Integrating gallium nitride optoelectronics on silicon

Researchers combine light-emitting diodes, photodetectors and waveguides on single chips, reports Mike Cooke.

Nanjing University of Posts and Telecommunications in China has been developing gallium nitride (GaN) on silicon technology with a view to monolithically integrated optoelectronic devices consisting of light-emitting diodes, photodiodes and waveguides [Wei Cai et al, Appl. Phys. Express, vol9, p052204, 2016]. Target applications include smart transmitters/receivers for wireless visible light communication (VLC).

The large difference in refractive index between gallium nitride (~2.45) and air (1) leads to total internal reflection, which makes it difficult to extract light from LEDs. However, total internal reflection is just what is needed for efficient low-loss confinement in waveguides.

The researchers comment on the particular fabricated structure (Figure 1): "The integrated device is similar to a bipolar junction transistor. The common n-contact is the base and the emitter is the LED, whereas the photodiode is the collector. The suspended waveguide is used for device connection. When the LED is turned on, photons are transported through the waveguide and absorbed in the photodiode, achieving the photonic integration of the emitter, waveguide, and photodiode on a single chip."

The devices were fabricated from heterostructure material deposited on 2-inch GaN-on-silicon templates. The layer structure consisted of a 900nm aluminium gallium nitride (AlGaN) buffer, 400nm of undoped GaN,

