Electronic Supplementary Information

NiO_x Schottky-Gated ZnO Nanowire Metal-Semiconductor Field Effect Transistor: Fast Logic Inverter and Visible Photo-Detector

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ESI 1: Bottom-gate transfer properties of the ZnO NW FETs with SiO_2/p^+-Si gate

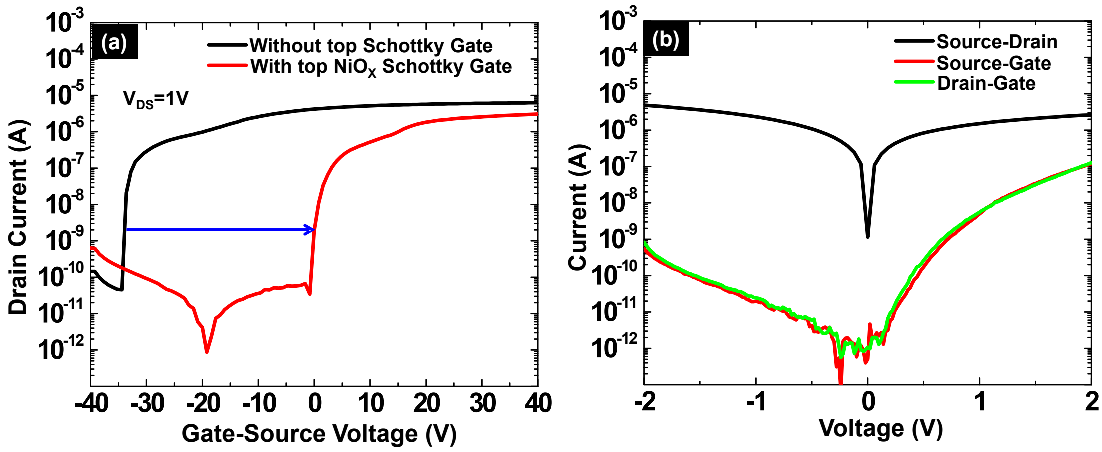
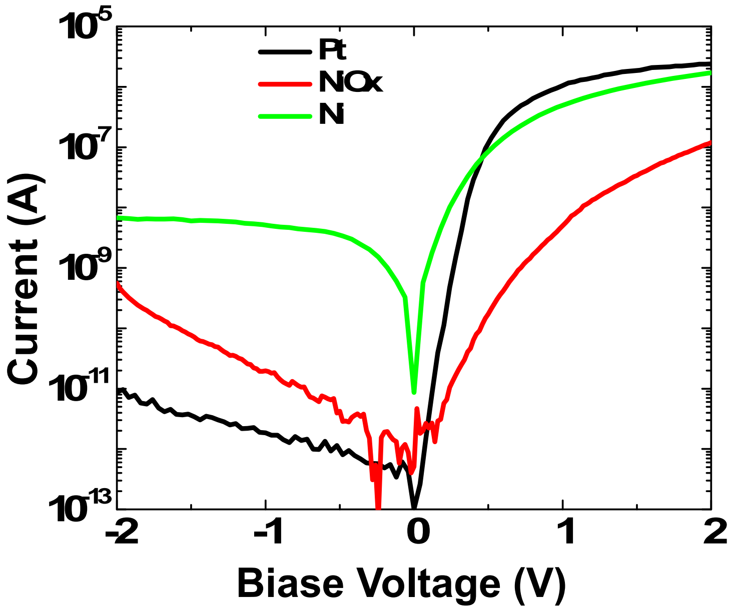


Figure S1: (a) Bottom-gate transfer I_D-V_{GS} properties of ZnO NW FET on a 200 nm SiO_2/p+-Si substrate with (red) and without (black) NiO_x which is deposited for top-gate MESFET. Transfer curves show the threshold shift to positive direction after NiO_x deposition due to depletion region formation as reported for CdS nano-belt MESFET.[1] **(b)** Current-voltage properties among MESFET electrodes. An ohmic nature is shown in the contact between ZnO NW and Au/Ti source-drain, while Schottky diode behavior is displayed between ZnO NW and NiO_x gate electrode.

