Like other schemes being researched, device commercialization is often a natural consideration, and there is no exception here given the great predicted technical impact of plasmonic PICs. As a new technology, the possibility of wide-ranging commercialization of plasmonics devices in the context of PICs depends on many factors. "Not only device performance, but also the cost and how long the industry can survive before adopting them," said Zayats. He predicted that one of the very near-future commercial applications, probably available within the next three to five years, could be a hybrid plasmonic PIC in which the plasmonic part makes it possible to produce high-power nanoscale light sources for use in high-density magnetic data storage. Such storage, where there is no way forward without plasmonics, is an excellent example.

"In other areas, there is interest from both small-to-medium enterprises and big internationals, but it is still a long way to go from the final device design to mass production, and from the laboratory to prototype. It could take a decade," suggested Zayats.

Some passive devices, such as thermo-optical modulators based on long-range plasmons, have already been commercialized, but this is niche market. Although plasmonic biosensors based on prism-coupling in the Kretschmann configuration have dominated the optical biosensing market for many years, they are mostly used in drug discovery applications. "I suspect that plasmonic PICs for biosensing might then be the first place where they are commercialized. Approaches are being pursued which should lead to cheaper and more compact solutions compared with the Kretschmann configuration," said Berini.

What are the challenges ahead? According to Zayats, integration of plasmonic components within standard photonic circuitry, and with silicon photonics, will boost the practical introduction of plasmonics in real-life devices. However, energy requirements and losses are the concerns. The good news is that, as mentioned before, there is at present a big drive to develop plasmonic amplifiers to compensate for these losses. All-optical control of signals in PICs is the ultimate goal, but this requires additional work to decrease the energy required per bit. For every potential application, it is necessary to select carefully the appropriate type of waveguide and use this as a basis for the active device required, Zayats added.

Berini raised the point that sustained interest in the field depends strongly on commercialization and that one important challenge is thus to develop good, competitive applications and get them to market. "Getting there, of course, will require overcoming several technical problems depending on the specific target. Although important strides have been made in recent times, much remains to be explored," said Berini. There are plenty of fundamental and technical problems to be solved and several applications to be explored. The most promising include SPP biosensors, lasers and detectors, he concluded.

"Ultimately, I can see plasmonic PICs of various sizes being main components of biosensing devices, active photonic interconnects of different scales between electronic components, ultrafast modulators and switches of optical signals, most definitely in nanoscale optical sources integrated in plasmonic or photonic circuitry," said Zayats. Although he holds the opinion that the potential of plasmonic PICs is very great, he would not argue for complete replacement of conventional PICs with plasmonic versions. "Both will be synergetic and in many applications. Probably plasmonic components will be a part of silicon PICs providing active functionalities."

All in all, the potential of integrated surface-plasmon devices that combine the high integration and functionality of electronic circuits with the bandwidth of photonic circuits on the nanoscale is apparent, and the community is active and progressive. It will be interesting to see how the field evolves and whether it will take less than a decade to bring plasmonic PICs to the market.

The next IPR conference will be held in Colorado Springs, Colorado, USA. ❒

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SEMICONDUCTOR LASERS

Expanding into blue and green

Are blue and green vertical-cavity surface-emitting lasers operating at room temperature just around the corner? New gallium-nitride-based vertical-cavity surface-emitting lasers are helping to overcome the intrinsic problem of low conductivities of p layers.

Hongxing Jiang and Jingyu Lin

In the research field of semiconductor lasers, there are at least two immediate challenges: the full extension of the lasing wavelength from blue to green, and the development of commercial devices. The latter effort means achieving high performance and desirable characteristics such as surface-normal output, circular beam shape, low beam divergence, low threshold currents, high-speed modulation, reliability and the capability to form two-dimensional arrays. The energy bandgap of GaN and our present technological level are such that nitride vertical-cavity surface-emitting lasers (VCSELs) currently operate at room temperature in the near-UV region[1–3] (wavelengths around 400 nm). However, operation around the blue and green wavelength regions remains challenging. This is possibly due to the difficulty of obtaining high-crystalline-quality multiple quantum wells (MQWs) with high indium content on a bottom-side dielectric distributed Bragg reflector (DBR) and the heat generation induced by current crowding in the side-by-side configuration[4].

Writing in *Applied Physics Express*, Daiji Kasahara and co-workers[5] from the Nichia Corporation now report that they have overcome these problems and have demonstrated operational room-temperature nitride blue (451 nm) and blue–green (503 nm) VCSELs. The work builds on a series of recent advances in nitride near-UV VCSELs[1–3,6,7] that moved the technology from pulsed, low-temperature operation to continuous-wave, room-temperature operation at blue wavelengths. Kasahara's team improved material quality by using GaN bulk substrates for epitaxial growth, and introduced new device designs to achieve the blue–green VCSELs.

Whereas edge-emitting lasers have cavities several hundreds of micrometres in size, VCSEL devices have cavity sizes of a few micrometres and optical-gain path lengths of a few to a few tens of nanometres via MQW active regions, and it is therefore challenging to produce commercial versions. In particular, owing to the relatively large activation energy of magnesium acceptors, the low contrast between the index of refraction of GaN and those of its alloys, and the poor conductivity of p-GaN and its alloys, it is extremely difficult to prepare highly reflective mirrors (with reflectivity larger than 99.5%) operating in the blue and green regions while retaining a reasonably good current-injection efficiency.

