

Remarkable Lifetime Improvement of Quantum-dot Light Emitting Diodes by Incorporating Rubidium Carbonate in Metal-Oxide Electron Transport Layer

Yujin Lee, Hyo-Min Kim, Jeonggi Kim and Jin Jang*

*Department of Information Display and Advanced Display Research Center, Kyung Hee University, 26 Kyungheedaero-ro, Dongdaemun-gu, Seoul 02447, Korea

KEYWORDS: Efficiency roll-off, Lifetime, Metal oxide, Quantum-dot, QLED, Rubidium carbonate, Solution process

Conductivity calculation from I-V characteristics of EODs

To calculate the conductivity of MZO, the electron only devices (EODs) were fabricated with the following structure: ITO/Al (2 nm)/pristine MZO or $\text{Rb}_2\text{CO}_3\text{:MZO}$ (~ 45 nm)/LiQ (1.5 nm)/Al (100 nm). From the ohmic region in the I-V characteristics of EODs, where the slope of current against voltage is 1, the resistivity of the MZO is obtained.

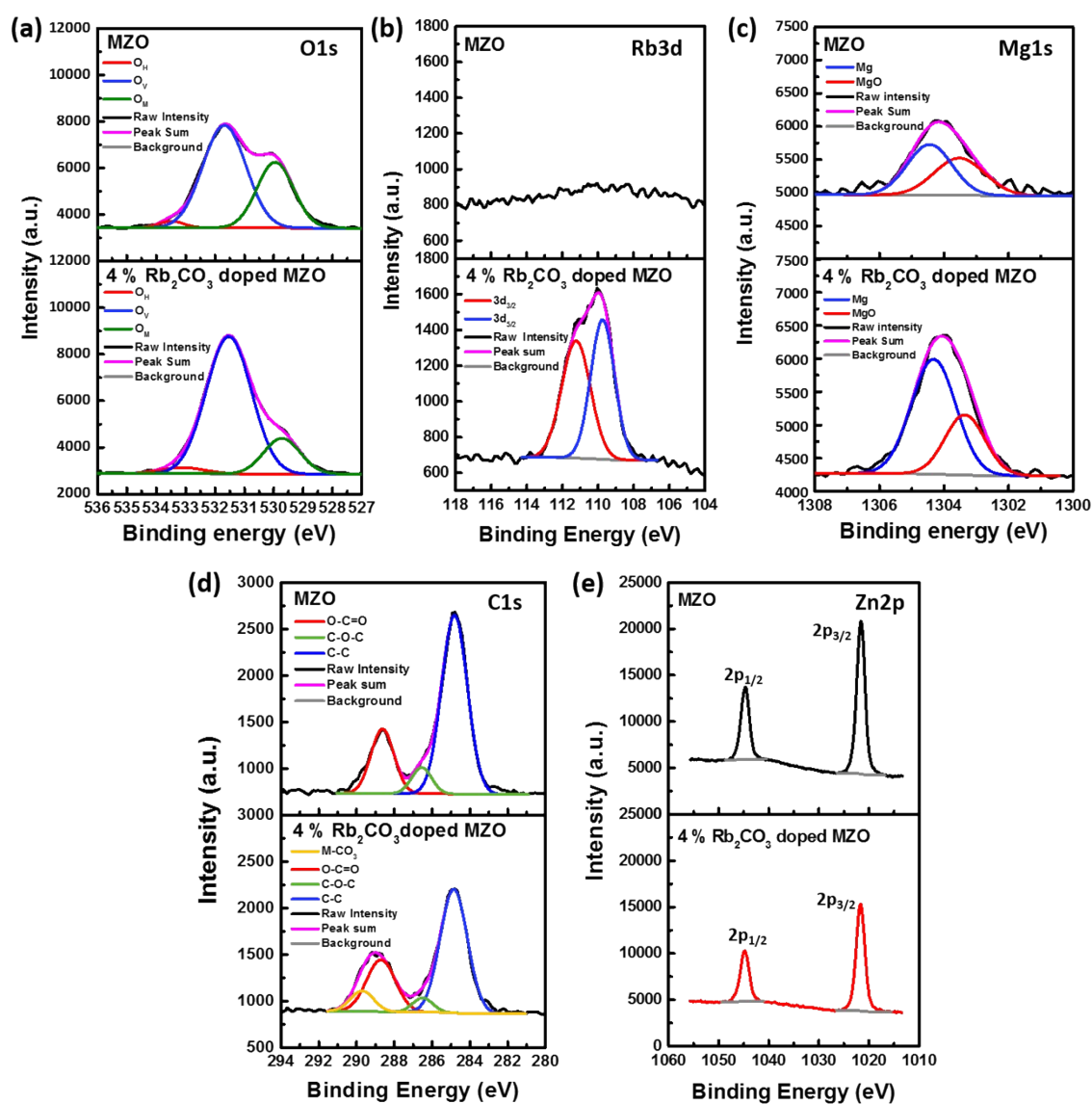


Figure S1. XPS spectra of pristine MZO and 4% Rb_2CO_3 doped MZO thin-films. The XPS intensities plotted as a function of binding energy for (a) O1s, (b) Rb3d, (c) Mg1s, (d) C1s and (e) Zn2p core levels.

