



HETEROGENEOUS INTEGRATION ROADMAP 2019 Edition

Chapter 9: Integrated Photonics

<http://eps.ieee.org/hir>

The HIR is devised and intended for technology assessment only and is without regard to any commercial considerations pertaining to individual products or equipment.

We acknowledge with gratitude the use of material and figures in this Roadmap that are excerpted from original sources.
Figures & tables should be re-used only with the permission of the original source.

Table of Contents

To download additional chapters, please visit

<http://eps.ieee.org/hir>

CHAPTER 1: HETEROGENEOUS INTEGRATION ROADMAP: OVERVIEW	1
CHAPTER 2: HIGH PERFORMANCE COMPUTING AND DATA CENTERS.....	1
CHAPTER 3: THE INTERNET OF THINGS (IOT).....	1
CHAPTER 4: MEDICAL, HEALTH & WEARABLES.....	1
CHAPTER 5: AUTOMOTIVE	1
CHAPTER 6: AEROSPACE AND DEFENSE	1
CHAPTER 7: MOBILE.....	1
CHAPTER 8: SINGLE CHIP AND MULTI CHIP INTEGRATION.....	1
CHAPTER 9: INTEGRATED PHOTONICS	1
CHAPTER 10: INTEGRATED POWER ELECTRONICS	1
CHAPTER 11: MEMS AND SENSOR INTEGRATION.....	1
CHAPTER 12: 5G COMMUNICATIONS.....	1
CHAPTER 13: CO DESIGN FOR HETEROGENEOUS INTEGRATION	1
CHAPTER 14: MODELING AND SIMULATION	1
CHAPTER 15: MATERIALS AND EMERGING RESEARCH MATERIALS	1
CHAPTER 16: EMERGING RESEARCH DEVICES	1
CHAPTER 17: TEST TECHNOLOGY	1
CHAPTER 18: SUPPLY CHAIN.....	1
CHAPTER 19: SECURITY	1
CHAPTER 20: THERMAL	1
CHAPTER 21: SIP AND MODULE SYSTEM INTEGRATION	1
CHAPTER 22: INTERCONNECTS FOR 2D AND 3D ARCHITECTURES	1
CHAPTER 23: WAFER-LEVEL PACKAGING (WLP)	1

Chapter 9: Integrated Photonics

This chapter is in preparation, and will be integrated into the Roadmap at Version 1.1, planned for the end of 2019. In its place is the following summary and a series of slides giving the current status of integrated photonics and some information that is relevant to the progress needed over the next 10 to 15 years.

Executive Summary

The global network requirements are changing with the rise of the internet of things (IoT) and the migration to the cloud of data, logic and applications. These changing requirements must be accommodated while maintaining the pace of progress in size, cost and power per function that we have enjoyed for more than 50 years. This progress was based primarily on the benefits of Moore's Law scaling of CMOS electronics. The introduction of photonics into the transmission, processing and even the generation of data through optical-based sensors is a key enabling factor for continued progress in these areas as we reach the limits of the physics, and the benefits of Moore's Law scaling slow.

There will be many specific challenges in integrating the benefits of photonics into the fabric of the global network. The solutions, however, cannot come from just the packaging of photonic components. The co-packaging of electronics, photonics and plasmonics will be required to address these substantial new challenges in order to meet the expanding requirement for higher performance, higher reliability, increased security, lower latency and continued decrease in cost per function. The packaging of photonic integrated circuits (PICs) will face the same challenges faced in packaging electronic ICs, with the added complexity of integrating both active and passive photonic elements as well as the necessary electronics. Wherever possible industry must adopt and adapt the packaging technologies developed for electronics to decrease cost and time-to-market for packaging of individual PIC circuits and incorporating PIC circuits and other photonic components into the complex 3D SiP through heterogeneous integration.

