Invited paper

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Heteroepitaxial technology for high-efficiency UV light-emitting diode

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A high-quality AlGaN layer with a low density of threading dislocations is realised for the use of ultraviolet (UV) light-emitting diodes (LEDs). The new crystal growth method of using a GaN seed crystal with ($11\bar{2}2$) facets and lateral growth of $Al_{0.22}Ga_{0.78}N$ through the low-temperature-deposited AlN interlayer enables the overgrown $Al_{0.22}Ga_{0.78}N$ to have a low dislocation density of 2×10^7 cm^{-2} and be crack-free over the whole wafer. Applying the AlGaN as a base layer in UV-LEDs, high-performance devices with high output powers of more than 0.1 mW under 50 mA drive are demonstrated in a wide range of emission wavelengths from 323 to 363 nm. The highest output power of 1.2 mW at 50 mA driving current is obtained with 363-nm emission wavelength.

Keywords: MOVPE, lattice mismatch, threading dislocation, UV, light-emitting diode.

1. Introduction

Nitride semiconductors are promising candidates for use in short-wavelength light-emitting devices because of their wide bandgap with direct transition. However, it had been quite difficult to grow high-quality epitaxial nitride film, and its conductivity had never been controlled. These problems had prevented the development of nitride-based devices for many years. Major breakthroughs in the second half of the '80s, i.e., the development of extremely high-quality GaN single crystal [1] and the discovery of p-type conduction in nitrides and the development of a p-n junction blue light-emitting diode (LED) [2] dramatically changed the situation, and led to the realisation of blue and green LEDs [3,4] and violet laser diodes (LDs) [5,6].

Recently, the development of UV light-emitting devices is being focused on as a leading edge of frontier applications. Such devices are applicable to lighting equipment in combination with three-colour-phosphors, light sources of high-density optical data storage system and sensing devices in biological use. Therefore, efforts for the development of UV LED have been carried out [7–10]. However, UV ($\lambda < 370$ nm) light-emitting devices with high quantum efficiency have not been realised. The efficiency of UV LEDs is still much lower than this of blue and green LEDs. Despite the high density of threading dislocations, visible or near-UV LEDs with a GaInN quantum well active layer have high emission efficiency because of the effect of In-rich clusters [7]. On the other hand, UV LEDs with wavelengths shorter than 370 nm have very low efficiency because of a lack of In-rich clusters. The active layer of UV light-emitting devices basically comprises In-free materials, such as AlGaN, due to the requirement of a wide bandgap, so carriers can easily diffuse into nonradiative recombination centres at or around threading dislocations. An AlGaInN quaternary active layer is expected to have both UV bandedge emission and high quantum efficiency with In-rich clusters, and it is applied to active layers in UV LEDs [8,9]. However, crystalline quality of the quaternary alloy is thought to be inferior, so that the efficiency of UV LEDs having the AlGaInN active layer is still very low [9]. Although the highest efficiency was obtained with 352 nm LED grown on a GaN substrate with low dislocation density [10], the GaN substrate is not commercially available at present, and is too expensive for the use as an LED substrate.

In this paper, we report an approach for achieving low dislocation density in AlGaN with AlN molar fraction of more than 0.2 to fabricate UV LEDs with short emission wavelength. A new growth method including lateral seeding epitaxy and a low-temperature-deposited (LT-) AlN interlayer makes it possible to reduce the density of threading dislocations in the AlGaN layer on the sapphire substrate, and results in highly efficient UV LEDs with emission wavelengths ranging from 323 to 363 nm.

