Supporting Information

# Enhancing Radiation-Resistance of Amorphous Indium-Zinc-Oxide Thin-Film Transistors by Group IV Transition Element Doping

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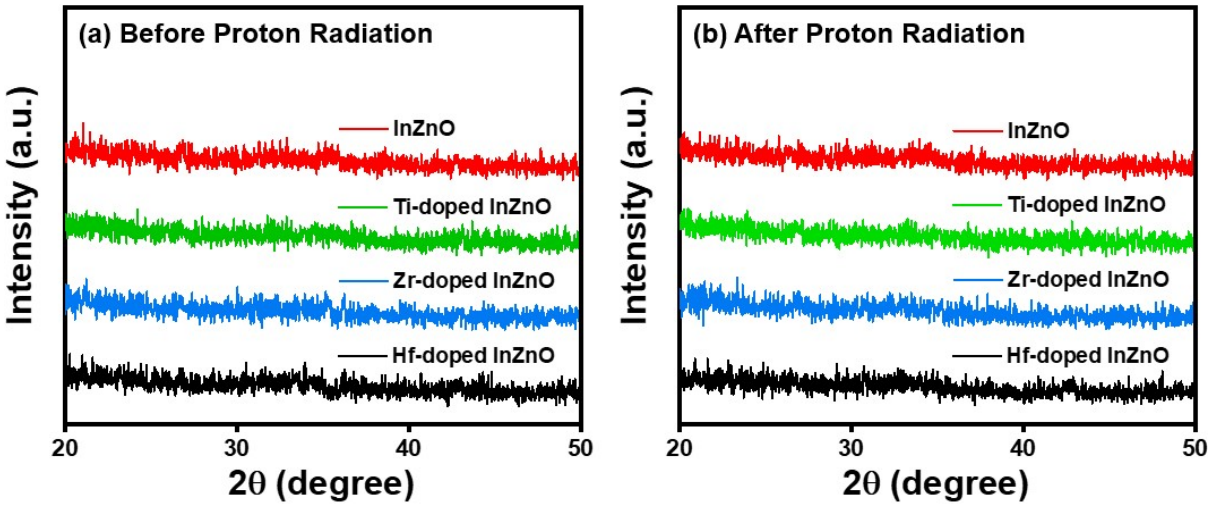


**Figure S1.** Grazing-incidence X-ray diffraction (GIXRD) spectra of amorphous oxide semiconductor thin films before and after proton irradiation (5 MeV, $10^{13}$ $cm^{-2}$ dose): the thin films of InZnO, Ti-doped InZnO, Zr-doped InZnO, and Hf-doped InZnO (a) before and (b) after the proton irradiation.