Heterogeneous Integration Roadmap

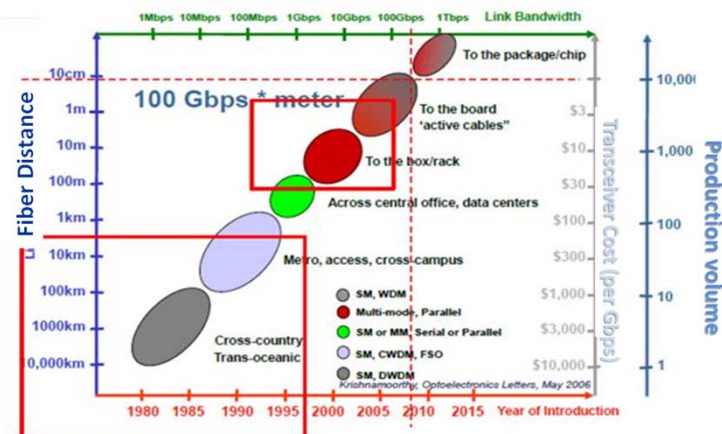
CHAPTER 9: INTEGRATED PHOTONICS

TWG Chair: Bill Bottoms PhD
TWG Co-Chair: Professor Amr Helmy



1

As Photons Move Closer to Transistors, Production Volume expands rapidly, Driving down cost



Source : Brocade



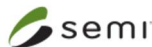
2

PACKAGING PHOTONIC DEVICES

There are a large number of devices involving photons which share the common requirement of providing a photon path either into or out of a system, or both. They include:

- Light emitting diodes (LEDs)
- Laser diodes
- Plasmonic photon emitters
- Photonic Integrated circuits (PICs)
- MEMS optical switching devices
- Camera modules
- Optical modulators
- Active optical cables
- E to O and O to E converters
- Optical sensors (photo diodes and other types)
- WDM multiplexers and de-multiplexers

Many have unique thermal, electrical, and mechanical characteristics that will require specialized materials and system integration (packaging) processes and equipment

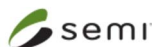


3

A Selection of Emerging Integrated Photonic Solutions

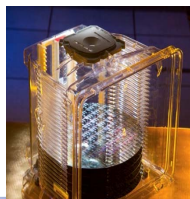
Addressing various

Heterogenous Integration Challenges

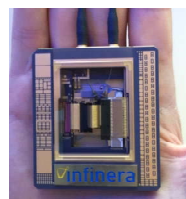


4

Si Photonics with 100Gbps Is Here Market demands for Tbps Is Not Far Behind



*Intel integrated
4x25Gbps technology,
with hybrid silicon
lasers*

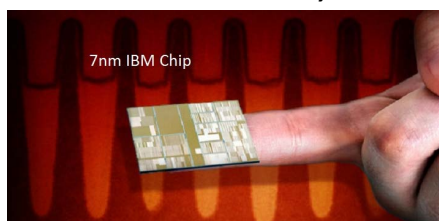
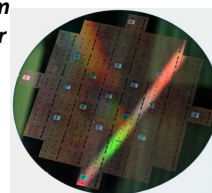


*500 Gb/sec Infinera
InP transceiver*



300mm vs 450mm wafers

*Dies attached to a 300mm
photonic interposer wafer
at SUNY Poly*



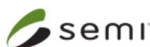
7nm IBM Chip

5

Si Photonics with 100Gbps Is Here Tbps Is Not Far Behind

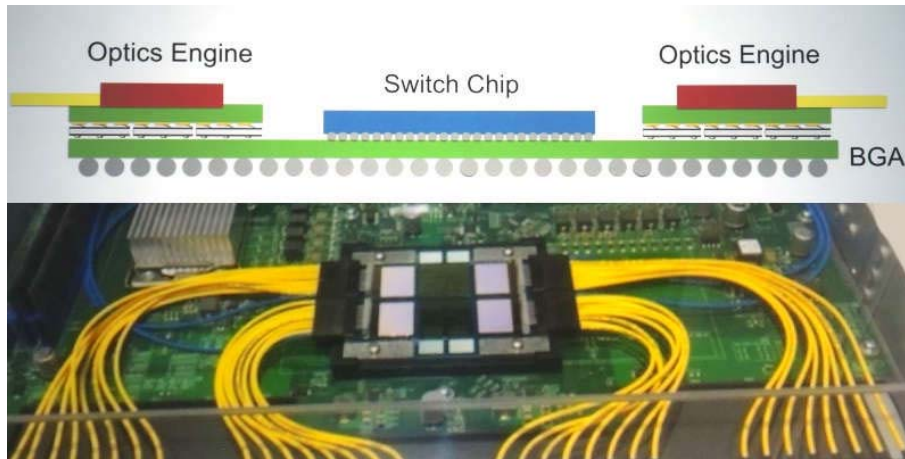


Photonics improves latency, provides the physical density of bandwidth needed and dramatically reduces power requirements

