III–nitride prospects for VLC applications

Mike Cooke reports on some recent research on various laser and non-laser emitters, along with detectors and waveguides.

Visible light communication (VLC) has been going on for a long time, from semaphore between ships to waving lanterns about to direct smuggling operations. And of course, sign languages date from prehistory and are still used by deaf communities and desperate tourists. Historical communication is based on writing. And at the dawn of the electronic age, Alexander Graham Bell experimented with a 'photophone' in the 1880s.

Electronic VLC systems need transmitters, receivers and a transmission medium. Although air is the most common medium, there is also interest in underwater optical communication (UWOC) and various waveguide materials such as short-range plastic optical fiber (POF) communication. For transmission, the use of smart lighting as transmitter could avoid the extra energy consumption needed for dedicated systems.

The III-nitride family provides a range of materials that can emit and detect light efficiently from green (570nm-) to deep into the ultraviolet (-200nm) range of wavelengths.

Silicon platform

Although silicon (Si) absorbs visible light, there is much interest in integrating visible light emitters with the complementary metal-oxide-semiconductor (CMOS) Si-based circuits used in the vast digital consumer market.

Researchers in China have successfully fabricated an indium gallium nitride (InGaN) microdisk laser on silicon that operated at room temperature under electrical pumping [Meixin Feng et al, Optics Express, vol26, p5043, 2018]. "This is the first observation of electrically pumped lasing in InGaN-based microdisk lasers grown on Si at room temperature," the team from Suzhou Institute of Nano-Tech and Nano-Bionics, University of Science and Technology of China, and Changchun Institute of Optics Fine Mechanics and Physics, writes.

Generally, reported microdisk lasers on silicon have been optically pumped, reducing their usefulness. Microdisk lasers use whispering-gallery modes of light reflecting/echoing around a circular structure to create a resonant cavity for laser excitation that can efficiently couple to on-chip waveguides.

The researchers used a sandwich structure on silicon (Figure 1) rather than the more usual stem-and-cap mushroom format normally employed for optically pumped microdisk lasers. The team adopted the sandwich format to give more robustness and to reduce the electrical and thermal resistance of the n-side of the device.

Since aluminium gallium nitride (AlGaN) has a lower refractive index than GaN, it was used as lower cladding, confining most of the optical field away from the absorptive highly defective buffer.

However, the sandwich structure did require a thicker buffer structure to overcome the 17% lattice mismatch and 54% thermal expansion coefficient difference with silicon. The buffer layers consisted of 370nm AlN nucleation, 280nm $Al_{0.35}Ga_{0.65}N$, 415nm $Al_{0.17}Ga_{0.83}N$, and 1μm GaN.

The n-contact layer was 1.6μm n-GaN. The n-side continued with 1.3μm $Al_{0.07}Ga_{0.93}N$ cladding and 80nm GaN lower waveguide.

The active region consisted of three well/barrier pairs of 2.5nm/7.5nm $In_{0.1}Ga_{0.9}N/In_{0.02}Ga_{0.98}N$. The upper 60nm GaN waveguide was undoped. The p-type layers were a 20nm $Al_{0.2}Ga^{0.8}N$ electron-blocking layer (EBL), 100x(3nm/3nm) $Al_{0.11}Ga_{0.89}N$/GaN superlattice cladding, and 30nm GaN contact.

Circular microdisks were fabricated using a nickel mask and dry etching. Sidewall damage was removed with tetramethyl ammonium hydroxide (TMAH) wet etching, smoothing the surface and reducing surface recombination centers and associated optical losses. The TMAH treatment reduced threshold currents for microdisks from ~1500mA to ~1000mA.

The researchers also fabricated micro-ring devices that concentrated current injection at the periphery for more efficient excitation of whispering-gallery modes (Figure 2). This also avoids Joule heating of the central region that can degrade performance. The micro-ring injection was ensured by removing the p-GaN and part of the p-AlGaN/GaN superlattice cladding from, and by depositing silicon dioxide (SiO_2) in, the center of the disk. ►

