Topical Review

Group-III-nitride and halide-perovskite semiconductor gain media for amplified spontaneous emission and lasing applications

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Abstract

Group-III-nitride optical devices are conventionally important for displays and solid-state lighting, and recently have garnered much interest in the field of visible-light communication. While visible-light laser technology has become mature, developing a range of compact, small footprint, high optical power components for the green-yellow gap wavelengths still requires material development and device design breakthroughs, as well as hybrid integration of materials to overcome the limitations of conventional approaches. The present review focuses on the development of laser and amplified spontaneous emission (ASE) devices in the visible wavelength regime using primarily group-III-nitride and halide-perovskite semiconductors, which are at disparate stages of maturity. While the former is well established in the violet-blue-green operating wavelength regime, the latter, which is capable of solution-based processing and wavelength-tunability in the green-yellow-red regime, promises easy heterogeneous integration to form a new class of hybrid semiconductor light emitters. Prospects for the use of perovskite in ASE and lasing applications are discussed in the context of facile fabrication techniques and promising wavelength-tunable light-emitting device applications, as well as the potential integration with group-III-nitride contact and distributed Bragg reflector layers, which is promising as a future research direction. The absence of lattice-matching limitations, and the presence of direct bandgaps and excellent carrier transport in halide-perovskite semiconductors, are both encouraging and thought-provoking for device researchers who seek to explore new possibilities either experimentally or theoretically. These

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combined properties inspire researchers who seek to examine the suitability of such materials for potential novel electrical injection devices designed for targeted applications related to lasing and operating-wavelength tuning.

Keywords: group-III nitride, halide perovskite, laser, amplified spontaneous emission, superluminescent diode

(Some figures may appear in colour only in the online journal)

1. Introduction

1.1. Group-III-nitride semiconductors

Group-III-nitride materials have been of significant interest to researchers and the industrial community for decades. The various versatile properties of these materials have led to broad interest for solid-state lighting, power electronics, and energy conversion devices, such as light-emitting diodes (LEDs) and lasers [1–4]; high-electron-mobility transistors [5, 6]; photodetectors [7]; solar cells; and photoelectrochemical [8] devices.

1.1.1. Material properties. Three binary group-III-nitride crystalline structures (i.e. InN, AlN, and GaN) exist physically: wurtzite, zinc blende, and rock salt, as shown in figure 1 [9]. Wurtzite structures exhibit better thermodynamic stability at ambient temperature and pressure than the latter two lattice structures [1]. Moreover, because of the large ionicities of the chemical bonds in wurtzite structures, group-III nitrides exhibit chemical and thermal stabilities that are superior to those of other covalent group-III-V compounds (i.e. InP, GaAs, and GaSb), and are thus suitable for use in harsh environments [1, 10].

However, the large ionicities of metal-nitride bonds and non-centrosymmetric atomic arrangements along the *c*-axis cause spontaneous polarization in wurtzite group-III nitrides [11–13]. These polarization fields can increase drift velocities and interfacial charges at heterojunctions [14–16]. This must be considered when designing optoelectronic and electronic devices.

As essential semiconductor materials, the group-III nitrides exhibit direct bandgap characteristics that allow effective radiative recombination and photon emission [1, 10]. The bandgaps of the binary compounds AlN, GaN, and InN are ~ 6.11 eV, ~ 3.42 eV, and ~ 0.65 eV, respectively [17, 18]. The bandgap of InN was initially accepted as 1.9 eV [19] until several pivotal experimental verifications eventually adjusted the value to ~ 0.65 eV. The new value was recognized after 2002 [18, 20, 21]. Simply tuning the group-III element composition (i.e. In, Ga, and Al) in ternary compounds allows the emission wavelengths of these materials at room temperature to provide broad coverage of the optical spectrum, i.e. from the deep-ultraviolet (~ 200 nm) to the infrared spectrum (~ 1771 nm), as shown in figure 2. This wavelength selection flexibility has inspired a wide range of optoelectronics, e.g. visible-wavelength LEDs and lasers, which eventually led to the development of deep-ultraviolet devices.

1.1.2. Material growth and other important issues. Hydride vapor phase epitaxy (HVPE) is an important technique used to grow single-crystal group-III nitride layers during their early development [22, 23]. The first GaN violet emitter was grown via this technique in the 1970s [24–26]. This technique has exhibited high growth rates and repeatable growth of relatively high-quality group-III nitrides. However, p-type dopant incorporation has remained an issue. After substantial growth optimization and device development, HVPE has been used for the production of group-III nitride bulk layers [27] and free-standing substrates [28, 29] since the 1990s, mainly because it offers high growth rates ($>100 \mu\text{m hr}^{-1}$).

Later, metal-organic chemical vapor deposition (MOCVD), also known as metal-organic vapor phase epitaxy, attracted substantial attention because of its eventual success in p-type doping of group-III nitrides [30] and the invention of the first blue LED [31]. Since then, MOCVD has become an industrial workhorse for the epitaxial growth of group-III nitrides. It typically operates at high temperatures and moderate pressures (10 Torr–760 Torr) and uses metal-organic precursors. The growth rates are relatively fast and can be controlled via chemical flows. There are reports of growth of various nanostructures [32], e.g. quantum dots (QDs) [33] and nanowires [34], as well as their subsequent implementations as LEDs or lasers [35]. Due to precursor availability, high growth rates, and growth technique scalability, they are appropriate for commercial mass production. To increase the In composition, the growth temperature and pressure must be lowered [36]. However, growing high-quality, In-rich InGaN is challenging because of the low thermodynamic stability and high evaporation rate of InN at high temperatures. This is the cause for the lack of green-yellow emitters for commercial solid-state lighting applications, which continues to exist despite some indications of research success [37–40] and even the pursuit of MOCVD-fabricated >630 nm GaN LEDs [41, 42].

In addition to the aforementioned chemical vapor deposition (CVD) techniques, physical vapor deposition techniques, especially molecular beam epitaxy (MBE), represent another group of established epitaxial growth methods used in research. One variant of the MBE growth technique uses ammonia gas as a group-V source in high growth rate implementations [43–46]. A nitrogen-plasma-assisted MBE system uses high-purity group-III metallic sources and a radio-frequency (RF) nitrogen plasma as a group-V source. Unlike MOCVD or ammonia-assisted MBE, nitrogen-plasma-assisted MBE growth can be performed in high vacuum environments. This provides much lower growth rates but excellent atomic layer arrangement controllability and high

Figure 1. Three basic group-III-nitride crystal structures. Adapted from [9], with permission of AIP publishing.

Figure 2. Tunable group-III-nitride ternary alloy bandgaps. Reproduced with permission from [11]. © Cambridge University Press. Reprinted with permission.

semiconductor crystal quality. Thus, it can be utilized to grow nanostructures such as QDs [47, 48] and nanowires [4, 49], as well as to grow monolayers such as quantum wells (QWs) [48] and distributed Bragg reflectors (DBRs) [50] in a precise manner. On the other hand, MBE can be performed at much lower temperatures than MOCVD. This can inhibit In desorption from the substrate surface and increase the In content while eliminating phase segregation [36].

Other growth techniques have also been reported, although these are not directly related to the epitaxial growth of laser structures. Their exploration has continued because of their potential to enable low-cost device application solutions. These techniques include reactive sputtering [51], thermal atomic layer deposition (ALD) [52], pulsed-laser deposition (PLD) [53], activated reactive evaporation (ARE) [54], and electrochemical solution syntheses [55]. Prabaswara *et al* [51] highlighted the technique of magnetron sputter epitaxy, which is a variant of reactive sputter deposition and a subset of the physical vapor deposition method. The technique was developed for high-vacuum GaN deposition, and has the potential for large-scale production of channel layers for thin-film transistors [56]. Banerjee *et al* [52] drew a parallel between the potential of poly-GaN and the proven industrial application of poly-Si to solar cell devices. The researchers described a poly-GaN deposition based on the thermal

ALD process that used thermal reactions at 400 °C, without cracking NH_3 into N radicals using a plasma, hot-filament, or electron beam. Vispute *et al* [53] conducted PLD of GaN on dissimilar substrates for scientific evaluation. This technique is still being studied. Biju *et al* [54] reported a modified ARE method based on nitrogen plasmas and gallium evaporation that can be used to grow polycrystalline films. Kang *et al* [55] further demonstrated the electrochemical deposition of GaN on silicon using an aqueous solution that contained $\text{Ga}(\text{NO}_3)_3$ and NH_4NO_3 . These examples further elucidate the motivation of the community to explore alternative deposition techniques for LED and non-LED applications and the direction towards low-cost, scalable production.

More recently, remote epitaxy using two-dimensional layers such as graphene has received substantial attention. For example, Jeong *et al* [57] reported the fabrication of deformable microrod LEDs and achieved substrate reuse. Zhao *et al* [4] and Min *et al* [58] further reported advances in nanowire and nanorod growth on unconventional substrates such as metal and quartz substrates.

Various low-dislocation-density planar epitaxial growth issues still remain [59].

1.1.2.1. Mismatch between epitaxy and substrates. One major concern is the substrate-epilayer mismatch in crystal structures, lattice constants, and thermal expansion coefficients. This leads to substantial challenges in selecting suitable substrates, managing structural defects, and manipulating polarization fields.

The growth of group-III nitrides is hindered by a lack of native substrates. Heteroepitaxial growth results in large mismatches between wurtzite group-III nitrides and conventional substrates such as silicon (111) and corundum sapphire (0001) (α -phase Al_2O_3 or α - Al_2O_3). This introduces high edge- and screw-dislocation densities, as well as hexagonal macro defects and even cracks [2, 60]. While GaN maintains its hexagonal lattice and epitaxial relationship with Si (111) in a straightforward manner, the GaN hexagonal lattice is spontaneously rotated by 30° when grown onto the trigonal lattice of sapphire (see figure 3) [61]. Interestingly, this allows the GaN lattice to align with the corresponding sapphire lattices and produces a ~16% coincidental lattice mismatch instead of the ~33% expected if we were to calculate the lattice mismatch value using the free-standing lattice constants of GaN and sapphire [62].

Differences in thermal expansion coefficients (see table 1) further result in dislocations and residual strain with regard to epitaxy. This contributes to the piezoelectric polarization fields in InGaN/GaN QWs, as well as to residual compressive and tensile strains in GaN grown on sapphire (0001) and Si (111), respectively (see figure 3). This can be measured using Raman backscattering spectroscopy or high-resolution x-ray diffraction. We should be aware that in actual LED epitaxial growth, a low-temperature AlN buffer layer is grown on the substrates to enhance strain field interactions and annihilate dislocations, as well as to ensure the growth of metal-polar group-III nitrides. Nevertheless, mismatch values

Figure 3. Lattice and thermal mismatches of (a) GaN on Si (111) and (b) GaN on Sapphire (0001). GaN experiences tensile and compressive strains on the two substrates, respectively, due to thermal mismatch. These strains can be measured using Raman spectroscopy or x-ray diffraction. *c* denotes the (0001) crystal orientation or the Ga-polar orientation. Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Journal of the Korean Physical Society [62], © 2013.

Table 1. Considerations for GaN epitaxial growth on foreign substrates (data relative to the GaN properties) [63]. Republished with permission of the Institution of Engineering and Technology, from [63] permission conveyed through Copyright Clearance Center, Inc.

Substrate	Bulk GaN	SiC	Sapphire	Silicon
Lattice mismatch ^a	None	3.5%	16%	17%
Thermal mismatch	None	+33%	−25%	+116%

^a Magnitude of lattice mismatch. Readers are referred to page 57 of [64] on definition and discussion on lattice mismatch and strain, as well as perpendicular lattice-mismatch.

remain excessively large and high-performance laser devices still require native substrates, i.e. GaN or potentially AlN.

