Graphene Oxide-Enhanced Mixed-Structure Quasi-2D Perovskites for Stable Low-Threshold Amplified Spontaneous Emission

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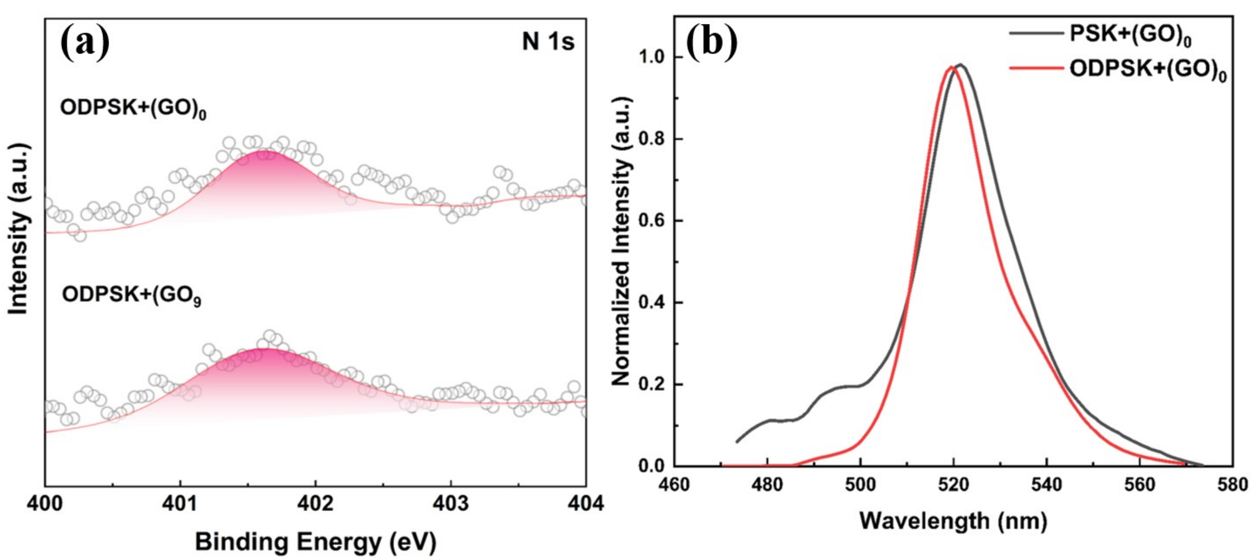

Figure S1. a) XPS spectra of N 1s in ODPSK+$(GO)_0$, and ODPSK+$(GO)_9$. b) PL spectra of PSK+$(GO)_0$ and ODPSK+$(GO)_0$ showing a blue shift.

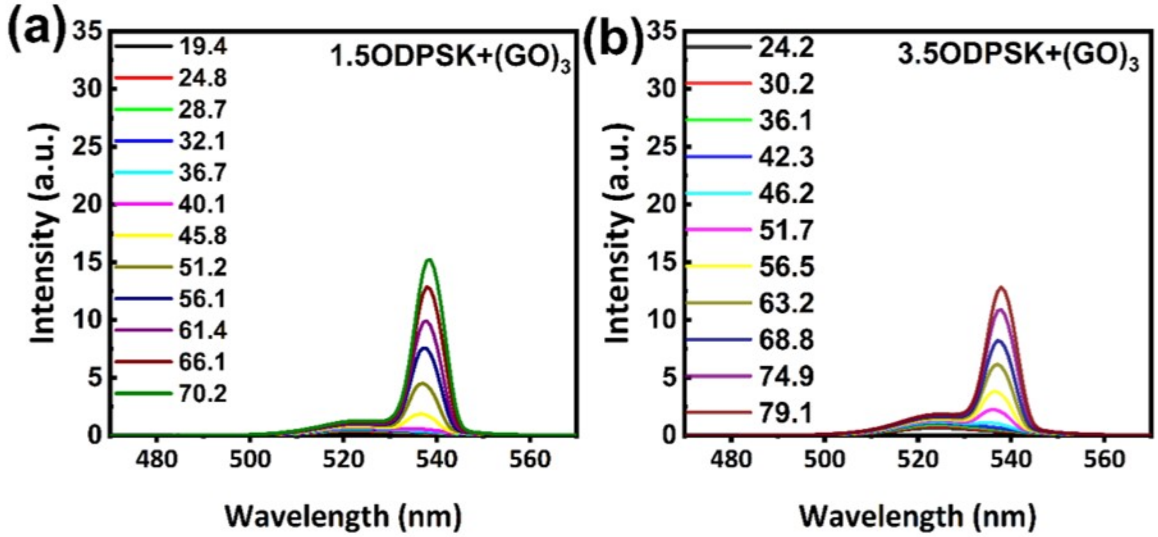

Figure S2. ASE characterizations of the perovskite films. a-b) Excitation fluence-dependent PL spectra of 1.5ODPSK+$(GO)_3$, and 3.5ODPSK+$(GO)_3$ quasi-2D perovskite films.

