Emerging Potassium Ion Intercalated Layered Metal Oxide (2D K-MnO_2) for Artificial Synaptic Device

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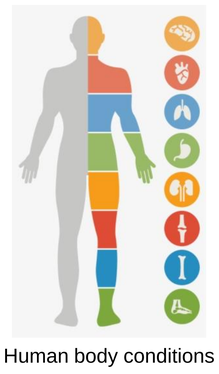
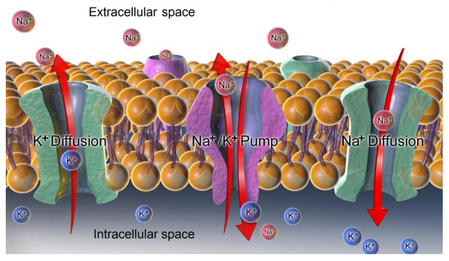
I. Introduction & Motivation

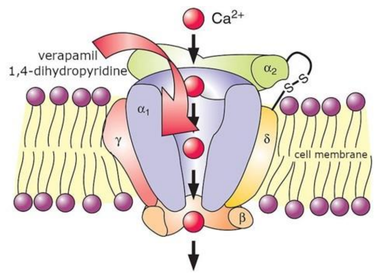
- Imitating biological ion-based neural system



Human body conditions



Na^+-K^+ ion pump

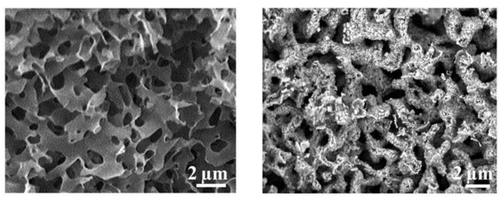


Ca^{2+} ion channel

Essential ionic-based functionalities of human body

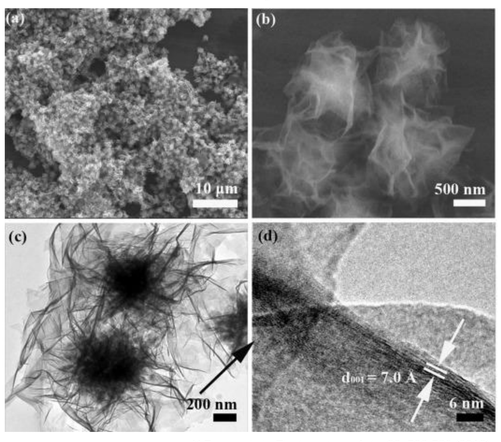
- Conventional alkali ion-intercalated metal oxide

$LiCoO_2$/carbon foam



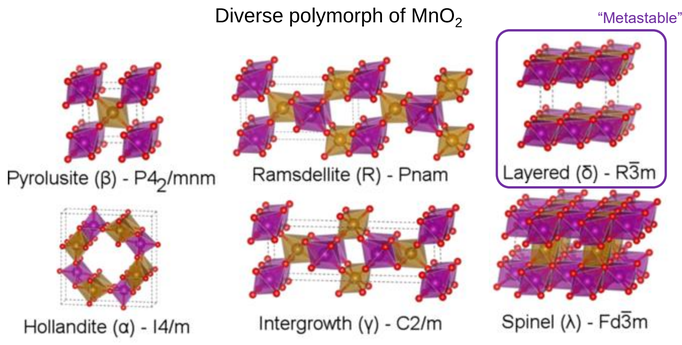
H Zhang *et al.*, *Science Advances.* **3**, e1602427 (2017).

Birnessite MnO_2 nanosheets



X Zhang *et al.*, *Electrochimica Acta.* **89**, 523-529 (2013).

Diverse polymorph of MnO_2



D. A. Kitchaev *et al.*, *Phys. Rev. B*, **93**, 045132 (2016).

Challenges for single devices

- Mesoporous
- Non-uniform
- 3D bumpy structure
- Diverse polymorph
- Metastable phase

Difficult to **synthesize** the high quality **layered metal oxide** with **stable** phase

" Limited for practical ion-related devices using alkali ion intercalated metal oxide "

