Distributed Bragg reflectors for III-nitride VCSEL structures

Mike Cooke reports on recent research in Japan and USA.

Extending the short-wavelength light-emitting capabilities of III–nitride (III–N) semiconductors to vertical-cavity surface-emitting laser (VCSEL) structures has been the aim of many research groups. VCSELs have a cavity axis perpendicular to the plane of the active region. Traditional edge-emitting laser diodes, by contrast, have lasing cavities in the plane of the active region.

The vertical structure of VCSELs enables multiple lasers to be produced on a single chip in array formations. Other advantages of VCSELs include relatively low threshold currents, high-frequency operation, low manufacturing cost, and high efficiency. More concretely, such features are desired for optical storage, laser printers, projectors, displays, solid-state lighting, optical communications and biosensors.

The original VCSELs were created using III–arsenide (III–As) compound semiconductors using group-III metals such as aluminium (Al), gallium (Ga) and indium (In). A particular feature was the ability to form cavities using conducting distributed Bragg reflectors (DBRs) from alternating layers of AlGaAs with different compositions and a large difference in refractive index. This provides a neat and compact structure for VCSELs that is more simply manufactured.

Such an option is not immediately available in the III–N family of compound semiconductors. The corresponding AlGaN range of alloys has a fairly narrow band of refractive index. This would require many more alternating DBR layers to provide a decent reflectivity.

In III–phosphide (III–P) VCSELs, a dielectric DBR is used, but this leads to more complex structures, adding to production costs. Dielectric DBRs are also commonly deployed in the III–N VCSELs presently under development. One further drawback of III–N VCSELs is the shorter wavelength of the emitted radiation, which therefore tends to prefer shorter cavities to avoid diffraction effects, impacting performance.

Here we look at the work of two research groups attempting to overcome some of these problems for III–N VCSELs.

Sony

Sony Corporation's researchers in Japan have been working on III–N VCSELs for some time [Tatsushi Hamaguchi et al, Appl. Sci., vol9, p733, 2019]. At the same time, Sony Semiconductor Solutions Corp has a range of products and foundry facilities covering various wavelength ranges: 780~850nm (AlGaAs), 635~680nm (AlGaInP) and 900~980nm (GaInAs).

Sony's GaInN VCSEL research aims to cover the 400–530nm region. The Sony group has focused on