ESI 2: Schottky diodes of different metals with ZnO nanowire



No.	Metal	Barrier Height ϕ_B (Volts)	Ideality Factor η	On/Off Current Ratio
1.	NiO_x	0.65	2.61	10^5
2.	Ni	0.47	2.6	10^3
3.	Pt	0.67	1.34	10^6

Figure S2: I-V properties of the NiO_x, Ni and Pt diodes with ZnO NW. The table shows the diode parameters i.e. barrier height, ideality factor, and on/off current ratio that are involved with the following equations.[1,2]

$$I = I_o\left(exp\left(q(V)/\eta kT\right)\right)$$

$$ln(I) = ln(I_o) + qV/\eta kT \qquad (1)$$

$$I_o = AA^*T^2exp\left(-q\Phi_{Bn}/kT\right) \qquad (2)$$

Where Richardson's constant for ZnO is $A^*=3.2\text{x}10^6$, $k=1.38\text{x}10^{-23}$ $J.K^{-1}$ and T=297 K. The ideality factor and barrier height were estimated by using the linear curve fitting of the log of diode current.

ESI 3: ZnO NW MESFET Mobility Estimation

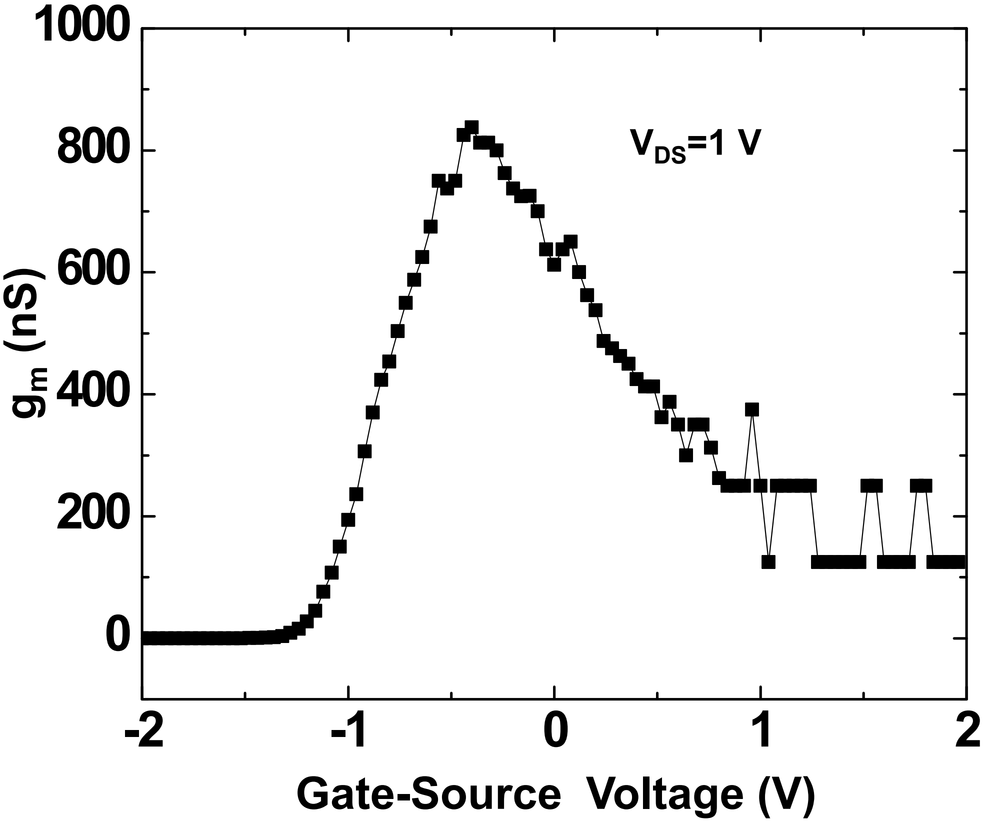


Figure S3: Trans-conductance of MESFET in the dark at V_{DS} of 1 V. The mobility and carrier concentration were estimated using the following equations. [1,2]

$$\mu_e = \frac{g_m a L}{Z \in_{ZnO} VD}; \quad g_m = \frac{dI_D}{dV_G} \qquad (3)$$

Radius of NW a=110 nm, Gate length, L = 5 μm, half cylinder Z = π x 110 nm, $[\epsilon_{ZnO\ NW}]_{220\ nm\ dia.}$=5 ϵ_o.[3]

$$\mu_e = \frac{8.38x10^{-7} * 110x10^{-7} * 5x10^{-4}}{\pi * 110x10^{-7} * 5 * 8.85X10^{-14} * 1}$$