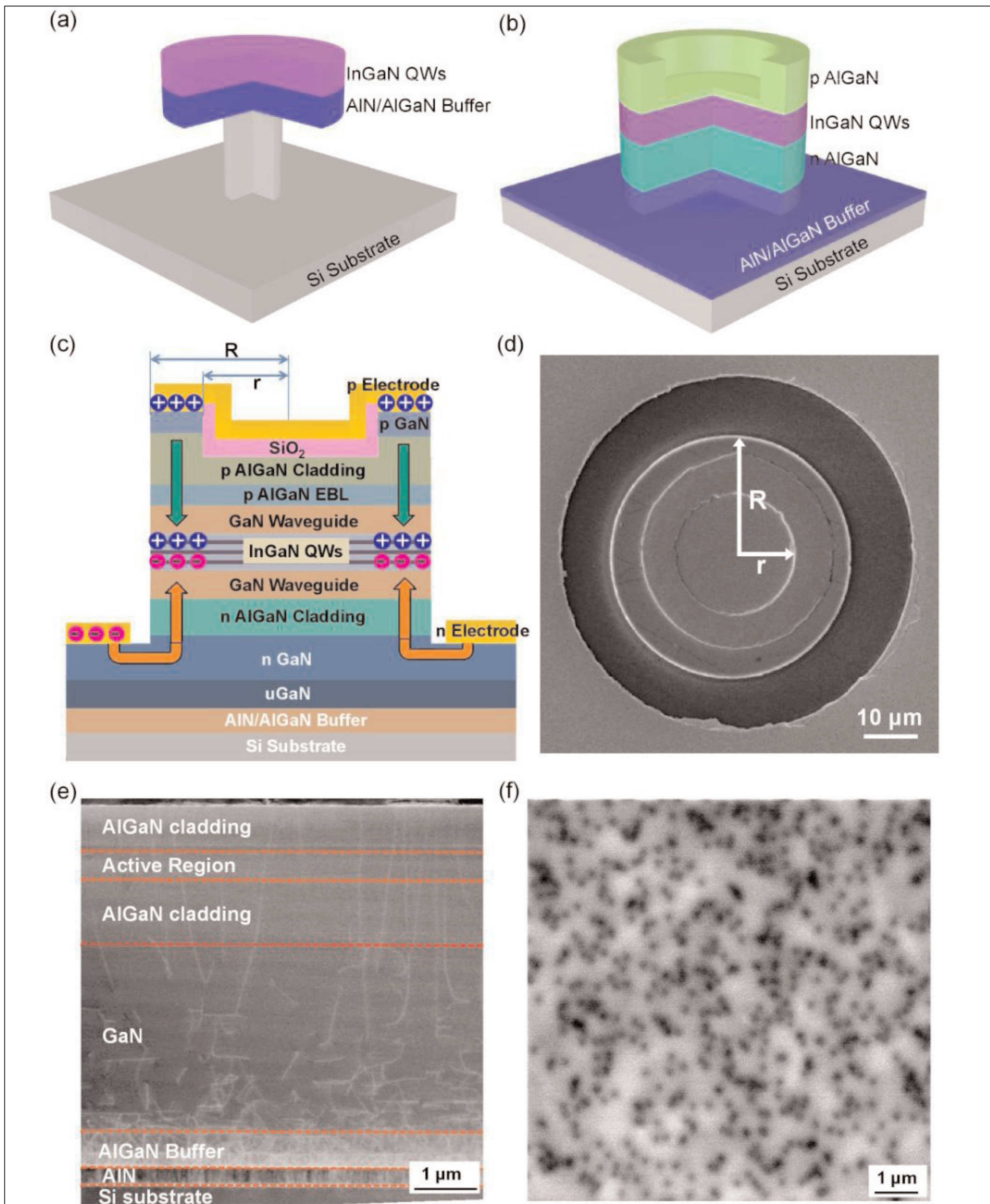

Figure 1. (a) Conventional 'mushroom-like' InGaN-based microdisk laser on Si with undercut structure and (b) 'sandwich-like' InGaN micro-ring laser grown on Si with AlGaN cladding layers. (c) Schematic structure of InGaN micro-ring laser. (d) Scanning electron microscope image. (e) Cross-sectional high-angle annular dark-field scanning transmission electron microscope (STEM) image. (f) Panchromatic cathodoluminescence image of GaN film grown on silicon, giving density of threading dislocations (TDs) of ~$6x10^8/cm^2$.

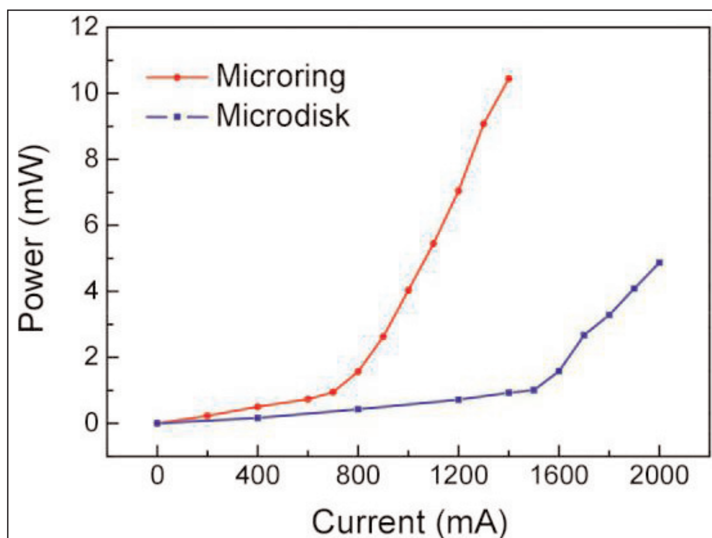

Figure 2. Peak light output power of InGaN-based micro-ring laser and microdisk laser grown on silicon measured under various 400ns, 10kHz pulsed currents at room temperature.

The researchers comment: "Compared with the conventional microdisk resonators, micro-ring resonators have more compact cavity volume and better high-speed modulation characteristics due to less effect of carrier space hole-burning and diffusion."

A micro-ring laser with outer and inner radii of 10μm and 5μm, respectively, emitted a peak wavelength of 412.4nm with 0.4nm full-width at half maximum (FWHM) under 250mA pulsed current at room temperature. Over a range of devices, the threshold occurred between 200mA and 450mA. Without TMAH treatment, micro-ring lasers had a threshold of ~800mA.

Nanjing University of Posts and Telecommunications and Zhengzhou University in China have also been developing III–nitride technology for VLC on a monolithic silicon platform [Xumin Gao et al, Optics Letters, vol42, p4853, 2017].

In particular, the team created a system of an LED transmitter and photodiode receiver linked by an InGaN waveguide in AlGaN cladding.

Layer	Material	Thickness
Contact	p-GaN	38nm
Cladding	p-AlGaN	600nm
Waveguide	InGaN	80nm
Multiple-quantum well	InGaN/GaN	120nm
Waveguide	n-InGaN	90nm
Cladding	n-AlGaN	1500nm
Contact	n-GaN	1500nm
Buffer	n-GaN	1500nm
Buffer	AlGaN	490nm
Nucleation	AlN	280nm
Substrate	(111) Si	2-inch diameter

Figure 3. Epitaxial structure.

