High performance lasers on Si

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Outline

• Motivation

• Heterogeneous integration
  - Sub-kHz optical linewidth lasers

• Direct epitaxial growth
  - Low-noise high-channel-count comb lasers

• Summary
Advantages of Si photonics

- Low power consumption
- High integration density
- High reliability
Many applications of Si photonics

From Jean Louis Malinge
SiPh already in a 300mm fab

First 65nm bulk CMOS wafers with working photonics and transistors!

A. Atabaki, S. Moazeni et al. Nature, April 2018
The biggest limitation of Si photonics

Indirect bandgap nature limits silicon to realize efficient light sources on-chip!

D. Liang, J. Bowers, Nature photonics, 2010
Efficient ways to generate light on Si

- Mature light source technology
  - Flip-chip bonding
  - Wafer bonding


S. Tanaka et al., ECOC, Cannes, 2014.
Current status of the heterogeneously integrated lasers on Si

UCSB largest integration demonstration

InGaAs PIN PD  AlGaNAs DFB  AlGaNAs EAM

300+ active units  2.56 Tbps

Zhang et al. Optica (2016)

Intel ships the Si transceiver to the market using their own commercial 300-mm wafer fabrication process.

Further improvement in terms of optical linewidth

Modified Schawlow Townes Henry linewidth equations:

$$\Delta \nu_0 = \frac{q \omega^2 n_{sp}}{2Q^2 (I - I_{th})} \left(1 + \alpha^2\right)$$

- Increase $Q$ – cold cavity quality factor, governed by the internal loss
- Reduce $I_{th}$
- Reduce $n_{sp}$, $\alpha$

Simulated Lorentzian linewidth

Measured Data on 231 nm Etched WG

Minh Tran, et al, Applied Sciences, 2018
0.16 dB/cm propagation loss Si waveguide

![Layer structure of Si waveguide with deposited SiO₂, Si, and thermal SiO₂ layers]

- Deposited SiO₂
- Si
- Thermal SiO₂
- Si Substrate
- 56 nm
- 500 nm
- 1 μm

**Measured OBR trace of 1.8 μm waveguide**

**Extracted loss vs. wavelength**

![Graph showing effective index vs. waveguide width and extracted loss vs. wavelength for TE0, TE1, and TE2 modes]
One more step to improve the optical linewidth

\[ \Delta \nu = \frac{\Delta \nu_0}{F^2} \quad F = 1 + A + B \quad A = -\frac{1}{\tau_{in}} \frac{d\varphi_{eff}(\omega)}{d\omega} \quad B = \frac{\alpha_H}{\tau_{in}} \frac{d}{d\omega} \left( \ln |r_{eff}(\omega)| \right) \]

- Reduce \( \Delta \nu_0 \)
- Increase \( A \) - Extended cavity length/ active length
- Increase \( B \) - Negative feedback effect (detuned loading)

Minh Tran, PhD thesis, UCSB, 2019
Ring Resonator Coupled Lasers

Using rings inside the cavity benefits the linewidth in two ways:

- **Resonance cavity length enhancement**
  - increasing the photon lifetime due to effective cavity length enhancement.

- **Negative optical feedback**
  - providing negative optical feedback by slight detuning from the ring (resonator) resonance.

B. Liu, J. Bowers, APL, 2001
• Designed Vernier FSR = 114 nm
✓ Passive SMSR > 8 dB across the whole tuning range
Laser performance characterization

\( T_{\text{stage}} = 20 \, \text{°C} \)

\( I_{\text{gain}} = 300 \, \text{mA} \)

SMSR on Tuning Map

> 40 dB for most of the operation points

\( 110 \, \text{nm} \)
Frequency Noise and Lorentzian Linewidth

- Measurement setup is limited. The noise spectrum has not flattened at 20 MHz yet.

- Lorentzian Linewidth < 220 Hz!
Emerging light source technology by direct epitaxial growth

Monolithic Growth is Difficult

- Lattice constant mismatch
  - High density of dislocations, antiphase domains, stacking faults
- Thermal expansion mismatch
  - Cracking, residual strain at room temperature

K. Nozawa et al., JJAP, 1999
Tremendous progress in the last five years

**Maturation of the Light Source**

- **InAs/GaAs QDs**
- **Demonstrating Reliable Operation**

A. Liu, J. Bowers, IEEE JSTQE, 2018

Y. Wang, et al, Optica, 2018

D. Jung, et al, ACS photonics, 2018
Advantage of the quantum dots
Quantum dots have advantages over Quantum well or bulk material

- inhomogeneously broadened gain spectrum
- ultrafast carrier dynamics
- superior temperature stability
- high saturation output power
- better back-reflection insensitivity
- low level of amplified spontaneous emission (ASE) noise

Excellent material for making mode locked lasers!

- Simple structure to generate a wide coherent spectrum with a fixed channel spacing
Mode locked laser device design

• Two section mode locked laser design
  ▪ 3 μm ridge width
  ▪ 2048 μm cavity length
  ▪ SA section length is 14% of the total cavity length

• Active region: chirped five stacks of InAs QD layers
  ▪ P modulation doped $5 \times 10^{17}$ cm$^{-3}$ in the spacer layer
  ▪ TDD as low as $7 \times 10^{6}$ cm$^{-2}$
  ▪ Chirped QD layers for broadened FWHM of 69 nm

$\text{PL}$ emission spectra of a single InAs DWELL layer with different InGaAs thicknesses in test run

PL spectrum of the material used.
Basic device performance

L-I-V curve

- Threshold: increase from 42 mA to 58 mA as SA section reverse bias increase
- Series resistance: $\sim 3.2 \, \Omega$

RF SNR mapping
- Mode locking criterion: being restricted to fundamental frequency tone signal to noise floor (SNR) ratio larger than 30 dB with the pulse width narrower than 12 ps.
- Wide mode locking regime is demonstrated.
Basic device performance

- A sharp fundamental RF tone at 20.02 GHz with a SNR of 64 dB and its higher-order harmonic can be clearly seen across the 50 GHz span, indicating very stable mode locking operation.
- The 3 dB RF linewidth is 1.8 kHz with a Voigt fit.
- The integrated timing jitter is 82.7 fs from 4 to 80 MHz of the ITU-T specified range, which is the lowest timing jitter ever reported to date for any passively mode-locked semiconductor laser diode.
Basic device performance

\[ I_{\text{gain}} = 180 \text{ mA}, \quad V_{SA} = -1.92 \text{ V} \]

- 3 dB bandwidth: 6.1 nm with 58 lines (80 lines within 10 dB), average linewidth is 10.6 MHz.
- Modes show beating signal at 20.665 GHz, indicating strong coherence.
- For the whole optical comb, the integrated average RIN value of $-152$ dB/Hz, individual comb line shows an integrated average RIN value of $-133$ dB/Hz (with QD SOA).
PAM-4 system level transmission demonstration

System-level PAM-4 transmission test setup


4.1 Tbps 64-wavelength 32 Gaud PAM-4 Demonstration

- 64 channels are utilized.
- 32 Gbaud Nyquist pulse shaped PAM-4 modulation format.
- With 61 channels below hard-decision FEC threshold and total 64 channels below soft-decision FEC threshold.
- An aggregate total transmission capacity is 4.1 terabits per second.
Summary

- Integrated lasers on silicon can provide a high performance, low cost, mass production and high energy efficiency solution.
  - Record ultralow noise chip-scale semiconductor lasers
  - Record ultrawide wavelength tuning ranges for chip-scale lasers
- Epitaxial lasers are progressing fast.

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