

L9: Synaptic Electronics

Instructor: Prof. Feng Xiong

Teaching Survey

The screenshot shows the My Pitt homepage. At the top, there's a navigation bar with links to University Services & Information, Academic Resources (which is highlighted in blue), Getting Around, Life on Campus, My Resources, Help Me, and Wellness. There's also a Box link and a My Pitt Email link. A banner features a photo of the Pitt Cathedral of Learning and the text "Need help finding something? Ask Cathy!". Below this, a large section titled "Academic Resources" contains a blue box with the text "Let *Cathy* lead the way! Ask how to..." and an "Access My Grades" button with a pencil icon. To the right, there are links to PeopleSoft Login, OMET Teaching Survey, and CourseWeb/Blackboard Learn.

Academic Resources

Let *Cathy*
lead the way!
Ask how to...

Access My Grades



PeopleSoft Login Login to the University of Pittsburgh's student administration system.
[Learn More](#)

OMET Teaching Survey Student Opinion of Teaching Dashboard

CourseWeb/Blackboard Learn Pitt's web-based course management system.
[Learn More](#)

The screenshot shows the CourseWeb dashboard. At the top, there's a header with the University of Pittsburgh logo, a search bar, and user information for "Student_01". Below the header, there are tabs for "My CourseWeb" and "Notifications Dashboard". The main content area has several sections: "Tools" (Announcements, Calendar, Lynda @Pitt, My Grades, Tasks), "CourseWeb Announcements" (CourseWeb Maintenance Scheduled for August 2016), "My Courses" (Courses where you are: Student, Anthro Blackboard Training - Sept 18, Training Course Template, Turnitin: OriginalityCheck, GradeMark, PeerMark, What's New in Blackboard - June 26, What's New in Blackboard - May 26, What's New in Blackboard - May 8, What's New in Blackboard - September 10th 2015), and "My Tasks". A red box highlights the "Teaching Survey - Students" section under the Tools tab, which includes "Description" and "Course Evaluations".

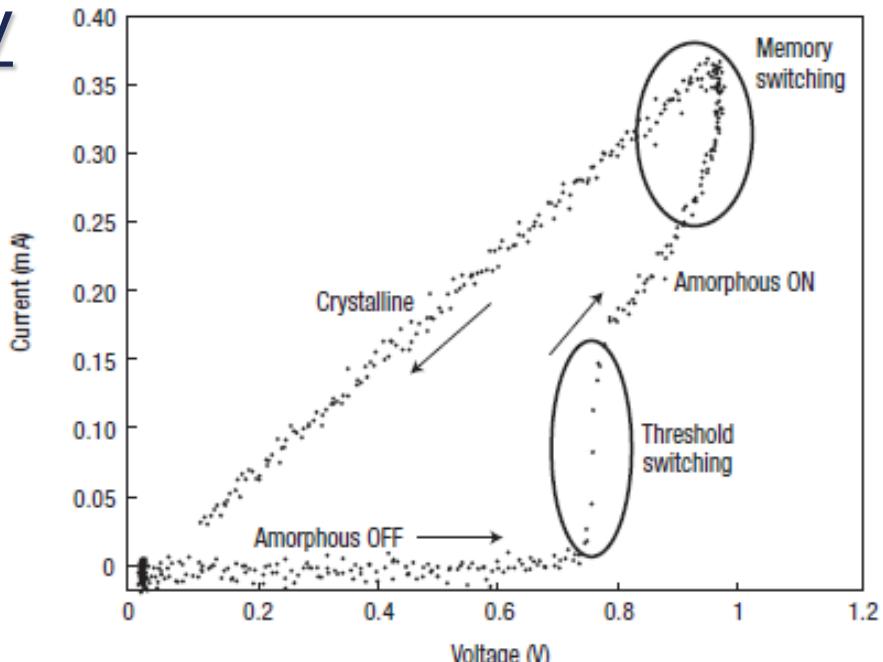
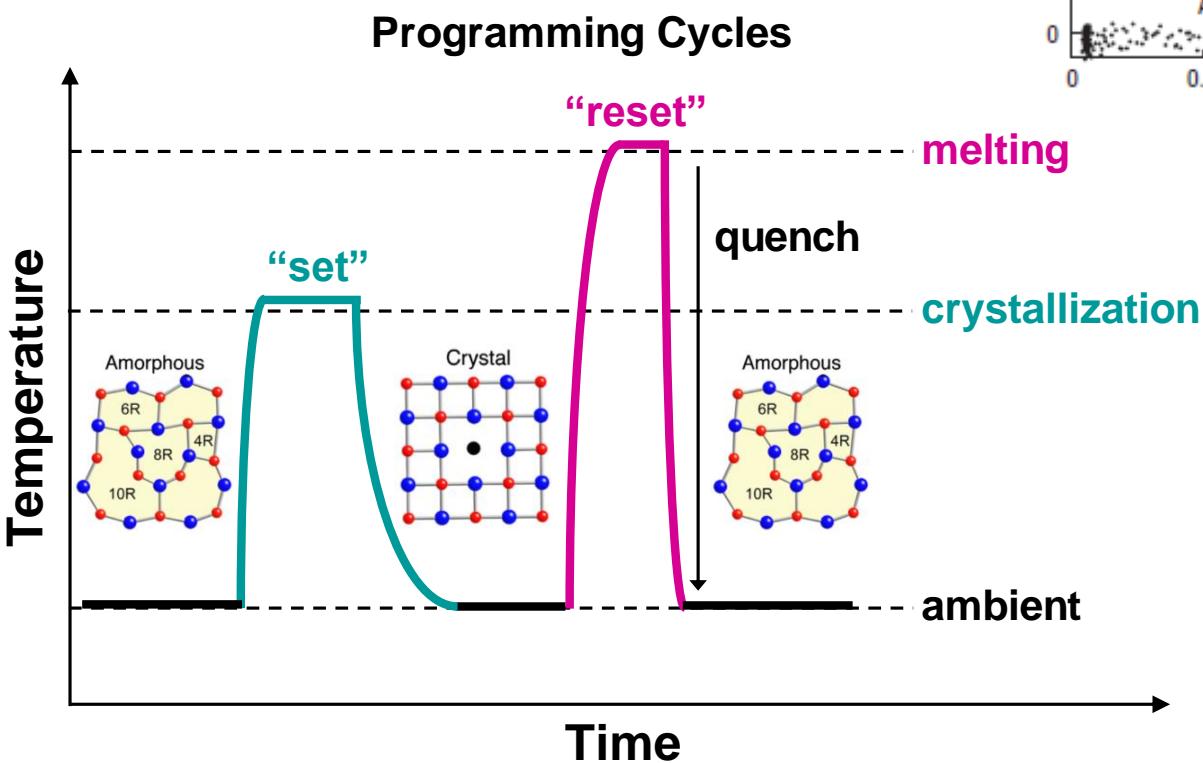
Outline

- PCM synapses
 - PCM for synaptic electronics
 - Pulse programming schemes
- RRAM synapses
 - Non-filamentary switching
 - Pros and cons
- Electrochemical synapses
 - Proton intercalation
 - Li intercalation

Synaptic Device Requirements

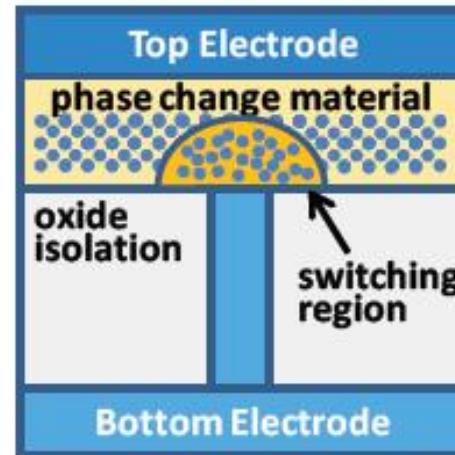
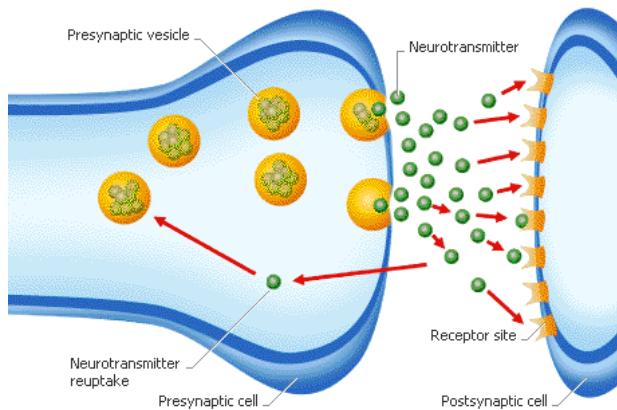
- Synaptic device = Memory?
- Similarities
 - data retention
 - Energy and speed
 - Reliability: variations, endurance, stability
 - scalability
- Differences
 - High-precision
 - High linearity and symmetry for DNNs
 - Temporal dynamics (both short-term and long-term) for SNNs