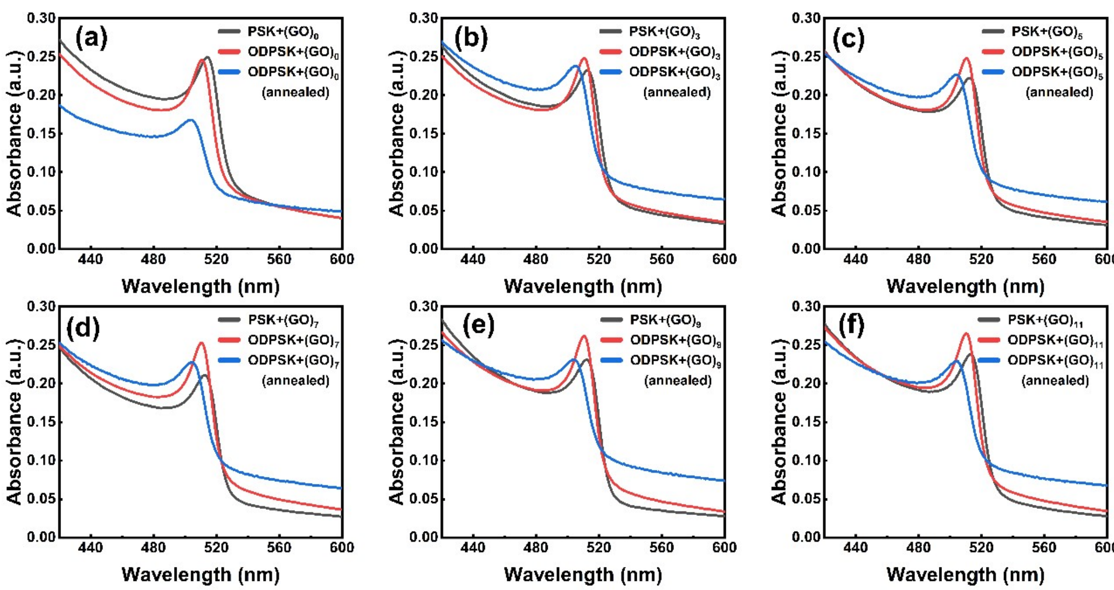

Figure S3. a-f) Absorption spectra of the pure PSK+$(GO)_0$, ODPSK+$(GO)_0$ (without annealing and annealed at 130 ^oC for 24 hours), and GO-treated perovskite films PSK+$(GO)_x$, ODPSK+$(GO)_x$ films (without annealing and annealed at 130 ^oC for 24 hours).

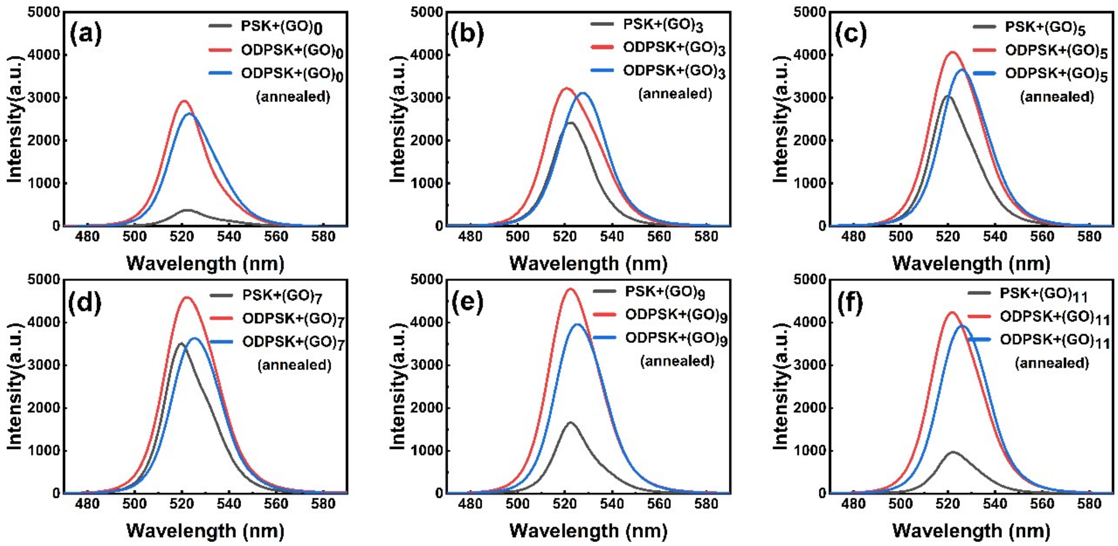

Figure S4. a-f) PL spectra of the pure PSK+$(GO)_0$, ODPSK+$(GO)_0$ (without annealing and annealed at 130 ^oC for 24 hours), and GO-treated perovskite films PSK+$(GO)_x$, ODPSK+$(GO)_x$ films (without annealing and annealed at 130 ^oC for 24 hours).

