Electronic Supplementary Information

Effect of Channel Thickness on Radiation Hardness of Solution-Processed Oxide Thin Film Transistors

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Table S1. A summary of measured optical bandgap (E_{gap}), the energy from the valence band maximum to the fermi level (ΔE_{VB}), and the conduction band offsets (ΔE_{CB}) for ZITO thin films with different t_{chS} from UV-vis spectroscopy and XPS

	E_{gap} (eV)	ΔE_{VB} (eV)	ΔE_{CB} (eV)
t_{ch} = 4 nm	3.81	2.61	1.20
t_{ch} = 5 nm	3.47	2.76	0.71
t_{ch} = 6.2 nm	3.38	2.91	0.44

Table S2. Representative charge-carrier mobility (μ, cm^2/Vs), current on/off ratio (I_{on}/I_{off}), threshold voltage (V_{th}, V), turn-on voltage (V_{on}, V), and subthreshold swing (SS, V/dec) ZITO TFT with t_{ch} value of 4 nm on SiO_2 100 nm devices during in-situ proton irradiation with a dose of 10^{13} cm^{-2}.[a] The average values are obtained from 5 samples.

ZITO / SiO_2 100nm	μ	I_{on}/I_{off}	V_{th}	V_{on}	SS
1st cycle	10.3 ± 1.1	(1.3 ± 0.5) × 10^7	0.2 ± 0.4	0 ± 0.3	1.1 ± 0.3
2nd cycle	11.7 ± 2.5	(3.6 ± 1.7) × 10^7	-0.6 ± 1.2	-4 ± 0.9	2.6 ± 0.5
3rd cycle	13.2 ± 2.9	(1.4 ± 0.7) × 10^4	-4.8 ± 1.4	-	3.1 ± 1.0
4th cycle	13.9 ± 3.3	(1.1 ± 0.6) × 10^4	-7.9 ± 1.6	-	3.8 ± 1.2
5th cycle	14.3 ± 3.9	(1.1 ± 0.5) × 10^4	-10.5 ± 2.0	-	4.0 ± 1.6
6th cycle	13.2 ± 3.1	(2.8 ± 1.6) × 10^6	-8.2 ± 1.5	-10.5 ± 1.2	2.9 ± 0.9
7th cycle	13.2 ± 1.5	(5.6± 3.1) × 10^6	-7.6 ± 1.4	-10.2 ± 1.2	2.6 ± 1.0
8th cycle	13.1 ± 1.4	(4.7 ± 2.0) × 10^6	-7.3 ± 1.3	-9.9 ± 1.2	2.4 ± 0.7
9th cycle	13.1 ± 1.5	(3.5 ± 1.0) × 10^6	-7.2 ± 1.3	-9.9 ± 1.2	2.4 ± 0.8
10th cycle	13.1 ± 1.4	(3.2 ± 1.4) × 10^6	-7.1 ± 1.4	-9.9 ± 1.2	2.3 ± 0.5
11th cycle	13.1 ± 1.3	(3.4 ± 1.9) × 10^6	-7.0 ± 1.3	-9.6 ± 1.5	2.2 ± 0.7
12th cycle	13.0 ± 1.4	(3.1 ± 2.1) × 10^6	-6.8 ± 1.2	-9.6 ± 1.5	2.1 ± 0.6
13th cycle	13.0 ± 1.4	(3.6 ± 1.8) × 10^6	-6.7 ± 1.3	-9.6 ± 1.2	2.0 ± 0.6
14th cycle	13.0 ± 1.3	(3.7 ± 2.0) × 10^6	-6.7 ± 1.3	-9.3 ± 1.5	2.0 ± 0.5

[a] Gray area indicates device characteristics during proton irradiation.

Table S3. Representative charge-carrier mobility (μ, cm^2/Vs), current on/off ratio (I_{on}/I_{off}), threshold voltage (V_{th}, V), turn-on voltage (V_{on}, V), and subthreshold swing (*SS*, V/dec) for ZITO TFT with t_{ch} value of 5 nm on SiO_2 100 nm devices during in-situ proton irradiation with a dose of 10^{13} cm^{-2}.[a] The average values are obtained from 5 samples.

