Supporting information

Nonvolatile ferroelectric field effect transistor based on vanadium dioxide nanowire with large on- and off-field resistance switching

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Synthesis of VO_2 NWs and PZT thin film. The VO_2 NWs were grown on the rough surface of SiO_2/Si substrate *via* chemical vapor deposition (CVD) method.[38] V_2O_5 powder was used as vanadium source and was placed in a quartz boat. The SiO_2/Si substrate was placed at downstream of the Argon (Ar) gas and 10mm away from the quartz boat. The VO_2 NWs were synthesized at 800 °C for 3 hours to fully react under the pressure of ~8mbar, then were naturally cooled to room temperature. On the other hand, the PZT thin film was deposited on Nb-doped $SrTiO_3$ (Nb:STO, 0.7wt%) substrate by pulsed laser deposition (PLD) technique. A KrF excimer laser (λ=248 nm) was employed to provide the pulsed laser with the energy of 300 mJ and the pulse frequency of 5Hz. The thin film was grown at the deposition temperature of 600 °C and the oxygen pressure of ~0.2mbar. After the deposition, the sample was annealed at 650 °C for 20min under ~50mbar oxygen pressure to avoid the generation of oxygen vacancies. Then, the sample was cooled down with a cooling rate of 30 °C/min.

Device Fabrication. The VO_2 NWs were separated from substrate by ultrasound and were dispersed in isopropanol. The isopropanol mixed with free-standing VO_2 NWs was dripped onto the surface of PZT thin film. The sample was put on a heating stage and was dried at 70 °C for 10min. The source and drain electrodes of Ni/Au (20/30 nm) patterned by electron beam lithography (EBL) were deposited by electron beam evaporator on the PZT thin film to form an ohmic contact with low resistance. The schematic diagram of the device fabrication process see supplementary material of Fig. S1.

Characterization. The morphology and crystallization of VO_2 NWs and PZT thin film were characterized by scanning electron microscope (SEM, Quanta 250FEG), X-ray diffraction (XRD, Rigaku D-MAX 2200 VPC), and piezoelectric force microscope (PFM, Asylum Research MFP-3D Infinity). All current−voltage ($I-V$) measurements were measured by semiconductor characterization system (SCS, Keithley 4200).

The cross-sectional SEM image of PZT thin film with a thickness of 240nm is displayed in Fig. S2. To evaluate the ferroelectric properties of the PZT thin film, the dual AC resonance tracking (DART) mode of PFM was used to measure the vertical piezoelectric response hysteresis loop. To visualize the ferroelectric domains of the PZT thin film, the school badge of Sun Yat-sen University was used as a custom pattern to write the polarization domain, as shown in Fig. S3. The domain was written by PFM under the voltage of 20 V (white area) and -20 V (black area). The distinct and stable domain pattern (see the insert of Fig. 2(d) in the main text) indicates that the PZT thin film has an excellent ferroelectric property.

The electron transport property of another VO_2 NW-FeFET device with a smaller VO_2 diameter was also studied. Fig. S5(a) and S4(b) show the I_{DS} curves under positive and negative electric fields, respectively. The resistance changes ($\Delta R_{V_G}\%$) of the VO_2-NW-FeFET under the positive and negative electric fields were also depicted in Figs. S5(c) and S5(d), respectively, and the channel resistance change is about 30% to 40%.