Phase Change Memory



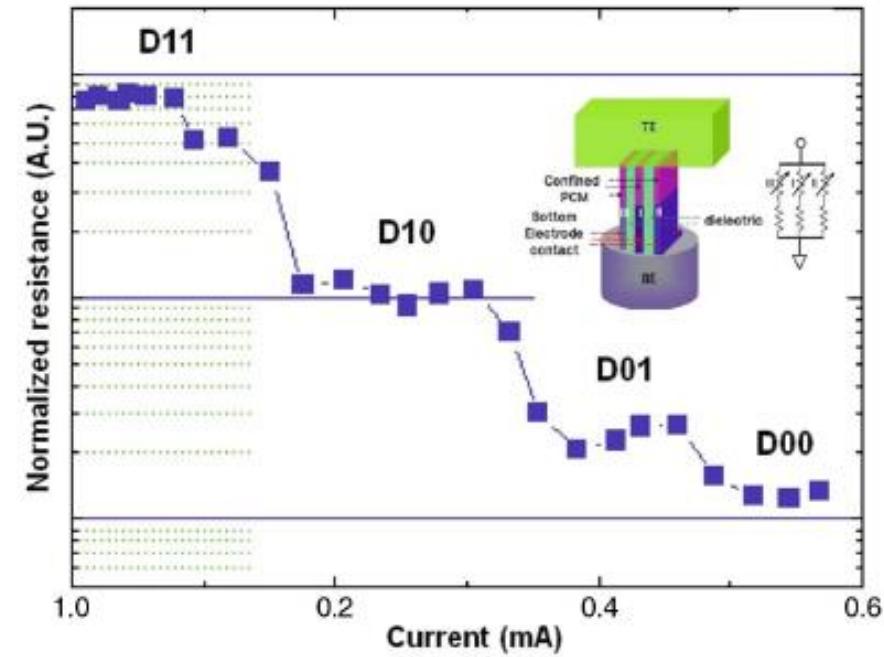
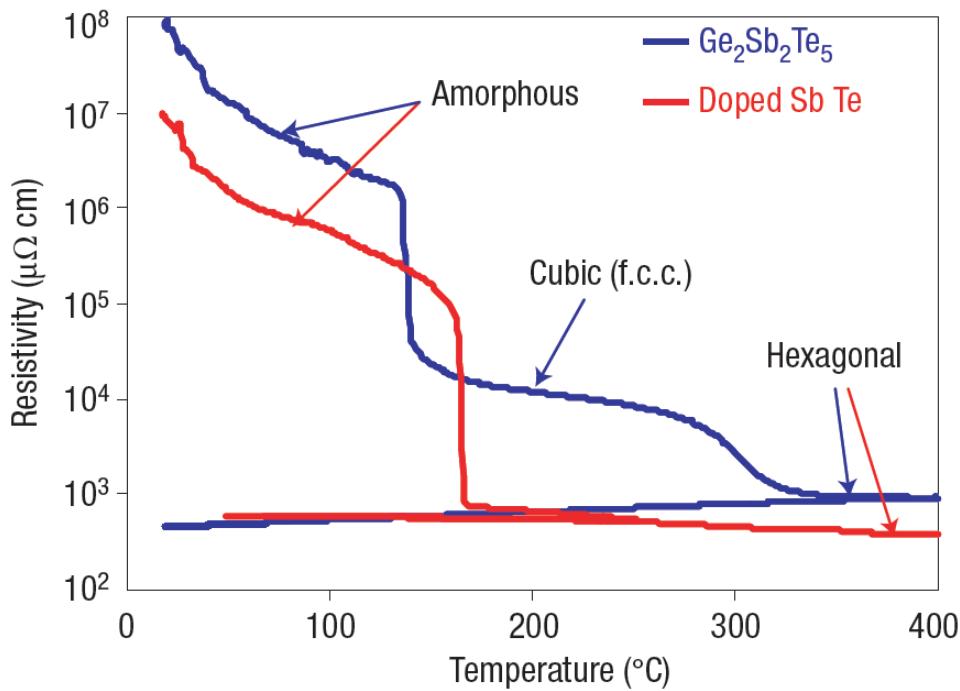
Why is PCM Suitable for Synaptic Electronics?

- Biological synapse
 - non-volatile
 - continuous
 - endurance $\sim 10^{10}$
 - energy $< 50 \text{ fJ}$
 - speed $\sim 1\text{-}100 \text{ ms}$
- PCM
 - non-volatile
 - analog
 - endurance $\sim 10^{12}$
 - energy $< 1 \text{ pJ}$
 - speed $\sim 1 \text{ ns}$

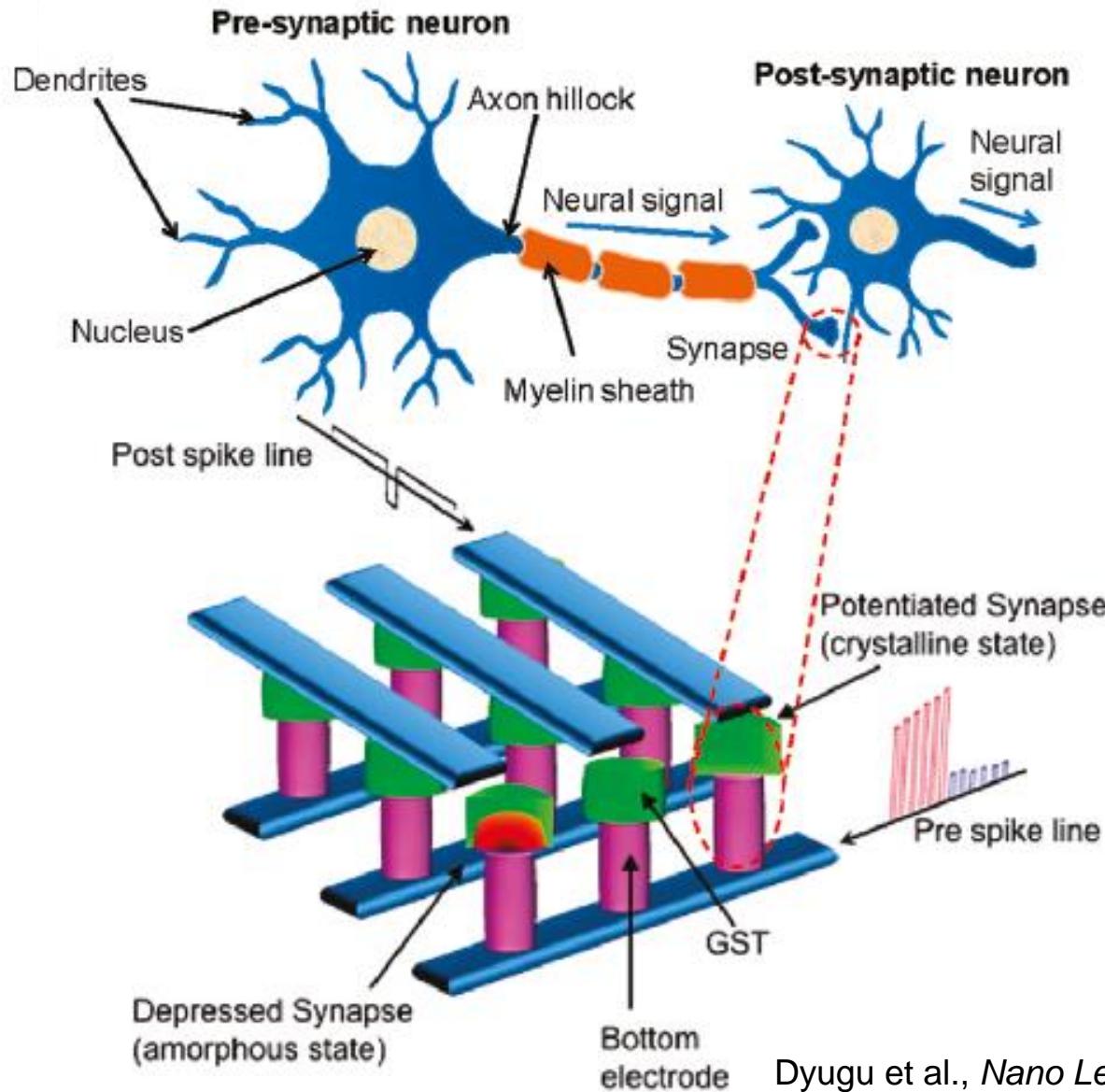


Analog Conductance

- Targeted synaptic electronics: 1% change per switching
- PCM: multi-level of resistances possible



