AlGaN-based ultraviolet light-emitting diodes (UV LEDs) are of technological importance because of their applications in numerous areas such as water purification, biological analysis, sensing, epoxy curing, high-density optical storage, white light illumination, and many other areas. AlGaN-based UV LEDs have increased from less than 0.1% to about 1–10%, which depend on the Al content (namely, emission wavelength). In this review, recent advances in the growth of high-quality AlGaN-based UV LEDs are reviewed. The progresses of the growth and fabrication process of group III-nitride-based UV LEDs are presented. The limiting factors of the performance of AlGaN-based UV LEDs and the possible solutions are described and discussed. More specifically, ways of enhancing the crystal quality of AlGaN, carrier concentrations, ohmic behavior (electrical and injection efficiencies), and LEE are presented.

**Growth of High-Crystal-Quality AlGaN Epilayers**

The epitaxial growth of a high-quality material is the most important issue for developing efficient optoelectronic devices because defects, such as cracks, dislocations, and unintentionally incorporated impurities, can act as an energy-loss path by generating defect states inside the bandgap or non-radiative recombination centers. The growth of high-quality AlGaN layers is particularly difficult because to the unique valence band structure of AlGaN with a high Al molar fraction (> about 25%). Thus, to fabricate high-EQE UV LEDs, a great deal of effort has been taken to solve these fundamental problems. Consequently, in the past decade, the EQEs of AlGaN DUV LEDs have increased from less than 0.1% to about 1–10%, which depend on the Al content (namely, emission wavelength). In this review, the progresses of the growth and fabrication process of group III-nitride-based UV LEDs are presented. The limiting factors of the performance of AlGaN-based UV LEDs and the possible solutions are described and discussed. More specifically, ways of enhancing the crystal quality of AlGaN, carrier concentrations, ohmic behavior (electrical and injection efficiencies), and LEE are presented.
of the large lattice mismatch and thermal expansion mismatch between AlGaN and sapphire substrate. The tensile stress in AlGaN epitaxial layers is accumulated as the epitaxial layer thickness increases, and cracks are initiated on the surface of the epitaxial layer to relax the stress.\textsuperscript{10} In addition to cracks, threading dislocations are another stress relaxation path. The threading dislocation density of AlGaN epitaxial layers on sapphire substrates is typically of the order of $10^{10}$ cm$^{-2}$, which is much higher than that $(\sim 10^8$ cm$^{-2}$) of GaN epitaxial layers due to the low surface mobility of Al adatoms during growth.\textsuperscript{3,11,12} The threading dislocations are known to act as non-radiative recombination centers and severely degrade the IQE. Furthermore, oxygen impurities in AlGaN layers produce impurity-related states inside the bandgap, causing parasitic emission or phonon non-radiative recombination centers and severely degrade the IQE.\textsuperscript{13} Such defects ruin the emission of the carriers inside the bandgap, causing parasitic emission or phonon non-radiative recombination centers in high-quality hetero-epitaxial layers with low densities of threading dislocations.\textsuperscript{23,24} The principle of the ELO technique is that a portion of the first-step grown AlN that probably has a high threading dislocation density is covered by a dielectric mask layer, which is followed by the second growth step. At the beginning of the second growth step, the deposition only occurs on the exposed AlN areas, not on the dielectric mask. The threading dislocations are prevented from propagating into the second-step grown layer by the dielectric mask, whereas the AlN layer grown above the opening (coherent growth) retains the same threading dislocation density as the template. However, because of the lateral growth, the masked areas are covered by laterally regrown AlN that has a significantly low dislocation density. Recently, nanoscale lateral overgrowth of AlN was demonstrated,\textsuperscript{25} leading to low dislocation densities in AlN and successive epitaxial layers. As shown in Figure 3b, the exposed sapphire surface is partially modified by the chemical or mechanical damage; the AlN layer growth is initiated only from the unmodified sapphire region, forming AlN islands. Subsequently, each AlN island starts to grow laterally as well to cover the modified areas, exhibiting a significantly reduced threading dislocation density in the fully overgrown epitaxial layer.

High crystal-quality epilayers for DUV LEDs can be obtained by using a bulk AlN substrate with a low threading dislocation density, referred to as a homoepitaxy method. The advantage of homoepitaxy is that the lattice and thermal expansion mismatches between epitaxial layers and substrates can be minimized, thus drastically decreasing the dislocation density of epitaxial layers. Indeed, the use of a bulk AlN substrate reduced the dislocation density in the epitaxial layers by more than four orders of magnitude, specifically, down to $10^8$ cm$^{-2}$.
10⁻¹⁰ cm⁻². A popular growth method for high-quality bulk AlN is the physical vapor transport (PVT) method, which utilizes Al and N₂ vapor transport to recrystallize at temperatures ranging from 1800 °C to 2400 °C. However, substantial light absorption in the DUV spectrum caused by Al vacancies and substitutional impurities was observed in PVT-grown AlN crystals. Recently, hydride vapor phase epitaxy (HVPE) was employed, by which a thick AlN substrate was grown on a PVT-grown AlN, demonstrating the epilayer with a low threading dislocation density and high UV transmission.