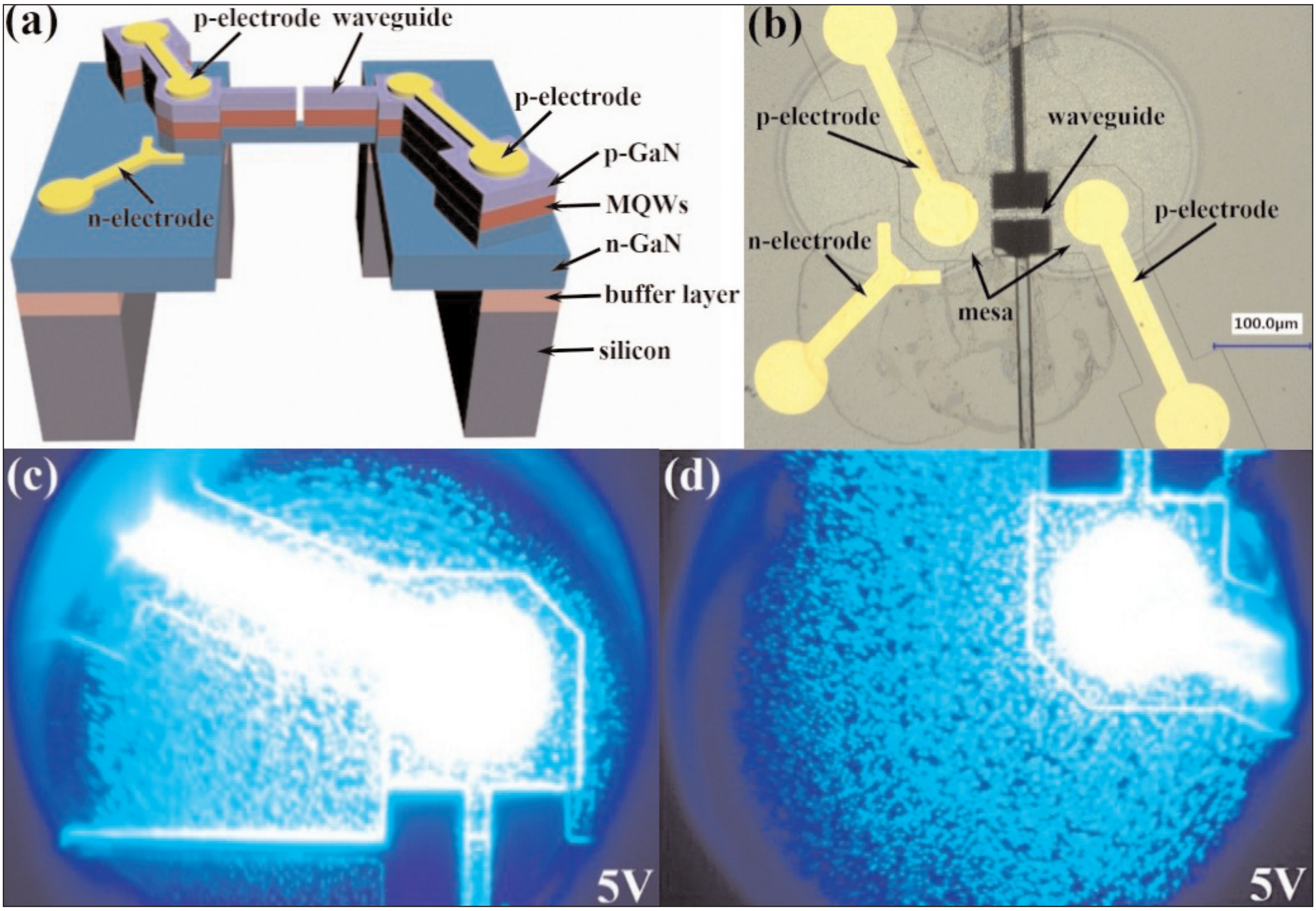