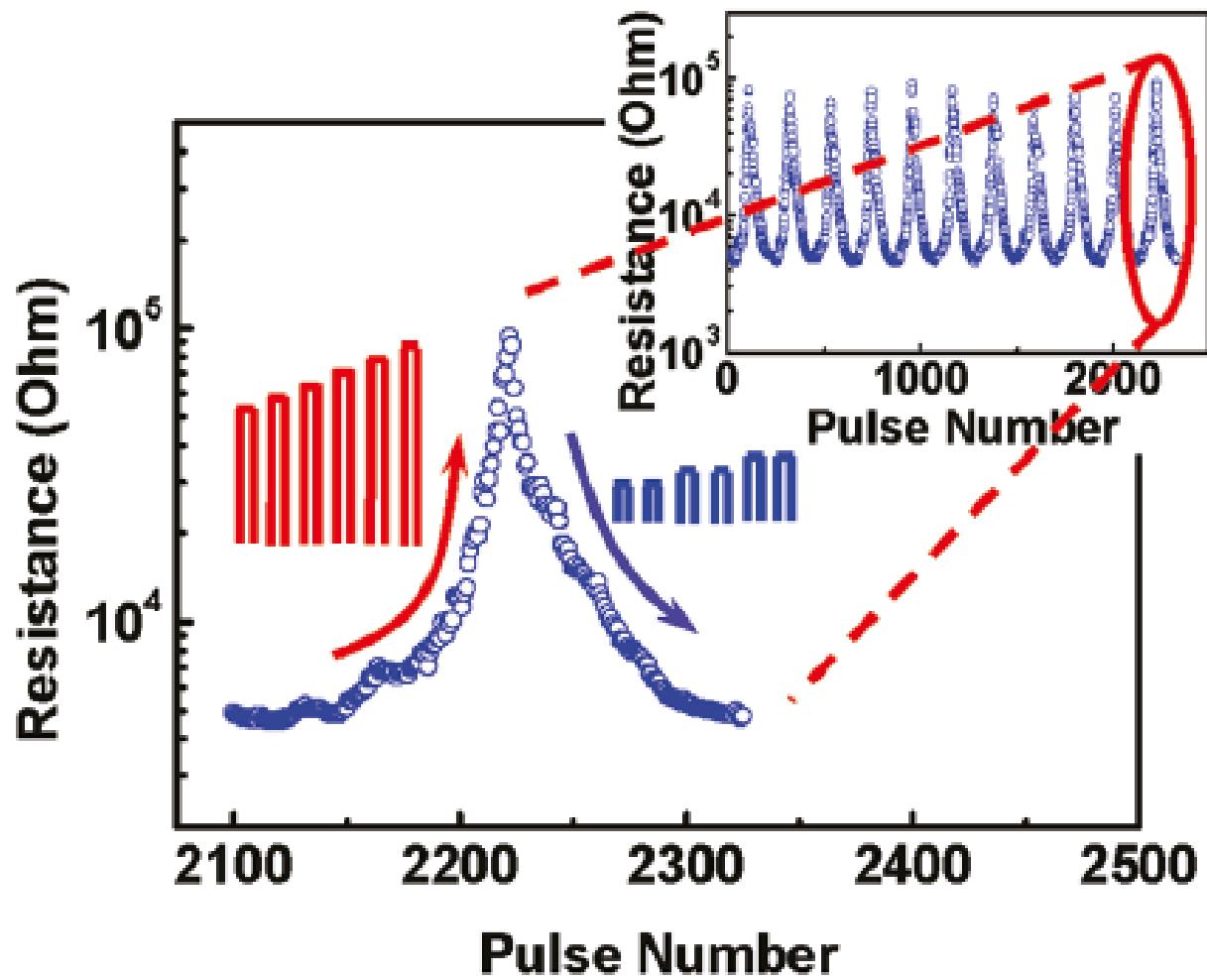
PCM as a Synapse



- PCM = Synapse
- Potentiation = Crystallization = SET
- Depression = Amorphization = RESET

Dyugu et al., *Nano Lett.*, 2012

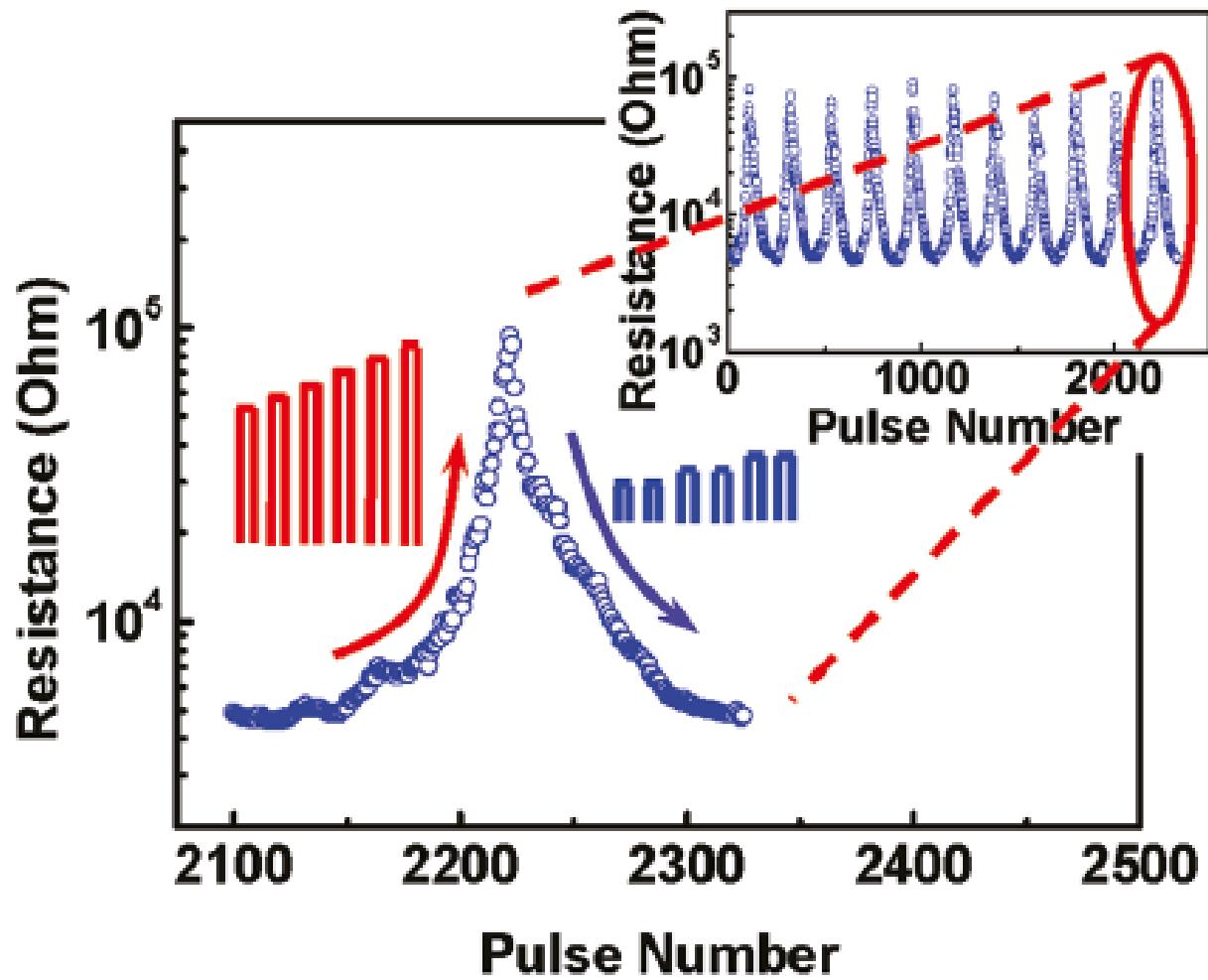
Potentiation/Crystallization (SET)



