapore

- **Facebook’s 1st Data Center in Asia (Hub).**
  - IT Talent & Fiber connectivity
  - 170,000 m²
  - 150MW
- **5000 servers**
  - Each server supports 100 petabytes or 100,000 TB*

*2015 Facebook Video, 1PB=1000TB
• Wired communication network.
  – High Speed, High Data Rate, Low Latency requirements.
Requirements for Data Center – Energy Efficiency

- Biggest challenge – Not Speed but Reducing power consumption!
- Power Usage
  - 40% - Server & Switch
  - 40% - Cooling
- Today, Data Centers consume ≈7% of Earth’s power
- *By 2025, 20%?*
Requirements for Data Center – Energy Efficiency

- Urgent need for Energy-Efficient Data Centers
- SiPh technology is rising star in high speed data transfer.
Why Silicon Photonics?

- **Improvements in Thin Film Growth**
  - High Quality Ge on Si
  - Excellent Lattice Matching
  - Hi-Speed Ge-on-Si Photodiodes

- **Exploiting Silicon Technologies**
  - Low-Cost High-Volume Production
  - Low-Power Logic devices
  - High-Speed RFCMOS devices
  - Heterogenous Integration/Packaging

Dr Choon Beng Sia

SWTest | June 2-5, 2019
SiPh Optical Transceivers for Data Centers

Components on SiPh Transceivers

1. CMOS Logic Chip
   - Data Encoding (also decoding)

2. Optical Transmitter
   - Optical Modulators - Varying voltage modulate Data onto Light
   - Lasers not implemented on Silicon

3. Optical Receiver
   - Ge Photo detectors
   - Converts Light to Voltage

4. CMOS Logic Chip
   - Data Decoding (also encoding)

For a 10Gb/s Link

<table>
<thead>
<tr>
<th>Copper Interconnect</th>
<th>Optical Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Required</td>
<td>10 W</td>
</tr>
<tr>
<td>Range</td>
<td>meters</td>
</tr>
</tbody>
</table>

Evolution of Optical Transceivers

<table>
<thead>
<tr>
<th>Type</th>
<th>Ports/Chassis</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFP</td>
<td>4</td>
<td>24W</td>
</tr>
<tr>
<td>CFP2</td>
<td>8-10</td>
<td>8W</td>
</tr>
<tr>
<td>CFP4</td>
<td>16-18</td>
<td>5W</td>
</tr>
<tr>
<td>QSFP28</td>
<td>18-20</td>
<td>3.5W</td>
</tr>
</tbody>
</table>

Why Wafer-level Tests?

- Si Electronics -Die attach onto SiPh-Die (TSV)
- Continuous Wave Laser Diode on SiPh-Die
- Si Photonics IC (0.18μm?)
- Si Photonics IC (7nm)
- Si Electronics IC (7nm)
- Si Photonic IC
- Laser Diode
- Fiber Array
- Electronics IC
- Photonics IC
- Laser Diode
- SiP-based Optical Transceiver Chipset for QSFP28 module

Dr Choon Beng Sia

Integrated Optical Transceiver Market

- **SiPh Transceivers** - US$2.3B, CAGR >35% (2022).
- **Demonstrate using SiPh in Switches for Data Centers.**

**SWTest | June 2-5, 2019**
Integrated Wafer-Level Photonics Test Solution

Optical Test Instruments & Software

6-Axis/Piezoelectric Positioner, Single Fiber/Fiber Array, Displacement Sensors

RF probes, ISS, Cal. Software & DC probes

Software for Optical Positioners & Probe System

Fully Automatic Probe System with Wafer Loader

Dr. Choon Beng Sia

SWTest | June 2-5, 2019
Overview

• Why Huge Demands for Silicon Photonics?
• Why Wafer-Level Photonics Tests?
• What are the Photonics Test Challenges & Possible Solutions?
  1. How to Optimize Test Setup for Accurate & Repeatable Measurements?
     • How to couple light into a photonics chip (wafer-level)?
     • Optimizing Fiber Height and Incident Angle.
  2. How to correlate wafer level test to final product test?
  3. How to Achieve Fully Automatic Wafer-Level Production Solution?

• Summary
1.1. How to Couple Light into a Photonics Chip (Wafer-level)?

