Supplementary Material

Realization of high efficiency AlGaN-based multiple quantum wells grown on nano-patterned sapphire substrates

Yuanhao Sun,[ab] Fujun Xu,[*ab] Na Zhang,[ab] Jing Lang,[ab] Jiaming Wang,[ab] Baiyin Liu,[ab] Liubing Wang,[ab] Nan Xie,[ab] Xuzhou Fang,[ab] Xiangning Kang,[ab] Zhixin Qin,[ab] Xuelin Yang,[ab] Xinqiang Wang,[abc] Weikun Ge,[ab] and Bo Shen[abc]

[a] State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, China

[b] Nano-optoelectronics Frontier Center of Ministry of Education, Peking University, Beijing 100871, China

[c] Collaborative Innovation Center of Quantum Matter, Beijing 100871, China

S1. The zoomed-in inset STEM-HAADF images of MQWs samples.

The zoomed-in insets of the TEM images grown at 1060 °C and 1100 °C are shown in Fig. S1, indicating that the interfaces of MQWs samples grown under 1100 °C are actually clear and abrupt.

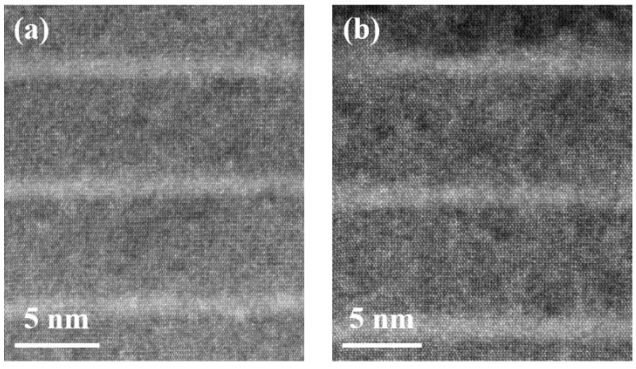

Fig. S1 (a) The zoomed-in inset STEM-HAADF images of MQWs samples with growth temperatures of 1060 °C (a) and 1100 °C (b).

S2. The trend of IQE values changing with variable excitation power.

The IQE values of the MQWs adopting different V/III ratios regarded as a function of excitation power are shown in Fig. S2. The chosen excitation powers are 0.1, 0.75, 2, 4 and 10 mW. It is observed that the IQE values of all the samples increase with increasing excitation power and then saturate under higher excitation power, indicating that the experiments with the excitation power over 2 mW are all under saturation conditions.

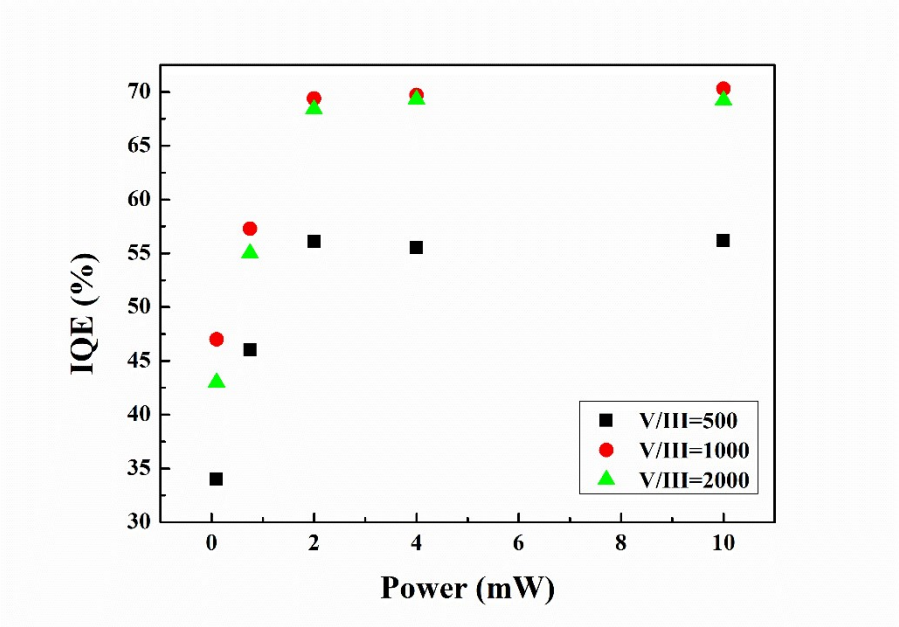

Fig. S2 The IQE values as a function of excitation power for the samples with different V/III ratios.

S3. XRD results of the AlN template grown on a common planar sapphire substrate.

XRD ω-scan FWHM values for the (0002) and (10-12) planes are 129 and 563 arcsec, respectively. And the calculated TDD of the AlN template is 3.77×10^{9} cm^{-2}.