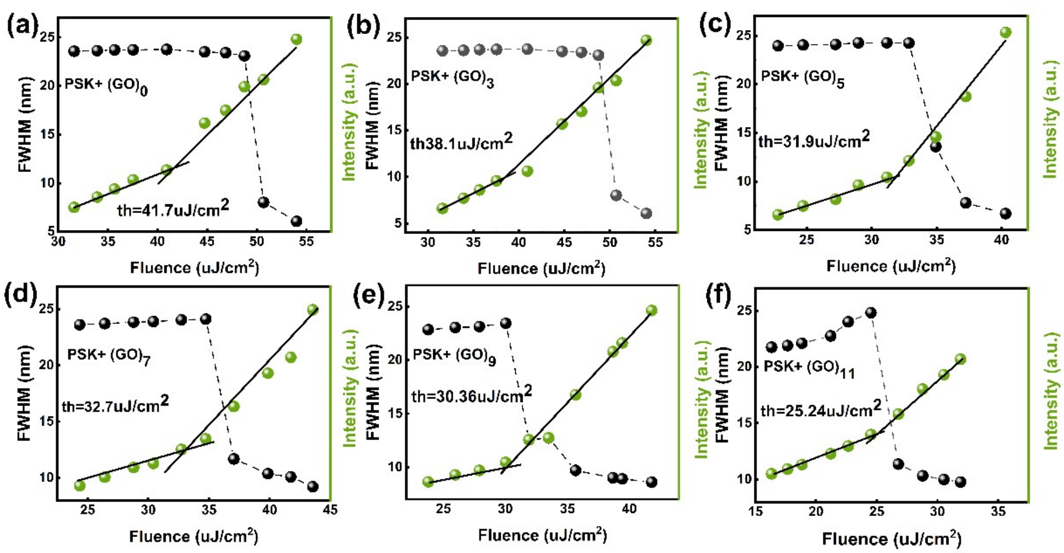

Figure S5. a-f) The FWHM and ASE intensity versus excitation fluence of the PSK+$(GO)_0$, PSK+$(GO)_3$, PSK+$(GO)_5$, PSK+$(GO)_7$, PSK+$(GO)_9$, and PSK+$(GO)_{11}$ thin films after annealing at 130 ^oC for 24 hours under a nitrogen atmosphere. (Fitted with the formula ($y = ax + b$)).

