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Over the last decade the physics of micro-size photonic structures and devices have been investigated and much progress made. Although many possible applications for these devices were identified long ago, it is only recently that technological advances have enabled a transition from basic research to practical devices.

Advances in III-nitride micro-size light emitters

By varying indium content in the InGaN active layers, the emission wavelengths of the micro-size LEDs can be varied from green to purple... We have succeeded in interconnecting hundreds of III-nitride micro-size LEDs...so that they are turned on and off simultaneously and fit into the same device area as a conventional LED of 300 x 300 μm².

The various types of micro-photonic devices range from arrays of micro-emitters, detectors and waveguides to optical switches and photonic crystals.Together with their two-dimensional array nature, they enable many important applications such as optical communications, signal and image processing, optical interconnects, computing, enhanced energy conversion and storage, and chemical, biohazard substance and disease detection. Other applications include micro-satellites, smart cards, etc.

In particular, III-nitride optoelectronic devices offer benefits including:

- UV/blue light emission (allowing higher optical storage density and resolution as well as the ability for chemical- and biohazard substance detection);
- the ability to operate at very high temperatures and power levels (due to their mechanical hardness and larger bandgaps);
- high speed (due to the intrinsically rapid radiative recombination rates); and
- a large band offset of 2.8 eV or 4.3 eV for GaN/AlGaN or InGaN/AlGaN heterostructures (allowing novel quantum well devices, and high emission efficiencies).

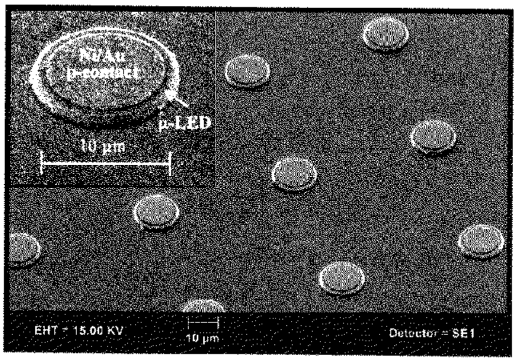


Figure 1. Scanning electron microscope (SEM) image of a III-nitride micro-size LED array.

Together, these may allow the creation of micro-size optoelectronic and photonic devices with unprecedented properties and functions. Here we discuss some of the recent advances in III-nitride micro-size light emitters.

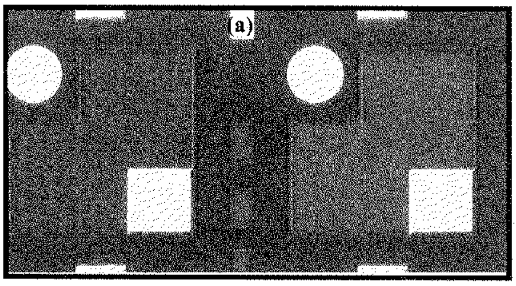
III-nitride micro-LED fabrication

Recently our research group at Kansas State University has successfully fabricated electrically pumped individual III-nitride micro-size LEDs and micro-LED arrays and observed enhanced quantum efficiencies.

The micro-size LEDs were fabricated from our research-laboratory-grown LED wafers, based on the InGaN/GaN quantum well (QW) LED structure. Our LED structures were grown on sapphire substrates with 30 nm GaN buffer layers. The QW device layers comprise:

- 3.5 μm of silicon-doped GaN,
- 0.1 μm of silicon-doped superlattice (consisting of alternating layers of 50Å/50Å of AlGaN/GaN),
- 50Å of silicon-doped GaN,
- a 20Å undoped InGaN active layer,
- 0.14 μm of Mg-doped superlattice (consisting of alternating layers of 50Å/50Å of AlGaN/GaN), and
- 0.5 μm Mg-doped GaN epilayer.

This is followed by a rapid thermal anneal at 950°C for 5 s in nitrogen.



