COMMENTS AND OPINIONS

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Research status and prospects of deep ultraviolet devices

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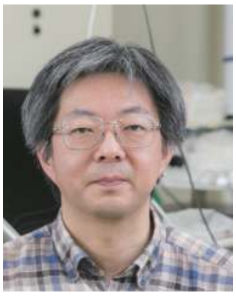

Hideki Hirayama received his Ph.D. from Tokyo Institute of Technology in 1994. He joined RIKEN from 1994 and he was appointed Chief Scientist and Director of Quantum Optodevice Laboratory since 2012. His research interests include crystal growth of wide bandgap AlN-based nitride semiconductors and development of deep-UV emitters.

Ultraviolet (UV) radiation, which is an important component of solar radiation, can be divided into three bands, comprising the UV-A band (320–400 nm), the UV-B band (280–320 nm), and the UV-C band (100–280 nm). UV radiation affects not only the survival and continuing development of humankind, but also has a variety of important applications, including high-resolution light sources, phototherapy, disinfection, sterilization, deodorization, organic decomposition, photo catalysis, gas sensing, optical dialysis dosage monitoring, and the identification of hazardous biological agents[1].

1. UV light-emitting devices

Taking the advantages of AlGaN materials of the direct wide bandgap character, great progress has been made in UV optoelectronic active devices, such as light-emitting diodes (LEDs) and laser diodes (LDs). Compared with traditional solid-state light sources, AlGaN-based UV-LEDs (Fig. 1) have numerous advantages, including short wavelength operation, small size, compact structure, operational stability, high efficiency, low power consumption, low operating voltage, environmental friendliness, and long lifetimes, which make them suitable for application in the UV radiation field[2–4]. Over the past two decades, AlGaN-based materials and devices experienced rapid development. Deep ultraviolet AlGaN-based LEDs with improved efficiency of 20.3% (at 275 nm) have been produced.

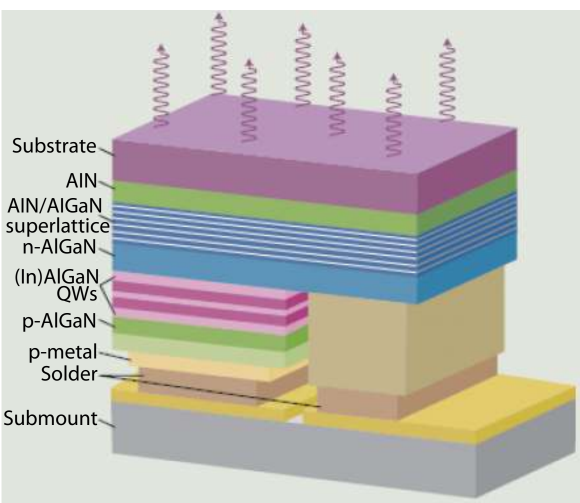

Fig. 1. (Color online) Schematic illustration of the DUV-LEDs structure.

AlGaN-based UV-LDs with their unique high spatial and temporal coherence properties have many merits, including high light beam quality, high power density, and high modulation speeds, which can be widely used in applications of precision laser processing, high-density data storage, nanopattern-type photolithography, medical diagnostics, disinfection, biochemical technology, gas sensing, and materials science[5, 6]. Recently, Zhang *et al.* presented a deep-ultraviolet semiconductor laser diode that operates under current injection at room temperature and at a very short wavelength. The laser structure was grown on the (0001) face of a single-crystal aluminum nitride substrate. The measured lasing wavelength was 271.8 nm with a pulsed duration of 50 ns and a repetition frequency of 2 kHz (Fig. 2)[7].

2. Problems of UV light-emitting devices

In order to realize high-performance devices, further op-

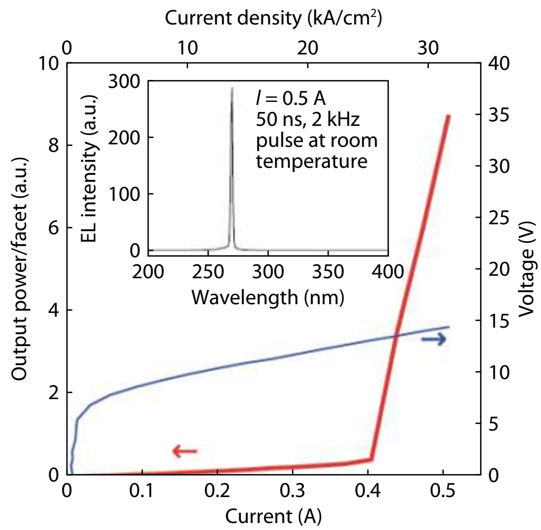

Fig. 2. (Color online) I–V and edge emission I–L characteristics of the measured UV-C LD. The inset figure shows the edge emission spectrum at 0.5 A forward current[7].