ZITO / SiO_2 100nm	μ	I_{on}/I_{off}	V_{th}	V_{on}	*SS*
1st cycle	13.2 ± 1.5	(7.0 ± 3.2)× 10^6	-2.0 ± 0.8	-3 ± 0.6	1.1 ± 0.4
2nd cycle	18.5 ± 3.0	(1.9 ± 1.0) × 10^7	-4.5 ± 3.1	-	-
3rd cycle	19.9 ± 3.3	(2.1 ± 0.8) × 10^2	-19.2 ± 5.9	-	-
4th cycle	20.9 ± 3.5	(1.8 ± 0.6)× 10^1	-35.5 ± 8.6	-	-
5th cycle	21.6 ± 3.6	6.8 ± 4.2	-45.8 ± 12.2	-	-
6th cycle	16.4 ± 4.5	4.9 ± 3.7	-58.0 ± 15.4	-	-
7th cycle	16.2 ± 1.8	5.1 ± 3.2	-62.1 ± 7.4	-	-
8th cycle	16.5 ± 1.7	5.1 ± 3.3	-60.2 ± 8.7	-	-
9th cycle	16.5 ± 1.7	5.3 ± 3.1	-59.4 ± 8.4	-	-
10th cycle	16.2 ± 1.8	5.3 ± 3.2	-58.8 ± 8.1	-	-
11th cycle	16.3 ± 1.9	5.4 ± 3.0	-58.2 ± 7.6	-	-
12th cycle	16.1 ± 1.8	5.7 ± 2.9	-57.7 ± 7.2	-	-
13th cycle	16.1 ± 1.7	5.8 ± 2.6	-57.6 ± 7.0	-	-
14th cycle	16.0 ± 1.8	5.8 ± 2.5	-57.1 ± 7.4	-	-

[a] Gray area indicates device characteristics during proton irradiation.

Table S4. Representative charge-carrier mobility (μ, cm^2/Vs), current on/off ratio (I_{on}/I_{off}), threshold voltage (V_{th}, V), turn-on voltage (V_{on}, V), and subthreshold swing (*SS*, V/dec) for ZITO TFT with t_{ch} value of 6.2 nm on SiO_2 100 nm devices during in-situ proton irradiation with a dose of 10^{13} cm^{-2}.[a] The average values are obtained from 5 samples.

ZITO / SiO_2 100nm	μ	I_{on}/I_{off}	V_{th}	V_{on}	*SS*
1st cycle	15.6 ± 1.2	(7.8 ± 2.9) × 10^6	-3.5 ± 1.0	-3.7 ± 0.9	2.0 ± 0.5
2nd cycle	21.8 ± 3.4	(1.7 ± 0.8) × 10^6	-6.0 ± 3.1	-	-
3rd cycle	23.6 ± 3.7	(7.4 ± 5.3) × 10^1	-22.5 ± 8.2	-	-
4th cycle	25.3 ± 3.6	7.3 ± 2.6	-37.0 ± 9.5	-	-
5th cycle	23.7 ± 3.9	5.5 ± 2.1	-55.1 ± 14.4	-	-
6th cycle	17.7 ± 4.1	3.5 ± 2.3	-85.3 ± 19.3	-	-
7th cycle	17.6 ± 3.5	3.6 ± 2.1	-77.1 ± 10.3	-	-
8th cycle	17.5 ± 3.1	3.5 ± 2.3	-76.1 ± 10.7	-	-
9th cycle	17.4 ± 3.0	3.6 ± 2.4	-75.5 ± 9.5	-	-
10th cycle	17.4 ± 3.2	3.5 ± 2.3	-75.0 ± 9.4	-	-
11th cycle	17.4 ± 3.1	3.6 ± 2.2	-74.9 ± 8.8	-	-
12th cycle	17.3 ± 3.3	3.7 ± 2.1	-74.6 ± 9.1	-	-
13th cycle	17.2 ± 3.1	3.7 ± 2.0	-74.4 ± 9.0	-	-
14th cycle	17.2 ± 2.8	3.8 ± 2.0	-74.3 ± 8.7	-	-

[a] Gray area indicates device characteristics during proton irradiation.

Table S5. Representative charge-carrier mobility (μ, cm^2/Vs), current on/off ratio (I_{on}/I_{off}), threshold voltage (V_{th}, V), turn-on voltage (V_{on}, V), and subthreshold swing (*SS*, V/dec) for ZITO TFTs with different t_{ch} values on SiO_2 100 nm devices before and right after and 6 h after proton irradiation with a dose of 10^{13} cm^{-2}. The average values are obtained from 5 samples.

ZITO / SiO_2 100nm	**Dose**	μ	I_{on}/I_{off}	V_{th}	V_{on}	*SS*
	Reference	10.3 ± 1.1	(1.3 ± 0.5) × 10^7	0.2 ± 0.4	0 ± 0.3	1.1 ± 0.3
t_{ch} = 4 nm	**10^{13} dose**	14.3 ± 3.9	(1.1 ± 0.5) × 10^4	-10.5 ± 2.0	-	4.0 ± 1.6
	After 6 h	10.4 ± 0.9	(4.0 ± 2.1) × 10^6	-0.7 ± 0.3	-1 ± 0.6	1.5 ± 0.6
	Reference	13.2 ± 1.5	(7.0 ± 3.2)× 10^6	-2.0 ± 0.8	-3 ± 0.6	1.1± 0.5
t_{ch} = 5 nm	**10^{13} dose**	16.4 ± 4.5	4.9 ± 3.7	-58.0 ± 15.4	-	-
	After 6 h	16.0 ± 1.4	(1.6 ± 0.7) × 10^4	-22.1 ± 6.3	-	-
	Reference	15.6 ± 1.2	(7.8 ± 4.3) × 10^6	-3.5 ± 1.0	-3.7 ± 0.9	2.0 ± 0.5
t_{ch} = 6.2 nm	**10^{13} dose**	17.7 ± 4.1	3.5 ± 2.3	-85.3 ± 19.3	-	-
	After 6 h	17.0 ± 1.0	(1.5 ± 0.7) × 10^1	-39.1 ± 7.5	-	-

