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Advances in III-Nitride Micro-Photonic Devices

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Over the last decade the physics of micro-size photonic structures and devices has been investigated. 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 device. These micro-photonic devices range from arrays of micro-emitters, detectors, waveguides to optical switches and photonic crystals. Together with their two-dimensional array nature, these micro-photonic devices open many important applications such as optical communications, signal and image processing, optical interconnects, computing, enhanced energy conversion and storage, chemical, biohazard substance, and disease detection.

III-nitride optoelectronic devices offer benefits including UV/blue 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 band gaps, high speed due to the intrinsically rapid radiative recombination rates, and large band offset of 2.8 eV or 4.3 eV for GaN/AlGaN or InGaN/AlGaN heterostructures allowing novel quantum well (QW) devices, and high emission efficiencies. These together may allow the creation of micro-size optoelectronic and photonic devices with unprecedented properties and functions. 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 QW LED structure. Microdisk arrays with individual disk size varying from 5 to 20 μm were fabricated by photolithographic patterning and inductively coupled plasma (ICP) dry etching. The emission wavelengths of our micro-size LEDs vary from green to purple (390 to 450 nm) by varying In content in the InGaN active layers [1-4].

I. Micro-size LEDs for Boosting Emission Efficiencies

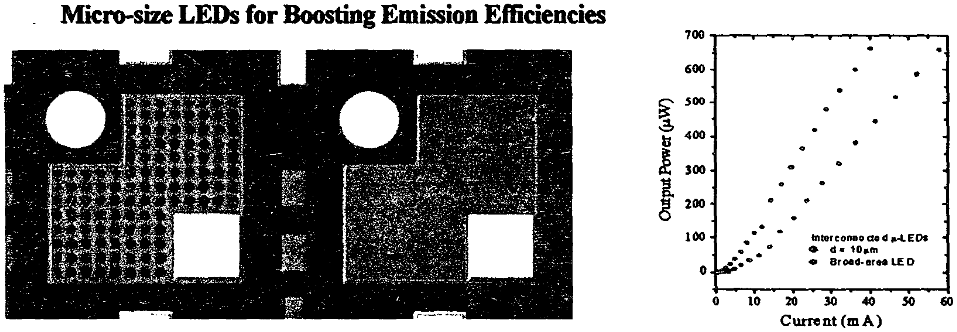

Figure 1. (Left) A KSU interconnected μ-disk LED and a conventional broad area LED. (Right) Comparison of output power versus input current (L-I characteristics) of an interconnected InGaN/GaN QW μ-disk LED with individual disk diameter of 10 μm and a conventional broad-area LED with the same device area (300 x 300 μm²) fabricated from the same InGaN/GaN quantum well LED wafer measured on the top surface of unpackaged chips.

Improving the LED efficiency is a key step for many applications. We have succeeded in interconnecting hundreds of III-nitride micro-size LEDs (size on the order of 10 μm in diameter). As illustrated in Fig. 1, these microdisk LEDs are interconnected in a manner that they are turned on and off simultaneously and fit into the same device area taken up by a conventional LED of about 300 x 300 μm^2. The performance characteristics of the novel devices were compared with those of the conventional LEDs fabricated from the same LED wafers. It was shown that, while the forward biased voltage (V_F) was slightly higher at 20 mA, the interconnected microdisk LEDs can boost the overall emission efficiency by as much as 60%. It is believed that the novel device can overcome two biggest problems facing LEDs - the low extraction efficiencies due to the total internal reflection occurring at the LED/air interface and the problem of current spreading. Additionally, the strain induced piezoelectric field in the active QW regions may be reduced in micro-size LEDs, resulting in increased internal quantum efficiency. Furthermore, the processing steps of these interconnected micro-size LEDs are the same as those of the conventional LEDs. It is thus expected the manufacture yield of these novel LEDs to rival with the conventional LEDs.

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II. 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. For examples, when an array was forward biased and individually addressed, we have successfully demonstrated the operation of a prototype blue microdisplay. The prototype device has a dimension of 0.5 x 0.5 mm^2 and consists of 10 x 10 pixels of 12 microns in diameter. Figure 2 shows optical microscope images of a blue microdisplay in action, displaying letters KSU. This demonstrates the operation of the first prototype semiconductor microdisplay.

Fig. 2 Optical microscope image of a III-nitride blue microdisplay in action, displaying letters "KSU".

The bonding scheme of these microdisplays was also utilized to characterize individual III-nitride micro-LEDs under current injection conditions. 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-luminescent, high brightness/resolution/contrast, high temperature/high power operation, high shock resistance, wide field-of-view, full color 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 make III-nitride micro-LEDs as a potential candidate for light sources in short distance optical communications.

III. III-Nitride Sub-micron Waveguides

We have successful fabricated sub-micron waveguide structures based on AlGaN/GaN multiple-quantum wells (MQWs). The MQWs were grown by MOCVD on sapphire substrates and the waveguides were fabricated by electron-beam lithography and inductively-coupled plasma (ICP) dry etching. The waveguides were patterned with fixed width but orientations varying from -30° to 60° relative to the a-axis of GaN. Optical emission from these structures was studied by photoluminescence spectroscopy. It was found that, when the waveguide width was reduced to below 0.7 μm, the peak position and line-width of the exciton emission peak varied systematically with orientations of the waveguides and followed the six-fold symmetry of wurtzite structure. This is most likely related to the anisotropy of the exciton/carrier diffusion coefficient along the different crystal orientations in quasi one-dimensional case and presents a good example of unforeseen phenomena that could occur in structures with reduced dimension.

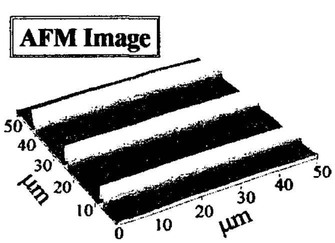

Fig. 3 AFM image of AlGaN/GaN MQW waveguides

The light propagation in AlGaN/GaN MQW waveguides was investigated by time-resolved photoluminescence (PL) spectroscopy. The waveguides were patterned with fixed width of 0.5 μm and length 500 μm. Our results reveal a remarkable decrease in the PL intensity as well as increase in time delay of the temporal response as the location of the laser excitation spot on the waveguide is varied. These results can be understood in terms of polariton propagation in the waveguides. From the time delay of the temporal response, it has been determined that the speed of generated polaritons, with energy corresponding to the well transitions in the waveguides, is approximately $(1.26 \pm 0.16) \times 10^7$ m/sec. The implications of these results to waveguiding in optical devices based on the group III-nitride semiconductors will be discussed.

1. S. X. Jin, J. Li, J. Z. Li, J. Y. Lin, and H. X. Jiang, "GaN Microdisk Light Emitting Diodes," Appl. Phys. Lett. **76**, 631 (2000).
2. S. X. Jin, J. Li, J. Y. Lin, and H. X. Jiang "InGaN/GaN Quantum Well Interconnected Microdisk Light Emitting Diodes," Appl. Phys. Lett. **77**, 3236 (2000).
3. H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-Nitride Blue Microdisplays," Appl. Phys. Lett. **78**, 1303 (2001).
4. S. X. Jin, J. Li, J. Shakya, J. Y. Lin, and H. X. Jiang, "Size Dependence of III-Nitride Microdisk Light Emitting Diode Characteristics," Appl. Phys. Lett. **78**, 3532 (2001).