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III-nitride blue microdisplays

H. X. Jiang,[a)] S. X. Jin, J. Li, J. Shakya, and J. Y. Lin
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601

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Prototype blue microdisplays have been fabricated from InGaN/GaN quantum wells. The device has a dimension of $0.5\times0.5\,\text{mm}^2$ and consists of 10×10 pixels 12 μm in diameter. Emission properties such as electroluminescence spectra, output power versus forward current ($L-I$) characteristic, viewing angle, and uniformity have been measured. Due to the unique properties of III-nitride wide-band-gap semiconductors, microdisplays fabricated from III nitrides can potentially provide unsurpassed performance, including high-brightness/resolution/contrast, high-temperature/high-power operation, high shock resistance, wide viewing angles, full-color spectrum capability, long life, high speed, and low-power consumption, thus providing an enhancement and benefit to the present capabilities of miniature display systems.
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Microdisplays are small displays that are of such high resolution that they can only be viewed or projected with lenses or mirrors. With the use of the viewing or projection optics, the apparent size of a microdisplay is much larger than that of the actual image on the chip. For example, when viewed through a lens, a high-resolution 1 in. diagonal microdisplay can provide images comparable to viewing a 21 in. diagonal TV/computer screen. Microdisplays can satisfy demands for hands-free and highly mobile applications and meet such diverse needs as computing, entertainment, military, law enforcement, fire fighting, medical, etc. Current microdisplays are based on liquid-crystal display (LCD) technology[1] or organic light-emitting diodes (OLEDs).[2] No one else has ever tried or succeeded to fabricate semiconductor microdisplays, which require an integration of dense array microsize LEDs on a single semiconductor chip. Furthermore, color conversion for full-color displays cannot be achieved in conventional III–V or Si semiconductors. So far, large flat-panel displays based on semiconductor LEDs used on large buildings are made up of a massive number of discrete LEDs.

III-nitride wide-band-gap semiconductors have attracted great interest due to their applications for optoelectronic devices which are active in the blue and ultraviolet (UV) wavelength regions and electronic devices capable of operation at high temperatures, high-power levels, and in harsh environments.[3,4] Bright blue LEDs based on III nitrides have already paved the way for full-color displays as well as for mixing three primary colors to obtain white light for illumination by semiconductor LEDs. Due to the unique properties of III-nitride wide-band-gap semiconductors, including variable band-gap from 1.9 eV (InN) to 3.4 eV (GaN) and to 6.2 eV (AlN) with alloys, extremely high emission efficiency by indium incorporation, high-power and high-temperature operation, and extremely high shock resistance due to their mechanical hardness, ease of color down conversion from UV/blue/green to red or yellow can be obtained. Thus, there is no question that microdisplays fabricated from III nitrides can potentially provide superior display performance to LCD and OLED displays, thus providing an enhancement and benefit to the present capabilities of miniature display systems. Unlike LCDs that normally require an external light source, III-nitride blue microdisplays are self-luminescent and result in both space and power saving and allow viewing from any angle without color shift and degradation in contrast. On the other hand, current OLEDs must be driven at current densities many orders of magnitude lower than semiconductor LEDs to obtain reliable devices and, hence, are not suitable for high-intensity use. Additionally, III nitrides are grown on sapphire substrates which are transparent to light and, hence, can serve as a nature surface for image display, reducing the steps for device packaging.

Previously, we have fabricated current-injected p-GaN/InGaN/n-GaN quantum-well (QW) individual μ-disk LEDs with diameters varying from 5 to 20 μm by photolithographic patterning, inductively coupled plasma (ICP) etching, and Ohmic contact metalization.[5] It was shown that the quantum efficiency (QE) was higher in III-nitride μ-disk LEDs than in the conventional broad-area LEDs. The enhanced QE in μ-LEDs may be an inherent attribute due to microsize effects, a more efficient usage of injected current, and a possible reduction of the piezoelectric field within the QWs. Based on this result, we have also fabricated interconnected μ-disk LEDs that fit into the same device area taken up by a conventional broad-area LED. We found that by replacing a conventional broad-area LED with an interconnected μ-disk LED the external quantum efficiency was enhanced by as much as 60% due to an increased extraction efficiency and possible microsize effects.[6] In this letter, we describe the fabrication and characterization of a prototype semiconductor blue microdisplay based on p-GaN/InGaN/n-GaN QW μ-disk LEDs. Emission properties including electroluminescence (EL) spectra, $L-I$ characteristics (output power versus forward current), angular distribution of light emission or viewing angle, and light output uniformity have been measured.