Table S1. Summarized peak area for Rb3d, C1s, Zn2p, Mg1s and O1s core levels in pristine MZO and 4% Rb₂CO₃ doped MZO thin-films obtained from XPS results.

Core Level								
Rb ₂ CO ₃ doping concentration		O1s			Rb3d		Mg1s	
		O _H	O _V	O _M	Rb3d _{3/2}	Rb3d _{5/2}	Mg	MgO
0%	Area (%)	2.4	63.3	34.3	-		54.8	45.2
4%		3.4	79.8	16.8	50.35	68.1	31.9	67.7

Core Level								
Rb ₂ CO ₃ doping concentration		C1s				Zn2p		
		M-CO ₃	O-C=O	C-O-C	C-C	Zn2p _{1/2}	Zn2p _{3/2}	
0%	Area (%)	-	22.5	7.8	69.7	32.2	67.8	
4%		8.4	26.5	5.1	60	32.3	67.7	

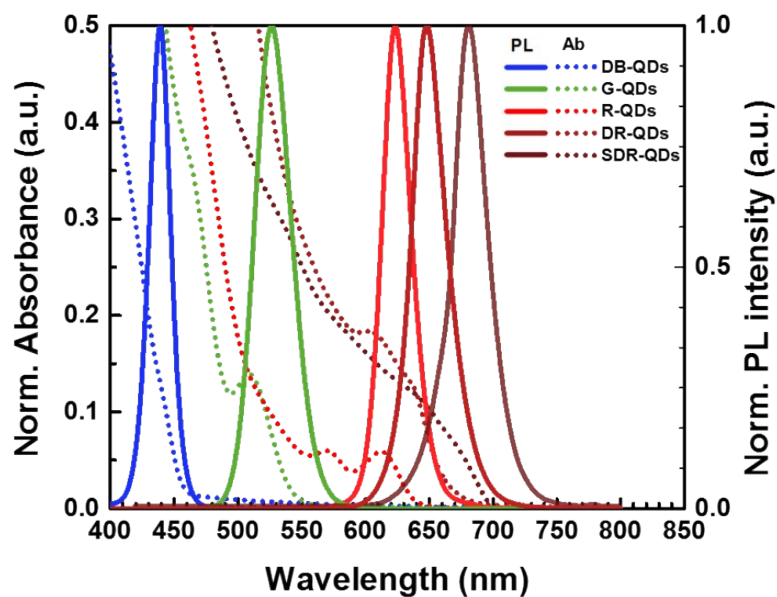


Figure S2. Optical absorptions and PL intensities of SDR-, DR-, R-, G- and DB-QD solutions.

Table S2. Summarized material information for SDR-, DR-, R-, G- and DB-QDs used in this study.

Color	Composition	d_{avr} (nm)	PL_{peak} (nm)	FWHM (nm)	QY(%)
Super deep-red (SDR-)	CdZnSeS/ZnS	10	679	38	88
Deep-red (DR-)	CdZnSeS/ZnS	13	644	31	77
Red (R-)	CdZnSeS/ZnS	10	620	26	91
Green (G-)	CdZnSeS/ZnS	9	527	34	91
Deep-blue (DB-)	CdS/ZnS	7	447	19	76

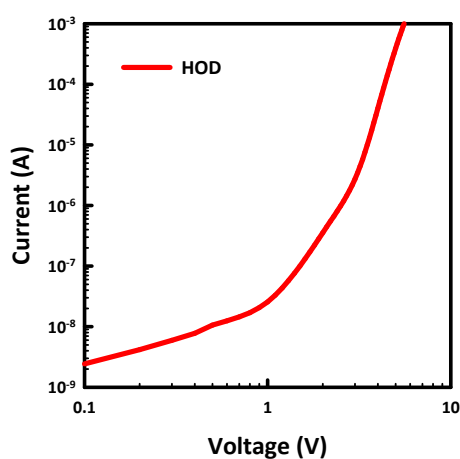


Figure S3. I-V characteristic of hole only device (HOD). Structure: ITO/ PEDOT:PSS:WO_x(40 nm)/ R-QDs (20nm)/ TCTA (10nm)/ NPB(20nm) / HAT-CN(20nm) / Al(100nm)

Table S3. Summarized current efficiencies at 30k cd/m² and maximum luminances of R-QLEDs reported in literatures.