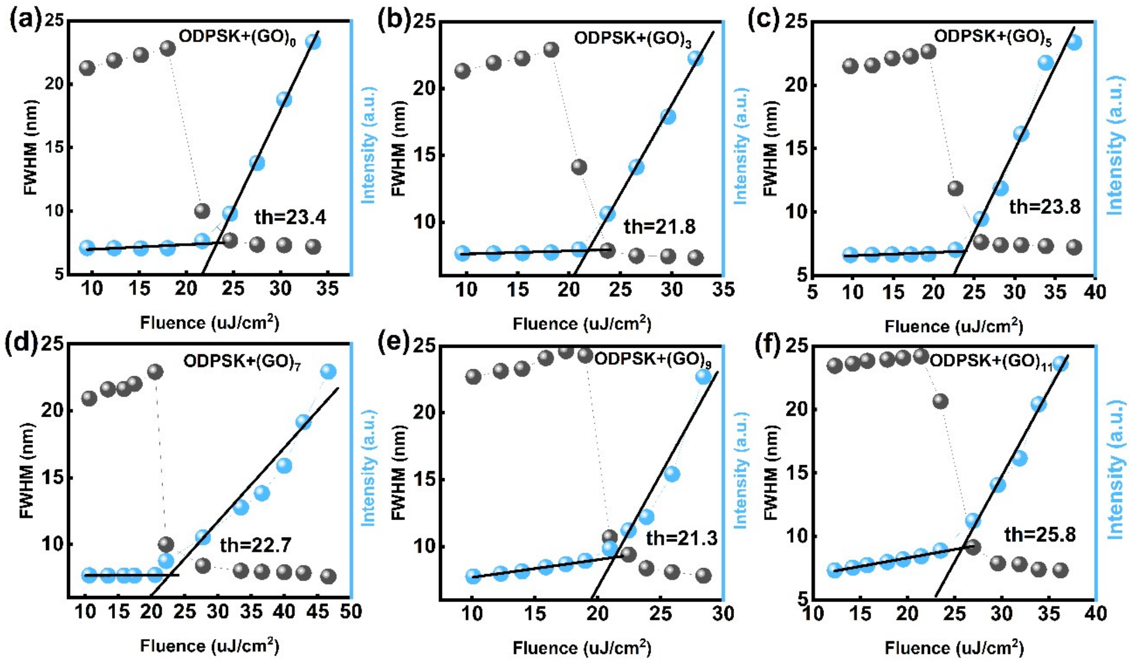

Figure S6. a-f) The FWHM and ASE intensity versus excitation fluence of the ODPSK+$(GO)_0$, ODPSK+$(GO)_3$, ODPSK+$(GO)_5$, ODPSK+$(GO)_7$, ODPSK+$(GO)_9$, and ODPSK+$(GO)_{11}$ thin films after annealing at 130 ^oC for 24 hours under nitrogen atmosphere. (Fitted with the formula (y = ax + b)).

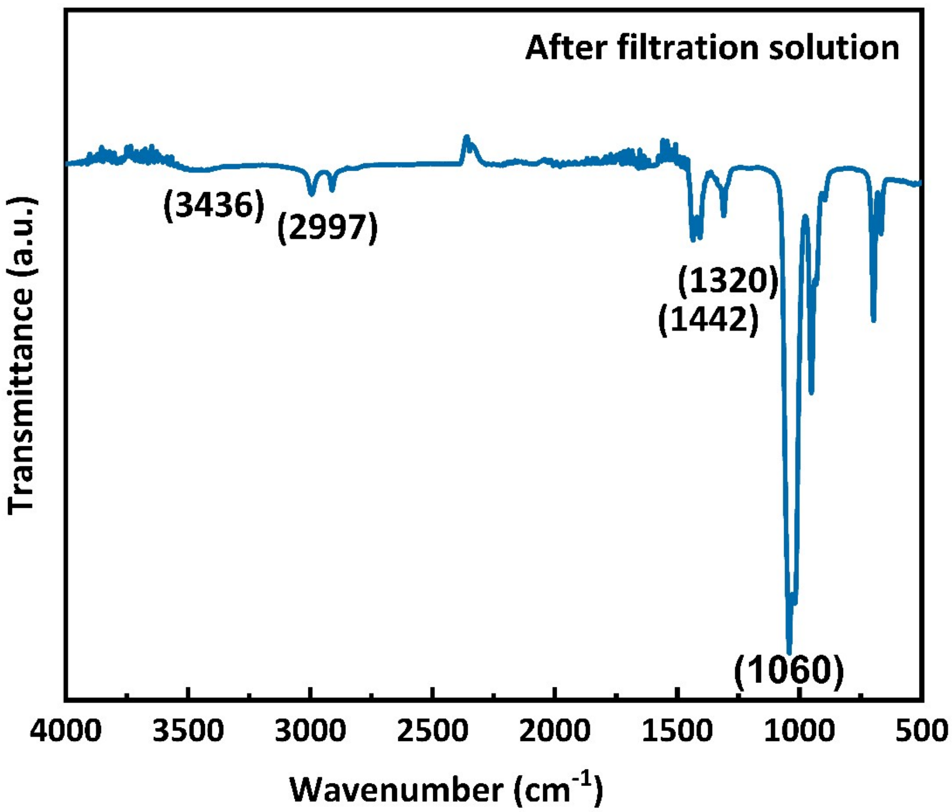

Figure S7. FTIR spectra of ODPSK+$(GO)_{11}$ solution after filtration.