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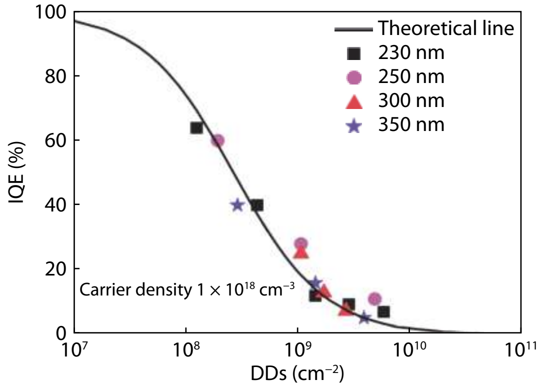

Fig. 3. (Color online) IQE as a function of DD in an underlying layer under weak excitation with excess carrier density of 1×10^{18} cm^{-3}.

timization and improvement of structure and manufacturing are required, mainly focusing on three aspects: reducing the defect density of AlGaN materials, improving the light extraction efficiency of device structures and achieving high-efficiency P-type doping of AlGaN materials.

(1) Poor-quality of AlGaN material

AlGaN-based materials own direct transition energy bands and wide bandgap and thus can be used in high-efficiency ultraviolet (UV) emitters. Compared with GaN-based blue and green LEDs and LDs, the efficiency of AlGaN-based UV LEDs and LDs is lower. Dislocations usually act as the nonradiative recombination center in AlGaN-based active devices, thus the quality of AlGaN is crucial to the device performance. Fig. 3 illustrates the relationship between the internal quantum efficiency (IQE) and the dislocation density (DD) in AlGaN multiple quantum wells (MQWs) underweak excitation with an excess carrier density of 1×10^{18} cm^{-3}[8]. It is difficult to obtain high-quality AlGaN material, and the crystalline quality of the material deteriorates with increasing Al content. The main reasons for the poor crystalline quality are a lack of lattice-matched substrates for growth and the presence of pre-reactions or parasitic reactions between the trimethylaluminum (TMAl) precursors and NH_3 used in growth of the material.

(2) Low light extraction efficiency

Due to the higher refractive index of nitride materials, the light emitted by quantum wells is totally reflected at the interface between DUV LED and air. A large amount of light is confined inside the LED and absorbed by the epitaxial material, resulting in very low light extraction efficiency. N Lobo's simulations show that the light extraction efficiency of mirrorless and unpackaged flip-chip UV LEDs is only 7%–9% level[9]. In addition, the luminescence of GaN-based visible light LEDs is mainly TE mode polarization, while in AlGaN-based UV LEDs, as the Al composition increases and the wavelength decreases, the TE mode is converted to the TM mode. For the LEDs on the c-plane sapphire, the TE mode and the TM mode polarized light propagate vertically and horizontally, respectively, so the TE mode polarized light is easier to extract from the vertical direction than the TM mode polarized light, that is, TE mode has higher extraction efficiency than TM mold. Therefore, for AlGaN-based UV LEDs, as the Al composition increases and the wavelength decreases, the TM mode polarization increases and the TE mode polarization decreases, which becomes another important factor for its low light extraction efficiency.

(3) P-type doping problem of AlGaN

High-conductivity AlGaN is required to realize high performance AlGaN-based UV devices. However, a problem that has persisted since the early 1990s and is becoming increasingly troublesome is the high resistivity of p-type GaN and AlGaN layers. The activation energy E_A of the most commonly used acceptor dopant (Mg) in GaN is ~200 meV[10], several times the thermal energy k_BT at room temperature (where k_B is the Boltzmann constant, and T is temperature). The activation energy of acceptors increases with the band gap, reaching E_A ~ 630 meV in AlN. Thus, the thermal activation of holes is highly inefficient at room temperature for GaN and becomes increasingly problematic for higher-band-gap AlGaN and AlN layers. As a result, injection of holes is a severe impediment for light-emitting devices in the UV and deep-UV spectral windows. High p-type resistance leads to excessive Joule heating of p-doped AlGaN layers for Al composition $x_{Al} \geqslant$ 20%. Instead, p-GaN layers must be used and absorption losses incurred in the narrower-bandgap region. Furthermore, hole reflection and trapping at heterojunction valence-band offsets block hole injection into optically active AlGaN regions[1] and reduce the efficiency of such devices. An alternative strategy for efficient p-type doping and hole injection in wide-bandgap semiconductors is therefore highly desirable at this time.

In order to solve the above problems, the researchers have also made many efforts. For growing high-quality AlGaN film on sapphire substrates, a high-quality AlN film is mainly used as a template layer of AlGaN, so researchers used various methods to grow high-quality AlN films, such as pulse growth method, insertion of low-temperature buffer layer or two-dimensional materials such as graphene buffer layer and epitaxial lateral overgrowth (ELO) technology on patterned sapphire substrates (PSS)[11–13]. Meanwhile, drawing on the light extraction experience of GaN-based blue LEDs, on the basis of improving the transmittance of the p-type layer of the UV LED and reducing the self-absorption of the epitaxial layer, techniques such as pattern substrate, surface roughening and electrode mirrors can further improve the LEE and EQE of UV LEDs. SET Inc. used the transparent p-type cladding and contact layers to reduce the light absorption[14]. Mi *et al.* demonstrated a light extraction efficiency of more than 70% using nanowire DUV LED[15].

