Supporting Information

Precise Turn-On Voltage Control of MIOSM Thin-Film Diodes with Amorphous Indium-Gallium-Zinc Oxide

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Author Contributions

The manuscript was written through the contribution of all authors. All authors have given approval to the final version of the manuscript. These authors K.K. and J.-W.P. contributed equally to this work.

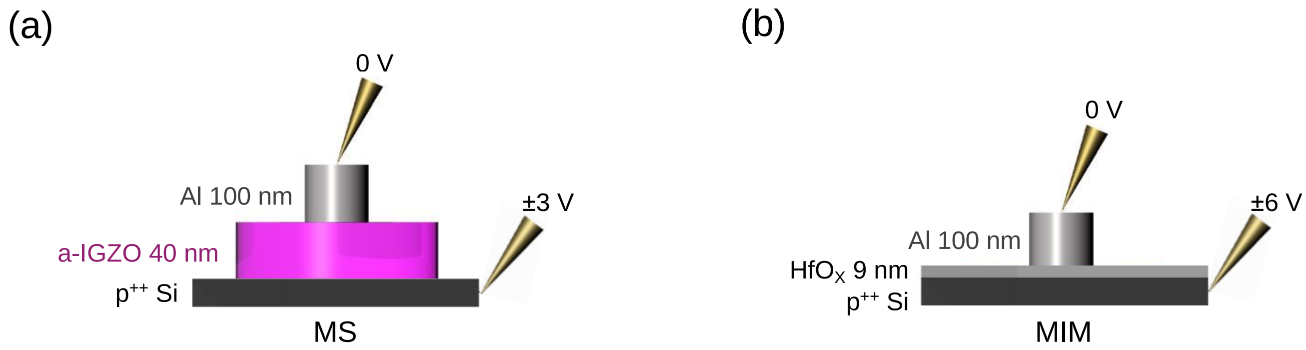

Figure S1. Schematic diagram of (a) metal-semiconductor (MS) Schottky contact and (b) metal-insulator-metal (MIM) structures.

