Electronic Supporting Information

A high thermal stability Cr³⁺-doped gallate far red phosphor for plant lighting: structure, luminescence enhancement and application prospect

Cheng Zhou,†[a,b] Lu Peng,†[a,b] Zihui Kong,[a,b] Meihan Wu,[a] Maxim S. Molokeev,[a,d] Jing Wang *,[a,b,c] and Mao Xia*,[a,b]

a.School of Chemistry and Materials Science, Hunan Agricultural University, Changsha 410128, PR China. E-mail: xiamao2019@hunau.edu.cn.

b.Hunan Optical Agriculture Engineering Technology Research Center, Changsha 410128, PR China.

c.State Key Laboratory of Optoelectronic Materials and Technologies, School of Chemistry, Sun Yat-Sen University, Guangzhou 510275, PR China. E-mail: ceswj@mail.sysu.edu.cn.

d.Siberian Federal University, Krasnoyarsk, 660041, Russia.

*Corresponding authors:

Prof. Jing Wang

E-mail: ceswj@mail.sysu.edu.cn

Prof. Mao Xia

E-mail: xiamao2019@hunau.edu.cn

†These authors contributed equally to this work.

Table S1. The morphological indicators of tomato plants

Field planting		1-1	1-2	1-3	1-4	1-5	Average (cm-1)
CK	Plant height	13.30	8.80	8.20	6.30	12.90	9.90
	Stem thickness	0.60	0.62	0.68	0.52	0.75	0.64
	Leaf length	3.80	3.10	4.20	2.90	4.80	3.76
	Leaf width	2.30	2.60	2.10	2.00	3.60	2.52
T_1	Plant height	10.00	7.40	6.10	8.30	7.20	7.80
	Stem thickness	0.59	0.58	0.61	0.47	0.56	0.56
	Leaf length	3.90	4.70	3.20	3.80	3.10	3.74
	Leaf width	3.20	2.50	2.90	2.70	2.80	2.82
Mature							
CK	Plant height	59.70	32.20	43.30	35.30	29.60	40.02
	Stem thickness	0.77	0.76	0.82	0.78	0.89	0.80
	Leaf length	5.60	4.70	6.00	4.30	5.20	5.16
	Leaf width	3.80	3.20	3.90	3.00	3.30	3.44
T_1	Plant height	16.60	24.30	29.10	23.90	37.20	26.22
	Stem thickness	0.70	0.48	0.60	0.59	0.65	0.60
	Leaf length	4.20	3.90	4.70	5.00	5.50	4.66
	Leaf width	3.60	3.20	4.00	3.20	2.50	3.30