To minimize the lattice mismatch between group-III nitride and substrate, 6H-SiC was also studied. Devices grown on SiC have lower defect densities and exhibit relatively good performances compared to those grown on sapphire. Despite the high costs that almost inhibit the commercialization of these devices [50], 6H-SiC was adopted by Cree as the substrate of choice for LED production. Meanwhile, other efforts based on the use of sapphire substrates have demonstrated buffer layer insertion [27] and epitaxial lateral overgrowth techniques [2, 33], although the overall processes employed are often complex.

Although the free-standing native substrates are expensive and challenging with regard to substrate up-scaling,

direct epitaxial growth on native substrates leads to high-performance lasers and superluminescent diodes. This will be discussed further in section 2.

Because of the economies of scale relevant to producing group-III-nitride LED devices, Si substrates can be used as an alternative platform for lowering the cost of production while enabling the integration with Si electronics through wafer bonding. However, the thermal expansion coefficient and lattice mismatches tend to cause cracking issues that degrade device performance. To tackle the problem, researchers have demonstrated group-III nitride epitaxial growth on Si substrates using GaN templates by MBE [36]. Another team carefully suppressed the wafer bow and flattened the (In,Ga)N LEDs-on-Si wafer by designing the buffer layer as AlN/step-graded-AlN in an MOCVD growth process [65]. Another option can be growing low-dimensional nanostructures [4], including QDs [35] and nanowires [4]. Lateral nanowire strain relief can result in dislocation-free active regions, while large surface-to-volume ratios offer larger electrochemical reaction interaction areas than planar epitaxy [3, 4].

Lattice mismatch between binary group-III nitrides, e.g. InN and GaN or AlN and GaN, is another impediment to epitaxial development. It leads to high defect densities in their ternary compounds. These can act as non-radiative recombination centers and greatly reduce minority carrier lifetimes. Moreover, lattice mismatch can cause many structural defects between layered optoelectronic structures. One example of a structural defect is DBR cracking, which is especially relevant to AlGaIn-based UV-emitting vertical-cavity surface-emitting lasers (VCSELs) [66, 67].

In addition, the external strain caused by lattice mismatch between different wurtzite epilayers can lead to piezoelectric polarization and further increases the total polarization fields [15, 16]. These large polarization fields can reduce electron–hole wavefunction overlap and further lead to severe issues, including the quantum confined Stark effect (QCSE), potentially Auger recombination-induced efficiency droop, and carrier leakage [4, 68, 69]. In this case, the active region should be designed carefully to suppress such polarization and achieve better carrier confinement.

1.1.2.2. P-type doping issues. Effective p-type doping is another major issue for group-III nitride optoelectronics. The problem was solved by the Nobel laureates Amano, Akasaki, Nakamura *et al* when they achieved Mg-doping of GaN during MOCVD growth using an *ex situ* low-energy electron beam treatment and post-growth annealing [30, 70], and later fabricated the first blue GaN laser [71]. The research field of InGaIn/GaN-based LEDs and lasers has since gained a significant boost. However, effective Mg doping remains somewhat unresolved, mainly because of limited acceptor solid solubility and the high activation energy of Mg in the GaN matrix, as well as self-compensation of the intrinsic n-type characteristics of native nitrogen vacancies in group-III nitride lattices [72–74]. A high Mg doping level in the order of $>10^{19}$ – 10^{20} cm^{-3} is required to yield a carrier concentration in the order of 10^{17} cm^{-3} . However, excessive dopant is known

to deteriorate crystal quality and cause high optical losses of $\sim 65 \text{ cm}^{-1}$ [2].

Although ultraviolet-C (200–280 nm) AlGaIn/GaN-based LEDs have been demonstrated, e.g. 275 nm LED with EQE of more than 20% as demonstrated by Takano *et al* [75], electrically injected ultraviolet-C laser diodes did not exist for a long time. This is because it is even more challenging to activate Mg in AlGaIn materials compared to that in GaN, as Al mole fractions increase, as the acceptor activation energy increases from 0.17 eV for GaN to 0.51 eV for AlN [74]. It was not until 2019 that Zhang *et al* [76] demonstrated the first AlGaIn-based ultraviolet-C laser diode at 271.8 nm under pulsed current injection. This successful demonstration was attributed to the ability of distributed polarization-induced carrier density enhancement in the p-cladding layer to achieve high conductivity and hole injection with low internal loss. During the global pandemic in 2020, ultraviolet-C light-emitting devices appeared to have a beneficial impact on healthcare governance and the healthcare industry, as they enabled speedy disinfection of unoccupied rooms and public transport vehicles.

1.1.2.3. TE-TM polarization issues. In-plane strain in QWs can affect laser emission due to its strong polarization dependence. In particular, the progressive change from in-plane compressive strain to in-plane tensile strain causes the valence band structures to either be in a degenerate state or split into three valence sub-bands due to crystal field and spin-orbit splitting. In [77, 78], as the Al increases from 0 to 0.25 mole fraction (see figures 4(a) and (b), respectively), the valence band structure changes from having a heavy hole (HH, $\Gamma_{9\text{vbm}}$) at the top-most valence sub-band to exhibiting a degenerate state where the valence sub-bands merge. For the mole fraction of 1, the crystal field split-off hole band (CH, $\Gamma_{7\text{vbm}}$) crosses over the heavy hole band and became the top-most valence band in AlN (see figure 4(c)). An early description of the valence band structure can be found in [79], and a recent discussion of the related topics of optical polarization and the light-extraction efficiencies of ultraviolet-C AlGaIn-based LEDs that emit between 264 nm and 220 nm is reported in [80].

Since the electron-HH transition leads to transverse electric (TE)-dominant emission ($\mathbf{E} \perp \mathbf{c}$), while the electron-CH transition favors the transverse magnetic (TM)-dominant emission ($\mathbf{E} \parallel \mathbf{c}$), switching from TE- to TM-polarized light occurs as the Al content increases. The degree of polarization ($P_{\text{TE/TM}}$) is defined as $P_{\text{TE/TM}} = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$, where $I_{\perp}$ and $I_{\parallel}$ are the integrated photoluminescence intensities for the polarization components of $\mathbf{E}$ perpendicular and parallel to $\mathbf{c}$, respectively. Using $\text{Al}_x\text{Ga}_{1-x}\text{N}$ grown on the sapphire substrate as an example, the corresponding degree of polarization changes from positive in GaN to negative in AlN, as depicted in figure 4. The broader beam profile of the TM-polarized light results in mode leakage into the p-cladding region and thus reduces AlGaIn device performance [77, 78, 85]. Readers are referred to [81–84, 86] for further reading on the unique challenges that affect AlGaIn development in the ultraviolet-C regime and the optical properties of GaN.

Figure 4. Band structure near the Γ -valley. The horizontal axis and vertical axis are wavevector and energy respectively. The electron (cbm), heavy hole (HH), light hole (LH), and crystal field split-off hole (CH) bands for $\text{Al}_x\text{Ga}_{1-x}\text{N}$ materials grown on sapphire with Al mole fractions of: (a) $x = 0$ (GaN), TE-(polarized light)-dominant, (b) $x = 0.25$, and TM-(polarized light)-dominant are shown. The symbols $P_{\text{TE/TM}}$, $\mathbf{E}$, $\mathbf{c}$, cbm, and vbm denote the degree of TE/TM polarization, electric field, [0001] crystal orientation, conduction band minimum, and valence band maximum, respectively. The dotted arrows are offset from the Γ -valley for clarity. Adapted from [77], with the permission of AIP Publishing. Prior investigation of the valence band structure is provided in [79] and a recent discussion of device implementation for ultraviolet-C AlGaIn-based LEDs between 264 nm and 220 nm is reported in [80]. The band structure of AlGaIn and related properties are widely documented by multiple sources [81–84].

1.1.3. State-of-the-art devices and applications. Group-III-nitride optoelectronics are attractive mostly because of their superior material characteristics, such as broad bandgap tunability, thermal and chemical stability, and relatively mature growth techniques. Therefore, despite the challenges mentioned above, excellent optoelectronic devices, e.g. LEDs, lasers, superluminescent diodes and photodetectors, have been demonstrated via growth optimization and meticulous device design.

As mentioned before, active-region polarization fields can lead to QCSE and reduced radiative recombination efficiency. Hence, suppression of undesired polarization fields in the active region is essential to various optoelectronic devices. There are several reports on tailoring group-III element mole fractions in QWs and quantum barriers to enhance laser recombination efficiency [87–89]. Another solution that has received significant attention is the growth of device structures on native non-polar and semipolar GaN substrates [90–93]. This solution seeks to address several polarization-field related problems that affect c -plane GaN devices [94], e.g. reduction of carrier recombination lifetimes and increase in the electron–hole wavefunctions overlap, to provide higher radiative recombination efficiencies. The use of native non-polar and semipolar GaN substrates has also been demonstrated to produce higher In incorporation efficiency than a c -plane substrate, thus allowing the growth of devices such as green LEDs that require high In contents [95].

However, in AlGaIn-based deep-UV devices, the polarization field helps to tackle p-type doping issues as shown in figure 5. Conventional thermally activated doping of the structure in figure 5(a) produces a limited activated hole carrier concentration. As shown in figure 5(b), the polarization field ($\mathbf{P}$) in the graded-AlGaIn layer results in a bulk bound

Figure 5. Band diagrams and polarization-induced charge distributions in (a) bulk-AlGaN, (b) graded-AlGaN, and (c) SL-AlGaN EBLs. Representations of interface and bulk charges are included for (a) and (b), respectively. $\mathbf{P}$ is the polarization vector.

charge $\rho_{\text{bound}} = -\nabla \cdot \mathbf{P}$. These unbalanced negative polarization charges exist as a mobile 3D electron slab/gas and create an electric field. Holes can be field-ionized from the deep acceptor level to compensate for the negative polarization charge, thereby increasing the free hole concentrations. In similar scenarios, the term polarization-induced ‘doping’ has been widely used in the literature, which should be physically referred to as an increase in ‘carrier’ concentrations (not the dopant concentration). Further, a graded-AlGaN layer [76, 96–99] can assist the hole transport from the p-type cladding layer towards the active regions [100–102]. As shown in figures 5(a)–(c), hole transport can be facilitated by replacing the bulk AlGaN electron blocking layer (EBL) with a graded-AlGaN EBL or alternating AlN/AlGaN superlattice (SL) layers, thereby reducing the valence band offset or increasing the hole tunneling probability [96, 97, 103, 104].

While blue InGaN-based LEDs and laser diodes have received significant attention and broad adoption for solid-state lighting, the green LED still suffers from a low external quantum efficiency (EQE) of <60% because the strain and QCSE increase with the indium mole fraction in the active region and because of the lack of an effective p-doping method [105, 106]. This is far from the approximately 80% peak EQE reported for the violet-blue wavelength region using group-III nitrides [107–109] and for the red wavelength region using group-III arsenide/phosphide materials [110]. Thus, we reference the well-known ‘green gap’ in the vicinity of 530 nm [111]. It is noted, however, that the peak EQE of an InGaN-based LED can be as high as 53.3% in the green wavelength region, as demonstrated by Li *et al* [112]. A peak EQE of 32.7% was demonstrated in the yellow wavelength region by Jiang *et al* [113]. In this work, the ‘green-yellow gap’ references the range of approximately 530–600 nm.

To improve quantum efficiencies, green InGaN-based LEDs have been optimized via surface roughening of the p-GaN layer, as well as the introduction of V-pits in the green LED layer structure. In particular, the V-pits produce epitaxy that suppresses diffusion of charged carriers into the non-radiative recombination centers formed at threading dislocations [114, 115]. Despite the green LED efficiency

improvements mentioned above and the recent development of Watt-class 532 nm laser diodes by Nichia, as well as 530 nm and 465 nm laser diodes on semipolar substrates by Sony and Toyoda Gosei with peak wall-plug-efficiencies of ~19%, ~18%, and ~37% respectively [116, 117], efficient true-green (555 nm) laser diodes have yet to be demonstrated. Devices with emission near the true-green color are essential to matching the peak sensitivity of human photopic vision, and thereby achieving the highest possible luminous intensity and efficacy. These (true-)green-emitting laser devices are needed for spectroscopy, picoprojectors, and micro-display applications [118].