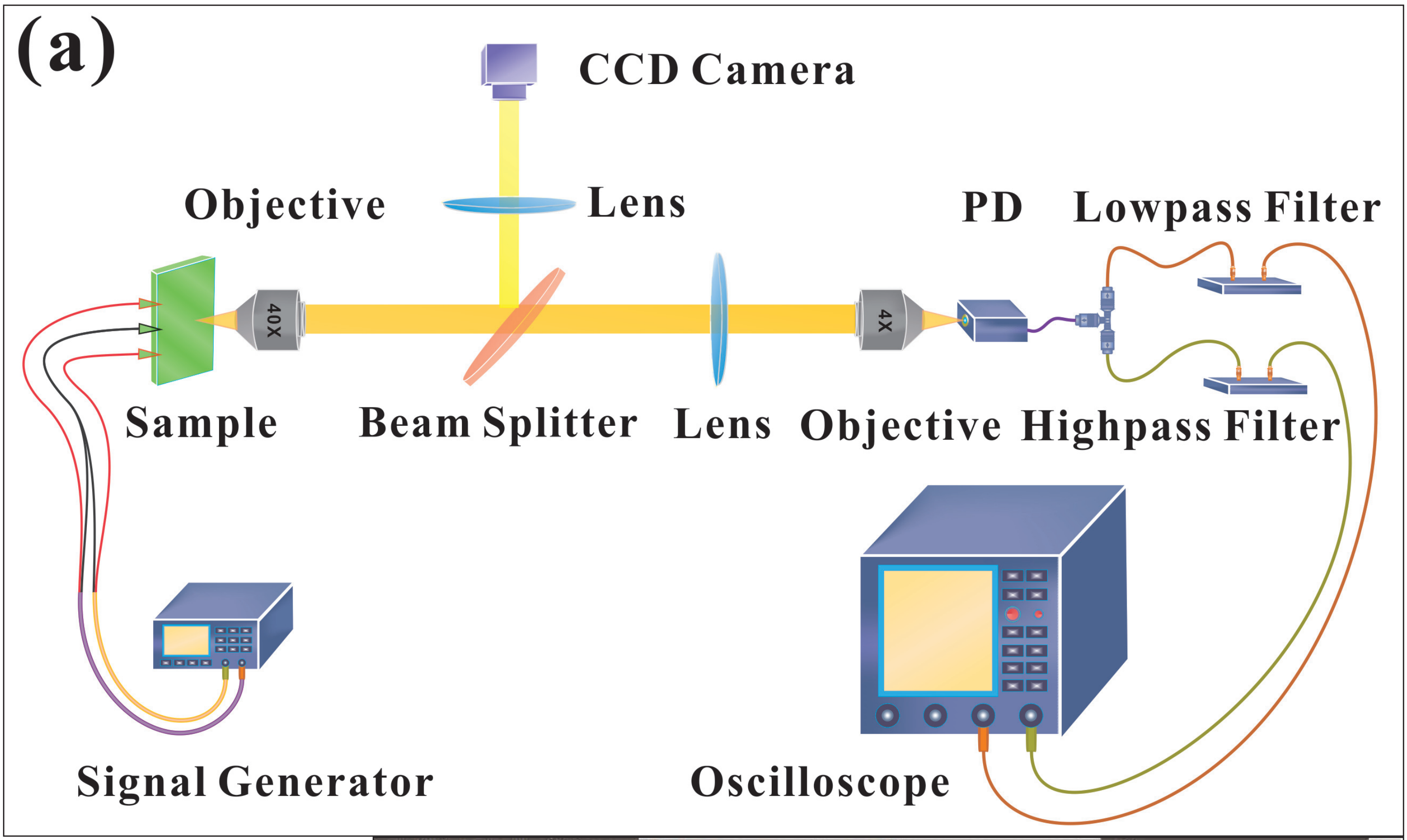


