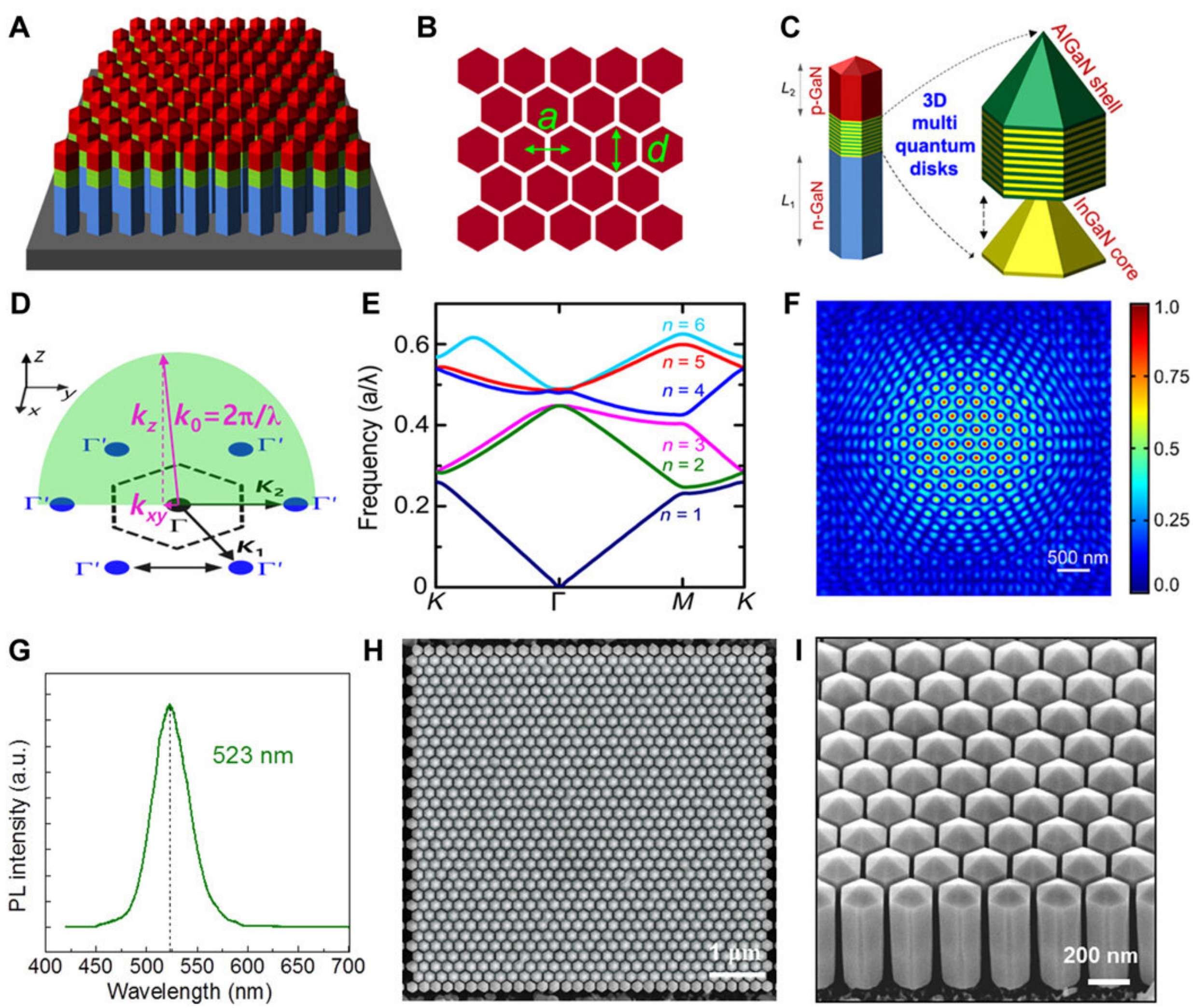
An electrically pumped surface-emitting semiconductor green laser