Reference

38 C. Cheng, K. Liu, B. Xiang, J. Suh and J. Wu, *Appl. Phys. Lett.*, 2012, **100**, 103111.

Figure S1

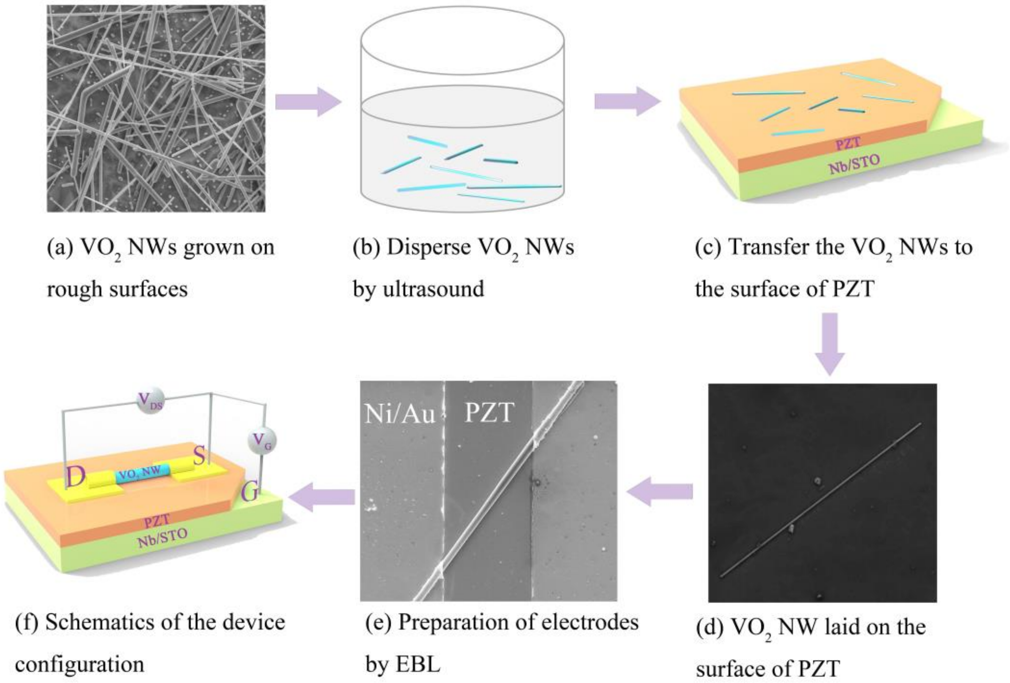

Fig. S1 A schematic diagram of the fabrication process for VO_2 NW-FeFET.

Figure S2

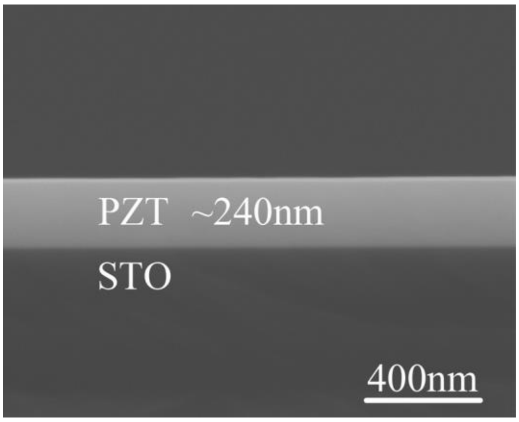

Fig. S2 The cross-sectional SEM image of PZT thin film.

Figure S3

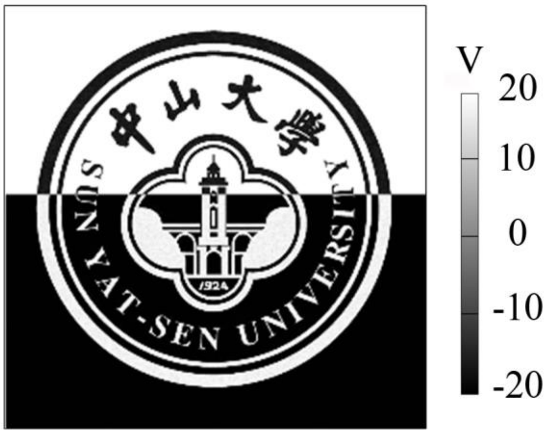

Fig. S3 Choreographed pattern used to write domains.

