GaN-based light-emitting diodes prepared on vicinal sapphire substrates

J.C. Lin, Y.K. Su, S.J. Chang, W.H. Lan, K.C. Huang, W.R. Chen, Y.C. Cheng and W.J. Lin

Abstract: Thin InGaN epitaxial layers and GaN-based light-emitting diodes (LEDs) on conventional and vicinal cut sapphire substrates are prepared. It is found that indium atoms are distributed much more uniformly in the samples prepared on vicinal cut sapphire substrates. It is also found that stronger electroluminescence intensity can be achieved without the band-filling effect of localised states from the LEDs with vicinal cut sapphire substrate. With 20 mA current injection, it is found that 44% electroluminescence intensity enhancement can be achieved by using the 1° tilted sapphire substrate.

1 Introduction

Over the past 15 years, III-nitride semiconductor materials have attracted much attention. These materials can be used as high-brightness blue/green light-emitting diodes (LEDs) [1] and laser diodes (LDs) [2]. In fact, nitride-based LEDs prepared on sapphire substrates have already been used extensively in various applications, such as traffic lights, full-colour display and lighting [3]. However, a threading dislocation density in the order of $10^9-10^{12}\,cm^{-2}$ will still remain in the devices due to the large differences in lattice constant and thermal expansion coefficient between GaN-based epitaxial layers and the sapphire substrates below. To improve the performance of GaN-based devices, we thus need to reduce threading dislocation density. Recently, it was found from Hall, X-ray diffraction and photoluminescence (PL) measurements that one can effectively reduce the number of threading dislocations by growing GaN epitaxial layers on vicinal cut sapphire substrates [4–7]. However, no GaN-based devices prepared on vicinal cut sapphire substrates have been reported to our knowledge. In this article, we report the preparation of GaN-based LEDs on tilted and untilted sapphire substrates. Properties of the fabricated LEDs will also be discussed.

2 Experiments

Samples used in this study were all grown by metalorganic chemical vapour deposition either on c-plane (0 0 0 1) sapphire substrates with a vicinal-cut angle of 1° toward the a-plane (1 1 −2 0) or on exactly oriented (i.e. 0° tilted) (0 0 0 1) sapphire substrates [8–10]. We first prepared thin InGaN layers. For these samples, we deposited a 25 nm-thick GaN nucleation layer at 520°C, a 4 μm-thick Si-doped n-GaN layer at 1120°C and a 3 nm-thick $In_{0.15}Ga_{0.85}N$ layer on the sapphire substrates. Figs. 1*a* and *b* show atomic force microscopy (AFM) photographs of these thin InGaN epitaxial layers grown on 0° and 1° tilted sapphire substrates, respectively. It can be seen from Fig. 1*a* that quantum dots (QDs) with an average size of 100 nm and a density of $5.4 \times 10^8\,cm^{-2}$ were formed in the InGaN epitaxial layer grown on untilted sapphire substrate. Formation of the self-assembled InGaN QDs on GaN surface could be attributed to the Stranski–Krastanow (SK) growth mode when indium composition is higher than 12% [11]. For an epitaxial system with small interface energy and large lattice mismatch, initial growth is layer by layer. As the epitaxial layer becomes thicker, however, the large strain energy can lower the total energy by forming three-dimensional (3D) islands in which the lattice parameter relaxes to its equilibrium value (i.e. SK growth mode). Using the untilted sapphire substrates, it has been shown that 3D growth will become dominant when the InGaN epitaxial layer thickness is larger than its critical thickness [11]. In contrast, no such QD was observed from the InGaN epitaxial layer grown on 1° tilted sapphire substrate. Previously, it has been shown that GaN epitaxial layers prepared on tilted sapphire substrates were grown with step-flow mode, whereas those on untilted sapphire substrates were grown with spiral growth mode [4]. During the epitaxial growth on untilted substrate, the direction of micro-steps on the surface is random and has a sharp curvature. This results in the spiral growth of the epitaxial layers. In contrast, the direction of the micro-steps inclines towards the tilted direction when titled substrate is used. Thus, a step-flow pattern is formed on the sample surface. It has also been shown that the flow pattern on the GaN surface depends strongly on the tilted angle of sapphire substrates [4]. Instead of SK growth, group III adatoms should be able to migrate easily to the steps and terraces on the sample surface with a step-flow growth mode [12]. Thus, no InGaN QDs are observed in Fig. 1*b*. The smooth surface also suggests that indium atoms are distributed much more uniformly in the InGaN epitaxial layer prepared on 1° tilted sapphire substrate.