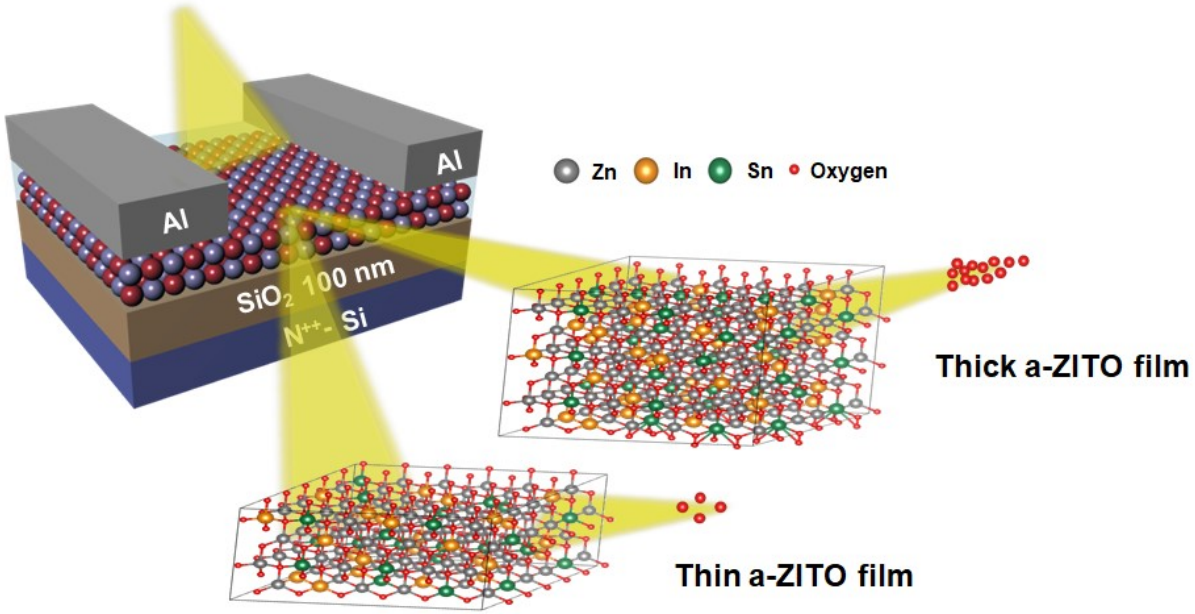

Figure S1. Schematic diagram of high-energy proton irradiation on bottom-gate/top-contact amorphous zinc-indium-tin oxide (a-ZITO) thin-film transistor device.

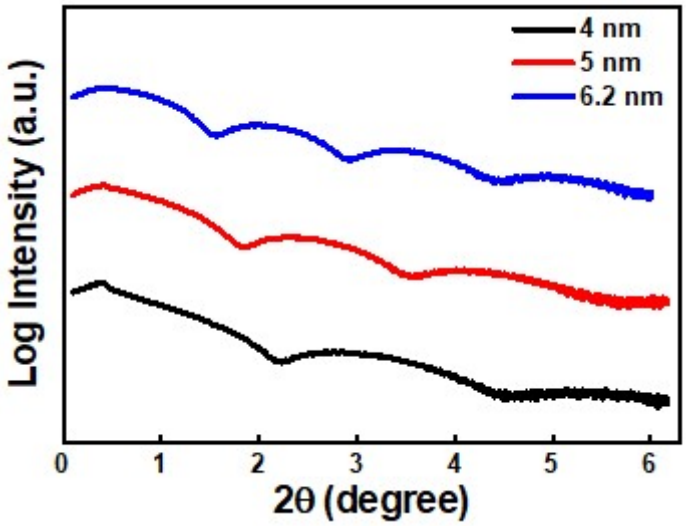

Figure S2. X-ray Reflectometry (XRR) of ZITO thin films with different t_{ch} values of 4 nm, 5 nm, and 6.2 nm.