- SET = 100 total pulses \rightarrow 20 pulses \times 5 different amplitudes (0.5 to 1 V with 0.1 V step)
- Pulse width = 1 μ s width and 500 ns rise/fall edge
- Gradual SET is possible with constant amplitude

Dyugu et al., *Nano Lett.*, 2012

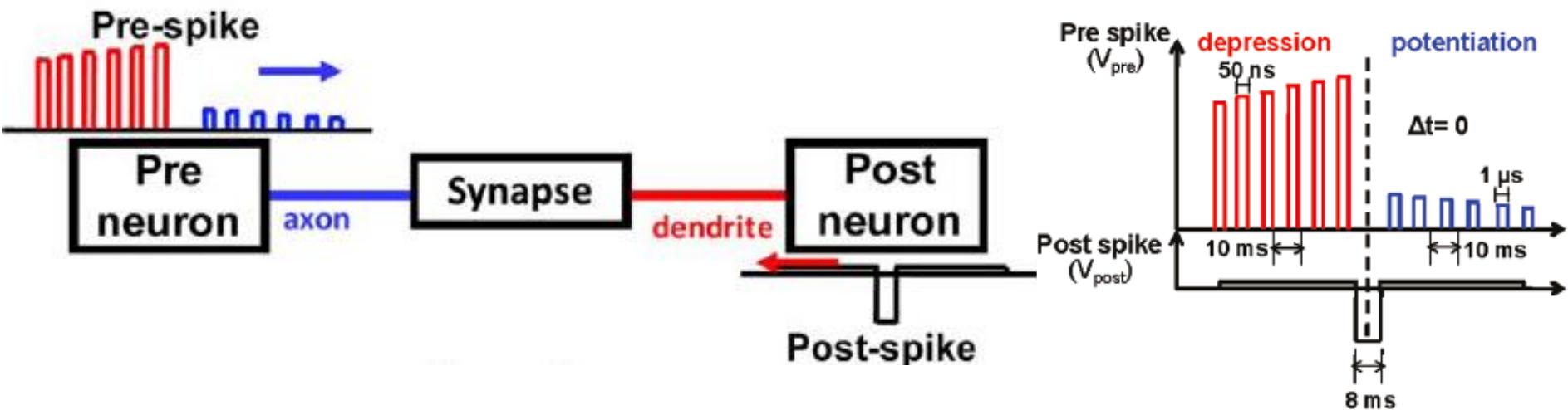
Depression/Amorphization (RESET)



- RESET = 100 total pulses → 2 to 4 V with 20 mV step
- Pulse width = 50 ns width and 25 ns rise/fall edge
- Intentionally slow fall edge for gradual R change
- Gradual RESET has to be with increasing amplitude

Dyugu et al., *Nano Lett.*, 2012

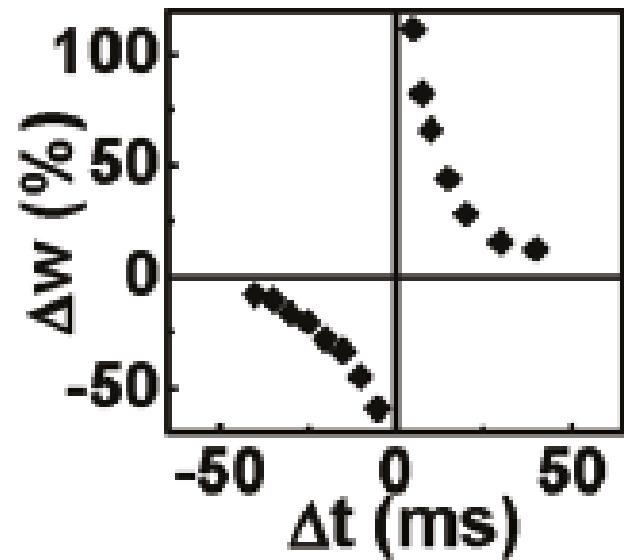
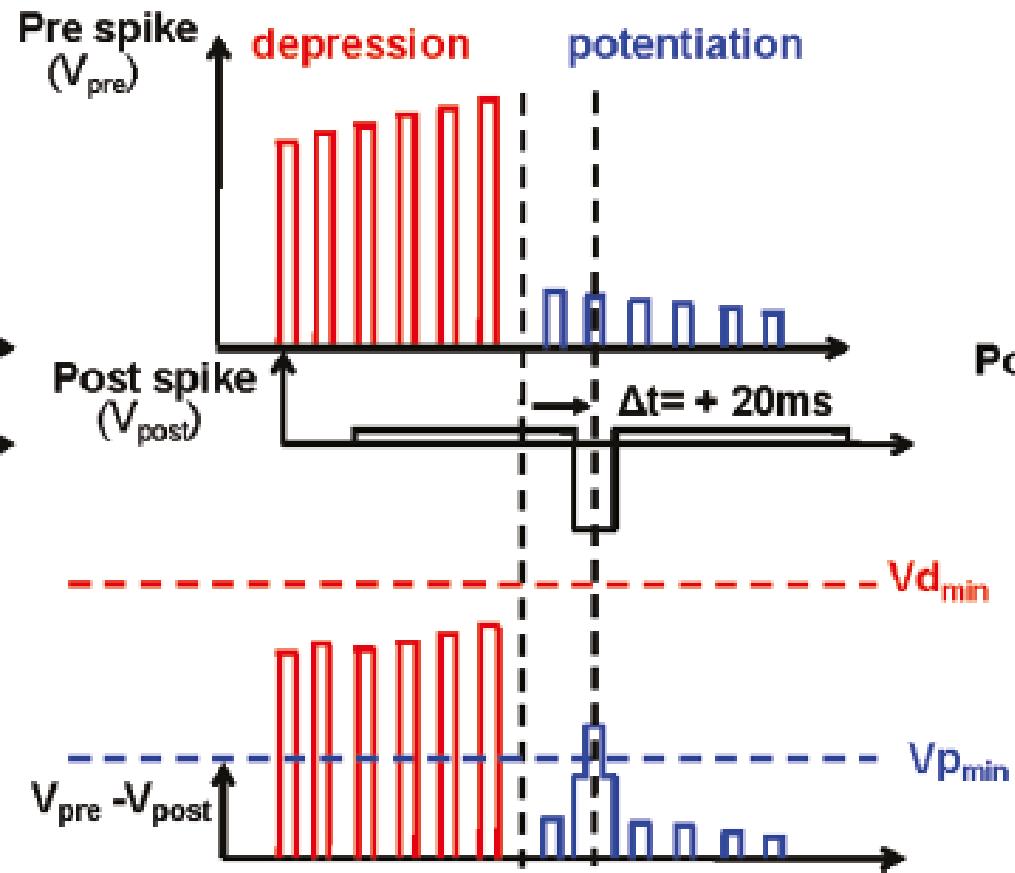
Pre-Spike and Post-Spike Pulses



- Pre-spike signals = pulse trains with 10 ms interval
- Post-spike signal = single negative pulse for gating
- Post-spike pulse is 8 ms; could only overlap with one pulse