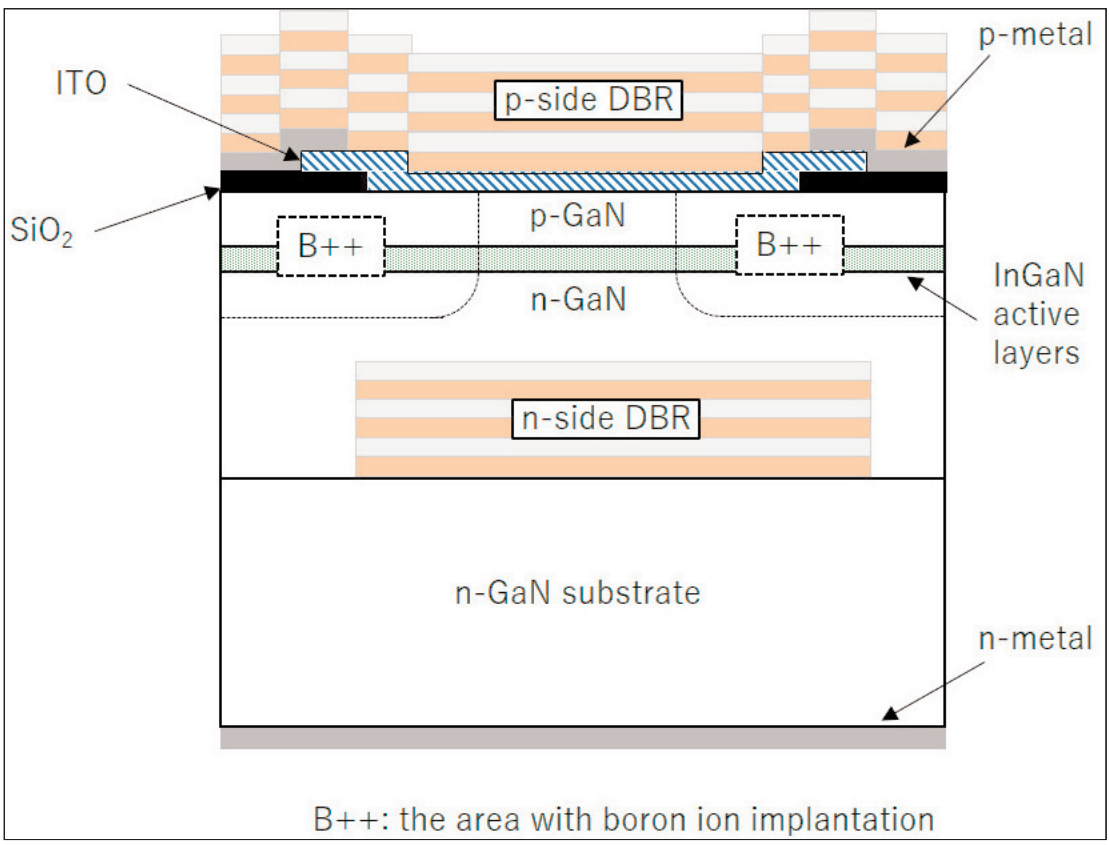

Figure 1. Schematic of all-dielectric DBR GaInN VCSEL in which the bottom reflector is encased in n-GaN using epitaxial lateral overgrowth.

dielectric DBRs. In one piece of work [S. Izumi et al, Appl. Phys. Express, vol8, p062702, 2015], Sony targeted cavity lengths less than 5µm by using epitaxial overgrowth techniques. This involved depositing dielectric on a GaN substrate, and then opening windows in the DBR to seed subsequent growth by metal-organic chemical vapor deposition (MOCVD) — see Figure 1.

A 4.5µm-cavity-length device had a threshold current of 18mA (35.8kA/cm^2 density) and a maximum light output power of 1.1mW. The emission at 20mA was a single longitudinal mode at 453.9nm wavelength. Below threshold there was a series of peaks separated by 6.7nm, consistent with the cavity length of 4.5µm.

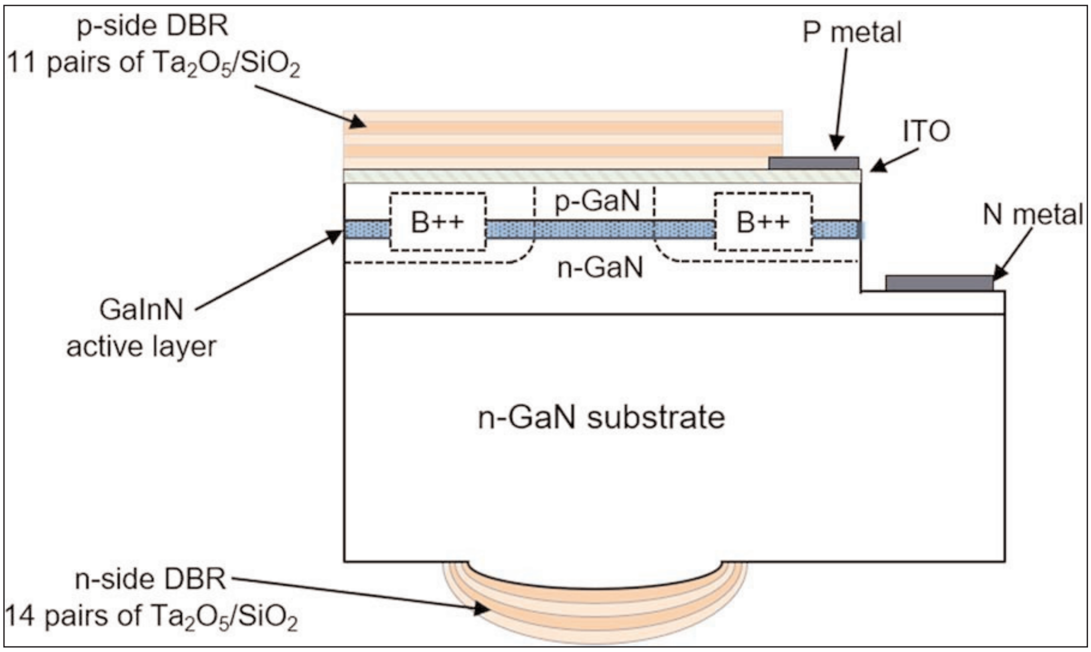

Figure 2. Schematic of VCSEL with curved back-mirror.