January 16 2020, by Thamarasee Jeewandara

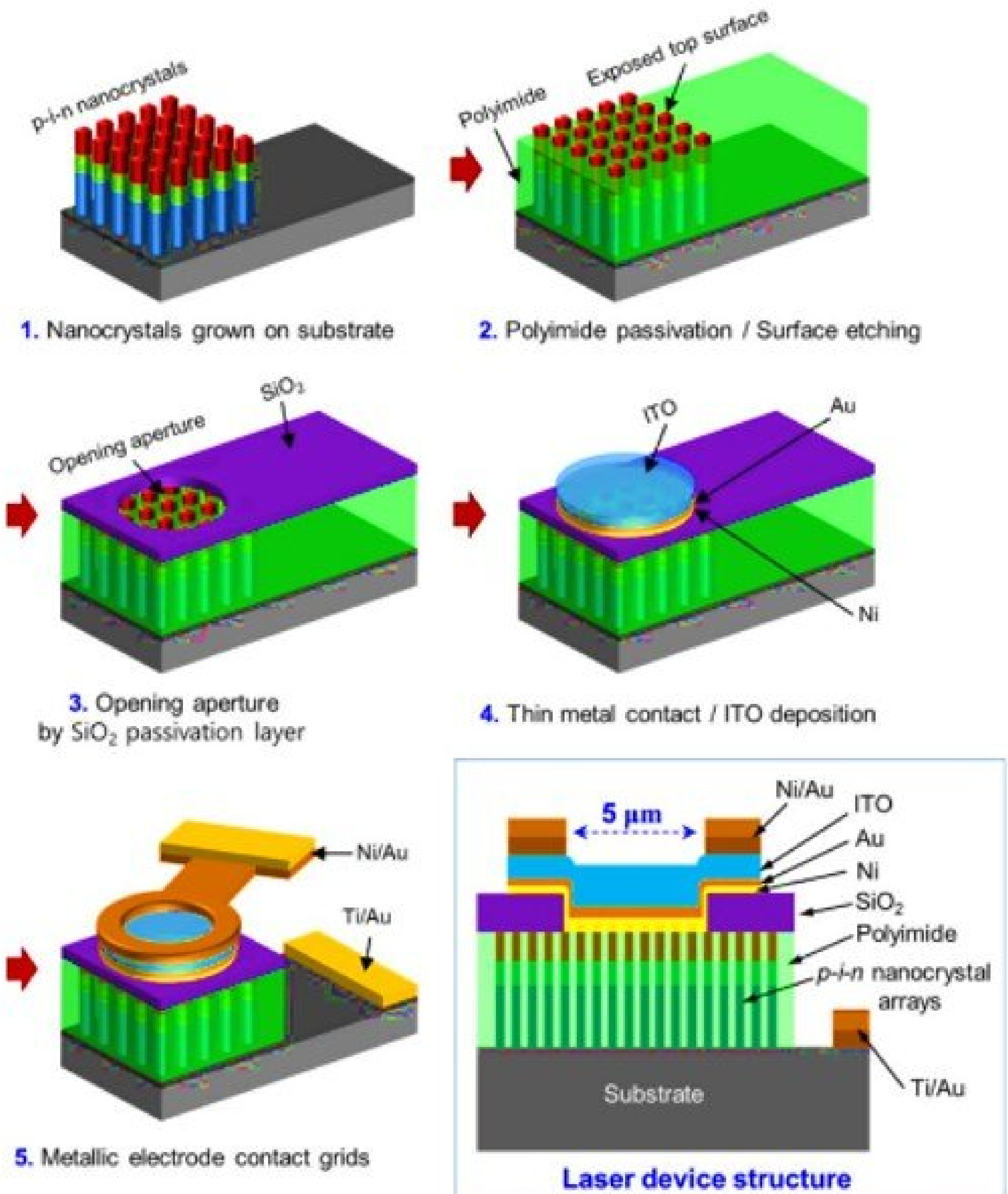


Design of InGaN NCSEL diodes operating in the green wavelength. (A) Schematic of the InGaN nanocrystal arrays for the surface-emitting laser diode. (B) The diameter and lattice constant of the nanocrystals denoted as d and a, respectively. (C) Schematic of the InGaN/AlGaN nanowire heterostructure, which consists of an n-GaN cladding layer, a core-shell InGaN/AlGaN multiple quantum disk active region, and a p-GaN cladding layer. (D) The reciprocal lattice of a photonic crystal structure has six equivalent Γ′ points, which are coupled together by the Bragg grating vectors K1 and K2. (E) Calculated photonic band structure for transverse magnetic (TM) polarization from 2D finite-element method (2D-FEM) simulation. (F) The electric field profile of the band edge mode (λ = 523 nm) calculated by the 3D finite-difference time-domain method. (G) PL spectrum of an InGaN/AlGaN calibration sample showing spontaneous green emission. a.u., arbitrary units. (H and I) The top-view and titled-view scanning electron microscopy (SEM) images of an InGaN nanocrystal array. Credit: Science Advances, doi: 10.1126/sciadv.aav7523

Scientists and Engineers have used surface-emitting semiconductor lasers in data communications, for sensing, in FaceID and within augmented reality glasses. In a new report, Yong-Ho Ra and a research team in the departments of Electrical and Computer Engineering, and Advanced Electronics and Photonics in Canada, Korea and the U.S., detailed the first achievement of an all-epitaxial, distributed Bragg reflector (DBR)-free, electrically injected surface-emitting green laser. They optimized the