Transmission at up to 200Mbits per second (Mb/s) was demonstrated for both in-plane and out-of-plane set ups. The in-plane transmission to an on-chip receiver could be used in practice as a power monitor.

The team sees particular benefit arising for 'Internet of Things' applications, along with integrated biomedical analysis systems and monolithic photonic circuits. "From a mass-production point of view, the III–nitride-on-silicon platform offers a feasible approach that is compatible with Si-fab for wafer-level fabrication," the researchers add.

The device fabrication was performed on 2-inch III–nitride on Si substrates produced by metal-organic chemical vapor deposition (MOCVD, Figure 3). The further processing (Figure 4) consisted of 590nm mesa isolation etch, formation of annealed nickel/gold (Ni/Au) p-contact, etching to the n-contact layer, plasma-enhanced chemical vapor deposition (PECVD) of 200nm SiO_2 isolation, buffered oxide etch of elec-

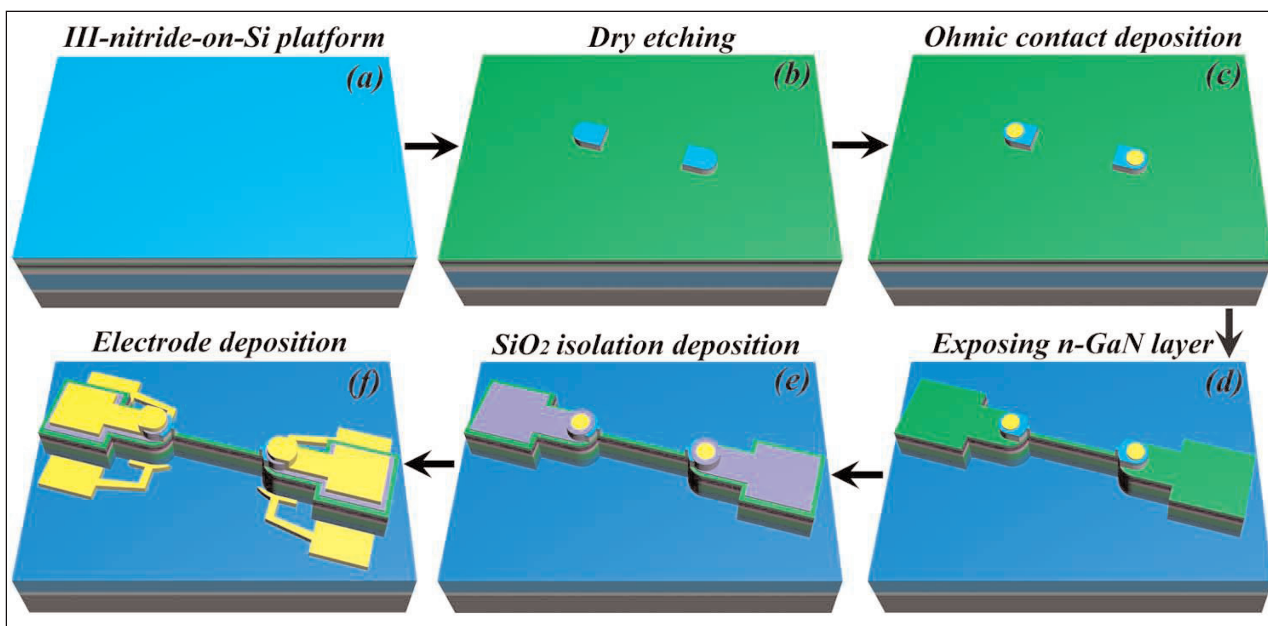

Figure 4. Fabrication processes of multi-component system on III–nitride-on-Si platform.

trode regions, and titanium/platinum/gold (Ti/Pt/Au) metalization. The transmitter and receiver were isolated from each other by the removal of the p-GaN layer from the top of the waveguide.

The photonic circuit consisted of an 8μm-wide 200μm-long InGaN waveguide connecting transmitter and receiver. The transmitter was found to emit radiation with a wavelength around 452nm. The transmitter diode turn-on voltage was around 2.5V. The capacitance of the device was around 2.33pF at 500kHz. A lower capacitance would improve the modulation capability.

The photocurrent through the receiver diode was found to follow the increased emission from the transmitter with increased current injection. The response to an on-off keying modulation, pseudo-random binary sequence (PRBS) data stream gave 'open eye' diagrams with rates up to 200Mb/s, the limit of the measurement system.

Out-of-plane light was collected by 20x objective lens with 0.5 numerical aperture (NA) and transmitted through a confocal system to a photodiode (Figure 5). Under 200Mb/s data streams the system again gave open-eye diagrams.