1.2. Halide-perovskite semiconductors

The inherent bandgap tunability of halide perovskite resembles that of group-III nitrides. Halide perovskite was first discovered by the German mineralogist Gustav Rose in the Ural Mountains of Russia in 1839. It was then named after the Russian mineralogist, Count Lev Alekseyevich von Perovski [119]. This situation remained until 1893, when Wells reported the synthesis of bulk perovskite compounds from aqueous solutions [120]. The crystal structure of perovskite was first described by Norwegian mineralogist Victor Moritz Goldschmidt in 1926 [121] and subsequently established by Helen Dick Megaw, a renowned Irish x-ray crystallographer, in 1945 [122]. Since then, this material system has received substantial attention that has led to several key reports, such as that of the first hybrid organic-inorganic perovskite by Weber in 1978 [123, 124], as well as the development of perovskite-based solar cells following their first demonstration by Miyasaka *et al* in 2009 [125].

1.2.1. Material properties. Perovskite material has the chemical form ABX_3 and the same crystallographic structure as CaTiO_3 , as shown in figure 6. The perovskite crystal structure is an ideal cubic unit cell with cation A in the center with 12-fold cuboctahedral coordination, cation B at the corners with six-fold coordination, and anion X at the midpoints of the edges. However, it is noteworthy that the crystal structure can transform between cubic, tetragonal, and orthorhombic phases depending on the ionic or elemental radii of the elements [126, 127].

While oxide perovskites, in which X is an oxygen anion, exhibit interesting features such as piezoelectricity, ferromagnetism, magnetoresistance, and multiferroic properties [129], halide perovskites, where X is a halide anion, are widely used in optoelectronic devices due to their inherent semiconducting properties. The latter can be further categorized into inorganic and hybrid organic-inorganic halide perovskites. Hybrid organic-inorganic halide perovskites are made by substituting an organic cation for A. The most common types of halide perovskites are shown in table 2. Furthermore, readers are referred to a review article by Ono *et al* [130] that addresses progress in organic-inorganic halide-perovskite materials and devices.

As with various group-III-nitride (e.g. GaN, InN, and AlN) and colloidal group-II–VI (e.g. CdSe) materials, perovskites

Figure 6. Perovskite crystal structure of CaTiO_3 with the general formula of ABX_3 . Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature Reviews Materials [128], © 2019.

Table 2. Common types of halide perovskites.

Inorganic perovskite	Organic-inorganic perovskite
CsPbBr_3	MAPbI_3^a
CsPbCl_3	MAPbBr_3^a
CsPbI_3	$\text{MAPbI}_{3-x}\text{Cl}_x^a$
—	$\text{FAPb(I}_{1-x}\text{Br}_x)_3^b$
—	FAPbBr_3^b

^a MA refers to methylammonium (CH_3NH_3).

^b FA refers to formamidinium ($\text{CH}(\text{NH}_2)_2$).

Figure 7. Normalized photoluminescence (PL) spectra of compositionally tunable metal-halide-perovskite semiconductors and their wavelength-tunability across the visible-to-NIR regime. [131] John Wiley & Sons. Copyright © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

exhibit typical semiconductor direct bandgaps. The metal-halide perovskite has a general formula of ABX_3 ($X = \text{Cl}, \text{Br}, \text{or I}$). Depending on the constituent elements and composition, this class of semiconductor exhibits wide wavelength tunability across the visible-to-NIR region, i.e. from 400 nm to 1.1 μm (see figure 7).

The tunable emission wavelength characteristics of halide perovskite within the visible light spectrum can be explored using various strategies. One of the most explored methods

Figure 8. Schematic illustrations and DOSs versus energy for halide perovskites with various dimensionalities. Reproduced from [142] with permission of The Royal Society of Chemistry.

is the exploitation of quantum-size effects. It is well known that nanoparticle dimensionality changes lead to emission wavelength changes [132]. However, the most direct way to achieve tunability is via anion or cation substitution. For instance, Cs cation substitution for MA in a CsPbBr_3 nanoparticle can change its emission wavelength from ~ 510 nm to ~ 525 nm [133].

Similarly, exchanging the anion of CsPbX_3 changes the corresponding bandgap from 3.11 eV ($X = \text{Cl}^-$) to 2.3 eV ($X = \text{Br}^-$) or 1.55 eV ($X = \text{I}^-$) [133, 134]. Easy solution-processable emission wavelength tuning is highly advantageous for various optoelectronic devices. For laser-based devices, tunable emission from perovskite-based materials has also been reported simply by varying the nanoimprinted perovskite thin film grating period [135, 136]. Thus, the possibility of covering the entire visible spectra using perovskite-based materials is highly attractive and worth exploring with regards to optoelectronic device gain media.

Furthermore, low-dimensional nanostructures of metal-halide perovskites based on nanoplatelets, nanowires, and QDs have received significant attention because of their inherent quantum size effects. It has been reported that these low-dimensional nanostructures exhibit enhanced photogenerated carriers because they offer higher crystallinities, larger quantum confinement effects, and larger surface-to-volume ratios than their bulk counterparts [137–139]. For light-emitting and lasing devices, both one-dimensional (1D) and zero-dimensional (0D) nanostructures have received extensive attention because of their high photoluminescence quantum yields (PLQYs), which are driven by large quantum confinement effects, as well as because of their high crystallinities and low defect state contents [140, 141]. Figure 8 shows the effect of dimensionalities of halide perovskites on their corresponding densities of states (DOSs), which resemble those of group-III-nitride semiconductors.

Broad operating wavelengths are ideal for various optoelectronic devices such as solar cells [131, 143–145], radiation detectors [146], photodetectors [147–150], LEDs [151, 152], and lasers [128, 153]. Solution-based processing is typically

utilized to avoid the need for costly, rigorous epitaxial growth technologies, such as MBE and MOCVD, when producing low-cost optoelectronic devices. As mentioned above, it remains challenging to achieve high wall-plug efficiencies among group-III-nitride light-emitting devices that operate in the ‘green-yellow gap’. Hence, halide-perovskite could fill in the wavelength gap where group-III nitrides is inefficient.

1.2.2. Material growth and key issues. Compared to group-III-nitride semiconductors, which typically rely on epitaxial growth methods such as MBE, MOCVD, and PLD, perovskite-based materials can be synthesized via solution-phase growth or CVD [137, 139, 142]. In particular, low-dimensional perovskite nanostructures, e.g. QDs or nanowires, can be prepared primarily via solution-phase growth.

While solution-phase growth is relatively low-cost and helps researchers to understand fundamental material properties, CVD-based growth of perovskite-based materials has received increasing attention in recent years, as it offers better scalability than solution-based growth methods [137]. Vapor-phase growth has been used to produce perovskite-based multiple quantum well (MQW) structures [154] similar to those produced via epitaxial growth of group-III-nitride semiconductors. Such methods offer higher flexibility and scalability so that we can provide sub-micrometer thicknesses and layered structures, as well as crystallinity favorable to the design of perovskite-based optoelectronic devices.

While the synthesis method of perovskite has reached a certain level of maturity, the pressing photostability issue related to perovskite-based material and devices, especially under exposure to high temperature and moisture conditions, has also improved significantly in recent years. During the early development, a lack of stability constrained the practical application of perovskite-based materials, particularly for photovoltaic (PV) applications, where stable operation is required for reliable characterization and atmospheric environment device applications. Air-stable operation has become one of the key requirements for sustained development in this field. To move towards commercialization, many groups have sought to improve and prolong the operational stabilities of perovskite-based devices using either intrinsic (via e.g. mixing with different cations, stoichiometric changes, surface passivation, or core/shell structures) [155–157] or extrinsic modifications (e.g. coating with an encapsulation layer) [158, 159]. Readers are referred to the comprehensive review article by Castro-Hermosa *et al* [160] that addresses stability in perovskite devices.

The Goldschmidt tolerance factor (t) in equation (1) is often used as a rule of thumb when improving material stability:

$$t = \frac{r_A + r_X}{\sqrt{2}(r_B + r_X)} \quad (1)$$

where r_A , r_B , and r_X are the effective radii of the ions in the perovskite ABX_3 structure [161]. Importantly, the size of the A-cation may allow it to induce distortion in perovskite crystal phases [162]. A typical tolerance factor of

between 0.8 and 1 is known to maintain the formation of the perovskite structure. For cases in which the A-cation is too small (i.e. $t < 0.8$) or too large (i.e. $t > 1$), it will distort the formation of perovskite, and may result in alternative non-perovskite structures [163]. Inorganic cations such as Cs^+ typically yield better thermal, moisture, and optical stabilities than organic-based cations such as MA (methylammonium, CH_3NH_3) and FA (formamidinium, $\text{CH}(\text{NH}_2)_2$). For instance, the all-inorganic CsPbBr_3 perovskite is widely used in LEDs [164–166] and optically pumped laser devices [136, 167, 168].

1.2.3. State-of-the-art devices. Metal-halide perovskites, which have outstanding optoelectronic properties, were first demonstrated as PV cells in 2009 by Miyasaka *et al* [125]. Since then, the perovskite-based solar cell research community has grown substantially. Over the years, the power conversion efficiency (PCE) has increased from 3.8% at the first demonstration to 25.2%, as demonstrated in 2019 by a team from the Korea Research Institute of Chemical Technology and Massachusetts Institute of Technology [169]. Oxford Photovoltaics has achieved a PCE of 28% using perovskite-silicon tandem solar cells [170], surpassing various other categories of solar cells, such as single-junction Si, cadmium telluride, CuInGaSe (CIGS), and a-Si:H solar cells. Such achievements within this short timeframe may suggest that perovskite-based materials offer immense potential for various other optoelectronic devices because of their easy processability and the compositional tunability of halide-perovskite materials.

In fact, halide-perovskite materials have already received significant attention for applications related to LEDs and photodetectors. For instance, green-emitting Br_3 -based LEDs with EQEs of up to 17.5% and 20.3% have been demonstrated by Zhang *et al* [171] and Lin *et al* [172], respectively. While these EQEs are far from those offered by InGaN -based LEDs, easy solution-processability makes these materials attractive for applications in solid-state lighting and next-generation display technologies [164, 173–177]. In addition, various perovskite-based photodetectors with high responsivities [178–180], flexibility [181–184], and fast response speeds [150, 178, 185–187] have also been demonstrated widely [188].

The extraordinary properties of lead-halide perovskite have enabled the aforementioned optoelectronic applications. This is because of their favorable emission linewidths and the ability to tune direct bandgaps by simply modifying chemical compositions [133, 189]. Using quantum-confined nanostructures, perovskite also exhibits stimulated emission with low lasing thresholds due to high defect tolerance, high optical gain, long carrier lifetime, long charge carrier diffusion lengths, and high optical absorption coefficients [153]. In particular, the inherent advantage of high optical gain ($>3000 \text{ cm}^{-1}$) [190] exhibited by perovskite thin films is attractive for applications in micro- and nano-lasers. This creates an alternative research path that is distinct from the technologically mature group-III-nitride platform.

Figure 9. A complete suite of halide-perovskite-based optoelectronic devices, including solar cells, LEDs, and photodetectors, that have received substantial attention. Further device exploration includes the potentially viable light emitters based on electrically driven laser and ASE devices to complement group-III-nitride-based materials in various photonic applications.