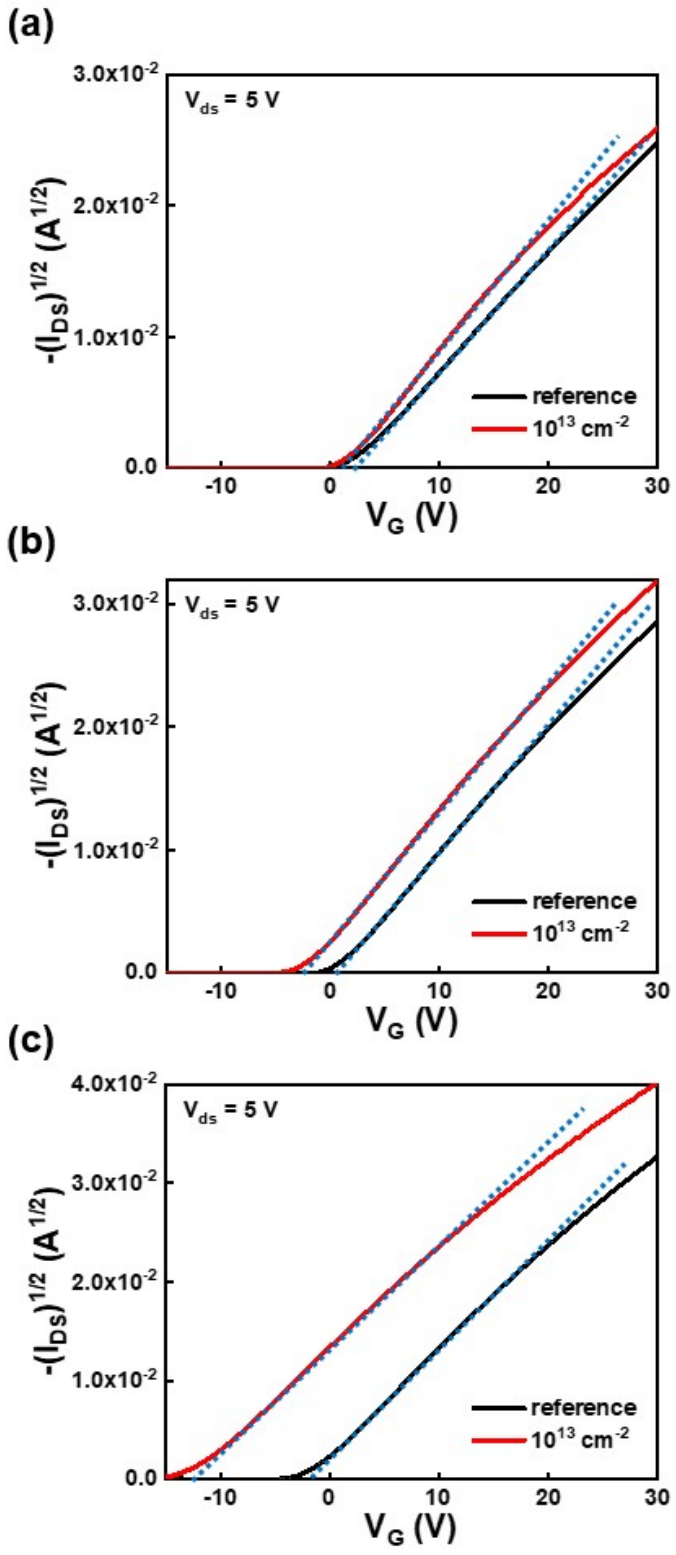

Figure S3. $(I_{ds})^{1/2}$ vs V_g plots of pristine ZITO thin film transistors (a) with different t_{ch} values (4 nm, 5 nm, and 6.2 nm), (b)-(d) before (solid black lines) and 6 h after 5 MeV proton irradiation dose of 10^{13} cm^{-2} (solid red lines): t_{ch} value of (b) 4 nm, (c) 5 nm, and (d) 6.2 nm.