device by exploring the photonic band edge modes formed in dislocation-free gallium nitride nanocrystal arrays, without using conventional DBRs. They operated the device at approximately 523 nm, with a threshold current of 400 A/cm^2—an order of magnitude lower than previously reported blue laser diodes. The studies opened a new paradigm to develop low-threshold, surface-emitting laser diodes, ranging from the ultraviolet region to the deep visible range (approximately 200 to 600 nm). At this range, the device performance was not limited by the lack of high-quality DBRs, large lattice mismatch, or substrate availability. The results are now published on *Science Advances*.

Vertical cavity surface-emitting laser (VCSEL) diodes were first presented in 1979; they emit a coherent optical beam vertically from the device surface, to offer a number of advantages compared to conventional edge-emitting lasers. The advantages include lower threshold, circular and low divergence output beam, longer lifetime and easy production of dense two-dimensional (2-D) arrays. Commercial VCSELs can be fabricated on gallium arsenide (GaAs) and indium phosphide (InP) that mostly emit light within the near-infrared wavelengths. For lasers operating in the visible and ultraviolet spectral ranges, physicists use gallium nitride (GaN)-based semiconductors as the material of choice, with substantial research efforts in the past decade to develop GaN-based VCSELs. However, their operation wavelengths are largely limited to the blue spectral range and therefore researchers are yet to engineer all-epitaxial, surface-emitting laser diodes operating in the green wavelength region that are most sensitive to the eye.