=301 $cm^2.V^{-1}.s^{-1}$

And the carrier concentration is approximately estimated, assuming the resistivity, ρ as minimum at the maximum transconductance; $\rho = A/g_m L$, where A is πa^2.

$$n = \frac{1}{\mu \rho e} \qquad (4)$$

$$n = 4.6X10^{16} cm^{-3}$$

ESI 4: ZnO NW MESFET transfer and gate leakage under various drain biases along with the output curves showing linear and saturation regimes

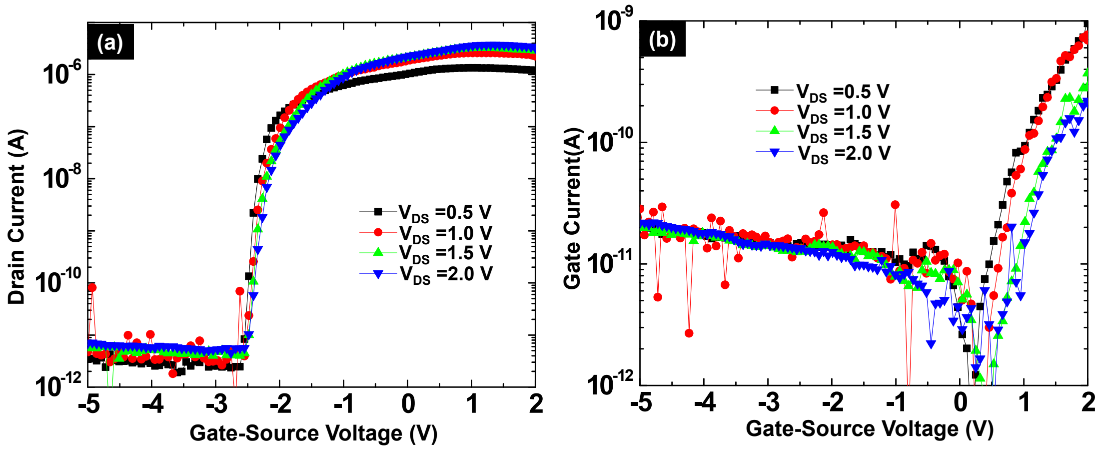
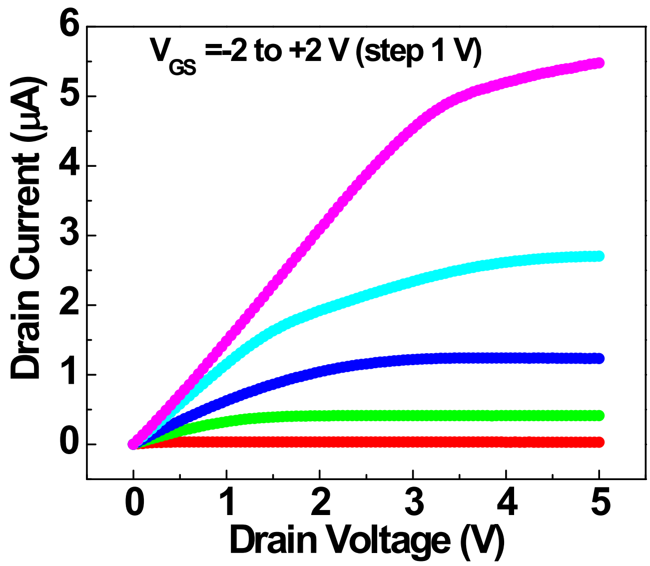


Figure S4: (a) Transfer I_D-V_{GS} and (b) gate leakage I_G-V_{GS} properties of MESFET at various V_{DS}.

We have shown the output curves in Fig. 2(b) until V_{DS} of 1 V (linear regime) however, if we increase V_{DS} more upto 5 V, the saturation is observed as shown below.



ESI 5: MESFET vs. MISFET for inverter dynamics and Cutoff frequency

Inverter Dynamics comparing the frequency response of MESFET and MISFET. The MISFET based inverter is comprised of a ZnO NW MISFET and a 0.8 MΩ/10 MΩ external resistor as load. ZnO NW MISFET has the same gate length as that of MESFET, but with a 30 nm atomic layer deposition system deposited Al_2O_3 as gate dielectric and a 100 nm thick gold as top gate electrode. Dynamic responses of the MISFET are shown in Fig. S5. The output signal of the MISFET starts distorting at 100 Hz whereas we saw in the main text that there is no apparent distortion in output signal for MESFET until 1 kHZ which is limit of our parameter analyser.

