## Electronic Supplementary Information for

# High internal quantum efficiency ZnO/ZnMgO multiple quantum wells prepared on GaN/sapphire templates for ultraviolet light emitting diodes

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## Figures

**Figure S1**. XRD $\omega$-rocking curves of GaN (102) diffraction peak for the GaN/$Al_2O_3$ template. The FWHM value of the diffraction peak is 303 arcsec.

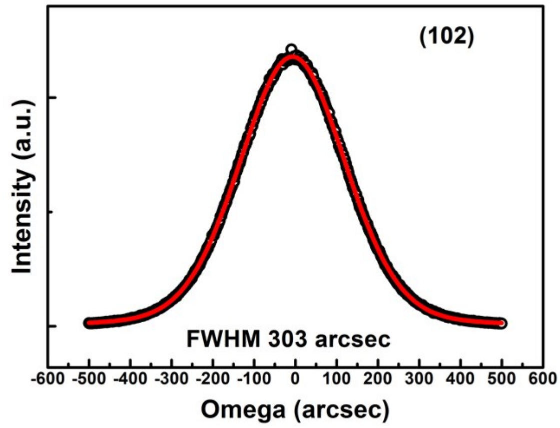
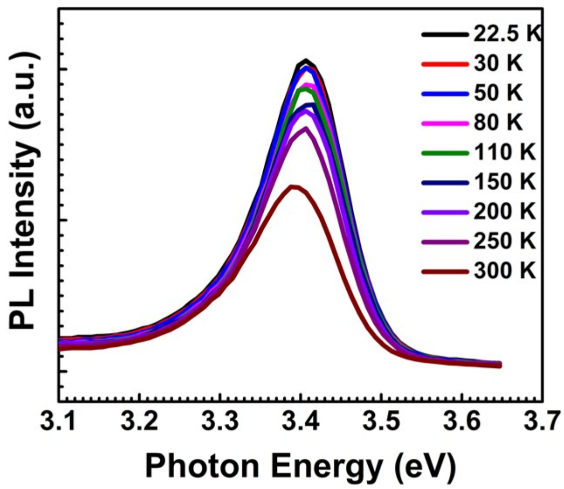



**Figure S2**. The LE emission temperature dependence of PL intensity for the ZnO/$Zn_{0.9}Mg_{0.1}O$ MQWs grown on GaN/$Al_2O_3$ substrate.



**The measurement of IQE**

In this work, as for the determining of IQE, an equivalent IQE of the LE emission peak at 300 K deduced by PL measurement is used instead since the direct measurement is very complicated. This optical method is described in detail by Kawakami (Ref. 25), and has been widely applied (Ref. 26-Ref. 30). Generally, this optical method is as follows. IQE is given by the ratio of the radiative ($k_{rad}$) and non-radiative ($k_{non}$) recombination rates of electron-hole pairs: IQE = $k_{rad}/(k_{rad} + k_{non})$. There is a case where the non-radiative recombination process can be ignored, where the temperature dependence of luminescence intensity I(T) is constant ($I(T) = I_C$) in a low temperature region ($T < T_C$), and then decreases gradually with increasing temperature ($T > T_C$). In such a case, it can be assumed that IQE is nearly equal to unity at temperature below $T_C$, so that IQE can be expressed by $IQE(T) = I(T)/I_C$. Therefore, the IQE at 300 K is approximated as the integrated PL intensity at 300 K divided by that at low temperature below when the emission shows a plateau. Figure S2 shows the LE emission temperature dependence of PL intensity I(T). In this study, the emission is almost a plateau when temperature is lower than 50 K. Thus, IQE(300 K) = I(300 K)/$I_C$, where $T_C$ is lower than 50 K. The related temperature dependence of integrated PL intensity is as the inset of Fig. 2(a) and the IQE is about 61%.

## Tables

**Table S1** The FWHM values of (002) and (102) rocking curves for ZnO and $Zn_{0.9}Mg_{0.1}O$ films grown on sapphire substrates.

| Samples | FWHM (arcsec) | |
|---|---|---|
| | (002) | (102) |
| ZnO on sapphire | 101 | 930 |
| $Zn_{0.9}Mg_{0.1}O$ on sapphire | 123 | 1077 |

**Table S2**. A review of the reported IQE for ZnO/ZnMgO MQWs, ZnO films and nanostructures.

| | IQE | Substrate | Reference |
|---|---|---|---|
| ZnO/ZnMgO MQWs | 1% | SCAM | J. Appl. Phys. 2003, 93, 5929 |
| | 4.9% | Sapphire | ECS J. Solid State Sc. 2013, 2, R21 |
| | 20% | a-plane ZnO | Appl. Phys. Lett. 2010, 97, 081903 |
| | 30% | Sapphire | Laser phys. Lett. 2013, 10, 055902 |
| | 15% | ZnO | Nanoscale, 2018, 10, 14812 |
| ZnO films | 6.3% | SCAM | J. Appl. Phys. 2006, 99, 093505 |
| | 9.6% | ZnO | J. Appl. Phys. 2008, 103, 063502 |
| | 5.5% | Sapphire | Appl. Phys. Lett. 2010, 97, 131913 |
| ZnO nanostructures | 13% | Si | Appl. Phys. Lett. 2005, 86, 153119 |
| | 28% | $SnO_2$-coated glass | Appl. Phys. Lett. 2008, 92, 161906 |
| | 33% | 6*H*-SiC | J. Appl. Phys. 2009, 106, 063111 |