### Growth of Conductive Layers

#### Technological issues of doping AlGaN

Because an LED is a semiconductor diode based on a p-n junction, which converts electrical power to optical power, both the electrical and optical properties are important factors in enhancing the overall performance of an LED. Highly doped n-type and p-type semiconductor layers are generally required for desirable electrical and optical characteristics. The n-type conductivity of AlGaN is achieved by incorporating Si atoms that substitute Al or Ga atoms in the lattice, providing loosely bound electrons. It is, however, difficult to obtain a high n-type conductivity in high-Al-content AlGaN because of the large donor ionization energies and a self-compensation effect. The ionization energy of the Si donors increases with increasing Al content, ranging from 15 meV for GaN to 62 meV for AlN, which is larger than the thermal energy at room temperature, leading to a highly resistive high-Al-content AlGaN. The insufficient n-type doping of AlGaN causes negative effects on LED performance, such as a resistive contact and high sheet resistance, leading to a high operation voltage and poor EE. In addition, a resistive n-type AlGaN layer intensifies the localization of the current path, referred to as the current crowding effect. Current crowding induces local device heating and degrades the electrical and optical characteristics.

P-type doping in AlGaN has probably been the most difficult challenge in the realization of efficient AlGaN DUV LEDs. The Mg acceptor in GaN has a very high activation energy of approximately 170 meV, which is much larger than the thermal energy at room temperature. Moreover, hydrogen atoms presented during the MOCVD growth passivate the Mg dopants, which necessitates an additional process for the dopant activation. Although reasonably conductive p-type GaN has been obtained, it is still rather difficult to achieve p-type conductivity in high-Al-content AlGaN because the dopant activation energy increases with increasing Al content, up to 630 meV for AlN. A lack of p-type conductivity in high-Al-content AlGaN gives serious problems in developing high-efficiency UV LEDs: (i) extremely poor ohmic contacts for p-type AlGaN, thereby causing a high operating voltage; (ii) very poor injection of holes into the active region. To tackle these problems, a conductive p-type GaN layer, serving as a contact and hole-supplying layer, is typically grown on top of p-type AlGaN in DUV LEDs, as shown in Figure 2. However, it causes poor EE because of its strong UV absorption.

Furthermore, asymmetry in the carrier transport related to both the concentration and mobility between electrons and holes also becomes serious when the Al content in AlGaN increases. The activation energy of Mg acceptors is much larger than that of Si donors, which causes a large disparity between electron and hole concentrations. Furthermore, the mobility of holes is much slower than that of electrons due to the large effective mass of holes. Taken together, these characteristics lead to strong asymmetry in the electron and hole transport into the active region. This asymmetry becomes more severe for AlGaN because the heavy hole effective mass in Al₀.₃₈Ga₀.₆₂N increases from 0.80 mₑ (mₑ: free electron mass) to 3.53 mₑ as the Al mole fraction increases from 0% to 100%. Resulting in the overshooting of electrons from the MQWs to a p-type region without recombination and hence leading to unbalanced carrier injection.

#### Methods of growing conductive layers

It is obvious that such fundamental limitations in achieving high p-type doping of AlGaN cause failure in the realization of highly-efficient DUV LEDs, giving low EE, poor hole IE, and low LEE. There has been a strong desire for significantly improving the p-type doping of AlGaN by solving the intrinsic material problems. One way to achieve a highly conductive p-type AlGaN was provided, in which a superlattice structure of p-type AlGaN showed an improvement in the free hole concentration in AlGaN by a factor of 10⁻⁷. Mg-doped AlGaN/GaN or AlGaN superlattices had been introduced for visible and UV LEDs to increase the hole concentration and efficiently prevent electrons from escaping the active region. However, the carrier transport perpendicular to the superlattice planes is less than that parallel to the superlattice planes due to the multiple potential barriers at the superlattice heterointerfaces. The superlattice-EBL with graded Al compositions, referred to as graded superlattice-EBL (GSL-EBL), was used to improve the hole transport in the superlattices. The LEDs with GSL-EBL exhibited an increased overall efficiency and reduced efficiency drop compared to the LEDs with superlattice-EBL and conventional bulk AlGaN EBL due to the enhanced hole injection efficiency.

Other method for p-type doping in AlGaN, referred to as polarization-induced hole doping, has been proposed. A nitride semiconductor material system grown on a (0001) sapphire substrate possesses spontaneous polarization due to the non-centrosymmetry of their wurtzite crystal structure. When the crystal is strained, a piezoelectric polarization evolves as well in proportion to the strain. Thus, the total polarization in the strained structure is determined by the sum of the piezoelectric and spontaneous polarization. The polarization discontinuity at the abrupt junction, i.e., the AlGaN/GaN interface, can induce bound charges at the interface and lead to two-dimensional free carriers at the interface. In the case of the Al-composition-graded AlGaN layer, the polarization discontinuity is gradually stacked so that three-dimensional bound charges are naturally formed. In particular, in an Al-composition-graded AlGaN layer with increasing Al content along the [0001] direction, negative bound polarization-induced charges can be formed, generating a built-in electric field, as shown in the Figure 4. The free holes are then field-ionized to neutralize the negative polarization-induced charges, preventing energy band bending greater than the bandgap of the semiconductor, as shown in Figure 4c. Consequently, a high-density mobile three-dimensional hole gas is generated. Furthermore, the smooth valence band structure of the AlGaN grading layer facilitates vertical hole transport. Based on the concept of the polarization-induced doping, p-type graded AlₓGaN₀₋ₓN (x = 0.7–1) and dopant-free AlGaN-based p-n junction were demonstrated. Furthermore, Carnevale et al. demonstrated the UV electroluminescence from AlGaN nanowires that contain polarization-induced p-n junctions.