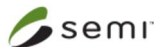


6

Integrated Photonic Switch



Luxtera 2.5D stack mounted on a switch board



7

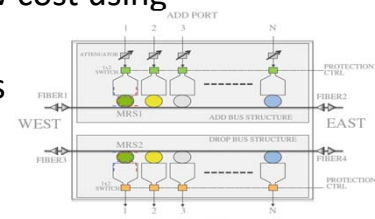
Photonics Is Key Component of 5G

(see Chapter 12)



Integrated photonic devices with lower cost, smaller size, and a lower power will replace optical modules designed for long haul. It offers many advantages:

- Large-scale integrated switching devices due to easy integration with control electronics
- Miniaturization, mass producibility, high yield, and low cost using CMOS production infrastructure
- A new integrated switching device, Mini-ROADM, uses silicon photonics to perform the MUX/DEMUX of all WDM channels and ADD/DROP local channels.

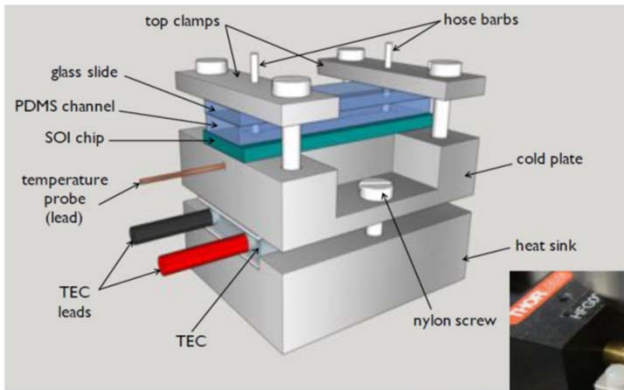


Mini-ROADM device



8

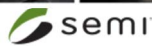
Integration of microfluidics and temperature control



PHOTONIC SENSORS

R&D for optical sensors is progressing rapidly with 4 categories of sensors listed below that have different packaging requirements.

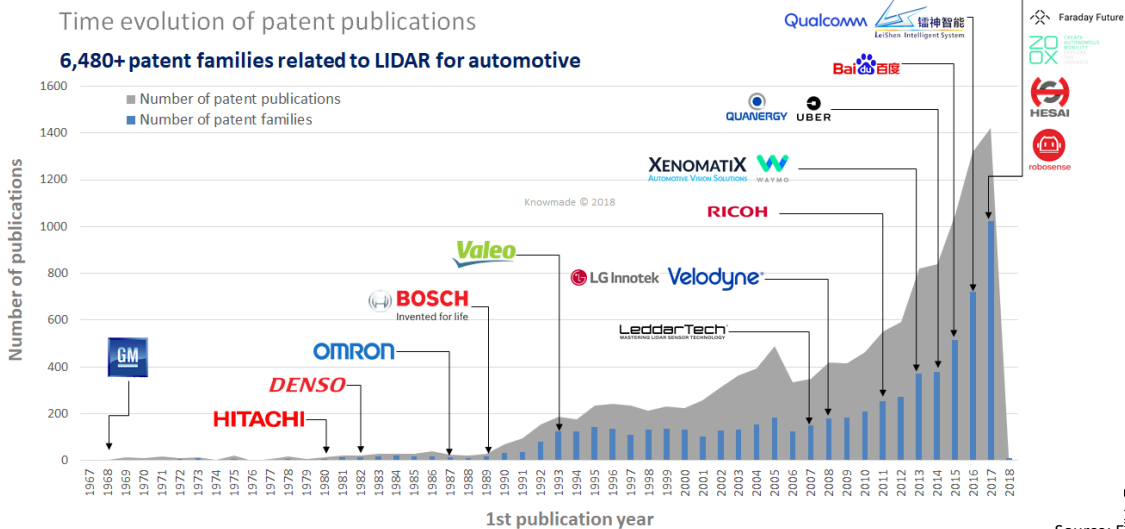
1. Spectroscopy based
2. Capture based (functionalized capture surfaces or volumes)
3. Gas based detection (atmospheric and other gases)
4. Liquid based



9

Lidar Is Driven By Automotive Market

With high volume will come cost drops by more than an order of magnitude



10

Light Detection and Ranging Demand is Growing; Volume is limited by cost



Lidar sensor for extended range: 64 beams, >200m range
Priced at only **\$3,500** – least expensive high-performance sensor on the market.