The LED wafer structure used for the fabrication of microdisplays was grown on a sapphire substrate with a 30 nm GaN buffer layer and consists of 3.5 μm of Si-doped GaN, 0.1 μm of a silicon-doped superlattice comprising alternating layers of 50 Å/50 Å of AlGaN/GaN, 0.05 μm of silicon-

[a)]Electronic mail: jiang@phys.ksu.edu

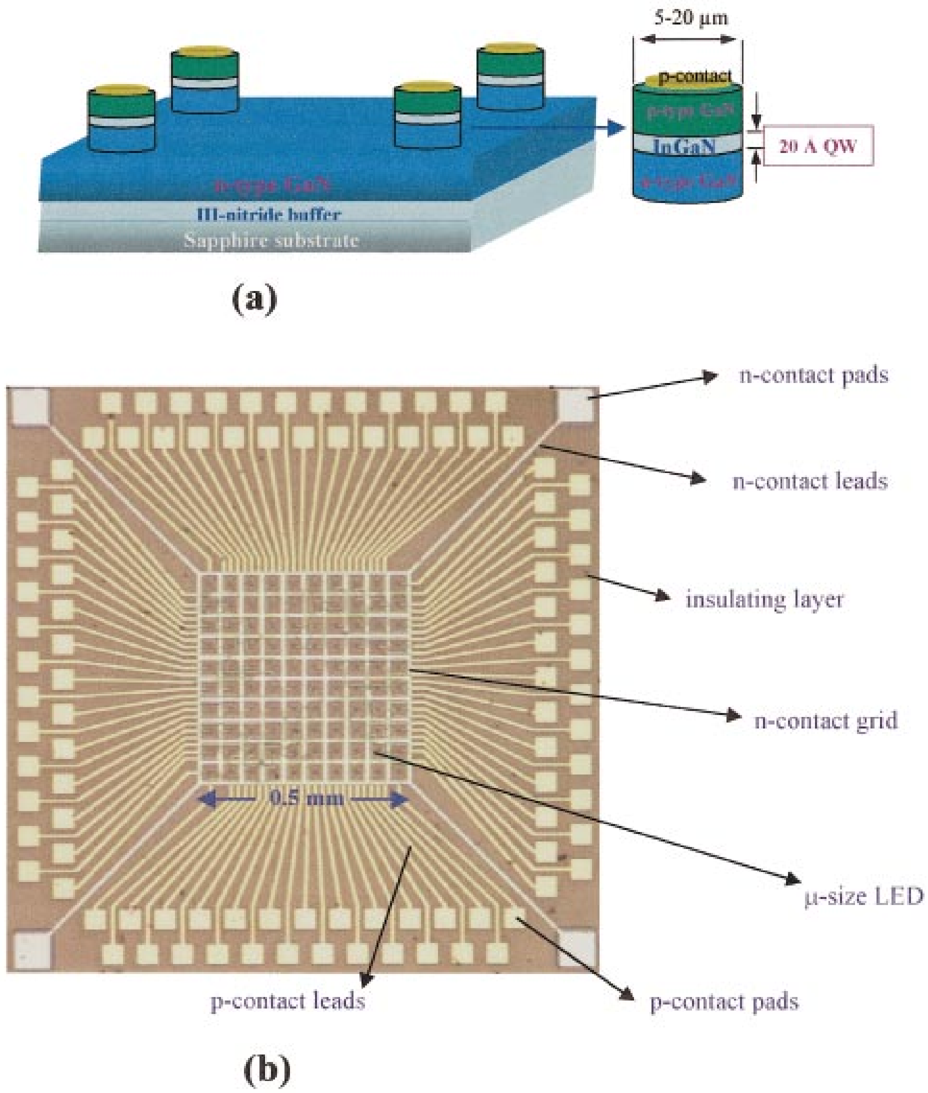

FIG. 1. (Color) (a) Schematic of μ-disk LEDs based on p-GaN/InGaN/n-GaN QWs. (b) Optical microscope image (top view) of a microdisplay fabricated from an individually addressed μ-disk LED array. The dimension of the microdisplay is $0.5\times0.5\,\mathrm{mm}^2$ (made up of 10×10 pixels, 12 μm in diameter).

doped GaN, 20 Å undoped InGaN optical active layer, 0.14 μm of a Mg-doped superlattice comprising alternating layers of 50 Å/50 Å of AlGaN/GaN, and a 0.5 μm Mg-doped GaN epilayer. The structure was then rapid thermal annealed at 950 °C for 5 s in nitrogen. This process produced p-layer concentrations of 5×10^{17} (hole mobility 12 $\mathrm{cm}^2/\mathrm{V\,s}$) and n-layer concentrations of 1.6×10^{18} (electron mobility 310 $\mathrm{cm}^2/\mathrm{V\,s}$). By incorporating the AlGaN/GaN superlattice structure[7,8] into our LED device layers, the p-type concentration