II. Alkali ion intercalated 2D-layered metal oxide

- Spontaneous intercalation dynamics

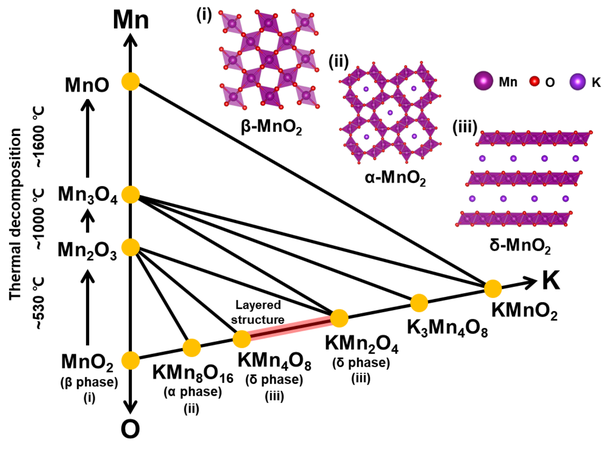
Spontaneous intercalation

Intrinsic **metastable** layered metal oxide ⇒ **Stable layered metal oxide** with **alkali ions**

Supplied alkali ion (K^+, Na^+, Li^+ …) during the growth process

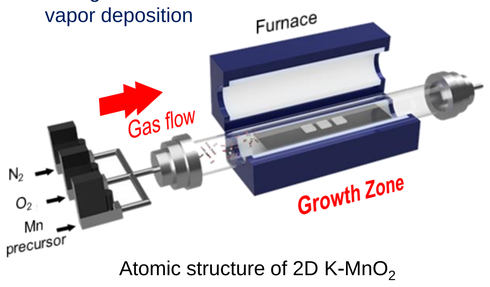
ΔG_x (Free energy of X phase MnO_2 α, β, γ, λ, R) > $\Delta G_{\delta\text{-}MnO_2\cdot H_2O}$ (Free energy of δ-MnO_2 with H_2O)

Thermodynamically stable phase with alkali ion intercalated layered structure



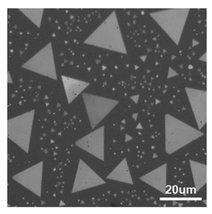
- K^+ intercalated layered MnO_2 (2D K-MnO_2) by MOCVD system