11

Integration Platforms For Photonics

Use Electronics Technology Whenever Possible

1. Chip-Level Integration

The integration of electrical and photonic circuits in one single product, with sequential chip connection processes. This process is slow and expensive.

2. Wafer Level Integration

Fabrication processes & assembly for photonic circuits at wafer level has already started and will decrease costs as it matures.

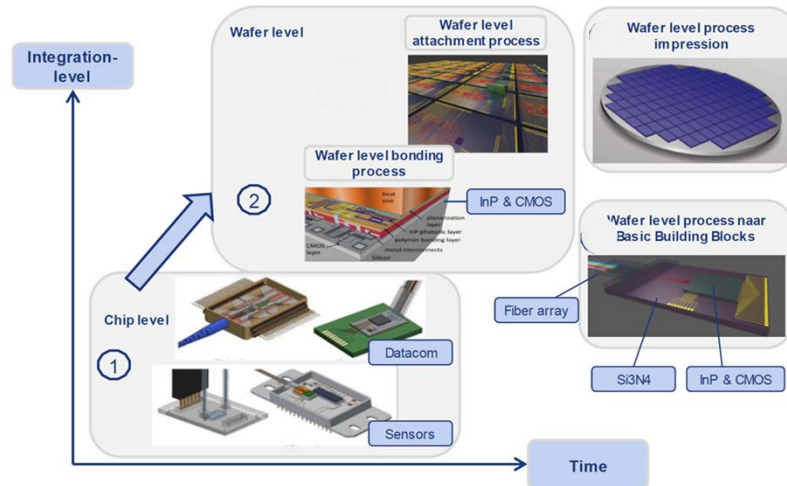
3. System-in-Package integration

Components and sub-systems integrated into a system at package level offers highest functional density & performance at lowest latency, cost and power but it has more difficult challenges to be overcome



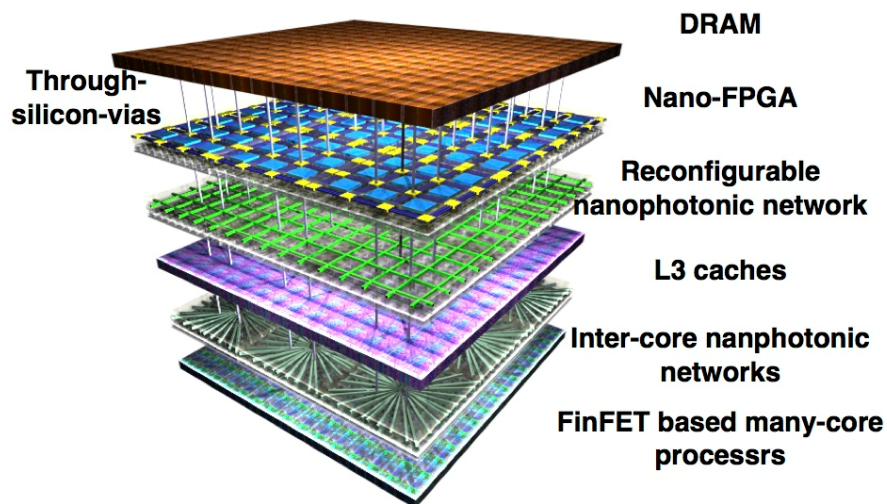
12

Chip & Wafer Level Integration



13

SiP Integration Of Photonics Is Coming



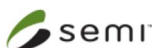
14

Potential Optical Test Issues

Photonic System Testing Is Complex (see Chapter 17)

Active Alignment
Responsiveness
Detector bandwidth
Sensitivity
Receiver Spectrum width
Reliability
EYE(amplitude, jitter, etc)
Laser lane/channel width
optical coupling defects
Sensitivity (4x)
Response time (delay/latency)
Frequency response
Polarization
Coupling efficiency
Crosstalk
Dark current

