Supporting Information

A Monolithic Electrically Injected Nanowire Laser on (001) Silicon

Thomas Frost[1], Shafat Jahangir[1], Ethan Stark[1], Saniya Deshpande[1], Arnab Hazari[1], Chao Zhao[2], Boon S. Ooi[2] and Pallab Bhattacharya[1*]

[1]Center for Photonics and Multiscale Nanomaterials, 1301 Beal Avenue, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109

[2] Division of Computer, Electrical and Mathematical Sciences and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

[*]Email: pkb@eecs.umich.edu

The supporting information contains text and 2 figures in support of the main text. It discusses three topics:

1. Methods
2. Output polarization
3. Gain measurements

1. Methods

Epitaxial growth of nanowire laser heterostructure on (001) silicon

The InGaN/GaN disk-in-nanowire laser heterostructure was grown on (001) Si substrates by plasma-assisted molecular beam epitaxy (PA-MBE). To remove the surface oxide the substrate was cleaned with a hydrofluoric acid solution, and was heated inside the MBE chamber at 900^{o}C for 60 min before growth. The GaN nanowires were grown on Si at a substrate temperature of 800^{o}C without any initial self-catalysis step. The growth was carried out in a nitrogen rich environment maintaining a constant N_2 flux of 1.0 sccm and the Ga flux was kept at 1.18x10^{-7} Torr. 150 nm of Si doped n^{+}GaN layer (n~6×10^{18} cm^{-3}) was first grown, followed by n-$Al_{0.11}Ga_{0.89}N$ cladding layer, $In_{0.06}Ga_{0.94}N$ waveguide in the center of which is placed 6 $In_{0.34}Ga_{0.66}N$ disks (2 nm)/GaN barrier (12 nm), 15 nm p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer (EBL) and 550 nm p^{+}GaN layer. During the growth of the quantum disks, the substrate temperature was lowered to 590^{o}C and an In flux of 6.5×10^{-8}Torr was used. Mg-doped p^{+}GaN layer (p~7.5×10^{17} cm^{-3}) was grown at 700^{o}C. The Mg flux was increased during the growth of the final 20 nm of p^{+}GaN to achieve a better ohmic contact.

Fabrication of nanowire waveguide and laser.

Edge-emitting lasers were fabricated with a two-step mesa in a ridge geometry, patterned with a stepper and optical photolithography. The mesas were etched using reactive ion etching with the first mesa (ridge) etched to the cladding/waveguide heterointerface and the second (wider) mesa etched to the n-GaN buffer layer. The ridges were patterned with widths of 4-10μm with the wider mesa 20μm wider than the respective ridge width. parylene was deposited by thermal vapor deposition to planarize the device and passivate the nanowire surface. The p-side of the nanowires were treated with ammonium sulfide ($(NH_4)_2S_x$) to reduce the p-contact resistance. The p-GaN contacts were formed with Ni/Au ohmic contacts (5nm/5nm) deposited by electron beam evaporation and ITO (250nm) deposited by sputtering. The n-GaN contacts were formed with Al/Ti/Au (100nm/10nm/300nm) by e-beam evaporation. SiO_2

passivation was deposited by plasma enhanced chemical vapor deposition. Via holes for the contacts were etched using a solution of $HF:H_20$ (10:1). The laser heterostructures were mechanically thinned to ~100 μm, cleaved along the direction perpendicular to the laser cavity and then focused ion beam (FIB) etching is used to form the laser facets. Dielectric DBRs (SiO_2/TiO_2) were deposited on the facets by e-beam evaporation to achieve a reflectivity of ~0.72 and ~0.95 on the two facets, respectively.

Measurements of dc laser characteristics.

The electrical characteristics of the lasers were measured with a Keithley 2611 sourcemeter under cw and pulsed (500μs pulse, 1% duty cycle) current bias. The light-output characteristics were measured with a power meter and a calibrated silicon photodetector. The laser temperature was kept fixed with an adequately heat sinked thermoelectric cooler during the measurements. The spectral characteristics of the laser were measured using a high resolution (0.03nm) monochromator and detected using a photomultiplier tube.