This motivates the present review, which discusses the technological readiness of both classes of semiconductors with regard to light-emitting applications. We consider both horizontal waveguide devices (Fabry–Pérot lasers and superluminescent diodes, as well as related amplified spontaneous emission (ASE) devices) and vertical waveguide devices (VCSELs or ASE devices), respectively, in section 2 (group-III nitrides) and section 3 (halide perovskites). In section 3, we further discuss the heterogeneous integration of halide perovskites and group-III nitrides into an integrated gain medium for laser or ASE devices, and thus explain the relevance of both classes of semiconductors.

Figure 9 summarizes key perovskite-based devices that are currently receiving focused attention (e.g. solar cells, LEDs, and photodetectors), as well as the desired perovskite-based components, such as electrically driven lasers and ASE devices. Significant effort is still required to accelerate progress in using halide-perovskite semiconductors to produce a complete suite of electrically injected perovskite-based optoelectronic devices.

The use of halide-perovskite is still in its infancy as compared to the group-III-nitride light-emitters, which is likely to remain the mainstay for laser technology. This review set off to steer the interested research community and readers toward utilization of halide-perovskite for eventual electrically injected tunable wavelength lasing and ASE applications. Section 3 brings out the recent limited hybrid group-III-nitride/halide-perovskite examples (section 3.1) before reviewing the relevant halide-perovskite lasing and ASE devices (section 3.2). Although the approach of combining the robust process technology of group-III nitride with the ease of processing and tunable wavelength (by composition tuning) of the halide-perovskite is challenging, the future realization of electrically injected halide-perovskite can potentially be resolved by the group-III-nitride/halide-perovskite hybrid. It is believed that the topic is a new research direction that could harness the effort of the research community at large.

2. Group-III-nitride lasers and superluminescent diodes

In this section, we first review the techniques of Fabry–Pérot lasers and their integrated variants, such as single-section and multi-section laser diodes (section 2.1). Next, we highlight the unique properties of distributed feedback (DFB) laser, which incorporates a surface grating for achieving narrow-linewidth emission (section 2.2). Finally, the technology of superluminescent diodes is described in section 2.3.

2.1. Fabry–Pérot and integrated lasers

2.1.1. Overview. Fabry–Pérot cavities are the mainstay of semiconductor lasers as a light source, which is the focus of this section. However, to shed light on new integrated optical functionalities of a modulator and a photodetector, additional sub-sections are included. Prior to the work described herein, a different approach to enhance the laser functionality was undertaken by Chua *et al* by introducing additional contacts resulting in a laser that can serve as an optoelectronic ‘AND’ gate [191], a photo triggerable laser [192] and a beam sweeping laser [193]. Central to all these concepts is the manipulation of the gain medium with differential current pumping either through multiple contacts in one cavity or in separate cavities.

Fabry–Pérot laser diodes based on the group-III-nitride system are commonly designed to operate at 405 nm (violet), 450 nm (blue), and 520 nm (green). These devices are essential to consumer electronics and optoelectronics and are already widely reported as discrete devices for applications in optical communication [194, 195], biology [196–198], and cutting-edge instrumentation [199, 200]. However, the group-III-nitride laser diode family requires a substantial market push for the demonstration of photonic integrated circuits and integrated device architectures, which are well established for their near-infrared counterparts [201, 202]. The desired technologies include monolithic tunable lasers, integrated mode-locked lasers, and multisection laser-modulator-amplifier devices.

Conventionally, a laser diode [71] is composed of a layered epitaxial structure with a horizontal waveguide design comprising an active region, a separate confinement heterostructure, cladding, and contact layers. Subsequent fabrication of ridge-waveguides enhances lateral mode confinement via index or gain guiding. Further formation of the laser cavity is achieved via substrate thinning and facet cleaving or etching to form parallel mirrors, which are further coated to increase the modal gain and improve the optical properties. Metal contact deposition completes the fabrication, forming an electrically injected Fabry–Pérot laser diode (see figure 10(a)).

A general form of a multi-section InGaN-based laser diode involves isolating the contact region of the laser structure to obtain separate sections (e.g. the gain, absorber, modulator, and photodetector). The resulting sections are therefore electrically isolated but coupled because the cladding, waveguide, and active region remain connected. For example, a two-section laser diode (see figure 10(b)) can be implemented for purposes such as generation of high-power ultrashort

Figure 10. Elevation and top views of: (a) a conventional ridge-waveguide laser diode, (b) a two-section laser diode, (c) a three-section laser diode, and (d) a laser diode with an integrated optical element (e.g. an air/semiconductor DBR).

pulses [203], superluminescence [204], superradiance [205], light amplification [206], Q-switching [207], mode-locking [208], or fast modulation [209]. Variants of the multi-section laser, such as three-section devices, have been developed using the same principle (see figure 10(c)). Concepts such as gain-absorber-gain [210], and gain-modulator-photodetector [211] integrated devices open the path for highly tunable self-pulsating lasers and photonic integrated circuits. Other types of multi-section lasers include tapered structures for laser amplification [212] and diffraction gratings for vertical emission [213], which can incorporate external elements such as DBRs [214] (see figure 10(d)).

It is noted that the reported work on multi-section lasers focused on wavelengths between 400 nm and 450 nm. Lasing emission at longer wavelengths using group-III-nitride multi-section lasers clearly represents a gap to be addressed.

2.1.2. Device performance and applications

2.1.2.1. Integrated laser-modulator. One of the main advantages of integrated modulators is their small footprint, which leads to low capacitance and high-speed modulation. In these devices, the principle of operation is the electroabsorption modulation, i.e. the control of the optical absorption in the modulator section by applying an electric field. For GaN-based devices, the piezoelectric fields found in the InGaN QWs enable this scheme even though the laser and the modulator section share the same active region. By applying a reverse voltage at the modulator section, the piezoelectric fields of InGaN are compensated and its absorption edge is modified, counteracting the QCSE and changing the effective bandgap of the modulator section. Utilizing these characteristics, it is possible to turn the laser on and off by simply modifying the

Figure 11. Schematic of a modulator-integrated two-section GaN laser diode showing the 100 μm modulator section (modulation voltage, V_{mod}), 700 μm gain section (operating current, I_{gain}), and a common ground. The depicted laser diode includes the following layers grown on a sapphire substrate: p-electrode, top GaN:Mg and bottom GaN:Si contact layers, core structure consisting of GaN:Mg and GaN:Si waveguide layers that encapsulate MQW charge-carrier confinement layers, and a doped AlGaIn optical-confinement waveguide structure. Adapted from [215], with the permission of AIP Publishing.

voltage at the modulator section. This is promising for high-speed applications such as visible light communication and high-frequency laser displays.

Two-section InGaN laser diodes with integrated modulators were first reported by Kneissl *et al* in 2002 ($\lambda = 401$ nm, where λ is the operating wavelength), as shown in figure 11 [215]. A 15 μm shallow-trench isolation was used to create a front-facet modulator section (100 μm) that operated under reverse bias down to -7.2 V with absorption-change as large as 5000 cm^{-1} and power modulation from approximately 3 mW to 0.5 mW. These parameters resulted in an on/off ratio ($R_{\text{on/off}}$) of ~ 7.8 dB and a modulation efficiency ($R_{\text{on/off}}/\Delta V$) of $\sim 1.1\text{ dB V}^{-1}$. The device had a 3 μm wide ridge-waveguide and a 700 μm long gain section. Due to the piezoelectric built-in fields in *c*-plane GaN, the modulator exhibited the lowest extinction at the highest reverse bias. Further progress was made more than 10 years later.

Shen *et al* reported an integrated 2 μm wide ridge-waveguide laser-modulator in a semipolar (20 $\bar{2}$ 1) GaN-based platform ($\lambda = 448$ nm) [209]. A 200 μm modulator section was isolated from a 1290 μm laser gain section by a 10 μm shallow trench. Unlike the modulator from *c*-plane GaN, this semipolar device exhibited a higher extinction at -3.5 V, with power modulation from 15.9 mW to 1.8 mW leading to an on/off ratio ($R_{\text{on/off}}$) of 9.4 dB and a modulation efficiency ($R_{\text{on/off}}/\Delta V$) of 2.68 dB V^{-1} . A larger modulation efficiency of 4.5 dB V^{-1} was also reported using a similar structure ($\lambda = 404$ nm) based on semipolar (20 $\bar{2}$ 1) GaN [216]. The improved modulation efficiency of the semipolar GaN platform is characteristic of the increased wavefunction overlap [217], alongside reduced built-in piezoelectric fields and the corresponding band edge dynamics [218].

Feng *et al* reported on an integrated laser-modulator ($\lambda = 412.8$ nm) with a third photodetector section on a silicon substrate [211]. A 4 μm wide, 790 μm long ridge-waveguide

gain section preceded a 190 μm long modulator and a 290 μm photodetector, all of which were electrically isolated by a 10 μm wide shallow trench. Power modulation (as measured at the photodetector section) from approximately 30 mW to 22 mW corresponded to modulator bias from 2 V to -4 V, thus giving an $R_{\text{on/off}}$ of 1.35 dB and modulation efficiency of 0.22 dB V^{-1} . Further improvement of GaN-on-Si platform may enable large-scale, low-cost integration while retaining the high modulation efficiencies of lasers grown on native substrates.

In terms of the applications of the integrated laser–modulator based on the GaN-based platform, Shen *et al* demonstrated optical communications of up to 1.7 Gbit s^{-1} [216] with a modulation bandwidth of ~ 1 GHz [209, 216], limited by the bandwidth of the characterization setup, i.e. the receiver. Nevertheless, these demonstrations are not conclusive regarding the modulation bandwidth of integrated GaN laser–modulators. No other reports have been made on this platform, and thus the full potential of GaN-based integrated laser–modulator has yet to be realized. As a reference, a traditional group-III-V-based integrated laser–modulator is capable of achieving ~ 14 GHz of modulation bandwidth and 10 Gbit s^{-1} transmission speed [219]; however, unlike the GaN platform, the group-III-V devices require selective area growth, and thus their realization is more involved.

2.1.2.2. Integrated laser–saturable-absorber. The ability to control the absorber section independently and at different laser cavity locations (see figure 12) enables broad tunability across different regimes of operation. Among the various functions that have been developed based on the laser–saturable-absorber structure, we should highlight the self-pulsating laser. The role of the absorber section in generating a pulsed laser beam has been a subject of detailed investigation that includes observation of self-pulsating operation at zero absorber bias [220]. Figure 13 shows ps-scale pulses from a three-section laser with a saturable absorber integrated at its center. Self-pulsating lasers offer high peak output power in a compact form and have the potential to replace conventional solid-state lasers used in multiphoton physics and other applications.

Initially reported by Tronciu *et al* in 2004 [222] ($\lambda = 400$ nm), self-pulsation frequencies between 1.6 GHz and 2.2 GHz were achieved using a so-called ‘tandem’ laser diode, where a 52.3 μm long absorber section was grounded while biasing a 490 μm long gain section. Since then, Q-switching and mode-locking of multi-section laser diodes with integrated saturable absorbers have been the subjects of numerous reports ($\lambda = 400$ nm to ~ 430 nm) [203, 207, 208, 210, 220–240] that cover a range of self-pulsating frequencies and pulse widths as small as 2 ps. Moreover, femtosecond pulse durations with peak power and energy levels of up to 9 kW and 3 nJ, respectively, have been reported by integrating these multi-section lasers into an external cavity configuration, e.g. to form the GaN-based master oscillator power amplifier (MOPA) [236].

Figure 12. Integrated laser-saturable-absorbers with three-section Gain (G)-Absorber (A)-Gain (G) (left) and two-section Gain (G)-Absorber (A) (right) configurations. Adapted with permission from [221]. Copyright (2013) Society of Photo-Optical Instrumentation Engineers (SPIE).

Figure 13. Pulsing characteristics of an integrated laser-saturable-absorber based on a three-section Gain (G)-Absorber (A)-Gain (G) configuration, as seen via a streak camera. The saturable absorber is maintained at zero bias. Adapted from [220]. © IOP Publishing Ltd. All rights reserved.

