Driving forward microLED video displays

Micron-size light-emitting diode arrays based on nitride semiconductors have been developed for displays and light sources for more than a decade. By combining such arrays with silicon CMOS active drive circuits, US researchers have now created microdisplays capable of delivering video images. Mike Cooke reports.

US university, commercial and military researchers have reported the realization of high-resolution solid-state self-emissive microdisplays based on III-nitride semiconductor micro-size light-emitting diodes (μLEDs) capable of delivering video graphics images [Jacob Day et al, Appl. Phys. Lett., vol99, p031116, 2011]. The research team is variously based at Texas Tech University, III-N Technology Inc, and the US Army's Night Vision and Electronic Sensors Directorate.

According to the Texas/III-N/US Army researchers, their work "clearly demonstrated that III-nitride microdisplays are a favorable competing technology compared to liquid-crystal display (LCD), organic LED (OLED), digital light processing (DLP), and laser beam steering (LBS) for ultra-portable products such as next-generation pico-projectors, wearable displays, and head-up displays."

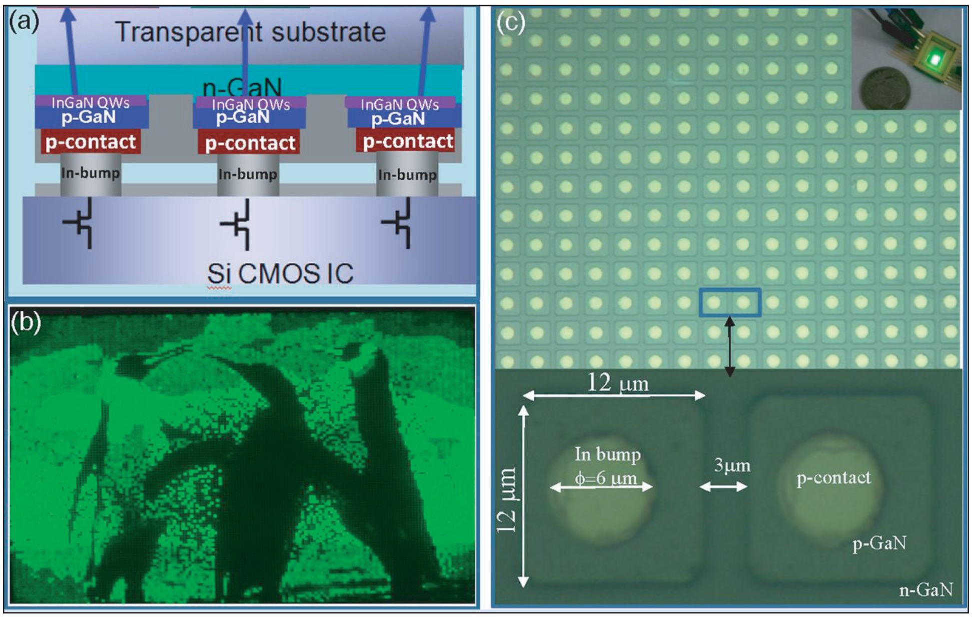

Figure 1. (a) Flip-chip bonding between μLED matrix array and CMOS driver IC via indium bumps making highly integrated single-package microdisplay. (b) Grayscale projected image of penguins from green InGaN microdisplay (pixel size 12μm, pitch 15μm) operating at 1μA/pixel drive current. (c) Zoom-in image of segment of InGaN μLED array chip showing μLED pixels and indium bumps viewed from transparent sapphire side. Top inset shows fully assembled green InGaN microdisplay (160x120 pixels) in operation.

Potential advantages of μLEDs for display applications, according to these researchers, include compact format and lower power use, compared with systems that require an external light source, such as LCD (Table 1).

Also the angle of view does not create color shifts or contrast degradation, as happens in LCD systems. Similar problems arise with DLP/LBS systems that use micro-electro-mechanical systems (MEMS) to direct light in particular directions.

Organic LEDs are another possibility for self-emissive displays, but the present efficiency of such devices is low. Lifetimes are also limited in many systems using laser diode or MEMS parts in their operation.

Further attractions of μLEDs for self-emissive displays include high brightness, contrast, resolution, reliability, and long-life. The μLED displays can also be viewed under bright sunlight, unlike standard LCD systems.

Displays based on nitride semiconductor LEDs also have features of particular interest for the military since they can be operated in harsh environments of high and low temperature with high humidity conditions. Operational lifetimes can also reach beyond 100,000 hours.

Despite fast response times of 0.2ns previously being measured in III-N μLEDs, up to now video performance has not been reached in nitride μLED technology.

One drawback has been that previous attempts to use μLED arrays to form 'monolithic' displays incorporating all the wiring to the n- and p-contacts of the individual LED pixels have been restricted to passive drive circuits that access the devices a row at a time with the pixel columns

Table 1. Texas/III–N/US Army comparison of various technologies for microdisplays.