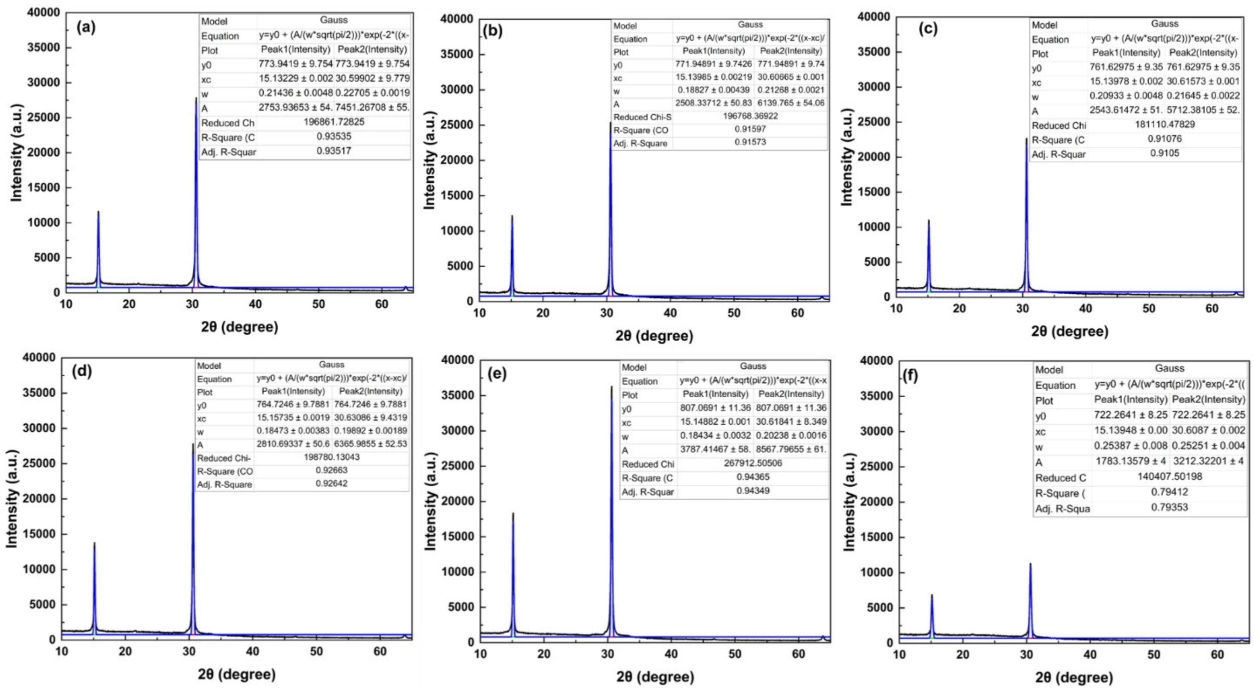

Figure S8. XRD patterns of ODPSK+$(GO)_0$, ODPSK+$(GO)_3$, ODPSK+$(GO)_5$, ODPSK+$(GO)_7$, ODPSK+$(GO)_9$, and ODPSK+$(GO)_{11}$ films showing the FWHM variations along with the fitting formula without annealing.