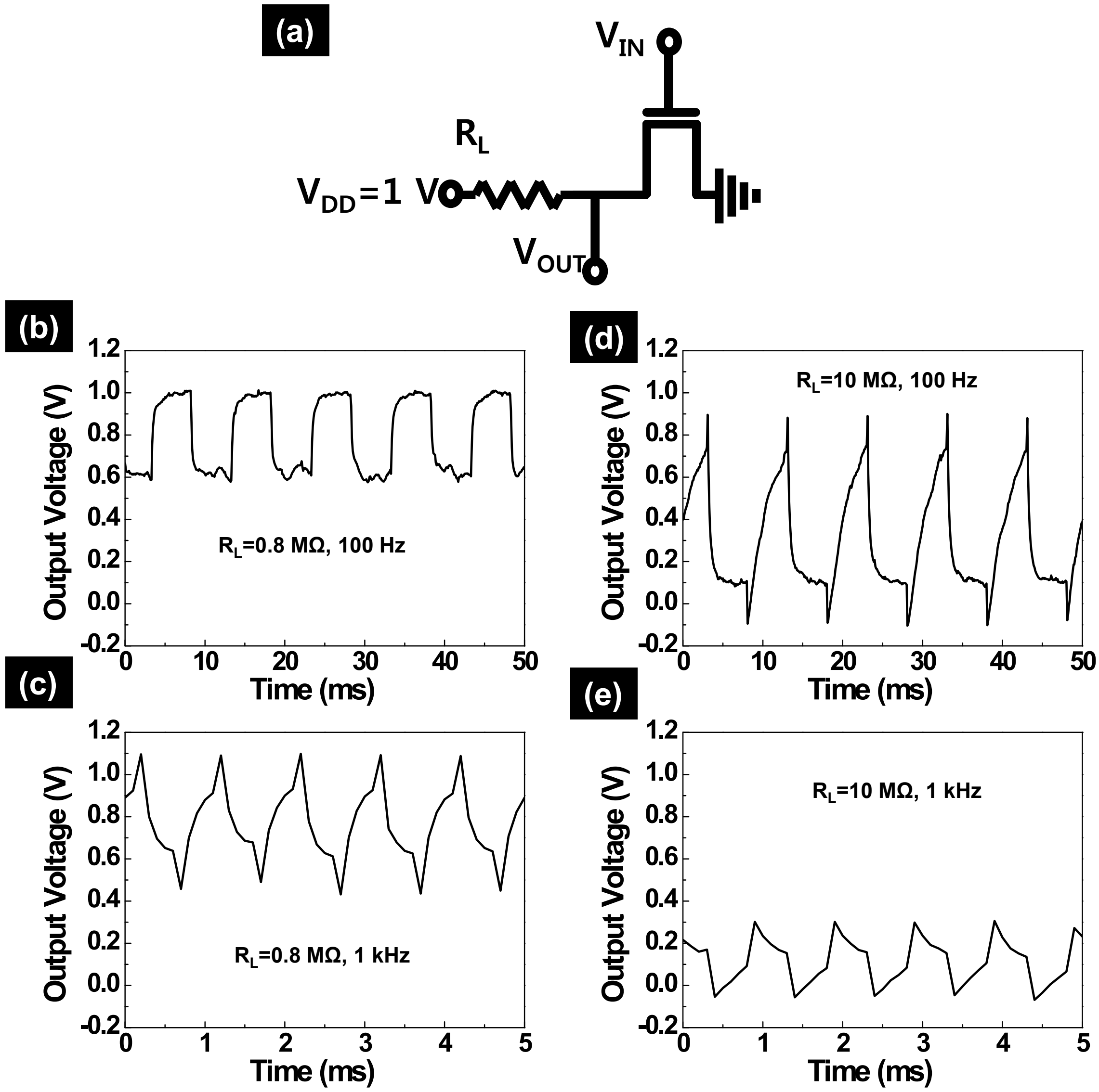


Figure S5: (a) The MISFET inverter circuit diagram. Dynamic switching properties of a ZnO nanowire MISFET-based inverter with load resistance of (b, c) 0.8 MΩ and (d, e) 10 MΩ under square wave input at frequencies of 100 Hz and 1 kHz.