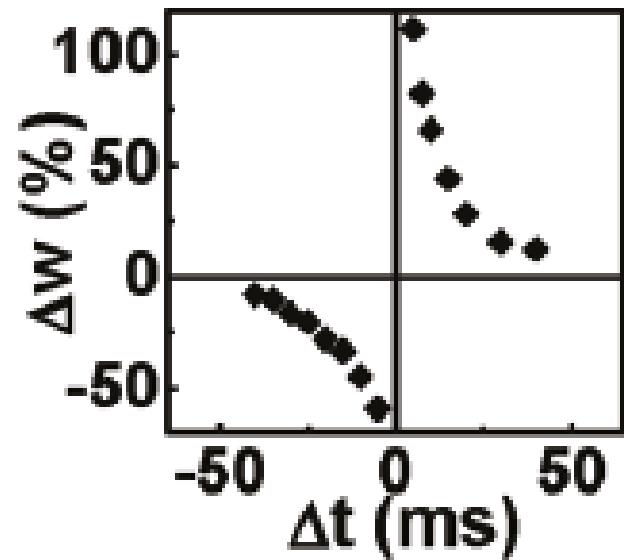
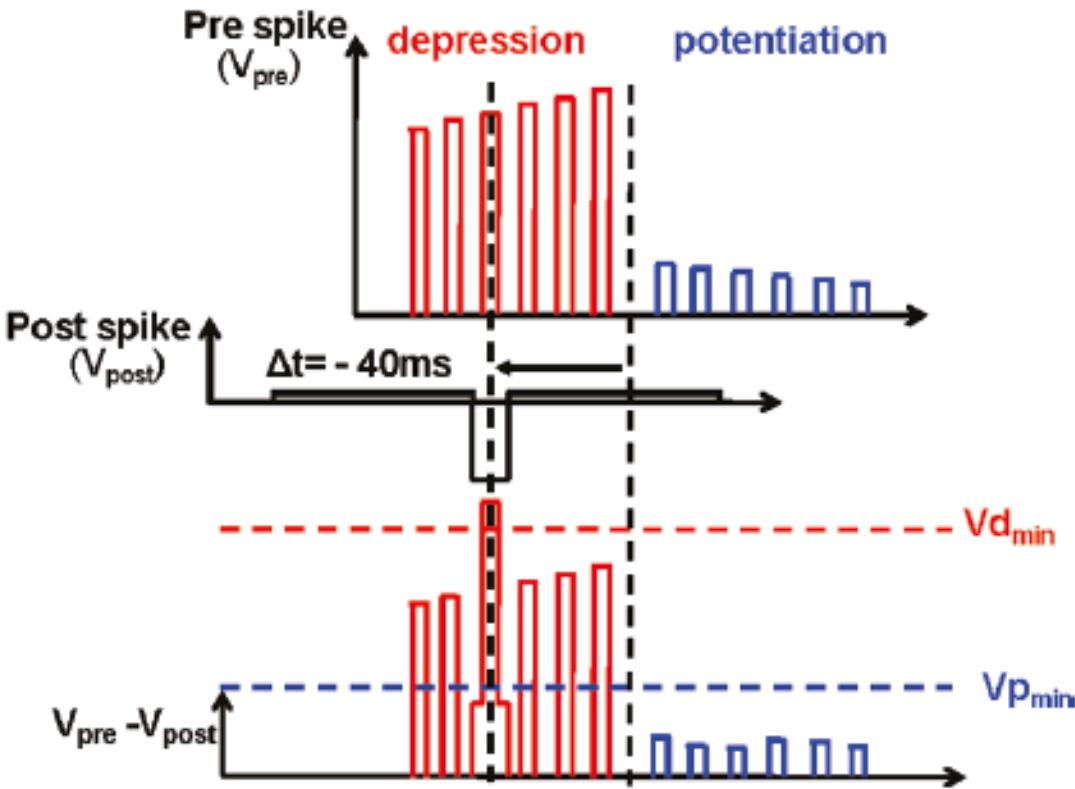
Dyugu et al., *Nano Lett.*, 2012

Asymmetric STDP



- Programming only happens when two overlaps
- Δw depends on timing \rightarrow asymmetric STDP

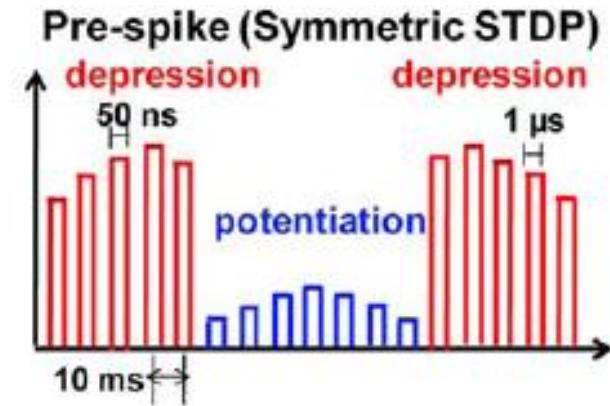
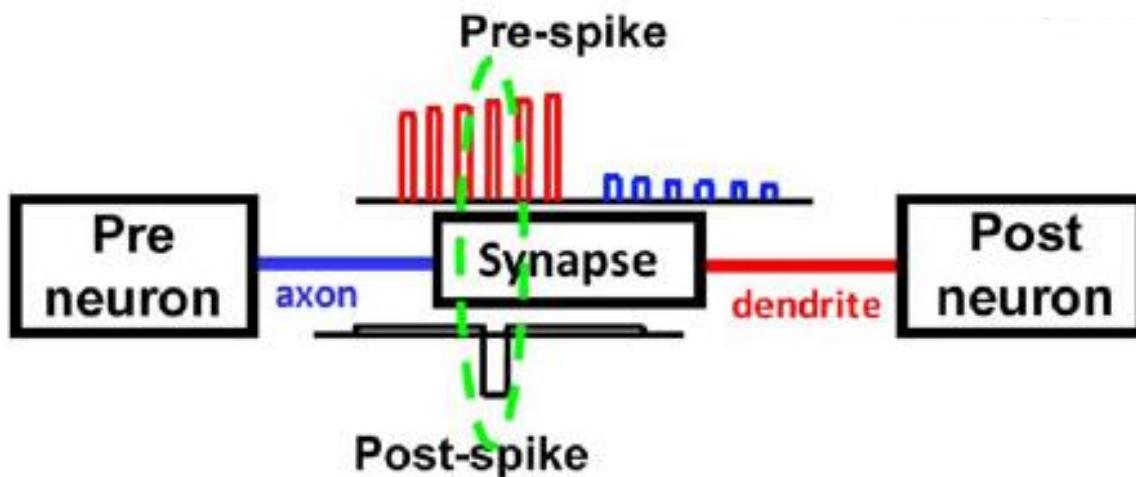
Asymmetric STDP



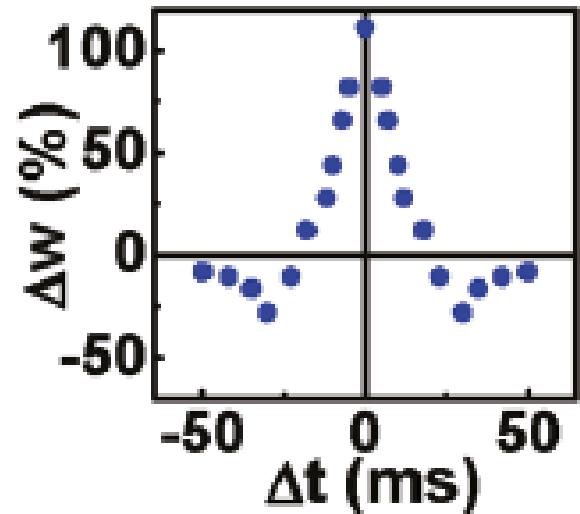
- Programming only happens when two overlaps
- Δw depends on timing \rightarrow asymmetric STDP