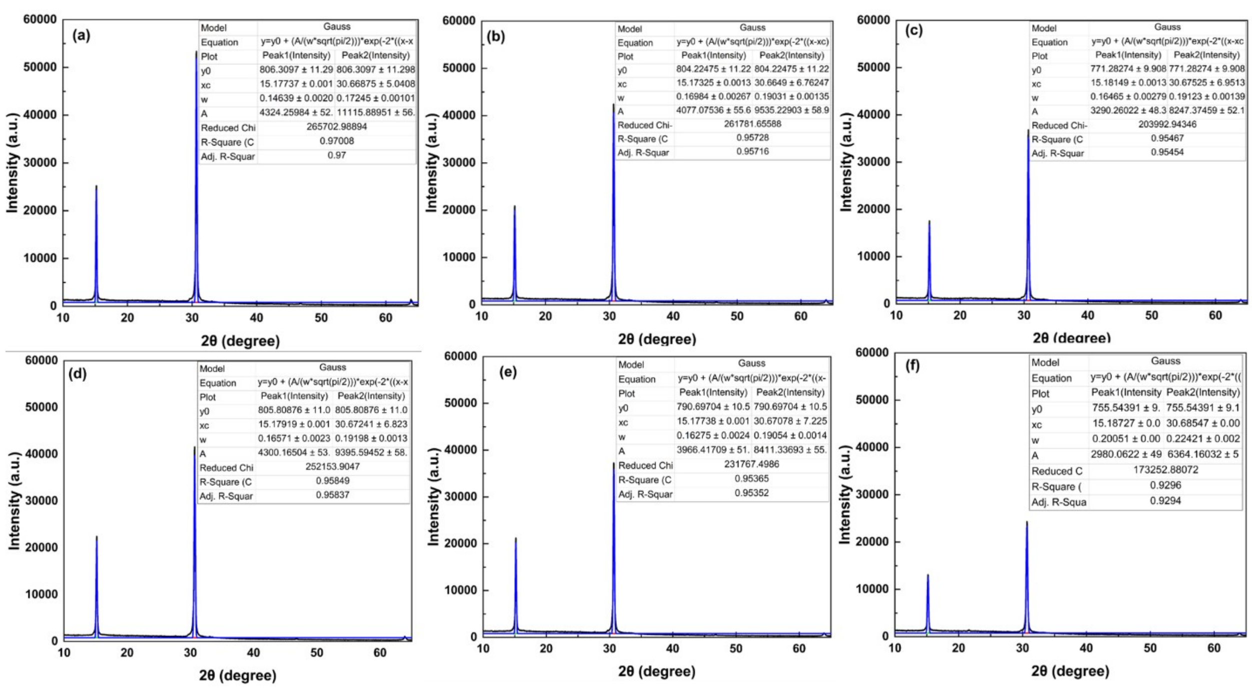

Figure S9. XRD patterns of ODPSK+$(GO)_0$, ODPSK+$(GO)_3$, ODPSK+$(GO)_5$, ODPSK+$(GO)_7$, ODPSK+$(GO)_9$, and ODPSK+$(GO)_{11}$ films showing the FWHM variations along with the fitting formula after annealing at 130 ^oC for 24 hours under nitrogen atmosphere.

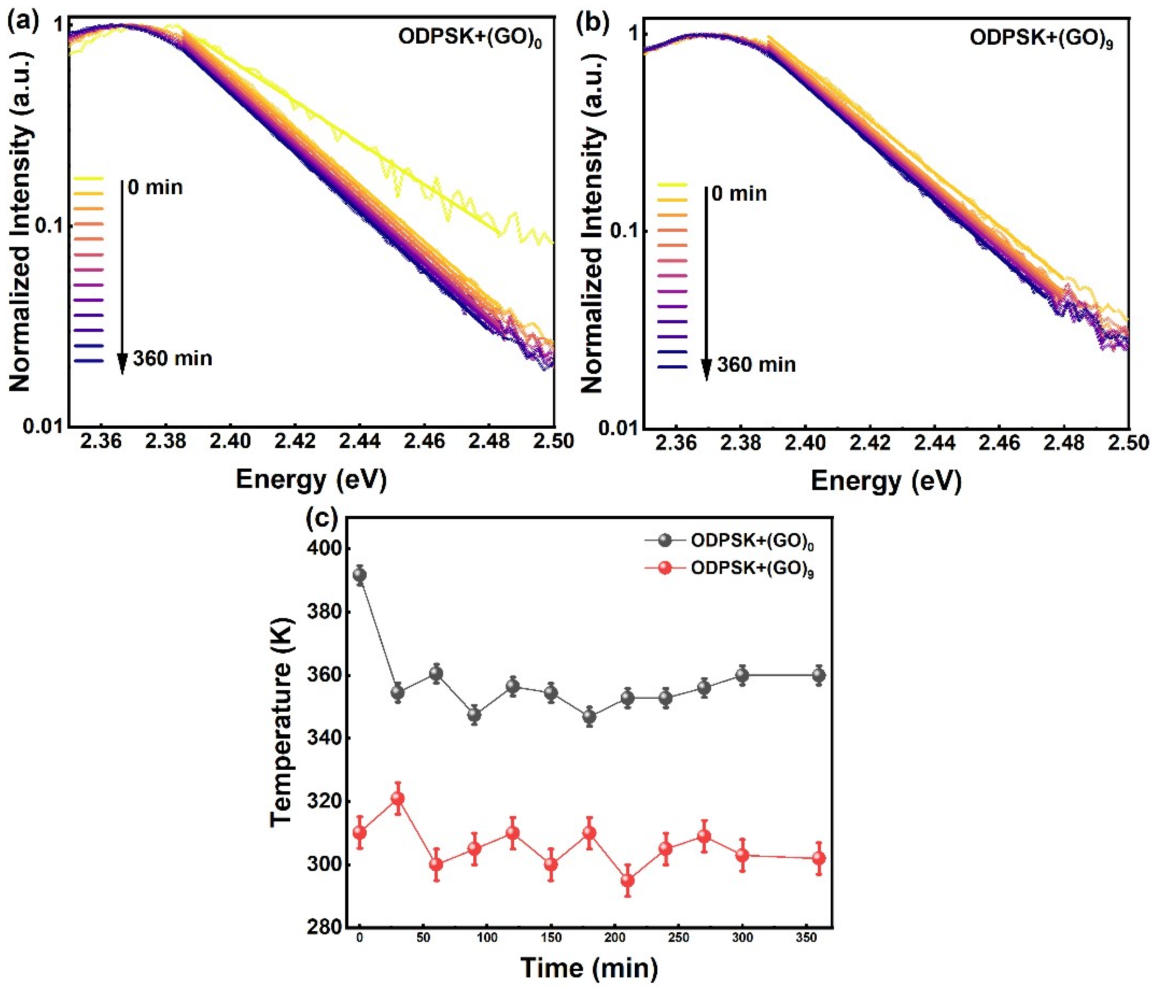

Figure S10. a-b) The normalized PL spectra of the ODPSK+$(GO)_0$ and ODPSK+$(GO)_9$ films during the CW irradiation, and c) The plasma temperature varies with irradiation time of 6 hours. These temperatures are determined by fitting the high-energy tail of photoluminescence spectra to an exponential function, I = A$e^{-\ E/kb\mathrm{T}}$, which reflects a Boltzmann thermal distribution, where E, I energy of the photon, and the intensity of the PL spectra, k_b is the Boltzmann constant, and T represents the plasma temperature.

