Wide Bandgap Semiconductor-Based Surface-Emitting Lasers: Recent Progress in GaN-Based Vertical Cavity Surface-Emitting Lasers and GaN-/ZnO-Based Polariton Lasers

By Ryoko Shimada and Hadis Morkoç

ABSTRACT | With edge-emitting GaN-based lasers in commercial systems, attention is shifting to more demanding and rewarding emitters. These encompass microcavity (MC)-based vertical cavity surface-emitting lasers (VCSELs) and polariton lasers. The impetus centers on applications such as high-speed/high-resolution laser printing/scanning technology, lighting, and new types of coherent but nearly thresholdless optical sources. Room-temperature operations of GaN-based VCSELs by electrical injection have been recently reported, and the research on GaN-based VCSELs is segueing into new opportunities such as polariton-based lasers. While still in its infancy, polariton lasing in GaN-based MCs at room temperature has been observed. Observation of spontaneous emission buildup in polariton lasing emission is attributed to a Bose–Einstein condensate of cavity polaritons. However, the realization of a polariton laser by electrical injection is still being pursued. In this paper, we discuss the recent progress in wide-bandgap semiconductor-based VCSELs and GaN-/ZnO-based polariton lasers.

KEYWORDS | Polariton lasers; vertical cavity surface-emitting lasers; wide-bandgap semiconductors

I. INTRODUCTION
Wide-bandgap semiconductor optical emitters have experienced tremendous progress and are now commercially available in the form of blue-violet GaN-based edge-emitting laser diodes (LDs) [1] and light-emitting diodes (LEDs), which are sufficiently bright that general lighting applications, dubbed solid-state lighting (SSL), are being pursued vigorously. With increasing efficiencies and output...
power levels, LEDs are now seriously considered for SSL due to reduced power consumption, high durability, and lower maintenance cost, not to mention reduced the carbon footprint on the environment [2]. These developments and our demands pushed the GaN technology early on to attain low defect density materials despite the lack of native substrates. For example, blue-nitride-based LDs are the core component of Blu-Ray high-definition DVD technology, made possible in part by Sony’s control and/or influence over the content. Research on nitride-based semiconductors has now shifted towards further improvements of the materials quality and device performance, including all too important packaging and the development of the new devices such as surface-emitting lasers. With high-efficiency LEDs for illumination of industrial pursuit, a part of the focus has now shifted towards other types of emitters with certain inherent advantages such as resonant cavity LEDs (RCLEDs) and vertical cavity surface-emitting lasers (VCSELs). One of the salient features of VCSELs is that they can be integrated as two-dimensional arrays on the wafer level that would pave the way for high-density optical storage with significantly reduced readout time and high-speed/high-resolution laser printing/scanning technology. Surface-emitting lasers are also well suited for parallel optical communication and potential optical computing. Furthermore, when the cavity size is on the order of the emission wavelength, the spontaneous emission rate can be controlled and the lasing threshold can be reduced owing to the large optical gain arising from the large joint density of states available in wide-bandgap semiconductors, providing that the losses can be reduced. Moreover, VCSELs exhibit completely circular field patterns, as opposed to the elliptical beam profile with an aspect ratio of about four between the vertical and horizontal modes in the edge-emitting lasers, which makes light coupling relatively easier in the former. However, VCSEL realization using GaN- and ZnO-based active regions faces major challenges in terms of the reflector stack fabrication and current confinement, to cite a few. Owing to significant efforts and ensuing continual advances in GaN technology, optically [3]–[10] and electrically [11], [12] pumped GaN-based VCSELs have been reported at low and room temperature. The study on GaN-based VCSELs is now poised to enter a new era wherein the threshold current, optical power emitted, efficiency, and longevity will be drawing more attention.