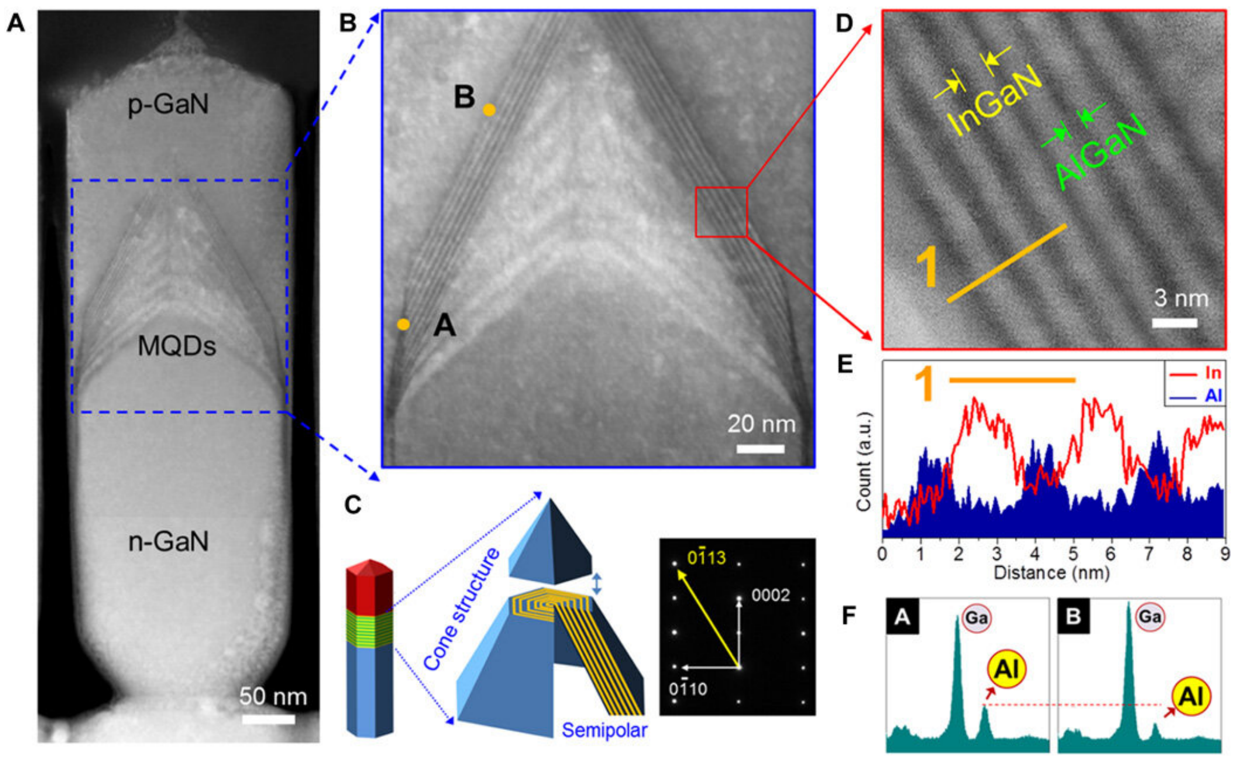
A previously reported room temperature continuous wave (CW) surface-emitting green laser diode relied on dual dielectric distributed Bragg reflectors (DBRs) and water bonding to a copper plate for low thermal resistance. The resulting devices exhibited a very large threshold current density at room temperature with the operation wavelengths limited to 400 and 460 nm. The ability to form a low-threshold, highly efficient, all-epitaxial surface emitting green laser diode will allow many exciting applications in the field, including projection displays such as pico projectors, plastic optical fiber communication, wireless communication, smart lighting, optical storage and biosensors.



The NCSEL device fabrication. The nanocrystal surface-emitting laser (NCSEL) device was fabricated by the following steps. Schematic illustration of the full device fabrication, including passivation, planarization, photolithography, and contact metallization techniques. Credit: Science Advances, doi: 10.1126/sciadv.aav7523

In the present work, Ra et al. proposed and demonstrated a nanocrystal surface-emitting laser (NCSEL) diode, free of DBRs to function efficiently in the green spectrum. The NCSEL consisted with InGaN/AlGaN (indium gallium nitride/aluminum gallium nitride) nanocrystal arrays of precisely controlled size, spacing and surface morphology. Due to efficient strain relaxation, such nanostructures were free of dislocations. Ra et al. included multiple InGaN quantum disks in the semipolar planes of the active region to significantly reduce the quantum confined stark effect (QCSE). To suppress surface recombination in the setup, they formed a unique AlGaN shell structure around the active region of the NCSEL.