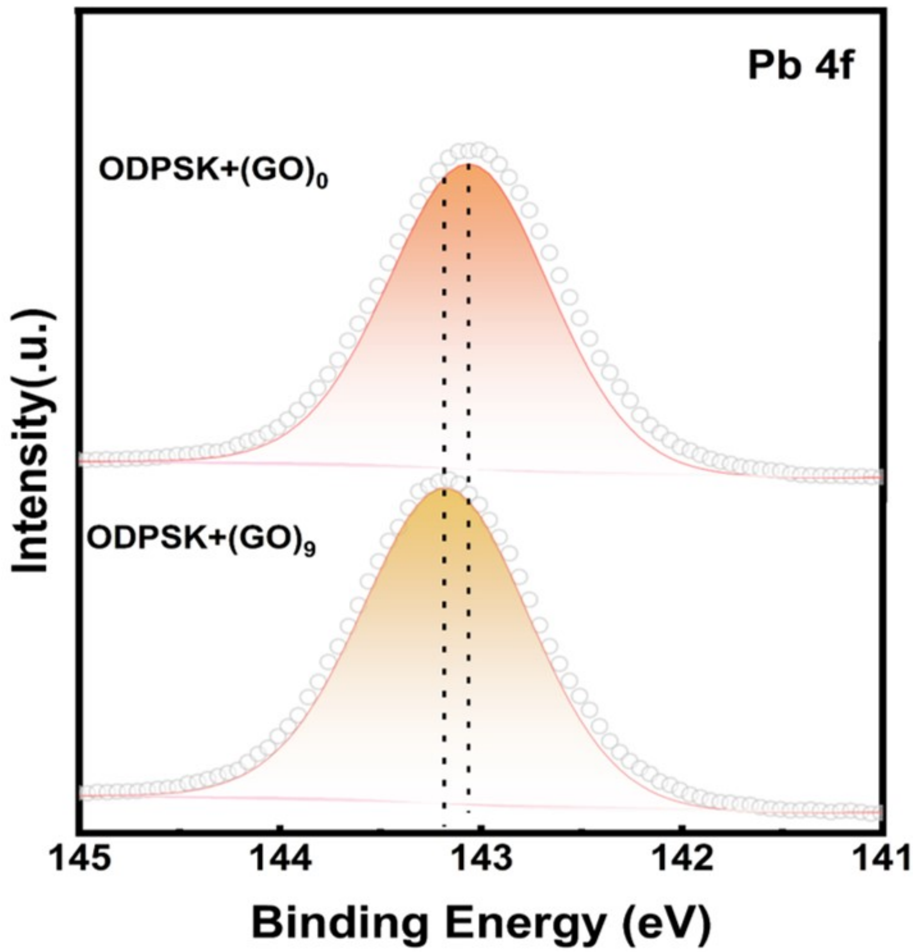

Figure S11. XPS spectra of Pb 4f in ODPSK+$(GO)_0$, and ODPSK+$(GO)_9$.

