

## Supporting Information

### **Radiation Resistant Chalcopyrite CIGS Solar Cells: Proton Damage Shielding with Cs Treatment and Defect Healing via Heat-Light Soaking**

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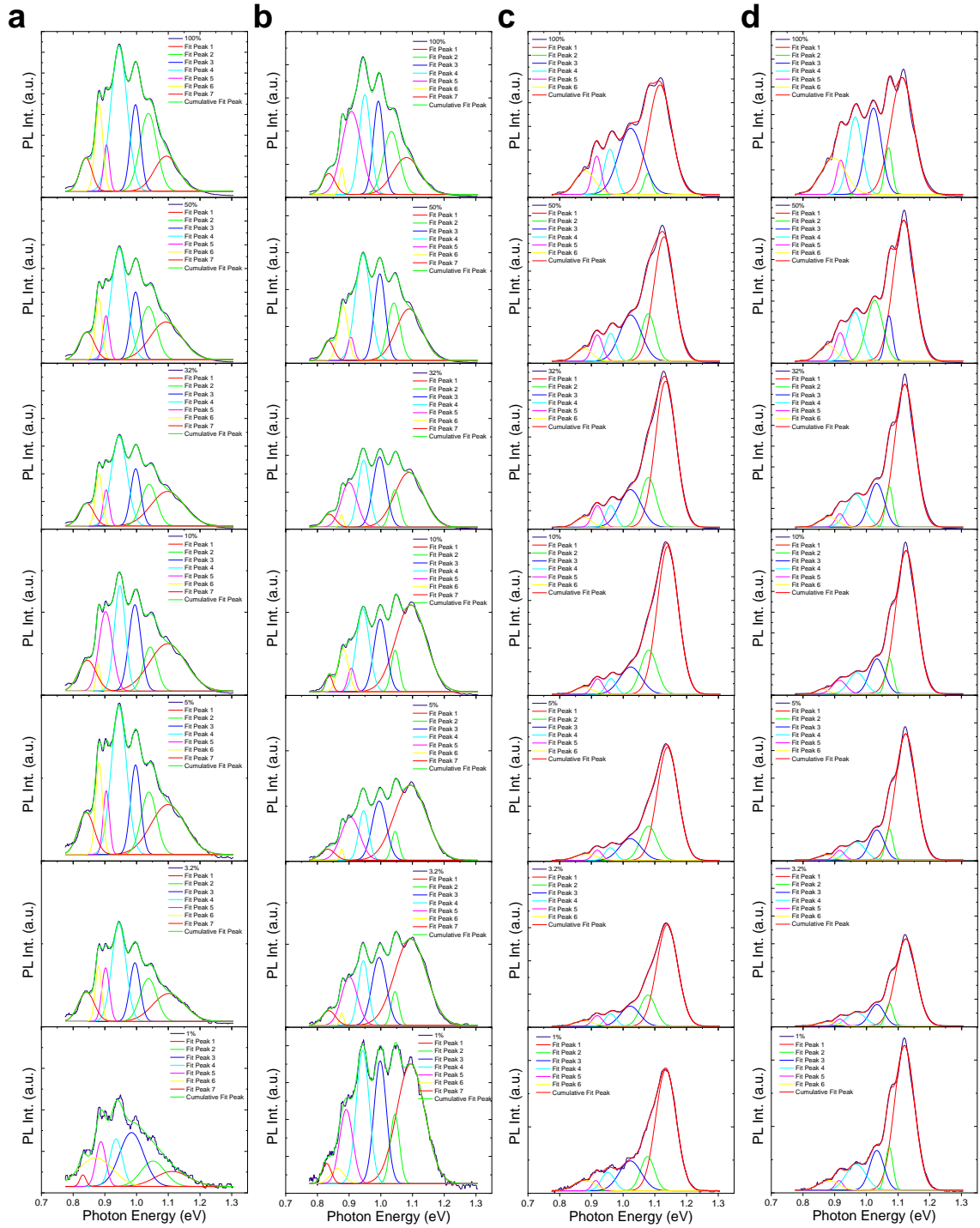
