Supplementary Information

Improved Switching Characteristics of p-Type Tin Monoxide Field-Effect Transistors through Schottky Energy Barrier Engineering

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1. LEAKAGE AND OUTPUT CHARACTERISTICS

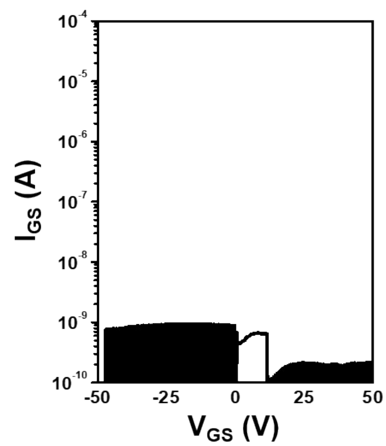

Figure S1. Current versus voltage (I_{GS}-V_{GS}) characteristics of p-type SnO FET using Pt S/D electrode.

2. CONTACT RESISTANCE EXTRACTION BY CTLM METHOD

We extracted the contact resistance (R_C) for MS contact and MIS contact with 0.5-nm-thick IL for Au and Pt electrode by using circular transmission line method (CTLM). The geometric of CTLM pattern is depicted in Figure S2. Table S1 summarizes the extracted R_C values.

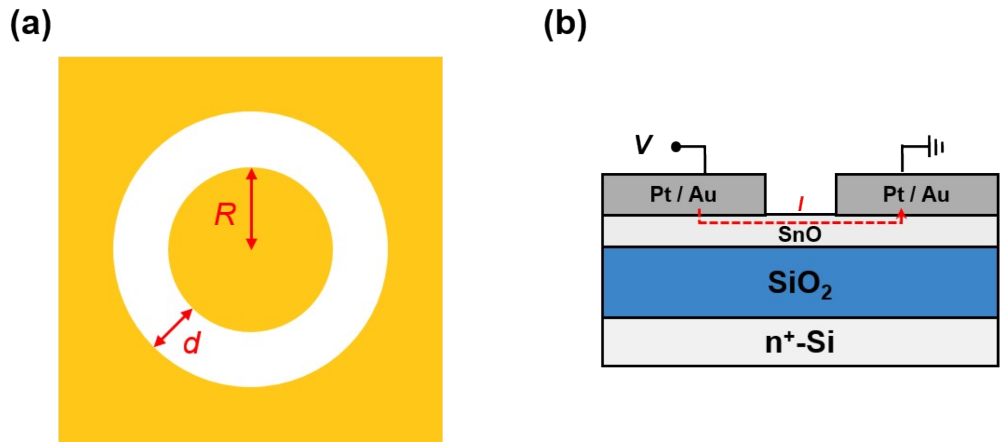

Figure S2. (a) Top view of the geometric of circular transmission length method (CTLM) pattern. (b) Cross-sectional diagram of the CTLM device.

Table S1. Contact and total resistance in the MS and 0.5-nm-thick MIS FETs.

Contact type	Pt		Au	
	R_C (MΩ)	R_T (MΩ)	R_C (MΩ)	R_T (MΩ)
MS (W/O Al_2O_3)	0.13	1.57	0.12	1.56
MIS (Al_2O_3 = 0.5 nm)	0.47	2.26	0.66	2.61

3. OUTPUT CHARACTERISTICS AT LOW V_{DS} REGION

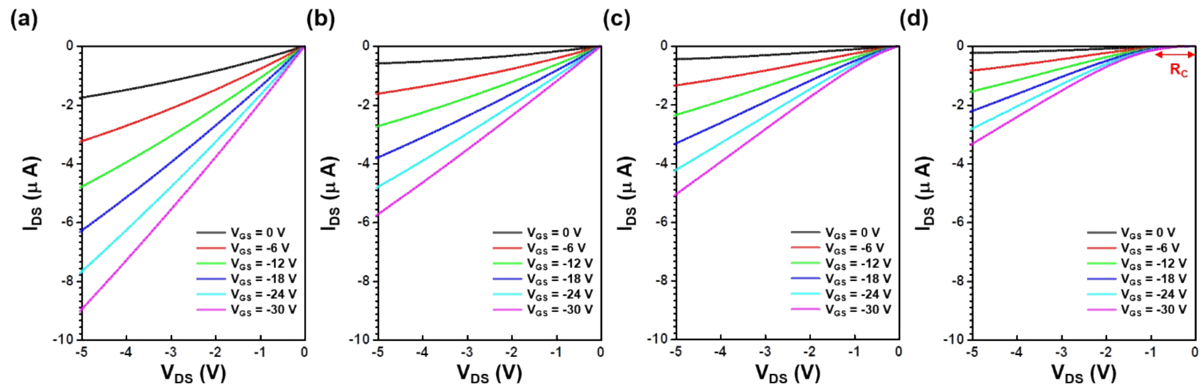

Figure S3. Output characteristics of the MIS FET using Pt electrode in the low V_{DS} region depending on the IL thickness. (a) 0 nm. (b) 0.25 nm. (c) 0.5 nm. (d) 1 nm.