Optical Amplitude Modulation
Polarizations
Wavelength
Optical power
Wavelength spacing
Optical Modulation Rate
BER - eye mask (4x)
EYE(amplitude, jitter, etc)
Laser lane/channel width
Lasing threshold variation
Frequency spectrum variation
Optical power variations
Coherence time
Optical path defects (optical coupling defects: surface defects: core defects misalignment)
Power output (4x)
System Loss - coupling
Extinction Ratio
Reliability



15

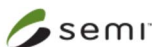
Challenges and Potential Solutions

Difficult Challenges

- Physical density of bandwidth
- Thermal management
- Test access for SiP, 3D & Heterogeneous integration
- Photonic Switching to the package
- Cost

Potential Solutions

- Single-mode WDM fibers
- New materials; multiple temp zones
- BIST, continuous test while running, intelligent redundancy & self-repair
- WDM mux-demux on chip
- High-volume production and a strong and competitive supply chain



16

Challenges and Potential Solutions



**These challenges cannot be met
without Heterogeneous Integration**



17

Critical Limiting Factors for Future Integrated Photonics Systems



- Co-Design and Co-simulation tools (Ch 13)
- Prototypes at affordable cost and adequate yield
- Temperature-stable Photonic components (laser, modulator, etc.)
- Reduced size of optical components (closer to electronics)
- Move photonics closer to the transistors at low cost
- Design verification in the computer
- Multi-project wafers now available; more coming
- Plasmonics, quantum dot lasers, plasmonic lasers
- New devices for laser, modulator, O-to-E and E-to-O, etc.
- New solutions on system circuit board, on package and maybe on chip; low-loss connectors and waveguides needed



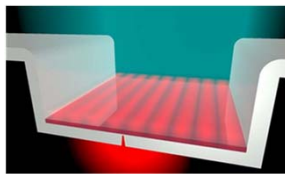
18

Many New Components / Technologies For Integrated Photonics with New Capabilities are in an Advanced State of Development

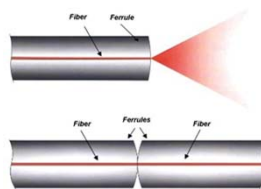


19

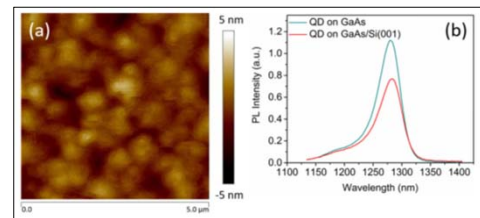
Many New Devices are Coming Addressing Difficult Challenges for Integrated Photonics



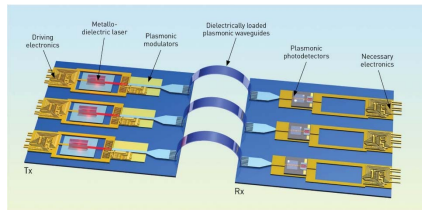
Plasmonic Laser W. Zhu et al.
NIST Science Advances (2017)



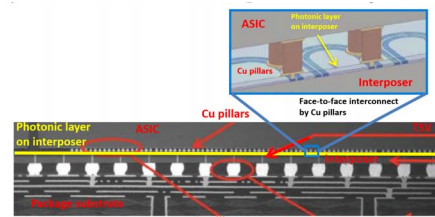
Low-loss Photonic Connectors



Quantum Dot Laser S. Chen et al.
Vol. 25, No. 5 | 6 Mar 2017 | OPTICS EXPRESS 4632



Plasmonic Communication J. Leuthold et al.
Optics & Photonics News(2013), pp. 28-35.



Electronic/Photonic Interposer

20

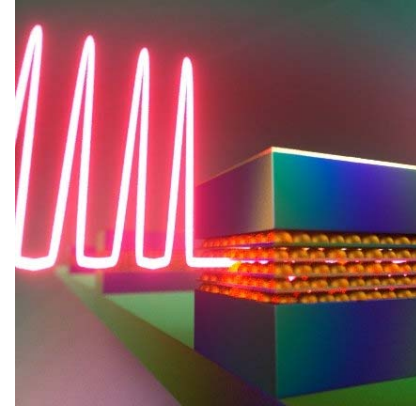
Quantum Dot Lasers



Advantages

- Better temperature stability
- Can be deposited on Si with MBE
- More power efficient than conventional junction lasers
- Compatible with CMOS processing
- Wide operating temperature range