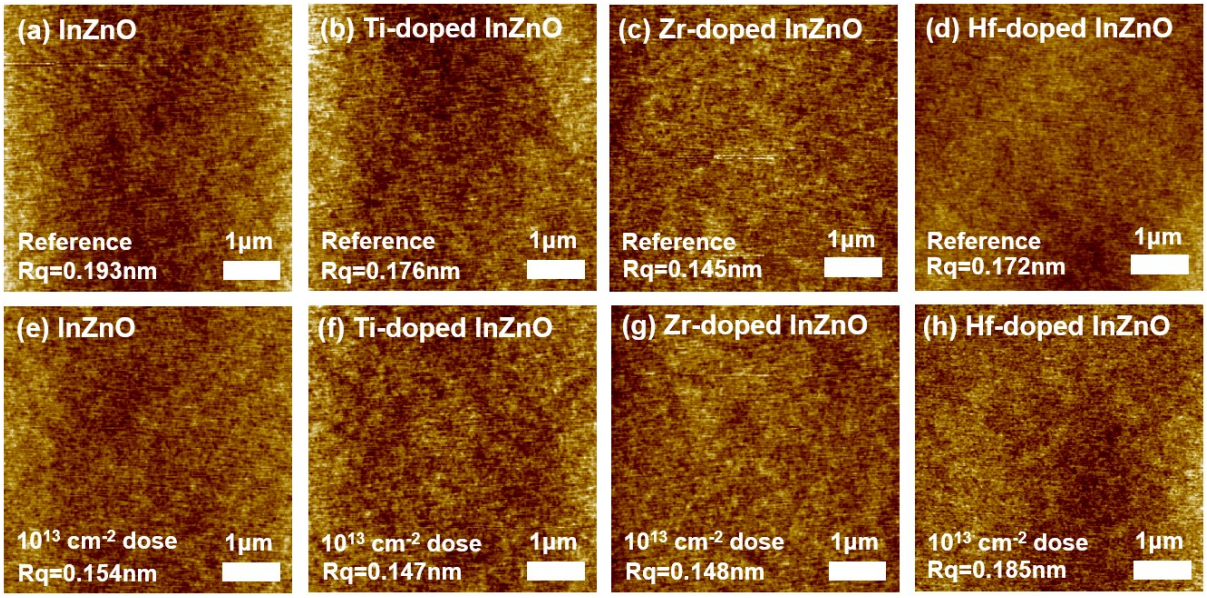


**Figure S2.** Atomic force microscopy (AFM) images of the surfaces of amorphous oxide semiconductor (AOS) films before and after proton irradiation (5 MeV, $10^{13}$ $cm^{-2}$ dose): (a) InZnO, (b) Ti-doped InZnO, (c) Zr-doped InZnO, and (d) Hf-doped InZnO films before proton irradiation; (e) InZnO, (f) Ti-doped InZnO, (g) Zr-doped InZnO, and (h) Hf-doped InZnO films after proton radiation. $R_q$ is the RMS (root-mean-square) roughness.