Figure 1. (a) Schematic cross section of integrated devices; (b) optical micrograph of suspended devices; (c, d) optical micrographs of light emission images obtained from silicon substrates.



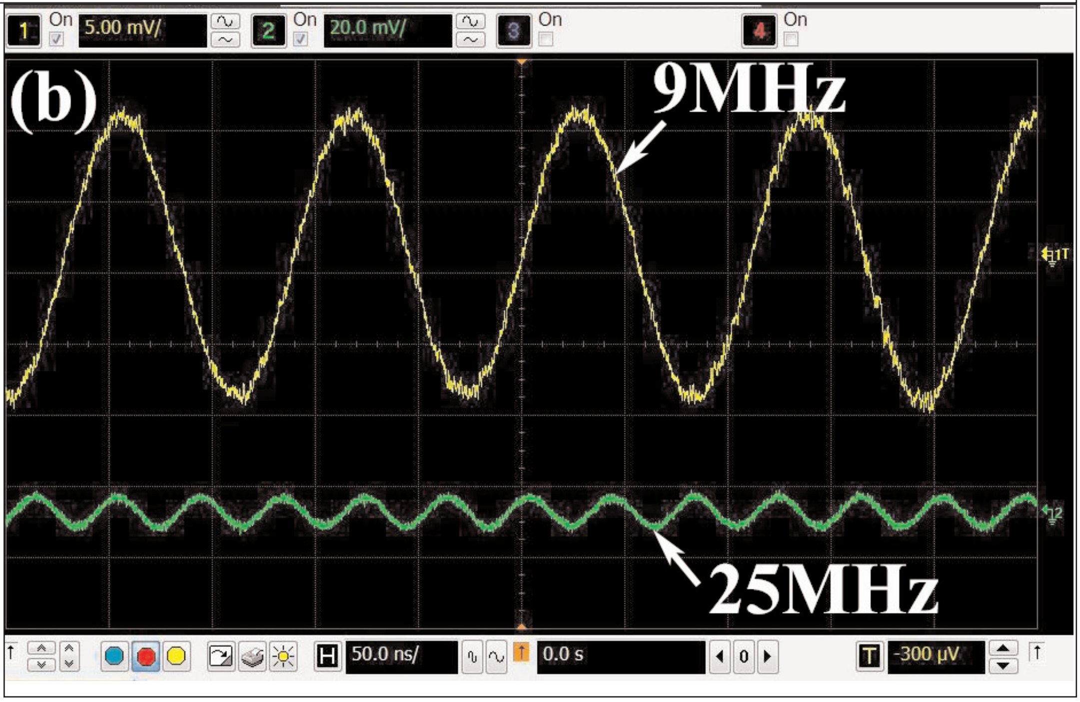


Figure 2. (a) Micro-transmittance setup. (b) Received output signals for integrated devices.

a 3.2µm n-GaN contact, a 250nm indium gallium nitride (InGaN) multiple quantum well with GaN barriers, and a 220nm p-GaN contact.