As another approach, there is an effort to substitute the p-type AlGaN layer with other UV-transparent p-type materials. The p-type hexagonal boron nitride (h-BN) was proposed to replace resistive p-AlGaN to fabricate UV LEDs. The h-BN has a honeycomb layered structure is a member of the group III-nitride semiconductor family. The advantages of h-BN as a p-type semiconductor layer for UV LEDs are its small Mg-acceptor activation energy of about 31 meV and the UV transparency due to its large bandgap energy of around 6 eV. The free hole concentration of Mg-doped p-type h-BN was reported to be up to approximately 10¹⁸ cm⁻³ and the rectifying I–V characteristic of the p-n junction diode composed of n-type Al₀.₆₂Ga₀.₃₈N and p-type h-BN was demonstrated. Although no electroluminescence from the p-type h-BN-included UV LEDs has been reported so far, further optimization of p-type h-BN may contribute to the development of highly efficient DUV light emitters.

In addition, modifying the LED epitaxial structures rather than attempting to increase the hole concentration in the p-type AlGaN is another notable idea. A polarization-engineered tunnel junction (TJ) is particularly useful for the high hole injection into the active region from the p-type AlGaN that has an initially low hole concentration. The schematic design, transmission electron microscope image, and energy band diagram of a TJ incorporated UV LED are shown in Figure 5. The TJ-incorporated UV LED possesses additional structures of a GaN layer and a top n-type AlGaN layer upon a conventional UV LED structure. Polarization-induced interface charge
Figure 4. Schematic illustration showing polarization-induced p-type doping in polar heterostructures. (a) Sheets of charge dipoles in every unit cell of the crystal. (b) Distribution of the net unbalanced polarization charges. (c) The electric field caused by the unbalanced polarization charge. (d) The energy-band bending in the valence band. (e) Energy band structure affected by the electric field. Acceptors are field-ionized to neutralize the negative polarization charges, resulting in a three-dimensional free hole gas. From Ref. 41 [J. Simon et al., Science, 327, 60 (2010)]. Reprinted with permission from AAAS.

Figure 5. (a) HAADF-STEM image, (b) epitaxial stack, and (c) equilibrium energy band diagram of TJ-based UV LED structure, in which the TJ enables electrons to tunnel from the p-type AlGaN to the n-type AlGaN, leaving holes in the p-type region. Reprinted with permission from Ref. 47. Copyright [2015], American Institute of Physics.
density at hetero-interfaces can be quite high (10^{13} \text{ cm}^{-2}) and create significantly high electric fields, resulting in band bending across the GaInN layer and consequently an increase in the tunneling probability. This TJ layer is reversely biased when the forward bias is applied to the LED, therefore, the electrons in the valence band of p-type AlGaN directly tunnel into the empty states in the conduction band of the n-type AlGaN, leaving behind holes in the p-type AlGaN. The additional advantage of such an approach is that the top of the TJ- incorporated LED is not a p-type AlGaN layer but an n-type AlGaN layer, which is able to have a low current spreading resistance, form low resistance ohmic contacts, and be transparent in the UV spectral region.\(^{48}\)

An electron-beam pumping (excitation) method was proposed to realize a highly efficient DUV emitter based on electron-hole generation.\(^{69}\) The electron-beam pumping used highly accelerated electrons to generate hole-electron pairs inside the AlGaN/AIN QW grown on a c-plane sapphire substrate. At an acceleration voltage of 8 kV, a maximum power efficiency, defined as the optical power over the electrical power, of 40% was obtained from AlGaN/AIN QWs emitting at ~240 nm. This significant improvement was ascribed to carrier confinement within the high-quality QWs along with the appropriate design of sample structures for electron-beam pumping.

**Ohmic Contacts to p-GaN for Near UV LEDs**

*Transparent p-type ohmic contacts using transparent conducting oxides.*—Transparent conducting oxides (TCOs), such as Sn-doped indium oxide (ITO) and ZnO, have been widely used as transparent conductive electrodes (TCEs) because of their low electrical resistances and high transmittances in the visible spectrum.\(^{50-54}\) However, TCO-based TCEs with desired electrical resistance have fairly low transmittances in the UV spectrum. Thus, to enhance both the UV transmittance and the electrical properties of TCEs, various approaches, including metal-doped TCOs,\(^{55-60}\) oxide/metal/oxide structure,\(^{61}\) and surface treatments,\(^{62,63}\) have been investigated.