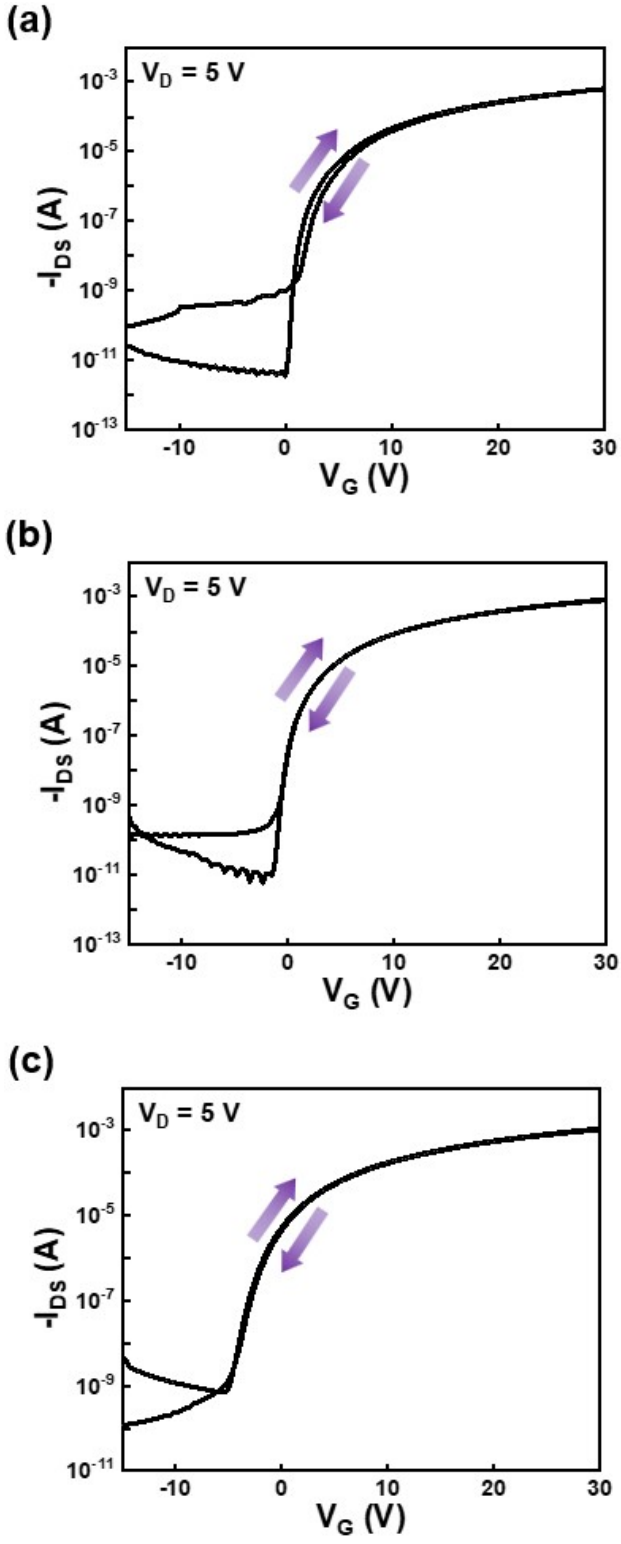

Figure S4. Transfer curves of the ZITO TFTS with different t_{ch} values measured bidirectionally before proton irradiation: t_{ch} value of (a) 4 nm, (b) 5 nm, and (c) 6.2 nm.