Beyond the standard VCSEL mentioned above, another type of laser, polariton, is very attractive owing to its nearly thresholdless operation, using cavity polaritons whose genesis lies in the interaction between photons and excitons. This is similar to Bose–Einstein condensation (BEC), which is in thermodynamical equilibrium, while the phenomenon based on polaritons is not. Polariton lasers and microcavity (MC) structures, operative in the strong coupling regime [13], can produce ultracohherent light. As one can construe, polariton lasers are technologically more demanding. The first demonstration of polariton parame-
wavelengths is sandwiched between two DBRs. Since the gain region is very short in vertical cavity devices as compared the edge-emitter varieties, the required reflectivities of the top and bottom DBRs must be well above 90% in order to overcome optical losses for lasing. In fact, the bottom DBR should be nearly 100% reflective, while the top one is made to have a slightly smaller reflectivity depending on the desired optical power to be extracted. To provide the requisite high reflectivity, a large number of stacked semiconductor layers is necessary as, generally, the refractive index contrast between the two compatible semiconductors forming the DBR is rather small. If a large refractive index contrast is employed as in the case of the AlGaN/GaN system with higher Al content, the DBR cracks due to strain with adverse consequences in the form of reduced reflectivity and increased optical losses, both of which are simply detrimental in VCSELs. Moreover, due to the large optical gain arising from the giant joint density of states in wide-bandgap materials, the lasing threshold can be reduced. Prior to VCSEL demonstration, the gain characteristics of the edge-emitting InGaN/GaN quantum-well (QW) LDs already established that room-temperature operation of nitride VCSELs is possible. Clearly, a major obstacle to the realization of room temperature GaN-based VCSELs is the attainment of high-quality DBRs. Epitaxially grown GaN-based high-quality heterolayers forming the DBR sections have a large difference in thermal expansion coefficient and lattice mismatch [17]. Despite the difficulties, much effort devoted to improving the quality of DBRs led to high-quality-factor vertical cavities [18], which paved the way for substantial progress in GaN-based VCSELs. Three different VCSEL structures have been reported by several groups: 1) hybrid cavity structures consisting of the bottom epitaxial GaN-based DBR and top dielectric DBR, 2) all-nitride monolithically grown vertical cavity structures, and 3) vertical cavity structures sport both top and bottom dielectric DBRs. Usually, the number of QWs in the active layer is more than ten in order to increase the gain in order to overcome the optical losses. In the case of electrically pumped LDs, the optimized number of QWs is between three and five because of a tradeoff between the modal gain and threshold current [2].

A. Optically Pumped GaN-Based Vertical Cavity Surface-Emitting Lasers

Someya et al. demonstrated low-temperature (77 K) laser emission by optical pumping at 381 nm from an InGaN hybrid VCSEL having a 187-nm-thick In0.1Ga0.9N active layer straddled by two GaN layers to add up to a 3λ-cavity, a 35-pair GaN/Al0.33Ga0.67N bottom DBR, and a 6-pair TiO2/SiO2 top DBR [3]. Soon after, Someya et al. also demonstrated room-temperature lasing at 399 nm from an InGaN/InGaN MQW hybrid VCSEL under pulsed optical excitation [4]. The VCSEL structures were grown by metalorganic chemical vapor deposition (MOCVD) and composed of a 43-pair GaN/Al0.34Ga0.66N DBR, a 2.5λ-cavity containing 26 sets of In0.01Ga0.99N/In0.1Ga0.9N MQWs, and a 15-pair ZrO2/SiO2 top DBR. A two-dimensional array of disk-shaped 18 μm diameter VCSEL structures with 22 μm spacing has been fabricated by reactive ion etching. Excitation by a dye laser (367 nm), which in turn was pumped by a nitrogen laser, was from the back side of the sample to avoid degradation of the top dielectric DBR. A clear threshold ~43 nJ, which corresponds to 10 mJ/cm2 was observed. Assuming a 50% reflectivity of the nitride DBR at 376 nm, 50% absorption in QWs, and 10% quantum-well efficiency, the estimated sheet carrier density at threshold is in the range of 2 × 1012 to 4 × 1012 cm−2. Lasing emission at 399 nm was confirmed by narrowing of the spectral width, from 0.8 nm in the spontaneous emission regime below threshold to 0.1 nm in lasing emission above threshold.

Song et al. demonstrated an optically pumped dielectric DBR for VCSELs, which consists of five sets of InGaN/GaN MQW with GaN/AlGaN optical and a separate confinement heterostructure geometry sandwiched by top and bottom SiO2/HfO2 DBRs [5]. After the cavity layer was grown by MOCVD, the Al/λ stack of SiO2/HfO2 was deposited by reactive ion beam sputtering. A laser liftoff technique using pulsed excimer laser radiation at 308 nm was performed to remove the sapphire substrate. This is followed by a second SiO2/HfO2 DBR deposition directly onto the exposed bottom GaN layer to complete the VCSEL structure. The top and bottom DBR reflectivities achieved were 99.5% and 99.9%, respectively. A quality factor (Q-factor) exceeding 600 was demonstrated, suggesting that this approach can be useful for ultraviolet (UV)-blue VCSELs and RCLEDs. Thereafter, Zhou et al. demonstrated quasi-continuous-wave (CW) lasing operation at room temperature using a hybrid cavity structure [6]. The structure consists of a 60-pair GaN/Al0.25Ga0.75N DBR, 20 sets of In0.01Ga0.99N/GaN MQWs having 4 nm well width, and 6 nm barrier width and a multilayer SiO2/HfO2 DBR. The VCSEL structures were optically pumped by a frequency tripled 355 nm CW mode-locked Nd:YAG laser operating with a repetition rate of 76 MHz, having a pulse duration ~0.1 ns, and laser spot size ~20 μm diameter. At an average excitation power of ~14 mW, the spontaneous emissions corresponding to cavity modes were observed at room temperature. Increasing the excitation power up to ~40 mW led to the dominant cavity modes having a spectral width of < 0.1 at 383.2 nm. The lasing threshold was ~30 mW and output power ~3 mW. The estimated carrier density at threshold was ~1019 cm−3, which are within the range of typical injection conditions in the best edge-emitting InGaN LDs.