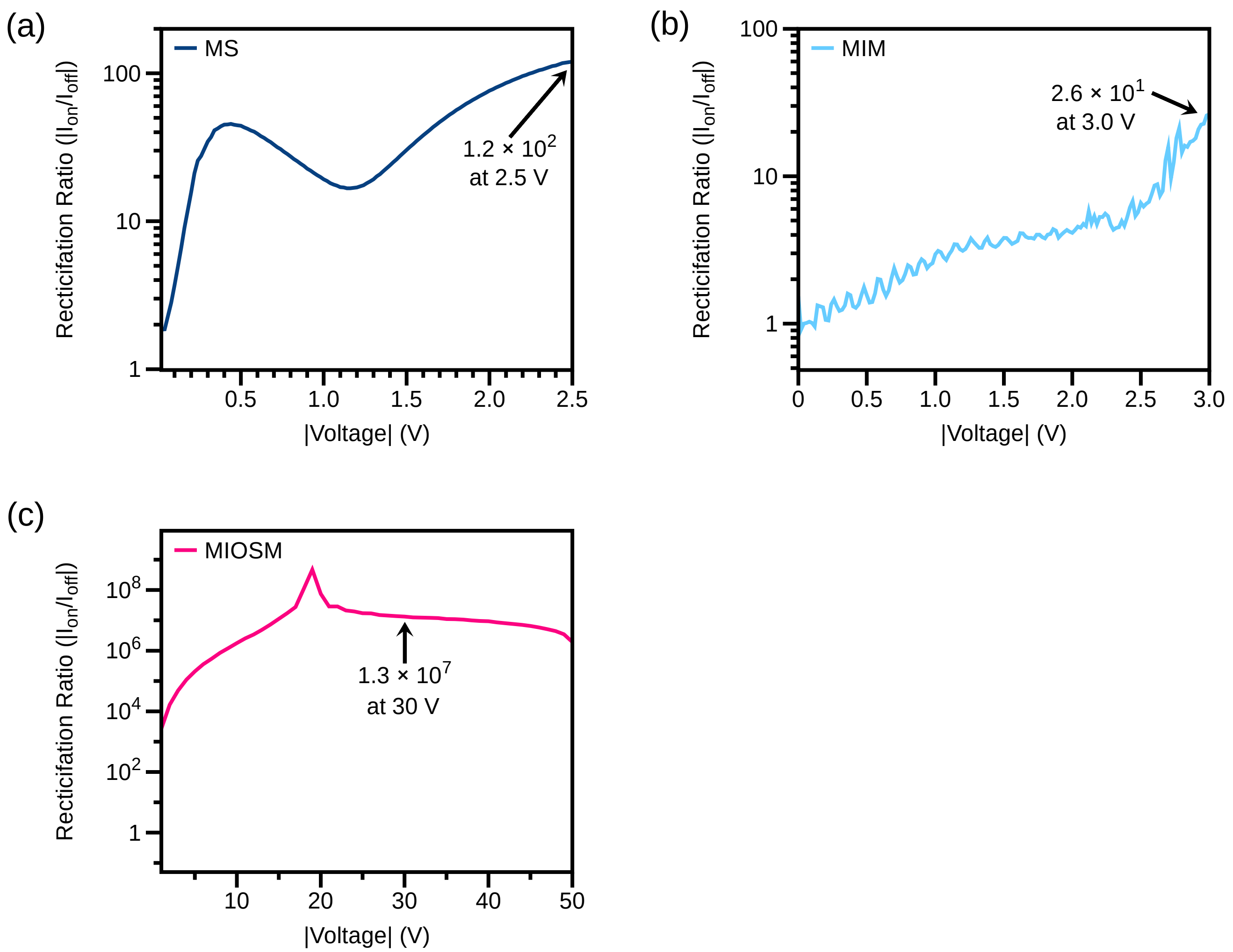

Figure S2. Rectification ratio according to voltage variation of (a) MS, (b) MIM, and (c) metal-insulator-oxide semiconductor-metal (MIOSM) thin-film diodes (TFDs). The absolute values of the on-current (I_{on}) and off-current (I_{off}) levels were compared when the forward and reverse biases applied to the bottom electrode of each TFD have the same absolute value. The rectification ratio was compared only up to a voltage lower than the applied bias in the graphs for MS and MIM TFD because breakdown occurred in the device at higher voltages. The rectification ratio at a specific voltage indicated in each graph was randomly selected as a representative value for each diode's rectification ratio.

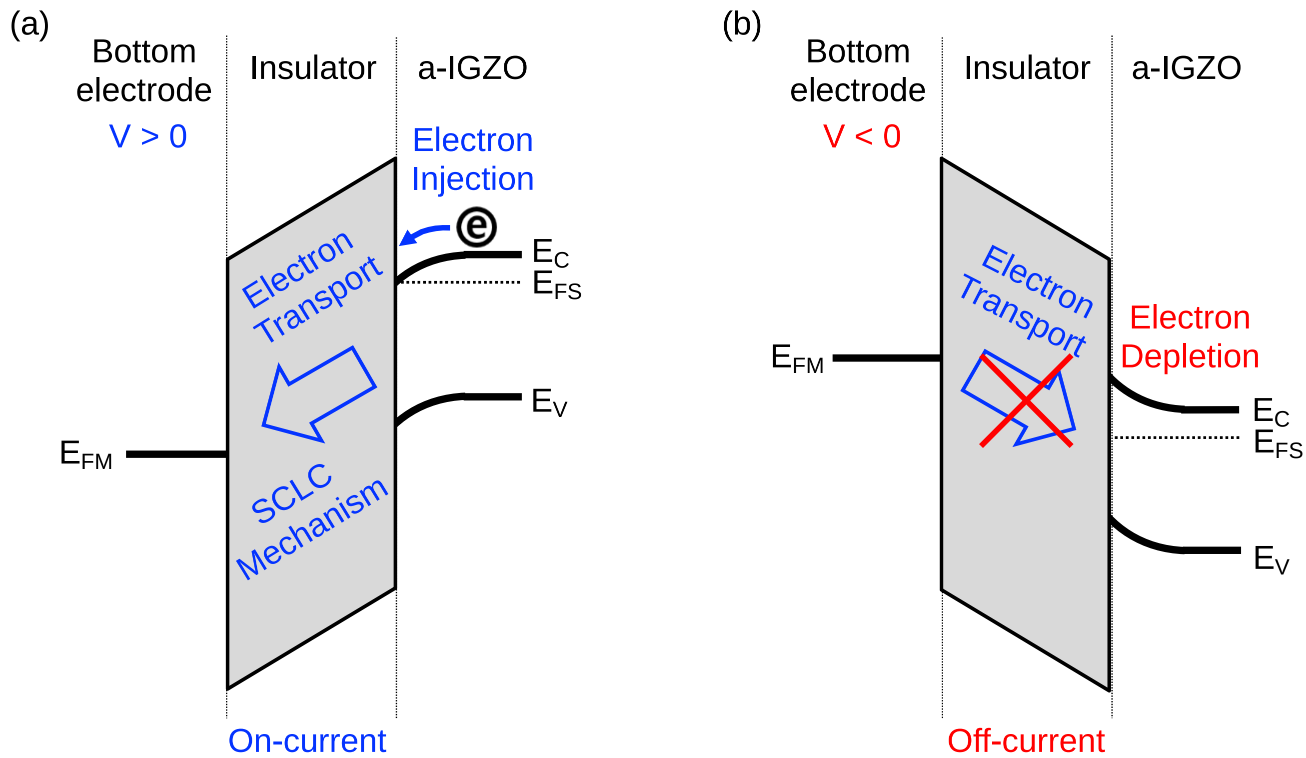

Figure S3. Band structure showing rectification characteristics according to the direction of the voltage applied to the bottom electrode of MIOSM TFD. (a) When the positive bias is applied to the bottom electrode, charges accumulated at the interface of a-IGZO are injected into trap states inside the insulator. The injected electrons are transported to the bottom electrode while filling the trap states by the electric field. (b) When a negative bias is applied to the bottom electrode, electrons are depleted at the interface of a-IGZO, preventing electrons from being injected from the bottom electrode to the trap states inside the insulator.