Curved mirror

The Sony team also more recently has claimed the lowest threshold current recorded for a GaInN-based blue VCSEL [Tatsushi Hamaguchi et al, Appl. Phys. Express vol12, p044004, 2019].

The researchers say that their achievement was enabled by lateral optical confinement by incorporation of a curved mirror in the vertical cavity structure. The team adds: "According to classical Gaussian optics, the current aperture can theoretically be as small as the diffraction limit, i.e. the order of the light wavelength, which suggests that further miniaturization and reduction of GaN-based VCSELs with curved mirrors could be achieved."

A low threshold was enabled by reducing the current aperture to 3µm. The lateral confinement of the curved mirror reduced the beam waist to 1.3µm on the top planar mirror (Figure 2).

The epitaxial material was grown on a {0001} GaN substrate. The active light-generating region was a GaInN quantum well structure sandwiched between n- and p-type GaN contacts.

Fabrication on the top-side of the wafer added layers of transparent indium tin oxide (ITO) conductor and a DBR constructed from 11.5 tantalum pentoxide/silicon dioxide (Ta_2O_5/SiO_2) pairs.

Boron (B^{++}) implantation restricted current flow to a 3µm-diameter aperture. The metal electrodes on the ITO and n-GaN consisted of titanium/platinum/gold. ►

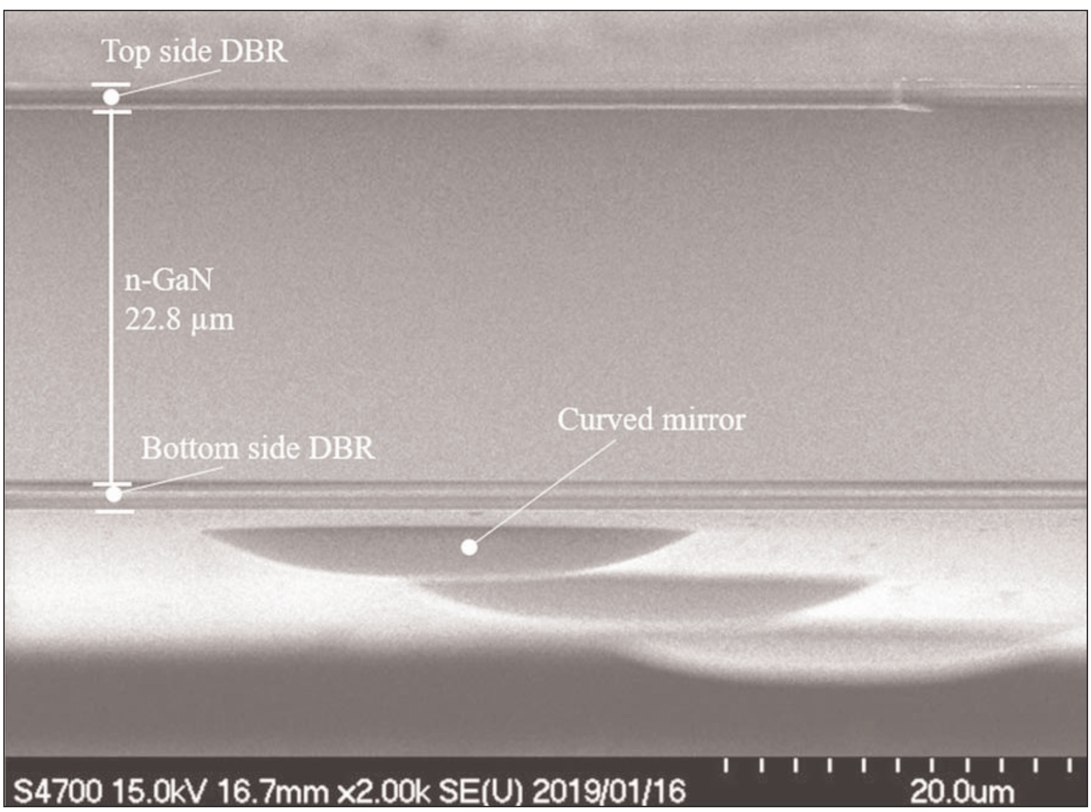

Figure 3. Cross-sectional scanning electron micrograph of device.