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J.C. Lin, Y.K. Su and S.J. Chang are with the Institute of Microelectronics and Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Republic of China

W.H. Lan is with the Department of Electrical Engineering, National University of Kaohsiung, Kaohsiung 811, Republic of China

K.C. Huang is with the Department of Electrophysics, National Chiao Tung University, Hsinchu 300, Republic of China

W.R. Chen is with the Department of Electronic Engineering, National Formosa University, Huwei 632, Republic of China

Y.C. Cheng and W.J. Lin are with the Materials and Electro-Optics Research Division, Chung Shan Institute of Science and Technology, Taoyuan 325, Republic of China

E-mail: changsj@mail.ncku.edu.tw

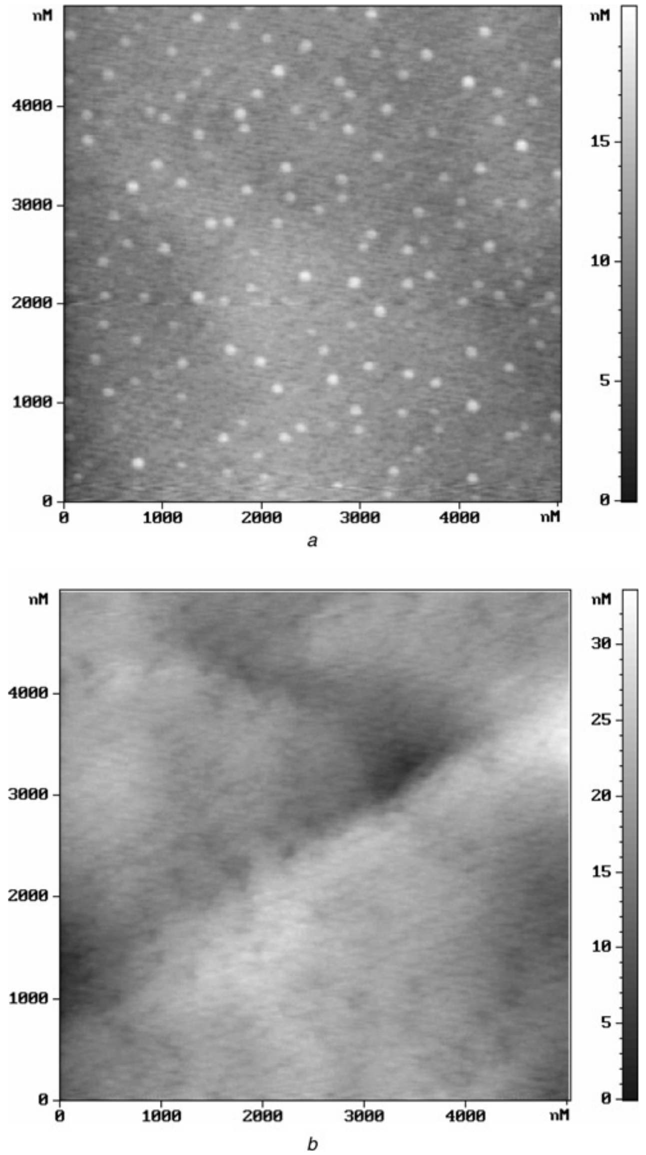

Fig. 1 *AFM photographs of thin InGaN epitaxial layers grown on (a) 0° and (b) 1° tilted sapphire substrates*