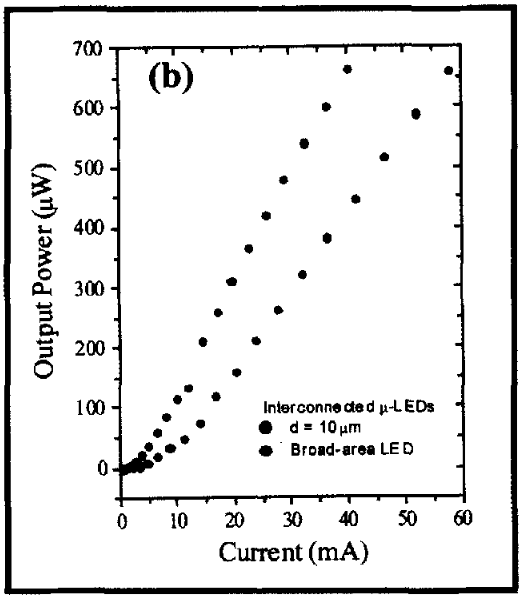


Figure 2. (a) Optical microscope images of a Kansus State University conventional broad-area (300 x 300 μm²) LED (right) and a Kansus State University interconnected microdisk LED with individual disk diameter of 10 μm (left). (b) Comparison of L-I characteristics of an interconnected InGaN/GaN quantum well microdisk LED and a conventional broad-area LED fabricated from the same wafer measured on the top surface of unpackaged chips.

This process produced p-layer concentrations of 5×10^{17} cm^{-3} (with hole mobility of 12 cm^2/Vs) and n-layer concentrations of 1.6×10^{18} cm^{-3} (with electron mobility of 310 cm^2/Vs).

By incorporating the AlGaN/GaN superlattice structure into our LED device layers, the p-type concentration was enhanced from 2×10^{17} to 5×10^{17} cm^{-3}.

Microdisk arrays such as that shown in Figure 1 with individual disk size varying from 5 to 20 μm were fabricated by photolithographic patterning and inductively coupled plasma (ICP) dry etching. Bi-layers of Ni (20nm)/Au (200nm) and Al (300nm)/Ti (20nm) were deposited by electron-beam evaporation as p- and n-type Ohmic contacts. These were thermally annealed in nitrogen ambient for 5 minutes at 500°C and 650°C, respectively.

By varying indium content in the InGaN active layers, the emission wavelengths of the micro-size LEDs can be varied from green to purple (390 to 450 nm).

Micro-size LEDs for boosting emission efficiencies

Bright blue LEDs based on III-nitrides paved the way for full-colour displays and raised the possibility of mixing three primary colours to obtain white light for general illumination by LEDs.
If all household 100 W light bulbs were replaced by white LEDs, the total energy savings in the world would approach US$100bn/year and the associated reduction in environmental pollution would be enormous.

The current approach for achieving white light using LEDs is to use phosphors to down-convert the emission from a blue or UV LED. In such an application, improving the LED efficiency is a key step.

We have succeeded in interconnecting hundreds of III-nitride micro-size LEDs (of the order of 10 μm in diameter) - see Figure 2 - so that they are turned on and off simultaneously and fit into the same device area as a conventional LED of about 300 x 300 μm².

The performance characteristics were compared with those of conventional LEDs fabricated from the same wafers. While the forward biased voltage (V_F) was slightly higher at 20 mA, the interconnected microdisk LEDs can boost overall emission efficiency by as much as 50%.

It is believed that the device can overcome the two biggest problems facing LEDs: the low extraction efficiencies (due to the total internal reflection occurring at the LED/air interface) and current spreading.

Additionally, the strain-induced piezoelectric field in the active QW regions may be reduced, resulting in increased internal quantum efficiency.

Furthermore, the processing steps of these interconnected micro-size LEDs are the same as for conventional LEDs. It is thus expected that the manufacture yield will rival with conventional LEDs. Currently, our group is working on the optimal configuration of this novel LED architecture, including the size of micro-LEDs, the spacing between the micro-LEDs, and the etching depth.

III-nitride microdisplays

We have also developed and patented a bonding scheme that allows us to address microdisk pixels individually in an array comprising many III-nitride micro-emitters/micro-detectors.

Our research group at Kansas State University has successfully fabricated electrically-pumped individual III-nitride micro-size LEDs and micro-LED arrays and observed enhanced quantum efficiencies.

Micro-LED arrays may be used to replace lasers as inexpensive short-distance optical links.