Table S2. The leaf pigments and fruit quality of tomato plants

| Mature	Chl a (mg/g)	Chl b (mg/g)	Carotenoids (mg/g)	Lycopene (μg/g)	Soluble sugar（%）
CK	3.07	0.95	0.65	0.19	115.83
	3.02	0.93	0.64	0.12	90.77
	3.09	0.94	0.64	0.24	113.28
Average	3.06	0.94	0.64	0.18	106.63
T_1	1.43	0.47	0.32	0.40	196.54
	1.13	0.38	0.26	0.41	102.71
	1.34	0.44	0.31	0.39	106.64
Average	1.30	0.43	0.30	0.40	135.30
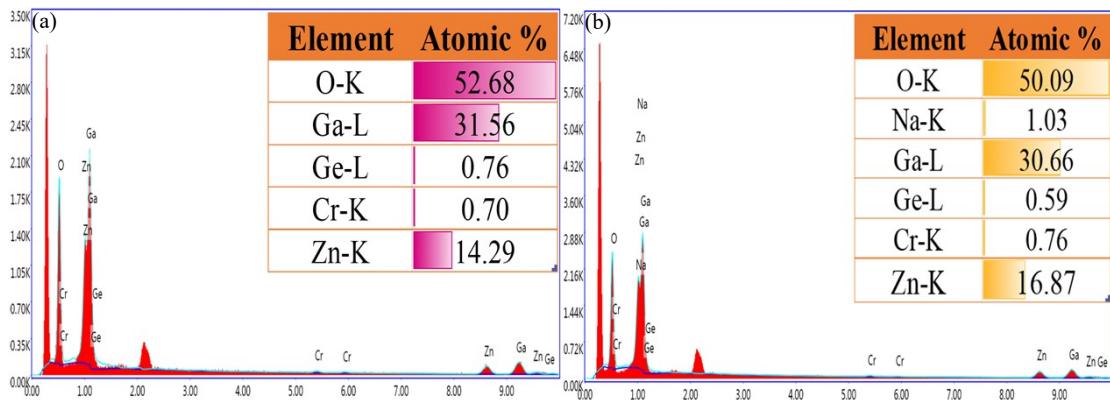
Fig.S1. EDS spectra of ZGO:0.02Cr³⁺,0.03Ge⁴⁺,0.11Li⁺ and ZGO:0.02Cr³⁺,0.03Ge⁴⁺,0.03Na⁺, the inset shows the proportion of the elements.
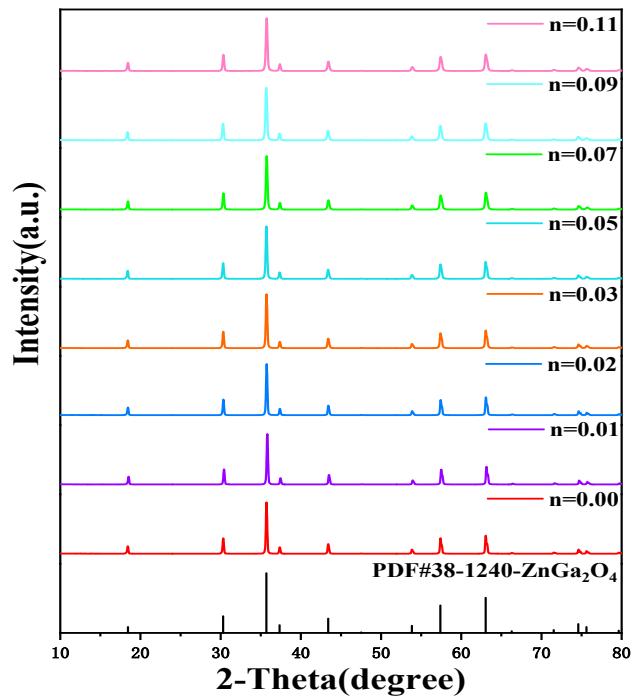
Fig.S2. XRD pattern of excess Na$^+$ doped ZGO:0.02Cr^{3+},0.03Ge^{4+},nNa$^+$.
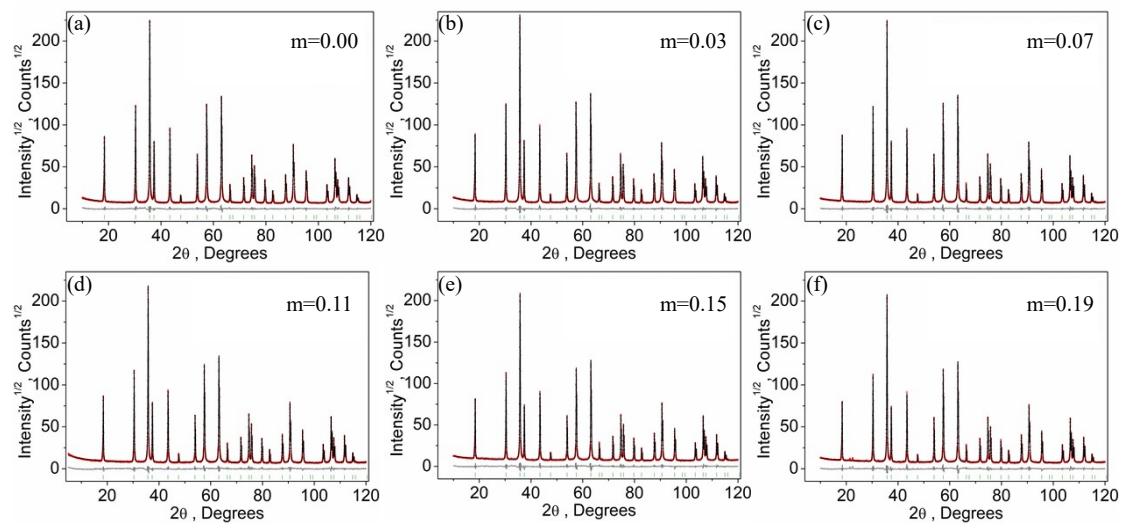
Fig.S3. a-f: Rietveld refinement of ZGO:0.02Cr^{3+},0.03Ge^{4+},mLi^{+}.
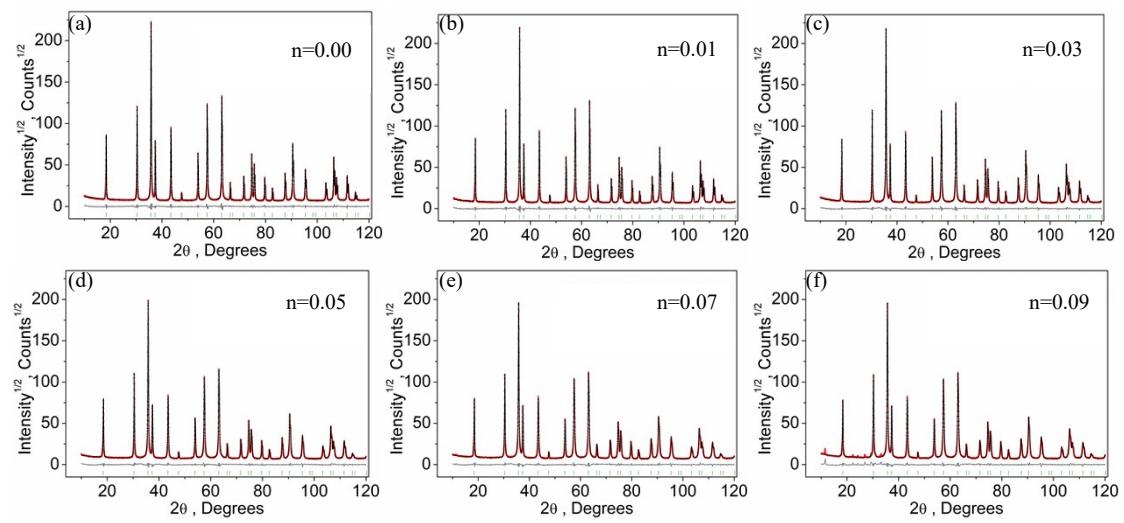
Fig.S4. a-f: Rietveld refinement of ZGO:0.02Cr^{3+},0.03Ge^{4+},nNa^{+}.