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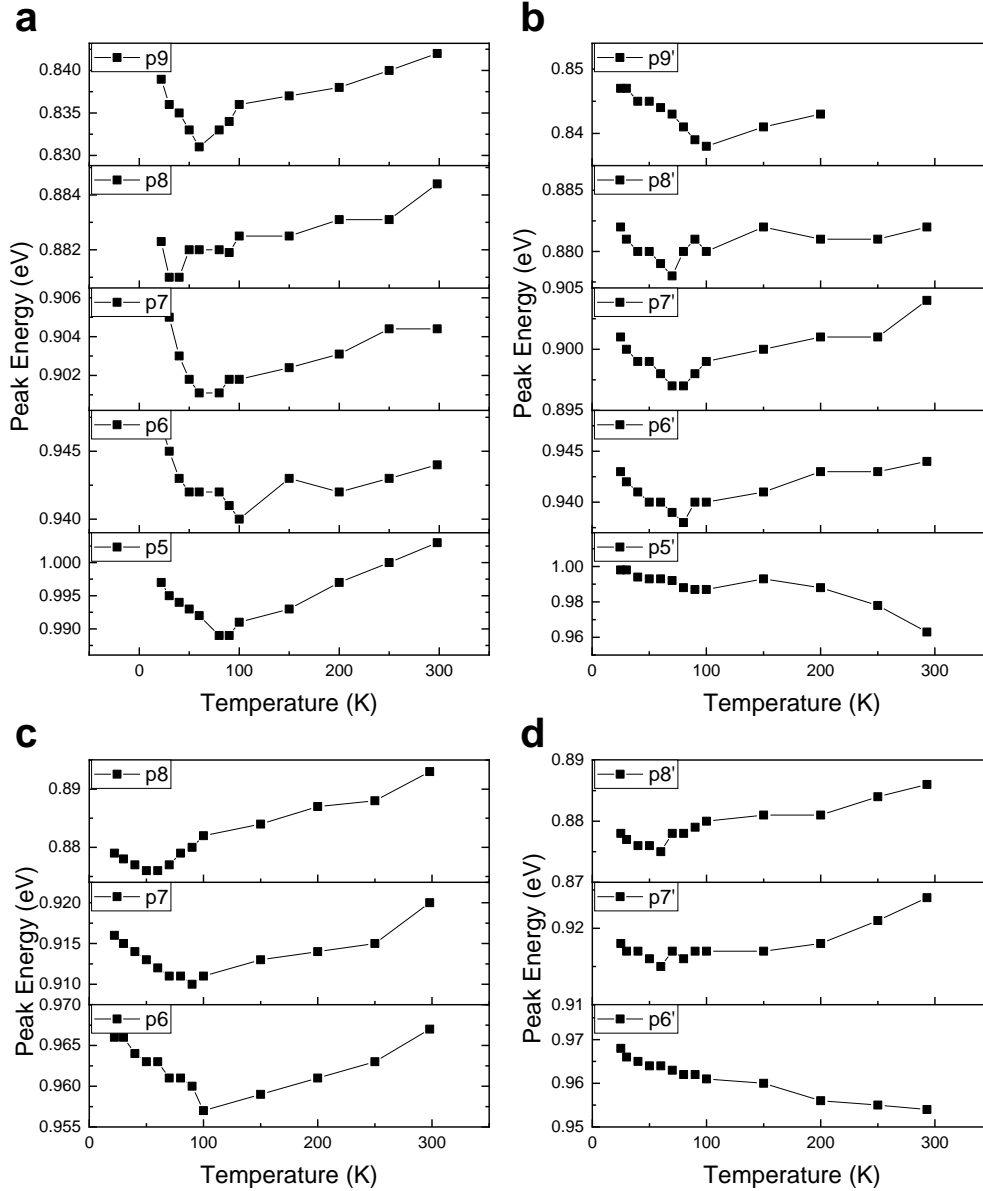
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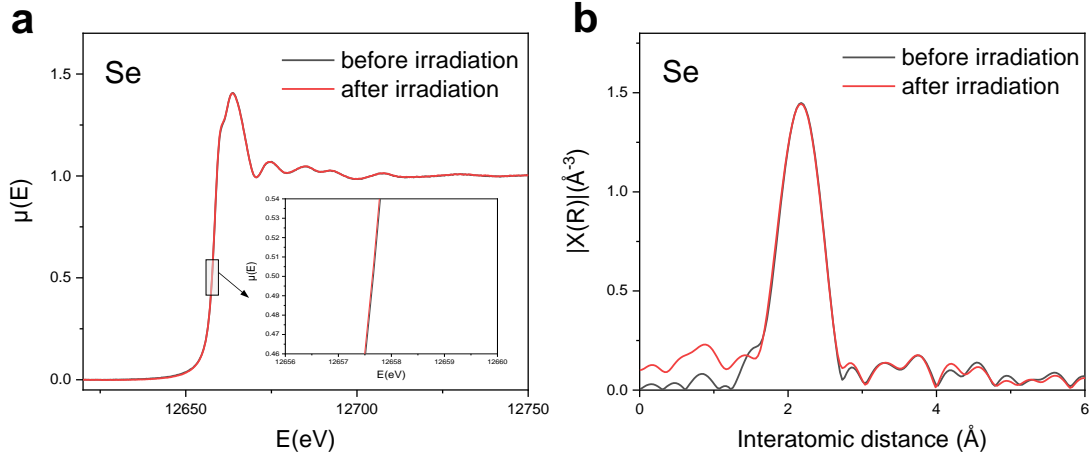
Keywords: CIGS, proton, irradiation, Cs, shielding, defect healing, HLS