Q-switching refers to changing the quality factor (Q-factor) of the laser cavity via the absorber section. A low Q-factor is present when light generated in the gain section is captured by the absorber section (usually under a high reverse bias) [231]. Upon increasing electrical injection into the gain section, the absorber continues to capture light until it achieves optical transparency. This suddenly allows the laser cavity to achieve a high Q-factor. This process creates a sudden release of laser light in the form of a pulse. This rapid release of energy depletes the excited carriers in the gain section and the absorber becomes opaque again, and is ready to repeat the Q-switching process once again. In a mode-locked laser, self-pulsation involves synchronous phase relations among the various longitudinal cavity modes of the laser. The absorber section can be selectively modulated or reverse biased to influence the phases of the various longitudinal modes [229], thus creating losses for out-of-phase modes. This means that pulse formation in a mode-locked laser simply occurs when the various longitudinal modes arrive at the output facet simultaneously. Therefore, the pulsation frequency of a mode-locked laser is related to the roundtrip time inside the cavity. Consequently, Q-switching typically provides higher optical power levels than mode-locking, but mode-locked lasers may achieve higher repetition rates. It is expected that exploring these types of self-pulsating lasers across the visible spectrum may enable new imaging capabilities, such as compact

two-photon microscopy and on-chip multi-photon applications. The reader can refer to detailed descriptions of both Q-switched and mode-locked lasers such as those in [241] and [242].

Monolithic integration of the saturable absorber in a laser diode also enables investigation of the concept of ultrashort pulse generation created by superradiance and superfluorescence using InGaN-based emission across wavelengths in the violet-blue color range (i.e. $\lambda = 408$ nm to ~ 423 nm) [205, 243–247]. Nonetheless, achieving superradiance and superfluorescence in semiconductors appears to be a controversial topic that requires further examination.

In a different role, the integrated absorber section can be used to suppress lasing. This leads to the production of a superluminescent diode that operates in the ASE regime [204, 234, 248–251]. In section 2.3, the InGaN-based superluminescent diode is discussed separately, and a review article is recommended for further reading.

2.1.2.3. Semiconductor optical amplifier integrated laser. A two-section laser diode that implements a semiconductor optical amplifier (SOA) section is attractive for optical amplification of modulated or continuous wave (CW) laser signals. Under electrical injection, an SOA produces excited carriers leading to population inversion. This is needed to amplify incoming light via stimulated emission [252]. SOAs are important for telecommunication wavelengths, but recent attention has been given to visible SOAs in support of the development of new technology platforms such as MOPAs [236] and swept sources [253]. Integration of an SOA alongside a laser in a chip opens a pathway for realizing visible-range photonic integrated circuits that could exhibit immunity to the intrinsic optical loss of visible-light waveguides [254].

To this end, Shen *et al* reported an integrated laser-SOA based on an InGaN-based laser ($\lambda = 404$ nm) grown on a semipolar (20 $\bar{1}$) GaN substrate in 2018 [206] (see figure 14). A nonlinear gain of 5.7 dB was achieved upon applying 6.25 V to the amplifier section. The 2 μ m wide ridge-waveguide laser, which had a 300 μ m long SOA section integrated in front of a 1190 μ m long gain section, gave a maximum output optical power of 30.5 mW.

In 2012, Stanczyk *et al* reported a single top-contact device ($\lambda \sim 408$ nm) composed of a 3 μ m straight ridge-waveguide section (between 150 μ m and 325 μ m long) and a flared waveguide section used for amplification (between 325 μ m and 500 μ m long with a taper angle between 2° and 5°) [212]. This configuration produced a maximum optical output power of 600 mW.

While the integration of the SOA-laser is an attractive topic, gain saturation challenges should be addressed. Gain saturation is due to the inability of the SOA to continuously amplify incoming light at increasing optical power levels. This is related to the rate at which carriers can be injected into the SOA while the photon density increases along the SOA. This problem affects SOAs and superluminescent diodes (section 2.3) alike [255, 256].

Figure 14. Schematic and microscope images (inset below) of an SOA integrated laser diode implemented using a 2 μ m ridge-waveguide structure and a semipolar (20 $\bar{1}$) GaN substrate. The dimensions of the amplifier and gain sections are indicated accordingly. Adapted with permission from [206]. © The Optical Society.

Figure 15. Schematic of a device in which the detector and modulator are integrated with the gain section to form a three-section laser diode. The dimensions of the various sections and layer structures are indicated. © 2018 IEEE. Reprinted, with permission, from [211].

2.1.2.4. Integrated laser-photodetector. A necessary step towards multicomponent integration and the development of photonic integrated circuits based on InGaN/GaN is the study of integrated laser-photodetectors, which can aid in monitoring the operation of laser diodes in stand-alone integrated devices and photonic integrated circuits. This was investigated by Shen *et al* in 2017 using a semipolar (20 $\bar{1}$) GaN-based platform ($\lambda = 405$ nm) [257] with a photodetector responsivity of 0.051 A W $^{-1}$ at -10 V and a modulation bandwidth of 230 MHz. This strategy was further explored in 2018 by Feng *et al* ($\lambda \sim 413$ nm) [211], who demonstrated a three-section gain-modulator-photodetector configuration (see figure 15). This device was demonstrated using a *c*-plane InGaN/GaN laser structure grown on a silicon substrate, and could potentially offer a low-cost, large-scale implementation. The photodetector exhibited a responsivity of ~ 0.015 A W $^{-1}$ at -4 V.

The fact that the photodetector section shares the epitaxial structure with the laser and modulator provides a significant device integration advantage. In contrast, traditional silicon photonics and photonic integrated circuits require individual

growth of the laser source and photodetector, followed by device transfer [258]. This increases the complexity of large-scale integration.

2.1.2.5. Integrated laser-optical element: air/semiconductor mirrors and diffraction grating. The monolithic integration of passive optical elements with a laser diode via a single etching step is attractive for large-scale photonic integration. A small footprint can be achieved by forming passive optical elements in the same semiconductor structure as the laser.

Air-semiconductor DBRs (figure 16(a)) were initially developed to improve reflectivity at laser facets and thus reduce the threshold current and improve the lifetime of the GaN laser. This approach is important for lasers that are integrated into monolithic photonic circuits where it is difficult to implement facet cleaving and dielectric mirror coatings. Available reports discuss discrete laser-DBR integration (λ range of 400–407 nm) [214, 259–264], but further investigation is required at the level of photonic circuit integration. Similarly, integration of laser diodes with a special type of diffraction grating enables vertical emission from in-plane lasers at λ of 407 nm (see figure 16(b)) [213, 265]. This can be attractive for board-to-board free-space data transfer, as well as diagnostics of processes that occur within a photonic integrated circuit and post-fabrication device testing.

2.2. Narrow-linewidth laser via integration of a DFB grating

2.2.1. Overview. DFB gratings were demonstrated using InGaN-based lasers to overcome low reflectivity at the facets during early development [266]. Now, DFB lasers are being designed to achieve single-frequency operation. Ideally, DFB gratings would selectively diffract light from the laser diode back into the cavity based on the Bragg condition [267] and the chosen dominant wavelength or frequency. DFB lasers differ from the above-mentioned multi-section lasers because the DFB grating is incorporated within the gain section instead of being a separate section. The DFB grating can be implemented near the active region as a buried grating (e.g. 80 nm period and 100 nm depth) via electron-beam lithography, inductively coupled plasma etching, and subsequent overgrowth. A 405 nm DFB laser (see figure 17(a)) based on such a fabrication scheme utilized a first-order grating to achieve CW operation at 25 °C showing a threshold current and slope efficiency of 22 mA and 1.44 W A⁻¹, respectively [268]. This first GaN-based continuous-wave DFB laser determined the goals of later efforts.

Alternately, a DFB grating can be formed on the surface of a laser device but outside of the p-contact stripe, as shown in figure 17(b). The scanning electron microscope (SEM) images show the DFB grating in the form of V-shaped grooves fabricated beside the p-contact stripe. The violet (λ of approximately 405–410 nm) laser sustained CW operation and was based on a 10th order laterally coupled surface grating [269].

To put things in perspective, buried gratings represent a significant challenge for the already complex growth of group-III-nitride lasers. This has driven the use of surface gratings

Figure 16. (a) Device schematic and SEM image of an air/semiconductor DBR-integrated edge-emitting laser on a sapphire substrate. Adapted from [260], with the permission of AIP Publishing. (b) Schematic of integrated laser-DBR grating designed to achieve vertical laser emission. Green and orange colors indicate the SiO₂ layer and top or bottom electrodes, respectively. Epitaxial layer structures and the SiC substrate are indicated accordingly. Republished with permission of the Institution of Engineering and Technology (IET), from [213], permission conveyed through Copyright Clearance Center, Inc.

as the dominant grating technology in recent years. Together with surface gratings, higher order gratings have also been adopted to relax fabrication requirements. Together, these two approaches have led to the successful demonstration of high-performance DFB lasers and are expected to remain relevant.

2.2.2. Device performance. Since 1996, the development of InGaN-based DFB lasers has produced improved electrical operation, narrower linewidths, increased side-mode suppression ratios (SMSRs), and higher optical output power [268–295]. Most studies have focused on violet-to-blue emission (λ of approximately 400–450 nm) due to material availability, although recent reports have addressed sky-blue (λ of approximately 480 nm) [288] (see figure 18) and green (λ of approximately 514 nm) lasers [287, 296]. These recent efforts indicate strong progress in the development of DFB single-frequency emitters. CW operation has become the norm [269, 278, 282, 287, 288], with output power as high as ~90 mW (continuous wave) [269] and 200 mW (pulsed) [286], as well as SMSRs as high as ~42 dB [288] (see figure 18). It is important to mention that measurement of

Figure 17. (a) Device schematic of a 405 nm DFB laser with a first-order grating implemented on an n-type cladding layer (buried grating with an 80 nm period and 100 nm depth via electron-beam lithography). Adapted from [268]. © IOP Publishing Ltd. All rights reserved. (b) Scanning electron microscope images of 10th order laterally coupled surface gratings in the form of V-shaped grooves fabricated beside the p-contact stripe of a violet (approximately 405–410 nm) laser diode. Adapted with permission from [269]. © The Optical Society.

the linewidths of InGaN-based DFB lasers has not been well established, as it mostly relies on the resolution provided by optical spectrum analyzers. Characterization of the real linewidth is a necessary step towards understanding GaN DFB laser noise and frequency stability. This could lead to the eventual implementation of such compact devices in frequency standards and atomic clocks. A comprehensive report on the wavelengths and linewidths required for such applications can be found in [297].

DFB lasers at visible wavelengths are aimed at enabling compact solutions for atomic clocks, spectroscopy, and optical communication. DFB lasers provide a monolithic solution capable of being deployed in space or underwater probes

Figure 18. The characteristic emission spectrum of an InGaN-based DFB laser diode exhibits a single lasing mode centered at approximately 480 nm with an SMSR of approximately 42 dB. High-speed optical wireless communication of up to 10.5 Gbit s^{-1} was demonstrated using such a laser in [288, 298]. Adapted with permission from [288]. © The Optical Society.

where small device sizes and immunity to vibration are important. A recent demonstration of high-speed optical communication (up to 10.5 Gbit s^{-1}) using an InGaN-based DFB laser shows the potential for further development of these devices for data transmission and fast modulation [288, 298].