Metal-doped TCOs, such as Sn-doped tin oxide (ATO),\(^{64}\) Ga-doped ZnO (GZO),\(^{56}\) Al-doped ZnO (AZO),\(^{57} \) and Ti-, Al-, Ga-, and Ge-doped ITO,\(^{57,58}\) have been investigated as a candidate for near UV (NUV) p-type TCEs because of their reasonable electrical resistance and high optical transmittance in the NUV spectrum. It was shown that Ti-doped ITO thin films gave a 22% higher transmittance than 380 nm than ITO-only film and consequently NUV LEDs produced a 52.1% higher output power than NUV LEDs with ITO-only electrode.\(^{57,58}\) The Ti-doped ITO films exhibited a resistivity of 4.248 \times 10^{-4} \text{ \Omega cm}, which was comparable to that of the ITO only film.

Oxide/metal/oxide (O/M/O) multilayers were employed as p-type TCEs for NUV LEDs. The electron-beam irradiation of ITO/Ag/ITO multilayers resulted in a decrease in the sheet resistance from 65 \Omega/sq to 3.6 \Omega/sq and an increase in the optical bandgap from 3.7 eV to 4.35 eV, corresponding transmittance was ~80% at 375 nm.\(^{55}\) NUV LEDs (375 nm) fabricated with electron-beam-irradiated ITO/Ag/ITO electrode yielded a 19% higher output power than NUV LEDs with non-irradiated ITO/Ag/ITO electrode. This enhancement was attributed to the improved crystal quality of the ITO films and Ag interlayer caused by the electron-beam irradiation.

Surface treatments, such as plasma treatment and electron beam irradiation, were shown to improve the electrical and optical properties of TCOs.\(^{62,63}\) For instance, S\(_{F6}\) plasma treatment was performed on ITO films (100 nm thick) to modify their opto-electrical properties.\(^{62}\) It was shown that NUV LEDs (380 nm) fabricated with F-doped ITO electrode produced a 148% higher light output power at 100 mA than NUV LEDs with untreated ITO electrode. The S\(_{F6}\) plasma treatment (namely, F-doping) increased the work function and bandgap of ITO films and accordingly improved the electrical and optical properties. The specific contact resistance and transmittance of optimal F-doped ITO were measured to be 9.12 \times 10^{-6} \text{ \Omega cm}^2 and 86.9% at 380 nm, respectively, while those of untreated ITO were 1.04 \times 10^{-3} \text{ \Omega cm}^2 and 79.7%.

**Nanomaterial-based transparent p-type electrodes.**—Recently, nanomaterials, such as graphene (GR), carbon nanotubes (CNTs), and silver nanowires (Ag NWs), have been widely investigated as TCEs in LEDs because of their low electrical resistances and high UV transmittances. Their attractive opto-electrical properties notwithstanding, high contact resistance between nanomaterials and p-GaN remained to be a challenging issue. Few-layer GR electrodes were employed to fabricate GaN-based UV LEDs (372 nm) that exhibited excellent current spreading and UV transmittance.\(^{65}\) However, the LEDs with few-layer GR had a high forward voltage larger than 10 V at 2 mA and were burnt out at high current injection. Thus, to improve the contact resistance and the stability of nanomaterial-based TCEs, various techniques, including interface engineering,\(^{66-78}\) hybrid nanomaterial structures,\(^{76-83}\) and chemical doping,\(^{84-87}\) have been extensively studied.