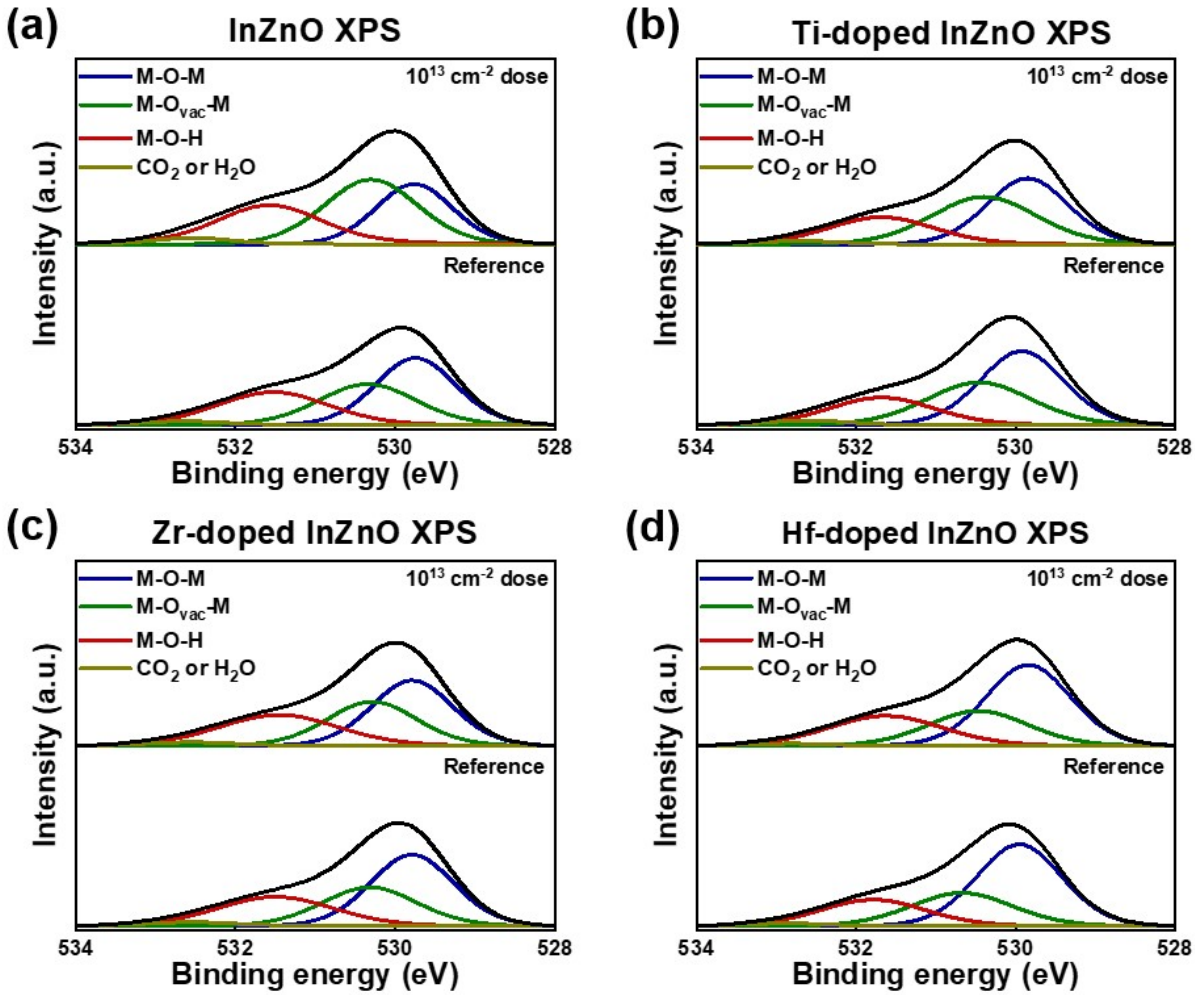


**Figure S3.** O1s spectra of (a) InZnO, (b) Ti-doped InZnO, (c) Zr-doped InZnO, and (d) Hf-doped InZnO from X-ray photoelectron spectroscopy (XPS) analysis of thin film before and after proton irradiation (5 MeV, $10^{13}$ cm$^{-2}$ dose).

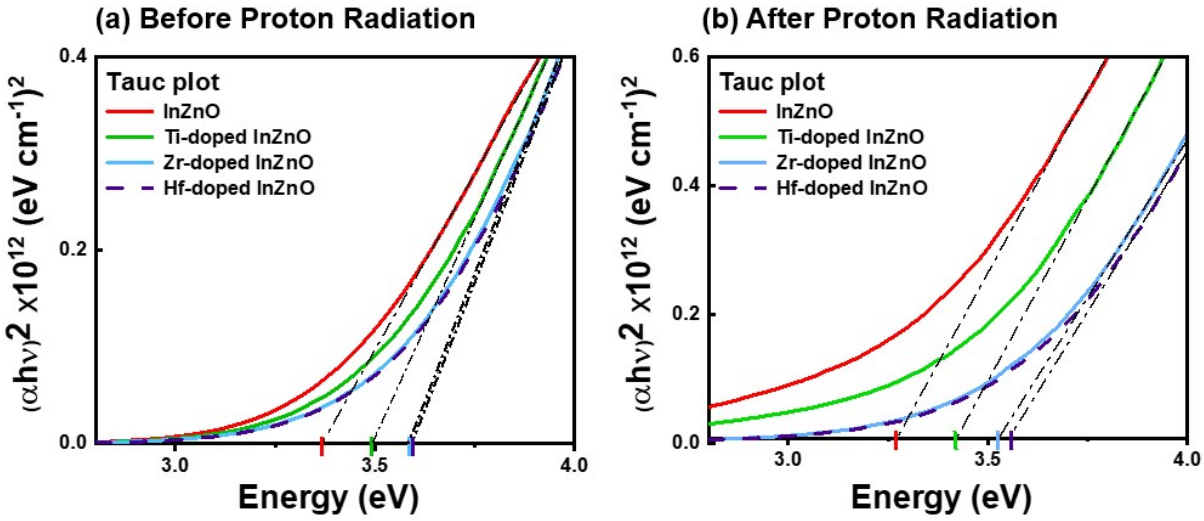


**Figure S4.** Tauc plot spectra of amorphous oxide semiconductor thin films before and after 5 MeV proton irradiation with a dose of $10^{13}$ $cm^{-2}$: (a) InZnO, (b) Ti-doped InZnO, (c) Zr-doped InZnO, and (d) Hf-doped InZnO before proton irradiation; (e) InZnO, (f) Ti-doped InZnO, (g) Zr-doped InZnO, and (h) Hf-doped InZnO after proton irradiation.