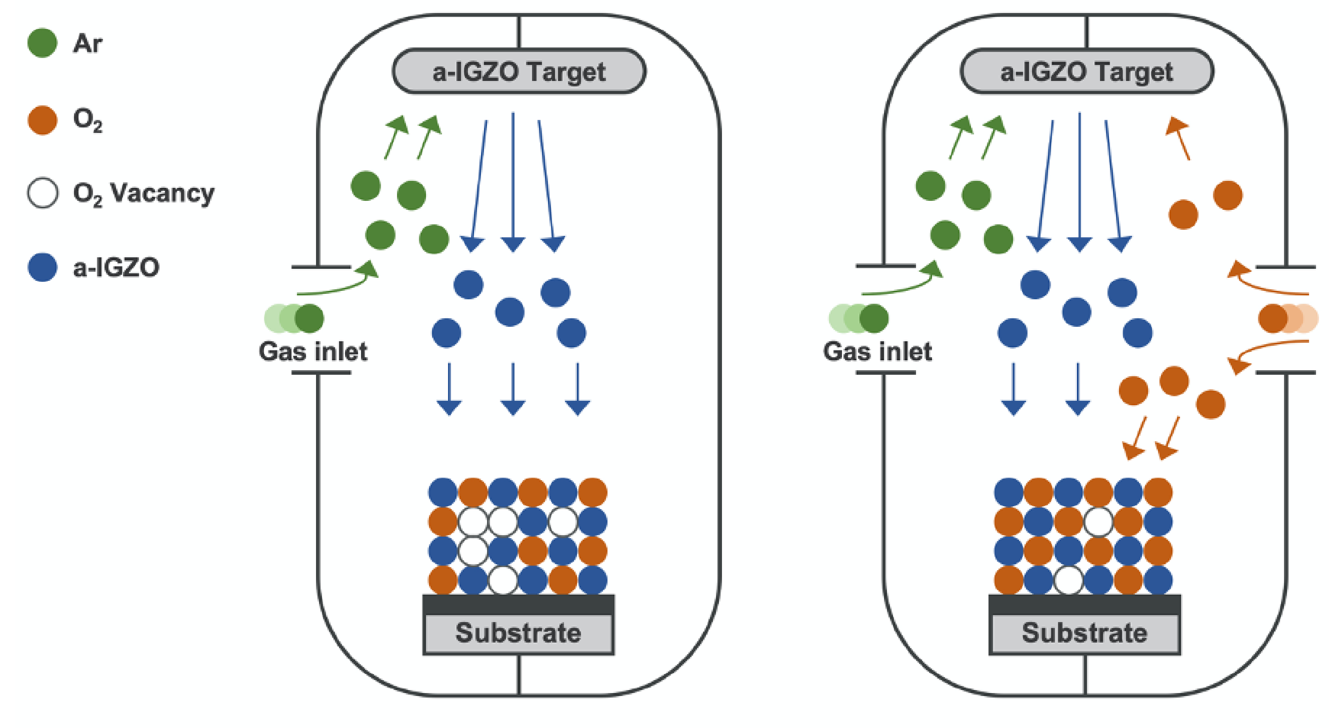

Figure S4. The process of reducing oxygen vacancies in a-IGZO. Schematic diagram of the sputtering deposition system with Ar and O_2 gas flow for the reduction of O_2 vacancies in a-IGZO.