The back-side fabrication consisted of substrate thinning to less than 50μm thick, followed by reactive ion etch to form a curved mirror structure (Figure 3). The device was completed by vacuum deposition of 14 Ta_2O_5/SiO_2 pairs to form a curved DBR back-side reflector.

The threshold for continuous-wave lasing came at 0.25mA current (3.5kA/cm^2 density). This value was lower than the researchers' previous achievement of 40mA in a pulsed injection set up. Normally, pulsed injection leads to lower thresholds than continuous-wave operation due to self-heating effects in the latter case.

The improvement in the latest device is variously attributed to factors such as "reduction in the ITO layer thickness and number of quantum wells". The group's previous device had four wells — this was reduced to three in the latest VCSEL. The ITO thickness was decreased from 30nm to 20nm.

The dominant peak had a blue wavelength of 445.3nm (λ). The peak width was at the 0.1nm order of resolution of the spectral analyzer. Other peaks came at 1.27nm separation in wavelength, consistent with a 27μm cavity length based on a refractive index of 2.45 (n) with −0.001/nm variation in wavelength (dn/dλ).

Nanoporous DBR

An approach that results in workable conducting DBRs has been developed by University of New Mexico and Sandia National Laboratories in the USA using nanoporous GaN to achieve refractive index contrast [Saadat M. Mishkat-Ul-Masabih et al, Appl. Phys. Express, vol12, p036504, 2019]. The team claims the first electrically injected non-polar m-plane GaN-based VCSELs with conducting lattice-matched nanoporous bottom DBRs (Figure 4). Optically pumped m-plane GaN VCSELs with nanoporous DBRs had been previously reported by the group, and others have presented c-plane devices.

The epitaxial structure was grown on non-polar m-plane freestanding GaN substrates from Mitsubishi Chemical, processed using metal-organic chemical vapor deposition. The active light-emitting region consisted of six InGaN quantum wells. Electron leakage into the p-type region was blocked by an AlGaN electron-blocking layer (EBL) barrier.

Mesa etching with inductively coupled plasma exposed the n^+-GaN contact layer. A titanium/gold mask was used to define the current aperture that was then created by aluminium ion implantation at Leonard Kroko Inc. The implant mask was removed and a second mesa etched to a depth of 400nm was followed by blanket deposition of 150nm silicon dioxide protection of the epitaxial structure during DBR porosification.

Deep trenches were then etched in the c-direction to expose the bottom DBR sidewalls. An electro-chemical process selectively etched the n^+-GaN layers of the bottom DBR structure to porosify the layer, reducing its refractive index. The DBR consisted of 16 pairs of 41nm/60nm undoped-/n^+-doped GaN. The refractive index difference of the resulting layers was around 0.83.

The blanket silicon dioxide was removed and silicon nitride passivation applied to the active region sidewalls of the first mesa. The top contact structure included 50nm annealed transparent ITO conductor. The metal contacts consisted of titanium/gold and titanium/aluminium/nickel/gold, respectively, for the p- and n-electrodes. The device was completed with a dielectric DBR constructed from quarter-wavelength pairs of silicon dioxide and silicon nitride (SiO_2/SiN_x) on a silicon nitride cavity spacer. The optical thickness of the cavity was designed to be eight wavelengths.

The team reports: "The layer thicknesses were designed to ensure that the active region of the device aligned with a peak and that the ITO aligned with a null of the standing wave profile in the cavity to maximize gain and minimize optical loss."

Pulsed measurements of 50ns width and 0.05% duty cycle were used to characterize the devices (Figure 5).