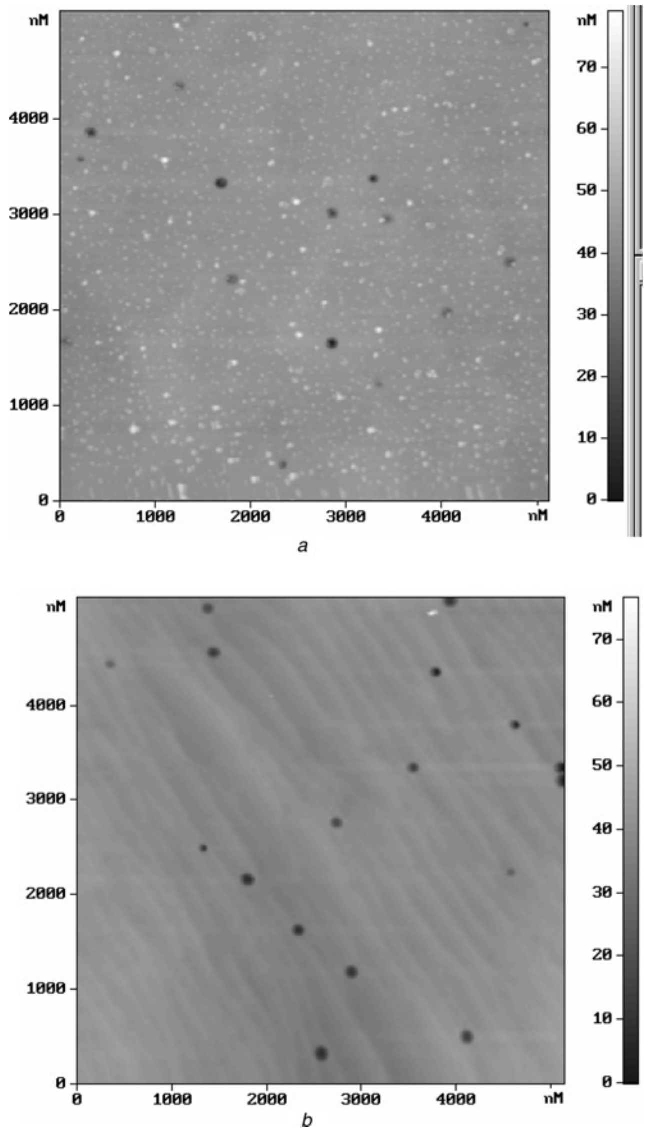

Fig. 2 *AFM photographs of fabricated LEDs prepared on (a) 0° and (b) 1° tilted sapphire substrates*

GaN-based LEDs were also prepared on these two different kinds of substrates. The LED structure consists of a 25 nm-thick GaN nucleation layer grown at 520°C, a 4-μm thick Si-doped n-GaN layer grown at 1120°C, an InGaN/GaN MQW active region grown at 770°C and a 0.2-μm thick Mg-doped p-GaN cap layer grown at 1110°C. The MQW active region consists of six periods of 3 nm-thick $In_{0.15}Ga_{0.85}N$ well layers and 11 nm-thick GaN barrier layers. We then used AFM and double crystal X-ray diffraction (DCXRD) to characterise surface morphology and crystal quality of the LEDs. Room temperature PL was then used to characterise the samples. During PL measurements, a 25-mW He-Cd laser was used as the excitation source, while the output luminescence was analysed by a SPEX 1000 M spectrometer and a photomultiplier tube.

The surface of the LEDs was then partially etched until the n-type GaN layer was exposed. Ni/Au was subsequently evaporated onto the sample surface to serve as the upper contact. In contrast, Ti/Al/Ti/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode. The epitaxial wafers were then lapped down to about 90 μm. We then used scribe and break to complete the fabrication of 350 × 350 μm blue InGaN/GaN LED chips [13–17]. Electroluminescence (EL) spectra of the LEDs were then measured on the wafer by injecting DC currents into the LED chips.

3 Results and discussion

Figs. 2*a* and *b* show AFM photographs of the fabricated LEDs prepared on 0° and 1° tilted sapphire substrates, respectively. From these figures, it was found that root-mean-square (RMS) roughness of the sample surfaces were 2.63 and 1.15 nm for the LEDs prepared on 0° and 1° tilted sapphire substrates, respectively. In other words, surface morphology of the 1° LED sample is much smoother than that of the 0° LED sample. This should be related to the different InGaN growth modes observed in Figs. 1*a* and *b*. Fig. 3 shows measured DCXRD spectra of the two LEDs. Compared with the LED sample prepared on 0° tilted sapphire substrate, it was found that we can observe more DCXRD satellite peaks from the LED sample prepared on 1° tilted sapphire substrate. Such an observation indicates that the crystal quality of the LED prepared on the 1° tilted sapphire substrate was better.