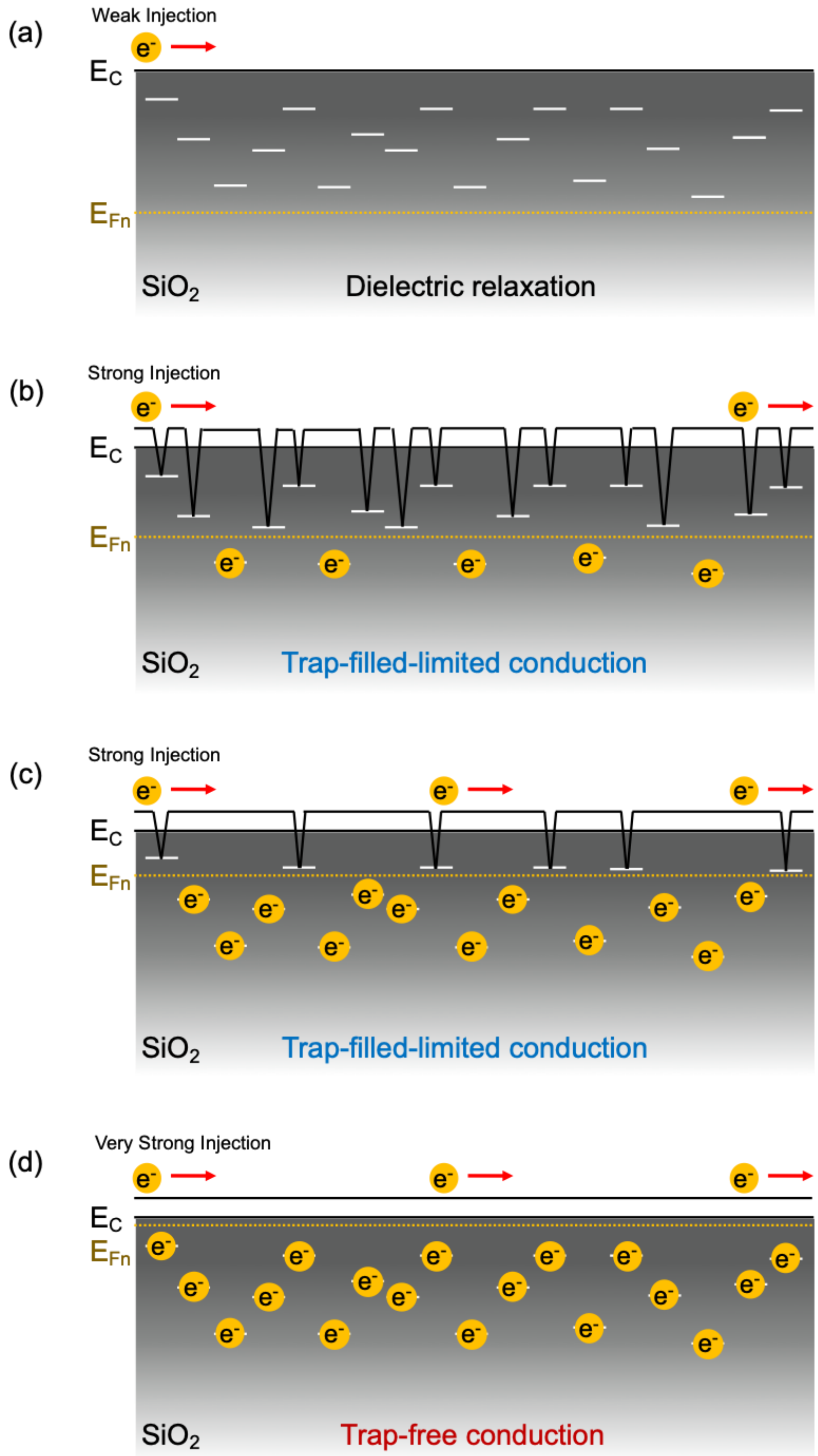

Figure S5. Charge carrier injection and flow following SCLC mechanism in an insulator. Schematic diagram of the SCLC mechanism in an insulator[1-3]. When a positive voltage is applied to the bottom electrode, electrons supplied from the top electrode are injected into the insulator by a-IGZO. As the voltage on the bottom electrode increases, the number of charge carriers injected from the a-IGZO layer into the trap states inside the insulator increases. (a) When the number of charge carriers is not sufficient (weak injection), the carrier transit time is longer than the insulator's dielectric relaxation time, so the insulator's trap states cannot be filled, and the current cannot flow. (b) As the voltage applied to the bottom electrode increases, the charges injected from a-IGZO fill the deep trap states inside the insulator (strong injection), and the current begins to flow. While the traps are filled up, the quasi-fermi level (E_{Fn}) begins to rise close to the conduction band. The trap-filled-limited (TFL) conduction is when the E_{Fn} is located between the insulator's deep trap states and the shallow trap states. (c) While the voltage at the bottom electrode increases further, and the E_{Fn} is located just below the shallow trap states. (d) When the voltage applied to the bottom electrode becomes higher than a specific voltage (very strong injection), the insulator's shallow trap states are also filled by electrons injected from a-IGZO, showing trap-free conduction.