A quantum dot is a mode-locked laser passively generating ultrashort pulses less than one picosecond in duration



Credit: Peter Allen

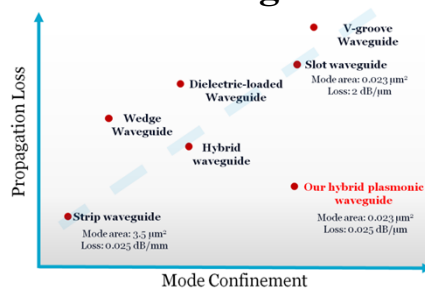
S. A. Kazakis et al, Optical properties of InGaN thin films in the entire composition range, *Journal of Applied Physics* (2018)



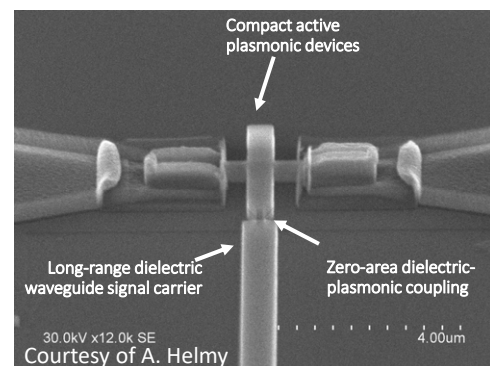
21

Plasmonics

Efficient Integration - Good Mode Confinement



- Nanoscale mode localization and enhanced light-matter interaction via hybrid plasmonics
- Efficient integration between silicon photonics and plasmonics
- Highly tunable absorption within the same technology process
- Extremely sensitive detection within a $5\mu\text{m}$ -long photodetector with 0.2nA dark currents and 1.2nW static power consumption



- ✓ Low temperature processing of amorphous materials for non-intrusive back-end integration above existing electronics

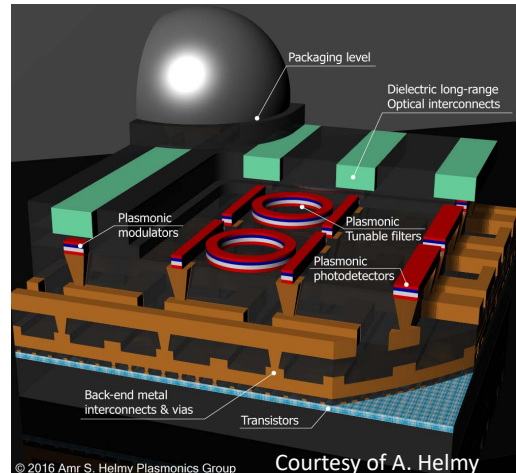


22

Plasmonics Will Be Revolutionary For Electronic/Photonic Integration In IT



- High-bandwidth information transport between modules
- Reduced scale mismatch between optics and back-end electronics
- Vertical integration (no increase in die sizes)
- Non-intrusive modifications to existing manufacturing techniques
- Integration challenges such as material compatibility and thermal budget need to be addressed



© 2016 Amr S. Helmy Plasmonics Group

Courtesy of A. Helmy



23

Key Attributes & Challenges for SiP Reliability



Selected Table Attributes

- Thermal load for each component
- Temperature stability requirements
- Stress sensitivity of each component
- Sensitivity to vibration
- Test access for package contents
- CTE for each component
- Dimension specs for components
- Power delivery (voltage/current/noise/control)

System Reliability Challenges

- Optical path contamination
- Cost of single mode fiber alignment
- Large size of optical components
- Hot spots from on-chip lasers, etc.
- CTE mismatch (for optical bench components)
- Out gassing of encapsulant, die attach, underfill, etc.
- Temperature Sensitivity of components



24

Conclusion

Integrated photonics will be a key enabler, delivering the low power, low cost, low latency and increased bandwidth density and performance required to meet the demands of the data and data traffic explosion that will continue rapid growth.

The physical bandwidth density needed to support big data, data analytics, artificial intelligence and neuromorphic and quantum computing will be much greater, and photonics will continue to get closer to the logic supporting these emerging technologies for decades to come.

This view of the future cannot be realized without increasing performance and density in Integrated Photonics