Table S3. Main parameters of processing and refinement of the ZGO:0.02Cr^{3+},0.03Ge^{4+},mLi$^+$ and ZGO:0.02Cr^{3+},0.03Ge^{4+},nNa$^+$ samples

m, n	Dopant	Space Group	Cell parameters (Å), Cell Volume (Å^3)	R_{wp}, R_p, R_B (%), χ^2
m=0	Li	*Fd*-3*m*	*a* = 8.33458 (4), *V* = 578.864 (8)	5.66, 3.87, 1.04, 1.14
m=0.03	Li	*Fd*-3*m*	*a* = 8.33178 (8), *V* = 578.379 (16)	6.16, 4.41, 1.56, 1.25
m=0.07	Li	*Fd*-3*m*	*a* = 8.32911 (4), *V* = 577.525 (8)	6.57, 4.74, 1.26, 1.30
m=0.11	Li	*Fd*-3*m*	*a* = 8.32628 (3), *V* = 577.235 (7)	6.60, 4.71, 1.18, 1.25
m=0.15	Li	*Fd*-3*m*	*a* = 8.32317 (4), *V* = 576.589 (9)	7.21, 5.42, 2.07, 1.34
m=0.19	Li	*Fd*-3*m*	*a* = 8.32036 (11), *V* = 576.00 (2)	7.63, 5.72, 2.45, 1.43
n=0	Na	*Fd*-3*m*	*a* = 8.33320 (8), *V* = 578.675 (17)	5.47, 3.84, 0.96, 1.09
n=0.01	Na	*Fd*-3*m*	*a* = 8.33301 (6), *V* = 578.636 (12)	5.52, 3.84, 0.94, 1.09
n=0.03	Na	*Fd*-3*m*	*a* = 8.33347 (4), *V* = 578.733 (8)	5.09, 3.54, 1.04, 1.03
n=0.05	Na	*Fd*-3*m*	*a* = 8.33445 (6), *V* = 578.935 (12)	5.15, 3.68, 0.99, 1.01
n=0.07	Na	*Fd*-3*m*	*a* = 8.33564 (16), *V* = 579.19 (3)	5.18, 3.62, 0.96, 1.03
n=0.09	Na	*Fd*-3*m*	*a* = 8.33692 (8), *V* = 579.451 (17)	6.60, 4.17, 1.17, 1.33

