Electronic Supplementary Material (ESI) for Nanoscale.

Electronic Supplementary Information (ESI)

Promising ultra-short channel transistors based on OM_2S (M=Ga, In) monolayer for high performance and low power consumption

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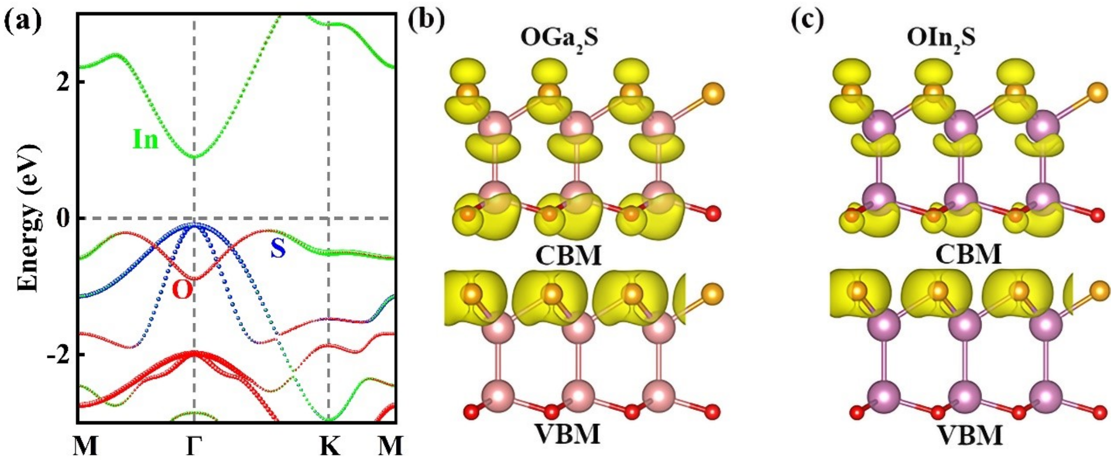

Fig. S1 (a) Projected band structures of OIn_2S monolayer. Band-decomposed charge-density distributions relevant to conduction band minimum and valence band maximum of (b) OGa_2S and (c) OIn_2S. Isovalue is 0.008 e/bohr^3.

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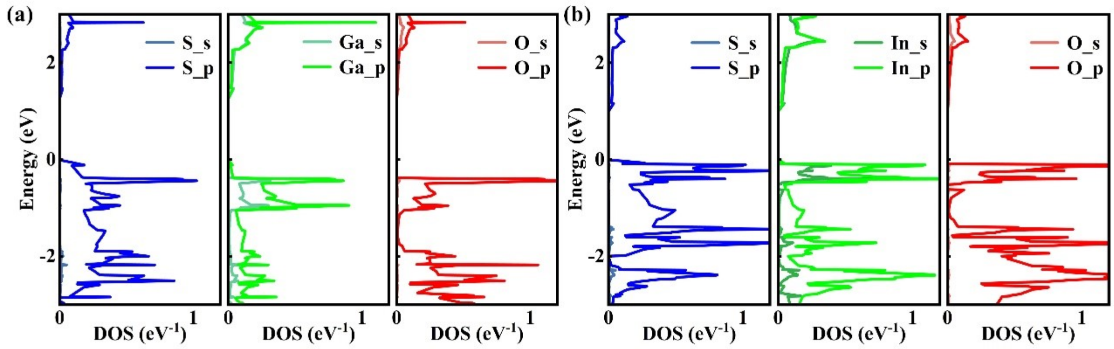

Fig. S2 Projected density of states (PDOS) of (a) OGa_2S and (b) OIn_2S.

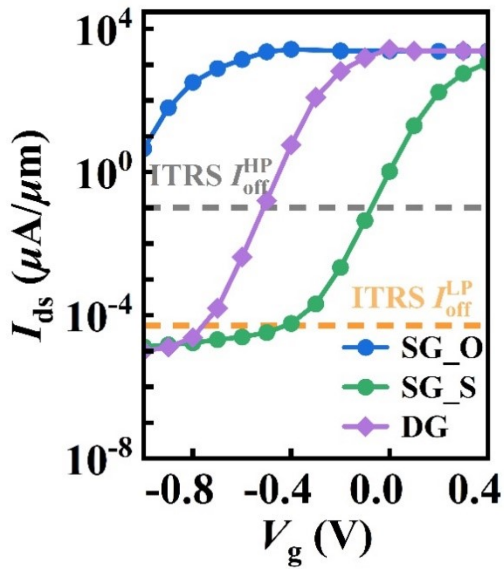

Fig. S3 Transfer characteristics of dual-gate (DG) and single-gate (SG) *n*-type OGa_2S MOSFETs with L_g equal to 5nm. The doping concentration in the electrode region is 3×10^{13} e/cm^{-2}. The gray and orange lines stand for ITRS off-state current standards for HP and LP applications, respectively. The SG_O and SG_S indicate that the gate electrode is added to the oxygen and sulfur terminals, respectively.