2. Reduction of threading dislocations in AlGaN/GaN heterostructure

In the case of UV light-emitting devices with In-free active layers, reduction of threading dislocations is indispensable for achieving high emission efficiency, as mentioned above. However, the conventional epitaxial lateral overgrowth (ELO) technique using dielectric masks, which is a common method for growing GaN with a low density of dislocations, is not applicable for AlGaN growth, due to a

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strong adhesion of AlN on the dielectric masks. When the AlGaN layer is grown on GaN with low density of dislocations, it also has a low dislocation density. However, tensile stress caused by the lattice mismatch between AlGaN and GaN layers generates cracks in the AlGaN consequently making it useless in device fabrication. We propose a growth method for achieving a high-quality AlGaN layer with low density of threading dislocations that involves lateral seeding epitaxy on periodically grooved GaN and an LT-AlN interlayer [11]. Figure 1 shows a schematic drawing and an image taken with the transmission electron microscope, where the top AlGaN layer is grown on periodically grooved GaN through a (LT-) AlN interlayer. The AlGaN over the grooves has a dislocation density as low as mid-10^7 cm^{-2} due to the lateral growth effect, in contrast with a high dislocation density of more than 10^{10} cm^{-2} over terraces. The LT-AlN interlayer can suppress the stress caused by the lattice mismatch [12], so there are no cracks on the surface of the AlGaN layer.

A micro-photoluminescence (μ-PL) mapping is shown in Fig. 2, where the emission at 352 nm occurs at GaN/AlGaN multi-quantum wells grown on the AlGaN layer shown in Fig. 1. High contrast of intensity is clearly observed as the bright and dark regions. The bright regions have a low density of dislocations, and the dark ones have a high density of dislocations. The PL intensity at the bright regions is about 20 times higher than that of the dark regions, which is evidence that threading dislocations act as nonradiative recombination centres. However, the regions with a low density of dislocations occupied only half of the whole emitting area, so the expansion of the area with a low density of dislocations is necessary for obtaining high-efficiency UV light emitters.

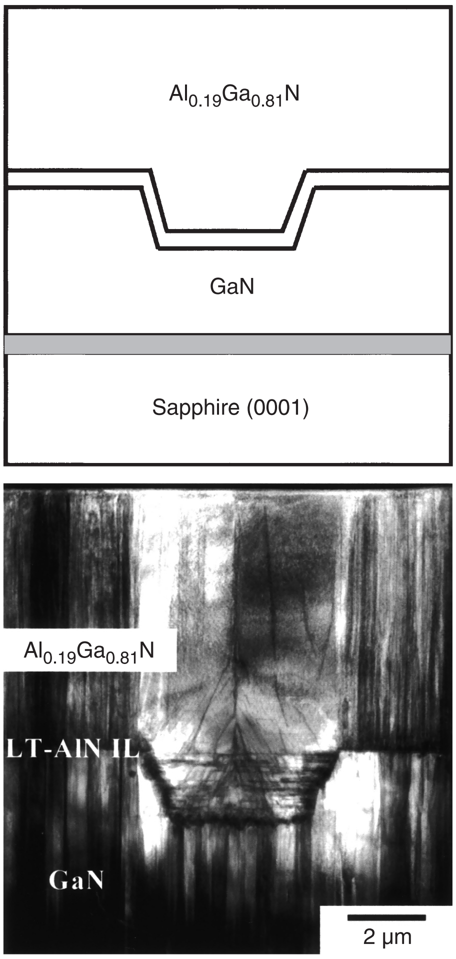

Fig. 1. Schematic drawing and an image of transmission electron microscope of AlGaN layer grown on periodically grooved GaN layer through LT-AlN interlayer. The width, depth and spacing of the grooves are 5, 2, and 5 μm, respectively.

For the expansion of the area with low dislocation density, we adopted another method of using selectively grown seed crystals with particular crystallographic facets. This advanced crystal growth method comprises a first GaN epitaxial growth on a sapphire substrate, a second selective growth of GaN seed crystals through <$1\bar{1}00$> SiO_2 stripe masks and a third planarised growth of $Al_{0.22}Ga_{0.78}N$ through an LT-AlN interlayer [13]. After the 1st growth, SiO_2 stripe masks were formed along the <$1\bar{1}00$> axis on the GaN surface. In the 2nd step, the GaN seed crystals were selectively grown on the window: they have triangular cross sections with ($11\bar{2}2$) facets when grown under optimum growth conditions. Similar to previous work using particular crystallographic facets [14], dislocations in GaN seed crystals maintaining ($11\bar{2}2$) facets during growth bent horizontally, and only a few dislocations propagate vertically as shown in Fig. 3.

