

Kinetically Controlled Memory in Nanoconfined Ionic-Electronic Memtransistors

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Abstract:

Solvated ions confined within biological nanochannels regulate information processing and memory, motivating efforts to replicate such mechanisms for energy-efficient neuromorphic hardware. Artificial synaptic devices, including two-terminal nanofluidic memristors [1,2] and three-terminal electrolyte-gated transistors [3-5], have demonstrated history-dependent conductance modulation and diverse neuromorphic functionalities. However, memory in existing systems originates from specific ion-ion[1], ion-channel[1,2], or ion-host [3-5] interactions, making retention strongly dependent on material choice and chemical environment. Here, we establish a distinct, kinetically driven route to memory by confining electrolytes within an ultrathin crown-ether polymer sandwiched between two semiconducting molybdenum disulfide (MoS_2) monolayers. The confining polymer, along with a single-sided electrolyte opening, imposes an extended ion-diffusion pathway, kinetically retarding ion transport and enabling history-dependent conductance modulation of the underlying MoS_2 channel (Fig 1). Critically, in highly polar solvents where strong ion-solvent interactions suppress hysteresis in the non-confined device, nanoconfined devices show significant hysteresis that persists across cation identity and electrolyte concentration, establishing confinement as a route to achieve memory beyond previously established ion-environment interactions. Additionally, independent drain and gate-driven Na^+ motion enables electrical tuning of ion relaxation dynamics and memory timescales within a single device (Fig 2), allowing emulation of both basic synaptic functions (Fig 3) as well as higher-order heterosynaptic plasticity (Fig 4). These results establish nanoconfinement in three-terminal ionic-electronic heterostructures as a general platform for achieving hysteretic ion transport, controlling memory timescales and enabling biomimetic, multi-terminal neuromorphic devices.