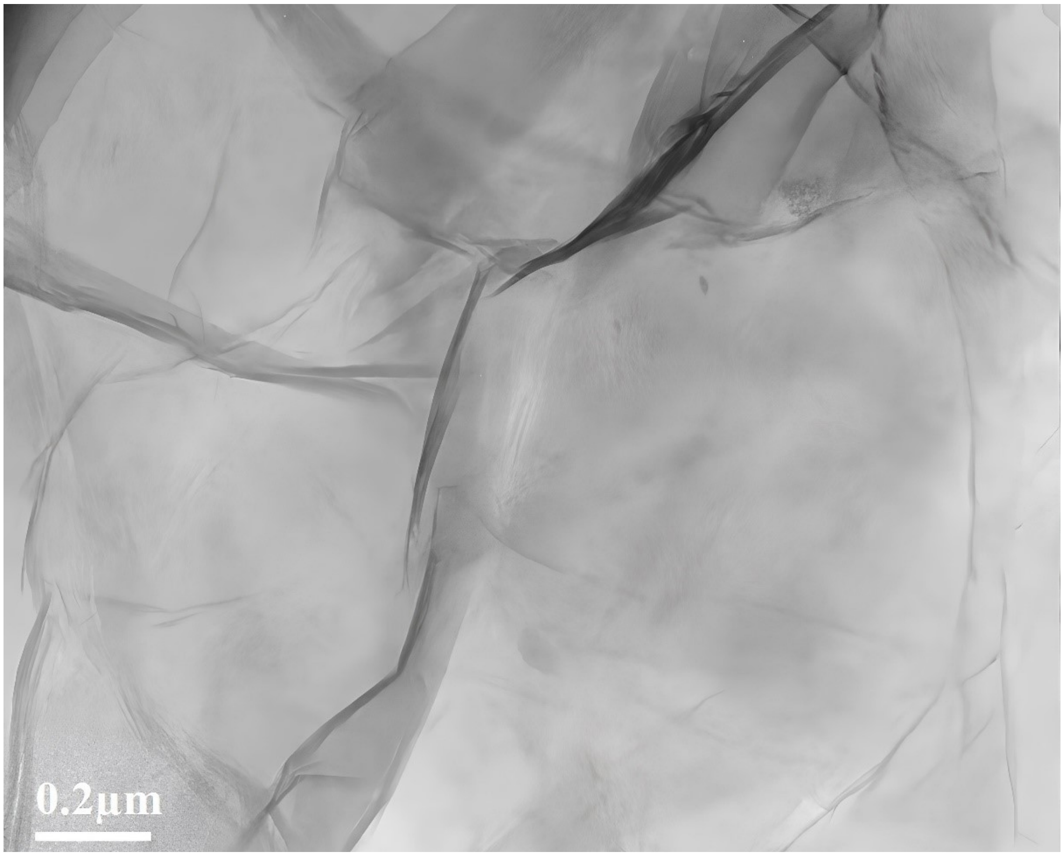

Figure S12. HR-TEM image shows sheet-like morphology of GO.

Table S1. Comparison of FWHM and threshold values of different types of films after annealing at 130 ^{o}C for 24 hours.

Film Type	FWHM after Annealing PSK+$(GO)_x$	FWHM after Annealing ODPSK+$(GO)_x$	Threshold values after Annealing PSK+$(GO)_x$	Threshold values after Annealing ODPSK+$(GO)_x$
$CsPbBr_3$	11 nm	7.2 nm	41.7	21.3
$CsPbBr_3$+0.3 wt% (GO)	9.3 nm	7.3 nm	38.1	21.1
$CsPbBr_3$+0.5 wt% (GO)	8.7 nm	7.2 nm	31.9	23.1
$CsPbBr_3$+0.7 wt% (GO)	8.1 nm	7.6 nm	32.1	22.5
$CsPbBr_3$+0.9 wt% (GO)	8.1 nm	7.8 nm	30.4	20.7
$CsPbBr_3$+1.1 wt% (GO)	7.2 nm	7.3 nm	25.2	25.4

Table S2. The average longitudinal crystal sizes of the ODPSK+$(GO)_0$ film and the ODPSK+$(GO)_x$ films before and after annealing at 130 ^{o}C for 24 hours.

Film Type	Before Annealing	Annealed at 130 ^{o}C after 24 hours
ODPSK+$(GO)_0$	35.3 nm	47.9 nm
ODPSK+$(GO)_3$	39.1 nm	42.2 nm
ODPSK+$(GO)_5$	36.5 nm	43.1 nm
ODPSK+$(GO)_7$	40.6 nm	42.3 nm
ODPSK+$(GO)_9$	41.7 nm	43.8 nm
ODPSK+$(GO)_{11}$	32.1 nm	36.9 nm

Table S3. Comparison of reported thermal stability results of ASE films

Study	Condition	RH (%)	Atmosphere	Phase+ PL shift+ Degradation)	Ref.
ODPSK+$(GO)_0$	130	50	Air	Stable Phase + No shift + Significant degradation (95%) observed	**This work**
ODPSK+$(GO)_7$	130	50	Air	Stable Phase + No shift + Significant improvement in stability with (27%) degradation.	**This work**
CPB-CN film	60	60	Air	split peaks observed with structure transformation + shift toward yellow+ (97%) degradation	(Huang et al., 2017)
$MAPbBr_3$	60-180	NA	PMMA CB solution coating protection	The intensity of the diffraction peaks slightly increases between (60-90 °C), then decreases at 180 ^{o}C, indicating the decomposition + No Shift +NA	(Cao et al., 2023)
MAPbI3	150	NA		Stable Phase + No shift + %50 degradation of PCE	(You et al., 2020)

References

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