Erratum: “Semipolar InGaN/GaN nanostructure light-emitting diodes on c-plane sapphire” [Appl. Phys. Express 9, 032101 (2016)]

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On the 8th line from the top on column two of page 1 of the paper, “wires14,16) and other nanostructures15,17,18) have been grown” should read “wires14,16) and other nanostructures15,17,18) have been grown”.

On the 24th line from the top on column two of page 1 of the paper, “consist exclusively of semipolar {10{11} planes. We analyze”, we need to add one sentence between “planes.” and “We analyze”. The sentence is: “Similar structures have been previously investigated by other groups.19,27,28)"

On the third line from the bottom on column one of page 2 of the paper, “conditions.27,29) Furthermore, the growth rate of p-GaN”, a new reference needs to be added as: “conditions.28,30,32) Furthermore, the growth rate of p-GaN”.

On the last line of column one of page 3 of the paper, “composition along GaN/InGaN nanowires of 300 nm height” should read “composition along semipolar SA grown active regions using micro-photoluminescence analysis28) and on GaN/InGaN nanowires of 300 nm height”.

Three new references need to be added, the numbering of the other references should be readjusted to match the added ones. The references are listed as follows:

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Semipolar InGaN/GaN nanostructure light-emitting diodes on c-plane sapphire

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The fabrication of electrically injected triangular-nanostripe core–shell semipolar III–nitrile LEDs (TLEDs) is demonstrated using interferometric lithography and catalyst-free bottom-up selective-area metal–organic chemical vapor deposition (MOCVD). This alternative approach enables semipolar orientations on inexpensive, c-plane sapphire substrates, in comparison with planar growth on free-standing GaN substrates. Transmission electron microscopy and energy dispersive X-ray spectroscopy reveal nonuniform quantum well thickness and composition, respectively, as a function of location on the triangular stripes. The broad electroluminescence spectra, wavelength shift with increasing current density, and nonlinear light vs current characteristics are well correlated with the observed quantum-well nonuniformities.

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II–nitrile LEDs and lasers grown on conventional polar c-plane sapphire substrates suffer from internal polarization-related electric fields and high dislocation densities, which limit device performance. The internal polarization-related electric fields result from discontinuities in spontaneous and piezoelectric polarization at heterojunction interfaces and lead to a low radiative efficiency due to the spatial separation of the electrons and holes within the quantum wells (QWs). This phenomenon is more pronounced in the high-indium-content wells that are needed to achieve green and yellow emission. High dislocation densities result from the heteroepitaxial growth techniques typically used for III–nitriles. Thus, there has been considerable interest in homoepitaxial devices grown on low-dislocation-density nonpolar and semipolar freestanding GaN substrates.

Although LEDs and lasers grown on free-standing nonpolar and semipolar substrates have shown promising performance, the small area and high cost of the substrates is presently a hindrance to commercial adoption. The development of approaches to realize nonpolar and semipolar orientations on less expensive and large-area substrates has also been an area of active research. Selective-area growth (SAG) on c-plane sapphire substrates using metal–organic chemical vapor deposition (MOCVD) is one approach that enables bottom-up core–shell nanostructures with large-area nonpolar and/or semipolar facets. Bottom-up nanostructures grown by SAG exhibit very low dislocation densities and potentially enable strain-relaxed templates for sufficiently small nanostructure dimensions. In addition, the increased active region area compared with that of a planar structure results in a lower carrier density for a given drive current, which could be leveraged to mitigate the effects of efficiency droop. These potential advantages of III–nitrile nanostructure LEDs have prompted considerable investigation into their growth and device performance.