Fig. 4 shows measured PL spectra of the two as-grown LED samples. The multiple peaks observed from these spectra should be attributed to the internal reflection of light in the samples. Similar multiple peaks have also

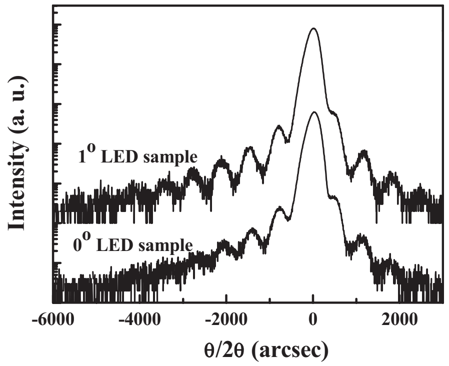

Fig. 3 *Measured DC×RD spectra of two LEDs*

been observed elsewhere [4]. Compared with the sample prepared on untilted sapphire substrate, the larger PL intensity observed from the sample prepared on 1° tilted sapphire substrate should again be attributed to its better crystal quality with fewer threading dislocations. It was also found that PL peak position occurred at a longer wavelength for the sample prepared on the untilted sapphire substrate. This could be attributed to the formation of InGaN QDs. As shown in Fig. 1*a*, severe indium compositional fluctuation and localised states occurred in the InGaN QDs because of phase separation and/or indium segregation [18–21]. Previously, it has been shown that one can use transmission electron microscopy (TEM) to identify the formation of SK growth QDs in InGaN/GaN MQWs [19, 20]. It has also been shown that the PL emission peak position of QDs is longer than that of the InGaN wetting layer (2D layer), which is attributed to the higher indium composition in the QDs [21]. With much larger average indium composition in the QDs, we thus observed PL peak positions, that occurred at longer wavelength from the sample prepared on untilted sapphire substrate.

Figs. 5*a* and *b* show normalised EL spectra of the two LEDs grown on the 1° tilted sapphire substrate (1° LED sample) and the untilted sapphire substrate (0° LED sample), respectively. With the same injection current, it was found that EL peak positions observed from the 0° LED sample were always longer than those observed from the 1° LED sample. This could be attributed again to the formation of InGaN QDs in the 0° LED sample. Fig. 6 shows the measured EL peak position of the two fabricated LEDs. As the injection current was increased from 5 to 40 mA, it was found that EL peak position blue-shifted significantly from 467 to 461 nm for the 0° LED sample. Such blue-shift could be attributed to the band-filling effect of localised states when InGaN QDs were formed [18, 19]. In contrast, EL peak position only blue-shifted slightly from 458 to

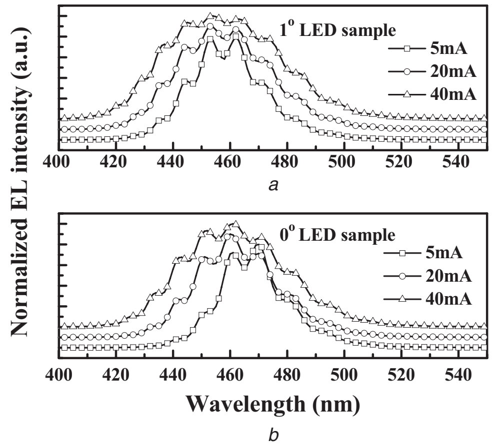

Fig. 5 *Normalised EL spectra of two LEDs grown on (a) 1° tilted sapphire substrate and (b) untilted sapphire substrate*

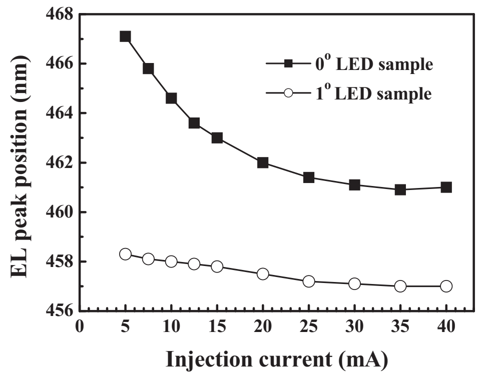

Fig. 6 *Measured EL peak position of two fabricated LEDs*

457 nm for the 1° LED sample with the same injection current increment. The much smaller blue-shift again suggests much more uniform distribution of indium atoms in the 1° LED sample. Fig. 7 shows measured intensity–current (*L–I*) characteristics of the two fabricated LEDs. It can be seen that EL intensity increased as we increased the injection current for both samples. It was also found that EL intensity observed from the 1° LED sample was larger than that observed from the 0° LED sample. With 20 mA current injection, it was found that we achieved 44% EL intensity enhancement by using the vicinal sapphire substrate. The larger EL intensity could again be attributed to the better crystal quality with fewer threading dislocations because of the use of 1° tilted sapphire substrate.