2.3. Superluminescent diodes and ASE

2.3.1. Overview. Superluminescent diodes are light sources that operate in the ASE regime [299], in which the amplification of spontaneous emission is achieved via stimulated emission, such as in laser diodes, but restricted by a lack of optical feedback. This lack of optical feedback restraining the resonating cavity is the main difference between the laser diode and both superluminescent diode and SOA. The superluminescent diode amplifies its own generated light, whereas an SOA merely amplifies incoming external light; nonetheless, their epitaxial structure can be identical. Superluminescent diodes achieve stimulated emission by utilizing a waveguide epitaxial structure equivalent to that of a laser diode, where spontaneous emission from the heterostructure is guided and amplified within the device. Disruption of the optical feedback is achieved by reducing the facet reflectivity using any of several methods including tilted facets [300], antireflection (AR) facet coatings [301], waveguide bending [302], passive absorbers [204], and facet roughening [303]. A combination of broad spectral emission, droop-free operation, and a high optical power density can then be achieved to support applications in optical coherence tomography [304] and fiber gyroscopes [305].

For ASE to occur, there must be sufficient material gain to overcome material losses (e.g. non-radiative recombination and absorption). One way to exploit this material gain is by using a double-pass superluminescent diode configuration, which relies on a cavity where the reflectivity of one facet is

enhanced by a dielectric DBR coating. Thus, the optical power (P_o) is proportional to the square of the optical gain (G_s) [306]:

$$P_o \approx P_{sp} R G_s^2, \quad (2)$$

where P_{sp} is the power of the spontaneous emission, R denotes the reflectance of the high-reflection DBR mirror, and G_s is the single-pass optical gain. The value of G_s is related to the current density J and cavity length L , as follows [306]:

$$G_s(J, L) = \exp \left[\left(\Gamma g_o \eta \frac{J}{d} - \alpha \right) L \right], \quad (3)$$

where Γ is the confinement factor, g_o is the gain of the active region, η denotes the internal quantum efficiency, d is the thickness of the active layer, and α is the modal absorption. Since the device length and current density can be adjusted simply, the optimal regime of operation can be achieved in standard epitaxial structures. Nonetheless, we should remember the gain saturation regime (similar to that of an SOA), where the photon density is higher than the carrier density and thus the amplification process is hindered [255, 256]. In this case, epitaxial engineering is needed to improve other parts of equation (3).

2.3.2. Device performance and applications. InGaN-based superluminescent diodes offer characteristics such as low speckle noise, large modulation bandwidth, high optical power density, and droop-free operation at short wavelengths [250, 256, 307, 308]. Since the first demonstration of GaN superluminescent diodes in 2009 [309], they have been included in applications such as white lighting [248] and visible-light communication [251, 310, 311]. Furthermore, to fulfill the needs of picoprojectors, sensing, and biomedicine, consistent research has been performed to enhance the optical bandwidth, output optical power, and emission at different wavelengths (e.g. near ultraviolet, blue, and green light) from GaN superluminescent diodes [307, 312–314].

The highest optical power from a CW InGaN-based superluminescent diode is 350 mW recorded for a ‘j-shaped’ curved-waveguide superluminescent diode that emits light at 405 nm and was reported by Castiglia *et al* [315]. In contrast, the highest obtained optical power of a pulsed superluminescent diode is 2.2 W, as reported by Cahill *et al*, who fabricated the superluminescent diode on a *c*-plane GaN-substrate that emits blue light at 416 nm [316]. This is a horizontal device that uses deflecting mirrors to produce vertical emission.

The highest superluminescent diode modulation bandwidth reported is 2.5 GHz by Rashidi *et al* and was produced using a non-polar GaN substrate [317]. The leading role of non-polar GaN in achieving record modulation bandwidths is likely to be maintained [217]. The shortest device cavity was reported by Zhang *et al*, who demonstrated a 40 μ m long superluminescent diode [318] with a significantly broadened emission (15 nm) but limited in optical power (~ 2 mW), as expected, due to its short device length.

The first report of a GaN-superluminescent diode grown on silicon was presented by Liu *et al* [319]. It provided a path for integrating monolithic silicon photonics and GaN sources. However, heteroepitaxy remains a challenge to provide the optical output power levels of such devices. A 15.5 nm broadest full-width at half-maximum (FWHM) was recorded from an InGaN violet superluminescent diode designed by Kafar *et al* using the concept of a non-linear indium content profile along the superluminescent diode waveguide [320]. This approach can provide a way to extend the limited optical bandwidths of GaN superluminescent diodes (usually 5–8 nm), but difficulties with optical absorption due to self-pumping of the active region remain to be solved.

In the latest development in green-emitting superluminescent diodes, Primerov *et al* at EXALOS demonstrated the provision of up to 10 mW of superluminescent diode light at 517 nm (targeted for picoprojection applications) [321, 322]. The production of such a green-emitting device indicates a level of GaN superluminescent diode design and fabrication maturity and the ability to overcome the drop in efficiency, reduced optical confinement, and related material issues that occur at longer wavelengths.

The future of GaN superluminescent diodes is affected by material constraints that affect device efficiency limitations that in turn affect green emission. Despite this, true-green superluminescent diodes may play a significant role in the upcoming augmented reality and virtual reality revolution, which includes consumer electronics. InGaN QDs [314] seem to offer a relevant development path, although this concept has barely been explored. Blue superluminescent diodes with increased modulation bandwidths will be necessary for smart lighting applications. Engineering approaches aimed at increasing energy efficiency [323] may eventually accelerate large-scale market adoption.

Readers are further referred to a review article by Shen *et al*, which provides a detailed account of progress in InGaN-based superluminescent diodes [307].

3. Group-III nitride and halide perovskite lasers and ASE towards the green-gap

Recent reports on the use of halide perovskite as an optical gain medium that can exhibit ASE and lasing action bear testament to its potential for producing ‘green-yellow gap’ lasers. Such lasers are currently difficult to produce efficiently using group-III nitride or group-III phosphide-arsenide material systems due to lattice and thermal mismatches and physical limitations related to bandgap structures. Ease of solution processability can reduce the cost of fabrication relative to conventional epitaxial growth methods. Most importantly, while InGaN- and AlGaInP-based lasers have correspondingly been demonstrated to cover the 375–530 nm wavelength region and the red wavelength region at >630 nm, respectively, they are inadequate for efficient operation in the green-yellow wavelength range, which remains a topic of research focus [324].

Figure 19. Combinations of laser and superluminescent diode devices with varying gain-medium constituents. Blue and green colors represent devices with only group-III-nitride- or perovskite-based gain media, respectively. Transitional blue-green colors indicate the utilization of both semiconductors in a heterogeneous, integrated manner.

3.1. Towards hybrid integration

As noted in figure 19, laser and ASE devices can be implemented using horizontal and vertical waveguide configurations. The laser and superluminescent diodes described in section 2 mostly focus on horizontal emission made up of group-III-nitride semiconductors on sapphire or GaN substrates. Using such a horizontal waveguide configuration and $\text{SiO}_2/\text{TiO}_2$ DBRs, nanowire was grown on a silicon substrate and fabricated into a laser emitting at 533 nm [325].

In addition, a VCSEL [326, 327] and ASE device or random laser based on a nanowires ensemble [328, 329] were demonstrated on hybrid-dielectric or all-dielectric DBRs, as well as photonic crystal (PhC) elements. Apart from that, Br-based perovskite can be integrated with DBRs [330, 331] or porous-GaN/GaN DBRs [332] to produce vertical emission devices, as discussed below.

Despite the rapid development of halide-perovskite-based materials as preferred gain media, heterogeneous integration between solution-processed perovskite films and existing device technology, e.g. in-plane and VCSELs, remains a major challenge. In particular, although optically pumped VCSELs realized based on all-dielectric DBR structures have been widely reported in recent years, it is still challenging technologically in implementing electrically-conducting DBR structures, which would allow current-injection devices. In 2017, Chen *et al* [332] were among the earliest to produce a perovskite-based optically pumped VCSEL based on $\text{CH}_3\text{NH}_3\text{PbI}_3$ thin films and a custom-designed GaN-based high-quality-factor optical resonator. Here, we highlight an encouraging work based on nanoporous-GaN VCSEL with a bottom conductive DBR structure [333], which could be promising in future electrically injected halide-perovskite VCSELs if successfully integrated.

Lattice-matched nanoporous-GaN (NP-GaN) and GaN stacks are deposited as a DBR structure on the VCSEL in figure 20(a), and layered with the perovskite thin films. The VCSEL structure exhibits a single-mode lasing peak at 778.4 nm (see figure 20(b)), an SMSR of more than 20 dB, and a low threshold density of $113.9 \mu\text{J cm}^{-2}$. Instead of relying on

Figure 20. (a) SEM image of a perovskite-based thin film with a lattice-matched NP-GaN/GaN DBR structure intended for perovskite-based VCSEL. (b) Single-mode lasing at 778.4 nm with an SMSR that exceeds 20 dB. [332] John Wiley & Sons. Copyright © 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

dielectric DBR structures typically consisted of oxide-based layers, this represents a significant step towards monolithic integration of a perovskite-based cavity medium with a nitride-based DBR to produce an electrically pumped VCSEL. This effort seeks to address the scarcity of visible light-based lasers, and in particular the ‘green-gap’ in conventional group-III-nitride-based materials. Moreover, by simply substituting the halide-anions in the perovskite gain medium, this would allow reconfigurable, solution-processable and wavelength-tunable light-emitting devices without the need of considering the issues of lattice-mismatch, which remained a key consideration in group-III-nitride growth processes.

Although the integration of perovskite with group-III-nitride materials is still not well studied, it would be of great interest to explore multifunctional properties available via hybrid structures and potentially open up a new avenue for novel applications. Along with the development in this regard, there remain a few key challenges that need to be resolved. For instance, it has been noted that perovskite might suffer from poor thermal dissipation under high electrical injection [128] and could possibly degrade the long-term performance of the lasing devices due to the sensitivity of the perovskite gain medium to the heating effect. Thus, integration of GaN-based

DBRs on bulk-metal substrates may potentially relieve heating issues and extend the lifetimes of future electrically driven perovskite-based laser devices. In terms of device fabrication and processability, the dissociation of perovskite structure under external heating ($>150\text{ }^{\circ}\text{C}$) could be challenging for integration with nitride-based DBR structures, as the deposition of group-III-nitride-based materials requires a higher growth temperature of up to $>500\text{ }^{\circ}\text{C}$.

A recent demonstration by Kelvin *et al* [334] has also provided a promising perspective on the formation of composite structures from MAPbBr₃ and nanoporous GaN. Infiltration of MAPbBr₃ into the highly porous GaN layer via a low-temperature post-processing step may enhance spatial confinement in the perovskite within the encapsulation matrix while preserving perovskite photostability [335]. Although this remains to be demonstrated, such a composite may be promising with regard to monolithic integration of phosphor-LED technology, as well as for its potential for random lasing due to its improved quantum confinement effect.

3.2. Perovskite lasing and ASE

In addition to their inherent high defect tolerances, high absorption coefficients, high exciton binding energies, and high PLQYs, semiconducting metal-halide perovskites exhibit promise for development as optical gain materials [336–338]. In particular, perovskite-based materials may be used for low-cost optoelectronic devices operating in the green-yellow gap in which the conventional group-III-nitride-based materials face significant challenges, as well as offering an alternative approach for wavelength-tunable visible lasers in which solution-processed perovskite is used as an optical gain medium. This section summarizes the recent development of perovskite-based materials as a gain medium for optically pumped devices. We further provide perspectives on the choice of gain medium and design structures.

An earlier study of perovskite-based gain media for ASE and lasing devices was performed by Xing *et al* in 2014 [339]. Despite the low PLQY demonstrated, the solution-processed perovskite-based gain media (e.g. MAPbCl₃, MAPbCl_{1.5}Br_{1.5}, MAPbBr₃, MAPbBr₂I, and MAPbI₃) exhibit ASE across the entire visible wavelength region (i.e. 390–790 nm) through simple halide substitution, as shown in figure 21. In the subsequent year, Priante *et al* [340] demonstrated true-green ASE at 553 nm using MAPbBr₃ as an optical gain medium. The emission spectra of MAPbBr₃ thin films are correlated to bulk defect states that have also been shown to generate radiative energy levels and lead to strong ASE. This work represents an alternative path for replacing InGaN-based platforms for emission at these wavelengths, particularly low indium incorporation efficiency in MOCVD-grown commercial LEDs, high lattice mismatch, and excessive threading dislocations that lead to low EQEs of typically less than 20%.