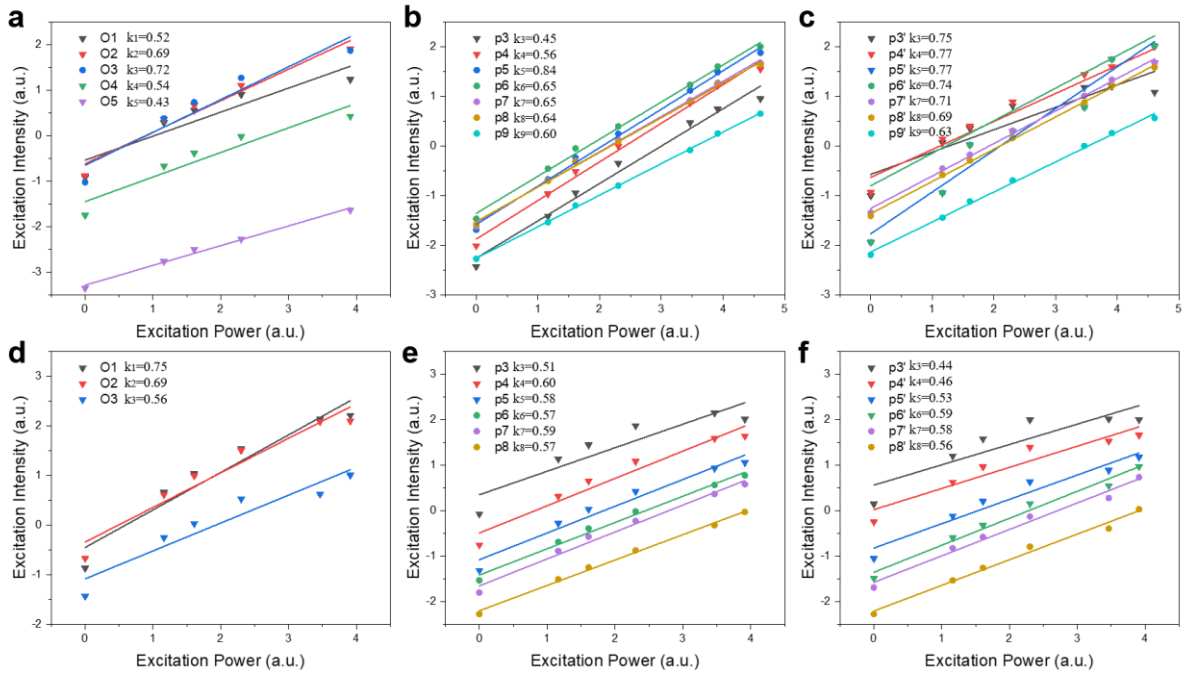
**Figure S1.** Details of deconvolution in power dependence PL of (a) irradiated control CIGS (p-C2), (b) irradiated control CIGS followed by HLS (HLS-p-C2), (c) irradiated Cs-treated CIGS (p-Cs2), and (b) irradiated Cs-treated CIGS followed by HLS (HLS-p-Cs2).