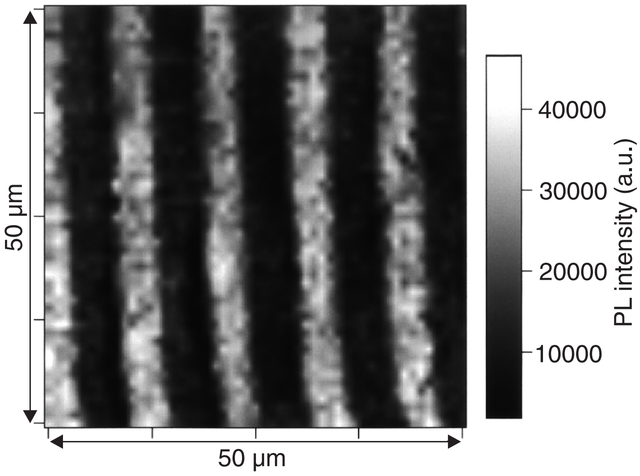

Fig. 2. A micro-photoluminescence (μ-PL) mapping of GaN/AlGaN multi-quantum wells grown on the AlGaN layer with periodic low density of threading dislocations. The measurement was carried out using He-Cd laser with approximately 1-μm spot at room temperature.

Figure 4 shows a cathode luminescence image of $Al_{0.22}Ga_{0.78}N$. Observed dark spots, the density of which is as low as 2×10^7 cm^{-2} over the whole wafer, may correspond to dislocations. Furthermore, similar to the previous method, the LT-AlN interlayer makes it possible to relax the tensile stress in the AlGaN layer; therefore, the overgrown AlGaN

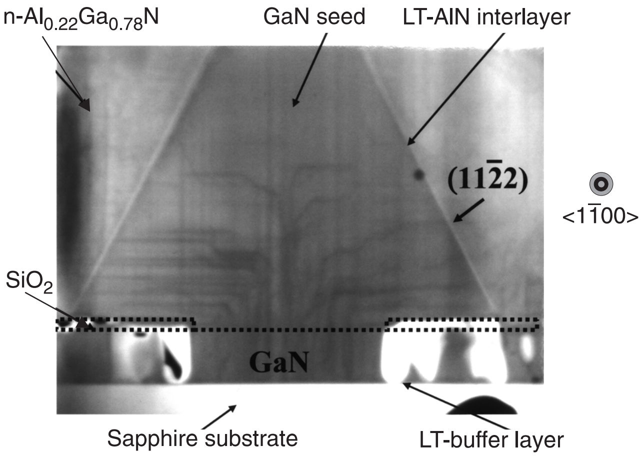

Fig. 3. Transmission electron microscopic image around selectively grown GaN seed crystal with $(11\bar{2}2)$ facets.

layer has no cracks. The AlGaN layer is promising for use as base layer of UV light-emitting devices.

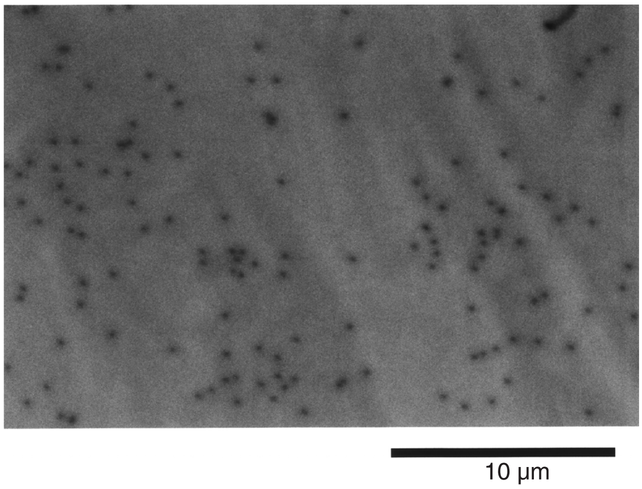

Fig. 4. Cathode luminescence image of $Al_{0.22}Ga_{0.78}N$ with low density of threading dislocations.