Low-threshold lasing at room temperature from 4λ-thick In0.02Ga0.98N/In0.15Ga0.85N VCSELs with both dielectric top and bottom DBRs has been demonstrated by Tawara et al. [8]. The fabrication process is as follows: 4X-thick cavity layers consisting of three periods of In0.02Ga0.98N (5 nm)/In0.15Ga0.85N (2.5 nm) QWs
sandwiched between Al$_{0.07}$Ga$_{0.93}$N layers were grown on $n$-type 6H-Si substrates by MOCVD. The SiC substrate was removed from the InGaN/AlGaN cavity layers by a conventional dry etching technique. The peeled off cavity layer was then adhered to a SiO$_2$/ZrO$_2$ DBR deposited on a sapphire substrate separately by wafer bonding. The bare DBR reflectivity was $\sim$99% at 400 nm with a 100 nm stopband width. The optical excitation measurements were performed using 10 ns pulses from a YVO$_4$/LBO laser emitting at 355 nm with repetition rate of 20 kHz. The spontaneous emission spectrum was measured at room temperature showing a full width at half-maximum $\sim$0.87 nm at 400 nm and a Q-factor of 460. The emission intensity dependence versus the optical excitation power exhibited a clear nonlinear characteristic, and the lasing emission at 401 nm was obtained. The threshold excitation energy was $\sim$17.5 nJ/pulse, which corresponds to an energy density of 5.1 mJ/cm$^2$. The estimated carrier density was on the order of $10^{20}$ cm$^{-3}$ assuming a DBR reflectivity of $\sim$60% at 355 nm and absorption coefficient of $10^5$ cm$^{-1}$. A fairly large spontaneous emission factor $\beta \sim 10^{-2}$ was deduced, which suggests that the spontaneous emission in this structure is some 1000 times the lasing mode compared to a typical edge-emitting laser with $\beta \sim 10^{-5}$ [19].

In order to prevent cracking during growth/cooldown and have high-quality VCSEL structures, Feltin et al. reported on the use of the Al$_{1-x}$In$_x$N/GaN material system for DBRs [20]. Al$_{1-x}$In$_x$N ($x \approx 0.17$) is nearly lattice-matched to GaN, avoiding the inevitable additional structural damage such as new dislocations and/or cracks. A 40-pair AlInN/GaN DBR was reported to be absolutely crack-free with a peak reflectivity value of 99.4%. Moreover, monolithically grown In$_{0.15}$Ga$_{0.85}$N/GaN MQW VCSEL structures by MOCVD were also demonstrated. The VCSEL structure shown in Fig. 2(a) consists of a 3$\lambda$/2-thick cavity layer with two sets of In$_{0.15}$Ga$_{0.85}$N/GaN MQWs sandwiched between a bottom 28-pair AlInN/GaN DBR and a top 23-pair AlInN/GaN DBR. Fig. 2(b) shows the photoluminescence (PL) spectra at room temperature from the etched area (top DBR removed by reactive ion etching) and another containing the full structure under low excitation power $\sim$2 mW. The spontaneous emission with a very narrow spectral width $\sim$0.52 nm was achieved underscoring the very high Q-factor $\sim$800. This high Q-factor stands above the values measured in other hybrid nitride VCSEL structures made of one top dielectric DBR, $\sim$500–740 [4], [21], and two dielectric DBRs, $\sim$400 [8]. This confirms the suitability of AlInN/GaN-based system for VCSEL structures. Thereafter, lasing at room temperature in optically pumped lattice matched AlInN/GaN VCSEL structure was reported by the same group [9]. This is also conductive for electrical injection as shown in Fig. 3. A low average threshold pump energy density of 200 $\mu$J/cm$^2$ was achieved in a crack-free planar hybrid 5$\lambda$/2-thick GaN microcavity containing three InGaN QWs with a bottom lattice-matched AlInN/GaN DBR and a top dielectric (SiO$_2$/Si$_3$N$_4$) DBR. The VCSEL structures were grown by MOCVD and the cavity region had both $n$- and $p$-type regions as well as an AlGaN electron blocking layer on the $p$ side of the $p$–$n$ junction, making such a planar design in all aspects identical to a practical electrical injection VCSEL. A spontaneous emission coupling factor $\beta \sim 2 \times 10^{-5}$ was derived from the input–output characteristics for this VCSEL structure, which is some five times smaller than that reported in [8].