In summary, both thin InGaN epitaxial layers and GaN-based LEDs prepared on conventional and vicinal

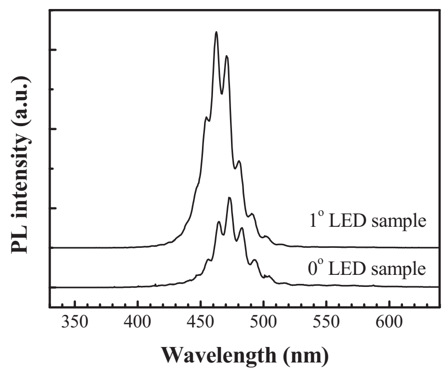

Fig. 4 *Measured PL spectra of two as-grown LED samples*

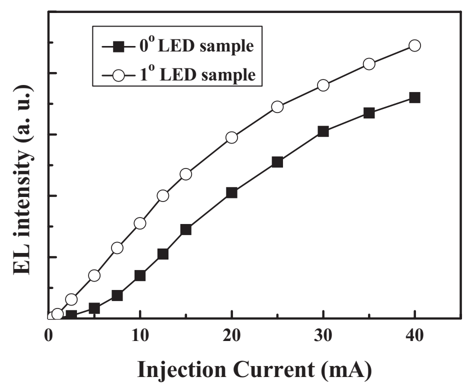

Fig. 7 *Measured L–I characteristics of two fabricated LEDs*

cut sapphire substrates were prepared. It was found that indium atoms distributed much more uniformly in the samples prepared on vicinal cut sapphire substrates. It was also found that we could achieve stronger EL intensity with emission wavelength much less sensitive to injection current from the LEDs with vicinal cut sapphire substrate.

4 References

1 Nakamura, S., Senoh, M., Iwasa, N., and Nagahama, S.C.: 'High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes', *Appl. Phys. Lett.*, 1995, **67**, pp. 1868–1870

2 Nakamura, S., Senoh, M., Nagahama, S., Iwasa, N., Yamada, T., Matsushita, T., Sugimoto, Y., and Kiyoku, H.: 'High-power, long-lifetime InGaN multi-quantum-well-structure laser diodes', *Jpn. J. Appl. Phys.*, 1997, **36**, L1059–L1061

3 Nakamura, S., and Fasol, G.: 'The blue laser diode' (Springer-Verlag, Berlin, Germany, 1997)

4 Lin, J.C., Su, Y.K., Chang, S.J., Chen, W.R., Chen, R.Y., Cheng, Y.C., and Lin, W.J.: 'Activation energy of *n*-GaN epitaxial layers grown on vicinal-cut sapphire substrates', *J. Cryst. Growth*, 2005, **285**, pp. 481–485

5 Shen, X.Q., Matsuhata, H., and Okumura, H.: 'Reduction of the threading dislocation density in GaN films grown on vicinal sapphire (0001) substrates', *Appl. Phys. Lett.*, 2005, **86**, pp. 021912–021914

6 Grudowski, P.A., Holmes, A.L., Eiting, C.J., and Dupuis, R.D.: 'The effect of substrate misorientation on the photoluminescence properties of GaN grown on sapphire by metalorganic chemical vapor deposition', *Appl. Phys. Lett.*, 1996, **69**, pp. 3626–3628

7 Kim, S.W., Aida, H., and Suzuki, T.: 'The effect of a slight misorientation angle of c-plane sapphire substrate on surface and crystal quality of MOCVD grown GaN thin films', *Phys. Stat. Sol. (c)*, 2004, **1**, pp. 2483–2486

8 Chang, S.J., Lai, W.C., Su, Y.K., Chen, J.F., Liu, C.H., and Liaw, U.H.: 'InGaN–GaN multiquantum well blue and green light emitting diodes', *IEEE J. Select. Topics Quantum Electron.*, 2002, **8**, pp. 278–283