Fabrication began with isolation mesa etching. Contact with the n- and p-contact regions was made with annealed nickel/gold. Waveguide structures were formed with reactive ion etch (RIE). Silicon was also removed to give suspended membrane structuring when the wafers were thinned on the silicon side. The suspended waveguide region was 60µm long, 3µm thick and 10µm wide. Removal of silicon avoids light absorption by the substrate material.

Both ends of the waveguide could emit light under current injection, although the side closer to the common n-electrode was naturally brighter. Light guided in-plane could emerge at mesa facets. Some light escaped to air from the roughened bottom surface caused by reactive ion etch. The peak electroluminescence emission was around 458.5nm wavelength at 6V bias.

The devices could be used with one for light emission and the other for photodetection. When a 10µm gap was made in the waveguide the photocurrent was much reduced, suggesting that the current was mainly induced by the guided light.

The researchers also tested the ability of both sides of the device to emit light modulated separately at 9MHz and 25MHz into free space (Figure 2). The researchers report: "The sine waves at 9MHz and 25MHz are

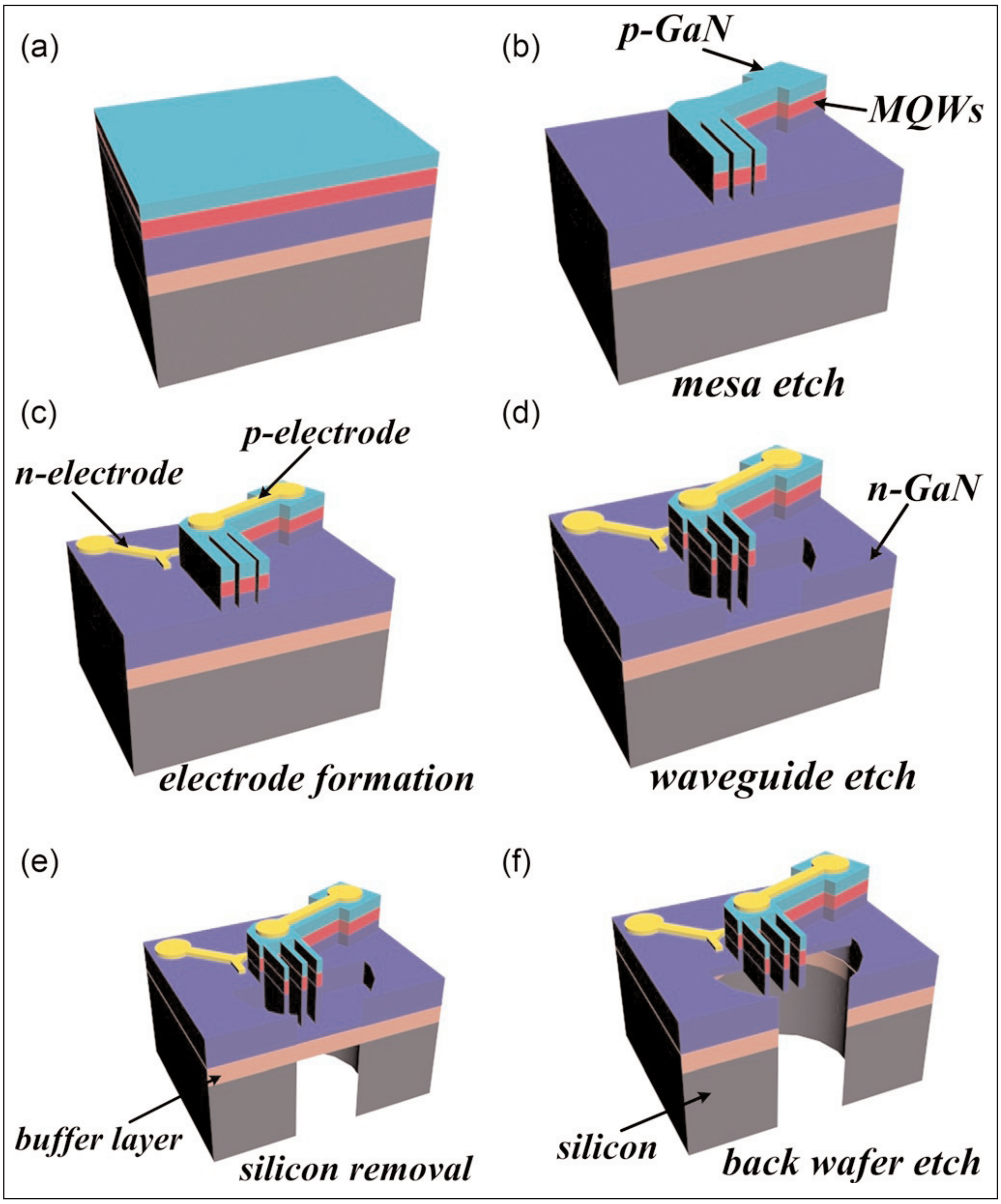


Figure 3. Schematic fabrication process of on-chip integration of suspended pn-junction InGaN/GaN MQW device and multiple waveguides.

clearly observed, indicating that the integrated devices can be feasibly used as multiple transmitters for wireless VLC applications."

In the other direction, both devices were also tested as simultaneous photodiodes. A fiber-coupled 450nm light beam was focused on the back-side of the device with a signal that was on for 0.2 seconds and off for 0.2 seconds. A photocurrent of –42nA was induced at 0V bias. The researchers comment: "The photocurrent temporal trace shows a distinct on/off switching performance, indicating its potential use as multiple receivers for wireless VLC applications."

The University of Posts and Telecommunications researchers have also worked with Nanjing Institute of Technology, China, on further work integrating III-nitride devices with III-nitride waveguides on silicon [Yongjin Wang et al, Appl. Phys. Lett., vol108, p162102, 2016].

The researchers used material with the same heterostructure as detailed above. The fabrication process was also similar. The resulting membrane structures (Figure 3) were somewhat deformed due to stress release after removal of the silicon. Three 50μm-long waveguides were produced with different thicknesses: 12μm, 10μm and 8μm. The height was given by the 3μm membrane thickness.

The device was wire bonded to a test pad for characterization. As an LED, the device emitted blue light with 449.2nm dominant wavelength at 4V bias. There were also two sub-peaks at 467.5nm and 494.1nm (blue-green).

In-plane data transmission from the LEDs driven by an arbitrary waveform generator showed good performance from the 12μm-wide waveguide up to 25 megabits per second (Mbps) with open eye diagrams, indicating low signal distortion (Figure 4). Narrower waveguides restrict the occurrence of multi-mode transmission. Since multi-mode transmission leads to pulse broadening due to the different transmission velocities (dispersion), narrow waveguides should have higher transmission rates.

Reversing the light direction, so that the device operated as a photodiode, 450nm light from an optical fiber was focused on the waveguide facets. With a mechanical shutter giving 0.2 seconds on and 0.2 seconds off, –42nA photocurrent at 0V bias was observed with 70μW input power on the 10μm waveguide.

In March another device was reported by the same researchers with 3 p-electrodes, 3 n-electrodes, and 2 sets of connecting waveguides [Wei Cai et al, Optics Express, vol24, p6004, 2016]. In this work, the low cost of GaN on silicon is stressed. "The obvious advantages, such as use of the cheaper, widely available silicon wafer and the ability to use automated back-end manufacturing tools in silicon fabs, make mass production of monolithic photonic integration possible," the team writes.

