Supporting Information

Monolithically Integrating III-Nitride Quantum Structure for Full-Spectrum White LED via Bandgap Engineering Heteroepitaxial Growth

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Comparison of carrier distribution in trichromatic MQWs active region with reverse order

To verify the reasonability of our designed trichromatic MQWs structure, QWs with different indium composition are reversely ordered based on the structure discussed in the manuscript and we compare the carrier distribution in MQWs of these two structures by numerical simulation. Figure S1a shows the energy band diagram. The corresponding electron and hole concentration profiles are presented in Figure S1b and Figure S1c, respectively. For MQWs with reverse order, electrons concentrate not only in the 1st QW, but also in the 8th QW, while holes mainly distribute in the 8th and 9th QWs. With the ununiform carrier distribution, radiative recombination will mainly take place in the 8th and 9th QWs, adverse to balance the trichromatic wavelengths intensity.

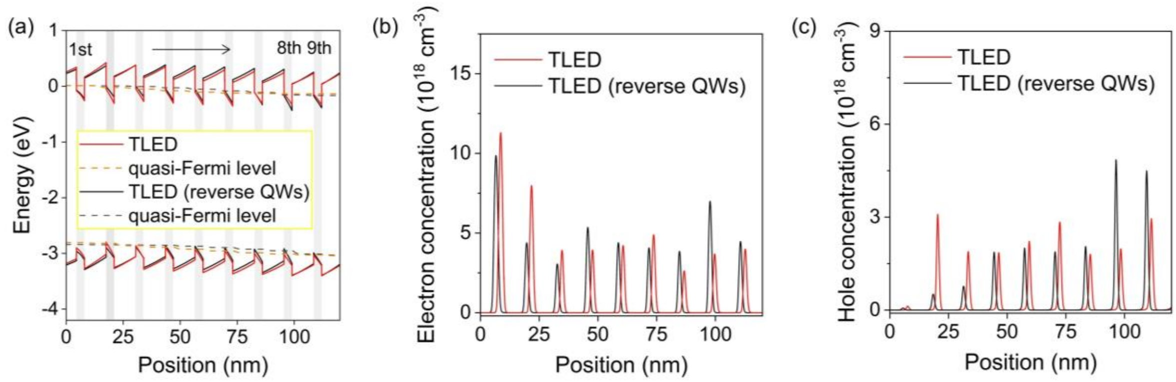

Figure S1. a) Energy band diagram of MQWs with different orders. b) Electron and c) hole concentration profiles of MQWs with different orders.

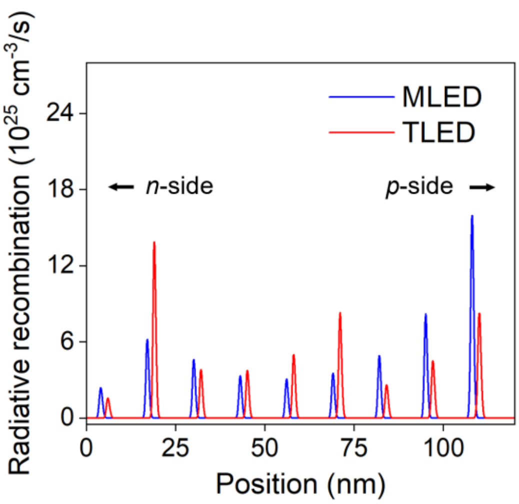

Figure S2. Radiative recombination characteristics in MLED and TLED.