After these initial studies, a significant number of recent works also demonstrated optically pumped ASE and lasing characteristics using a perovskite platform with an emphasis on the green-emitting region. Studies have also demonstrated

Figure 21. Tunable ASE wavelengths produced using perovskites with various halide substitutions as gain media. All spectra were measured at room temperature, except for CH₃NH₃PbCl₃, which was measured at a lower temperature of 150 K. Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature Materials [339], © 2014.

various design structure improvements, e.g. dimensional confinement, active region design, and surface-passivated gain media.

Table 3 summarizes recent progress in ASE and lasing using perovskite-based gain media. The table focuses on advances that target the true-green wavelength, i.e. 555 nm. Hybrid organic-inorganic perovskites based on MA⁺ and FA⁺ cations are the dominant choice of gain medium in early works starting around 2015. However, inorganic perovskites based on Cs⁺ cations have received progressively increased attention due to their greater tolerance for thermal-, moisture-, and photo-induced degradation relative to their organic-inorganic counterparts [145, 341]. Along with rapid advances in surface passivation [155, 342], core/shell structures [157], and the use of low-dimensional nanostructures with high confinement factors (e.g. QD and nanowires) [343, 344], the pumping thresholds of high-performance perovskite-based gain media have decreased from hundreds to few $\mu\text{J cm}^{-1}$ over a mere 4 year period. Moreover, at the current stage of development, further progress towards lowering the ASE and lasing thresholds will undoubtedly require an external optical feedback structure, e.g. DBR mirrors based on dielectric materials (e.g. SiO₂, Si₃N₄, Al₂O₃, HfO₂) [330–332, 345] and stamped DFB gratings on the perovskite-based active medium [135, 346]. Although lithographically defined perovskite-based superluminescent diodes and lasers remain a challenge, a recent demonstration of CW-pumped ASE and lasing [330] lays a strong foundation for the fabrication of multi-section devices that are critical to monolithic integration for various commercial applications and progress towards electrically injected halide-perovskite-based laser diodes. Importantly, optical gains related to Br-based nanorods have also been characterized at up to 980 cm^{-1} using the variable stripe

Table 3. Summary of the ASE and lasing characteristics reported using halide-perovskite-based gain media in the green wavelength region (495–570 nm).

Gain medium	Emission wavelength (nm)	ASE threshold ($\mu\text{J cm}^{-2}$)	Lasing threshold ($\mu\text{J cm}^{-2}$)	Gain (cm^{-1})	Year	Ref
MAPbBr ₃ (thin films)	553	350	—	—	2015	[340]
CsPbBr ₃ (QDs thin films)	502	22	11 600	98	2015	[167]
CsPbBr ₃ (NCs thin films)	536	5 ± 1	—	450 ± 30	2015	[168]
Surface passivated CsPbBr ₃ (QDs thin films)	533	192 (1 PA), 12 000 (2 PA)	—	—	2015	[155]
CsPbBr ₃ (NCs thin films)	525	—	2500 (2 PA), 5200 (3 PA)	—	2015	[348]
MAPbBr ₃ (microwire)	552.9 (single mode)	—	112 (2 PA)	—	2016	[349]
MAPbBr ₃ (microdisks)	550	2200 (2 PA)	—	—	2016	[350]
MAPbBr ₃ (thin films)	549	140	—	120	2016	[159]
CsPb ₂ Br ₅ (microplate)	540	—	21 500 (2 PA)	—	2016	[351]
FAPbBr ₃ (thin films)	560	190	—	—	2016	[352]
BnOH-treated MAPbBr ₃ (NCs thin films)	548	13.9 (1 PA), 569.7 (2 PA)	—	520	2017	[156]
CsPbBr ₃ /SiO ₂ (NCs thin films)	537	230.8 (2 PA)	—	—	2017	[157]
MAPbBr ₃ (thin films)	541	30	89 kW cm ⁻² (CW) ^a	—	2017	[330]
CsPbBr ₃ (QDs thin films)	522	—	0.39	—	2017	[345]
FAPbBr ₃ (flexible thin films)	552.7 (single mode)	—	40.6 ± 3.4	—	2017	[331]
CsPbBr ₃ /ZnO NPs (thin films)	535	207 (1 PA), 569 (2 PA)	—	—	2017	[353]
MAPbBr ₃ (thin films)	550	—	6	—	2017	[324]
CsPbBr ₃ (thin films)	534.3	25–30	—	100	2017	[354]
MAPbBr ₃ (thin films)	543.3–557.4	—	3.4	—	2018	[135]
CsPbBr ₃ (NCs thin films)	526.7	2550	—	12.9	2018	[355]
One-step co-evaporated CsPbBr ₃ (thin films)	542	3.3	1.7	324	2018	[356]
PbBr ₂ -surface-treated CsPbBr ₃ (thin films)	527	1.2	—	—	2018	[342]
CsPbBr ₃ (nanorods)	534	7.5	—	980	2019	[343]
CsPbBr ₃ (millimeter-sized single crystals)	543	650 (2 PA)	—	38	2019	[357]
CsPbBr ₃ (single crystals microplate)	537	—	159 000 (3 PA)	—	2019	[358]
CsPbBr ₃ /SiO ₂ (QDs)	536.4	—	430	—	2019	[359]
CsPbBr ₃ (thin films)	532–544	12.5	2.2	—	2019	[136]
CsPbBr ₃ -DA (QDs thin films)	538	89.76 (1 PA), 790 (2 PA)	—	—	2019	[344]

^a Alternate unit.

Demonstrated strategies towards ASE and lasing in perovskite-based gain media

Figure 22. A summary of demonstrated strategies for ASE and lasing in perovskite-based gain media.

length method by Wang *et al* [343]. This suggests an approach to further lowering lasing thresholds and enhancing the efficiencies of future electrically injected perovskite-based laser diodes [347].

Figure 22 summarizes the strategies commonly employed to achieve ASE and lasing in halide-perovskite-based gain media, including vertical VCSEL or horizontal DFB resonator schemes. The strategies are somewhat similar in concept and implementation to group-III nitride nanophotonics approaches [360]. Further, the existing work focused on optically pumped devices by using femtosecond-based lasers, including multiphoton-absorption pumping, to achieve ASE and lasing. Some devices were even operated under cryogenic conditions, which limits their practical implementation. Low dimensionality nanostructures and surface passivation are also employed to ensure high PLQY and lasing operation. The following summarizes and discusses these strategies:

3.2.1. VCSEL structure. CW optically pumped lasing system, with sustained population inversion and lasing, is a prerequisite for electrically driven laser diodes [361, 362]. For room temperature operation, in 2017, Alias *et al* [330] demonstrated CW optically pumped, green-emitting MAPbBr₃ VCSEL with a peak wavelength of 541 nm. As shown in figure 23(a), the optically pumped perovskite-based VCSEL is formed by sandwiching an active region consisting of MAPbBr₃ gain media with a SiO₂/Si₃N₄ DBR structure and the PMMA layers. Figure 23(b) shows lasing characteristics with an enhanced integrated intensity and a significantly reduced FWHM above the CW pumping threshold of 89 kW cm⁻². For improved thermal dissipation, a single-crystal sapphire was used as the substrate during the measurement. For the development of an electrically driven perovskite-based laser, it is critical to demonstrate the optical gain under uncooled CW operation at room temperature or at lower temperatures achievable via Peltier cooling for future electrically pumped configurations [347, 363].

Figure 23. (a) Scanning electron microscopy images showing a cross-section of the CW-pumped, green-emitting perovskite-based VCSEL with the active region thicknesses indicated. The active region is sandwiched between the top and bottom DBRs and the device is prepared on a sapphire substrate. (b) Integrated PL intensity and FWHM of a VCSEL under CW excitation by a 325 nm He-Cd laser with an optical power of ~ 8 mW. Adapted with permission from [330]. © The Optical Society.

For practical applications, such as high-speed optical fiber communication [364], atomic clocks [365], and sensing [366], single-mode lasing is required because of its high spectral purity and beam quality. While each of these applications

may require a specific laser linewidth depending on a specific situation, useful linewidths are regularly found to be a few MHz for optical communication [364]; sub-MHz to sub-Hz for atomic clocks [365]; and sub-MHz for high-resolution sensing [366]. Although most prior work has produced evidence of ASE and lasing in halide-perovskite-based gain media, various results indicate random or multi-mode lasing with high pumping thresholds. This is due to several challenges, including a random distribution of gain media that results from irregular morphology, defect sites on the gain medium, and poor interfaces.

To obtain high-quality coherent beams and single-mode lasing, in 2016, Chen *et al* [367] embedded red-emitting MAPbI₃ thin films with 2D PhC resonator, which is also employed in group-III nitride semiconductor diode lasers. Temporally coherent single-mode lasing in the green-emitting yet flexible FAPbBr₃-based VCSEL was also demonstrated by Chen *et al* [331] in 2017. Polycrystalline FAPbBr₃ thin films were sandwiched between sputtered dielectric HfO₂/SiO₂ DBR structures, which naturally form much-needed encapsulation layers for enhanced lasing lifetimes (i.e. up to ~ 20 h or equivalent to $\sim 10^8$ laser shots) under ambient conditions. For the flexible VCSEL, temporally coherent single-mode lasing is still observed with a peak wavelength of 552.7 nm. Even though the achieved quality factor (Q) of ~ 920 in the flexible substrate is lower than that in the rigid substrate (~ 1420), the ease of fabrication highlights the potential for solution-processable perovskite-based gain media to be used in flexible, single-mode laser devices. In comparison, a lift-off and fabrication process for group-III-nitride-based VCSEL is much more elaborate and challenging.

3.2.2. DFB resonator. To realize compact and high-performance perovskite-based emitters, the lithography-defined perovskite-based structures remained a critical issue due to the structural instability upon exposure to the ambient environment and other processing solvents; this, in particular, hinders the realization of resonator structures. It was until around 2018, where Pourdavoud *et al* fabricated second-order DFB resonator gratings with a periodicity of 300 nm formed on MAPbBr₃ thin film via thermal nanoimprinting, as shown in figure 24(a). The work demonstrated tunable lasing in the wavelength region between 543 nm and 557 nm, with a low lasing threshold of $\sim 3.4 \mu\text{J cm}^{-2}$ [135]. Due to the sensitivity of perovskite-based materials to various commonly used solvents in wet-chemical lithography, the formation of high-Q resonators had thus far been limited to direct thermal-nanoimprinting on perovskite thin film using pre-patterned SiO₂ mold [346] or linear photonic grating [135]. Using cavities formed by this method, optically pumped ASE and lasing actions have been observed. For instance, a shallow grating imprinted onto MAPbI₃ thin film results in a 16-fold reduction in linewidth from 38 nm to 2.4 nm, indicating ASE, as shown in figure 24(b).