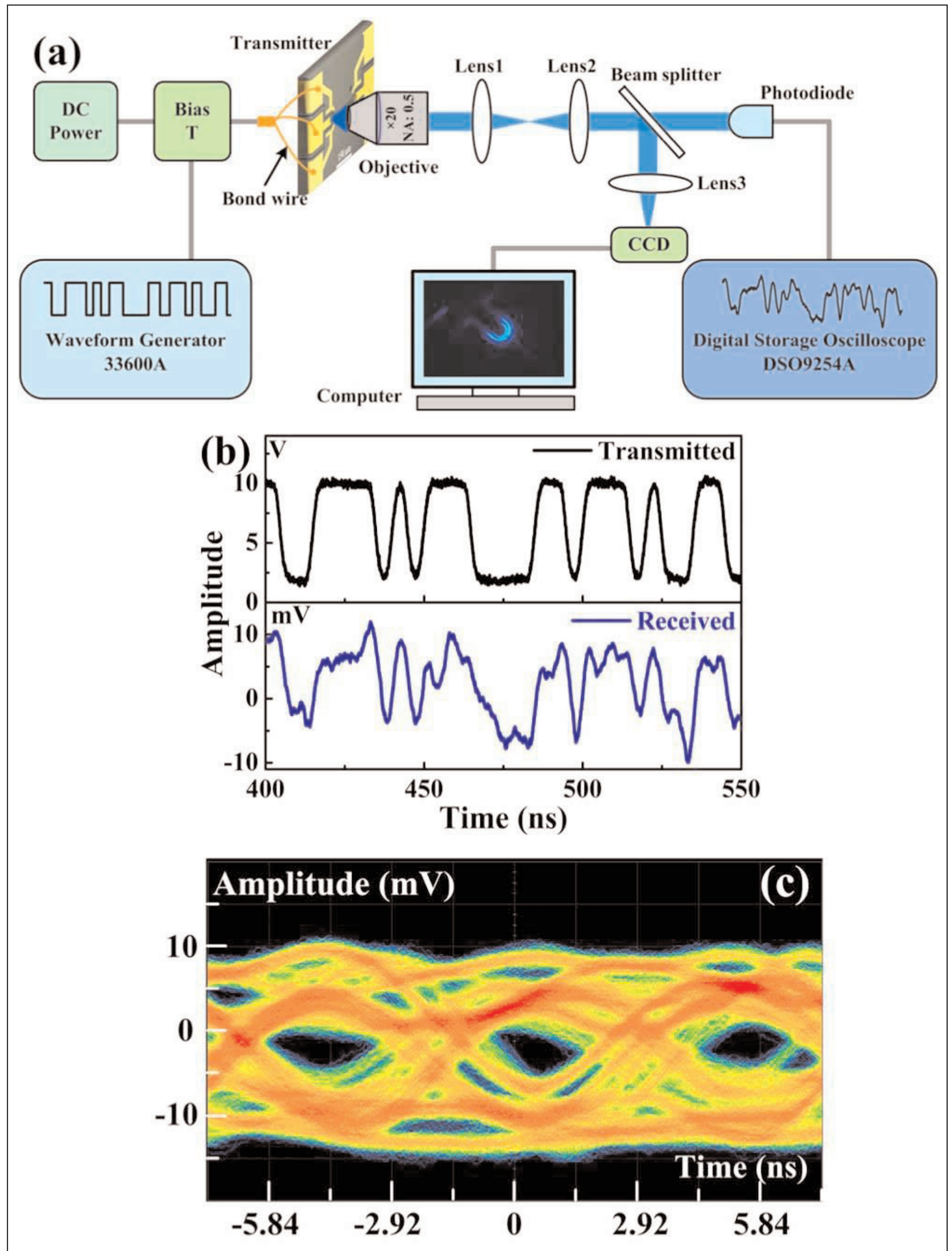

Figure 5. (a) Schematic out-of-plane visual light communication. (b) Transmitted and received PRBS data at 200Mb/s transmission rate. (c) Eye diagrams measured at 200Mb/s.

Semi-polar orienteering

Researchers based in Saudi Arabia and USA have used semi-polar InGaN quantum wells (QWs) to create a laser diode (LD) integrated with a semiconductor optical amplifier (SOA) for VLC, smart lighting, and UWOC [Chao Shen et al, Optics Express, vol26, pA219, 2018].

The team from King Abdullah University of Science and Technology (KAUST) in Saudi Arabia, University of California Santa Barbara (UCSB) in the USA, and King Abdulaziz City for Science and Technology (KACST) in Saudi Arabia, comments: "Since the on-chip integration of various photonic devices offers the advantages of small footprint, low cost and multi-functionality, it is of great interest to develop III–nitride photonic integrated circuits (PICs) at the visible wavelength." ➤