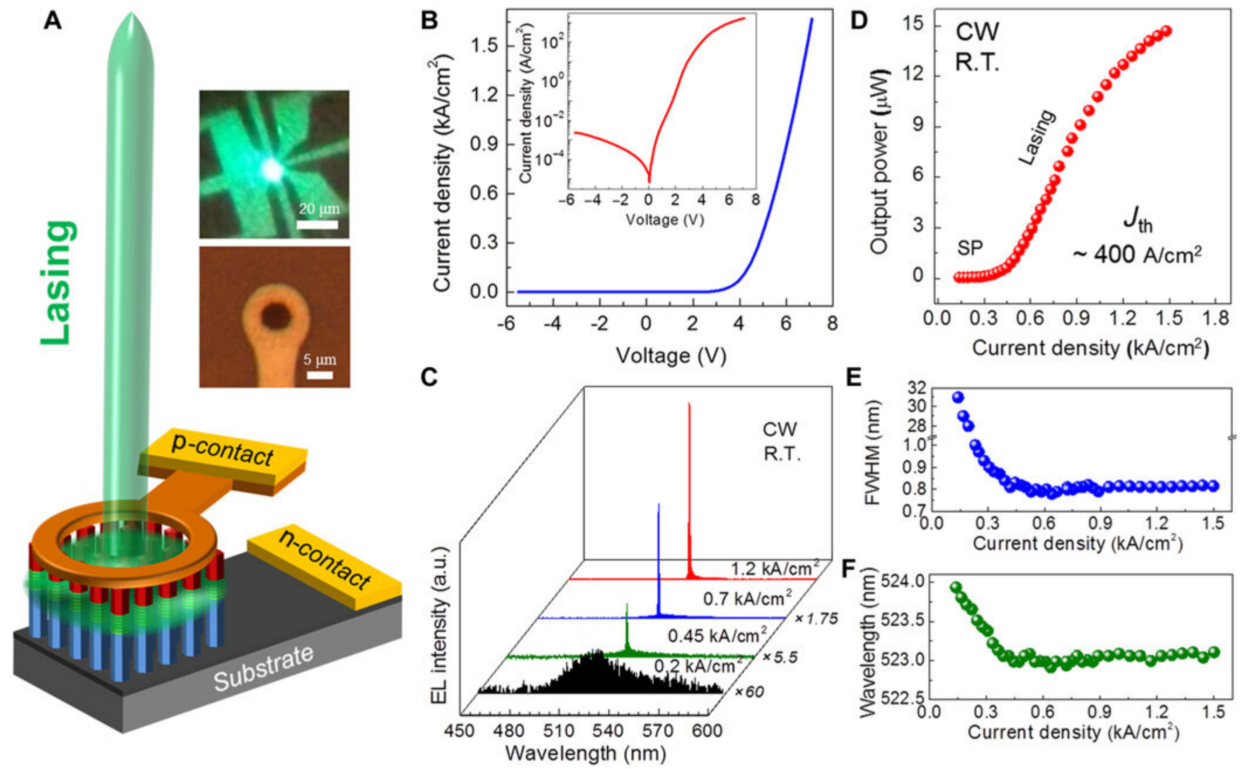
Ra et al. explored the photonic band edge resonant effect of the nanocrystal array to demonstrate an electrically injected surface-emitting green laser diode, without using conventional, thick and resistive DBRs. The device functioned at 523.1 nm and exhibited a low threshold current density approximating 400 A/cm^2, with highly stable operation at room temperature. The scientists confirmed coherent laser oscillation using far-field emission pattern and with detailed polarization measurements. The work showed a practical approach to realize high-performance, surface-emitting laser diodes from deep UV to the deep visible, which were previously difficult to achieve.



Structural characterization of InGaN/AlGaN core-shell quantum disk heterostructures. (A) STEM-HAADF image of a representative core-shell InGaN/AlGaN multiple quantum disk (MQD) heterostructure nanocrystal. (B) High-magnification image taken from the region marked in (A) and (C) schematic illustration for the quasi-3D structure of the semipolar active region and selected-area electron diffraction pattern of the InGaN/AlGaN core-shell heterostructure. (D) High-magnification HAADF image of the InGaN/AlGaN quantum disk region. (E) Energy-dispersive x-ray spectroscopy (EDXS) line profile of the InGaN/AlGaN quantum disks along the line labeled with “1” in (D). (F) EDXS point analysis of the AlGaN shell region marked as “A” and “B” in (B). Credit: Science Advances, doi: 10.1126/sciadv.aav7523

In the experimental setup, the InGaN NCSEL contained nanocrystals with a hexagonal shape arranged in a triangular lattice. The researchers performed the design and simulation, including energy band diagram and mode profile via 2-D [finite-element method](https://phys.org/tags/finite-element+method/) simulation. The nanocrystals maintained a spacing of 30 nm and the lattice constant was 250 nm. To realize NCSELs, Ra et al. required precise control of the nanocrystal size, spacing and uniformity across a relatively large area. To achieve such nanocrystal arrays, the team used selective area epitaxy via plasma-assisted molecular beam epitaxy (MBE). To reduce surface recombination, they included an AlGaN shell structure in the active region.