was enhanced from 2×10^{17} to $5\times10^{17}\,\mathrm{cm}^{-3}$. Arrays of μ-disk LEDs with individual disk diameters varying from 5 to 20 μm, schematically shown in Fig. 1(a), were then fabricated from the InGaN/GaN QW LED wafers by photolithographic patterning, ICP dry etching, and contact metalization. Bilayers of Ni (20 nm)/Au (200 nm) and Al (300 nm)/Ti (20 nm) were deposited by electron-beam evaporation as p- and n-type Ohmic contacts.

Based on these μ-disk LED arrays, blue microdisplays

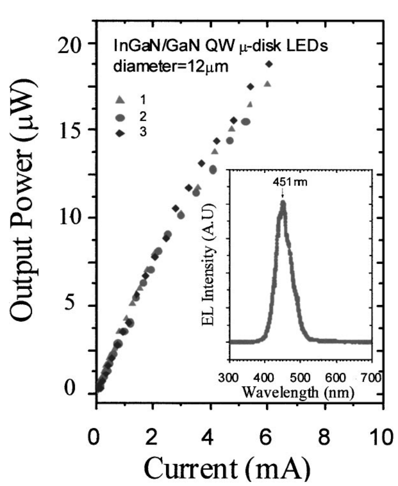

FIG. 2. $L-I$ characteristics (output power vs forward current) for three individual μ-disk LEDs within the microdisplay of Fig. 1(b) measured through the sapphire substrate on unpackaged chips. The inset is the electroluminescence (EL) spectrum of a blue μ-disk LED.

FIG. 3. (Color) Optical microscope images (top view) of the III-nitride blue microdisplay of Fig. 1(b) in action, displaying letters ''KSU,'' demonstrating the operation of a semiconductor microdisplay.

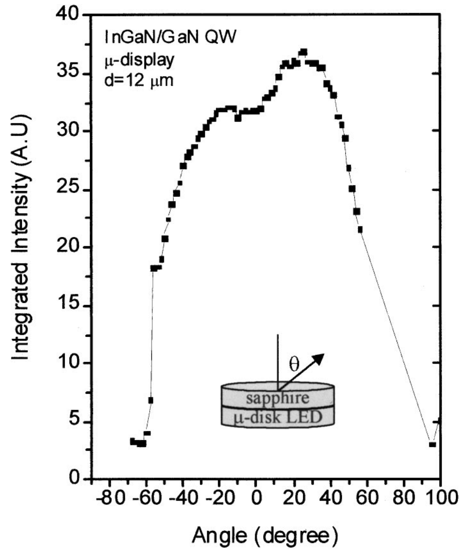

FIG. 4. Angular distribution of light emission from μ-disk LEDs measured through the sapphire substrate. The angle is measured with respect to the axis perpendicular to the μ-disk surface.