2. Output polarization

The polarization of the laser output was measured as a function of injection current by placing a linear polarizer between the laser facet and the silicon photodetector which is used to measure the output power. The L-I characteristics with the linear polarizer aligned along the TE and TM axes are shown in Fig. S1. While the TM-polarized light output remains low throughout the injection range, the TE-polarized light output increases sharply above 2 kA/cm^2, due to the higher confinement and gain of the TE mode than that of the TM mode [S1].

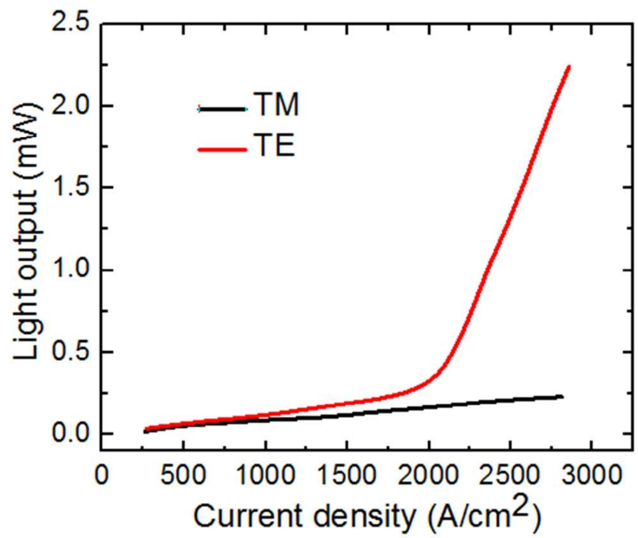

Figure S1 Output polarization. The light output from a 1.5 mm x 10 μm ridge waveguide laser as a function of injection is plotted at 300K showing the strong TE polarization of the output above threshold.

3. Gain measurements

The threshold current of a semiconductor laser and the dynamic characteristics including the small-signal modulation bandwidth, chirp and linewidth enhancement factor are ultimately determined by the gain in the active region. The gain of the nanowire lasing medium near threshold was measured by the Hakki-Paoli technique [S2] using the formula: $\Gamma g_i = 1/L \ln((r_i^{1/2}+1)/(r_i^{1/2}-1)) + 1/L \ln(R)$. Here Γ is the optical confinement factor, L is the cavity length, R is the facet reflectivity, and $r_i = (I_p+I_{p+1})/2I_v$, where I_p and I_{p+1} are adjacent peak intensities in the electroluminescence spectrum separated by the valley intensity, I_v. The emission spectra for increasing injection are recorded, till threshold is reached, when the spectra is characterized by a succession of peaks and valleys. The spectral gain is derived by analyzing these data. The modal gain Γg is plotted as a function of photon energy in Fig. S2. The peak modal gain at threshold is 24 cm^{-1}. The inset shows the spectral characteristics of the laser at threshold from which the gain spectrum is derived.

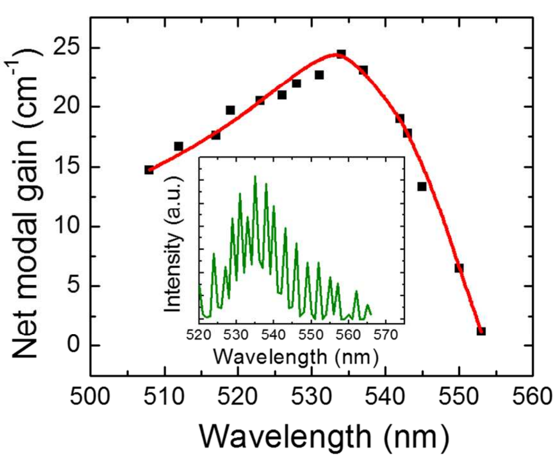

Figure S2 Gain spectrum. The modal gain spectrum is derived from the electroluminescence spectrum shown in the inset with a peak modal gain of 24 cm^{-1}.

References

S1. Kyono, T., Yoshizumi, Y., Enya, Y., Adachi, M., Tokuyama, S., Ueno, M., Katayama, K. & Nakamura, T. Optical Polarization Characteristics of InGaN Quantum Wells for Green Laser Diodes on Semi-Polar {2021} GaN Substrates. *Appl. Phys. Exps.***3**, 011003 (2010).

S2. Hakki, B. & Paoli, T. Gain Spectra in GaAs double-heterostructure injection lasers. *J. Appl. Phys.* **46**, 1299 (1975).