- **Fiber vs SOI Waveguide** – 2 order mag difference in Size
- **Direct Coupling** ≈ >96% Insertion Loss*

\*CMDITR (Center on Materials and Devices for Information Technology Research) Science and Technology Center
1.1. How to Couple Light into a Photonics Chip (Wafer-level)?

- **Edge Coupling**
  - Final Product (Die Level)
  - Sub-dB Loss Per Facet
  - 200nm – 300nm Bandwidth
  - Low Polarization Sensitivity
  - Harder to Fabricate/Test
  - Fixed Interface (Edge of Chip)
  - Low Fiber-Chip Alignment Tolerance

- **Grating Coupling**
  - Process Development & KGD (Wfr Level)
  - -2dB → -4dB Loss per Grating Coupler
  - Typically 60nm Bandwidth
  - Polarization Dependent
  - Easier to Fabricate/Test
  - Flexibility of interface positions
  - High Fiber-Chip Alignment Tolerance

---

Dr Johnny Yap

1.2. Optimizing Setup – Optical Coupling for Photonics Tests

- Grating Couplers (Wafer-Level Tests)
  - Fast & Repeatable Fiber to Grating Coupler Alignment is available today.
  - Fiber Height (Constant Height to Prevent Damage)
  - Incident Angle (Critical to determine Optimal Incident Angle before Production Tests)
1.2.1. Optimizing Setup – Fiber Height (Wafer-Level)

- 1. Set Fiber Height, 2. Peak Search, 3. Make Measurements → Repeat diff. Height
- No Significant Effect on Coupling Efficiency, Peak Wavelength & Bandwidth.
- Good Agreement with Simulation Data.
1.2.2. Optimizing Setup – Incident Angle (Wafer-Level)

  • Use 6-axis positioner to vary incident angle ±1°; Fiber height set with Z sensor (Pivot Cal needed).
– Critical to determine Optimal Incident Angle before Production Tests (1.5dB improvement).

### Fiber height vs. Incident Angle

- **Single Fiber**
  - Fiber height
  - Incident Angle

- **Fiber Holder with Fix Incident Angle**
  - Determine New Fiber height
  - Orient single fiber

- **Rotate Incident Angle + 1°**
  - A tilted Z displacement sensor after rotation

---

**If 1550nm is desired, with 8° Fiber Holder**

- **9° = Ideal Angle**, Lowest Loss at 1550nm

---

**Optical Power (dBm) By Wavelength (nm)**

- **Incident Angle**
  - 7deg
  - 7.5deg
  - 8deg
  - 8.5deg
  - 9deg

---

Dr Johnny Yap
2. Wafer-Level vs Final Product Tests (Passive Device)

Offset between Wafer-Level & Final Product

- Critical to correlate Wafer-Level & Final product Tests
- Using Optical Waveguides as Test Structures
  - Different Insertion Losses observed

Obtaining Coupling Losses

- Edge Coupling & Grating Coupling losses are obtained by Cut Back method.
  - Comparing output intensity of waveguides with different length
2. Wafer-Level vs Final Product Tests (Passive Device)

Offset between Wafer-Level & Final Product

- Critical to correlate Wafer-Level & Final product Tests
- Using Optical Waveguides as Test Structures
  - Different Insertion Losses observed

After Coupling Losses Correction

- Remove Coupling Loss
- Comparable Propagation Loss per unit Length.
- Establish Good Correlations between Wfr-level and Final product Tests!
2. Wafer-Level vs Final Product Tests (Active Device)

- Testing Optical Modulator (E-O)
- Measure 3 dB Bandwidth for all Dies through Grating Couplers.
- Small Difference in BW for Same Die
- Good Correlations between Wfr-level & Final Product Tests.
3. Achieving Automatic Production Photonics Tests