3. Highly efficient UV LEDs fabricated on high-quality AlGaN base layer

We applied the advanced growth technology shown in Fig. 3 to the fabrication of UV LEDs with various emission wavelengths. Figure 5 shows the schematic of the device structure, where an $n-Al_{0.25}Ga_{0.75}N$ 1st cladding layer (0.3 μm), an active layer, a $p-Al_{0.4}Ga_{0.6}N$ electron blocking layer (20 nm), a $p-Al_xGa_{1-x}N$ 2nd cladding layer (0.2–0.4 μm) and a p^+-GaN (0.05 μm) contact layer were successively grown on the $n-Al_{0.22}Ga_{0.78}N$ layer by metal-organic vapour phase epitaxy. The active layer and composition of the $p-Al_xGa_{1-x}N$ 2nd cladding layer varied with changing emission wavelength, as mentioned below. A Ni/Au semitransparent p-contact and an Au bonding pad electrode were deposited on the p-side, and a Ti/Al n-contact was formed on the n-side. Under the Au bonding pad, a thin Ti layer was deposited just on the p^+-GaN con-

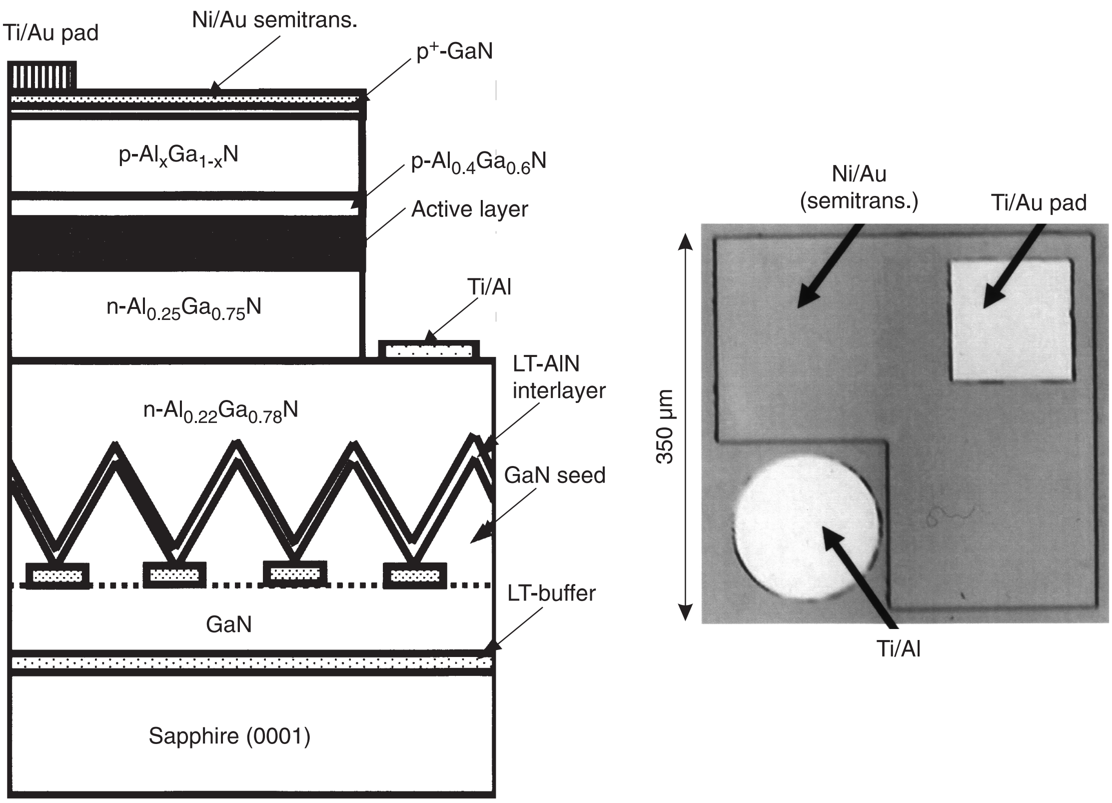

Fig. 5. Schematic UV-LED structure on $Al_{0.22}Ga_{0.78}N$ base layer with low density of threading dislocations.