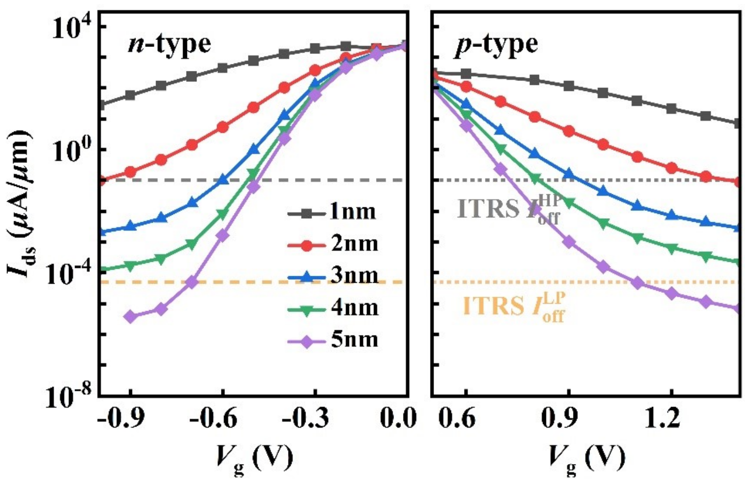

Fig. S4 Transfer characteristics of *n*-type and *p*-type OIn_2S MOSFETs with diverse L_g under supply voltage V_{ds} = 0.64 V. The doping concentration in the electrode region is 3×10^{13} e/cm^{-2}. The gray and orange lines stand for ITRS off-state current standards for HP and LP applications, respectively.

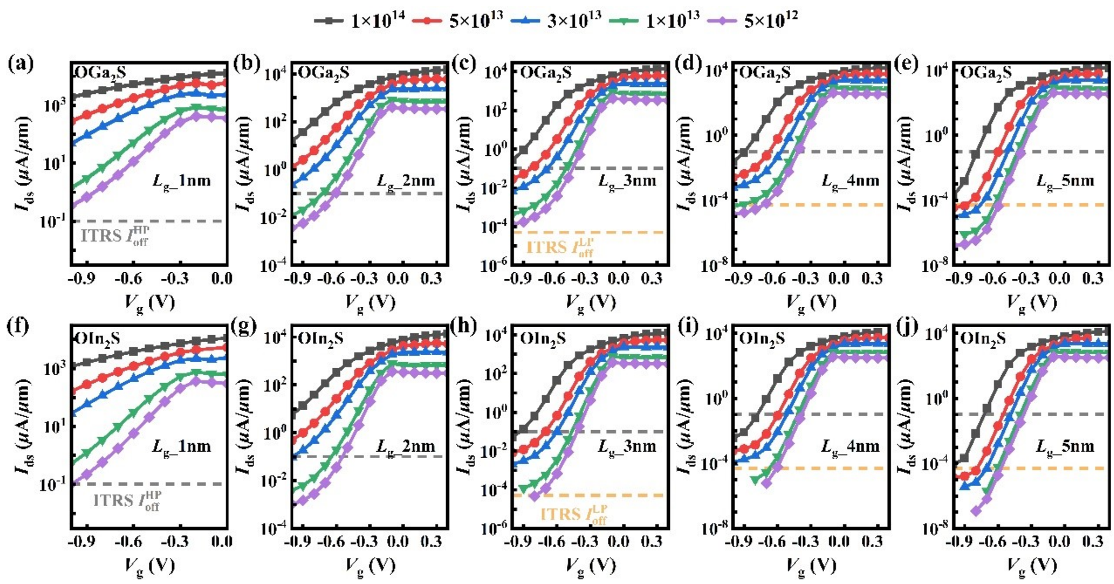

Fig. S5 Transfer characteristics of monolayer (a-e) OGa_2S and (f-j) OIn_2S MOSFETs under supply voltage V_{ds} = 0.64 V with diverse electrode doping concentrations of electron.