Dyugu et al., *Nano Lett.*, 2012

Symmetric STDP

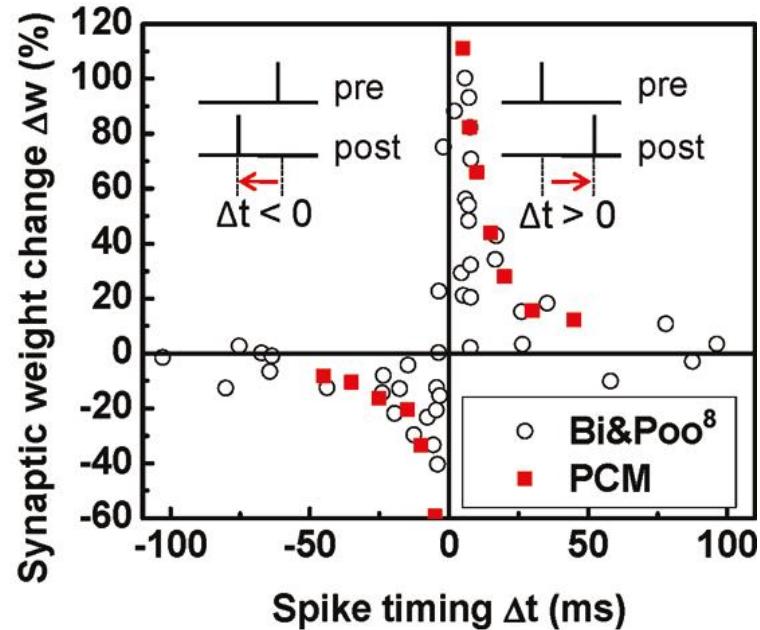
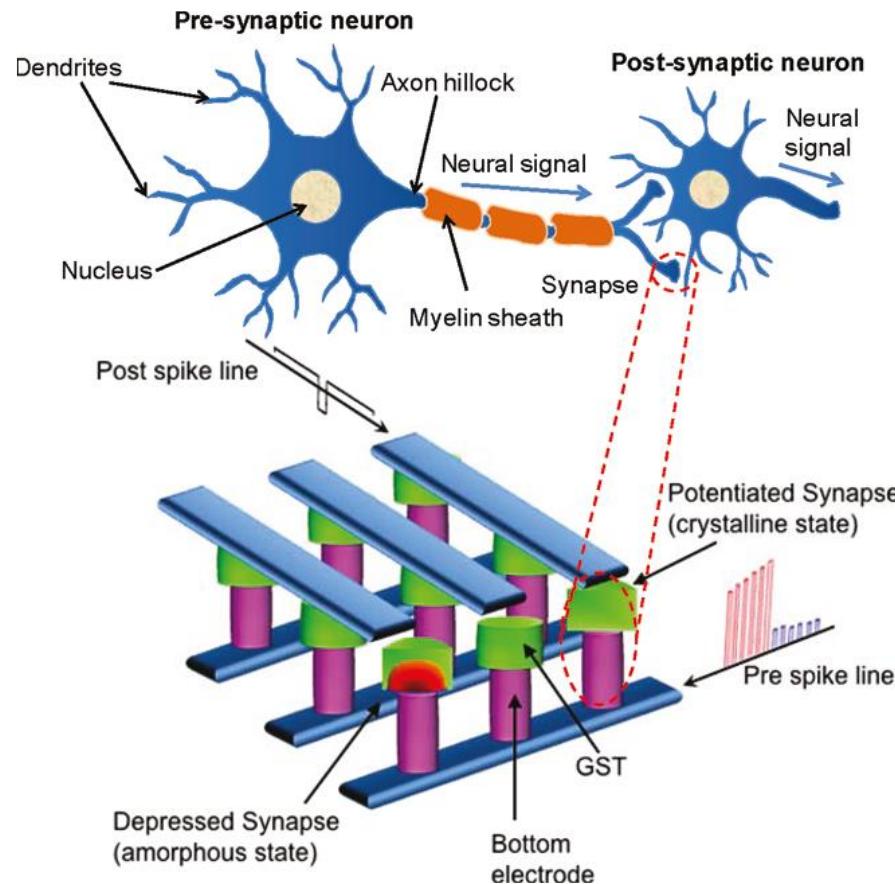


- Adjusting STDP with different schemes of pre-spike pulses
- Symmetric STDP



Dyugu et al., *Nano Lett.*, 2012

Drawbacks



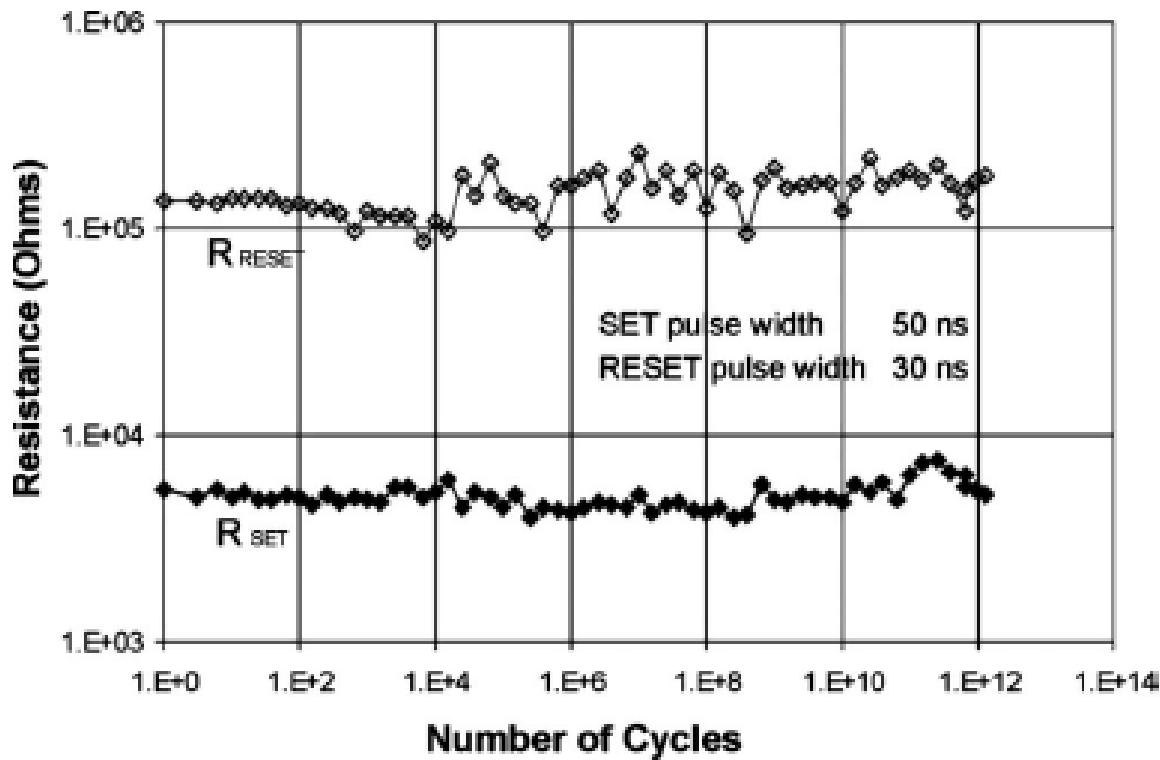
Dyugu et al., *Nano Lett.*, 2012

- Undesired programming and disturbance due to additional pulses
- Excess energy consumption

PCM Pulse Scheme

- Gating and response spike alone are not enough for programming
- Gating is used to ensure that only the intended synapse is programmed
- Possible to implement both
 - Asymmetric STDP: pre-neuron is reset and post-neuron is set
 - Symmetric STDP: quick response signal is set, slow is reset
- Disadvantage
 - computer-controlled pulse generator needs to be implemented

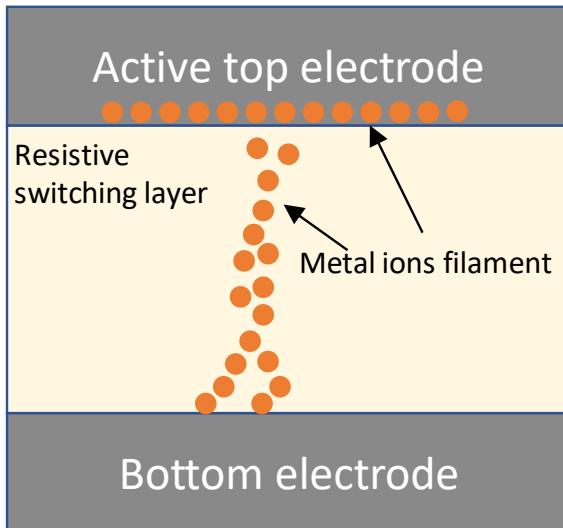
Challenges: Variability



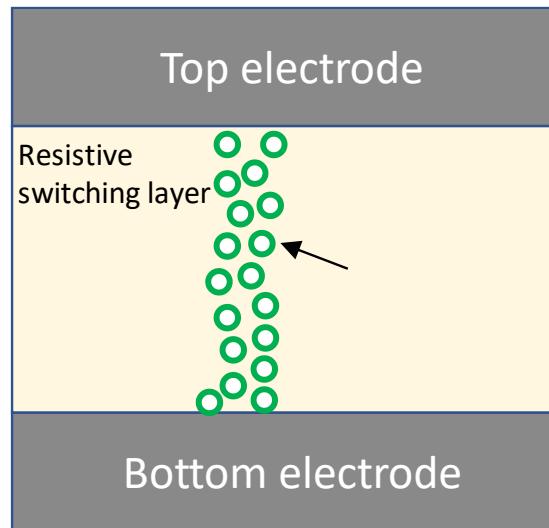
- Intra-device and inter-device variability
- Implication: less accurate, longer training time, consumes more energy