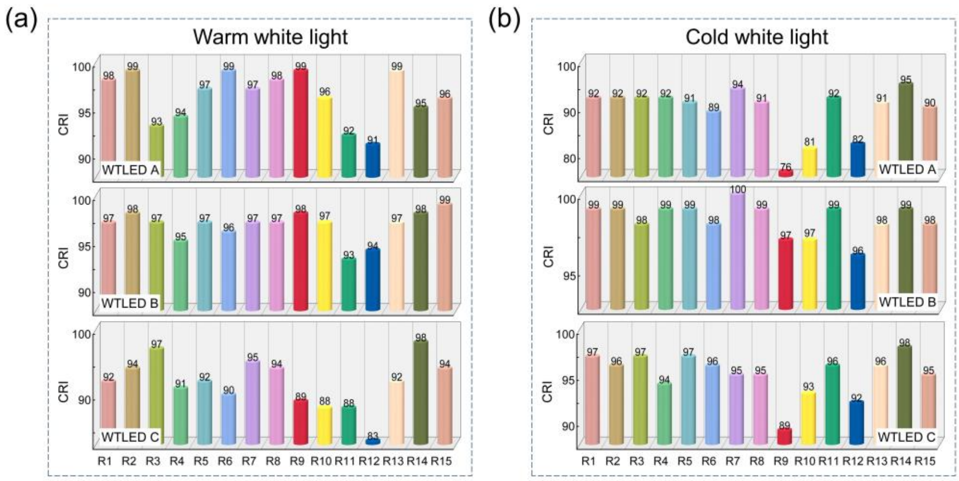

Figure S3. CRI points of the WTLED A, B and C with a) warm and b) cold white light emission.

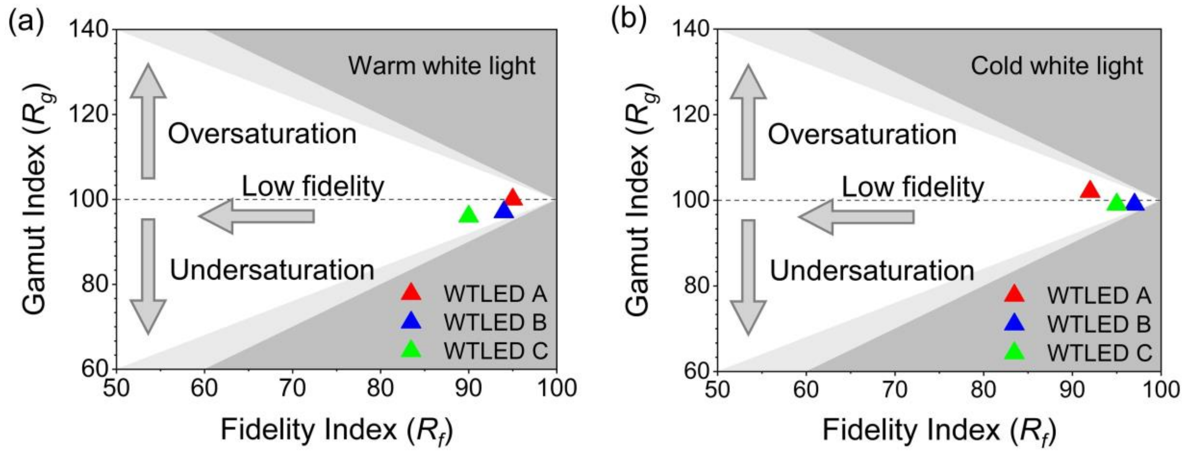

Figure S4. IES TM-30-18 R_f–R_g of the fabricated a) warm and b) cold WTLEDs. Light grey region represents the approximate limits for lighting sources on the Planckian locus, dark grey area represents the approximate limits for practical lighting sources.

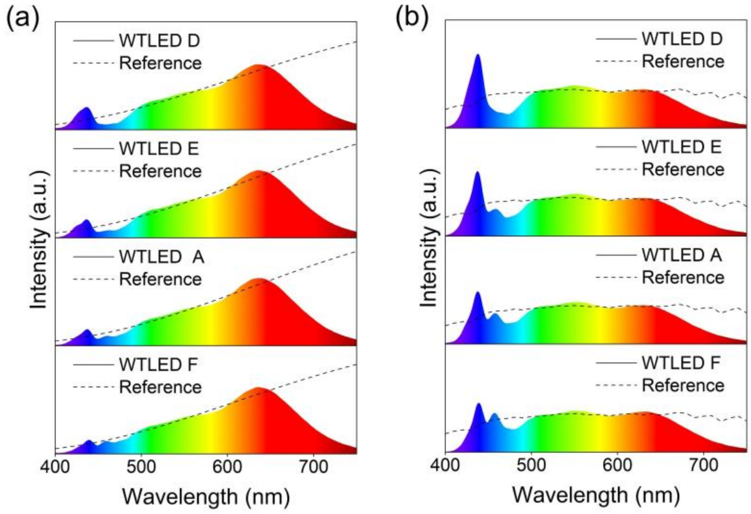

Figure S5. EL spectra of a) warm and b) cold WTLEDs based on excitation source with different intensity ratios.