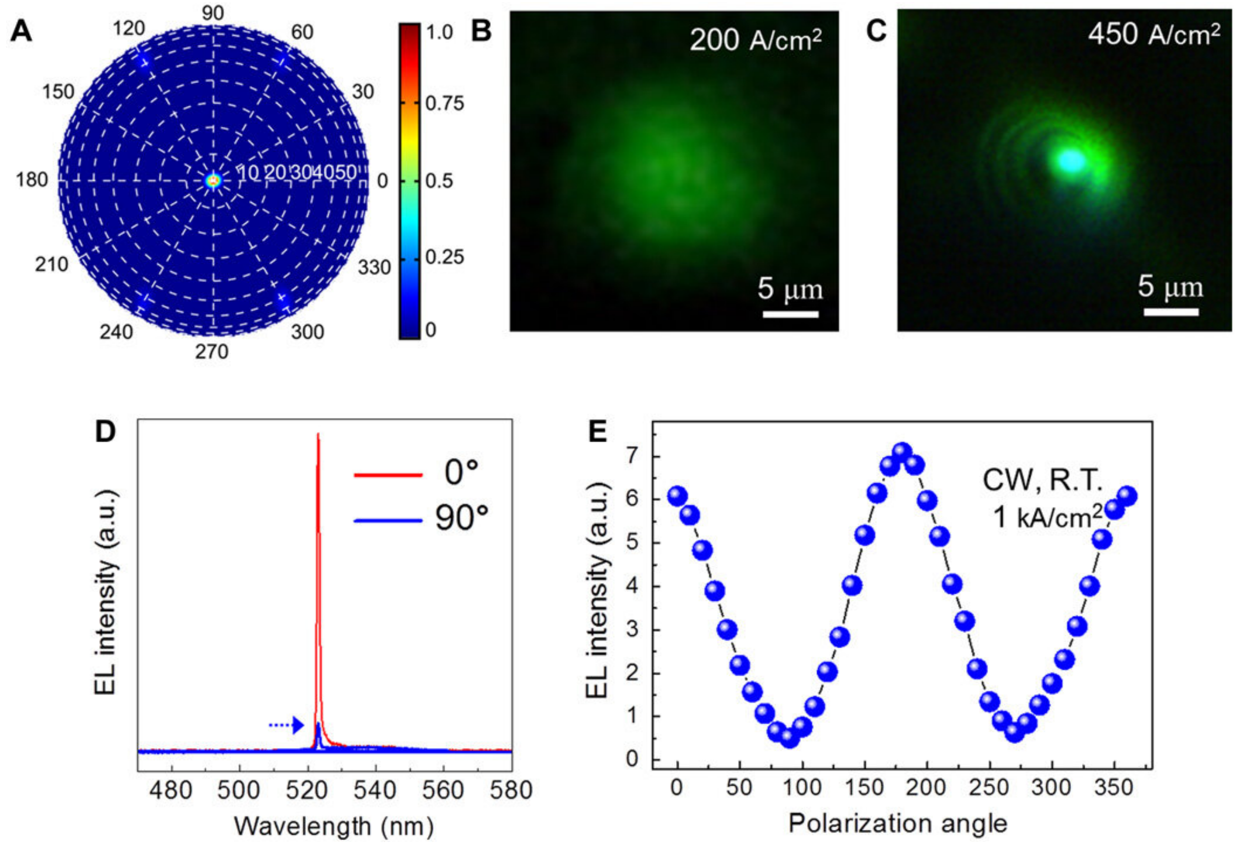
They performed additional structural characterization of InGaN nanocrystals using scanning transmission electron microscopy (STEM). Then they prepared a cross-section of the sample using a focused ion beam system to show high-angle annular dark-field (HAADF) atomic number contrast image of a representative InGaN nanocrystal. Ra et al. verified the resulting unique pyramidal/cone structure and formation of multiple quantum disk heterostructures using representative selected-area electron diffraction (SAED) pattern analysis. To further confirm elemental distribution of the active region, the team performed an energy-dispersive X-ray spectroscopy (EDXS) analysis, along the growth direction of InGan/AlGaN quantum disks.