were fabricated. An optical microscope image of one of such microdisplays (device dimensions of $0.5\times0.5\,\mathrm{mm}^2$) made up of 10×10 pixels 12 μm in diameter is shown in Fig. 1(b). To obtain a working device, a dielectric layer was deposited above the etch-exposed underneath *n*-type GaN layer to isolate the *p*-type contacts from the *n*-type layer. Shown in Fig. 1(b) are also the conducting wires used to make the connection between the *n*-type Ohmic contacts and the contact pads which are used for current injection into the *n*-type Ohmic contacts. There are also conducting wires to make the connections between individual pixels through the top *p*-type Ohmic contacts and the pixel control pads which are used for current injection into *p*-type Ohmic contacts. Each pixel has its own control pad. In this array, the state of the pixels can be individually controlled. The bonding scheme of Fig. 1(b) for these microdisplays also provides an opportunity for studying fundamental properties of individual microsize light emitters. New physical phenomena and properties are expected to dominate as the device size scale approaches the wavelength of light, including modified spontaneous emission, enhanced quantum efficiency, and lasing actions in microcavities.[9]

The emission wavelength of our blue μ-disk LEDs is around 450 nm and can be varied by varying the indium content in the active layers from 400 to 540 nm. Figure 2 shows the $L-I$ characteristics (power output versus forward current) of three individual 12 μm blue μ-disk LEDs within the microdisplay of Fig. 1(b) measured from the sapphire substrate side, which demonstrated that the uniformity among these μ-disk LEDs is quite good. The inset of Fig. 2 shows the electroluminescence spectrum of our blue μ-disk LEDs.

The operation of these InGaN/GaN QW microdisplays has been demonstrated. Figure 3 shows the optical microscope images of the blue microdisplay of Fig. 1(b) in action, displaying a sequence of letters ''KSU.'' The angular distribution of light emission from these μ-disk LEDs has been measured through the sapphire substrate and the result is shown in Fig. 4. It can be seen that the escape cone for the isotropic spontaneous emission from these μ-disk LEDs through the sapphire substrate is quite larger and is about 100°. The result thus demonstrated that microdisplays fabricated from III-nitride QWs grown on sapphire substrates can provide a very wide viewing angle.

In order to fabricate high information content matrix microdisplays, concepts of bonding schemes have to be adapted. For example, a real high-resolution microdisplay would contain 800×600 pixels or more. Since the sapphire substrate side is utilized to display images, flip-chip bounding may be employed to integrate the μ-disk LED array with a matrix of discrete electrodes through the *p*-type contacts, each one corresponding to a point in the matrix. Full-color displays can also be realized by color down conversion since InGaN/GaN QW μ-disk LEDs inherently emit blue light. Based on our preliminary results and the inherent physical properties of III nitrides, we believe that III-nitride microdisplays have an unsurpassed ability to provide high-brightness/resolution/contrast, wide temperature operating ranges, high shock resistance, wide viewing angles, full-color spectrum capability by color down conversion, long life, high speed, and low-power consumption.

In summary, we have fabricated and characterized blue microdisplays fabricated from InGaN/GaN QWs. These devices are useful in areas such as wearable displays, full-color minidisplays, emitters for remote free-space functions, short distance optical communication, and optical interconnects. Since the fabrication of microsize LEDs is much less sophisticated than vertical-cavity surface-emitting lasers (VCSELs), our blue microsize LED arrays are very attractive for inexpensive optical links. The bonding scheme of these prototype microdisplays can also be utilized to study the fundamental properties of individual microsize light emitters, including modified spontaneous emission, enhanced quantum efficiency, and lasing actions in microcavities, all of which are important for developing suitable materials and device design for future III-nitride microsize optoelectronic devices such as micro-LEDs, micro-vertical-cavity LEDs, microcavity laser diodes, microsize detectors, and VCSELs.

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