EL _{peak} (nm)	Device Structure	CE (cd/A, @ L=30k cd/m ²)	L _{max} (cd/m ²)	Ref.
640	ITO/AZO/R-QDs/TCTA/NPB/HAT-CN/Al	~2.7	31,030	(1)
612	ITO/PEDOT:PSS/TFB/F4TCNQ/R-QDs/ZnO/Al	~8	76,000	(2)
630	ITO/ZnO/R-QDs/Firpic:TCTA/NPB/HAT-CN/Al	~4.7	47,400	(3)
620	ITO/PEDOT:PSS/PVK/R-QDs/Ga:ZnO/Al	~13	~44,000	(4)
620	ITO/PEDOT:PSS/TFB/R-QDs/MZO/Al	~7	36,685	(5)
~630	ITO/ZnO:CsN ₃ /R-QDs/TAPC/HAT-CN/MoO ₃ / Al	~5.5	~ 30,000	(6)
622	ITO/ZnO:Cs ₂ CO ₃ /R-QDs/Poly-TPD/PEDOT:PSS/ Al	~4.8	75,444	(7)
620	ITO/LZO/Rb₂CO₃:MZO/TCTA/NPB/HAT-CN/Al	13.2	129,100	This work

Table S4. Summarized lifetime characteristics of inverted R-QLEDs reported in literatures.

year	color	Device Structure	EL _{peak} (nm)	L _{int} (cd/m ²)	Lifetime (T ₉₀ , hr)	Ref.
2016	Red	ITO/ZnO/QDs/Firpic:TCTA/NPB/Al	630	100	~6	(3)
2018	Red	ITO/ZnO NPs/Cs ₂ CO ₃ /QDs/NPB/HAT-CN/Al	620	100	~1,000	(8)
This study	Red	ITO/LZO/MZO:Rb₂CO₃/QDs/TCTA/NPB/HAT-CN/Al	620	100 1,000	~14,400 ~465	This work

REFERENCES

- Kim, H. M.; Bin Mohd Yusoff, A. R.; Youn, J. H.; Jang, J. Inverted Quantum-Dot Light Emitting Diodes with Cesium Carbonate Doped Aluminium-Zinc-Oxide as the Cathode Buffer Layer for High Brightness. *J. Mater. Chem. C* 2013, **1**, 3924–3930.
- Nam, S.; Oh, N.; Zhai, Y.; Shim, M. High Efficiency and Optical Anisotropy in Double-Heterojunction Nanorod Light-Emitting Diodes. *ACS Nano* 2015, **9**, 878–885.
- Liu, G.; Zhou, X.; Sun, X.; Chen, S. Performance of Inverted Quantum Dot Light-Emitting Diodes Enhanced by Using Phosphorescent Molecules as Exciton Harvesters. *J. Phys. Chem. C* 2016, **120**, 4667–4672.
- Cao, S.; Zheng, J.; Zhao, J.; Yang, Z.; Li, C.; Guan, X.; Yang, W.; Shang, M.; Wu, T. Enhancing the Performance of Quantum Dot Light-Emitting Diodes Using Room-Temperature-Processed Ga-Doped ZnO Nanoparticles as the Electron Transport Layer. *ACS Appl. Mater. Interfaces* 2017, **9**, 15605–15614.
- Wang, S.; Guo, Y.; Feng, D.; Chen, L.; Fang, Y.; Shen, H.; Du, Z. Bandgap Tunable Zn_{1-x}Mg_xO Thin Films as Electron Transport Layers for High Performance Quantum Dot Light-Emitting Diodes. *J. Mater. Chem. C* 2017, **5**, 4724–4730.

- 6 Pan, J.; Wei, C.; Wang, L.; Zhuang, J.; Huang, Q.; Su, W.; Cui, Z.; Nathan, A.; Lei, W.; Chen, J. Boosting the Efficiency of Inverted Quantum Dot Light-Emitting Diodes by Balancing Charge Densities and Suppressing Exciton Quenching through Band Alignment. *Nanoscale* 2018, **10**, 592–602.
- 7 Triana, M. A.; Chen, H.; Zhang, D.; Camargo, R. J.; Zhai, T.; Duhm, S.; Dong, Y. Bright Inverted Quantum-Dot Light-Emitting Diodes by All-Solution Processing. *J. Mater. Chem. C* 2018, **6**, 7487–7492.
- 8 Hyvonen, J.; Titov, A.; Ying, C. Y.; Holloway, P. H.; Acharya, K. P. 73-2: Invited Paper: High-Performance Quantum Dot Light Emitting Diodes and Their Challenges. *SID Symp. Dig. Tech. Pap.* 2018, **49**, 969–972