tact layer in order to reduce the current injection there. Four kinds of active layers were used in UV LEDs for the variation of emission wavelength. The active layers used in UV LEDs were (a) bulk GaN, (b) GaN/$Al_{0.08}Ga_{0.92}N$:Si MQW, (c) bulk $Al_{0.10}Ga_{0.90}N$ and (d) bulk $Al_{0.16}Ga_{0.84}N$. The AlN molar fractions of the p-$Al_xGa_{1-x}N$ 2nd cladding layer were 0.15 for (a), 0.2 for (b), 0.25 for (c) and 0.3 for (d). All the bulk active layers were undoped. The thickness of the p-$Al_xGa_{1-x}N$ 2nd cladding layer was 0.4 μm in LED (a), and 0.2 μm in others.

The peak wavelengths of electroluminescence under 50 mA (DC) drive are 363 nm, 352 nm, 338 nm and 323 nm for LEDs (a), (b), (c) and (d), respectively. The output power as a function of peak wavelength at 50 mA (DC) bias is shown in Fig. 6. All LEDs have output powers of more than 0.1 mW, and they are greatly dependent on the peak wavelength. With shortening of the wavelength, output power linearly decreases. This may partly be due to the deterioration of current spread in p-layers, which leads to the reduction of light extraction from the device. However, compared with the best LED ever reported with 320 nm-wavelength [9], our 323 nm LED has almost one order higher output power at an equivalent driving current. The output power of the 363-nm device with the GaN active layer has the highest output power of 1.2 mW. This output power is still much lower than those of violet and blue LEDs with GaInN active layers. Some problems may remain, such as the still-unsolved nonradiative recombination in active layers, and low light-extraction efficiency caused by poor current spread in p-layers and light absorption in the p^+-GaN contact layer or semitransparent metals.

In order to investigate the light-extraction efficiency, we measure light output distribution at the surface of LEDs using a CCD camera. Figure 7 shows output intensity images of LED (c). As in the figure, light output is mainly extracted only near the bonding pad electrode and little light is emitted from the region distant from the pad electrode. Such a light output distribution is thought to reflect the hole distribution of highly resistive p-type layers, because the resistivity of the p-cladding layer is increased with decreasing emission wavelength. In our LEDs, a large number of holes must be injected just under the bonding pad, despite the high contact resistance between the p^+-GaN contact layer and Ti, and light generated there might be absorbed in the electrode. As a result, light-extraction efficiency seems to be quite low, particularly in shorter wavelength devices. Thus, one of the main reasons for the still low external quantum efficiency in UV LEDs is low light-extraction efficiency. For further improvement of the external quantum efficiency, it is necessary to optimise the device structure to increase the light-extraction efficiency.

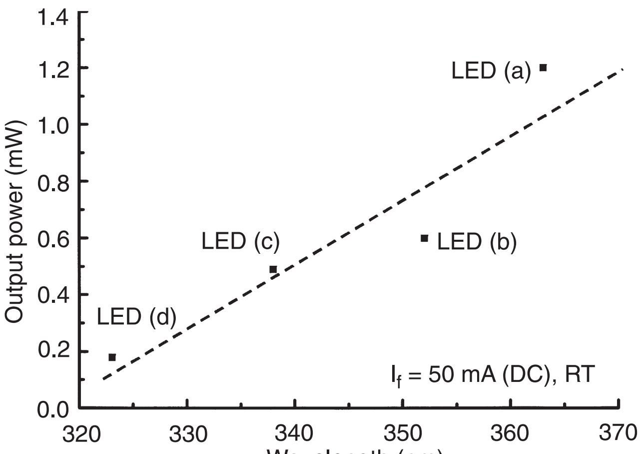

Fig. 6. Output power as a function of peak wavelength at 50-mA (DC) driving current.