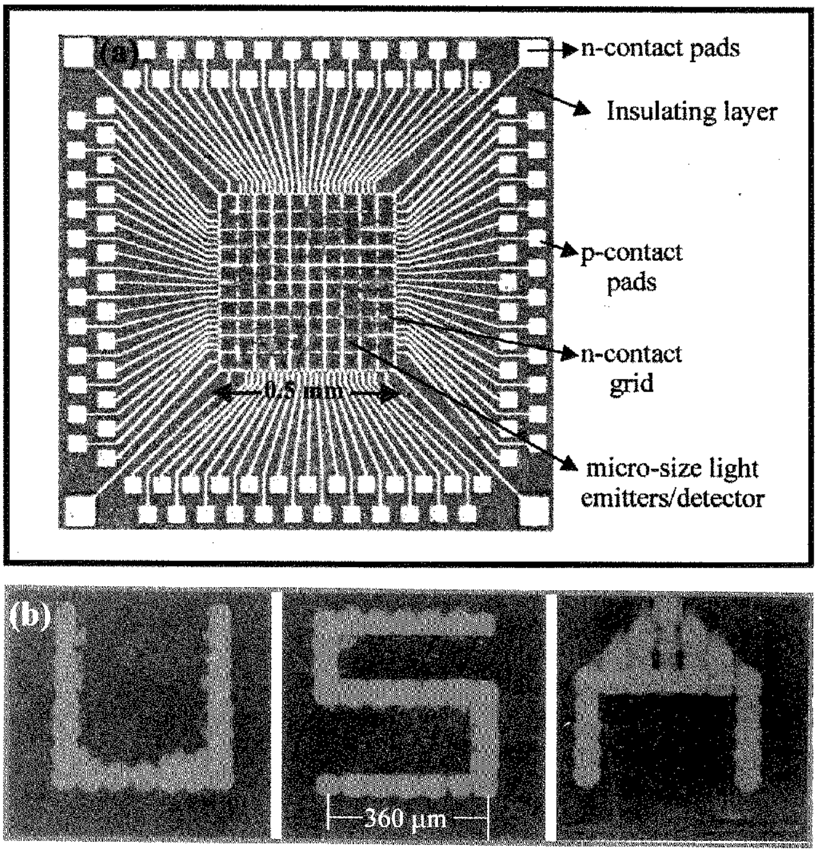


Figure 3. Optical microscope images of (a) a bonding scheme that allows us to address each microdisk pixel individually (or a III-nitride blue microdisplay); (b) the III-nitride blue microdisplay (a) in action.

For examples, when an array such as that in Figure 1 was forward biased and individually addressed, we successfully demonstrated the operation of a prototype blue microdisplay. The prototype device has dimensions of 0.5 x 0.5 mm^2 and consists of 10 x 10 pixels 12 μm in diameter (see Figure 3a). Figure 3(b) shows optical microscope images of a blue microdisplay in action, demonstrating the operation of the first prototype semiconductor microdisplay.

The bonding scheme of these microdisplays was also used to characterise individual III-nitride micro-LEDs under current injection conditions. Figure 4(a) shows the L-I characteristic (power output versus forward current) of three individual 12 μm micro-LEDs within a microdisplay of Figure 3, showing that the uniformity of light emission among these micro-LEDs is quite good.

The angular distribution of light emission has been measured through the sapphire substrate. It was seen that the escape cone for the isotropic spontaneous emission is quite larger (about 100°), so microdisplays fabricated from III-nitride QWs grown on sapphire substrates can provide a very wide viewing angle.

The operating speed of these micro-LEDs has also been measured. The turn-on response was very fast (below 30 ps), while the turn-off time τ_{off} decreased with a decrease in micro-LED size, e.g. from 0.21 to 0.15 ns when the size was reduced from 15 to 8 μm (Figure 4b). This behaviour is expected, since the effects of surface recombination are enhanced in smaller micro-LEDs.

On the other hand, the increased operating speed may also be a result of an enhanced radiative recombination rate in micro-LEDs due to the micro-cavity effect.

With this fast speed and other advantages such as long operation lifetime, III-nitride micro-LED arrays may be used to replace lasers as inexpensive short-distance optical links, e.g. between computer boards with operating frequencies of up to 10 GHz.