RRAM Synapses

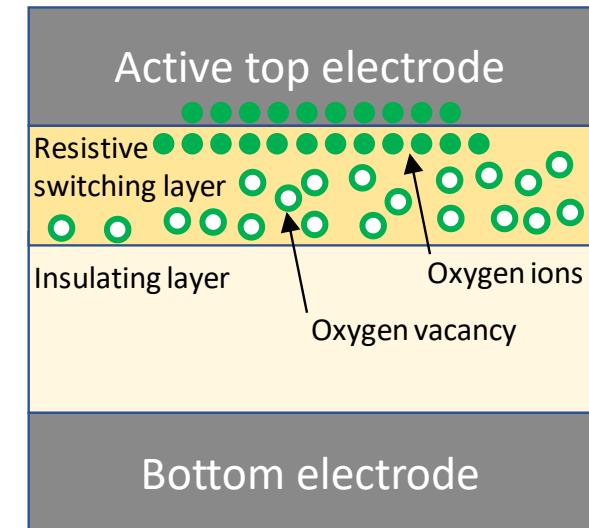
CBRAM



Filamentary RRAM



Non-filamentary RRAM



- Synaptic devices prefers analog switching behaviors
- Non-filamentary devices show more analog switching

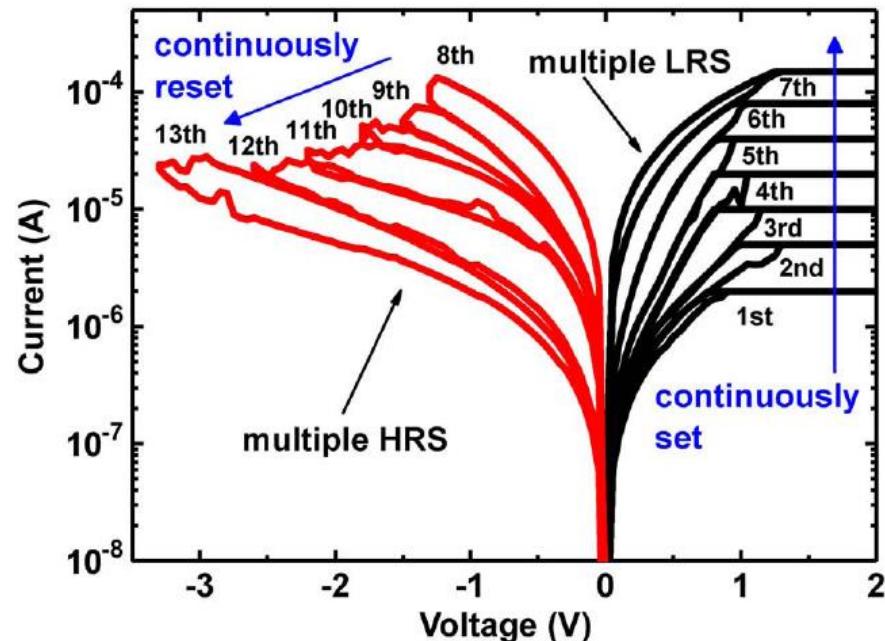
RRAM for Synaptic Electronics

- Advantages

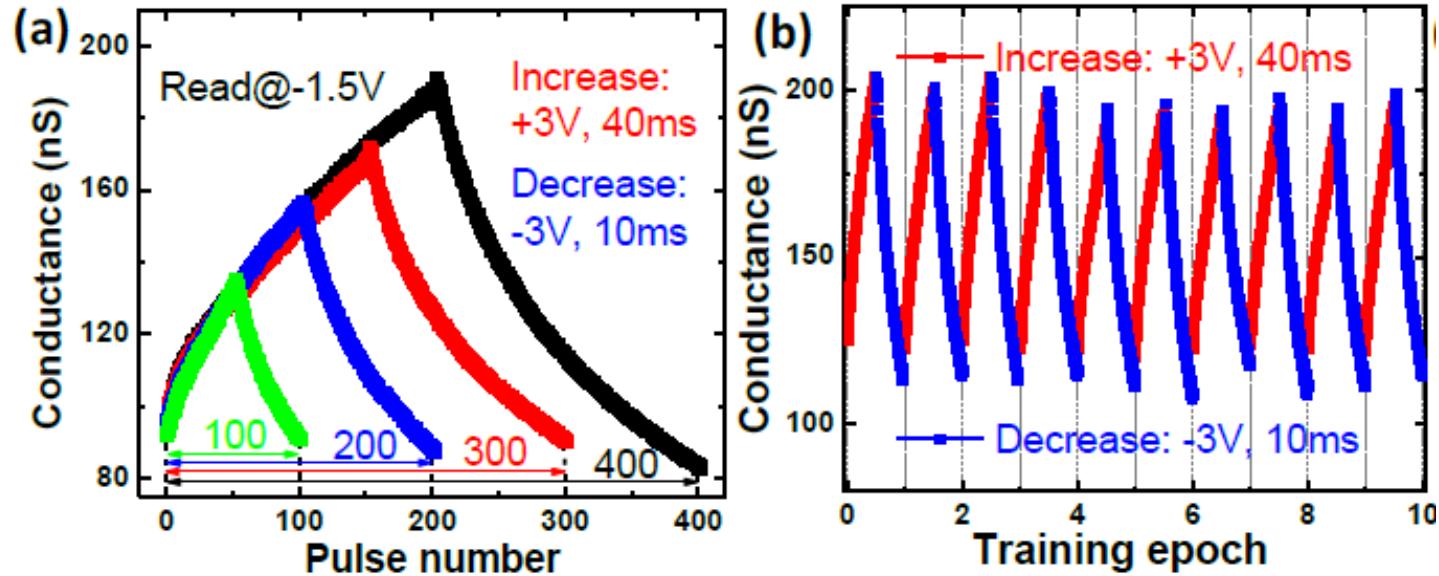
- non-volatile
- analog with large on/off ratio
- endurance $\sim 10^8$
- energy $< 1 \text{ fJ}$
- speed $\sim 1 \text{ ns}$
- two-terminal

- Disadvantages

- Large device variations
- non-linear IV, especially abrupt tuning
- limited precision
- the need for a forming step
- No built-in temporal component



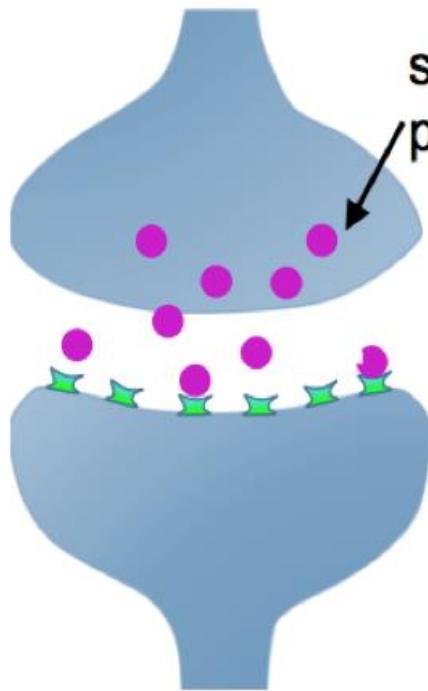
Non-Filamentary Switching



- Higher precision → high density
- More linear and symmetrical → better for online training