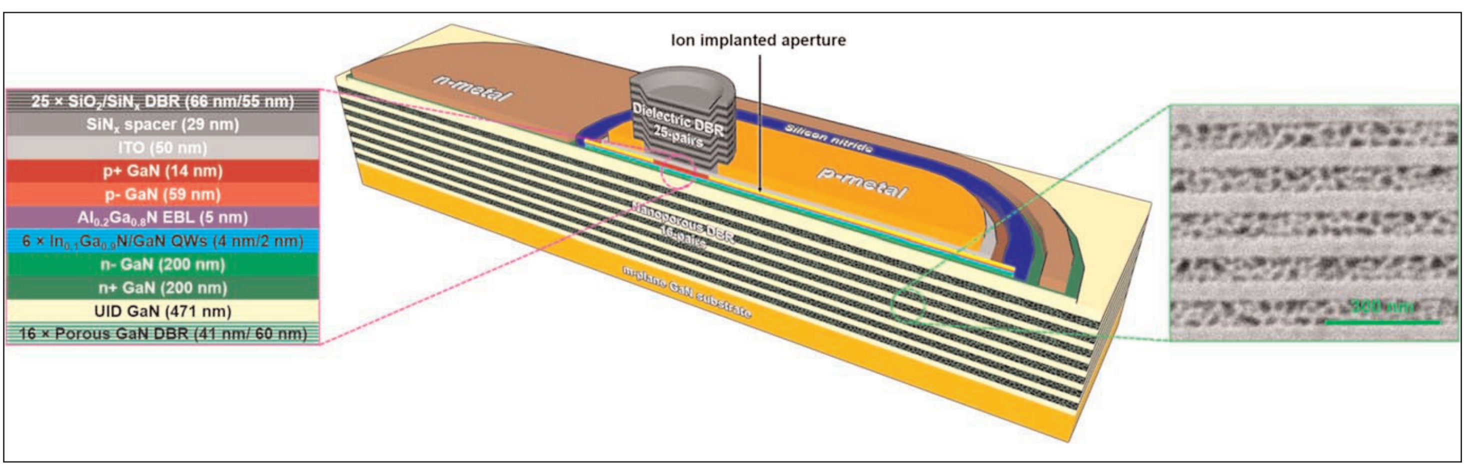

Figure 4. Cross-sectional schematic of m-plane nanoporous VCSEL and scanning electron micrograph of bottom nanoporous DBR.

Pulsed operation avoids self-heating that results in performance degradation. The threshold current density of a device with 20μm-diameter aperture was ~20kA/cm^2. The corresponding voltage was 9.6V. The top DBR had a reflectivity of 99.7%. From the fraction of light emitted from the top and bottom of the device, the researchers estimated the bottom DBR's reflectivity at 99.9%. The maximum output power was around 1.5mW — "higher than any previously reported m-plane GaN-based VCSEL," according to the team.

At twice the threshold current injection the longitudinal mode peak was at 408.7nm with a full-width at half-maximum (FWHM) of ~0.6nm. A secondary peak was seen at 409.1nm, but this is not thought to be from a higher-order mode since the expected spacing based on the cavity length was expected to be about 25.5nm. The researchers comment: "Our previous results indicate that non-uniformities in the optical cavity length due to localized changes in the effective refractive index of the nanoporous layers can lead to locally different single-longitudinal modes with the same mode number but different wavelengths, which could result in multiple peaks within the lasing spectrum."