By oxidizing the AlInN layer from the edges (from the periphery) within the $n$-type cavity region, current microapertures (current confinement) were achieved, which allowed high current densities ($>20$ kA/cm$^2$). Fig. 4(a) shows variation of the emission spectra obtained normal to the surface at room temperature for various pump powers. A clear threshold is observed at an average incident pump power of $\sim$1.4 mW. The spectral width of the emission below threshold is about 3.1 nm [Fig. 4(b)], which is essentially due to cavity thickness disorder, leading to a decrease of the effective Q-factor with increasing spot size and the measured cavity mode revealing the contributions of several narrow modes. Above threshold, the narrowest mode is about 0.37 nm wide, close to the spectral resolution limit of the system. As a promising step towards realization of VCSELs under electrical injection, InGaN/GaN LEDs using oxidized Al$_{0.8}$In$_{0.2}$N layers as current confining apertures were reported [10]. Fig. 5 shows the cross-sectional schematic of the LED structure and the electroluminescence image of the LED structures. A current density on the order of 20 kA/cm$^2$ has been achieved, a value that should fulfill the injection requirements of nitride-based VCSELs.

B. Electrically Pumped GaN-Based Vertical Cavity Surface-Emitting Lasers

As alluded to earlier, GaN-based VCSELs under electrical injection have been reported by several groups...
Lu et al. demonstrated CW lasing of blue GaN-based VCSEL at 77 K under electrical injection [11]. The particular VCSEL structure grown by MOCVD consists of a 29-pair AlN/GaN DBR, a 5\-cavity layer with 790-nm-thick n-type GaN, ten periods of In$_{0.2}$Ga$_{0.8}$N (2.5 nm)/GaN (7.5 nm) MQWs, a 120-nm-thick p-type GaN, and an 8-pair Ta$_2$O$_5$/SiO$_2$ DBR. Since the AlN/GaN quarter-wave-pair represents the largest lattice-mismatch, three sets of a 5.5-pair of AlN/GaN superlattice (AlN and GaN layers in the superlattice were \(3\)–\(5\) nm), corresponding to a half-wavelength stack, was inserted every four pairs of AlN/GaN \(\lambda/4\) stacks to reduce the biaxial tensile strain [22].

**Fig. 3.** Schematic cross-sectional electrical injection ready VCSEL structure. (Courtesy of R. Butté.)

---

**Fig. 4.** (a) Semilogarithmic plot displaying RT emission spectra at pump powers ranging from 50 \(\mu W\) to 2 mW at 0°, shifted for clarity. (b) Linear plot showing two emission spectra (below and above threshold) of the VCSEL structure. (Courtesy of R. Butté.)

**Fig. 5.** (a) Schematic cross-section of the micro-LED structures, (b) optical microscope image of a 20 \(\mu m\) mesa with a 3 \(\mu m\) nonoxidized aperture (dark area), and (c) electroluminescence from a micro-LED under forward bias (250 \(\mu A\), 5.8 V). (Courtesy of R. Butté.)
A 29-pair AlN/GaN DBR showed ~99.4% reflectivity and a stopband width ~25 nm. The epitaxially grown half-cavity structure (without the top dielectric DBR) was used to fabricate the intracavity coplanar p and n contacts for electrical injection, as shown in Fig. 6(a). A 200-nm-thick SiN film was used for current confinement and a light-emitting aperture of 10 μm in diameter. In order to match the resonance phase condition, a 240-nm-thick ITO layer, which corresponds to 1 optical length, was deposited on top of the aperture to serve as the transparent contact layer. To complete the VCSEL structure, an 8-pair Ta2O5/SiO2 DBR was deposited, having a reflectivity ~99% at λ = 460 nm. Fig. 6(b) shows a cross-sectional scanning electron microscope (SEM) image of the hybrid VCSEL structure. The VCSEL performance was characterized at 77 K. Fig. 7(a) shows the light output power versus CW injection current and current–voltage characteristics at 77 K. The turn-on voltage is ~4.1 V, which indicates good electrical contacts and efficient intracavity current injection scheme. Lasing action at 462.8 nm was achieved at a threshold current of ~1.4 mA. The laser emission spectra at various injections current levels are shown in Fig. 7(b). The laser emission line at 462.8 nm, having a linewidth of ~0.15 nm, can be deduced. From Fig. 7(c), the spontaneous emission coupling factor was estimated ~7.5 × 10^{-2}. This value is nearly four orders of magnitude higher than that of a typical edge-emitting laser. The laser beam divergence angle was ~11.7° and the angle of polarization was ~80%. Soon after, CW lasing at room temperature by electrical injection in a GaN-based VCSEL structure was reported by Higuchi et al. [12]. The cross-sectional schematic of the GaN-based VCSEL with vertical current injection is shown in Fig. 8. The epitaxial layers, which consist of an n-type GaN, a 2-pair of InGaN (9 nm) / GaN (13 nm) MQWs, and a p-type GaN were grown on c-plane sapphire by MOCVD. The epitaxial structure was processed to produce current confinement as follows: an 8 μm-diameter current aperture was formed by patterning a SiO2 layer deposited on the p-type GaN. Then a 50-nm-thick ITO layer was deposited as the p-type ohmic contact and the current spreading layer. Subsequently, an electrode was surrounded the bottom DBR. To minimize the absorption loss, ~λ/8-thick Nb2O5 was deposited on the ITO layer in such a way as to cause the ITO layer to be at a node of the optical standing wave. An 11.5-pair SiO2/Nb2O5 DBR was formed as the bottom mirror (depiction reflects the case after completion of the entire fabrication scheme). The sample was mounted on a highly conductive Si substrate, and the c-plane sapphire substrate was removed by laser liftoff. After removal of the sapphire substrate, the n-GaN was etched by chemical-mechanical polishing to form a ~7λ-thick optical cavity. The n-type contact was formed on the n-type GaN, and finally a 7-pair of top SiO2/Nb2O5 DBR was deposited to complete the VCSEL structure.