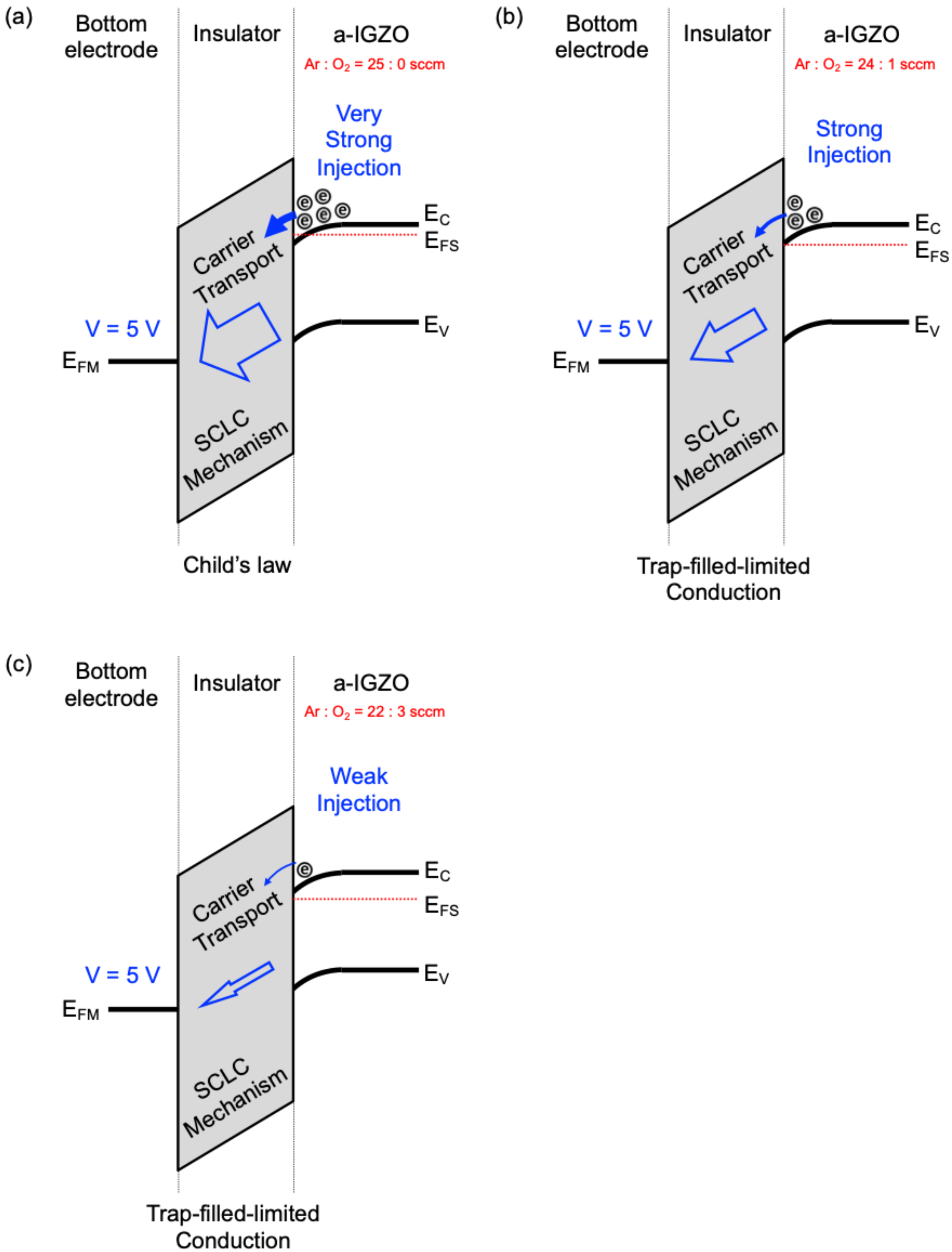

Figure S6. Band diagram showing that carrier transport inside the insulator following the SCLC mechanism depends on the amount of charge carrier injected from the outside. As the oxygen vacancies of a-IGZO are more filled, the charge carrier's amount accumulated at the interface decreases. Therefore, when the same voltage of 5 V is applied to the bottom electrode of every MIOSM TFD, the current level using a-IGZO deposited at a low oxygen gas flow rate is relatively high. (a) In the condition of Ar/O_2 = 25:0 sccm, a-IGZO has the most oxygen vacancies relatively, so very strong injection occurs from the oxide semiconductor interface to the trap states inside the insulator at the same voltage. (b) When the oxygen partial pressures in the sputter chamber increases with Ar/O_2 = 24:1 sccm, the oxygen vacancies are more filled, and fewer charge carriers are accumulated at the interface at the same voltage. As a result, strong injection occurs, and charge carriers injected inside the insulator move with trap-filled-limited conduction characteristics. (c) When the gas flow rate is Ar/O_2 = 22:3 sccm, fewer charge carriers accumulate at the interface due to the more filled oxygen vacancies. Accordingly, weak injection occurs and shows a relatively lower current level at the same voltage.

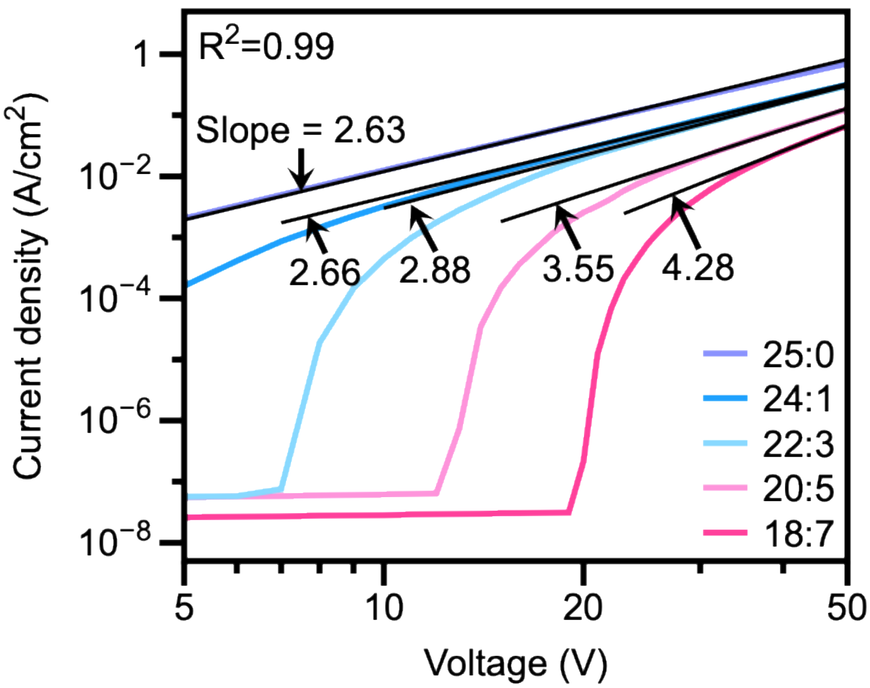

Figure S7. Space-charge-limited conduction (SCLC) characteristics of the MIOSM devices. Log *J*-log *V* characteristics and fitted slope values for verifying SCLC mechanism of the MIOSM (p^{++} Si/100 nm SiO_2/40 nm a-IGZO/100 nm Al) TFDs depending on the difference of a-IGZO deposition state by gas flow rate variation from Ar/O_2 = 25:0 to 24:1, 22:3, 20:5, and 18:7 sccm using radio-frequency sputter system.