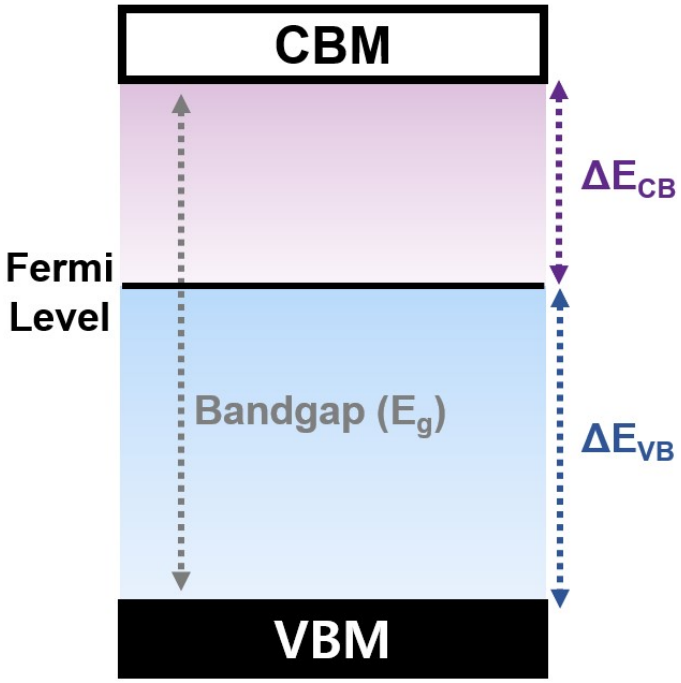


**Figure S5.** Schematic image of the energy band diagram which denotes the bandgap, $\Delta E_{CB,}$ and $\Delta E_{VB.}$