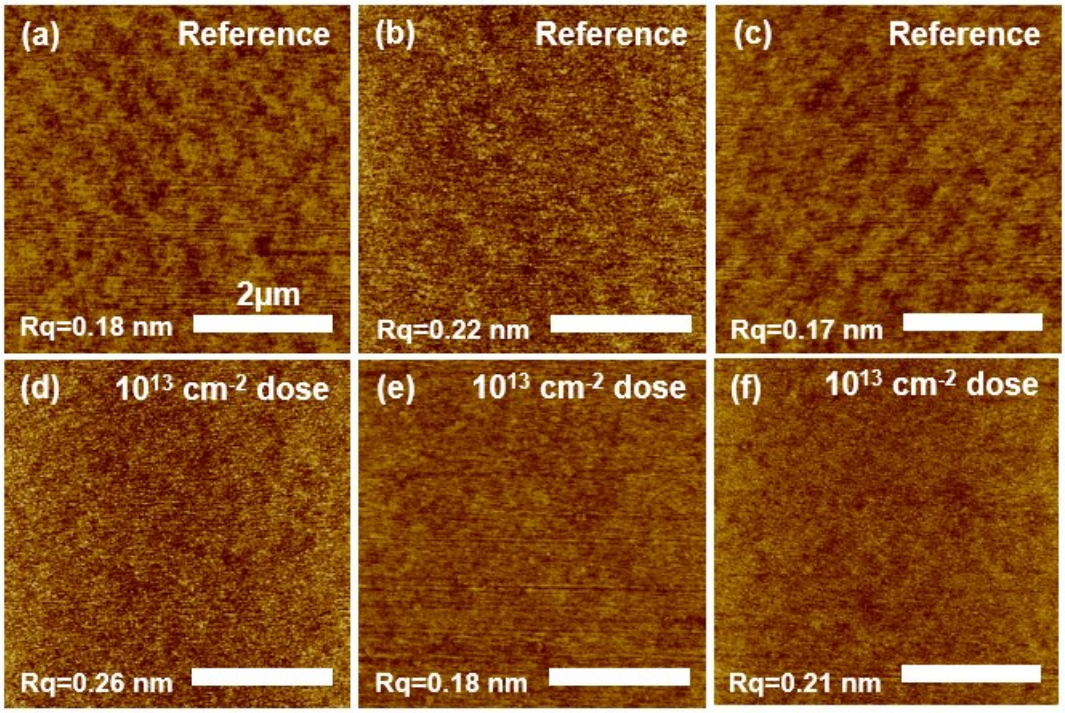

Figure S5. Atomic force microscope (AFM) images of ZITO thin films before and after 5 MeV proton irradiation (10^{13} cm^{-2} dose): ZITO thin films with different t_{chS} of (a) 4 nm before proton irradiation, (b) 5 nm before proton irradiation, (c) 6.2 nm before proton irradiation, (d) 4 nm after proton irradiation, (e) 5 nm after proton irradiation, (f) 6.2 nm after proton irradiation. The scale bars correspond to 2 μm. R_q is RMS (root-mean-square) roughness.

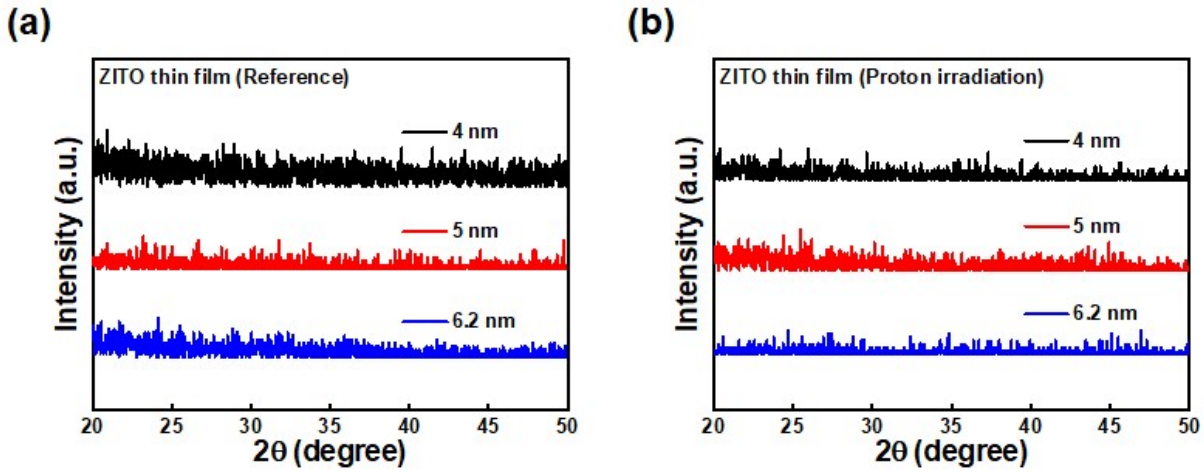

Figure S6. Grazing-incidence X-ray diffraction (GIXRD) spectra of ZITO thin films with different t_{ch} values before and after 5 MeV proton irradiation doses of 10^{13} cm^{-2}: ZITO thin film with t_{ch} values of 4, 5, and 6.2 nm (a) before and (b) after proton irradiation.