3.2.3. Multiphoton absorption scheme. While single-photon absorption (1 PA) schemes are widely used to obtain

Figure 24. (a) Schematic diagram of DFB resonator formed on optically pumped MAPbBr₃-based devices with the assignment of pump direction and laser emission normal to the sample surface. The inset shows the thermal-nanoimprinted gratings with a periodicity of 300 nm formed onto the active medium of MAPbBr₃. [135] John Wiley & Sons. Copyright © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) Comparison between the normalized spectra of pristine MAPbI₃ thin film (see dotted blue line) and with the thermal-nanoimprinted DFB cavity (see solid red line). The narrowing of linewidth to 2.4 nm with the incorporation of the DFB cavity indicating ASE. Adapted with permission from [346]. © The Optical Society.

the desired ASE and lasing phenomena, the non-linear optical properties of perovskite-based gain media that use multiphoton (two- to six-photon) absorption have also been explored. Multiphoton absorption minimizes photoinduced damage, increases penetration depths, and increases spatial resolutions [155, 348, 368]. Via their non-linear absorption properties, perovskite-based gain media may potentially produce an alternative path towards applications in high-capacity data storage [369, 370], bioimaging [371, 372], photodynamic therapy [373], and multiphoton lithography [374]. In 2015, Pan *et al* [155] demonstrated the first highly stable ASE based on two-photon absorption (2 PA) with surface-passivated, solution-processed CsPbBr₃ QDs. The ASE intensity with

an excitation threshold of 12 mJ cm^{-2} remained stable over 1.2×10^8 laser shots. These prior works highlight the potential of emerging perovskite-based materials as frequency-upconverted optical gain media for non-linear optoelectronic devices. They may serve to complement non-linear waveguides based on group-III-nitride materials [375, 376] under photonic chip integration schemes.

3.2.4. Low dimensionality nano/microstructures. In addition, while the ASE or lasing characteristics of primarily two-dimensional perovskite-based thin films have been reported widely, utilization of gain media with different dimensionalities, e.g. microwires and nanowires [349, 377], microplates [351, 358], and bulk single crystals [357], has also been explored. In particular, perovskite-based nanowires have received significant attention due to the naturally formed cavity effect that stems from having two end facets that are suitable for optical amplification [161, 349, 377]. In 2015, Zhu *et al* [377] were among the early researchers to demonstrate room-temperature, wavelength-tunable lasing in nanowires, with an average length of $\sim 20 \mu\text{m}$, fabricated from compositionally tunable $\text{CH}_3\text{NH}_3\text{PbBr}_y\text{I}_{3-y}$ and $\text{CH}_3\text{NH}_3\text{PbCl}_x\text{Br}_{3-x}$. These devices covered the approximate wavelength range of 500–787 nm. It is worth noting that the smooth rectangular end facets (see the inset of figure 25(a)) observed at both sides of the nanowire form Fabry–Pérot cavities necessary for optical amplification. Based on the observation of multiple, equally spaced lasing peaks, the Fabry–Pérot longitudinal cavity lasing modes are confirmed via the linear relationship between mode spacing ($\Delta\lambda$) and the reciprocal of the nanowire length (L^{-1}), as shown in figure 25(a). The $\Delta\lambda$ is calculated using equation (4) as shown below:

$$\Delta\lambda = \frac{\lambda^2}{2n_g L} \quad (4)$$

where λ is the wavelength of guided light and n_g is the group refractive index.

The optical amplification effect from perovskite-based nanowires is dominated by their intrinsic Fabry–Pérot resonators. In contrast, in 2016, Zhang *et al* [349] reported that perovskite-based microplates rely on whispering gallery mode (WGM) resonators for light amplification. Lasing action from perovskite-based microplates (with equal side length varying from 3.1 to $14.1 \mu\text{m}$) tends to localize on the four microplate edges (see inset of figure 25(b)) and the travelling wave is confined by total internal reflection within the boundary, whose characteristics resemble those of confined light in a WGM resonator. This is further evidenced by comparing the group refractive index (n_g) calculated from the WGM equation with other reported works. The WGM equation can be represented using equation (5), as shown below:

$$\Delta\lambda = \frac{\lambda^2}{n_g 2\sqrt{2}d} \quad (5)$$

where λ is the wavelength of guided light and d is the side length of a microplate. Figure 25(b) shows the fitted curve of

Figure 25. (a) Plot of mode spacing versus reciprocal of nanowire length based on the FP cavity formed by the two end facets. The inset shows the SEM image of the smooth end facet in the nanowire. Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature Materials [377], © 2015. (b) Plot of $\lambda^2/2\sqrt{2}\Delta\lambda$ versus the side length, d , of the microplate calculated based on WGM equation, as well as the plot of $\lambda^2/2\Delta\lambda$ versus d calculated based on FP equation. The inset shows the lasing emission from the microplate with a side length of $6.5 \mu\text{m}$ which is due to the WGM effect. [349] John Wiley & Sons. Copyright © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

$\lambda^2/2\sqrt{2}\Delta\lambda$ versus d (red curve), which yields the n_g of 7.1, closer to the value reported elsewhere. As compared to larger n_g of 11.3 that was determined based on the FP equation (see black curve in figure 25(b)), it is thus confirming that the lasing from the microplate is dominated by the WGM-based amplification effect. It is also noteworthy that single-mode lasing was achieved when the side length of the microplate was reduced to $3.1 \mu\text{m}$ since the mode spacing (5 nm, in this case) was greater than the transition linewidth. Reduced-dimensionality gain media are pivotal for enhanced quantum confinement, as well as for the development of nanophotonic devices and subsequent integration with existing photonic integrated circuits.

It is further envisaged that recent advances in ligand passivation may reduce defects in perovskite-based nanorods. For instance, Wang *et al* [343] recently reported a record-breaking

net mode gain of up to 980 cm^{-1} in CsPbBr_3 nanorod-based gain media with a diameter of $\sim 5.8\text{ nm}$ and a length of $\sim 26\text{ nm}$ using an intermediate monomer reservoir synthetic strategy. Similarly, group-III nitrides have benefitted from low-dimensionality nanostructures such as the previously discussed QDs [314, 378] and nanorods or nanowires [4, 327, 379].

3.2.5. Surface passivation. Perovskite-based material photostability has also improved substantially since early results where photoemission lasted for less than a few hours of continuous operation. For instance, a novel surface passivation technique demonstrated by Pan *et al* [155] in 2015, in which CsPbBr_3 -based QD surfaces were coated with an inorganic-organic hybrid ion pair, allowed passivated thin films to exhibit stable ASE operation for $\geq 34\text{ h}$ under ambient conditions. This demonstration laid a strong foundation for stable, heat- and moisture-resistant operation of perovskite-based gain media that is crucial to future applications.

Another passivation technique that uses a $\text{CsPbBr}_3/\text{SiO}_2$ core/shell structure was demonstrated by Hu *et al* [157]. The researchers achieved recoverable ASE operation even after 2 months of storage under ambient conditions, as well as comparably lower threshold and more stable emission than that of CsPbBr_3 QDs without a passivating shell. It was pointed out that the observed lower threshold and higher efficiency for ASE in core/shell structure could potentially be attributed to the large refractive index differences at the SiO_2 -air interface, which thus naturally forms a cavity that bounds the emitted light from the CsPbBr_3 QDs back into the gain medium. In particular, the core/shell passivating method is also known to effectively suppress the PL blinking effect from colloidal NCs, i.e. random switching between an emission state and dark state due to nonradiative Auger recombination via charge transfer. Such a passivation technique had also been commonly applied to other colloidal NCs, e.g. CdSe/CdS [380] and CdTe/ZnS [381]. Importantly, the core/shell structure is also known to isolate the perovskite-based QDs from moist environments, as well as to increase susceptibility when used as the amplification medium and for subsequent fabrication steps without causing undesirable quenching in the PL. The use of perovskite-based QDs encompassing with a passivating shell structure would also be crucial in addressing the instability in terms of photoluminescence, preventing structural dissociation due to external moist environment, as well as for the realization of long-lasting lasing devices and applications. However, in addition to concerns about photostability, thermal issues in perovskite-based lasing devices remain largely unexplored and require significant attention, especially with respect to future electrically pumped lasing device designs. These devices are often required to operate at elevated temperatures. This may lead to malfunctions unless the design addresses heat dissipation.

Electrically injected perovskite-based lasers are still far from reaching high levels of technological readiness with respect to fabrication techniques and on-chip monolithic integration, as compared to group-III-nitride. However, the development of related materials is on a promising path

because these materials benefit from lower capital costs than group-III-nitride materials. As shown previously, Br-based perovskite nanostructures have also been envisaged to partly address the ‘green-yellow gap’ in conventional group-III-nitride materials. Integration of group-III-nitride materials with perovskite-based gain media may allow the two technologies to further complement each other, for example via the enhanced quantum confinement effect, and thus completing a suite of technologies that covers the visible wavelength spectrum and supports various optoelectronic applications.

4. Conclusions and perspectives

As group-III-nitride laser and superluminescent devices have gained maturity and industrial adoption, halide-perovskite has emerged as another class of semiconductor with desired color-tunable characteristics. In a regime where group-III nitrides fall short, metal-halide-perovskite semiconductors can potentially fill important gaps, especially for low-cost production. Solution processability in the green-yellow gap (530–600 nm) promises further lasing and ASE devices that may complement group-III nitride devices. While it is noted that the operating lives of halide perovskites have improved significantly from a few tens of hours to thousands of hours over the years and with the commercialization of perovskite-based solar cells expected from companies such as Oxford PV, Saule Technologies, and Tandem PV [382], development of more rigorous processing techniques, e.g. grating patterning, facet polishing, and doping, is required for electrically injected perovskite-based superluminescent and laser diodes. The main sources of concern are chemical sensitivity to common processing solvents, e.g. photoresists, strippers, and wet etchants [383], and subsequent photodegradation of perovskite-based structures. Compatibility of perovskite-based materials with industry-standard processing remains critical and represents a challenge. Moreover, the inclusion of lead in perovskite is regarded as a barrier to commercialization because of concerns over environmental pollution. Although companies such as Oxford PV and Saule Technologies have rebutted these claims and indicated that only a negligible amount of lead is included [382], some researchers are developing lead-free perovskites [384–386] that may potentially pave a new path towards more environmentally friendly optoelectronic devices. In addition to general application to perovskite-based LEDs, superluminescent diodes, and laser diodes for solid-state lighting, perovskite-based media remain attractive as conversion phosphors for high-speed visible light communication at both the transmitter and receiver ends [150, 387]. Furthermore, heterogeneous integration of both classes of semiconductor, i.e. group-III nitrides and perovskites, can offer new opportunities not previously available due to constraints related to high electrical injection density, lattice constants, crystal structures, and thermal expansion coefficient mismatches. Such integration may offer simultaneous optical feedback and external passivation, while the high thermal conductivities of group-III-nitride media ($>230\text{ W m}^{-1}\text{ K}$) may mitigate thermal issues associated with perovskite-based gain media. This is known to

be important for improving device reliability [347]. However, as researchers pursue halide-perovskites and heterogeneous integration of group-III nitrides with halide-perovskites for lasing and ASE devices, standardized reporting of semiconductors and device characterization will be required to maintain scientific rigor [388] and address material stability [389] as the field gains popularity and moves towards technological maturity.

Current group-III nitride light emitting technology is moving towards new frontiers. Material-related developments are ongoing in the areas of polarization-assisted carrier concentration enhancement for ultraviolet emitters [76], tunnel junctions, and porous reflectors for blue vertical-emitting lasers [390, 391], and QDs and non- or semi-polar platforms for increased efficiency at green wavelengths [116, 314], including strain compensating engineering methods used to produce red-emitting InGaN-based devices [42]. While there is room for improvement in each of these segments, the device community has an interest to develop visible lasers into photonic integrated circuits [254, 392–394]. Heterogeneous integration of blue lasers with visible waveguides is an area of opportunity for topics of current interest such as beam steering for displays [395], optogenetics [396], and underwater applications where visible light exhibits the highest penetration [397]. Similarly, visible-light photonic integrated circuits can benefit from integrated DFB gratings, multiple section design including photodetectors, modulators, and amplifiers, and visible-light waveguide development [398]. The potential integration of this platform with perovskites remains to be explored but could eventually accelerate the utilization of a broader range of wavelengths, which is needed for reconfigurable multifunctional photonics on a chip.

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