The current versus light output and voltage characteristics for 8-μm-diameter current aperture devices were performed under CW operation at room temperature. From Fig. 9(a), a threshold current of 7.0 mA is obtained and the threshold voltage is ~4.3 V. The estimated threshold current density is ~13.9 kA/cm², suggesting that the current is uniform over the current aperture. Fig. 9(b) shows the emission spectra at different injection currents. Increasing the driving current, the peak intensity

![Fig. 6. (a) The schematic VCSEL structure and (b) cross-sectional SEM image of GaN-based hybrid VCSEL. (Courtesy of H. C. Kuo.)](image-url)
increased and the spectrum width became narrower. The lasing emission above the threshold current is at 414.4 nm and the spectrum width is \( \pm 0.03 \) nm, which is the resolution limit of the measurement setup. The uniform emission across the current aperture was observed below threshold and a bright spot appeared with increasing current, as shown in Fig. 10, which indicates that lasing action occurred within the current aperture. The laser emission was linearly polarized with a maximum orthogonal polarization ratio of 15 dB.
III. WIDE-BANDGAP SEMICONDUCTOR POLARITON DEVICES

To reiterate, planar semiconductor MCs in the strong coupling regime [13] have attracted a good deal of attention owing to their potential to enhance and control the interaction between photons and excitons, which leads to cavity polaritons. The control of the aforementioned interaction is expected to lead to the realization of coherent optical sources such as polariton lasers, which are based on Bose–Einstein condensation or, more strictly, nonequilibrium polariton population, due to the collective interaction of cavity polaritons with photon modes. In contrast to bulk polaritons, the cavity polaritons have a quasi two-dimensional nature with a finite energy at zero wave vector \( k = 0 \) and is characterized by a very small in-plane effective mass. These characteristics lead to bosonic effects in MCs that cannot be achieved in bulk materials. In particular, the large occupation number and nonequilibrium polariton population at the lower polariton branch (LPB) can be accessible at densities well below the onset of exciton bleaching. This can potentially pave the way to ultra-low-threshold polariton lasers. This feature is markedly different from those governing conventional lasers. Lasing in conventional lasers that we discussed above is predicated upon population inversion which requires substantial pumping/carrier injection. In a microcavity system involving polaritons, however, the lasing condition uniquely depends only on the lifetime of the lower polariton ground state. This is expected to lead to extremely low-threshold lasers, even when compared to VCSELs. Since the first observation of the vacuum Rabi splitting in GaAs-based QW-MCs [23], the strong coupling of light with excitons in semiconductor MCs has attracted a good deal of interest for fundamental studies of exciton–polariton BEC in solid state as well as promising applications such as very low-threshold vertical cavity lasers. So far, however, cavity polariton and BEC based on GaAs-based MCs are observable only at very low temperatures because of the slow relaxation of cavity polariton due to the bottleneck effect at the LPB [24]. In this respect, GaAs-based polariton LED [25] and electroluminescence from polariton state in the strong coupling regime [26] were reported in the 4–10 K temperature range. Moreover, GaAs-based polariton LED at room temperatures as high as 315 K was demonstrated by Tsintzos et al. [27], which could pave the way towards practical polariton emitters based on the well-established GaAs technology.

It is only natural, then, that wide-bandgap semiconductor-based MCs such as GaN and ZnO came to attract increasing attention for room-temperature polariton devices, such as polariton lasers, polariton LEDs, and polariton parametric amplifiers. This potential is due to the large exciton binding energies and oscillator strengths accorded to large-bandgap semiconductors. The GaN technology is now reasonably well developed, and it should come as no surprise that the strong coupling regime in GaN MCs has been observed by a number of research groups [28]–[35]. In principle, ZnO is even more attractive, as it has a much larger exciton binding energy of 60 meV, as compared to 26 meV for GaN. However, the ZnO technology is not so well developed as yet compared to that of GaN.