An interface engineering technique requires the insertion of transparent and conductive interlayer including ITO, Ni, NiOx, and metal nanoparticles. It was found that depositing a 3 nm-thick Ni film on GR (Ni/GR), serving as a current spreading layer, significantly reduced the operation voltage of NUV LEDs (380 nm) from 13.2 V for GR-only electrode to 7.1 V for Ni/GR electrode.\(^{75}\) NUV LEDs fabricated with Ni/GR electrode exhibited uniform spreading and reliable light emission, corresponding to 83% of the electroluminescence (EL) of that with ITO electrode. The uniform current spreading was ascribed to the reduced sheet resistance and contact resistance caused by the insertion of a Ni film. Furthermore, Ni nanoparticles were embedded within single-wall CNTs (NP-SWCNTs) by means of an electroless plating method in order to fabricate TCEs for AlGaN-based UV LEDs (375 nm).\(^{71}\) UV LEDs fabricated with NP-SWCNT TCEs was shown to produce a 32% higher optical output power than UV LEDs with conventional Ni/Au electrode. The Ni nanoparticles were suggested to improve the electrical conductivity of TCEs and formed ohmic contacts to p-GaN. The specific contact resistance and transmittance for NP-SWCNT TCEs were measured to be 6.2 \times 10^{-4} \text{ \Omega cm}^2 and 83% at 375 nm, respectively. It was also shown that NUV-LEDs with ITO (10 nm)/Ag NWs hybrid electrodes yielded a 14% higher light output power than the LEDs with ITO-only electrode.\(^{72}\) The thin ITO film (10 nm) was used to form ohmic contacts to p-GaN because the conductive thick ITO films (150–200 nm) have low transmittance in the UV spectrum. Thus, resistive thin ITO films were combined with highly conductive Ag NWs to increase conductivity and so effectively spread current. NUV-LEDs (385 nm) with ITO/Ag NWs spin-coated at 3000 rpm exhibited a forward voltage of 3.5 V at 20 mA that was comparable to that of LEDs with ITO-only electrode (3.45 V). ITO nanodots (NDs) were also combined with Ag NWs as a p-type electrode in NUV AlGaN-based LEDs to increase light output power.\(^{73}\) The Ag NWs were 30 ± 5 nm in diameter and 25 ± 5 μm in length. The 10 nm-thick ITO-only electrode had a transmittance of 98% at 385 nm, while the values for ITO ND/AgNW electrodes gave 83–88%. ITO ND/Ag NW films showed lower sheet resistances (32–51 Ω/sq) than the ITO-only film (950 Ω/sq). Figure 6 shows the schematic structures of LEDs with ITO-only, ITO NDs-only, and ITO NDs/Ag NW electrodes. As shown in Figure 6d, LEDs with the ITO-only and ITO NDs-only electrodes exhibited forward voltages (\(V_f\)) of 3.50 and 3.80 V at 20 mA, respectively, while LEDs with ITO NDs/Ag NW electrodes had higher \(V_f\) than the LEDs with the ITO-only electrode.\(^{74}\) The LEDs with the ITO NDs/Ag NWs electrodes produced higher output power than with those with the ITO-only electrode (Figure 6e), although the latter gave higher transmittance and lower forward voltage. This better performance was explained by the enhanced current spreading and the improved light extraction, as confirmed by finite-difference time-domain (FDTD) simulations.\(^{75}\)

Hybrid nanostructures have been widely investigated to enhance the current injection and stability of nanomaterials-based TCEs. Ag NWs were combined with graphene (GR) to form transparent and conductive spreading electrodes for NUV LEDs (375 nm), as shown in Figure 7a. NUV LEDs with bare GR, Ag NWs, and GR on Ag NWs (GR/Ag NWs) electrodes had forward voltages of 10.9, 6.7, and 4.48 V at 20 mA, respectively.\(^{76}\) The NUV LEDs with GR/Ag NWs...
electrodes produced significantly lower $V_f$ compared to those of LEDs with GR-only or Ag NWs-only electrodes because of the reduced sheet resistance and the effective current spreading, Figure 7b. This indicates that the GR/Ag NWs electrode provides efficient current diffusion pathways. The NUV LEDs with GR/Ag NWs electrode showed much higher EL intensity than those with other electrodes, Figure 7c. The improvement was attributed to combination of effective current spreading and injection efficiency toward $p$-GaN surface caused by the low sheet and contact resistance of the GR/Ag NWs electrode.\textsuperscript{79} Ag NWs were also combined with two-step grown graphene (A-2GE) or conventional one-step grown graphene (A-1GE).\textsuperscript{81} NUV LEDs having Ag NWs-only, A-1GE, and A-2GE gave forward voltages of 7.6, 4.9, and 4.6 V at 20 mA, respectively. The NUV LEDs with Ag NWs-only electrode showed poor output performance and no light emission when exceeding 40 mA because of severe voltage drop and junction breakdown, while the NUV LEDs with A-1GE and A-2GE remained stable even after one month up to 100 mA.\textsuperscript{81}

Figure 6. Schematic diagrams of LEDs fabricated with (a) ITO-only, (b) ITO NDs-only, and (c) ITO NDs/Ag NW electrodes. (d) Current-voltage ($I-V$) characteristics and (e) light output power of LEDs with various electrodes. Reprinted with permission from Ref. 78. Copyright [2017], Institute of Physics.

Chemical doping techniques were also shown to be effective in improving the contact properties between graphene (GR) and $p$-GaN. Chemical doping induces the modification of the Fermi level, increasing the work function of GR.\textsuperscript{88,89} GR was doped with Au to form good UV emission efficiency.\textsuperscript{86} It was reported that NUV LEDs (380 nm) fabricated with Au-doped GR electrode yielded a 20% higher EL intensity at 20 mA than conventional NUV LEDs with ITO-only electrode. The sheet resistance of the Au-doped GR electrode was significantly reduced from 500 to 90 $\Omega$/sq compared to that of pristine GR electrode. It was found that Au doping increased the work function of GR from 4.84 to 4.90 eV. The forward voltage of NUV-LEDs with Au-doped GR was 3.98 V, which was much lower than that for pristine GR (5.85 V) and close to that for ITO electrode (3.92 V). The electrical improvement was attributed to the low sheet resistance and increased work function of the Au-doped GR.

Ohmic Contacts for Deep UV LEDs

For NUV LEDs, a $p$-type GaN layer was usually employed as a contact and hole-supplying layer. However, the strong UV absorption of $p$-type GaN results in a poor light-extraction efficiency (LEE).