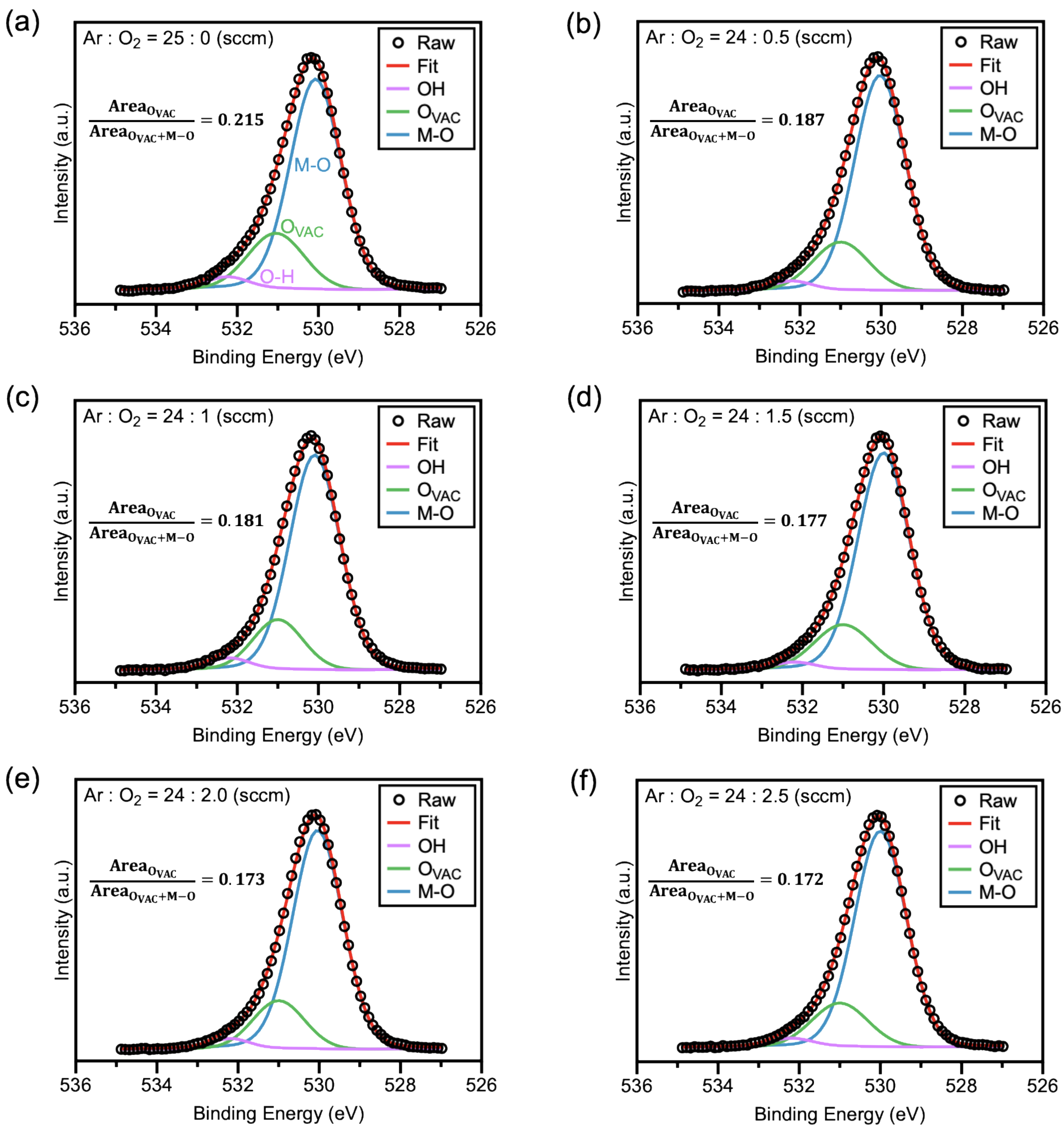

Figure S8. Oxygen vacancy composition of a-IGZO-based MIOSM TFDs with different gas flow rate. XPS O1s spectra of a-IGZO with variation of Ar/O_2 gas flow rate from (a) 25:0 to (b) 24:0.5, (c) 24:1.0, (d) 24:1.5, (e) 24:2.0, and (f) 24:2.5 sccm using radio-frequency sputtering system.

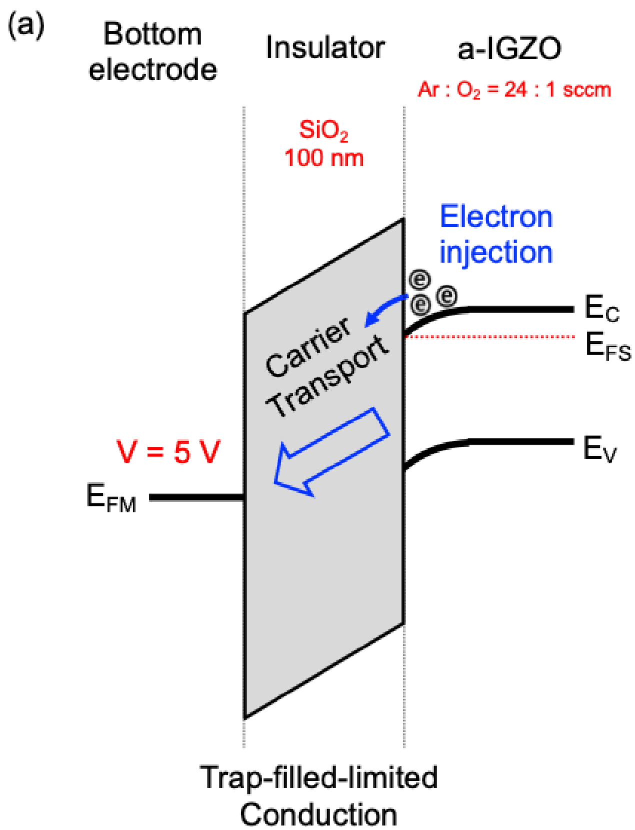

Figure S9. Band diagram shows that when the insulator is thicker, a higher voltage must be applied to achieve the same current level. (a) When 100 nm-thick SiO_2 is applied, 5 V is required to achieve 4×10^{-7} A. On the other hand, (b) when 9 nm-thick HfO_X is applied, a lower voltage of 1 V is sufficient to achieve 1.5×10^{-7} A. When the insulator's thickness is thicker, the amount of charge carriers to fill the trap states inside the insulator is required more than the thin insulator. As a result, when the thickness of the insulator is relatively thin, the trap states inside the insulator are filled at a lower voltage and the trap-free region appears more quickly. Conversely, a thicker insulator requires a relatively larger amount of charge carriers to fill the trap states, resulting in a trap-free region at higher voltages.