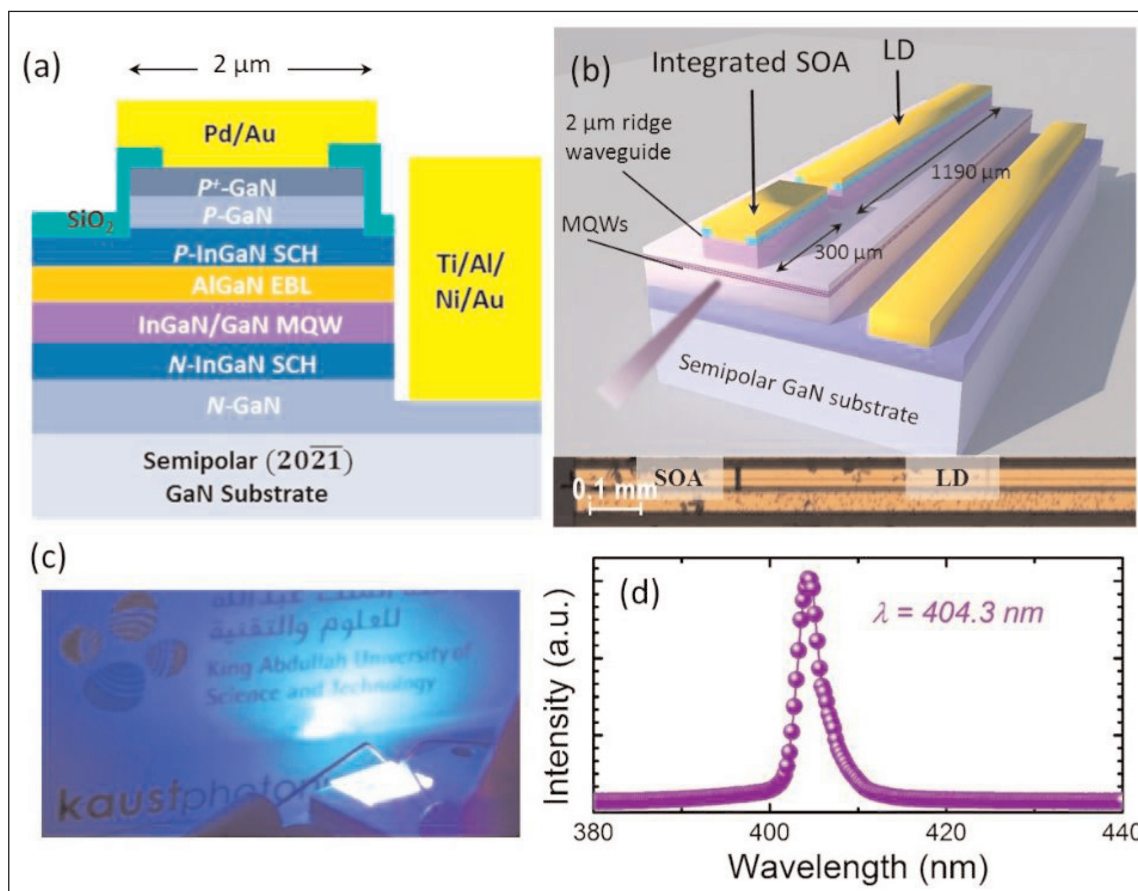

Figure 6. (a) Cross-sectional layered structure and (b) three-dimensional illustration of 405nm-emitting dual-section integrated SOA-LD on semi-polar GaN substrate. Inset: fabricated device under optical microscope. (c) Photo of device operating at room temperature. (d) Emission spectrum of device at laser gain section current of 250mA and zero SOA section driving voltage, showing peak at ~404.3nm.

The epitaxial structure for the device was grown by MOCVD on semi-polar (20$\bar{2}\bar{1}$) GaN (Figure 6). The active light-emitting region was four pairs of $In_{0.1}Ga_{0.9}N$/GaN quantum wells/barriers. A 16nm $Al_{0.18}Ga_{0.82}N$ layer served as an electron-blocking layer (EBL). The separate-confinement heterostructure (SCH) waveguides consisted of 60nm/60nm p-/n-$In_{0.025}Ga_{0.975}N$. The p- and n-GaN cladding layers were 600nm and 350nm, respectively.

The p- and n-electrodes were palladium/gold (Pd/Au) and Ti/Al/Ni/Au, respectively. The structure of the separate SOA and laser diode sections were defined by patterned etching of a 2μm-wide ridge. Electrical separation of the devices was achieved by etching the p-GaN contact layer between them, while maintaining a seamless optical connection.

When the SOA was unbiased, the light output power was low due to optical losses. The light output increased as the SOA bias increased to 6.25V. In fact, beyond 5V bias, the output was greater than for a laser diode without SOA, suggesting light amplification in the SOA itself beyond 4V bias.

With a laser diode current of 250mA, the light output power increased from 8.2mW to 30.5mW as the SOA bias increased from 0V to 6.25V. Between the same

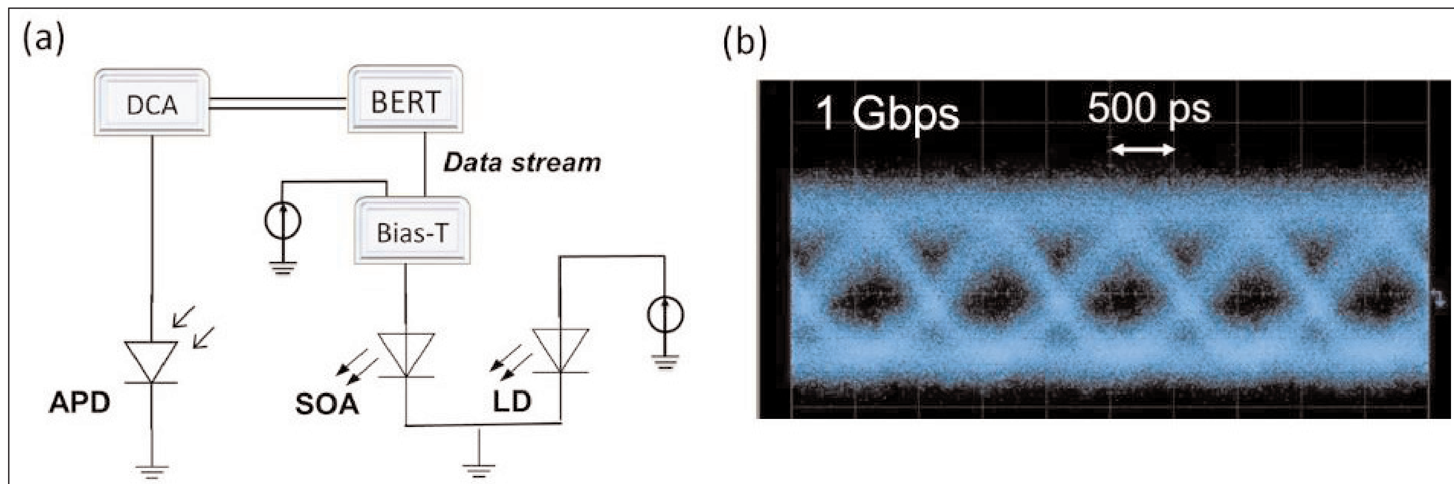

Figure 7. (a) Schematic of non-return-to-zero on-off keying modulation (NRZ-OOK) data transmission measurement using SOA-LD as transmitter and avalanche photodiode (APD) as receiver, along with bit error rate tester (BERT) and digital communication analyzer (DCA). (b) Eye diagram of 1Gbit/s data rate.