Figure 7. (a) Schematic diagram of a UV LED with Ag NWs/GR transparent and current spreading electrode. (b) $I-V$ curves and (b) EL spectra of UV LEDs with various TCEs. Reprinted with permission from Ref. 79. Copyright [2013], American Institute of Physics.
Thus, the low electrical and injection efficiencies of deep UV (DUV) LEDs due to highly resistive Al\(_x\)Ga\(_{1-x}\)N layers are most challenging issues to be resolved.\(^3,6,8,90\)

**Ohmic contacts to n-type Al\(_{x}\)Ga\(_{1-x}\)N.**—For n-type Al\(_{x}\)Ga\(_{1-x}\)N, ohmic contacts can be easily formed by using Ti/Al-based or V/Al-based metal schemes.\(^91–106\) The Ti/Al-based metal schemes are generally used as contacts to n-Al\(_x\)Ga\(_{1-x}\)N, producing contact resistivities of \(10^{-4}–10^{-6}\ \Omega\text{cm}^2\) after annealing at high temperatures.\(^91–95\) The ohmic contact formation was explained by the formation of AlN and TiN phases, generating donor-like nitrogen vacancies (VN) and hence increasing donor concentrations near the surface region.\(^92,95,101\) However, Ti/Al-based contacts had a tendency to form Schottky behavior as the Al mole fraction increases,\(^104,105\) while V/Al-based schemes provided lower contact resistance due to the formation of vanadium nitride (VN). The generation of VN and the low work function provided lower contact resistance due to the formation of vanadium nitride (VN). The generation of VN and the low work function (3.56 eV) of VN were shown to be responsible for the lower contact resistance.\(^97,99\)

**Ohmic contacts to p-type Al\(_{x}\)Ga\(_{1-x}\)N.**—The electrical and injection efficiency of AlGaN-based DUV LEDs strongly depends on the properties of p-Al\(_x\)Ga\(_{1-x}\)N because the hole concentrations of p-Al\(_x\)Ga\(_{1-x}\)N alloys with high Al mole fractions are much lower than that of p-GaN due to the high activation energy of Mg acceptors. It was reported that the activation energies of Mg acceptors for Al\(_{0.5}\)Ga\(_{0.5}\)N alloys and AlN, respectively, were 400 and 510 meV.\(^107,108\) Thus, the formation of ohmic contacts to Al-rich p-AlGaN is critical for the fabrication of high EQE DUV LEDs. For p-Al\(_x\)Ga\(_{1-x}\)N with low AlN mole fraction (AlN < 60%), the deposition of metals with high work functions (e.g., Pd, Ni, Au, and Pt), followed by post-deposition annealing (DA method), was used to form ohmic contacts.\(^108–115\) Ni, Pd, Pt, and Au ohmic contacts to p-Al\(_{0.15}\)Ga\(_{0.85}\)N were shown to give low contact resistances when annealed at temperatures above 700°C. The Au contact annealed at 850°C produced the lowest contact resistivity of \(1.8 \pm 1.1) \times 10^{-5}\ \Omega\text{cm}^2.\(^110\) Furthermore, Pd/Ni/Pd/Ru ohmic contacts to Mg-doped Al\(_{0.15}\)Ga\(_{0.85}\)N became ohmic with a contact resistivity of \(1.4 \times 10^{-5}\ \Omega\text{cm}^2\) after annealing at 600°C for 1 min in a N\(_2\) ambient.\(^112\) The contacts remained stable even after annealing at 600°C for 60 min. The X-ray photoemission spectroscopy (XPS) results showed evidence for the formation of Ru-(Pd-Ni solid solution), Pd-Ga chemical reaction, and a Ga-deficiency region near the p-AlGaN surface when annealed at 600°C for 1 min, as shown in Figure 8. The Pd 3d core-level peaks exhibited absence of chemical reaction and shifts, indicating the formation of Ru-(Pd-Ni solid solution), Figure 8a. The Ga 3d (Figure 8b) and Pd 3d peaks from the D region shifted toward the lower and higher binding energies, respectively. There was no evidence for the outdiffusion of N and Al atoms in the D region. The binding energy of the Ga 3d peak detected in the E area (∼5 nm below the AlGaN surface) is lower by 0.2 eV than that in the F area (∼15 nm below the AlGaN surface). The Ga core level behavior implies Pd-Ga chemical reactions at the interface, leading to the formation of Ga deficient region near the AlGaN surface. The SBH was obtained by the relation of \(\Phi_{b0} = E_{\text{b0}} - E_{v}\). Calculations based on Figure 8c exhibited that the SBHs for the as-deposited and annealed samples are 1.29 and 0.69 eV, respectively. The large reduction (0.6 eV) of the SBH, resulting in the low contact resistivity, was attributed to the reduced surface energy band bending due to the shift of the surface Fermi level toward the valence band edge of (AlGaN).

**Various methods of forming ohmic contacts.**—As previously mentioned, it is difficult to form ohmic contacts to Al-rich p-Al\(_x\)Ga\(_{1-x}\)N due to the low doping efficiency. Thus, various methods have been developed, including p-GaN contact layer\(^117–120\) and superlattice structures,\(^36,121–130\) in order to achieve efficient current injection into Al-rich p-Al\(_x\)Ga\(_{1-x}\)N. The use of a conductive p-GaN capping layer grown on p-AlGaN has been considered as the most fundamental solution to reduce the
So, the $p$-GaN contact layer causes the strong absorption of deep UV light.