Technology	Liquid crystal	Organic LED	III-N μLED	Digital light processing	Laser beam steering
Mechanism	Backlight/LED	Self-emissive	Self-emissive	Backlight/LED	Backlight/LD
Luminous efficacy	Medium	Low	High	High	High
Luminance (cd/m^2)	3000 (full color) ~10^4 (green)	1500 (full color) ~10^3 (yellow)	~10^5 (full color) ~10^7 (blue/green)	~1000 (full color)	~1000 (full color)
Contrast ratio	200:1 (intrinsic)	Very high >10,000:1	Very high >10,000:1	High	High
Response time	ms	μs	ns	ms	Ms
Operating temperature	0 to 60ºC requires heater	−50 to 70ºC	−100 to 120ºC	To be determined	To be determined
Shock Low resistance	Medium	High	Medium	Medium	
Lifetime	Medium	Medium	Long	Medium (limited by MEMS)	Short (limited by laser diodes)
Cost	Low	Low	Low	High	High

driven in series. This requires a source voltage of about 30V, which is not convenient for mobile devices. Heat dissipation is also a problem from such operation.

Active hybrid

The Texas/III-N/US Army team adopted instead a hybrid approach (Figure 1) that allowed direct 'active' connection between a driver IC and the individual μLED devices.

The nitride semiconductor structures were grown on sapphire substrates using MOCVD. The μLED arrays were produced through etching and metallization of this material. The pixel size was 12μm and the pitch between pixels was 15μm.

The researchers were particularly concerned about the poor hole transport properties in p-GaN that result from the high activation energy of the magnesium (Mg) doping (lowering sheet carrier density) and the low hole mobility in the material. These physical characteristics tend to create hole injection problems and high contact resistance. In practical terms, these properties lead to self-heating, high threshold currents and turn-on voltages, reduced reliability and shortening of operating life. In the μLEDs, the researchers used heavy Mg doping to minimize contact resistance.

The researchers also designed matching silicon CMOS active matrix 640x480 and 160x120 microdisplay controller ICs to provide the 0.5–1.0μA drive current for the μLEDs. An active-matrix display stores the value and provides the drive current for individual pixels in parallel, as opposed to the series arrangement of passive-mode.

The μLED array was flipped on to the driver IC and bonded using indium bumps that provided thousands of connections through this hybrid integration of the two devices. The anode (n-type contact) was the common terminal and the cathode (p-type contact) provided the lighting control.

The measured light output (Figure 2a) from green 12μm pixels was 1millicandela/microamp (mcd/μA), with almost linear dependence up to 100μA drive current. The wavelength of 517nm corresponds to blue-green, but is pretty close to true green (520–570nm). With 1μA driving each pixel in an array of 15μm pitch, one gets a brightness of $4x10^6 cd/m^2$ (=1mcd/$(15μm)^2$). "This luminance level is several orders of magnitude higher than those of LCDs and OLEDs," the team says.

The forward voltage for 1μA drive current was 2.6V. This gives power dissipation of 0.8W (640x480x1μAx2.6V) for a full 640x480 VGA display. A normal image would generally require less (~25%).

Current density in the 12μm pixels for 1μA is $0.7A/cm^2$ (1μA/$(12μm)^2$). Conventional 300μm x 300μm indicator LEDs driven at 20mA are subjected to current densities around $22A/cm^2$, i.e. about 30x the value for the video graphics array (VGA) pixels. Since high drive currents are associated with shortened lifetimes, the ability to drive at low current densities implies that the VGAs should be reliable beyond the 100,000 hours of 20mA standard indicator LED operation.

Temperature dependence was also assessed for 462nm blue μLED arrays (Figure 2b). It was found that increasing to 100ºC reduced the intensity of μLED emission by about 10%. In the opposite direction, reducing to −100ºC had no significant effect on emission.

The operating voltage at 0.1mA varied between 4.1V at −100ºC and 2.9V at +100ºC. The reduced voltage at high temperature is attributed to the higher equilibrium hole concentrations in the devices under these thermally activated conditions. The activation energy of the magnesium acceptors in GaN is about 160meV.