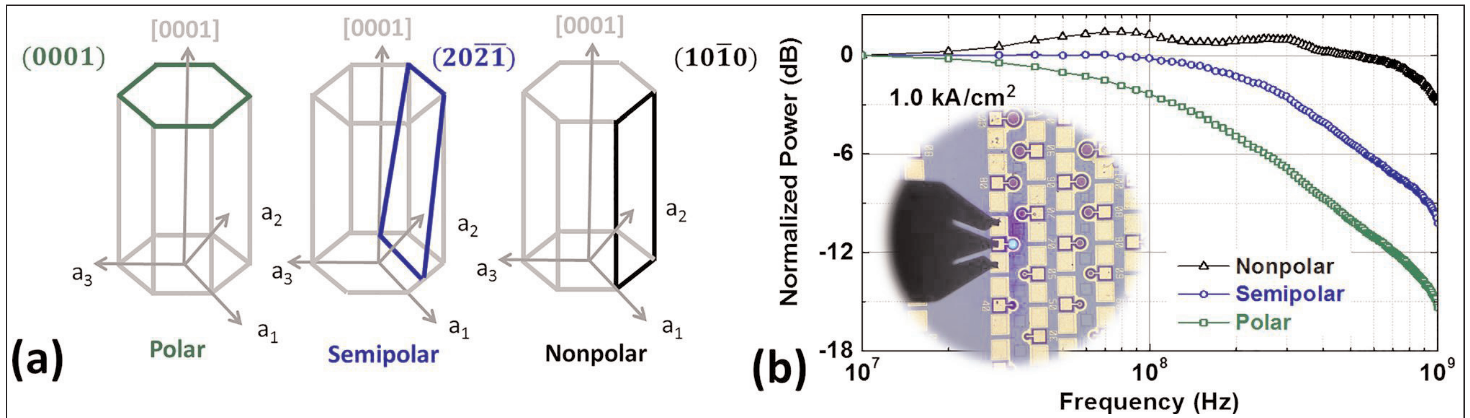

Figure 8. (a) Crystallographic planes studied and (b) normalized s-parameter (S_{21}) response of LEDs with polar (green squares), semi-polar (blue circles), and non-polar (black triangles) orientations with same device geometry operating at 1kA/cm^2. Inset: operating device probed using GSG RF electrode.

SOA biases, the laser threshold current decreased from 229mA to 135mA. With the laser diode at 250mA, the SOA current at 6V bias was 67mA, giving a total input power of 2.14W and wall-plug efficiency (WPE) of 1.3%. A separate laser diode with 317mA (250mA+67mA) current injection had a WPE of 0.54%.

The rate of increase in effective gain of the SOA as the bias increased from 4V to 6.25V was 2.36dB/V at 250mA laser diode injection. The team comments: "The high gain observed in the device is partially attributed to the large electron–hole wavefunction overlap in InGaN/GaN QWs grown on semi-polar (20$\bar{2}\bar{1}$) GaN substrate, which exhibits reduced polarization field compared to that in conventional [polar] c-plane devices." The peak amplification ratio between 0V and 6.25V SOA bias was 18.4 at 404nm wavelength and 200mA laser diode injection.

The combined device achieved 'open eye' data transmission at 1 gigabits per second (Gb/s) with SOA modulation and constant 250mA laser diode injection (Figure 7). The bit error rate was 3.4x10^{-4}, meeting the limit for forward error correction (FEC) of 3.8x10^{-3}.

University of New Mexico and UCSB in the USA have been studying the effect of crystal orientation (Figure 8) on the modulation bandwidth of InGaN light-emitting diodes [M. Monavarian et al, Appl. Phys. Lett., vol112, p041104, 2018].

In particular, the researchers sought high bandwidth at lower current injection where the efficiency of InGaN LEDs is higher, reducing 'droop' effects. The non-polar m-plane (10$\bar{1}$0) orientation was found to have the largest 3dB (half-power) bandwidth, with a value of more than 1GHz down to 500A/cm^2 injection.

The team promote LEDs over laser diodes for VLC, POF and UWOC applications: "For communication applications, advantages of LEDs compared to diode lasers include their lower cost, longer operating lifetime, lower temperature dependence, compatibility with existing lighting systems, and lower emission directionality."