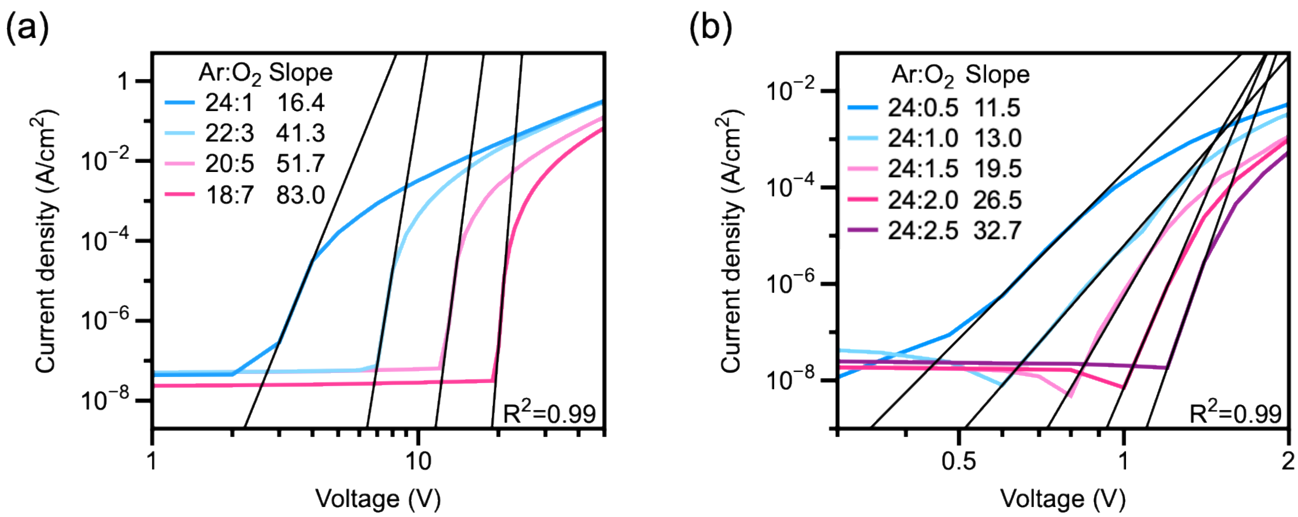

Figure S10. Changes in the electrical characteristics of a MIOSM TFDs according to a-IGZO's oxygen vacancy and insulator's thickness control. Log *J*-log *V* characteristics of the MIOSM TFDs in the trap-filled-limited (TFL) region depending on the insulator thickness and the variation of Ar/O_2 gas flow rate during a-IGZO deposition by radio-frequency sputter. The fitted slope value represents the highest slope value in the TFL region. The reason for showing a higher slope value when the turn-on voltage is higher is that charge carriers fill the trap states more rapidly inside the insulator as the MIOSM TFD turns on at a higher voltage. (a) Electrical properties change when 100 nm SiO_2 and various a-IGZO deposition gas flow rates (Ar/O_2 = 24:1, 22:3, 20:5, and 18:7 sccm) are applied. (b) Changes in diodes' electrical properties when 9 nm HfO_X and various a-IGZO deposition gas flow rates are applied from Ar/O_2 = 24:0.5 to 24:1, 24:1.5, 24 : 2, and 24:2.5 sccm.