Cutoff frequencies: The cutoff frequency is an important figure of merit for high frequency application of MESFET and it is defined as:[1]

$$f_T = \frac{g_m}{2\pi C_G} \qquad (5)$$

Here g_m is trans-conductance C_G is gate capacitance. By considering semi-cylindrical channel with area $A=\pi a L_G$ where L_G is gate length and a is radius of NW. With a depletion width approximately equal to radius of NW at threshold voltage V_T, the cut-off frequency is estimated to be:

$$f_T = \frac{g_m}{2\pi\left[\frac{\pi a L_G \epsilon_0 \epsilon_{ZnO\ NW}}{Depletion\ thickness}\right]}$$

$$f_T = \frac{8.38 \times 10^{-7}}{2\pi\left(\frac{\pi \times 110 \times 10^{-7} \times 5 \times 10^{-4} \times 8.85 \times 10^{-14} \times 5}{110 \times 10^{-7}}\right)}$$

1.92×10^8 Hz which is an order of magnitude higher than that estimated for of ZnO NW MISFET.[4]

One more method to estimate the cut-off frequency don't need the capacitance information and is given as follows: [5]

$$f_T = \frac{\mu_n q N_D a^2}{2\pi \epsilon_{ZnO\ NW} \epsilon_0 {L_G}^2} \qquad (6)$$

$$f_T = \frac{301 \times 1.6 \times 10^{-19} \times 4.6 \times 10^{16} \times (110 \times 10^{-7})^2}{2\pi(8.85 \times 10^{-14} \times 5) \times (5 \times 10^{-4})^2}$$

$= 3.68 \times 10^8$ Hz which is quite comparable with the previous calculation.

So, above frequencies are 100 times higher than those (~1 MHz) of reported ZnO NW MISFETs.[4]

ESI 6: Persistent Photoconductivity and Photo-gain of the MESFET

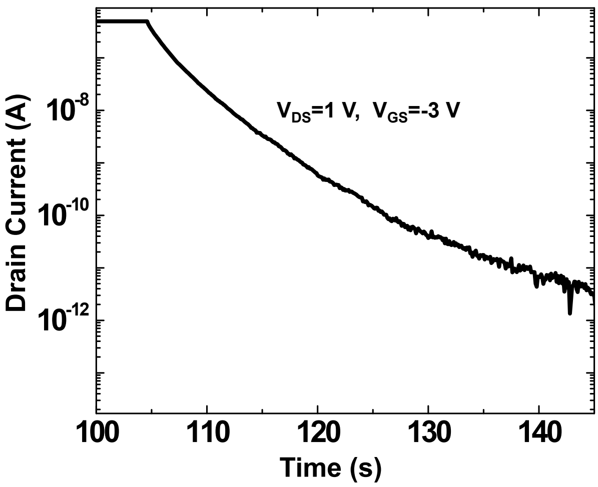


Figure S6: Dynamic photo-current i.e. I_D-t properties of the ZnO NW MESFET with NiO_x gate at a bias voltage of V_{DS} =1 V and V_{GS} of -3 V which shows a recovery time of almost 36 seconds due to persistent photoconductivity (PPC).

The photo-responsivity and photo-gain of the MESFET were estimated using following equations:

$$R = \frac{I_{light} - I_{Dark}}{P_{opt}A} \quad (7)$$

$$G = \frac{Rhc}{e\lambda} \quad (8)$$

Where R is responsivity, I_{light} & I_{Dark} are photo **&** dark currents, P_{opt} is optical power, A is effective illuminated area, e is electronic charge, λ is wavelength and h is plank constant. The effective area for visible light will be the area covered by the transparent SG. For visible lights (green and blue)

$A = \pi * Radius * Gate\ Length$ $= \pi$ x 110 x 10^{-7} x 5.0 x 10^{-4} =1.60x10^{-8} cm^2

R=2.5x10^4 A.W^{-1}

G=7.07 x10^4

References

1. R. M. Ma, L. Dai, G. G. Qin, *Nano Lett.* 2007, **7**, 868.
2. S. M. Sze, K. K. Ng, *Physics of semiconductor devices*, Wiley. com, 2006.
3. Y. Yang, W. Guo, X. Q. Wang, Z. Z. Wang, J. Qi, Y. Zhang *Nano Lett.* 2012, **12**, 1919.
4. Y. T. Lee, S. R. A. Raza, P. J. Jeon, R. Ha, H. J. Choi, S. Im *Nanoscale* 2013, **5**, 4181.
5. S. M. Sze, M. –K. Lee *Semiconductor Devices: Physics and Technology: Physics and Technology*. Wiley Global Education: 2012.