Recently, transparent $p$-AlGaN contact layer was used to minimize the light absorption in $p$-GaN contact layer. Consequently, the EQE of DUV LEDs (287 nm) increased from 2% to 5.5% by using a transparent $p$-AlGaN contact layer. However, the resistive $p$-AlGaN contact layer results in large forward voltage.

Superlattice (SL) structures generate a periodic oscillation of the energy bands created by strong polarization effects, leading to the high density of 2-dimensional hole gas (2DHG). Light emission patterns of $c$-plane $p$-AlGaN and $c$-plane AlN are isotropic and anisotropic, respectively. Therefore, the use of $p$-AlGaN contact layer results in large forward voltage.

Some photons cannot escape from the semiconductor due to the light trapping by total internal reflection and the light absorption by the elimination of the UV-absorptive $p$-Al$_0.23$Ga$_{0.77}$N layer in the DUV spectrum. This explains why a bottom-emitting flip-chip configuration is widely used for these DUV LEDs. To further optimize the LEE of UV LEDs in a flip-chip configuration, combination of a highly reflective $p$-type electrode and a UV-transparent top layer is required. As Al has a high reflectance (over 90%) in the DUV spectrum, a reflective $p$-type electrode can be obtained by using Al-based electrodes rather than Ni/Au electrode which is widely used for $p$-type GaN. An approach to the elimination of the UV-absorptive $p$-type GaN layer was reported with an AlGaN DUV LED emitting at 287 nm, in which a $p$-type GaN contact layer was replaced with a high-Al-content $p$-type AlGaN contact layer and a Ni/Au electrode was replaced with a Ni/Al electrode. The EQE increased from 2% to 5.5%, exhibiting a 1.7 times enhancement in the LEE. However, the proposed LED structure had worse electrical characteristics than conventional LEDs because of much higher contact resistance compared to that of $p$-type GaN.

In addition, the light emission from high Al-content wurtzite AlGaN materials has an anisotropic nature due to its unique valence band structure. The emission property is determined by the top-most valence band of the $c$-plane GaN. An approach to absorb light emission from GaN can be understood as the emission from a dipole along the $z$-axis.

Absorption and Trapping: Light Extraction Efficiency

Some photons cannot escape from the semiconductor due to the light trapping by total internal reflection and the light absorption by absorptive materials such as metal contacts in LEDs. Thus, the extraction of photons from LED chips is as important as the generation of photons inside the active region. Various light-extraction-enhancing techniques, such as surface or interface roughening, anti-reflective coatings, resonant cavity or photonic crystals, surface plasmonics, and the removal of an absorbing substrate, have been developed. Consequently, the high LEE (over 80%) of GaN-based visible LEDs was achieved. However, the LEE of high-Al-content AlGaN DUV LEDs is unsatisfactorily low (<25%). Such low LEE of high-Al-content UV LEDs is mainly due to two reasons: the usage of $p$-type GaN contact layer on top of the epitaxial layers and the strong anisotropic light emission from the AlGaN-based active region.

As previously described, lack of conductive high-Al-content AlGaN results in poor ohmic contacts to $p$-type AlGaN and low hole injection efficiency into the active region. Thus, typical DUV LEDs were equipped with a $p$-type GaN layer on top of the $p$-type AlGaN as an electrode contact and a hole-supplying layer. However, the top $p$-type GaN layer absorbs almost half the generated UV light because of narrower energy bandgap (~3.4 eV), causing a severe photon energy loss regardless of the use of conventional light extraction techniques. This explains why a bottom-emitting flip-chip configuration is widely used for these DUV LEDs. To further optimize the LEE of UV LEDs in a flip-chip configuration, combination of a highly reflective $p$-type electrode and a UV-transparent top layer is required. As Al has a high reflectance (over 90%) in the DUV spectrum, a reflective $p$-type electrode can be obtained by using Al-based electrodes rather than Ni/Au electrode which is widely used for $p$-type GaN. An approach to the elimination of the UV-absorptive $p$-type GaN layer was reported with an AlGaN DUV LED emitting at 287 nm, in which a $p$-type GaN contact layer was replaced with a high-Al-content $p$-type AlGaN contact layer and a Ni/Au electrode was replaced with a Ni/Al electrode. The EQE increased from 2% to 5.5%, exhibiting a 1.7 times enhancement in the LEE. However, the proposed LED structure had worse electrical characteristics than conventional LEDs because of much higher contact resistance compared to that of $p$-type GaN.