Crystal field and nephelauxetic effect

The crystal field and nephelauxetic effect are calculated by below formula. Three relevant parameters are evaluated: the crystal field parameter (Dq), the Racah parameters (B) and (C). According to the PLE and PL spectrum data, the values of Dq, B and C can be calculated by the following equations [1,2]:

$$Dq = \frac{E(^4T_2 - {}^4A_2)}{10} \tag{1}$$

$$\frac{Dq}{B} = \frac{15(x-8)}{(x^2 - 10x)} \tag{2}$$

$$x = \frac{E\left(^4A_2 - {}^4T_1\right) - E\left(^4A_2 - {}^4T_2\right)}{Dq} \tag{3}$$

$$\frac{E\left(^2E_g - {}^4A_2\right)}{B} = \frac{3.05C}{B} + 7.9 - \frac{1.8B}{Dq} \tag{4}$$

the β_1 nephelauxetic effect to comprehensively consider, the formula is as follow:

$$\beta_1 = \sqrt{\left(\frac{B}{B_0}\right)^2 + \left(\frac{C}{C_0}\right)^2} \tag{5}$$

where B_0 and C_0 are the Racah parameters for free ions, and the values of them are B_0=995cm^{-1} and C_0=3637cm^{-1} for Cr^{3+}, respectively [3,4].

Table S4. The calculated of crystal field strength and Racah parameters *B, C* and *β1*

Samples	$E(^4T_1)$ (cm^{-1})	$E(^4T_2)$ (cm^{-1})	$E(^2E)$ (cm^{-1})	*Dq*	*B*	*C*	*X*	*Dq/B*	*β₁*
ZGO:Cr^{3+}	24264	18235	14065	1824	573	3233	3.31	3.18	1.06
ZGO:Cr^{3+},0.03Ge^{4+}, 0.03Li$^+$	24332	18257	14061	1826	578	3220	3.33	3.16	1.06
ZGO:Cr^{3+},0.03Ge^{4+}, 0.03Na$^+$	24305	18298	14065	1830	570	3239	3.28	3.21	1.06
ZGO:Cr^{3+},0.03Ge^{4+}, 0.11Li$^+$	24290	18224	14053	1822	578	3220	3.33	3.16	1.06
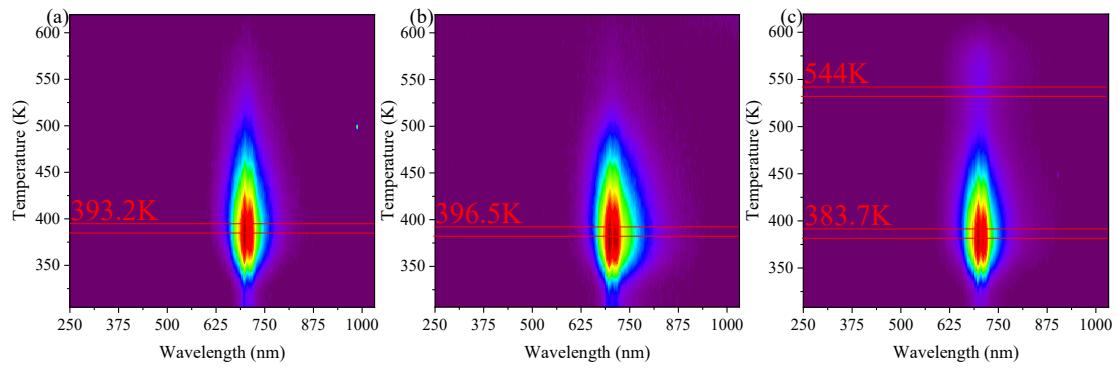
Fig.S5. a-c Wavelength-resolved TL spectra of ZGO:0.02Cr^{3+}, ZGO:0.02Cr^{3+},0.03Ge^{4+},0.03Li^{+}, ZGO:0.02Cr^{3+},0.03Ge^{4+},0.03Na^{+} charged for 1 min.

Notes and references

1 S.M. Gu, M. Xia and Z. Zhou, *Chem. Eng. J.*, 2020, 396, 125208-125216.
2 S.J. Gai, H.F. Zhu and M. Xia, *Ceram. Int.*, 2020, 46, 20173-20182.
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4 Uylings P.H.M., Raassen A.J.J. and Wyart J.F., *J Phys B: At Mol Phys* 1984, 17, 4103-4126.