Metal-organic chemical vapor deposition

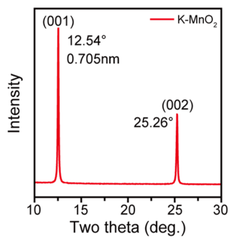


Characterization of K^+ intercalated δ-MnO_2

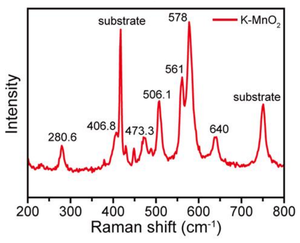
Optical image



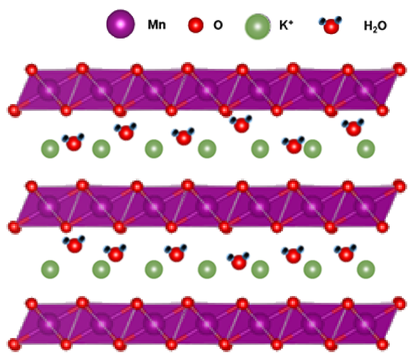
XRD



Raman spectrum

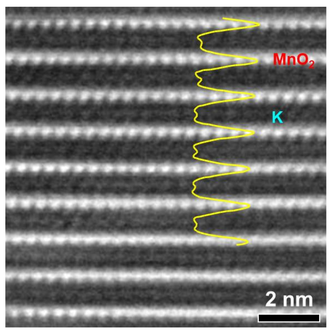


Atomic structure of 2D K-MnO_2

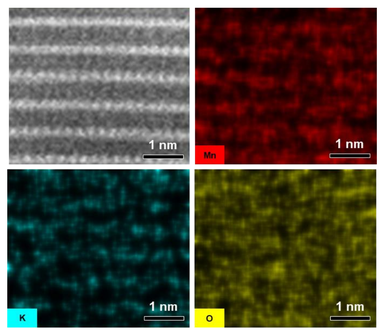


Front view

ADF-STEM

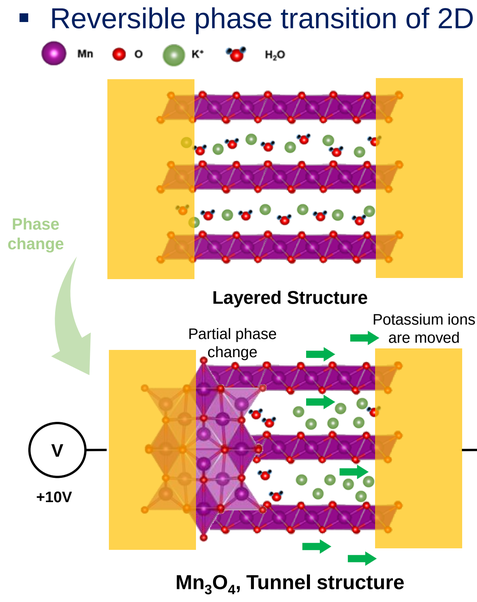


EDX

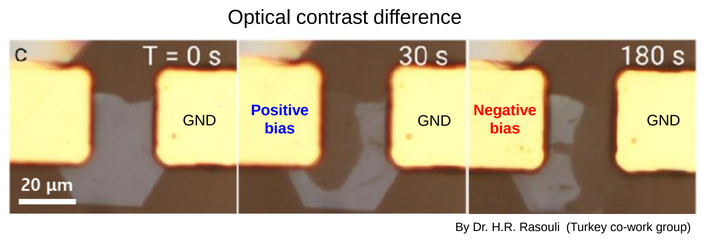


III. Electrical-driven Phase Transition of 2D K-MnO_2

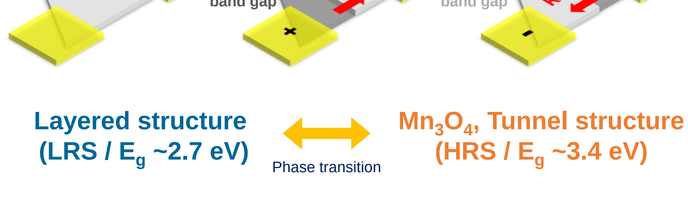
- Reversible phase transition of 2D K-MnO_2



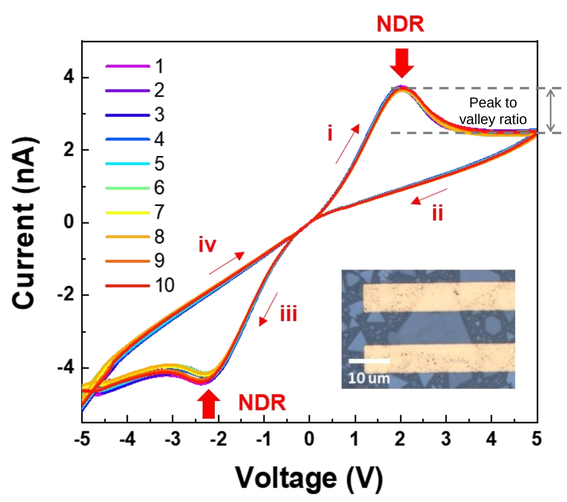
Optical contrast difference

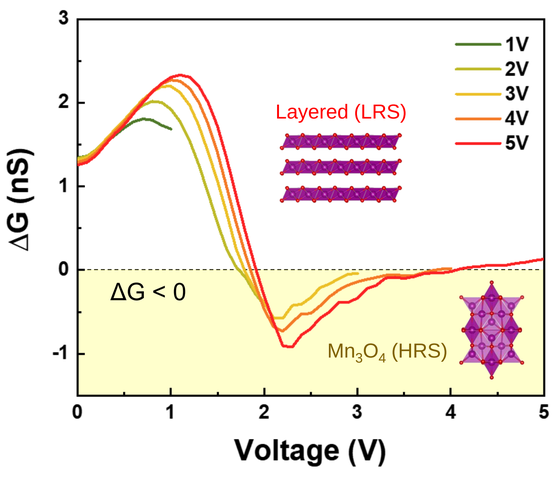


By Dr. H.R. Rasouli (Turkey co-work group)



Layered structure (LRS / E_g ~2.7 eV) ⟷ Phase transition ⟷ **Mn_3O_4, Tunnel structure** (HRS / E_g ~3.4 eV)