Figure 9. Valence band structure of $c$-plane (a) GaN and (b) AlN near $\Gamma$ point calculated by a 6 × 6 effective Hamiltonian matrix for the wurtzite semiconductors. Light emission patterns of $c$-plane (c) GaN, and (d) AlN are isotropic and anisotropic, respectively. Reprinted with permission from Ref. 147. Copyright © 2015, Rights Managed by Nature Publishing Group.
which results in a strong anisotropic emission, as shown in Figure 9d.\textsuperscript{146,147} Consequently, high-Al-content AlGaN has a similar valence band structure to AlN, therefore, it emits light propagating mainly along the in-plane direction of the active region, causing the light to be lost inside the LED chip. This explains why typical LEE-enhancing techniques are very effective for GaN-based visible LEDs but much less effective for AlGaN DUV LEDs because those techniques favor the extraction of isotropic light emission.

New light-extraction-enhancing approaches have been proposed to utilize the inherently strong TM-polarized light emission from the AlGaN active region. Figure 10a shows a schematic diagram of side-excitation-enhanced (SEE) structure which includes Al-coated selective-area-grown n-type GaN micro-reflectors. The SEE DUV LEDs exhibited better electrical properties as well as improved light output power because the sidewall-heading photons were redirected toward the top producing strong upward emission by the Al-coated micro-reflectors.\textsuperscript{147} An improved bottom-emitting SEE DUV LED structure was also proposed to avoid light absorption by a top p-type GaN layer.\textsuperscript{148} A DUV LED having multiple mesa stripes, whose inclined sidewalls are covered by a MgF\textsubscript{2}/Al omnidirectional mirror, was fabricated, as shown in Figure 10b. A significant improvement in the light extraction was reported from this structure and an analytic model was developed to deliver a precise estimation on the extraction of DUV photons from the AlGaN DUV LEDs. The outcoupling emission of an LED can also be controlled by adjusting the compressive or tensile strain of the active layer and by reducing the dimension of the active layer to nanoscale. Thus, these remain to be future works for the outcoupling of TM-polarized emission from a DUV LED chip.

Summary and Future Works

This review has dealt with recent developments in III-nitride UV LEDs, particularly, growth and device processing technologies. Extensive works have been so far performed to fabricate UV LEDs. However, state-of-the-art AlGaN DUV LEDs exhibit inadequately low efficiencies, compared to that of visible LEDs, although NUV LEDs give reasonable EQE. For NUV LEDs, to enhance both the UV transmittance and their electrical properties, various approaches including metal-doped TCOs, oxide/metal/oxide structure, and surface treatments, have been investigated. Furthermore, nanomaterials, such as graphene, CNTs, and Ag NWs, have been widely investigated as TCEs because of their high UV transmittances. For nanomaterials-based TCEs, poor ohmic contacts remained to be a challenging issue. Thus, to improve the contact resistance and the stability of nanomaterial-based TCEs, various techniques, including interface engineering, hybrid nanomaterial structures, and chemical doping, have been extensively studied. For DUV LEDs, their low efficiencies are related to the intrinsic material properties of high-Al-content AlGaN such as severely strained epitaxial layers, low n-type and p-type doping efficiencies, and strong TM-polarized light emission. Extensive efforts have been made to tackle such technical challenges. For the growth of high quality high-Al content AlGaN layers, different approaches, such as superlattices, LT nucleation layers, and bulk AlN substrates, have been adopted. To improve the concentration and injection efficiency of carriers, various methods, including superlattice structures, polarization-induced hole doping, p-type h-BN, a polarization-engineered TJ, and an electron-beam pumping (excitation) method, have been developed. Moreover, the formation of ohmic contacts to high-Al content Al\textsubscript{x}Ga\textsubscript{1-x}N layers is one of the most formidable tasks to be addressed. Thus, to achieve efficient current injection into Al-rich p-Al\textsubscript{x}Ga\textsubscript{1-x}N, methods, such as use of p-GaN contact layer and superlattice structures, have been developed. However, a p-GaN capping layer causes the strong absorption of deep UV light and so a transparent p-AlGaN contact layer is developed to minimize the light absorption. The extraction of photons from LED chips also plays a key role in enhancing EQE of UV LEDs. Various LEE-enhancing techniques, such as surface or interface roughening, anti-reflective coating, resonant cavity or photonic crystals, surface plasmonics, and the removal of an absorbing substrate, have been developed to increase the extraction efficiency of visible LEDs. However, these techniques were shown to be less effective for DUV LEDs. Thus, flip-chip configuration was widely employed for DUV LEDs that required combination of a highly reflective p-type electrode and a UV-transparent top layer. In addition, an LEE-limiting anisotropic emission nature of high-Al-content AlGaN was overcome by introducing side-excitation-enhanced (SEE) structure, leading to a significant improvement in the light extraction and TM-polarized light emission. Despite considerable efforts to improve the performance of UV LEDs, a significant breakthrough in the EQE of particularly DUV LEDs remains to be achieved by overcoming the intrinsic properties of a high Al content AlGaN.

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Figure 10. Schematic structures of (a) top-emitting SEE DUV LEDs, which enable the sidewall-heading photons to reflect toward the top direction by the Al-coated mirror; and (b) bottom-emitting SEE DUV LEDs, which can extract the sidewall-heading photons through the substrates by the inclined mirror structure. Reprinted with permission from Refs. 147, 148. Copyright © 2015, 2016, Rights Managed by Nature Publishing Group.