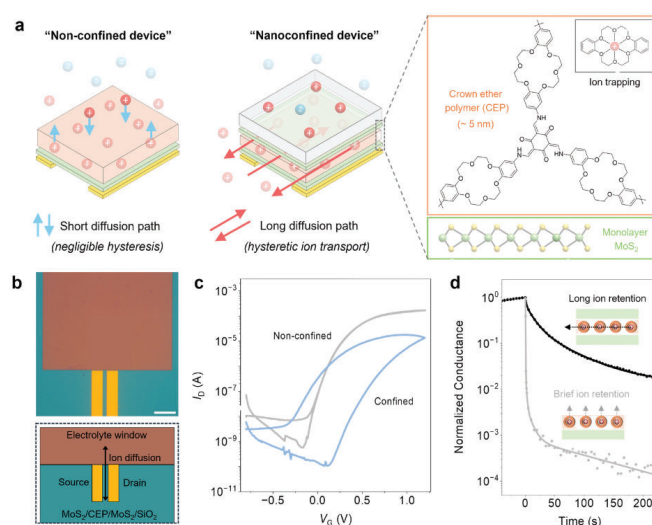


Figure 1: Ion dynamics governed by confinement geometry

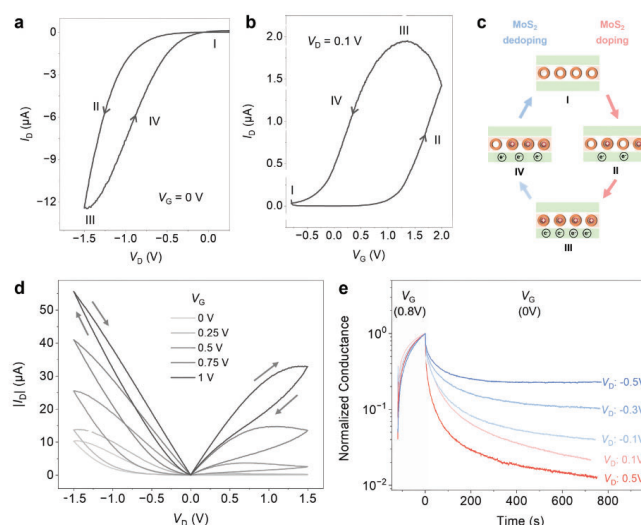


Figure 2: Electrical characteristics of nanoconfined devices

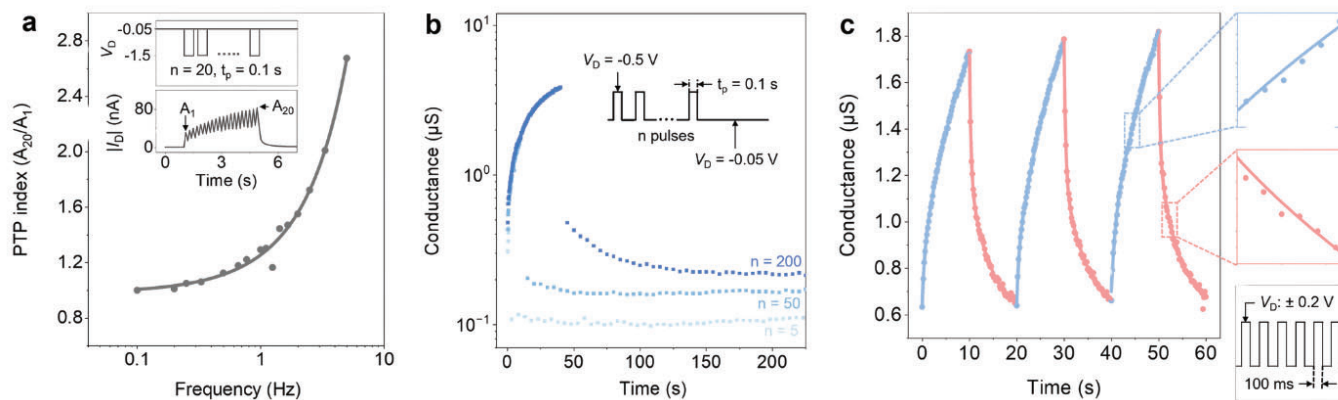


Figure 3: Synaptic plasticity functions emulated using drain bias.

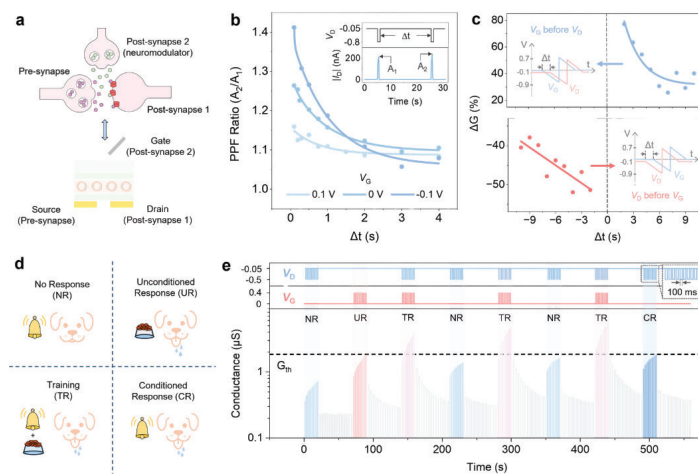


Figure 4: Heterosynaptic plasticity enabled by multi-terminal device operation

Summary of Research:

We establish geometric nanoconfinement as a kinetically driven route to ionic memory that does not require strong ion-ion, ion-host or ion-channel interactions. An extended ion-diffusion pathway enables robust hysteresis across solvents, cations and electrolyte concentrations, while independent drain and gate biases control ion relaxation and memory timescales, allowing replication of both basic synaptic functionalities and higher-order heterosynaptic plasticity.

Conclusions and Future Steps:

In conclusion, we demonstrate that memory can arise from kinetically retarded ion transport rather than from specific ion-ion, ion-channel or ion-host interactions. Geometric confinement within a three-terminal MoS_2 -polymer- MoS_2 heterostructure imposes an extended, lateral ion diffusion pathway that enables history-dependent conductance modulation of the underlying MoS_2 channel across different solvents, cations and electrolyte concentrations, including conditions in which unconfined devices show negligible hysteresis.

Independent drain- and gate-driven ion motion further enables electrical control over ion relaxation dynamics and memory timescales, replicating both traditional synaptic functionalities and higher-order heterosynaptic plasticity. These findings establish nanoconfinement as a general strategy for engineering hysteretic ion transport and tunable memory in multi-terminal ionic–electronic synaptic devices.

References:

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