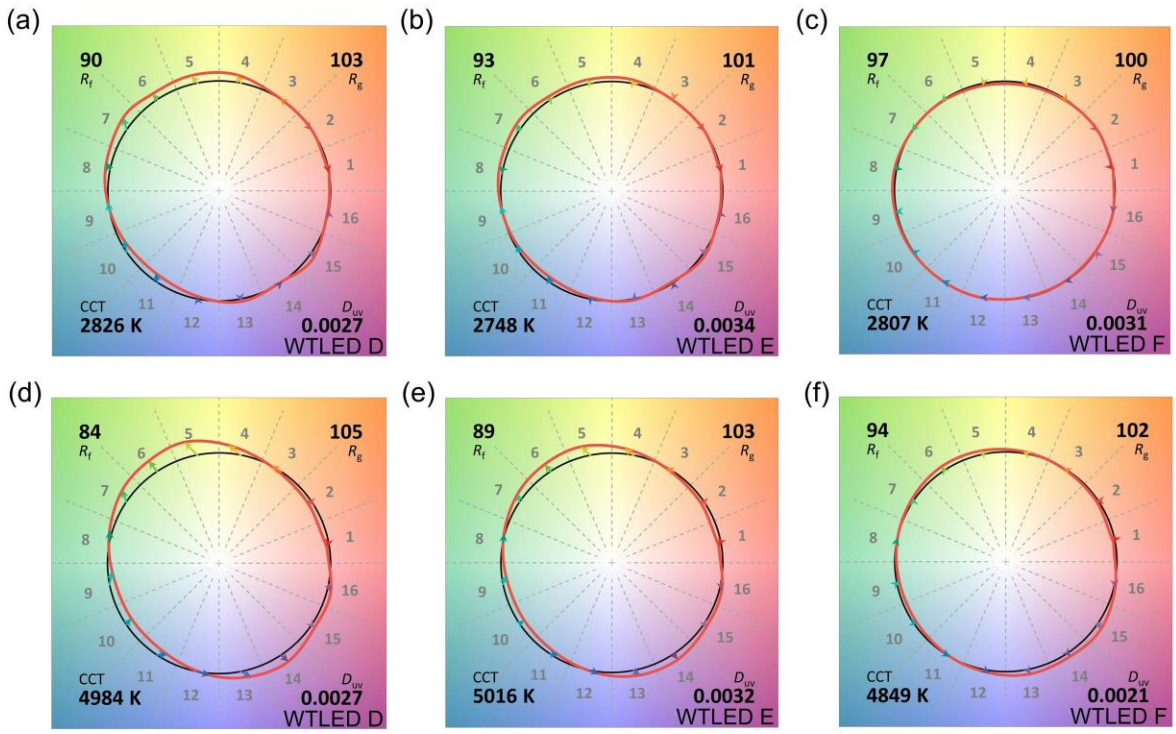

Figure S6. TM-30-18 color vector graphics (CVGs) for a) WTLED D, b) WTLED E and c) WTLED F emitting warm white light, and for d) WTLED D, e) WTLED E and f) WTLED F emitting cold white light.

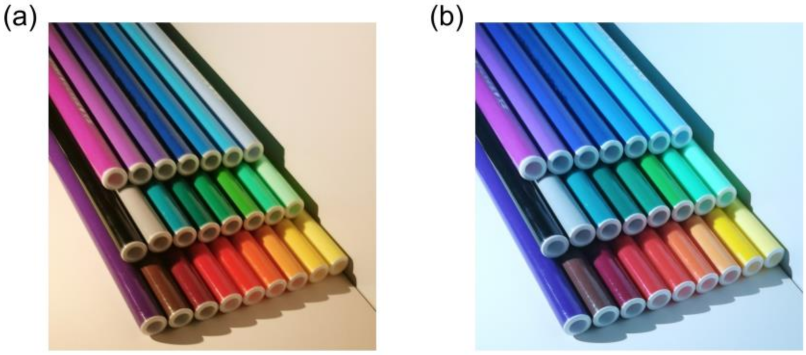

Figure S7. Color pens illuminated under a) warm and b) cold WTLED operating at 60 mA.