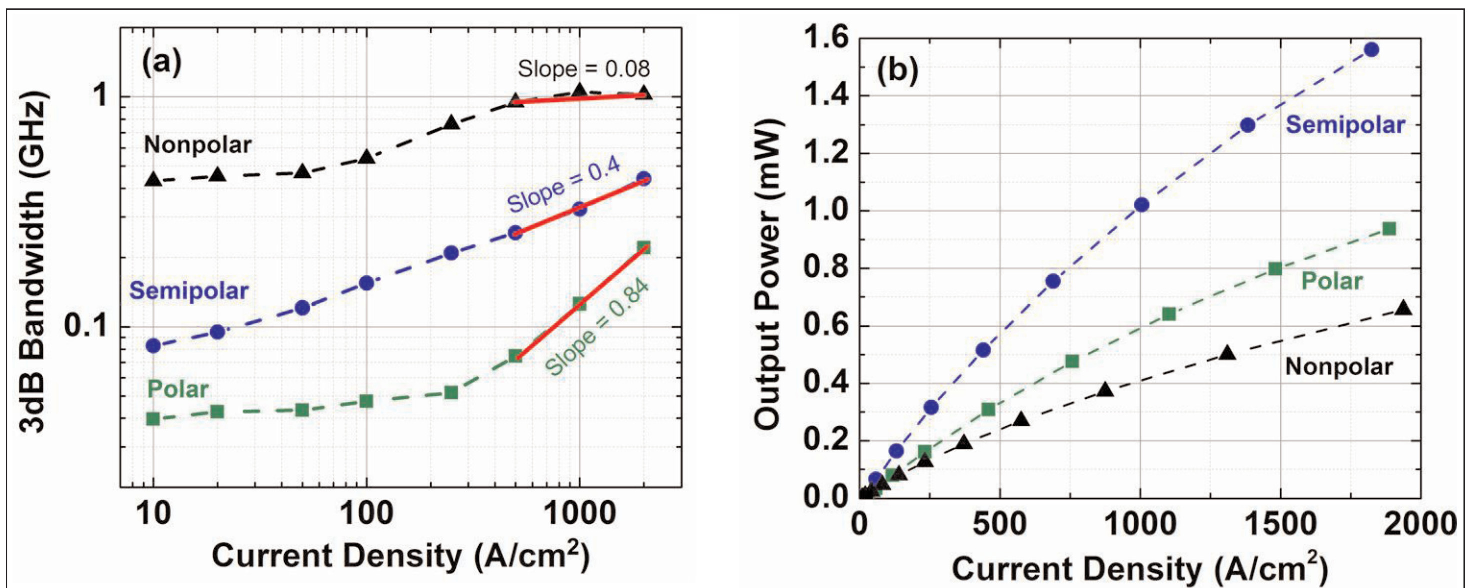

Figure 9. (a) Bandwidth and (b) optical output power versus current density for devices with polar (green squares), semi-polar (blue circles), and non-polar (black triangles) orientations.

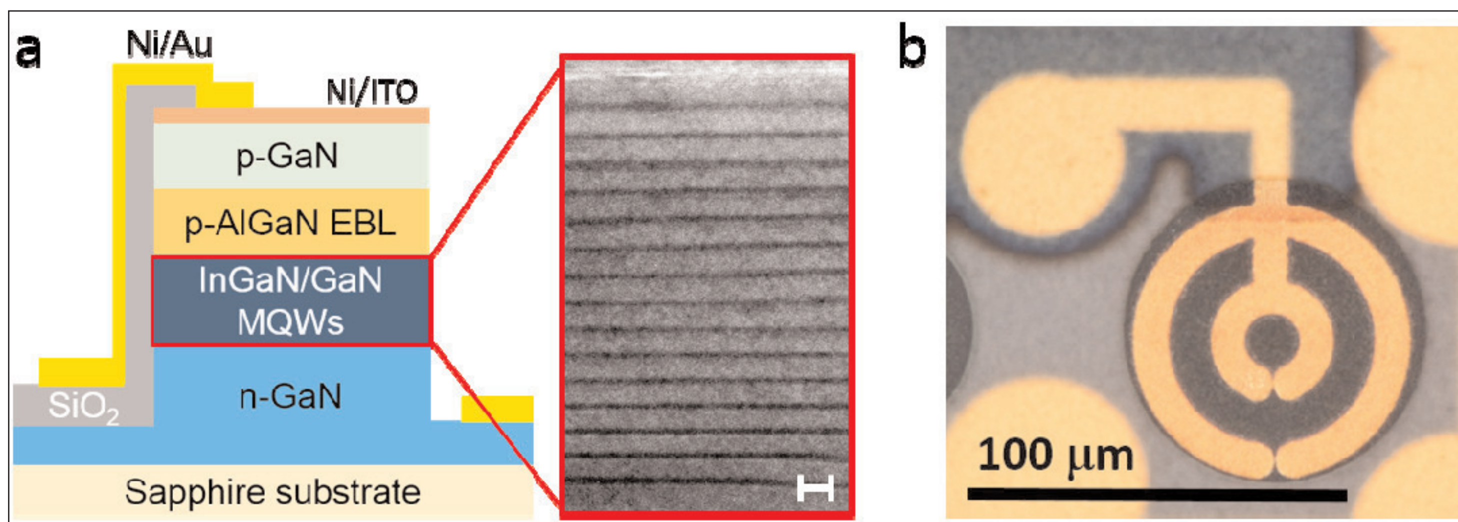

Figure 10. (a) Schematic of InGaN/GaN MQW μPD and transmission electron microscope image showing 15-pairs of 3nm InGaN/13.5nm GaN (scale bar 20nm). (b) Optical microscope image of μPD with diameter of 80μm.

The LEDs studied contained three InGaN quantum wells. The well thicknesses were chosen to maximize optical output power: 4nm for the polar c-plane (0001) and semi-polar ($20\bar{2}\bar{1}$) orientations, and 6nm for the non-polar sample. Free-standing semi-polar and non-polar GaN substrates were supplied by Mitsubishi Chemical. The polar sample was grown on c-plane sapphire.

The materials were fabricated into 60μm-diameter circular mesa LEDs with indium tin oxide (ITO) transparent conductor on the p-contact layer, Ti/Al/Ni/Au n-contact, chromium/gold contact pads, and ground-signal-ground radio frequency (GSG RF) electrodes. The micro-LED structures were designed to reduce the impact of parasitic resistance-capacitance time constant effects on modulation bandwidth.

The 3dB (half-power) bandwidths at 1kA/cm^2 current density injection were 1050MHz, 325MHz and 125MHz for the non-polar, semi-polar and polar LEDs, respectively, correcting for the frequency responses of the RF cables, bias tee and low-noise amplifier. The non-polar LED maintained its ~1GHz bandwidth down to 500A/cm^2 (Figure 9).

The researchers explain the larger bandwidth for the non-polar LED as being due to better wavefunction overlap between the electrons and holes that are desired to recombine into photons, compared with the semi-polar and completely polar orientations.

At higher current, the polar LEDs begin to benefit from coulomb screening of the charge polarization electric fields that impair performance. Hence, the bandwidth increases more rapidly above 500A/cm^2, compared with the semi-polar and non-polar orientations. In terms of raw output power, the semi-polar LED gives more than twice the intensity of the non-polar device.