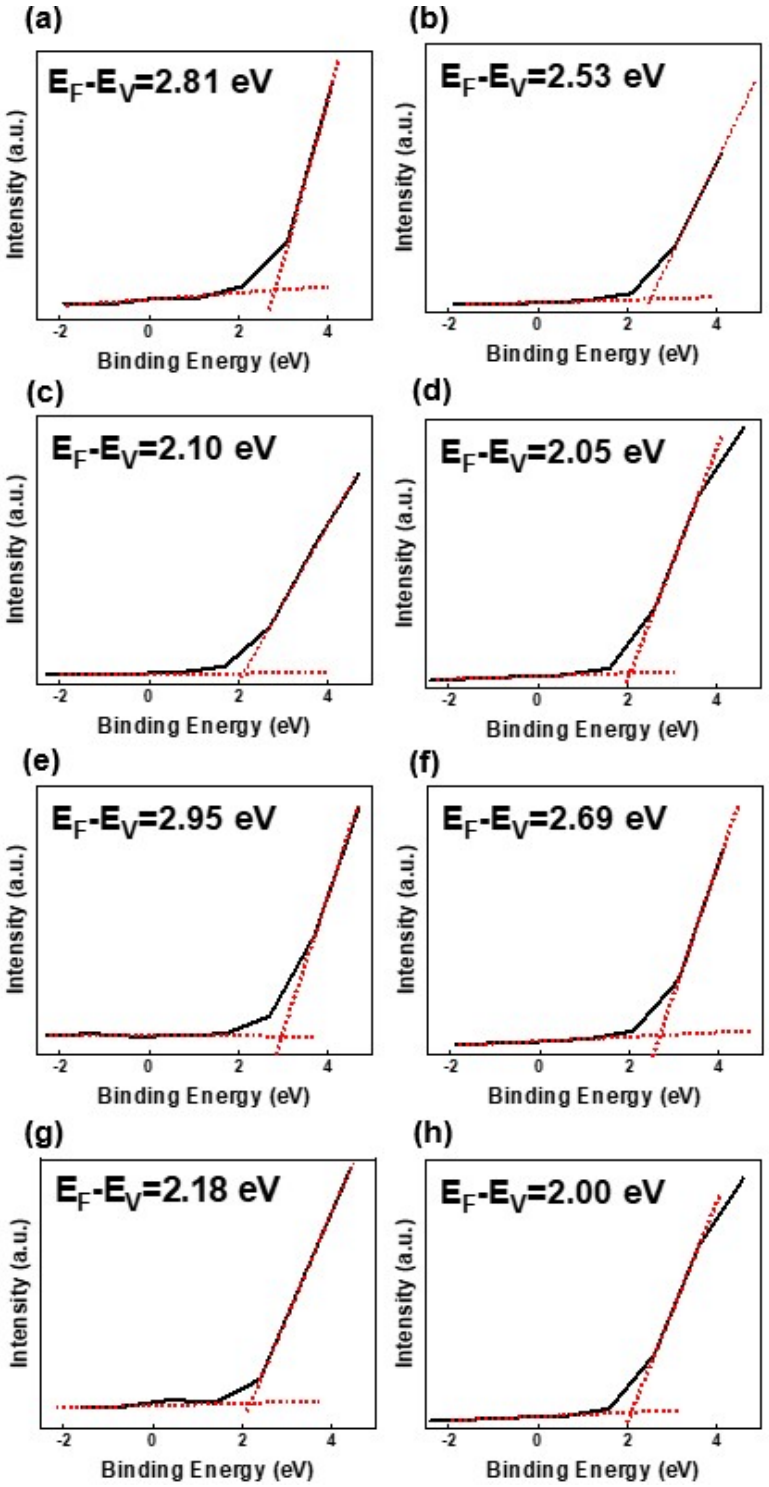


**Figure S6.** XPS spectra measured near the valence band for amorphous oxide semiconductor thin films before and after 5 MeV proton irradiation with a dose of $10^{13}$ $cm^{-2}$: (a) InZnO, (b) Ti-doped InZnO, (c) Zr-doped InZnO, and (d) Hf-doped InZnO before proton irradiation; (e) InZnO, (f) Ti-doped InZnO, (g) Zr-doped InZnO, and (h) Hf-doped InZnO after proton irradiation.