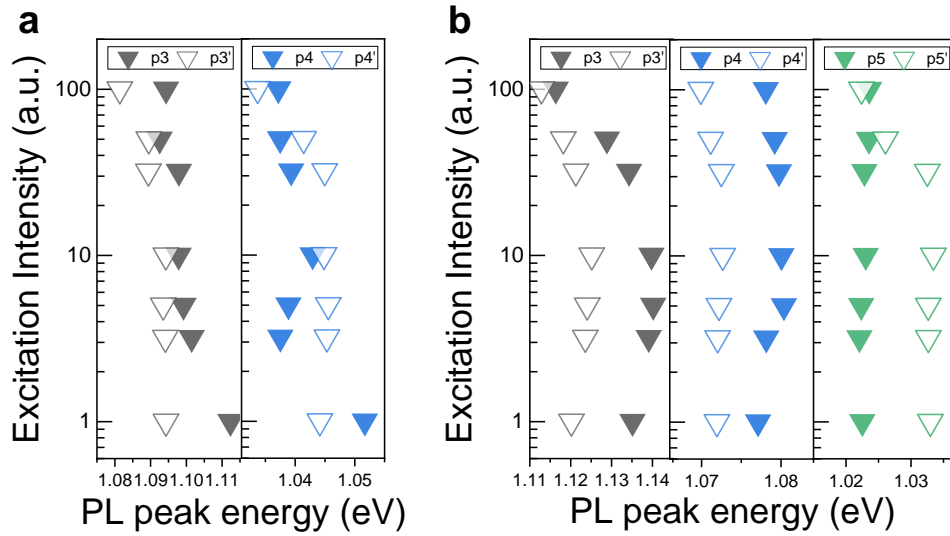
**Figure S2.** PL-peaks shift with temperature for (a) irradiated control CIGS (p-C2), (b) p-C2 followed by HLS (HLS-p-C2), (c) irradiated Cs-treated CIGS (p-Cs2), and (d) p-Cs2 followed by HLS (HLS-p-Cs2). The characteristic transition of DAPs with potential fluctuation is observed as the peak energy initially undergoes a redshift and then transitions to a blueshift when temperature increases from low temperature to room temperature. Some DAPs were annihilated by HLS, such as p5' in HLS-p-C2 and p6' in HLS-p-Cs2.