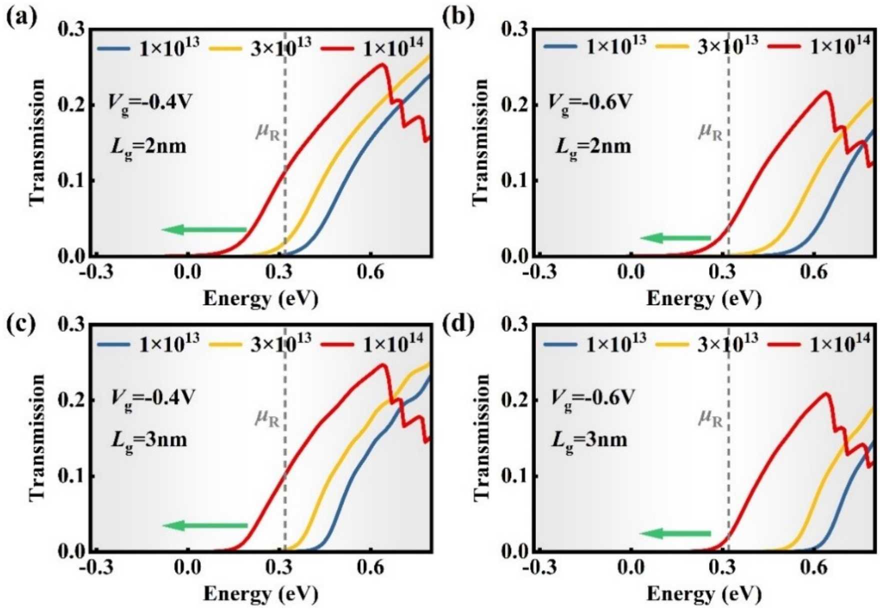

Fig. S6 Transmission spectra of the (a-b) 2nm and (c-d) 3nm OGa_2S MOSFETs with different doping concentrations and V_g. The V_{ds} is 0.64 V and the bias window is an energy window of -0.32~0.32 eV. The μ_R is the electrochemical potential of the right electrode.

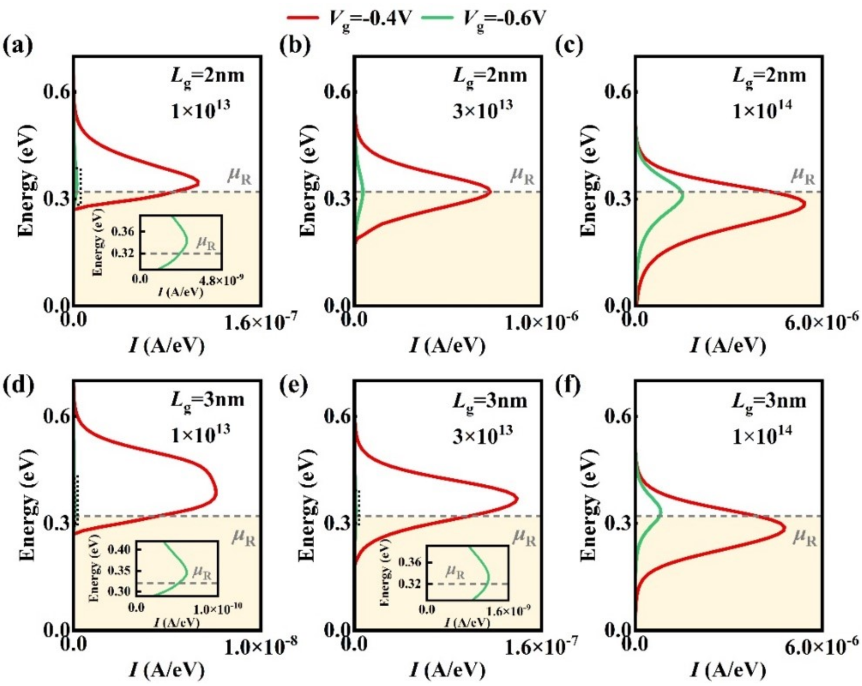

Fig. S7 The spectral current of the (a-c) 2nm and (d-f) 3nm OGa_2S MOSFETs with different doping concentrations. The insets in (a), (d) and (e) are enlarged images of the sections in dashed boxes.