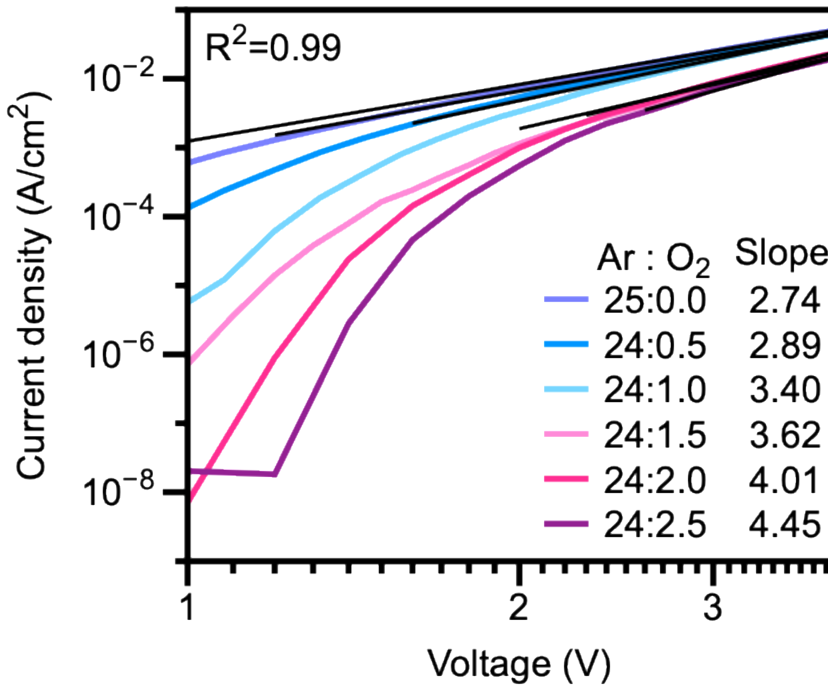

Figure S11. SCLC characteristics of the MIOSM TFDs applying thin insulator. Log *J*-log *V* characteristics and fitted slope values for verifying SCLC mechanism of the MIOSM (p^{++} Si/9 nm HfO_x/40 nm a-IGZO/100 nm Al) TFDs depending on the difference of a-IGZO deposition state by gas flow rate variation from Ar/O_2 = 25:0 to 24:0.5, 24:1.0, 24:1.5, 24:2.0, and 24:2.5 sccm using radio-frequency sputter system.

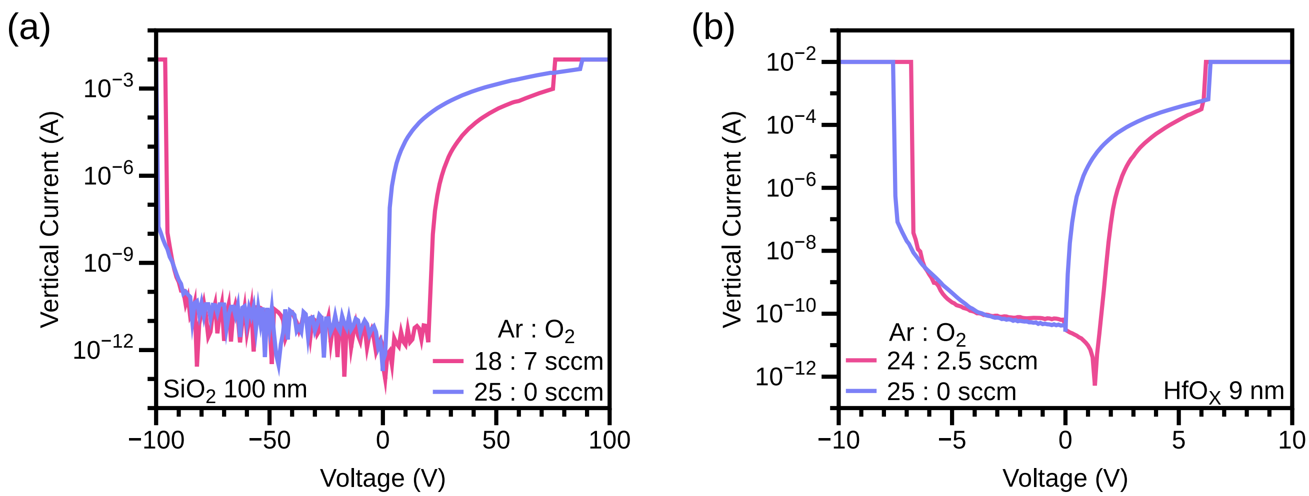

Figure S12. Breakdown voltage test of MIOSM TFD using (a) 100 nm-thick SiO_2 and (b) 9 nm-thick HfO_X as an insulator. Breakdown voltages were compared under the conditions of Ar/O_2 gas flow rates of 25:0 vs 18:7 sccm for SiO_2 and 25:0 vs 24:2.5 for HfO_X, respectively.

Table S1. MIOSM TFD's current level comparison for each gas flow rate reflecting the turn-on voltage shift offset.

Ar/O2 [sccm]	25:0	24:1	22:3	20:5	18:7
Turn-on voltage shift offset [V]	0	2	7	12	19
Applied voltage [V]	5	7	12	17	24
On-current [A]	5.12×10^{-6}	2.15×10^{-6}	4.39×10^{-6}	1.68×10^{-6}	1.05×10^{-6}
Applied voltage [V]	10	12	17	22	29
On-current [A]	3.14×10^{-5}	1.46×10^{-5}	2.57×10^{-5}	1.07×10^{-5}	9.06×10^{-6}
Applied voltage [V]	15	17	22	27	34
On-current [A]	8.88×10^{-5}	4.29×10^{-5}	6.76×10^{-5}	3.20×10^{-5}	2.73×10^{-5}
Applied voltage [V]	20	22	27	32	39
On-current [A]	1.84×10^{-4}	9.02×10^{-5}	1.27×10^{-4}	6.55×10^{-5}	5.69×10^{-5}

Current levels were compared to reference data reflecting the turn-on voltage offset for each gas flow rate condition. The current level compared by applying an offset to the voltage shows a tendency that the on-current level decreases at the same voltage as the O_2 gas flow rate relative to Ar increases during sputtering. This result is consistent with the XPS analysis (Figure 2 and S7) that a-IGZO's oxygen vacancy decreases as the O_2 gas flow rate increases during sputtering.

Table S2. Reverse and forward breakdown voltage of the MIOSM TFDs.

Insulator	Thickness [nm]	Gas flow rate Ar/O_2 [sccm]	Breakdown Voltage [V]	
			Reverse	Forward
SiO_2	100	25:0	-99	87
		18:7	-95	75
HfO_X	9	25:0	-7.5	6.3
		24:2.5	-6.7	6

The breakdown voltage of MIOSM TFD according to forward and reverse biases applied to the bottom electrode when using 100 nm-thick SiO_2 and 9 nm-thick HfO_X.

Supporting references

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