Current microdisplays are based on Liquid Crystal Display technology or Organic LEDs. High-information-content semiconductor

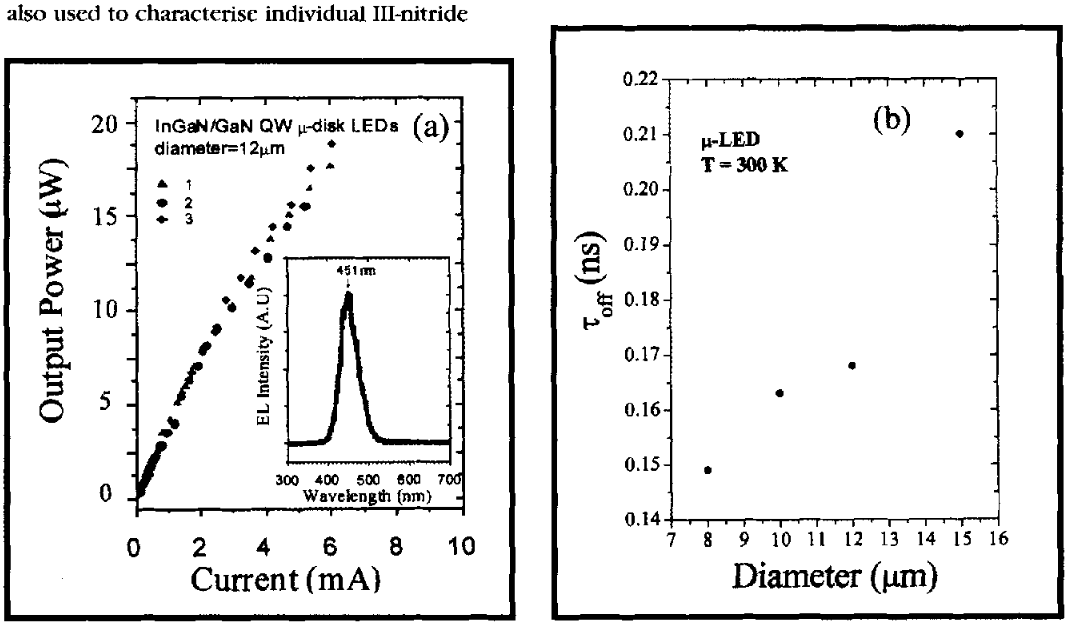


Figure 4. (a) L-I characteristics for three Kansas State University individual microdisk LEDs within a microdisplay. The inset is an electroluminescent (EL) spectrum of a blue microdisk LED. The measurements were made through the sapphire substrate on unpackaged chips. (b) The size dependence of the turn-off time of the III-nitride microdisk LEDs.

microdisplays - which require the integration of a dense array of micro-size LEDs on a single semiconductor chip - have not yet been successfully fabricated. Furthermore, colour conversion for full-colour displays cannot be achieved in conventional III-V or silicon semiconductors. So far, large Flat Panel Displays based on semiconductor LEDs used on large buildings and stadiums are made up of a massive number of discrete LEDs.

Based on the results obtained from this prototype microdisplay and the unique properties of III-nitrides, we believe that III-nitride microdisplays can potentially provide unsurpassed performance, including: self-luminescence, high brightness/resolution/contrast, high-temperature/high-power operation, high shock resistance, wide field-of-view, full-colour spectrum capability, long life, high speed, and low power consumption. On the other hand, the ability of 2D array integration with advantages of high speed, high resolution, low temperature sensitivity, and applicability under versatile conditions also make III-nitride micro-LEDs a potential candidate for light sources in short-distance optical communications.

Summary

We believe that micro- and nano-photonic devices are going to shape the next decade's infrastructures for communications, signal and image processing, energy conversion and storage, chemical-bio-hazard substance and disease detection.

Like the integration of silicon transistors in the 1960s, micro- and nano-photonics are expected to undergo integration in large arrays with other optical circuit elements to form optical chips.

Nevertheless, further understanding of fundamental properties is required, and novel materials (such as III-nitrides) and device structures must be explored to accelerate the development of micro- and nano-photonics technology to its full potential.

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