Table S1. Characterization of WLEDs Performance

	WMLED	WTLED
Luminous efficacy (lm/W)	132.14	125.6
CCT (K)	2765	2738
CIE (x, y)	(0.4585, 0.4165)	(0.4610, 0.4177)
	WMLED	WTLED
Luminous efficacy (lm/W)	162.84	152.58
CCT (K)	4945	4847
CIE (x, y)	(0.3480, 0.3664)	(0.3509, 0.3668)

Table S2. Characterization of WLEDs Excited by TLED with Different $\Delta\lambda$

	WTLED A	WTLED B	WTLED C
Luminous efficacy (lm/W)	125.60	125.06	120.43
CCT (K)	2713	2917	2748
CIE (x, y)	(0.4542, 0.4163)	(0.4618, 0.4203)	(0.4564, 0.4180)
	WTLED A	WTLED B	WTLED C
Luminous efficacy (lm/W)	152.58	145.26	141.84
CCT (K)	4847	4954	4857
CIE (x, y)	(0.3509, 0.3668)	(0.3474, 0.3630)	(0.3500, 0.3615)

Table S3. Characterization of WLEDs Excited by Trichromatic LED with Varying Intensity Ratios

		WTLED D	WTLED E	WTLED F
Luminous efficacy (lm/W)		126.88	114.72	124.35
CCT (K)		2826	2748	2807
CIE (x, y)		(0.4542, 0.4163)	(0.4618, 0.4203)	(0.4564, 0.4180)
CRI points	R_1	98	98	97
	R_2	97	98	99
	R_3	90	93	95
	R_4	91	93	95
	R_5	96	97	98
	R_6	97	98	99
	R_7	94	96	98
	R_8	95	97	98
	R_9	98	97	100
	R_{10}	92	94	98
	R_{11}	90	91	92
	R_{12}	79	85	98
	R_{13}	100	99	98
	R_{14}	94	95	96

	R_{15}	97	98	99
	R_a	94.8	96.3	97.4
		WTLED D	WTLED E	WTLED F
Luminous efficacy (lm/W)		152.33	152.07	149.68
CCT (K)		4984	5017	4850
CIE (x, y)		(0.3459, 0.3553)	(0.3453, 0.3582)	(0.3500, 0.3597)
CRI points	R_1	92	92	96
	R_2	88	90	94
	R_3	84	88	91
	R_4	84	89	96
	R_5	91	92	96
	R_6	85	88	92
	R_7	84	89	96
	R_8	86	89	97
	R_9	77	77	92
	R_{10}	72	78	86
	R_{11}	89	92	95
	R_{12}	74	81	83
	R_{13}	89	91	95
	R_{14}	91	93	95
	R_{15}	88	90	97
	R_a	86.8	89.6	94.8

Table S4 Comparison of phosphor-converted WLEDs with high CRI reported previously

Method	CRI	R_f–R_g	CCT (K)	Luminous efficacy (lm/W)	Ref.
Blue LED + $CsPb(Br_{0.75}, Cl_{0.25})_3$, $CsPbBr_3$, $CsPb(Br_{0.65}, I_{0.35})_3$, $CsPb(Br_{0.6}, I_{0.4})_3$, $CsPb(Br_{0.5}, I_{0.5})_3$, and $CsPb(Br_{0.35}, I_{0.65})_3$	96	(93.6, 100.8)	2605	43.3	1
Trichromatic LED + LuAG and $CaAlSiN_3$: Eu^{2+}	97.4	(97,100)	2807	124.35	This work
Trichromatic LED + $(SrCa)AlSiN_3$:Eu^{2+}	92	—	2900	100	2
2 Blue LEDs and 1 UV LED + GNYAG3757 and R6634	97.3	(93, 104)	2906	100.12	3
UV LED + $(Ca,Sr)AlSiN_3$:Eu^{2+}, $(Ba,Sr,Ca)_2SiO_4$:Eu^{2+} and $Sr_{3.4}Ba_{1.3}Eu_{0.3}(PO_4)_3Cl$	96	—	2987	49.84	4
Blue LED + $Ca_{1-x}LixAl_{1-x}Si_{1+x}N_3$:$Eu^{2+}$ and LuAG	95	—	3036	101	5
Blue LED + YAG:Ce3 (YAG04, intermax), Cs_2SiF_6:Mn^{4+}	85	—	3205	111	6
UV LED + blue, green CDs and AIZS nanoparticles	90–97	—	3387–8018	—	7