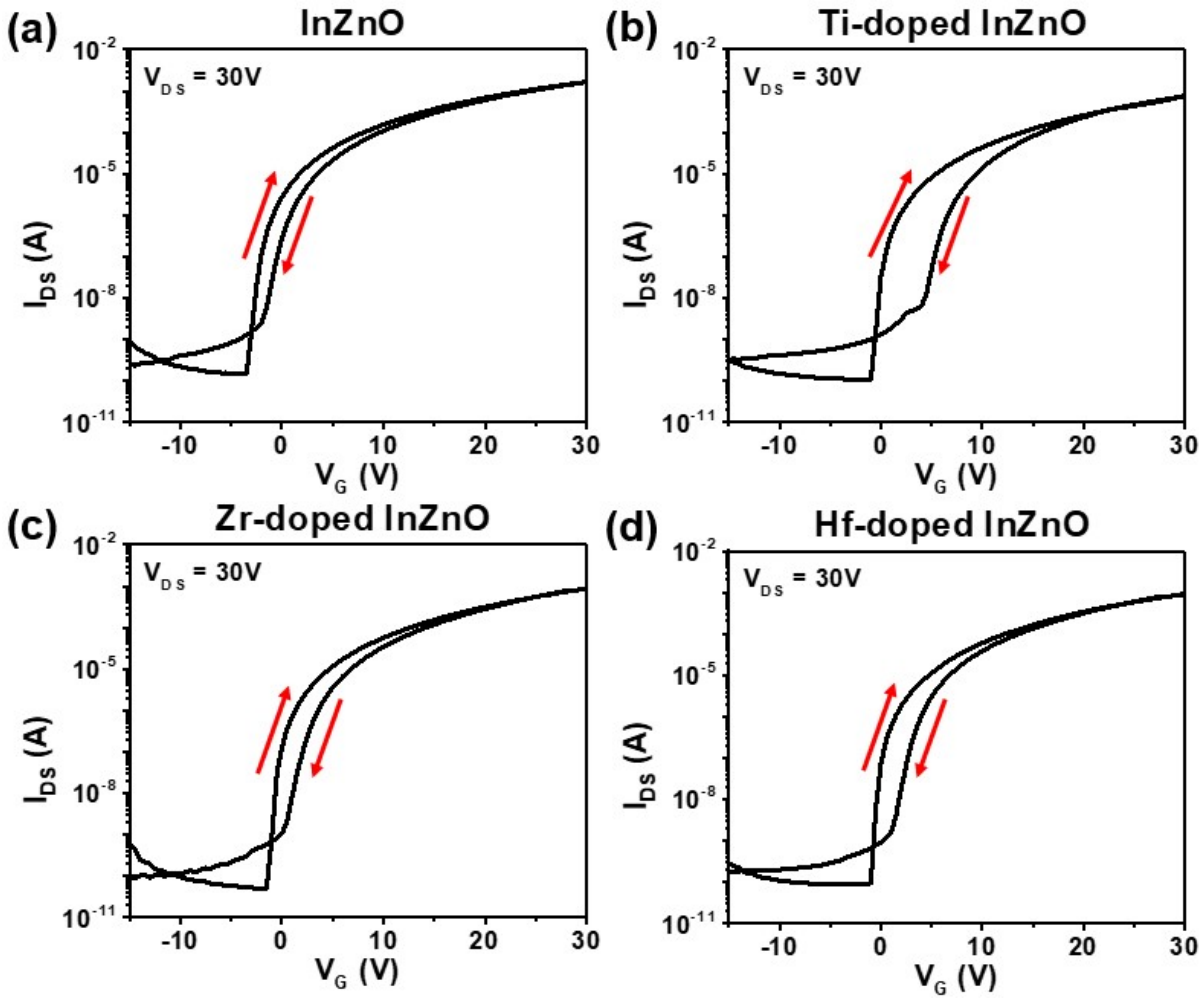


**Figure S7.** Transfer curve of amorphous oxide semiconductor thin-film transistors measured bidirectionally before proton irradiation: (a) InZnO TFT, (b) Ti-doped InZnO TFT, (c) Zr-doped InZnO TFT, and (d) Hf-doped InZnO TFT.