In addition, studies on p-doping of AlGaN have investigated common uniform Mg doping, Mg-δ doping, superlattice doping, co-doping, polarization induced doping and so on[16–18]. Simon *et al.* demonstrated high-efficiency p-type doping by ionizing acceptor dopants using the built-in electronic polarization in bulk uniaxial semiconductor crystals. Because the mobile hole gases are field-ionized, they are robust to thermal freeze out effects and lead to major improvements in p-type electrical conductivity. The new doping technique results in improved optical emission efficiency in prototype ultraviolet light-emitting diode structures (Fig. 4)[10].

3. Conclusions and outlook

AlGaN-based DUV-LEDs with short operating wavelengths have been achieved, and these wavelengths have been extended to 222 nm for AlGaN/AlN MQW devices and 210 nm for AlN PIN homojunction devices. The improved per-

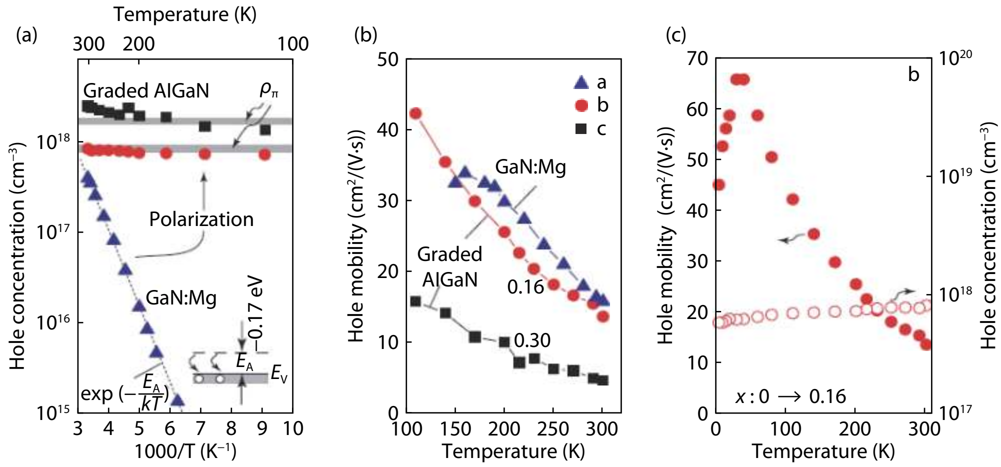

Fig. 4. (Color online) Hall-effect temperature-dependent (a) hole concentration, (b) hole mobilities, and (c) hole concentration and mobility measured down to $T = 4$ K.

formances of these LEDs have been achieved with EQEs of 20.3% at 275 nm. However, the EQEs of DUV-LEDs are still low when compared with those of GaN-based blue and green LEDs. There is also a considerable drop in efficiency, which is caused by high dislocation densities, low hole concentrations, and low LEEs for the AlGaN-based LEDs. Furthermore, the EQE also drops dramatically with decreasing wavelength, which is caused by deterioration in the AlGaN quality, the difficulty of p-type doping processes, and degradation of the optically polarized emission with increasing Al content. It is expected that high-efficiency DUV AlGaN-based LEDs will be realized by improving the quality and the p-type doping of AlGaN as well as optimizing the parameters of the AlGaN/AlN MQWs.

Due to the improvements in both AlGaN quality and p-type doping, UV stimulated emission has been achieved in AlGaN MQW LDs using electrical pumping at RT, with a shortest reported wavelength of 271 nm. At present, the development of UV AlGaN-based LDs is moving toward shorter wavelengths and low threshold voltage. However, many challenges still need to overcome to achieve high performance LDs of this type. First, the high densities of defects and dislocations in the active regions of these LDs will increase their internal losses, resulting in reduction of the EQE. Second, the difficulty involved in p-type doping of AlGaN will reduce the hole injection efficiency and increase the series resistance, which leads to an increased threshold and reduced efficiency for LDs operating under current injection conditions. Additionally, the difficulties faced in device fabrication processes such as etching, thinning, and cleaving will increase losses and reduce the efficiency of these LDs. In addition, suitable homoepitaxial substrates for AlGaN growth are not available at present. Therefore, appropriate substrates with high transparency and high electrical and thermal conductivities are required to improve the performance of these LDs. Furthermore, a suitable LD structure design is required to improve device efficiency. In conclusion, the low defect densities of bulk AlN substrates offer a promising strategy to enable fabrication of high-performance LDs.

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