Dichromatic LED + YAG and nitride composition	98.6	—	~3400	4	8
Blue LED + YAG04 and K_2TiF_6:Mn^{4+}	81	—	3556	116	9
Near-UV LED + CGHAO:0.04Ce^{3+}, 0.4Tb^{3+}, BAM:Eu^{2+}, and $CaAlSiN_3$:Eu^{2+}	94.4	—	3575	27.4	10
Blue LED + $CaY_2ZrScAl_3O_{12}$:1%Ce^{3+} and $CaAlSiN_3$:Eu^{2+}	96.9	—	3696	45.04	11
Blue LED + CsPbBr3@SiO_2 QDs and AgInZnS QDs	91	—	3689	40.6	12
Blue LED + LSAS:Ce^{3+} and $CaAlSiN_3$:Eu^{2+}	97.6	—	3718	62.53	13
UV LED + CsPbMnX3@SiO2 and CsPbBr3 QDs	91	—	3857	68.4	14
UV LED + red, green and blue carbon quantum dots	93	—	3875	31.3	15
Blue LED + $(CH_6N_3)_2MnCl_4$:8%Zn^{2+} and YAG:Ce^{3+}	93.7	—	3984	90.41	16
Blue LED + NKLSO:8%Eu^{2+}, YAG:Ce^{3+} and KSF:Mn^{4+}	95.2	—	4021	119.92	17
UV LED + (Sr, Ca)$AlSiN_3$:Eu, $(C_6H_9N_2)_2MnBr_4$ and $BaMgAl_{10}O_{17}$:Eu	97	(94.2, 99.5)	4245	0.18	18
Blue LED + YAG: Ce^{3+} and Ni^{2+} doping $CsPbBr_xI_{3-x}$ nanocrystals	94.9	—	4336	113.2	19
Blue LED + LuAG:Ce^{3+} and (Ca,Sr)$AlSiN_3$:Eu^{2+}	96.6	—	4577	67.46	20
Blue LED + $CsPbBr_3$@α-Al_2O_3, $CsPbBrI_2$@α-Al_2O_3 and YAG: Ce^{3+}	86.9	—	4608	86.58	21
UV LED + $K_3La(Ca)(PO_4)_2$:Eu^{2+} + $CaAlSiN_3$:Eu^{2+}	96.1	—	4853	73	22
Trichromatic LED + LuAG and $CaAlSiN_3$: Eu^{2+}	98.9	(97, 99)	4954	145.26	This work
UV LED + $CaAlSiN_3$:Eu^{2+} and $Cs_3Cu_2Cl_5$@SiO_x nanocrystals	94	—	5049	—	15
UV LED + CGO:0.02Bi^{3+},0.07Zn^{2+}, $CaAlSiN_3$:Eu^{2+}, β-SiAlON:Eu^{2+} and BAM:Eu^{2+}	97.4	—	5125	69.72	23
4 Blue LEDs + phosphor-in-glass (including $Y_3Al_{3.08}Ga1_{.92}O_{12}$:$Ce^{3+}$ CaAlSiN3:Eu^{2+})	95.4	(91, 102)	5260	65	24
Blue LED + $(C_5H_6N)_2MnBr_4$ and $C_5H_6NMnCl_3$	91	—	5331	—	25
UV LED chip + theobromine dye SBS composite	90	(90, 104)	5383	—	26
Blue LED + GAL535 and K_2TiF_6:Mn^{4+}	95	—	5954	115	9

Dichromatic LED + YAG: Ce^{3+}	91	—	6500	58.3	27
NUV LED + $CsPbBr_3$, $CsPbBr_3$:7%SCN^-, and PEA_2PbBr_4/PEA_2PbBr_4:Mn^{2+}	96	—	9376	—	28

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