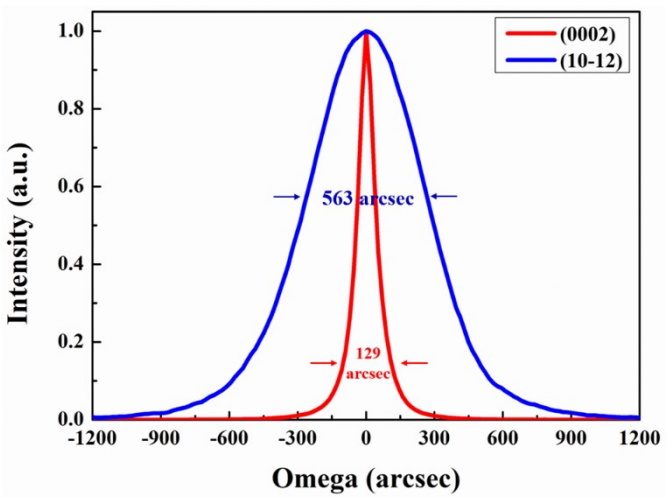

Fig. S3 XRD ω-scan rocking curves for (0002) and (10–12) planes.

S4. IQE values as a function of excitation power for the MQWs samples grown on NPSS measured at 10 K, 200 K and 300 K.

The IQE values as a function of excitation power for the MQWs samples grown on NPSS measured at 10, 200 and 300 K are shown in Fig. S4, indicating that the IQE values measured at 10 and 200 K also increase with the increase of excitation power density and the IQE value measured at 10 K slightly decreases at higher excitation density. It should be noted here that the IQE curves are normalized by the maximum value of the ratio between the intensity of PL spectra to the excitation power density at 10 K, which has been reported in previous studies.[1,2]

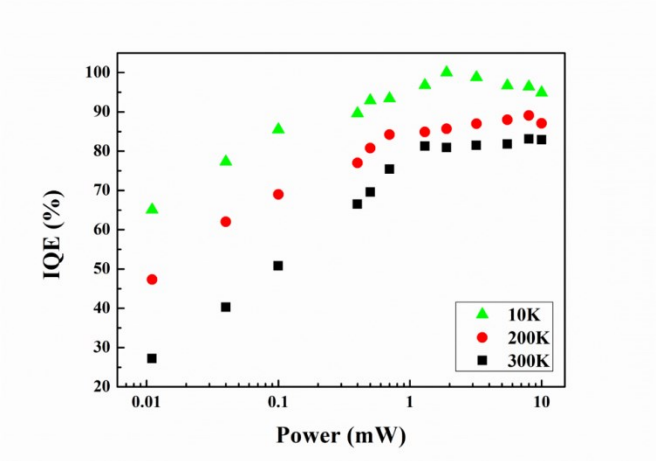

Fig. S4 IQE values as a function of excitation power for the MQWs samples grown on NPSS measured at 10 K, 200 K and 300 K.

S5. LEE results simulated through FDTD solutions and the IQE calculated from EQE.

The LEE of the flip-chips is obtained by simulation as shown in Fig. S5(a). The LEE at 275 nm is about 6.1%. Based on this LEE and highest reported CIE at 80% (the actual CIE in our sample should be much less than this value),[3] the IQE of the quantum wells can be derived from the EQE. The underestimated maximal IQE can reach 82.2% at 20 mA.

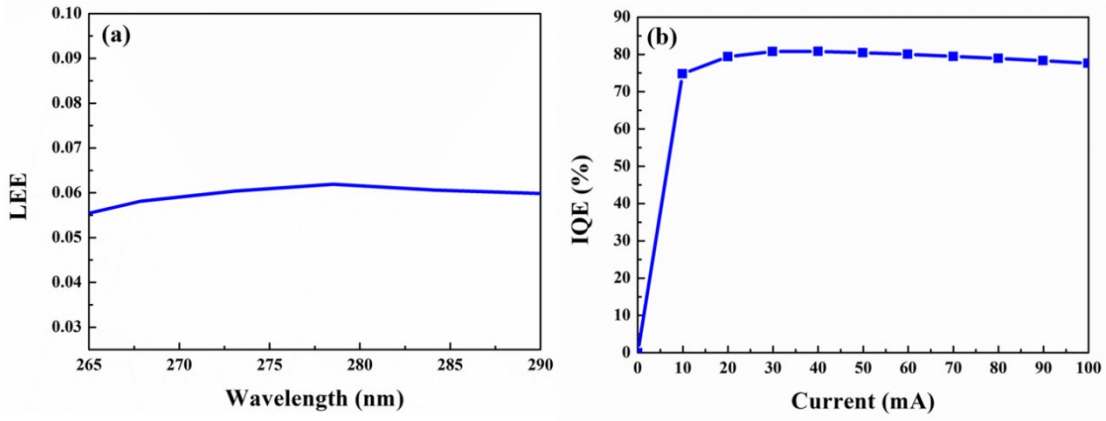

Fig. S5 (a) Light extraction efficiency (LEE) with the change of wavelength; (b) Dependence of the calculated IQE on injection currents.

Notes and reference

1 H. Murotani, D. Akase, K. Anai, Y. Yamada, H. Miyake and K. Hiramatsu, Appl. Phys. Lett., 2012, 101, 042110.

2 H. Murotani, R. Tanabe, K. Hisanaga, A. Hamada, K. Beppu, N. Maeda, M. A. Khan, M. Jo, H. Hirayama and Y. Yamada, Appl. Phys. Lett., 2020, 117, 162106.

3 M. Kneissl, T. Y. Seong, J. Han and H. Amano, *Nat. Photonics*, 2019, 13, 233–244.