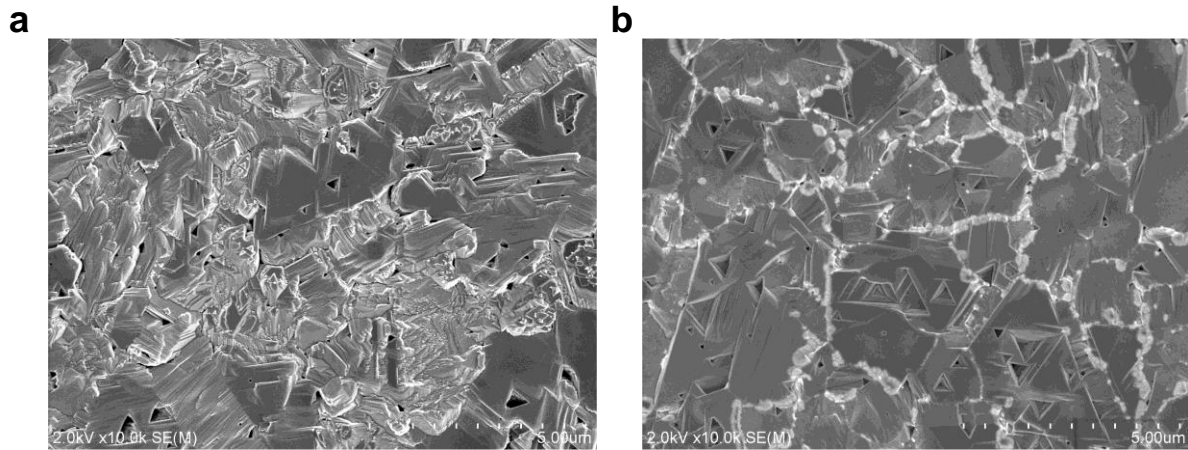
**Figure S3.** (a) XANES spectra for Se of CIGS sample before and after irradiation. The inserted figures show the enlarged K-edge spectra and the edges are overlapped without shifting. (b) Corresponding EXAFS spectra for Se before and after irradiation.



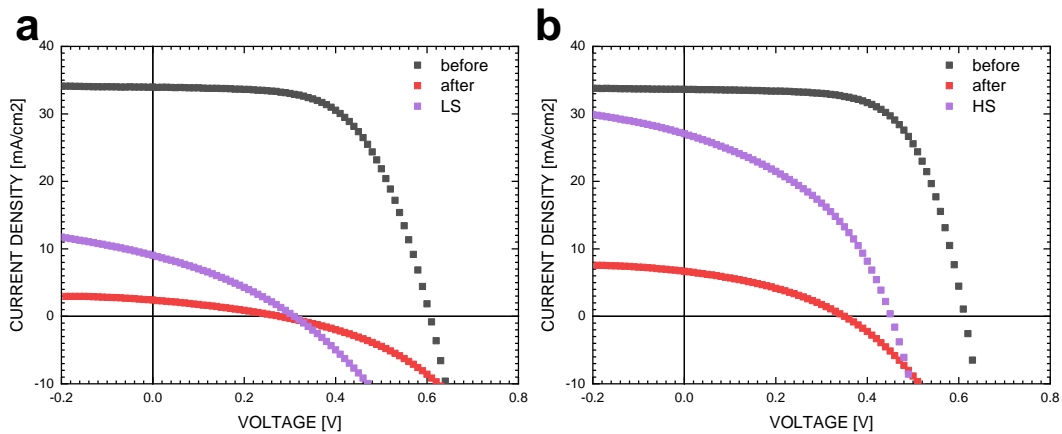
**Figure S4.**  $k$  factors fitted from equation  $I_{PL}(\phi) \propto \phi^k$  of samples (a) C2, (b) p-C2, (c) HLS-p-C2, (d) Cs2, (e) p-Cs2, and (f) HLS-p-Cs2, where  $I_{PL}$  is the PL intensity,  $\phi$  is the excitation intensity and  $k$  is a characteristic parameter. All the calculated  $k$  factors are  $< 1$ , indicating these analyzed peaks belong to donor-acceptor or free-bound transitions.



**Figure S5.** (a) Plot depicting peak energies of p3 to p4 (p-C2) and p3' to p4' (HLS-p-C2) in control CIGS. (b) Plot depicting peak energies of p3 to p5 (p-Cs2) and p3' to p5' (HLS-p-Cs2) in Cs-treated CIGS. Scatters of the inverted triangle ( $\blacktriangledown, \triangledown$ ) represent the FB transition.



**Figure S6.** SEM image of (a) control, and (b) Cs-treated CIGS before irradiation.



**Figure S7.**  $J$ - $V$  curves of (a) control 3 before, after irradiation, and followed by light soaking (LS); (b) control 4 before, after irradiation, and followed by heat soaking (HS).