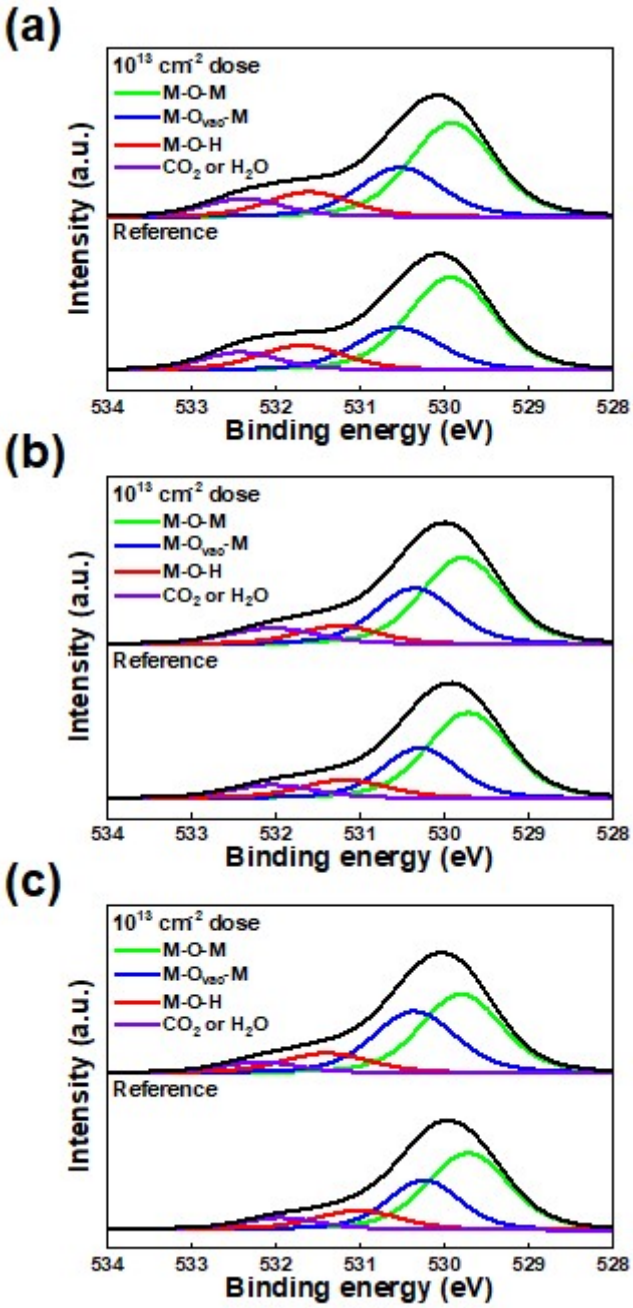

Figure S7. X-ray photoelectron spectroscopy (XPS) data of amorphous zinc-indium-tin oxide semiconductor thin film before and after 5 MeV proton irradiation (dose of 10^{13} cm^{-2}). O1s spectra for ZITO thin film with t_{ch} values of a) 4 nm, b) 5 nm, and c) 6.2 nm.

