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Supplementary Materials

Evolved photovoltaic performance of $MAPbI_3$ and $FAPbI_3$-based perovskite solar cells in low-temperatures

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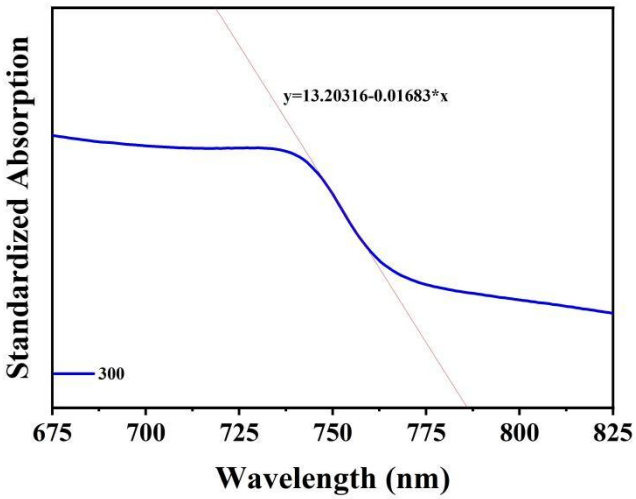
1 The calculation of bandgap

By drawing a tangent at the point where the absorption rate curve decreases most steeply and calculating its intersection with the x-axis, we can obtain an approximate band gap of the sample.

We illustrate the method for calculating the bandgap using the absorption curve obtained from UV-vis spectroscopy of $MAPbI_3$ thin film samples at a temperature condition of 300 K as an example. We draw a tangent line at the stage where the absorption curve significantly declines and use its equation to calculate the intersection with the x-axis. The x-coordinate of the intersection, which is the edge of the maximum absorption band, converted into electronic energy, represents the bandgap of the sample film under the current temperature conditions. Using the expression in the graph, we can determine that the absorption band edge at this temperature is 784.5 nm. Thus, we can calculate the bandgap by

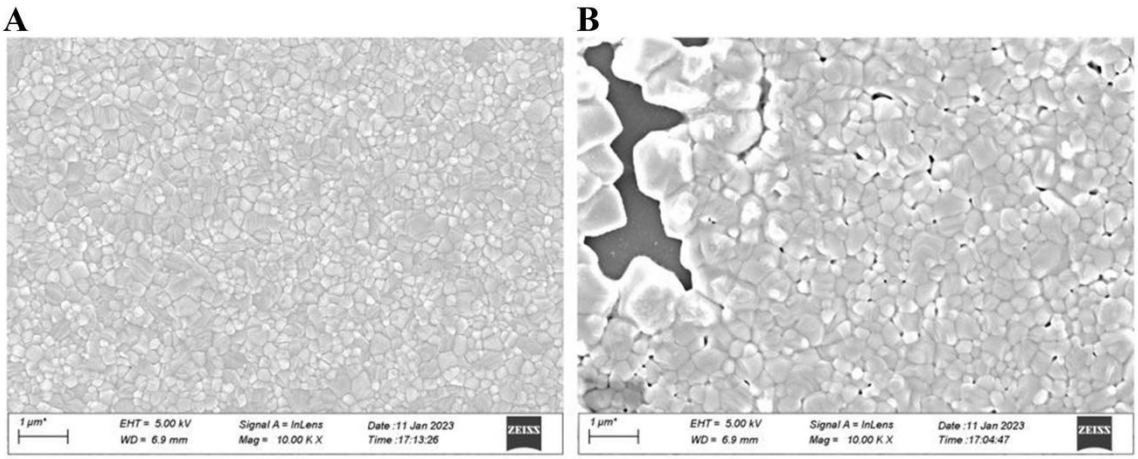
$$Eg = \frac{1240}{784.5}\ eV = 1.58\ eV$$

Using a similar method, we can obtain the bandgap information for $FAPbI_3$ and $MAPbI_3$ thin films under different temperature conditions.



Supplementary Figure 1. The tangent line at the stage where the absorption curve significantly declines of $MAPbI_3$ in 300 K.