A. GaN-Based Microcavities-Polariton Lasers

GaN-based MCs are beginning to receive interest in the research community. A realistic model for a room-temperature polariton laser has been proposed for a GaN MC by Malpuech et al. [36]. In the preceding report, the model structure was a \( 3\lambda/2 \) MC, which consisted of a cavity layer with 9 QWs four monolayers thick between \( \text{Al}_{0.2}\text{Ga}_{0.8}\text{N/Al}_{0.9}\text{Ga}_{0.1}\text{N} \) DBRs, 11 pairs on the top and 14 pairs at the bottom. The critical temperature of BEC of cavity polaritons was predicted to be 460 K with a room-temperature polariton lasing threshold as small as 100 mW. Several groups have already reported polariton luminescence at room temperature from bulk [31]–[34] and QW [35] MCs. The experimental results on the strong coupling regime in GaN-based MCs were reported by Antoine-Vincent et al. [28]. A \( \lambda/2 \) GaN layer sandwiched between a four-period \( \text{SiO}_2/\text{Si}_3\text{N}_4 \) mirror and a Si substrate was used for reflection measurements at 5 K, which...
led to the observation of $\sim 31$ meV vacuum Rabi splitting. After that, Tawara et al. observed a vacuum Rabi splitting of 6 meV by angle-resolved reflectivity measurements at room temperature in MCs fabricated by a wafer-bonding technique, which was composed of In$_{0.15}$Ga$_{0.85}$In$_{0.02}$Ga$_{0.98}$N QWs embedded in a GaN-based cavity layer sandwiched between two SiO$_2$/ZrO$_2$ DBRs. By increasing the number of QWs from three to ten, the vacuum Rabi splitting was increased to 17 meV. An impediment for the strong coupling regime in this particular InGaN QW-MC was a low finesse cavity and/or large inhomogeneous broadening of the QW emission [29]. Bulk GaN-based MCs were further studied for polariton emission in the strong coupling regime [31]–[34]. In a bulk GaN MC with lattice-matched AlInN/(Al)GaN DBRs, a strong bottleneck effect was observed at room temperature by PL measurements [33]. In an attempt to use ubiquitous Si substrates, bulk GaN MCs with a 10-pair AlN/Al$_{0.2}$Ga$_{0.8}$N DBR have been grown directly on Si (111) [31], [32]. A vacuum Rabi splitting of approximately 50 meV was observed up to room temperature by angle-resolved reflectivity and PL measurements. A vacuum Rabi splitting of 43 meV in GaN hybrid MCs in the strong coupling regime was reported by Alyamani et al. [34] despite a cavity Q-factor of about 160 or less. A GaN/Al$_{0.2}$Ga$_{0.8}$N QW-MC with a sharper linewidth enabled observation of cavity polaritons at room temperature using angle-resolved PL [35]. A vacuum Rabi splitting $\Omega$ of 30 meV was observed, and the exciton oscillator strength was estimated to be $\sim 3 \times 10^{13}$ cm$^{-2}$/QW.

Room-temperature polariton lasing in a bulk GaN MC under nonresonant pulsed optical pumping has been demonstrated by Christopoulos et al. [15]. The 3$\lambda$/2 bulk GaN cavity was sandwiched between a bottom 34-pair Al$_{0.85}$In$_{0.15}$/Al$_{0.5}$/Al$_{0.2}$Ga$_{0.8}$N DBR and a top 10-pair SiO$_2$/Si$_3$N$_4$ DBR. The Q-factor obtained was $\sim 2800$. Fig. 11 shows (a) the reflectivity from the MC, (b) and (c) theoretical angular dispersion both (b) without and (c) with the resonant exciton contribution to the GaN cavity ($\omega_{\text{cav}}$, dashed line, $\omega_{\text{exc}}$, dash-dotted line) for a slightly negatively detuned cavity ($\Delta = -10$ meV). (d) Angle-resolved PL at low powers up to 60, with lower (LP) and upper (UP) polariton, exciton (X), and Bragg (B) modes marked. (Courtesy of J. J. Baumberg.)

Fig. 11. (a) Microcavity reflectivity at room temperature and $\theta = 5^\circ$, with lower polariton mode. Dashed line shows nonresonant pump energy. (b), (c) Theoretical angular dispersion both (b) without and (c) with the resonant exciton contribution to the GaN cavity ($\omega_{\text{cav}}$, dashed line, $\omega_{\text{exc}}$, dash-dotted line) for a slightly negatively detuned cavity ($\Delta = -10$ meV). (d) Angle-resolved PL at low powers up to 60, with lower (LP) and upper (UP) polariton, exciton (X), and Bragg (B) modes marked. (Courtesy of J. J. Baumberg.)