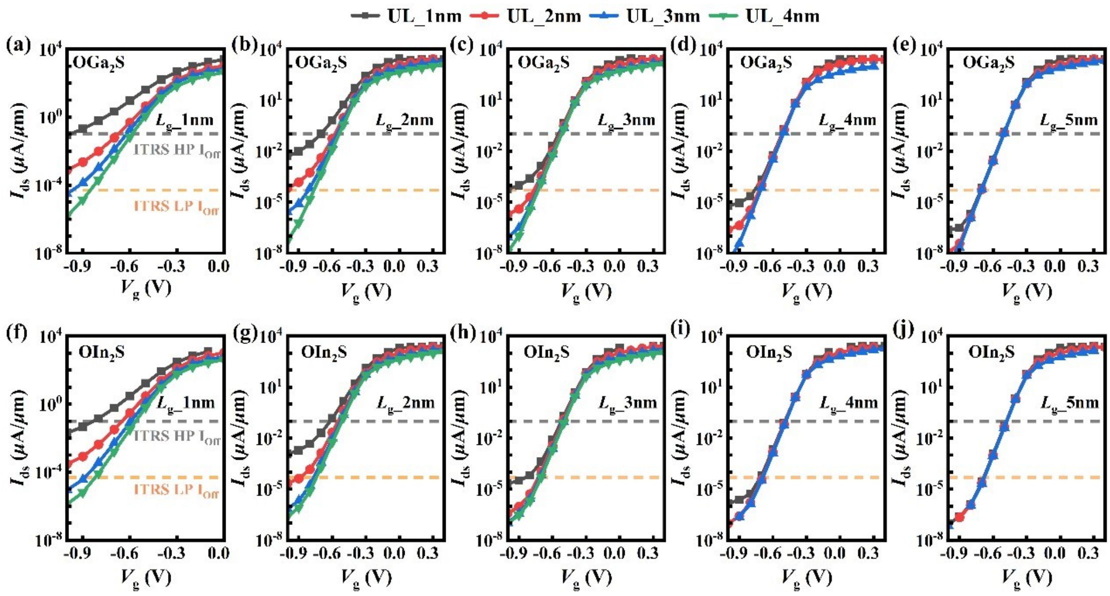

Fig. S8 Transfer characteristics of monolayer OGa_2S (a) and OIn_2S MOSFETs (b) with diverse underlap (UL) length at V_{ds} = 0.64 V.

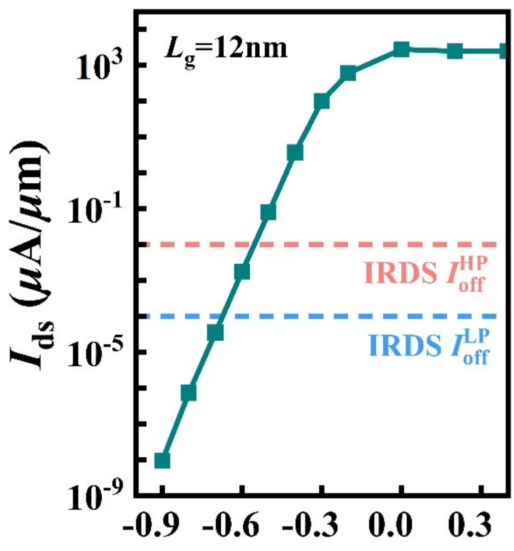

Fig. S9 Transfer characteristics of OGa_2S MOSFETs with L_g equal to 12nm. The doping concentration in the electrode region is 3×10^{13} e/cm^{-2} and the V_{ds} is 0.65 V. The red and blue dashed lines stand for IRDS off-state current standards for HP and LP applications, respectively.

Table S1. Performance metrics of OGa_2S MOSFETs with L_g equal to 12nm in our work against the requirements of the IRDS in 2028. L_g: Gate length; V_{ds}: Supply voltage; SS: Subthreshold swing; τ: Delay time; and PDP: Power dissipation, respectively.