The researchers used their results to assess the carrier life-times of the three devices, finding that the non-polar carriers had the shortest life-times, giving faster response to modulation. Unsurprisingly, the semi-polar structure gave a shorter life-time than the fully polar devices.

Short life-times reflect fast recombination, with the upshot of lower carrier density for a given injection current. The team sees the faster recombination of the non-polar orientation as reflecting the more complete overlap of electron and hole wavefunctions.

As the current density increases, the polar LED carrier life-time reduces and some c-plane LEDs with bandwidth of the order 1GHz have been reported at 5kA/cm^2 injection. However, high current injection means lower efficiency as a result of 'droop'.

The researchers comment: "LEDs fabricated on non-polar and semi-polar orientations are attractive for achieving higher bandwidths at lower operating currents, which is advantageous for maximizing efficiency, reducing power dissipation, and mitigating issues with thermal management."

Orthogonal-frequency division multiplexing

Finally, KAUST claims a record 3.2 gigabit per second (Gbps) data-rate performance for VLC at 405nm wavelength [Kang-Ting Ho et al, Optics Express, vol26, p3037, 2018]. The orthogonal-frequency division multiplex (OFDM) system used an InGaN multiple quantum well microphotodetector (μPD) receiver and laser diode source with quadrature amplitude modulation (QAM) coding.

The team wanted to address the bandwidth and data security challenges for future high-speed mobile internet, smart traffic, and Internet of Things (IoT). Bandgap limitations make the receiver portion of VLC systems particularly challenging.

The μPDs used a multiple quantum well with 15-period InGaN/GaN structure grown on c-plane sapphire by MOCVD (Figure 10). The p-AlGaN electron-blocking layer

was 100nm and the p-GaN was 150nm.

The μPD fabrication included annealed 5nm/250nm Ni/ITO transparent contact, 200nm SiO_2 electrical isolation, and 10nm/1μm Ni/Au contacts.

The device demonstrated wavelength selectivity with −3V reverse bias between 374nm and 408nm — a pass-band full-width at half-maximum (FWHM) of 34nm. Peak response was 70.7mA/W at 392nm wavelength. The dark current was 37.4pA. The −3V reverse bias gave the optimal performance in terms of dark current and −3dB cut-off modulation bandwidth for 405nm radiation from a laser diode (71.5MHz).

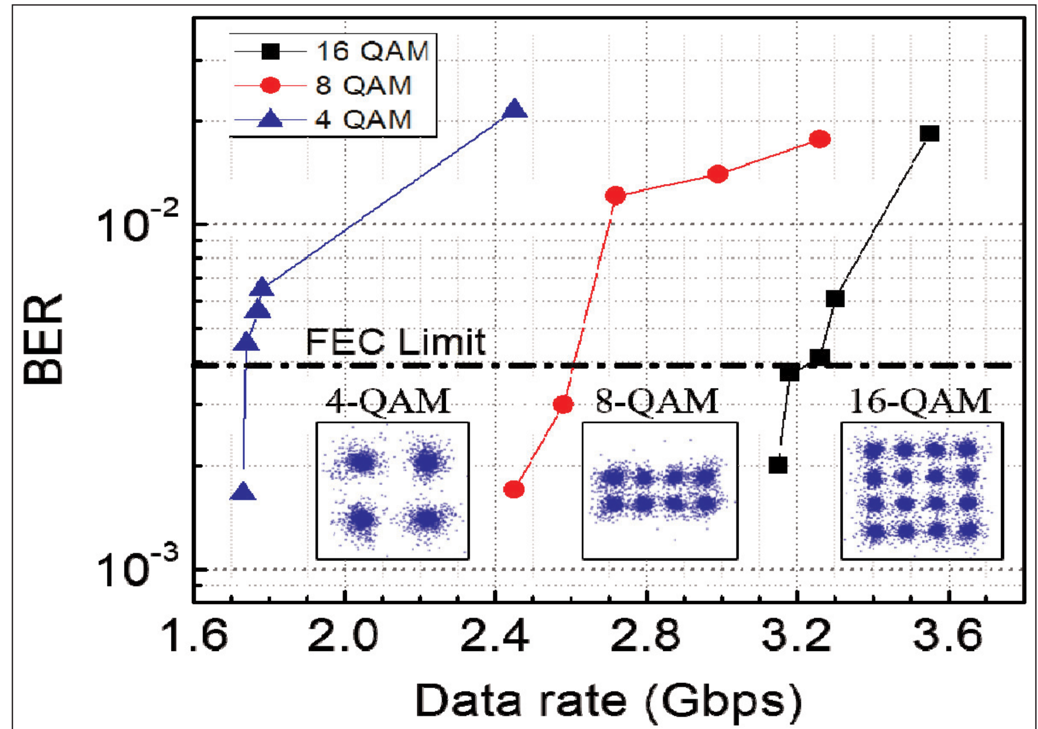

Figure 11. BER versus data rate of VLC link with different OFDM QAM order. Inset: corresponding constellation diagrams at 4-QAM, 8-QAM and 16-QAM.

An OFDM setup consisting of a 405nm laser diode and the μPD managed 16-QAM with a bit-error rate (BER) of $3.7x10^{-7}$ with 853MHz frequency response. This corresponds to a 3.2Gbps data-rate transmission (Figure 11). With a 7% overhead for forward-error correction, this is reduced slightly to 2.96Gbps for error-free transmission.

The researchers comment: "Our work features the record high data rate of VLC link using InGaN μPDs as receiver, which is the first demonstration of such system. In addition, compared with the prior reported results, our device was operated at lower bias voltage, and the carrier lifetime was shorter for high-speed modulation." ■

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