9 Chang, S.J., Kuo, C.H., Su, Y.K., Wu, L.W., Sheu, J.K., Wen, T.C., Lai, W.C., Chen, J.F., and Tsai, J.M.: '400 nm InGaN–GaN and InGaN–AlGaN multiquantum well light-emitting diodes', *IEEE J. Select. Topics Quantum Electron.*, 2002, **8**, pp. 744–748

10 Chen, C.H., Su, Y.K., Chang, S.J., Chi, G.C., Sheu, J.K., Chen, J.F., Liu, C.H., and Liaw, Y.H.: 'High brightness green light emitting diodes with charge asymmetric resonance tunneling structure', *IEEE Electron. Device Lett.*, 2002, **23**, pp. 130–132

11 Grandjenn, N., and Massies, J.: 'Real time control of $In_xGa_{1-x}N$ molecular beam epitaxy growth', *Appl. Phys. Lett.*, 1998, **72**, pp. 1078–1080

12 Cheng, Y.C., Tai, K., Chou, S.T., Huang, K.F., Lin, W.J., and Lin, A.C.H.: 'Reduction of spontaneous surface segregation in $(InP)_2/(GaP)_2$ quantum wells grown on tilted substrates', *Jpn. J. Appl. Phys.*, 1999, **38**, pp. 17–21

13 Chang, S.J., Chang, C.S., Su, Y.K., Chuang, R.W., Lai, W.C., Kuo, C.H., Hsu, Y.P., Lin, Y.C., Shei, S.C., Lo, H.M., Ke, J.C., and Sheu, J.K.: 'Nitride-based LEDs with an SPS tunneling contact layer and an ITO transparent contact', *IEEE Photonics Technol. Lett.*, 2004, **16**, pp. 1002–1004

14 Chang, S.J., Wu, L.W., Su, Y.K., Hsu, Y.P., Lai, W.C., Tsai, J.M., Sheu, J.K., and Lee, C.T.: 'Nitride-based LEDs with 800°C grown p-AlInGaN–GaN double-cap layers', *IEEE Photonics Technol. Lett.*, 2004, **16**, pp. 1447–1449

15 Chang, S.J., Chen, C.H., Su, Y.K., Sheu, J.K., Lai, W.C., Tsai, J.M., Liu, C.H., and Chen, S.C.: 'Improved ESD protection by combining InGaN/GaN MQW LED with GaN Schottky diode', *IEEE Electron. Devics Lett.*, 2003, **24**, (3), pp. 129–131

16 Chang, S.J., Chang, C.S., Su, Y.K., Lee, C.T., Chen, W.S., Shen, C.F., Hsu, Y.P., Shei, S.C., and Lo, H.M.: 'Nitride-based flip-chip ITO LEDs', *IEEE Tran. Adv. Packaging*, 2005, **28**, (2), pp. 273–277

17 Chang, S.J., Chang, C.S., Su, Y.K., Chuang, R.W., Lin, Y.C., Shei, S.C., Lo, H.M., Lin, H.Y., and Ke, J.C.: 'Highly reliable nitride-based LEDs with SPS + ITO upper contacts', *IEEE J. Quantum Electron.*, 2003, **39**, pp. 1439–1443

18 Shim, H.W., Suh, E.K., Hong, C.H., Kim, Y.W., and Lee, H.J.: 'Effect of well profile on optical and structural properties in InGaN/GaN quantum wells and light emitting diodes', *Phys. Stat. Sol. (a)*, 2003, **200**, pp. 62–66

19 Narukawa, Y., Kawakami, Y., Funato, M., Fujita, S., Fujita, S., and Nakamura, S.: 'Role of self-formed InGaN quantum dots for exciton localization in the purple laser diode emitting at 420 nm', *Appl. Phys. Lett.*, 1997, **70**, pp. 981–983

20 Ramaiah, K.S., Su, Y.K., Chang, S.J., Kerr, B., Liu, H.P., and Chen, I.G.: 'Characterization of InGaN/GaN multi-quantum-well blue-light-emitting diodes grown by metal organic chemical vapor deposition', *Appl. Phys. Lett.*, 2004, **84**, pp. 3307–3309

21 Grandjean, N., Damilano, B., Massies, J., and Dalmasso, S.: 'Enhanced luminescence efficiency due to exciton localization in self-assembled InGaN/GaN quantum dots', *Solid State Commun.*, 2000, **113**, pp. 495–498