III–nitrile nanostructure LEDs were previously fabricated by top-down etching of thin-film c-plane LEDs and have demonstrated improved radiative efficiency, not only due to reduced nonradiative recombination, but also due to enhanced strain relaxation and optical guiding effects. However, these LEDs still suffer from QCSE arising from polar c-plane GaN. Nanostructured LEDs with predominantly semipolar and nonpolar orientations have mainly been fabricated using the bottom-up catalyst-assisted vapor liquid solid (VLS) growth mode and catalyst-free self-assembled growth using an in situ SiNx growth dielectric. However, control of the nanowire size, morphology, and placement is difficult. Alternatively, ordered arrays of uniform nanowires and other nanostructures have been grown using SAG. The SAG method uses an ex situ-deposited dielectric that is subsequently patterned by e-beam lithography, nanoimprint lithography, or interferometric lithography to expose areas of the underlying GaN template where three-dimensional nanostructures with nonpolar and/or semipolar facets are grown. A key challenge with some nanostructure geometries (e.g., wires and rectangular stripes) is the spontaneous formation of multiple facets during the growth process. Each crystallographic facet exhibits a different surface polarity, indium incorporation, and growth rate, resulting in QWs with nonuniform thickness, indium content, and quality throughout the nanostructures. In an attempt to mitigate nonuniformities, we investigate the growth of ordered arrays of GaN-based nanostripes with triangular cross sections that consist exclusively of semipolar planes. We analyze the growth conditions of the InGaN QWs and the p-GaN on the semipolar planes, present initial results of electrically injected LEDs, and perform transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDS). Although the QWs exclusively form on semipolar planes, our studies still reveal persistent nonuniformities in the QW thickness and indium composition. Further optimization of these devices is necessary, with regards to QW uniformity and current injection, in order to compete with existing c-plane and other planar nonpolar and semipolar LEDs. A schematic of the electrically injected triangular-stripe core–shell nanostructure LED (TLED) is shown in Fig. 1.

The nanostructure LEDs were grown in a Veeco p-75 turbo-disc single-two-inch-wafer reactor using conventional MOCVD sources. First, a 2-μm-thick GaN template doped with silicon (n-type) was grown on a c-plane sapphire wafer
and functioned as the n-side of the LED. This was followed by the deposition of a 120-nm-thick growth dielectric [silicon nitride (SiN$_x$)] that was subsequently patterned into stripes using interferometric lithography. The growth dielectric also functions as an electrical isolation between the p-side and the n-side of the TLED. A secondary contact lithography step was used to selectively define LED devices with an interdigitated geometry out of the larger-area nanostructure array. This was followed by dry etching of SiN$_x$ and cleaning in piranha solution before reintroducing the wafer into the growth chamber for the LED growth.

The nanostructure growth was performed within the patterned openings in the SiN$_x$ using continuous-flow MOCVD. The nanostructure core was grown using trimethylgallium (TMGa) and ammonia (NH$_3$) as the precursors at a V/III ratio of 2000. The core was also doped with silicon to achieve n-type conduction and was grown in a mixed H$_2$–N$_2$ atmosphere (H$_2$ : N$_2$ = 2 : 1). The surface morphology of the nanostructures was analyzed using a scanning electron microscope (SEM). Under these growth conditions, the growth rate of the c-plane is much higher than that of the semipolar (1011) plane. This leads to the complete disappearance of the c-plane and the exclusive emergence of the semipolar (1011) plane, as shown in the SEM image in Fig. 2(a). The GaN triangular-stripe growth was followed by the growth of a thin layer of n-AlGaN to eliminate the reverse leakage current in the LEDs. This layer is considered to getter oxygen impurities and to fill defects in the masking pattern since AlGaN also grows on the dielectric mask. The detailed effects of the AlGaN layer are under investigation and will be discussed in a future publication. Subsequently, another layer of n-GaN was grown between the InGaN QW active region and the n-AlGaN layer to facilitate electron injection into the QWs. Four pairs of InGaN (3 nm)/GaN (9 nm) quantum wells/barriers were then grown using trimethylindium (TMIIn), triethylgallium (TEGa), and NH$_3$ under a high V/III ratio (12,000). This was followed by the growth of magnesium-doped GaN. The morphology of the triangular stripes changes after the p-GaN growth under typical hydrogen-rich conditions, as shown in Fig. 2(b). In particular, a reemergence of the c-plane is observed. This is attributed to the enhanced stability of the c-plane under hydrogen-rich growth conditions. Furthermore, the growth rate of the p-GaN on the semipolar (1011) plane is almost three times higher than that on the c-plane, as illustrated in the inset cross-sectional SEM image in Fig. 2(b). An SEM image of a fully fabricated TLED is shown in the upper inset of Fig. 3.

After the completion of the growth, electrically injected TLEDs were fabricated using standard contact photolithography techniques. An indium tin oxide (ITO) transparent-conducting current-spreading layer was deposited on the entire sample by e-beam evaporation. The ITO on the p-side was then patterned by wet etching using a solution of hydrochloric acid (HCl) and hydrogen peroxide (H$_2$O$_2$) with a ratio of 1 : 1, diluted with 10 parts water. The n-type GaN was exposed using a chlorine-based inductively coupled plasma (ICP) dry etching technique followed by electron-beam evaporation of the n-metal, which consists of 10 nm...
Fig. 4. Electroluminescence dominant wavelength as a function of current density from 0.1 to 50 A/cm². The inset shows the EL spectra for current densities ranging from 1 to 50 A/cm².