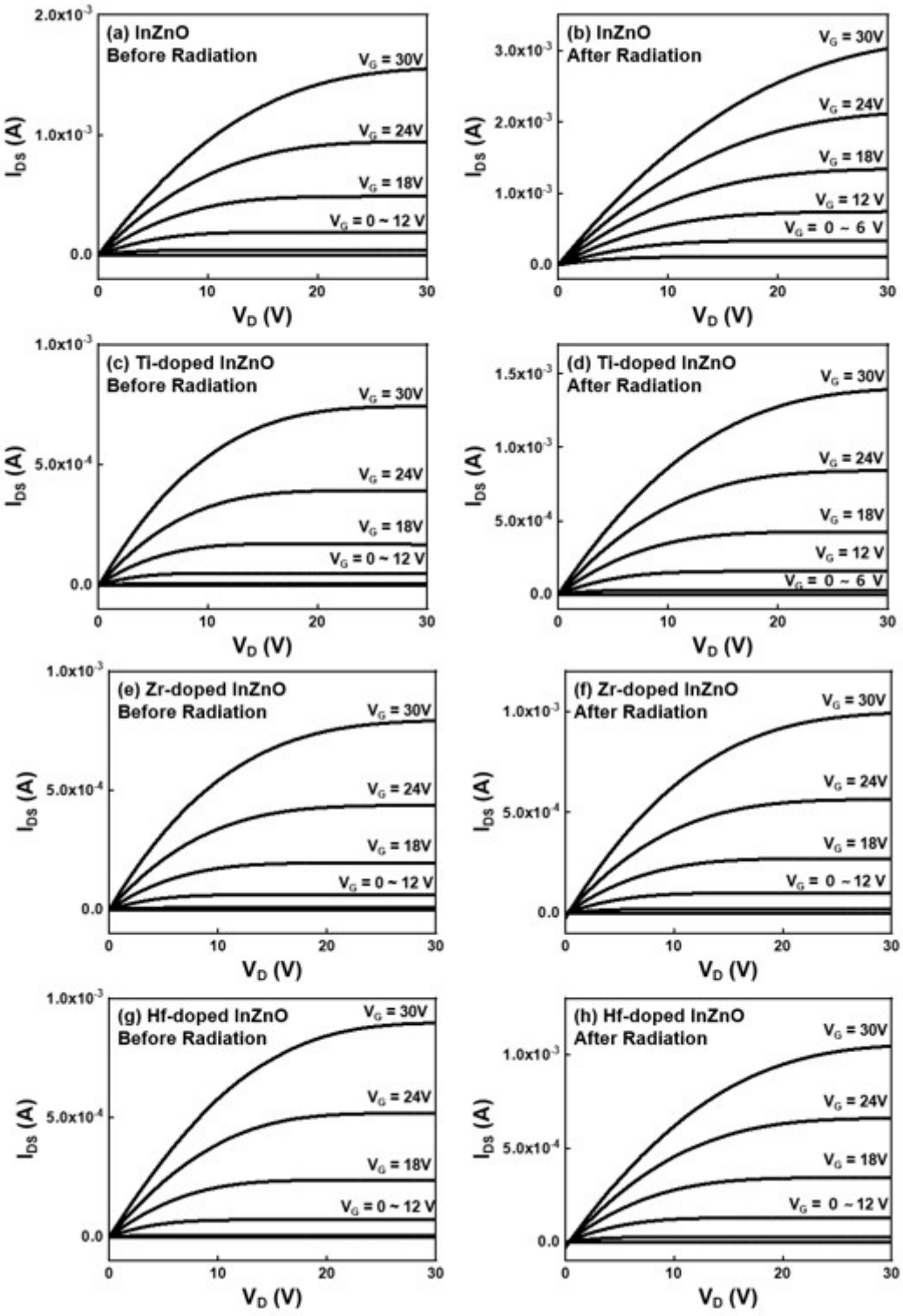


**Figure S8.** Output curves of amorphous oxide semiconductor thin-film transistors before and after proton irradiation (5 MeV, $10^{13}$ $cm^{-2}$ dose): (a) InZnO TFT, (b) Ti-doped InZnO TFT, (c) Zr-doped InZnO TFT, and (d) Hf-doped InZnO TFT before proton irradiation; (e) InZnO TFT, (f) Ti-doped InZnO TFT, (g) Zr-doped InZnO TFT, and (h) Hf-doped InZnO TFT after proton irradiation.

**Table S1**. The previous research on the bias stress or bias illumination stress stability of thin-film transistors based on amorphous oxide semiconductors doped with group IV transition elements.

| Year | Channel | Stress | | | Compositional Percentage of Dopant (%) | $\triangle V_{th}$ (V)[a] | Ref. |
|---|---|---|---|---|---|---|---|
| | | Type | Time (s) | Applied Voltage / Light Source | | | |
| 2013 | Ti-doped InZnO | PBS[a] | 1800 | $V_G$ = 20 V, $V_D$ = 10 V | 14 | 0.2 | [35] |
| | Zr-doped InZnO | PBS[a] | 1800 | $V_G$ = 20 V, $V_D$ = 10 V | 13 | ~ 2 | |
| | Hf-doped InZnO | PBS[a] | 1800 | $V_G$ = 20 V, $V_D$ = 10 V | 18 | ~ 5 | |
| 2014 | Zr-doped InZnO | PBS[a] | 1000 | $V_G$ = 20 V, $V_D$ = 10 V | 1 | 7.42 | [36] |
| | Zr-doped InZnO | NBS[b] | 1000 | $V_G$ = -20 V, $V_D$ = 10 V | 1 | -0.46 | |
| 2016 | Hf-doped ZnSnO | NBIS[c] | 10800 | $V_G$ = -10 V / 4000 Lux | 7.01 | -1.9 | [37] |
| 2019 | Zr-doped ZnSnO | NBIS[c] | 1200 | $V_G$ = -5 V / 2000 Lux white light | 2 | -0.34 | [38] |
| 2021 | Hf-doped InSnZnO | PBS[a] | 3000 | $V_G$ = 10 V | 5.09 | ~ 2 | [28] |
| | Hf-doped InSnZnO | NBS[b] | 3000 | $V_G$ = -10 V | 5.09 | ~ -2 | |
| 2023 | Ti-doped ZnSnO | PBS[a] | 3600 | $V_G$ = 20 V, $V_D$ = 0.1 V | 3.87 | ~ 13 | [39] |
| | Ti-doped ZnSnO | NBS[b] | 3600 | $V_G$ = -20 V, $V_D$ = 0.1 V | 3.87 | < 1 | |

[a] Positive bias stress, [b] Negative bias stress, [c] Negative bias illumination stress