	L_g (nm)	V_{ds} (V)	I_{off} (μA/μm)	I_{on} (μA/μm)	SS (mV/dec)	τ (ps)	PDP (fJ/μm)
IRDS 2028(HP)	12	0.65	0.01	1979	75	0.122	0.156
OGa_2S	12	0.65	0.01	2570.7	59.6	0.085	0.140
IRDS 2028(LP)	12	0.65	1×10^{-4}	1336	68	0.180	0.156
OGa_2S	12	0.65	1×10^{-4}	2279.8	58.7	0.088	0.128

Supporting Note: Comparison between dual-gate and single-gate OGa_2S MOSFETs and analysis of SS

The transfer characteristics of the single-gated (SG) and double-gated (DG) *n*-type OGa_2S MOSFETs with L_g equal to 5nm are calculated, as shown in Fig. S3. The off-state current of the SG_O device (the gate electrode is added to the oxygen terminal) is difficult to meet the high-performance (HP) requirement of ITRS 2028 level. The DG and SG_S devices (the gate electrode is added to the sulfur terminal) can approach this requirement at V_g = -0.51 V and -0.08 V, respectively. What's more, the off-state current of the DG and SG_S devices even can satisfy the low-power (LP) consumption standard of ITRS 2028 level at the V_g = -0.76 V and -0.45 V, respectively. However, the LP on-state current of the SG_S device (137.1 μA/μm) is unable to reach the ITRS requirement (295 μA/μm). By contrast, the LP on-state current of the DG device (1300.2 μA/μm) exceeds the ITRS demand and is about 10 times larger than that of the SG_S configuration. In addition, the subthreshold swing (SS) of DG OGa_2S MOSFET (63.6 mV/dec) is smaller than that of the SG counterpart (73.0 mV/dec).

The above phenomenon can be illustrated by the natural length λ, which is calculated by the formula $\lambda = (\varepsilon_{ch} \cdot t_{ch} \cdot t_{ox} / N\varepsilon_{ox})^{1/2}$. The t_{ch} (t_{ox}) is the thickness of channel (dielectric layer), ε_{ch} and ε_{ox} are the dielectric constant of channel and dielectric layer separately, and N is the gate numbers. Compared with the SG configuration, the DG device possesses a larger N and thus a smaller λ. Therefore, the gate controllability of the DG device is better than that of the SG device, which leads to lower leakage current and larger on-state current of DG device. Similar conclusions have been reported in previously published studies.[59-61] For example, the DG MoS_2 FET shows a smaller SS (65.5 mV/dec) than that of the SG counterpart (130 mV/dec) at the same drain voltage in the experiment.[60]

Fig. S6 and Fig. S7 plot the transmission spectra and spectral current of the 2nm and 3nm OGa_2S MOSFETs with different doping concentrations. When the doping concentration increases, the edge of the transmission spectrum gradually shifts towards the left, and the transmission possibility inside the bias window is larger, thus the larger I_{ds} can be gotten at high doping concentration. At the V_g= -0.4V, the OGa_2S MOSFETs with 2nm L_g possesses a larger transmission possibility inside the bias window than that of 3nm devices, which is consistent with the higher I_{ds} of the 2nm devices in Fig. S5. However, when V_g = -0.6V, a higher I_{ds} value is not conducive to the devices reaching the off-state. As can be seen from Fig. S6(b) and (d), the 3nm OGa_2S MOSFETs feature a lower transmission possibility within the bias window, so the 3nm OGa_2S MOSFETs are easier to approach the off-state than the 2nm devices. Moreover, for the OGa_2S MOSFETs with a doping concentration of 1×10^{13} e/cm^2, the edge of the transmission spectrum is far away from the μ_R, indicating the lower leakage current. The above conclusion can also be seen from Fig. S7, the spectral current of the 3nm OGa_2S MOSFETs is lower than 2nm devices, corresponding to the higher I_{ds} of the 2nm devices. And the spectral current of the OGa_2S MOSFETs with the doping concentration of 1×10^{13} e/cm^2 is lower than that with a doping concentration of 3×10^{13} e/cm^2 and 1×10^{14} e/cm^2. According to the $SS = \frac{\partial V_g}{\partial \lg I_{ds}}$, for the same V_g difference (ΔV_g), a large I_{ds} difference leads to a small SS. Fig S7 (a) and (d) show that the 3nm OGa_2S MOSFETs have a larger difference of I (at the same V_g difference, ΔV_g = -0.4V – (-0.6V)) compared to the 2nm devices, resulting in a lower SS. This conclusion is applicable to other doping concentrations. Moreover, with the decrease of doping concentration, the difference of I increases gradually, thus the SS decreases with the doping concentration declines

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