- **Challenging for one Test Setup to handle...**
  - Passive vs Active Device
  - Single Photonics Device & Complex Photonics Integrated Circuit Tests
  - Endless Permutations of Test Layouts
  - Establish Design Rules, Standardize Layout (Design-for-Testability)
  - Implement Automatic Testing Architecture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Probes Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiode Dark Current</td>
<td>nA</td>
<td>DC probes</td>
</tr>
<tr>
<td>N/P-doped Modulator Resistance</td>
<td>ohm</td>
<td></td>
</tr>
<tr>
<td>Heater Resistance</td>
<td>ohm</td>
<td></td>
</tr>
<tr>
<td>Waveguide Propagation Loss</td>
<td>dB/cm</td>
<td>Optical Fiber Probes</td>
</tr>
<tr>
<td>Y-splitter splitting ratio</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Tap Coupler Coupling Strength</td>
<td>%</td>
<td>Optical Fiber Probes</td>
</tr>
<tr>
<td>Modulator Extinction Ratio</td>
<td>dB</td>
<td>Optical Fiber Probe(s) +</td>
</tr>
<tr>
<td>Photodiode Responsivity</td>
<td>A/W</td>
<td>DC Probes</td>
</tr>
<tr>
<td>Modulator Bandwidth</td>
<td>GHz</td>
<td>Optical Fiber Probe(s) +</td>
</tr>
<tr>
<td>Photodiode Bandwidth</td>
<td>GHz</td>
<td>RF Probes</td>
</tr>
</tbody>
</table>
3. Achieving Automatic Production Photonics Tests

- **Layout Design Rules & I/O Standardization**
  - Establish Test Pads vs Grating Couplers Layout Design Rules.
  - Fix DC @North, RF @South, Optical I/Os @East&West side of the DUT.

---

Dr Johnny Yap

SWTest | June 2-5, 2019
3. Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  - Peak Search; Optimizing Polarization → Setup optical path
3. Achieving Automatic Production Photonics Tests

• Implement Automatic Testing Architecture - Modulator as Example
  – Bias Tuning to Measure Extinction Ratio (ratio of optical power levels of a digital signal, “1” and “0”)
3. Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  - Connect to LCA for RF Frequency Sweep to Measure Modulator Bandwidth
3. Achieving Automatic Production Photonics Tests

- Implement Automatic Testing Architecture - Modulator as Example
  
  Instrument Automation implemented with an Optical Switch. (automation vs power budget)
3. Achieving Automatic Production Photonics Tests
3. Achieving Automatic Production Photonics Tests

Dr Johnny Yap
3. Achieving Automatic Production Photonics Tests

- 2 Optical & 2 Motorized DC/RF positioners
- Handle diff. layout with remote commands
- Fully Automatic 300mm Probe System
- Automatic Wafer Loading/Unloading

Dr Johnny Yap

STest | June 2-5, 2019
Summary

• Why Huge Demands for Silicon Photonics?
  – Need for Energy-Efficient Data Centers is driving huge demands for SiPh.

• Why Wafer-Level Photonics Tests?
  – Determine Known-Good-Dies & Shorten Product Time to Market.

• What are the Test Challenges & Possible Solutions?
  – Must Optimize the Incident Angle for Production Tests.
  – Achieve Good Correlations between Wafer-level & Final Product Tests.
Acknowledgement

• GLOBALFOUNDRIES Singapore
  – Jun Hao Tan
  – Szu Huat Goh
  – Jacobus LEO
Thank You! Questions?

Dr Choon Beng Sia  
Choonbeng.sia@formfactor.com

Dr Johnny Yap  
tiongleh.yap@globalfoundries.com

June 2-5, 2019
Factors affecting Performance of Grating Coupler

- Top Silicon Thickness (TL), BOX thickness, Etch Depth (ED), Grating Period (GP) and Fill Factor (FF) are known to have impacts on the Coupling Efficiency, Peak Wavelength and Bandwidth.
Mach-Zehnder Modulator

Phase coherence

1

2

3

N-Doped Silicon

P-Doped Silicon

Reverse U

U_1 > U_2 > U_3

n_1 < n_2 < n_3

The phase depends on the applied voltage U.

GND

Inverse Taper Edge Coupler

SWTest | June 2-5, 2019
Requirements for Data Center – Energy Efficiency

• *Information Technology to consume 21% of Earth’s power by 2030.
  – Data Centers and Wired Access are largest consumers.

• †3% Total Electricity (in 2016), will double every 4 years.
  – 24% consumption by 2028?

• #Governments are now Regulating Data Centers!

**ELECTRICITY CONSUMPTION BY END USE SECTOR**

Widely cited forecasts suggest that the total electricity demand of information and communications technology (ICT) will accelerate in the 2020s, and that data centres will take a larger slice.

- Networks (wireless and wired)
- Production of ICT
- Consumer devices (televisions, computers, mobile phones)
- Data centres

**ENERGY FORECAST**

0-20.9% of projected electricity demand