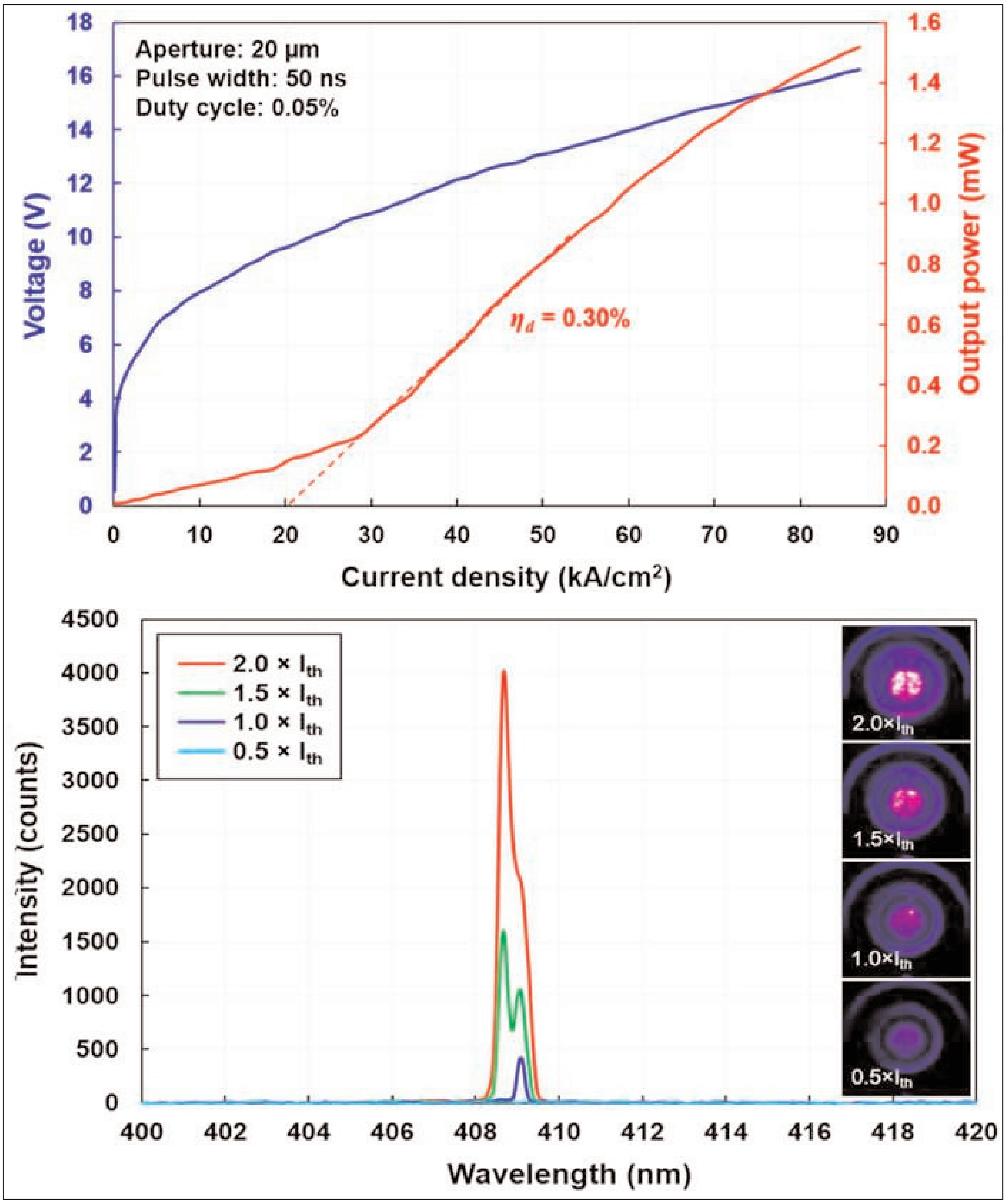

Figure 5. (a) Light output power-current density-voltage plot of 20μm-diameter nanoporous VCSEL under pulsed operation. (b) Emission spectrum under various pump currents and corresponding near-field images of aperture region.

Lasing filaments — 'spots' as seen in near-field images — with different wavelength emissions, are commonly observed in III–N VCSELs. Apart from filamentary non-uniformities, the researchers also saw a discrete divide across the aperture for the emission at twice the threshold. This was seen as being due to "the intersection of the nanopore etching fronts from the positive and negative a-directions forming a break in the aperture". The team hopes that moving the location of the aperture or pore etching from the c-direction could solve this issue.

The polarization of the light was around 94% with the maximum intensity measured when the polarizer angle was perpendicular to the [0001] c-direction — i.e. the polarization was along the [$1\bar{2}10$] a-direction.

In temperature-dependent measurements up to 333K, the characteristic temperature of the threshold current (T_0) was high at 357K. The researchers hope that reduced thresholds will result from use of a tunnel junction rather than ITO contact with the p-GaN hole injector in future devices. ■

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