Fabrication and characterization of InGaN NCSEL diodes. (A) Schematic illustration of the fabricated NCSEL device. Inset: Optical microscopy image of the device after metallic contact grids and electroluminescence (EL) image of the green lasing. (B) Current-voltage (I-V) characteristics of the NCSEL device. Inset: The I-V curve on a semi-log scale. (C) Electroluminescence spectra measured from different injection currents under CW biasing conditions at room temperature (R.T.). (D) Variations of the output power versus injection current. It shows a clear threshold of ~400 A/cm2. SP, spontaneous emission. (E) Variations of spectral linewidth (FWHM, full width at half maximum). (F) Peak wavelength position measured under different injection current densities. Credit: Science Advances, doi: 10.1126/sciadv.aav7523

The scientists observed the presence of an Al-rich AlGaN core-shell heterostructure using EDXS point analysis. The spontaneously formed AlGaN shell effectively suppressed non-radiative surface recombination; which was a primary limiting factor for the nanostructural device performance. The semipolar heterostructure provided several advantages including improved light emission efficiency, compared to conventional quantum disk/dot structures. The unique structure could not be engineered using a conventional top-down approach since the active region was predefined by the film fabricated in the study. The team therefore engineered InGaN NCSEL diodes using planarization, polyimide passivation, contact metallization and photolithography techniques.

The device exhibited excellent *I-V* (current-voltage) character, partly due to significantly reduced defect density and enhanced dopant inclusion within nanocrystal structures. They measured the electroluminescence character and collected the emitted light from the top surface of the nanocrystal. Ra et al. measured the electroluminescence spectra of the nanocrystal device under different injection currents in the setup to observe a significantly higher output power, compared to previous values of GaN-based VCSELs operating at 460 to 500 nm—the results can be further improved by optimizing the design and engineering method.



Far-field and polarization emission properties of InGaN NCSEL diodes. (A) Far-field radiation pattern of the nanocrystal laser structure simulated using the 3D FDTD method. Electroluminescence image of the far-field pattern observed below the threshold current density (200 A/cm2) (B) and slightly above the threshold current density (C) of the InGaN NCSEL recorded using a high-resolution charge-coupled device (CCD) camera above the device top surface. (D) Polarized electroluminescence spectra of the InGaN NCSEL measured under a current density of 1 kA/cm2. The polarization ratio is ~0.86. (E) The measured electroluminescence intensity as a function of the emission polarization angle (0° to 360°). Credit: Science Advances, doi: 10.1126/sciadv.aav7523

The lasing peak position remained stable at 523 nm above threshold to suggest highly stable lasing of the core-shell nanocrystal lasers. The observed low-threshold current density and highly stable emission was mainly related to the nanocrystal structure and reduced nonradiative surface recombination, with extended emission area in the InGaN/AlGaN cone-like shell active region. Ra et al. also simulated the far-field radiation pattern of the nanocrystal laser structure using the 3-D finite-difference time-domain method. The results provided strong evidence on achieving coherent lasing oscillation in InGaN nanocrystal arrays. The scientists measured the electroluminescence spectra to demonstrate remarkably stable and directional polarized emission, compared to conventional photonic crystal laser devices.

In this way, Yong-Ho Ra and colleagues detailed a new generation of surface-emitting diodes using bottom-up InGaN nanocrystals. The key characteristics included the presence of a clear threshold, sharp linewidth reduction, distinct far-field emission patterns and polarized light emission to provide evidence on achieving coherent lasing oscillation. They accomplished this without using thick, resistive and heavily dislocated DBRs in contrast to conventional techniques. The research can be applied across the entire visible as well as mid- and deep UV wavelengths to realize such lasers on low-cost and large-area Si wafers. These results will open a new paradigm to design and develop surface-emitting laser diodes.

More information: 1. Yong-Ho Ra et al. An electrically pumped surface-emitting semiconductor green laser. *Science Advances*. 03 Jan 2020; advances.sciencemag.org/content/6/1/eaav7523
2. Dhruv Saxena et al. Optically pumped room-temperature GaAs nanowire lasers. 17 November 2013, *Nature Photonics*; www.nature.com/articles/nphoton.2013.303?page=5 .
3. Si-Hyun Park et al. Room-temperature GaN vertical-cavity surface-emitting laser operation in an extended cavity scheme. *Applied Physics Letters*. July 2003; aip.scitation.org/doi/abs/10.1063/1.1611643.