Further challenging, room-temperature strong coupling regime and nonlinear effects in GaN-based QWs MCs were studied [16], [37], [38]. Christmann et al. employed GaN-based hybrid MCs, which consist of a 3$\lambda$ cavity...
layer with 67 period of GaN/Al$_{0.2}$Ga$_{0.8}$N MQWs sandwiched between a 35 pair of lattice-matched Al$_{0.85}$In$_{0.15}$N/Al$_{0.2}$Ga$_{0.8}$N DBR and a 10-pair SiO$_2$/Si$_3$N$_4$ DBR. Due to high quantum efficiency, InGaN-based emitting devices are commonly used. However, large inhomogeneous broadening of QWs at room temperature is a serious problem in efforts to attain the strong coupling regime [30]. By comparison, GaN/AlGaN QWs have a narrower emission linewidth with a broadening of $\sim 38$ meV, which is capable of paving the way for achieving the strong coupling regime.

In the lattice-matched GaN/AlGaN QWs MC system, the strong coupling regime at room temperature was demonstrated using angle-resolved reflectivity measurements, as shown in Fig. 13(a), observed at small angles followed by an asymptotic trend towards the uncoupled exciton energy ($X$). Fig. 13(b) shows the experimental polariton dispersion curve under nonresonant pumping by weak excitation power. Anticrossing between the LPB and the upper polariton branch (UPB) was observed at $17^\circ$, confirming that the system is in the strong coupling regime. The vacuum Rabi splitting of 56 meV is observed at room temperature. In order to observe the nonlinear optical properties, MCs were nonresonantly excited by a pulsed laser ($\lambda_{\text{pump}} = 266$ nm).

Fig. 14(a) shows a series of emission spectra at average pump power densities ranging from 0.16 to 28.8 W/cm$^2$ at $k_x = 0$. The nonlinear behavior is clearly observed at a relatively low threshold pump power density $\sim 18$ W/cm$^2$, corresponding to a calculated density of $8 \times 10^9$ cm$^{-2}$ per QW. This threshold pump power density is $\sim 1/3$ smaller than that in GaN-based VCSELs [9]. It should note that a further increase of the pump power results in broadening of the emission peak due to increasing polariton–polariton interactions occurring in the condensates. In Fig. 14(b), the emission peak shifts toward higher energies with increasing pump power densities due to the Coulomb interaction between polaritons along the dispersion curve [39]. Above the condensation threshold, new emission peaks appear that correspond to different condensates separated by in-plane photonic disorder, as shown in Fig. 14(a) and (c). Above threshold, the linewidth reduced from $\sim 15$ to $\sim 0.46$ meV.

![Fig. 13.](image)

**Fig. 13.** (a) Angle-resolved reflectivity spectra measured between $0^\circ$ and $41^\circ$. (b) Room-temperature experimental dispersion curve deduced from PL spectra (black squares) and fits of the LPB and the UPB (black lines). The position of the uncoupled cavity mode (C) and the uncoupled exciton ($X$) is also shown (dashed lines). (Courtesy of R. Butté.)
In a perfect polariton laser, polarization should randomly change for each realization of condensate. Baumberg et al. observed the spontaneous polarization build up in room temperature GaN-based polariton lasers excited by short optical pulses [40]. The Stokes vector of the emitted light changes its orientation randomly from one excitation pulse to the other. Although it was unpolarized below threshold, the polarization of polariton emission above threshold is linearly polarized but with no preferential orientation [38], [40]. This behavior is completely different from any conventional laser including VCSELs. A spontaneous buildup of polarization could be interpreted as spontaneous symmetry breaking in a Bose–Einstein condensate of exciton–polaritons.

B. ZnO-Based Microcavities

Another wide-bandgap semiconductor, ZnO, is an attractive candidate for UV optoelectronics devices. ZnO has an exciton binding energy (60 meV) that is more than twice that of GaN (~26 meV). Zamfirescu et al. [41] predicted a large vacuum Rabi splitting $\Omega \sim 120$ meV for cavity polaritons in a model ZnO MC sandwiched between $\text{Mg}_{0.3}\text{Zn}_{0.7}\text{O}/\text{ZnO}$ DBRs, which projects to an extremely low threshold polariton laser (~2 mW) at room temperature. A record $\Omega$ of ~191 meV [42] has been predicted but not yet experimentally observed. On the reflector side, Chichibu et al. [43] reported high-reflectivity $\text{SiO}_2/\text{ZrO}_2$ DBRs for ZnO-based MCs owing to the large refractive index contrast between $\text{SiO}_2$ and $\text{ZrO}_2$, giving rise to a high reflectivity (> 99%) and a wide stopband even for an 8-pair $\text{SiO}_2/\text{ZrO}_2$ DBR.