Ti/100 nm Al/100 nm Ni/200 nm Au. Finally, 5 nm Ti/300 nm Au metal pads were deposited on both the n-side and the p-side to facilitate probing of individual LEDs. The light–current density–voltage (L–J–V) characteristics under room-temperature pulsed operation (2% duty cycle, 2 µs pulse width) were obtained using a pulse generator, oscilloscope, and silicon photodiode, and the electroluminescence (EL) spectra were measured using a UV–vis spectrometer.

Figure 3 shows the L–J–V characteristics of a fully fabricated TLED, while the top inset shows an SEM image of a representative device and the bottom inset shows an optical microscopy image of a device operating at 50 A/cm². The EL spectra at different current densities are shown in the inset of Fig. 4. The EL exhibits a broad emission linewidth. In addition, the peak emission wavelength shifts significantly with increasing current density, which is not typically associated with semipolar active regions. Owing to the broad emission linewidth, the dominant emission wavelength, rather than the peak emission wavelength, was used to characterize the spectral shift. The dominant emission wavelength also exhibits a significant blue shift with increasing current density, although the shift is smaller than that of the peak emission wavelength. The dominant emission wavelength at 50 A/cm² is ~465 nm, while the peak wavelength is ~425 nm.

To investigate the origin of the broad emission linewidth and the rapid blue shift of the emission wavelength, a cross-sectional TEM image of a single triangular stripe was obtained and is shown in Fig. 5(a). The image shows the SAG mask (SiNₓ), the n-GaN, the n-AlGaN underlayer, the QWs, and the p-GaN. As shown in Figs. 5(b) and 5(c), the QWs are thicker near the apex of the triangle. Also, it is observed that the thickness of the p-GaN on the c-plane is significantly lower than that of the p-GaN on the semipolar planes. The spectral broadening and wavelength shift in Fig. 4 may be explained by the nonuniform QW thickness and long-range spatial variations in the QW indium composition. Regions with thick QWs have a lower transition energy (longer emission wavelength) than regions with thin QWs for a given indium composition. Other researchers have also observed more than a twofold variation in the indium composition along GaN/InGaN nanowires of 300 nm height using atom probe tomography (APT) and cathodoluminescence (CL), with the highest indium compositions occurring near the apexes of the nanostructures.30–32 Figures 5(d) and 5(e) show EDS measurements of the Ga and In raw atom counts, respectively, near the apex and sidewall of a nanostripe. The observed indium counts are approximately 1.5× higher near the apex. Current crowding effects at the apexes of the TLEDs were also confirmed using COMSOL Multiphysics (AC/DC module). For low injection currents, the path of least resistance is through the thick, high-indium-content QWs near the apex. This results in longer wavelength emission (~480 nm) at low current density, primarily from the QWs near the apexes. As the current density is increased, the current spreading across the nanostructure is improved and a short-wavelength EL peak near 425 nm emerges. This peak is attributed to the thin, low-indium-content QWs on the main sidewalls of the triangular stripe. The peak near 425 nm shows very small shift in wavelength as a function of current density, as expected for uniform semipolar QWs. The nonlinear nature of the L–J curve may also result from the nonuniform QW properties. We speculate that the radiative efficiency initially increases as the injection level rises owing to a more uniform current distribution on the nanostructures, leading to more emission from QW areas with higher uniformity and lower indium content.

In summary, we have demonstrated preliminary results for electrically injected triangular-nanostripe core–shell III–nitride LEDs fabricated using bottom-up SAG. TEM
and EDS reveal nonuniform quantum well thickness and composition, respectively, as a function of location on the triangular stripes. The broad EL spectra, wavelength shift with increasing current density, and nonlinear $L$–$J$ characteristics correlate well with nonuniformities in the thickness and indium composition of the QWs. The effects of these nonuniformities are likely exacerbated by poor current spreading on these nanostructures. Upon optimization of these TLEDs to being on par with existing technologies on freestanding GaN, the low cost associated with this approach could potentially become the driving force towards commercial adoption.

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