4. BAND DIAGRAMS OF THE MIS CONTACT WITH AND WITHOUT VBO

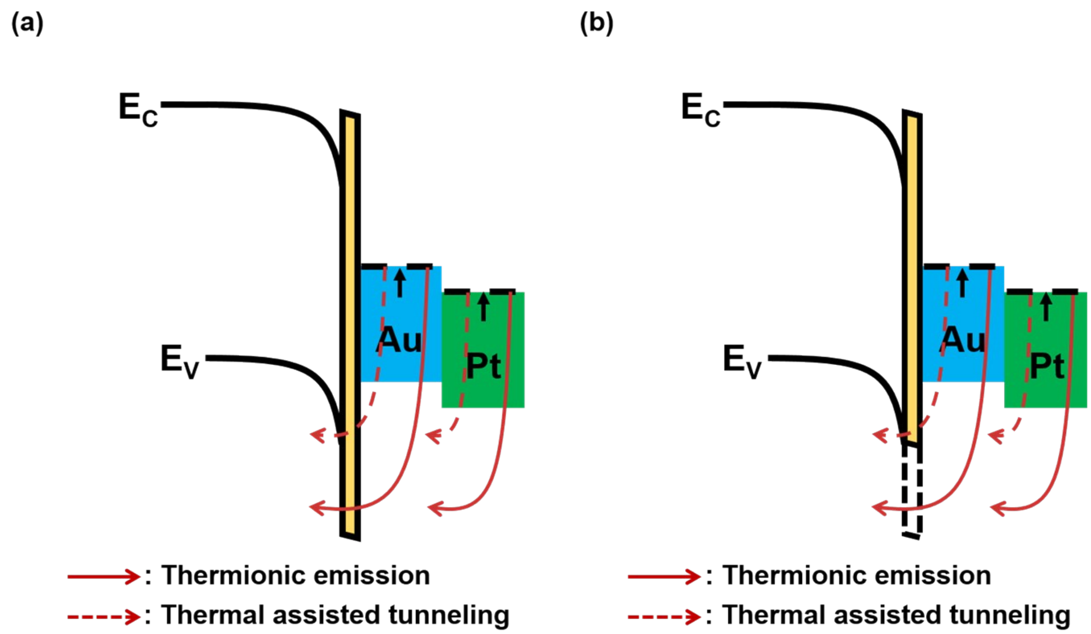

Figure S4. Band diagram of the MIS contact (a) with high VBO, and (b) without VBO.

As shown in Figure S3a, the thermionic emission current can be blocked by the interlayer (IL) in MIS contact with high VBO. This interruption from VBO can be surmounted by using IL with zero VBO as shown in Figure S3b. Moreover, the thermal assisted tunneling current can be increased by using IL with zero VBO, because the IL tunneling probability (T_{IL}) increases with the decrease of VBO by the following formula:

$$T_{IL} = exp\left[- 2d_{IL}\frac{\left(2qm_{h}^{*}T_{offset}\right)^{\frac{1}{2}}}{\hbar}\right] \quad \textbf{(S1)}$$

where d_{IL} is the thickness of the IL, m_h^* is the hole effective mass, $\hbar$ is the Dirac's constant, and T_{offset} is the value of the VBO. Therefore, we can predict that on-current of MIS contact will be enhanced by the adoption of low VBO IL, which induces Fermi-level unpinning without the formation of large tunneling barrier offset.

5. LINEAR RELATION BETWEEN V_{GS} AND ϕ_B

The physical origin of the linear relationship between V_{GS} and ϕ_B can be understood mathematically. The subthreshold I_D in the gate voltage region of $V_{GS} > V_{FB}$ can be described by the following Eq. (S2):

$$I_D \approx exp\left(-\frac{q(V_{GS}-V_{TH})}{c_r k_B T}\right), c_r = \left[1+\frac{C_d+C_{it}}{C_i}\right] \quad \textbf{(S2)}$$

where C_i is the dielectric capacitance per unit area, C_d is the depletion capacitance in the channel, and C_{it} is the fast interface state capacitance. Combining the Eq. 3 (in manuscript) and Eq. S2, the following Eq. S3 is given:

$$-A^* T^2 exp\left(-\frac{q\phi_B}{k_B T}\right) \approx exp\left(-\frac{q(V_{GS}-V_{TH})}{C_r k_B T}\right) \quad \textbf{(S3)}$$

Taking a log function on both sides of the Eq. S3, it can be shown that the ϕ_B increases linearly with the V_{GS} in this subthreshold region where $V_{GS} > V_{FB}$.

6. EXTRACTION METHOD OF S PARAMETER

SBH of MS contact with no charge transfer between metal and semiconductor interface, i.e., ideal contact formation without FLP, can be easily calculated by the well-known equation:

$$\phi_B = (\phi_m - \chi) \tag{S4}$$

where ϕ_B is the SBH, ϕ_m is the work-function of metal, and χ is the electron affinity of semiconductor. However, there are some charge transfer between metal and semiconductor interface states and thus, an interface dipole with atomic-scaled thickness is created. This charge transfer modifies SBH of MS contact as follows:[1]

$$\phi_B = S(\phi_m - \phi_{CNL}) + (\phi_{CNL} - \chi) \tag{S5}$$

Here, ϕ_{CNL} is the charge neutrality level (CNL) of interface states, which physically means the branch point where the density of donor-like states and that of acceptor-like states are same. S is the pinning factor which is given by[1]

$$S = \frac{1}{1 + (q^2 D_{it}\delta)/\varepsilon_\delta} \tag{S6}$$

where q is electronic charge, D_{it} is the density of interface states, δ and ε_δ are the dipole thickness at interface and the permittivity of it. The S parameter becomes close to zero as D_{it} increases and the Fermi-level at thermal equilibrium condition becomes close to the CNL regardless of metal work function. As shown in **Eq. S5**, this S parameter is the slope parameter of SBH as a function of metal work function. Hence, we can estimate the S parameters for MS and MIS contacts (IL thickness = 0.25 nm, 0.5 nm) by using the extracted SBH values for both Au and Pt metal electrodes, as given by

$$S = \frac{d\phi_B}{d\phi_m} \cong \frac{\phi_{B,Pt} - \phi_{B,Au}}{\phi_{m,Pt} - \phi_{m,Au}} \tag{S7}$$

REFERENCE

[1] J. Robertson, *J. Vac. Sci. Technol.,* 2000, 18, 1785.