Further, it is found that removal of the silicon substrate material from under the devices increases carrier concentrations and thus reduces resistance to current

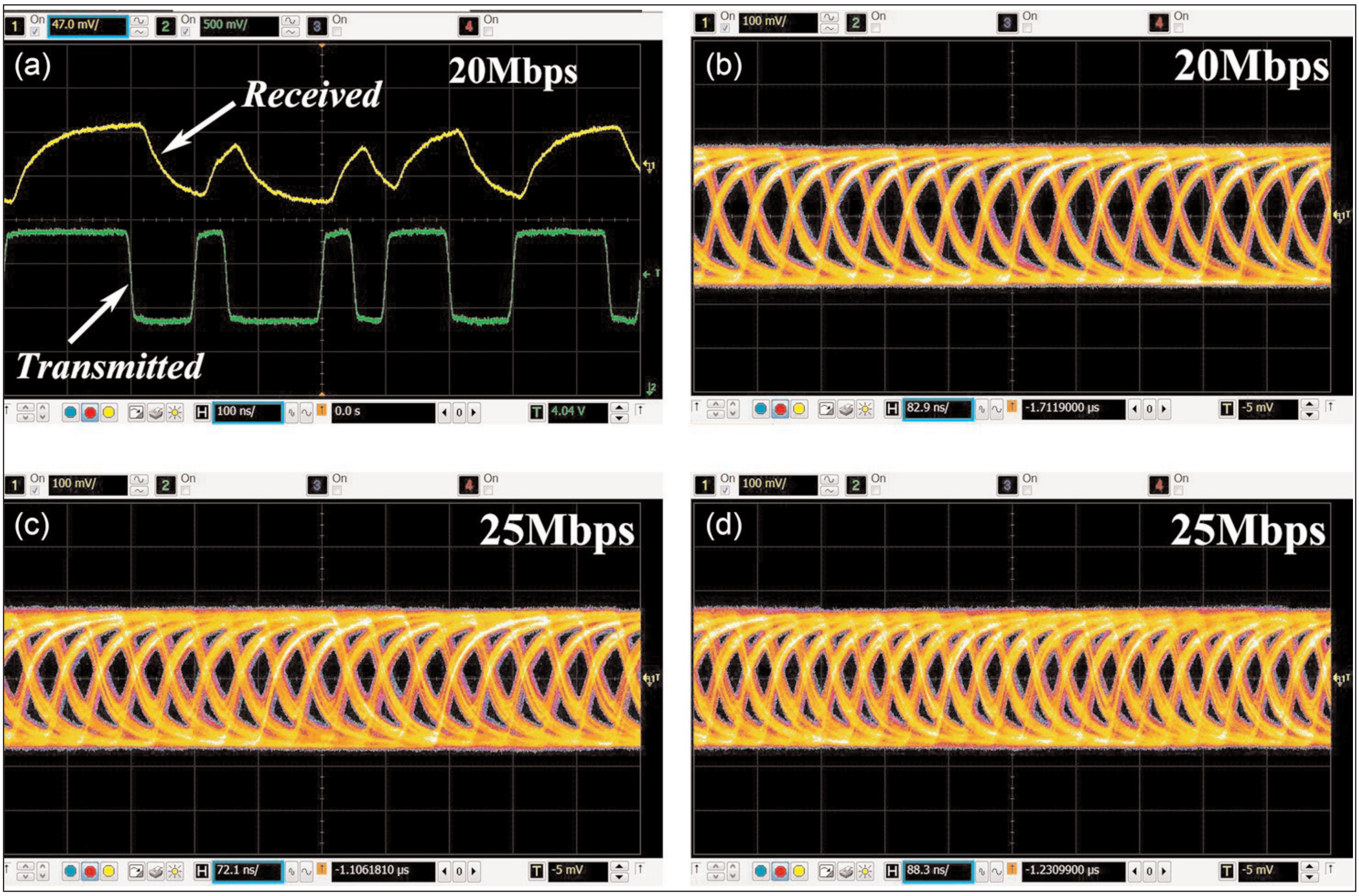


Figure 4. (a) Received output signal for 12µm-wide suspended waveguide; (b) eye diagram at 20Mbps for 12µm-wide suspended waveguide; (c) eye diagram at 25Mbps for 12µm-wide suspended waveguide; and (d) eye diagram at 25Mbps for 8µm-wide suspended waveguide.

spreading. Electronic performance is also enhanced by releasing residual stress arising from lattice mismatching between the silicon substrate and III-nitride layers. ■

Author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.