Figure S4

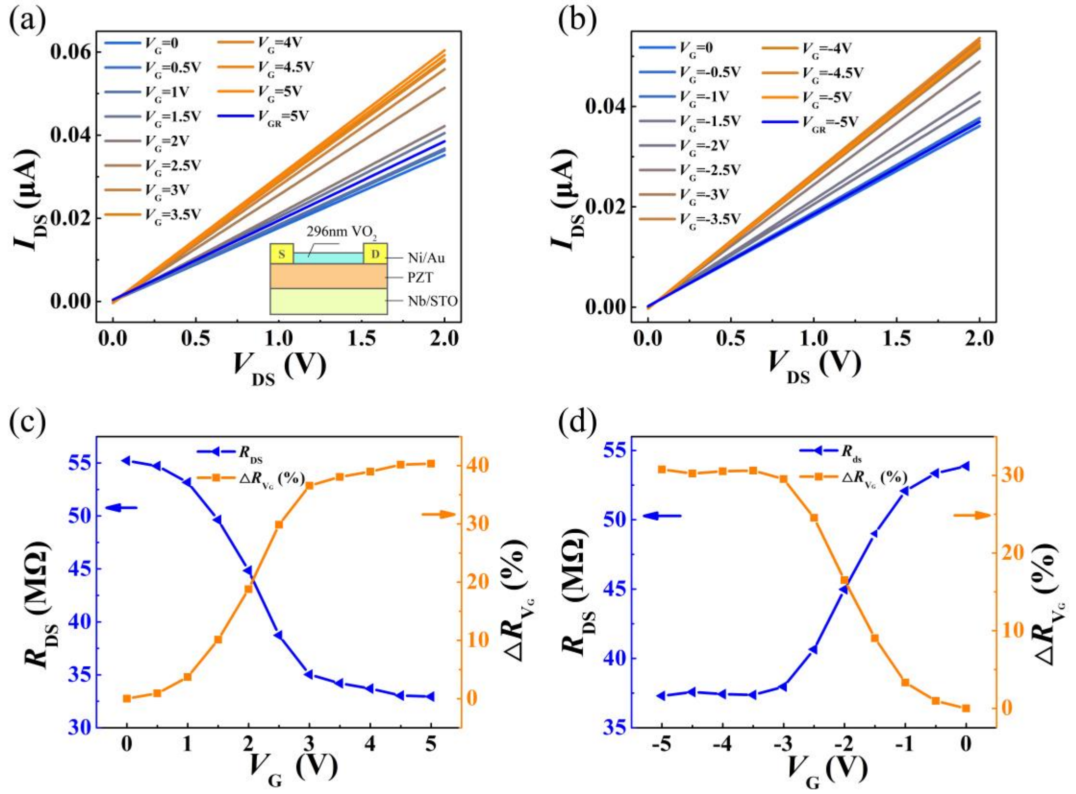

Fig. S4 Electrical property of VO_2 (296nm)-NW-FeFET modulated by the applied gate voltage. I_{DS}-V_{DS} curves under (a) positive gate voltages ranging from 0 to 5 V and (b) negative gate voltages from 0 to -5 V with step of 0.5 V. The resistance change (ΔR_{V_G}%) of VO_2 (296 nm)-NW-FeFET ranging from (c) 0 to V_G = 5 V and (d) 0 to V_G = -5 V.

Table S1 Comparison of the resistance change (△R%) and corresponding gate electric field values from various VO_2-based solid-state dielectric FET at room temperature. For comparison, the experimental values for the current work are also listed.

Gate dielectrics	Resistance change (ΔR%)	Electric field (MV/cm)
Al_2O_3/SiO_2 (Ref. 4)	~95%	1.6
Oxide/organic hybrid (Ref. 15)	0.55	0.94
SiO_2 (Ref. 16)	~0.3	~6
TiO_2 (Ref. 17)	~11	~1
SiO_2 (Ref. 18)	~5	0.5
HfO_2 (Ref. 20)	6	~1.25
VO_2/PZT Heterostructures (Ref. 33)	~0.7	~0.042
VO_2/PMN-PT Heterostructures (Ref. 34)	10.7	0.002
VO_2/PMN-0.3PT Heterostructures (Ref. 35)	9.8	~0.003
VO_x/PMN-PT Heterostructures (Ref. 36)	8	~0.0015
Current work (V_G= 18V)	85	0.75
Current work ($V_{G(R)}$= 23V)	50	0