Recently, ZnO-based MCs were grown by different growth techniques and tested under optical pumping [44]–[47]. Shimada et al. observed a vacuum Rabi splitting of 50 meV in ZnO-based hybrid MCs grown by molecular beam epitaxy (MBE) sandwiched between a 29 pair of AlGaN/ GaN bottom DBR and an 8-pair dielectric ($\text{SiO}_2/\text{SiN}_x$) top DBR [44]. Fig. 15(a) shows the angle-resolved PL spectra at room temperature up to 40°. It is clear that the lower polariton mode gets closer to the uncoupled exciton mode and the upper polariton mode is dispersed from the exciton mode to the cavity mode. The experimental cavity polariton dispersion curve shown in Fig. 15(b) exhibits a typical anticrossing behavior between the cavity mode and exciton mode when the cavity mode energy crosses the exciton mode. Schmidt-Grund et al. grew $\lambda/2$-thick ZnO-based planar MCs, which consist of a ZnO cavity layer surrounded by a 10.5-pair...
ZrO$_2$/MgO DBR prepared by pulsed-laser deposition (PLD). A large vacuum Rabi splitting of ~78 meV was obtained from angle-resolved reflectivity and PL measurements [45]. Using a dielectric MC consisting of a 17-thick ZnO cavity layer and two HfO$_2$/SiO$_2$ DBRs by PLD and radio-frequency magnetron sputtering, respectively, cavity polariton formation was demonstrated by Nakayama et al. [46]. The vacuum Rabi splitting energy was estimated ~80 meV. Recently, Chen et al. observed a large vacuum Rabi splitting of ~58 meV from a 3/2-thick ZnO cavity sandwiched between a 9-pair SiO$_2$/HfO$_2$ DBR and a 30-pair AlN/Al$_{0.52}$Ga$_{0.48}$N DBR, which are grown by plasma-assisted MBE, MOCVD, and electron-beam evaporation, respectively [47]. Note that the determination of the vacuum Rabi splitting should be treated carefully and classified as either cavity mode or Bragg mode coupling to prevent any misperception of the observed features [48]. Until now, no polariton lasing was reported in any ZnO-based MCs. Nevertheless, the above-mentioned results are promising towards the realization of room-temperature ZnO-based polariton devices [49]. Moreover, ZnO-based electrical injection polariton lasers may also be realizable in the future when reproducible and reliable p-type conductivity is achieved in ZnO [50], [51].

IV. CONCLUSION

We have reviewed the recent progress in wide-bandgap semiconductor-based surface-emitting laser structures such as GaN-based VCSELs and GaN/ZnO-based polariton lasers. The developments in GaN-based VCSELs have been remarkable in terms of improvements in materials quality and structural designs. CW lasing in GaN-based VCSELs by electrical injection at room temperature has been demonstrated by Nichia, Japan. GaN-based VCSELs are currently poised to pave the way for enhanced performance and integration levels. What is more is that wide-bandgap semiconductor-based polariton lasers are beginning to show signs of reality. Up to now, room temperature polariton lasing from bulk GaN-based MCs and MQW based MCs has been demonstrated by optical pumping, which is precursory to the realization of electrically injected polariton based lasers. Looking further down the line, ZnO-based MCs also have great potential for room temperature polariton lasers owing to its 60 meV exciton binding energy. Large vacuum Rabi splitting ~80 meV, which is ~1.5 times larger than that in GaN-based MCs, has been observed in ZnO, but no polariton lasing is reported yet. When reproducible and reliable high-quality ZnO is achieved, ZnO-based polariton lasers by optical or electrical injection would appear feasible, the latter hinges of successful attainment of p-type ZnO.

REFERENCES


ABOUT THE AUTHORS

Ryoko Shimada received the B.S. and Ph.D. degrees in physics from Japan Women’s University, Japan, and the M.S. degree in electrical engineering from University of Electro-communication, Japan.

She was with the University of Sheffield, U.K. (2001–2002); Institute for Chemical Research, Kyoto University (2002–2003); the Material Laboratory, Sony Corporation (2003–2004); and Toray Industry Inc. (2004–2006). In 2006, she joined the School of Engineering, Virginia Commonwealth University. In April 2009, she joined Japan Women’s University. Her current research interests are semiconductor microcavities, surface-emitting lasers, and inorganic/organic hybrid nanostructures.

Hadis Morkoç received the B.S.E.E. and M.S.E.E. degrees from Istanbul Technical University, Istanbul, Turkey, and the Ph.D. degree in electrical engineering from Cornell University, Ithaca, NY.

From 1976 to 1978, he was with Varian Associates, Palo Alto, CA, where he was involved in various novel field-effect transistor structures and optical emitters based on then new semiconductor heterostructures. He held visiting positions with AT&T Bell Laboratories (1978–1979); the California Institute of Technology, Pasadena; the Jet Propulsion Laboratory, Pasadena (1987–1988); and the Air Force Research Laboratories, Wright Patterson AFB, as a University Resident Research Professor (1995-1997). From 1978 to 1997, he was with the University of Illinois, Urbana-Champaign. In 1997, he joined the newly established School of Engineering, Virginia Commonwealth University, Richmond, VA.

Dr. Morkoç is a Life Fellow of the American Physical Society and a Fellow of the American Association for the Advancement of Science.
AUTHOR QUERY

No query.