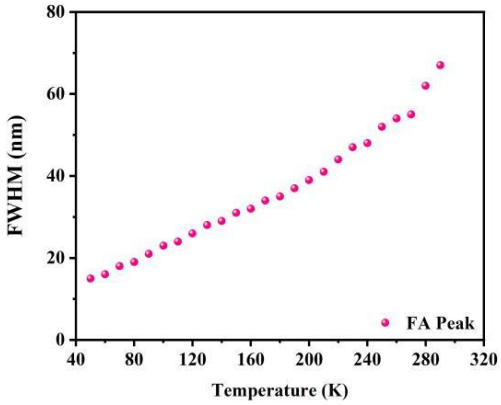
2 The morphology of $MAPbI_3$ before and after cooling process



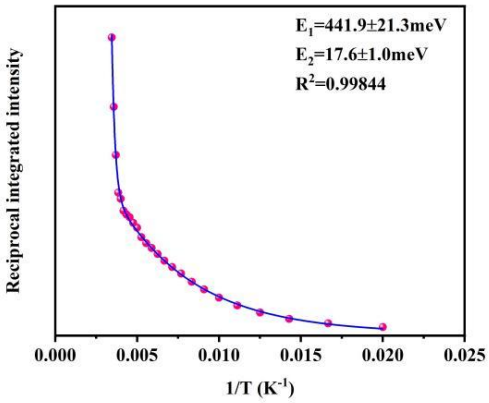
Supplementary Figure 2. The SEM photos of the $MAPbI_3$ film taken before and after the cooling process. (A) Before cooling process; (B) After cooling process.

The SEM photos of the $MAPbI_3$ thin film samples taken before and after the cooling process are shown in the figure above, where (A) represents the image taken before cooling, and (B) represents the image taken after cooling. It can be observed that, compared to before cooling, cracks appear in the $MAPbI_3$ film during the cooling process, along with voids between grain boundaries. These changes can be attributed to the grain alterations caused by the low-temperature phase transition.

3 Data analysis of temperature-dependent PL measurements

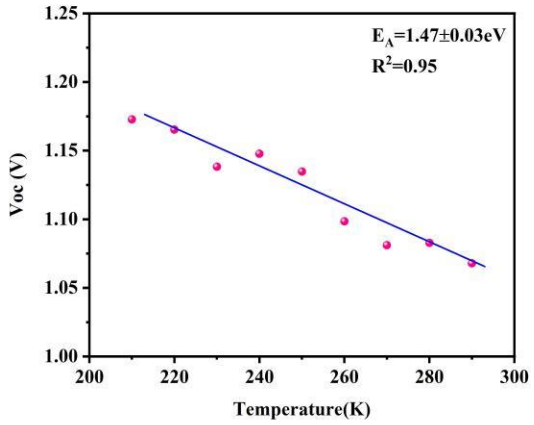


Supplementary Figure 3. The full width of half maximum of the excitonic peaks of $FAPbI_3$.

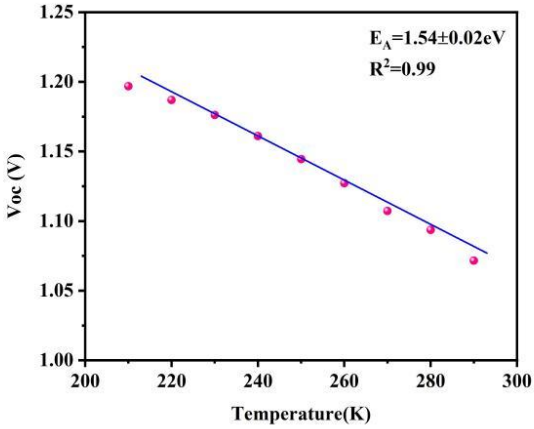


Supplementary Figure 4. Dependence of reciprocal integrated intensity for $FAPbI_3$ perovskite on temperature. The solid line is the fitting curve.

4 Linear fitting Voc with temperature for $FAPbI_3$-based and $MAPbI_3$-based PSCs



Supplementary Figure 5. Fitting results of the changing Voc with temperatures in $FAPbI_3$-based PSCs.



Supplementary Figure 6. Fitting results of the changing Voc with temperatures in $MAPbI_3$-based PSCs.