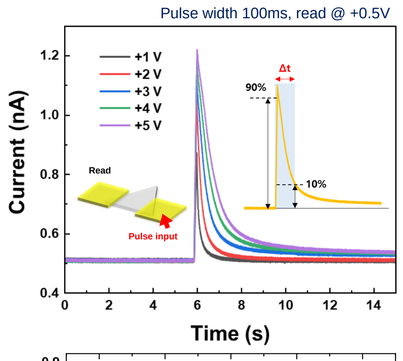


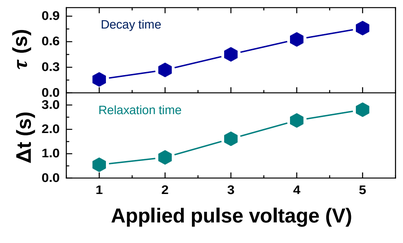


IV. Alkali Ion-driven Artificial Synaptic Device

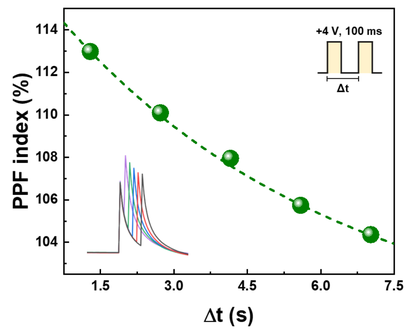
- Volatile memory (short-term memory, STM) characteristics

Pulse width 100ms, read @ +0.5V

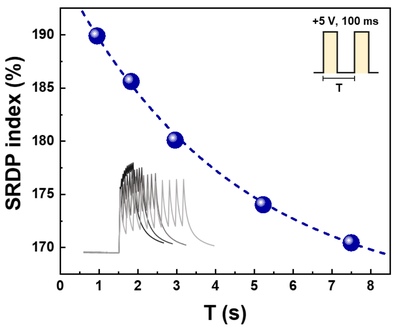




PPF



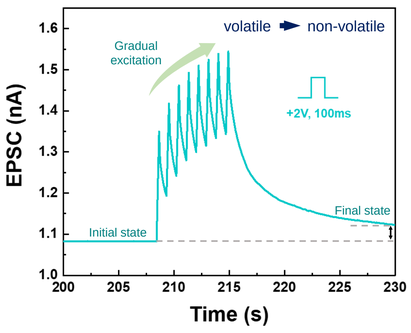
SRDP



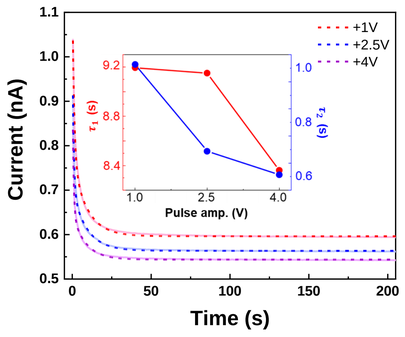
- **Potassium ion-based** artificial **synapse**
- Exhibit **phase transition** driven **volatile performance**
- **Decay time (150 ~ 800 ms) >> "phase transition driven"**

- Non-volatile memory (long-term memory, LTM) characteristics

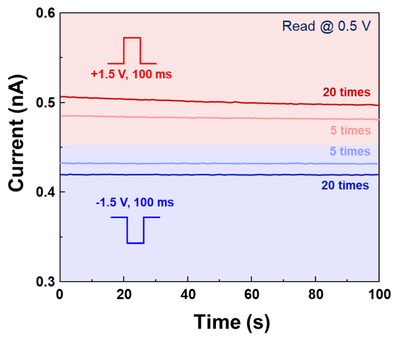
EPSC



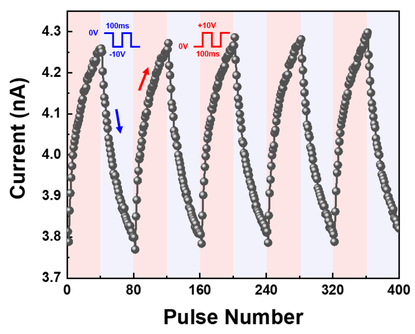
Pulse amplitude dependence



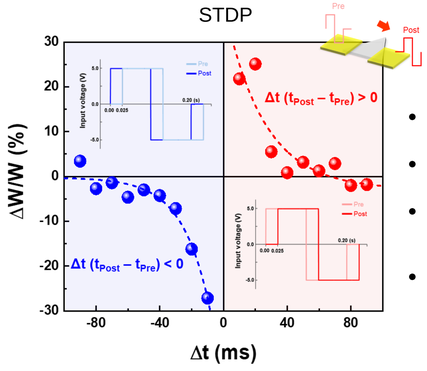
Retention



PD curve



STDP



- **Volatile → Non-volatile**
- **Pulse # ↑ ~ Mn_3O_4 phase ↑**
- **Stable synaptic plasticity** (40 states, 5 cycles)
- **STDP, ~27 % weight difference**

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Neuro DCR Neuromorphic Devices & Circuits Research Lab.

N2ML Synthesis & application