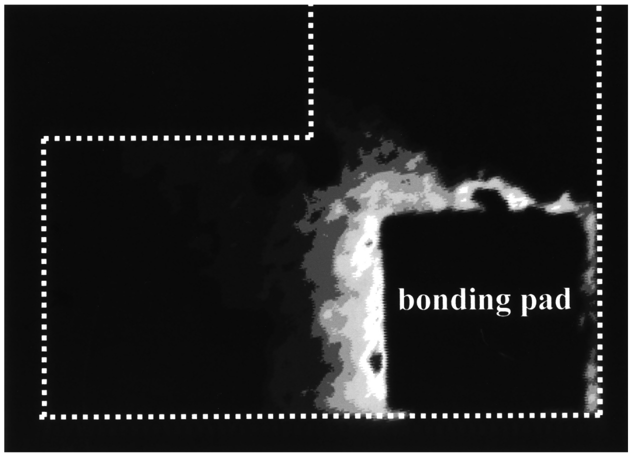

Fig. 7. Output intensity images of LED (c) with emission wavelength of 323-nm. LED is operating at 50 mA (DC).

4. Conclusions

We have realised a high-quality AlGaN layer with a low density of threading dislocations using lateral seeding epitaxial technology. The new crystal growth method of using a GaN seed crystal with $(11\bar{2}2)$ facets and lateral growth of $Al_{0.22}Ga_{0.78}N$ through the LT-interlayer enables the overgrown $Al_{0.22}Ga_{0.78}N$ to have a low dislocation density of 2×10^7 cm^{-2} and be crack-free over the whole wafer. With this AlGaN as a base layer, UV LEDs have high output powers of more than 0.1 mW under 50 mA drive in a wide range wavelengths from 323 to 363 nm. The highest output power of 1.2 W at 50 mA driving current is obtained with 363-nm emission wavelength. This 363-nm-wavelength device has the highest efficiency ever reported in UV LEDs with wavelength shorter than 370-nm on a sapphire substrate.

Acknowledgement

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PRESS INFORMATION

Fairchild Introduces Low-Voltage, Compact, Surface-Mount Blue LEDs for Cell Phones, PDAs, and Other Portable Products

New LEDs are Ideal for Edge Lighting, Back Lighting, and Illumination Applications

San Jose, CA – September 12, 2002 – Fairchild Semiconductor (NYSE: FCS) today announces the introduction of three new, blue, compact, surface-mount LEDs. The three LEDs feature low voltage operation for low power consumption ($V_f \leq 3.15$ V @ 5 mA) and a narrow forward voltage range (2.75 to 3.15 V) for better color and brightness consistency. The small size and low power consumption make the LEDs ideal for lighting and illumination applications in compact, portable products.

The right angle, surface mount configuration of the QTLP610CEB and QTLP611CEB LEDs makes them ideal for edge lighting LCD displays and other status indicators in cell phones, personal digital assistants (PDA), and other portable communications and electronic devices. Likewise, the low profile, surface mount configuration of the QTLP601CEB makes it ideal for back lighting keypads, push-buttons, and LCD displays in the same type of devices.

All three Fairchild LEDs have distinct advantages over conventional cold-cathode fluorescent lamps (CCFL) and electroluminscent lamps (EL) for illumination in compact devices: they are smaller, more reliable, use dc (rather than ac) voltage, and do not require auxiliary circuitry. In addition, low voltage operation and a narrow forward voltage range make the Fairchild LEDs preferable over similar sized, surface mount blue LEDs for portable devices.

The QTLP610CEB and QTLP611CEB are right angle, surface-mount LEDs. The QTLP610CEB measures 3.0 mm (long) by 2.0 mm (wide) by 1.0 mm (high) with a 120° viewing angle, and the QTLP611CEB measures 2.1 mm (long) by 1.0 mm (wide) by 0.6 mm (high) with a 130° viewing angle. The QTLP601CEB is a 0603 pcb-based surface-mount package footprint that measures 1.6 mm (long) by 0.8 mm (wide) by 0.6 mm (high) with a 100° viewing angle. All three components use an InGaN/Sapphire blue LED, water clear optics, and are available in 0.315 inch (8 mm) width tape on 7 inch (178 mm) diameter reel, with 2,000 units per reel.

Availability: Immediate delivery of volume production.

For more information, please visit the Fairchild web page at: http://www.fairchildsemi.com/products/opto or call your local Fairchild sales office.

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