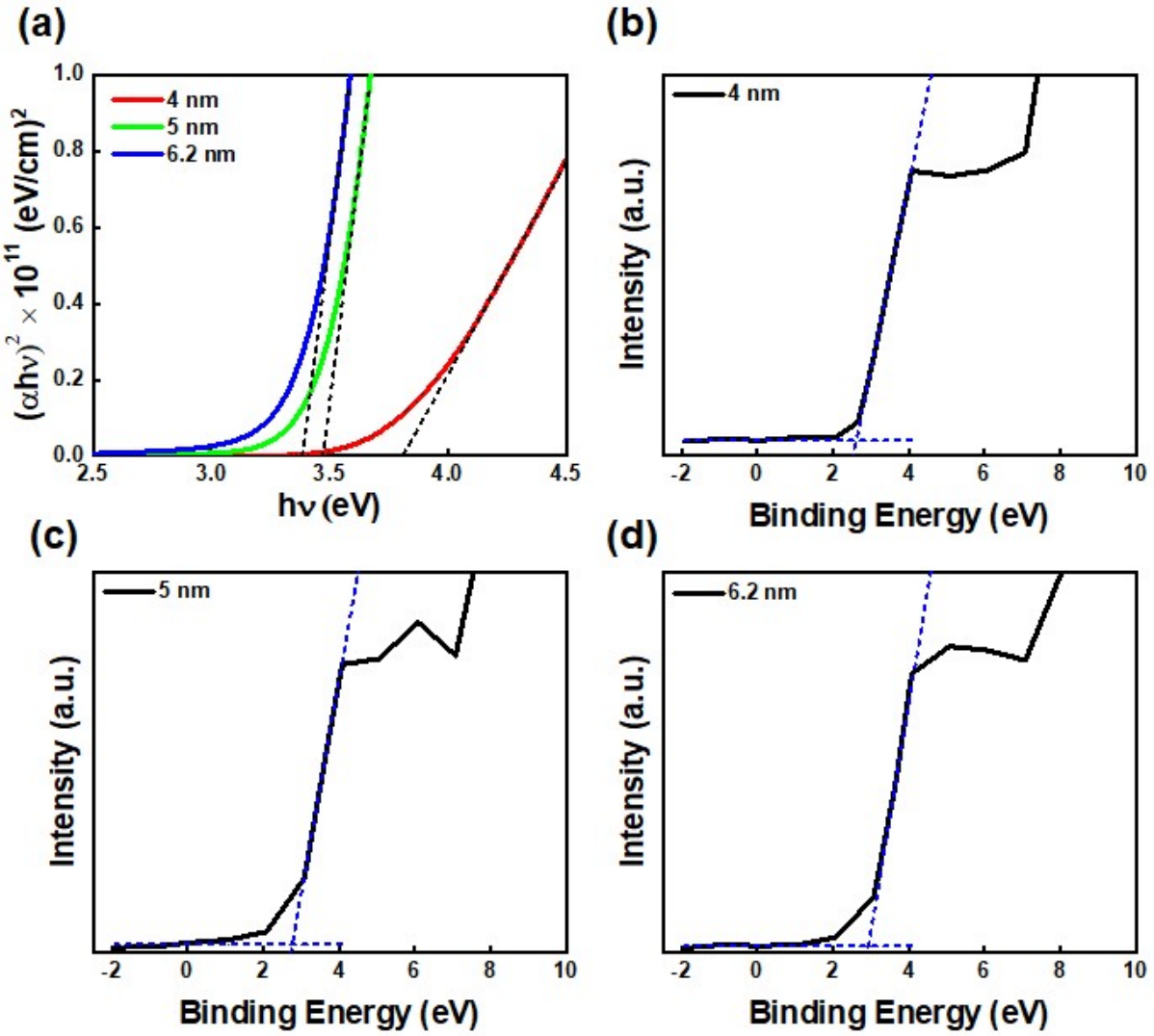

Figure S8. (a) Dependence of photon energy on $(\alpha h\nu)^2$ for ZITO thin films with different t_{chS} on glass substrate, XPS spectrum measured near the valence band for ZITO thin films with different t_{ch} of (b) 4 nm, (c) 5 nm, and (d) 6.2 nm.

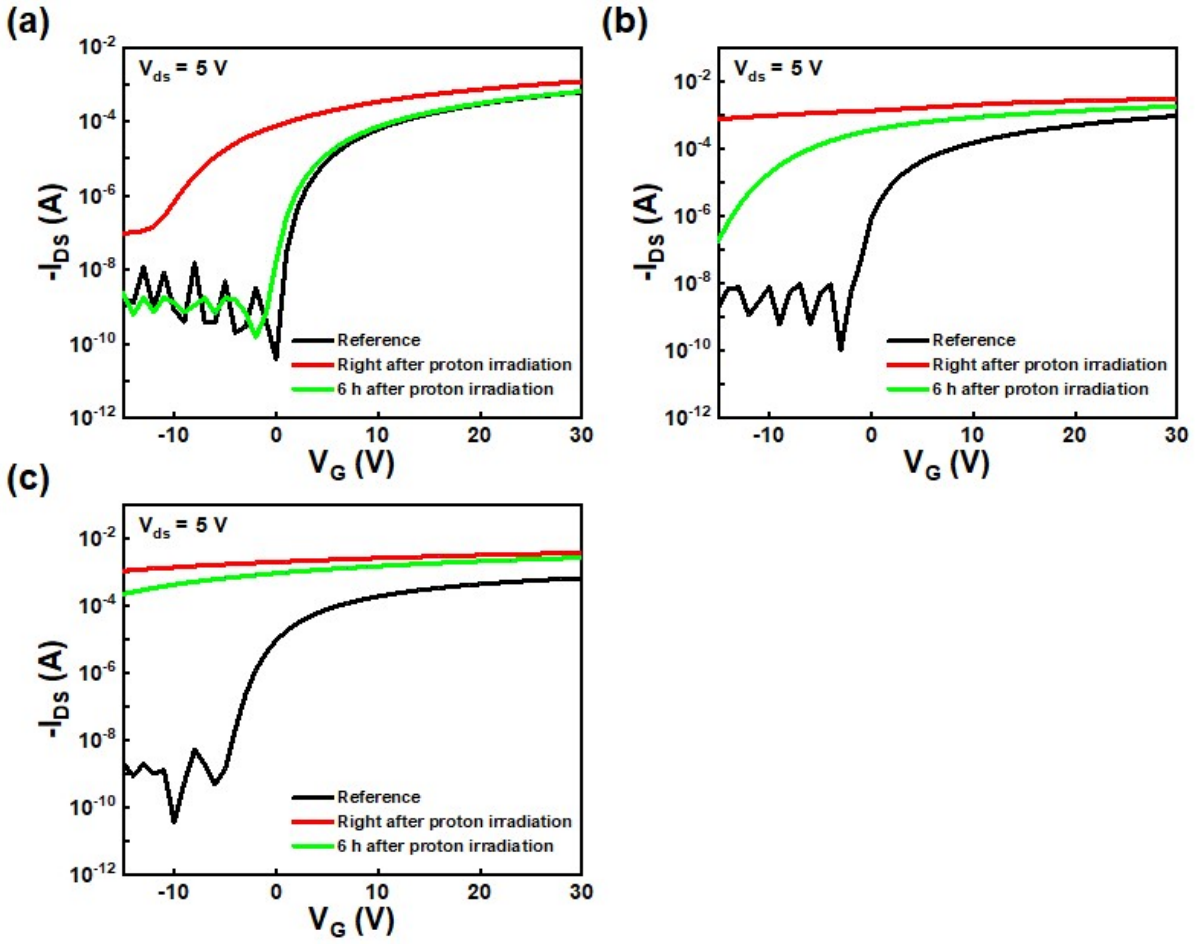

Figure S9. Transfer curve of ZITO thin film transistors with different t_{chS} in linear region at before proton (solid black lines), right after proton with electrical bias (solid red lines), 6 h after proton (solid green lines): ZITO TFT with t_{ch} values of (a) 4 nm, (b) 5 nm, and (c) 6.2 nm.