The new device designs of Kasahara and co-workers[5] are crucial to their development of nitride blue and green VCSELs. These include implementing DBR and intracavity transporting and conducting layers (Fig. 1). Overall, hole injection is always the weakest link in nitride photonic devices. In a standard VCSEL structure, a pair of DBR structures lies between the MQW active region and the carrier-injection contact region on both the n side and the p side. Owing to the relatively poor p-type conductivity of GaN and the low contrast between the index of refraction of GaN and those of its alloys, a p-side DBR with high enough optical reflectivity has the problem of low p conductivity and, thus, low free-hole injection into the centre of the active region[8]. In earlier works, laser cavities were formed by inserting dielectric DBR stacks on both the p side and the n side, or by a hybrid approach[2,9,10] (whereby the n-side DBR comprised epitaxially grown stacks and a dielectric DBR was used on the p side).

The nitride blue VCSEL structure consisting of InGaN/GaN MQWs as active layers was grown on *c*-plane GaN substrates by metal–organic chemical vapour deposition[5]. Standard processes including photolithography, etching, GaN-substrate thinning and metallization were also used to fabricate the devices. A pair of SiO_2/Nb_2O_5 dielectric DBRs was used to form a cavity. To obtain the optimal optical length of the cavity and to improve heat removal, the GaN bulk substrate was thinned by a combination of mechanical and chemical–mechanical polishing and the device was bonded to a highly conductive silicon substrate. The current aperture of the blue VCSEL (451 nm) is 8 μm in diameter and the thin indium tin oxide intracavity layer

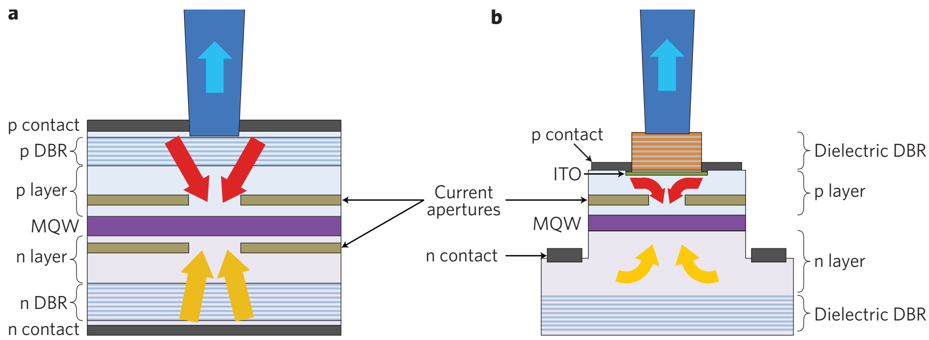

Figure 1 | VCSEL designs. **a,** Standard VCSEL. **b,** Nitride blue–green VCSEL using a pair of dielectric DBR mirrors and intracavity contacts on the p-layer side to enhance hole injection into the centre of the cavity region. Red, hole injection; yellow, electron injection; and blue, laser emission.

has an optical loss of less than 0.5% (ref. 1). The devices were characterized and tested at room temperature. The threshold current density of the blue VCSEL was 3.0 kA cm^{-2} at a voltage of 3.3 V. The far-field pattern and narrowing linewidth of the emission light demonstrated the lasing action. The maximum output power for the blue VCSEL was 0.7 mW. For the blue–green VCSELs (503 nm), which were more difficult to realize owing to the reduction in material quality concomitant with an increase in the indium content of the InGaN/GaN MQWs, only operation in pulsed mode was demonstrated (output powers of >0.8 mW).

Because VCSELs use a much smaller semiconductor wafer area than edge-emitting lasers, and can be produced in high yield, their availability is expected to reduce the price of nitride lasers significantly. Eventually, a blue laser beam may be as common and inexpensive as its counterpart red laser. Two-dimensional arrays of blue–green VCSELs may have applications in areas such as high-density data storage on CD and DVD, with the advantage of higher-speed access and high-resolution laser-printing technology, which has been demonstrated with infrared VCSEL arrays. These devices will have applications in ultraportable products such as microdisplays and next-generation picoprojectors. Two-dimensional arrays of blue–green VCSELs could also be important in emerging fields such as medical sensing, scanning of DNA arrays and optogenetics.

Although the nitride VCSEL structure is already very complicated, in future more sophisticated growth and fabrication processes could be introduced to improve device performance. Growth on semipolar or non-polar GaN is expected to reduce the built-in electric field and enhance the carrier recombination efficiency in the MQW active region. Further improving the p-type conductivity by using materials such as low-indium-content InGaN p layers with increased hole concentrations may boost the performance. The present nitride VCSEL structure has a current aperture only on the p side, for current confinement; introducing a similar aperture on the n side may also improve the efficiency.

Further advances in material quality and device design, to reduce threshold current density and improve performance, are needed to demonstrate room-temperature, continuous-wave green VCSELs. With the realization of continuous-wave green VCSELs expected soon, the demonstration of nitride visible VCSELs will mean semiconductor VCSELs exist for all three primary colours. This will add an important group of blue–green devices to the portfolio of photonic devices in the visible-wavelength region. Demonstration of these technologically sophisticated devices is also important for the field of nitride materials science, as a step towards the further extension of nitride photonic devices, both to longer wavelengths (red, infrared or even the terahertz frequency region) and to shorter wavelengths (deep or even extreme UV). ❐

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