Nanolasers Grown On Silicon

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Purpose & Achievements

- Laser materials grown on silicon substrates requires high growth temperatures → To overcome the barrier, the growth of single-crystal GaAs nano-needles on silicon at 400 °C under conditions compatible with CMOS technology is demonstrated.
- A novel helically propagating mode cavity that offers a unique feedback mechanism to enable on-chip laser oscillation is shown.
Nanopillar growth on silicon

- Core: InGaAs active region / GaAs shell: surface passivation
- Height and diameter of nanopillars scale easily and controllably with growth time
- Tiny footprints: $\sim 0.34 \, \mu m^2$
- Low-temperature and catalyst-free growth allows nanopillars to be monolithically integrated with silicon electronics without highly developed technology
Room-temperature laser oscillation is achieved by excitation using a mode-locked Ti:sapphire laser.

- Below threshold: broad spontaneous emission
- Above threshold: cavity mode emerges and laser oscillation is ultimately seen
- As many as three lasing modes have been seen from a single nanopillar
- Growing a thick GaAs cap is key in suppressing surface recombination to enable room-temperature operation
Sufficient optical feedback or Q is attained for laser oscillation despite minimal index contrast between InGaAs nanopillar ($n_r \approx 3.7$) and silicon substrate ($n_r \approx 3.6$).

Helically propagating modes can have TIR at nanopillar-silicon interface; wave vector strike that boundary with grazing incidence at extremely shallow angles.

Azimuthal components result in transverse field profiles similar to WG modes.

Axial standing wave as for Fabry-Perot resonance.

However, unlike WG modes, its resonances have net propagation in the axial direction.
Cavity modes are well confined in active material.

The confinement is strong enough that even nanopillars with subwavelength dimensions on all sides achieve laser oscillation.

Select mode number and control wavelength by controlling nanopillar dimension.

Fig. (c) First-order standing waves (d) Higher-order standing waves
(e) Strong light localization provided by helical modes enables nanolasers that are subwavelength on all sides.
Both nanopillar radius and height determine cavity resonances.
- Net propagation of nanopillar cavity modes along the nanopillar axis
- As nanopillar length decreases, higher-order axial modes are cut off so fewer axial maxima can be observed
- The axial maxima to helically propagating modes were supported despite oblique junctions of low index contrast between nanopillars and substrate

Fig. (f-h) Experimental images of nanopillar emission show standing-wave patterns along the nanopillar axes
Even an oblique interface between silicon and InGaAs can introduce a mode cutoff that strongly reflects and confines light in nanopillar.
At a certain height, the reduced nanopillar radius cuts off the mode in vertical direction and reflects it downwards – Modes are confined towards the base of nanopillar

The adiabatic reduction of nanopillar radius causes helical modes to become less resonant as they propagate upwards, resulting in increased light leakage through the cavity sidewalls.

Sidewall taper is the primary loss mechanism for as-grown cavities.

The stronger Fabry-Perot characteristic of higher-order axial modes causes larger penetration and loss into substrate.
Wavelength control of laser emission

- Match semiconductor gain to designed cavity resonances to maximize spontaneous emission coupling into cavity modes by varying indium composition
- Using bottom-up approach: provides far smoother facets allowing minimizing scattering loss / have symmetry structure which prevents polarization splitting

Fig. (a) Wavelength control of nanopillar lasers by composition variation (b) Indium composition variation for emission wavelength control
Discussion

- The scheme presented is promising for photonic integration with CMOS circuits
  → However electrically pumped lasers are required
- Another critical aspect of silicon optoelectronics is coupling of laser emission into waveguides
- They could not get a desirable wavelength (1550 μm)
Conclusion

- The first room-temperature III-V nanolaser grown on silicon with subwavelength volume
- A new class of helically propagating modes implant their unique on-chip optical cavities
“Supplementary Information” from www.nature.com/naturephototonics