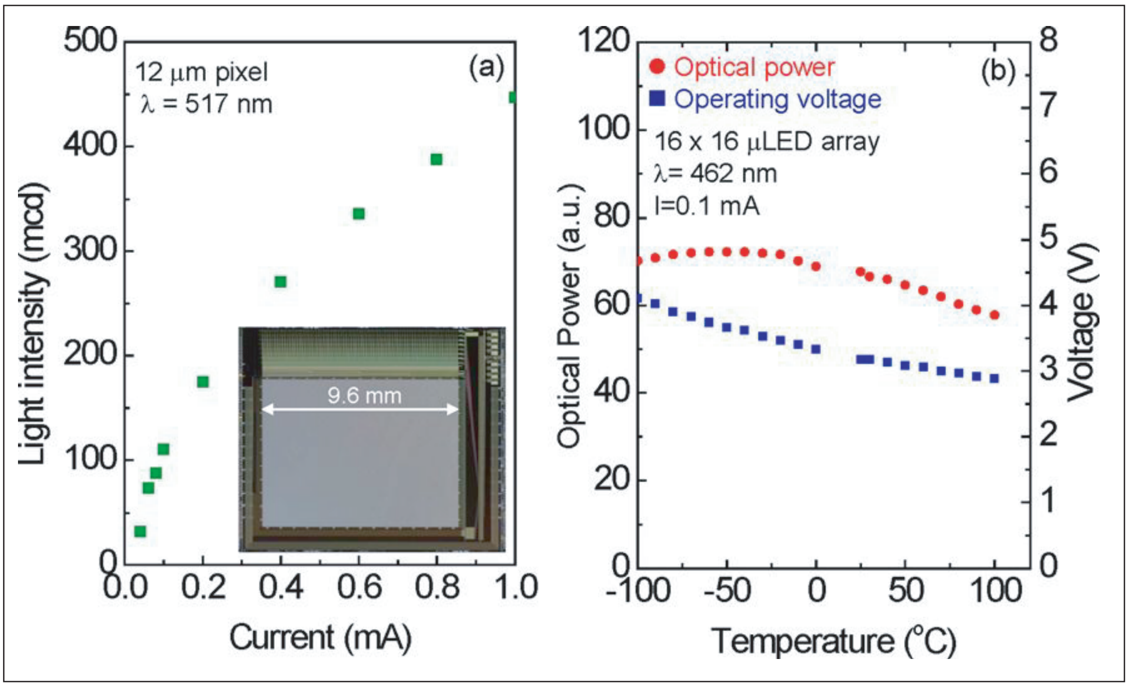

Figure 2. (a) Luminance of single green μLED pixel as function of drive current; inset shows micrograph of fully assembled VGA microdisplay (640x480 pixels). (b) Temperature dependence of relative emission optical power of InGaN μLED array.

The k_BT values of –100ºC, room temperature (300K, ~27ºC) and +100ºC are 15meV, 26meV, and 32meV, respectively.

The researchers comment: "The T dependence of the μLED emission intensity in Figure 2b represents the lowest thermal quenching ever reported for any type of microdisplay." This thermal stability is attributed to the use of nitride semiconductors.

μLED light works

Work on μLED arrays has not just been on the self-emissive display application, but also includes various light source circuits such as single-chip high-voltage AC-LEDs for solid-state lighting, biophotonics, and for microscopy.

Three of the researchers from the Texas/III-N/US Army group — J. Li, J. Y. Lin, and H. X. Jiang — have been working on μLED arrays since 1999, when they were based at Kansas State University. Since then, husband and wife team professors Hongxing Jiang and Jingyu Lin have co-founded III-N Technology Inc and AC LED Lighting LLC. These companies hold several patents concerning the application of μLED arrays to high-voltage DC/AC (110V, 220V, etc.) and general lighting.

Optogenetics [www.stanford.edu/group/dlab/optogenetics] is a new biological research technique that combines genetic engineering and light to control events in targeted cells. These cells can be located in living tissue, such as freely moving animals, including mammals. The control signals can have a millisecond timescale.

The genetic engineering involves incorporating light-sensitive parts from one species into cells of other species. In particular, a light-activated ion channel in the cell wall of a species of swamp algae was discovered in 2003 by the Max-Planck Institute for Biophysics in Germany. This was followed by genetic engineering efforts to incorporate this ChannelRhodopsin-2 (Ch-R2) structure in the cells of other animals (including mice). The channel can transport sodium and calcium ions, which are used in neural cells to create and suddenly change potential differences. The Ch-R2 channel has a blue absorption peak around 470nm that can be matched by nitride semiconductor blue light-emitting structures.

Nitride semiconductor μLEDs have been used by UK-based researchers at the Institute of Biomedical Engineering and the Department of Neuroscience of Imperial College, King's College and University of Strathclyde to control the firing of neurons with light in this way. In addition to optogenetic neuromodulation, Imperial College has used nitride semiconductor μLEDs as controllable light sources for microscopy.

(Incidentally nitride semiconductors may provide more suitable substrates for neuronal growth in-vitro than silicon, making nitride semiconductors a suitable candidate for microelectrode arrays. Otto-von-Guericke-University-Magdeburg has recently reported the use of unipolar source–drain voltage pulses from GaN/AlGaN high-electron-mobility transistors (HEMTs) to stimulate cultured neuronal networks obtained from embryonic rat cerebral cortex.)

Nitride semiconductor sources would seem suitable for further biophotonic applications. For example, nitride LEDs are being developed to produce ultraviolet (UV) radiation to sterilize surfaces and purify water. University of Strathclyde has produced 370nm UV 8x8 arrays of 72μm-diameter μLEDs. ■

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