More then Moore with Electronic-Photonic Integration

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Changing role of electronics
Enhanced CMOS enables new applications

1997
One of the first CMOS radios
Rudell & Gray

1990
Inductors in IC process
Nguyen & Meyer

2004
World’s first 60GHz CMOS Amplifier
Niknejad & Brodersen

2012
World’s first SiPhotonic transmitter in 45nm SOI
Stojanovic, Popovic, Ram
• Every major foundry has a Silicon-Photonic process
What is happening in Semiconductor Industry? – Part II
Our Process Platforms

- **Fully-Customized SOI Photonics (CNSE)**
  + any CMOS (currently 65nm bulk)

- **Deposited Photonics**
  180nm (Micron) and 65nm (CNSE) bulk CMOS

- "Zero-change" (45nm and 32nm SOI)
Photonics next to the fastest transistors

- $f_T/f_{\text{max}}$ have not improved since 32nm node
- $f_T/f_{\text{max}}$ affect speed, energy-efficiency, ... of electronic-photonic systems
- 32/45nm: Fastest Transistors + Thick-enough Si bodies to guide the light
  - Si body in SOI nodes below 32nm (FDSOI) cannot guide the light!
IBM/GF 12SOI (45nm) CMOS

- 300mm wafer, commercial process
- MOSIS and TAPO MPW access
- Advanced process used in microprocessors
- Photonic enhancement enables VLSI photonic systems (no required process changes)
“Zero-Change” Optics in 45nm

- Photonics for free! (No modification to the process)
- Closest proximity of electronics and photonics
- Single substrate removal post-processing step

Monolithic photonics platform with the fastest transistors

[C. Sun, JSSC 2016]
World’s first processor to communicate with light

Silicon-Photonic components integrated directly in the chip

Zero-change DARPA POEM & PERFECT – Stojanović, Ram, Popović, Asanović
45nm SOI

70+M transistors, thousands of photonic devices

Si Waveguides

- 470nm width
- 700nm width
Key Device Components

Vertical couplers

Waveguide  Diffraction Grating

Waveguide Taper

[Wade OIC 2015]
SiGe from PMOS strain engineering used in Photodetectors

SiGe Photodetector

Waveguide Taper

Waveguide

[Orcutt 2013, Alloatti APL 2015]
Key Device Components

Modulator Microring
Drop Waveguide
Integrated Heater
Output Waveguide
Input Waveguide

[Shainline OL 2013, Wade OFC 2014]
Resonant-Rings

- Interleaved planar PN junctions
  - Enabled by advanced lithography of this process
- Highly sensitive structures that can be used in a number of applications
  - Q factors up to 200k
Higher-speed and higher-order modulation

Moazeni and Lin et al [ISSCC17, JSSC17, OptEx18]

Transmitter Macro

Grating Coupler

Digital PLL

Driver

Serializer

Digital Backend

Heater Driver

Chip 3.0x3.0mm

Transmitter Test Macros

Modulator & Driver 40 fJ/b

Digital PLL 360 fJ/b

Serializer & Clock Divider/Buffer 290 fJ/b

Modulation

<table>
<thead>
<tr>
<th>Modulation</th>
<th>40 Gb/s NRZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full TX Energy</td>
<td>0.33 pJ/b</td>
</tr>
<tr>
<td>Full TX + PLL</td>
<td>0.69 pJ/b</td>
</tr>
</tbody>
</table>

IL 4.7dB, ER 3.0dB 50 µW 40Gb/s

20ps

40Gb/s PAM4

10 ps/div 20 µW/div
Anatomy of FMCW LIDAR

- Advantages over pulsed LIDAR
  - Sensitivity shot-noise limited
  - Less sensitive to background noise
Photonic array distortions

- Extensive modeling framework
  - Various phase-shifter types (AM/PM distortion)
  - Quantization
  - Index variations, coupling and pitch mismatch, etc

![Graph showing PM-AM Distortion Effects and Cumulative Beam Power vs. Phase Shifter Type]

- Injection Shifter: -23.5dB
- Depletion Shifter: -17.2dB
- Kerr Shifter: -13.1dB

37 mrad
Laser chirp control via optical PLL

- Optical PLL enables closed-loop control of laser wavelength

**CMOS**

- Frequency ($\propto$ chirp rate) has to be constant

**Photonics**

- Asymmetric MZI: FMCW measurement with known delay $\tau$ (Laser chirp rate sensing)

- All-digital implementation enables the loop to address multiple different chirp rates & optimize phase noise through loop filter reconfiguration

**Chips currently in packaging**
- CMOS: GF 45nm SOI process
- Photonics: CNSE 300mm process
Coherence distance barrier

- Spectral peak degrades as distance increases ($\propto e^{-\Delta\omega\tau}$)
  - Beyond “coherence distance,” lineshape converges to laser lineshape (e.g. Lorentzian)
  - Big challenge for using compact semiconductor lasers (>1MHz linewidth) for long-distance (>100m) LIDAR
Beyond the coherence limit with optimized detection

- Improved detection algorithm
  - Take into account the phase-noise basis shape
    - Wide-range tunable laser with DBR mirror used ($\Delta v \sim 1$MHz)
    - Path delay (110m) emulated by long fiber, path loss emulated by VOA
    - Simulated path loss $\sim -80$dB (corresponding to 110m target, 3x3mm aperture)

[Kim et al ICASSP18, CLEO18]
Future MIMO System Challenges
• mm-wave operating frequency
• 100’s of beams, 1000’s of antennas
• Power
• Density
• Chip-to-chip communication

Electronic-Photonic System Goals
• mm-wave LO distribution
• Direct mm-wave photonic link from antenna to remote hub

NF and SNDR relaxed in massive MIMO systems
Cellular and Molecular Sensing

[Anwar, Stojanovic, Niknejad]
• Reduced measurement time (sub 1s)
  – Capture faster kinetics
• Increased SNR (allows lower ring Q factors)
• Integrated thermal tracking

[Anwar, Stojanovic, Niknejad]
Packaging and functionalization

- Substrate released chip (45nm SOI)
  - Successful functionalization with APTES/biotin and biotin-streptavidin binding
First sensitivity and kinetics results

Bulk RI Sensitivity: 5nm/RIU

First kinetic binding results
Ring resonator based Ultrasound Imaging

- Ultrasound RX phased array
  - Real-time 3D ultrasound imaging
- Reduced cable count and pitch compared to piezo/cmut alternatives
  - more aggressive scaling of ultrasound probes targeting IVUS, TEE
- Resonant shift induced by
  - Acoustic pressure wave straining the waveguide and causing $\Delta n_{\text{eff}}$
  - Acoustic resonance vibration
• Ring picks up the ultrasound (good agreement between ring and transducer receive response)

• Intrinsic sensitivity $S_i = 60\text{fm/kPa}$ – comparable to existing polymer based ring related work (ring is not optimized for this application)
Electronic-Photonic Quantum SoCs

45nm SOI

[Popovic, Stojanovic, Kumar]

[Gentry et al, Optica’15, CLEO’18]
• Deposited on deep-trench oxide
• The only way to integrate photonics in advanced nodes
First 65nm bulk CMOS wafers with working photonics and transistors!

A. Atabaki, S. Moazeni et al. Nature, April 2018
Conclusions

• Silicon-photonics – enabler of new capabilities
  – Think “new on-chip inductor” or “new on-chip t-line”

• Potentially revolutionize many applications despite slowdown in CMOS scaling

• Deposited polySi-photonics key to monolithic integration with advanced transistors