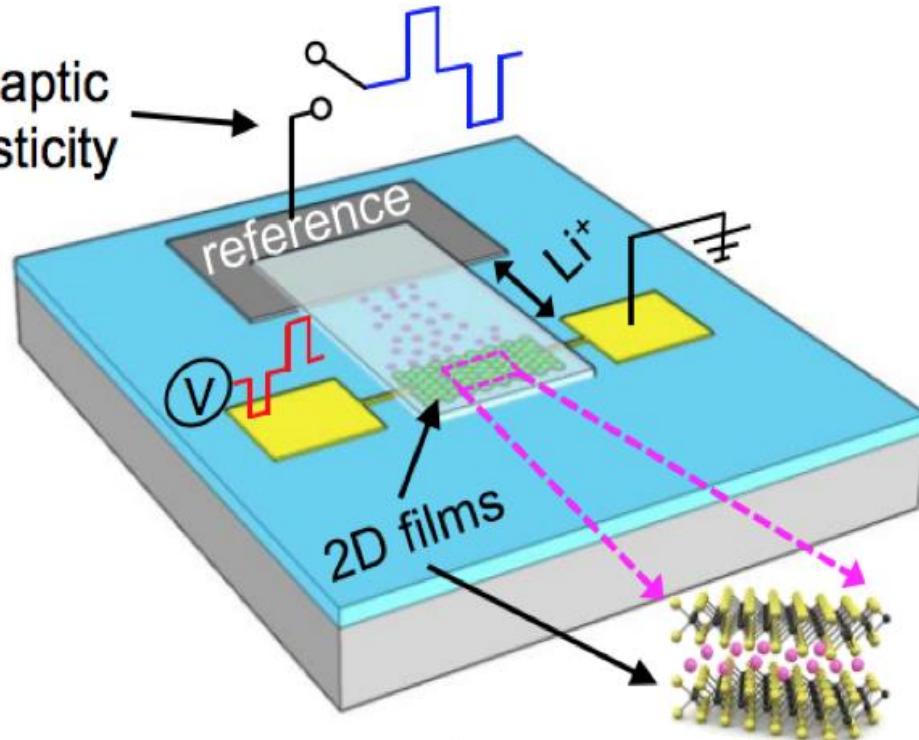
2D Electrochemical Graphene Synapse

Bio-Synapse



2D Gr-Synapse

M. Sharbati, ..., F. Xiong, *Adv. Mater.*, 2018

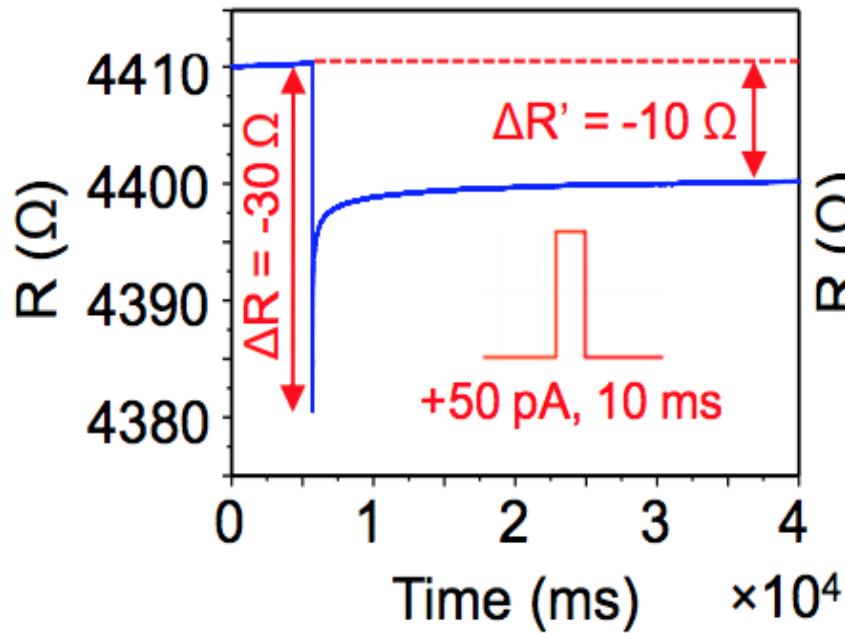


- Synaptic weight = graphene conductance
- Synaptic plasticity = electrochemical intercalation

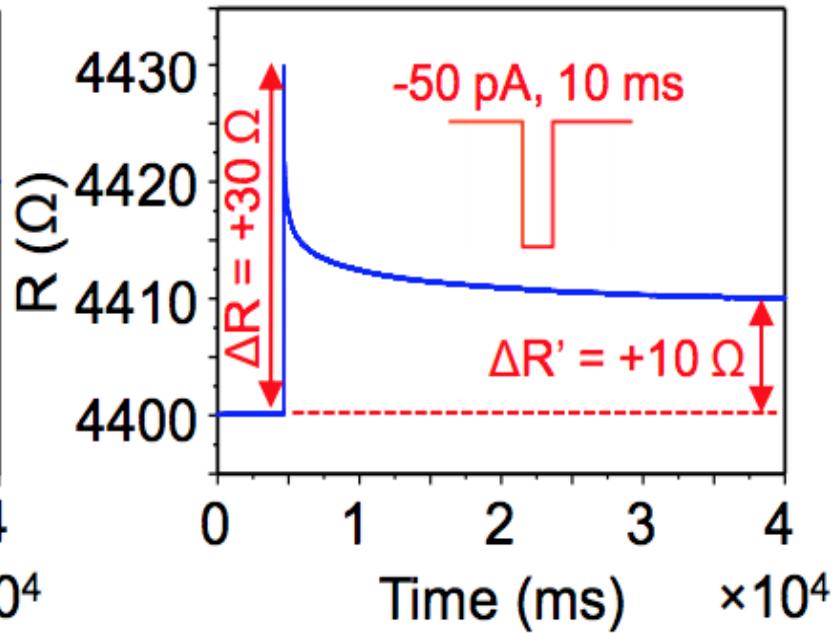
Excitatory and Inhibitory Synapses

M. Sharbati, ..., F. Xiong, *Adv. Mater.*, 2018

Excitatory



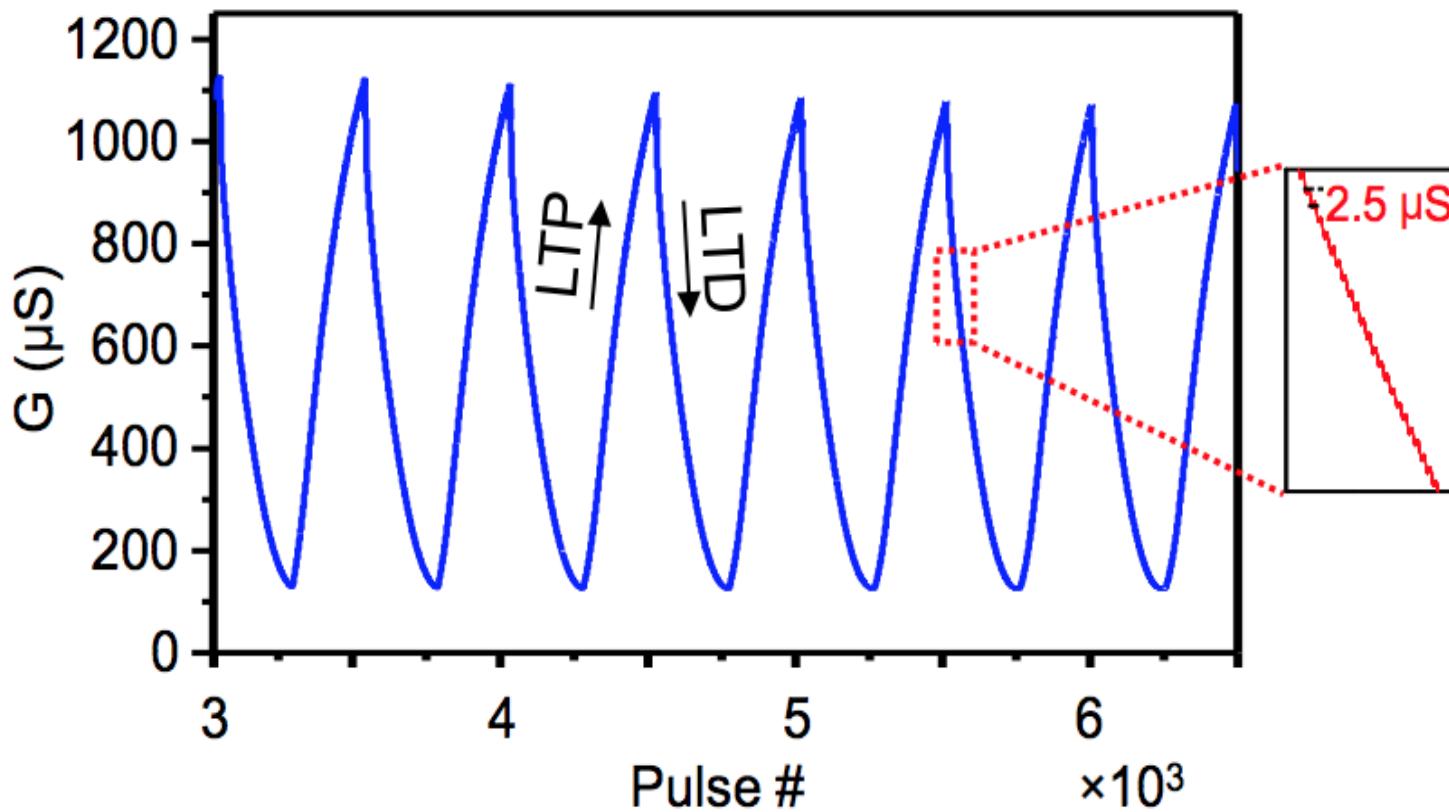
Inhibitory



- Li doping: non-volatile effect
- Electric double layer (EDL) gating effect: transient change

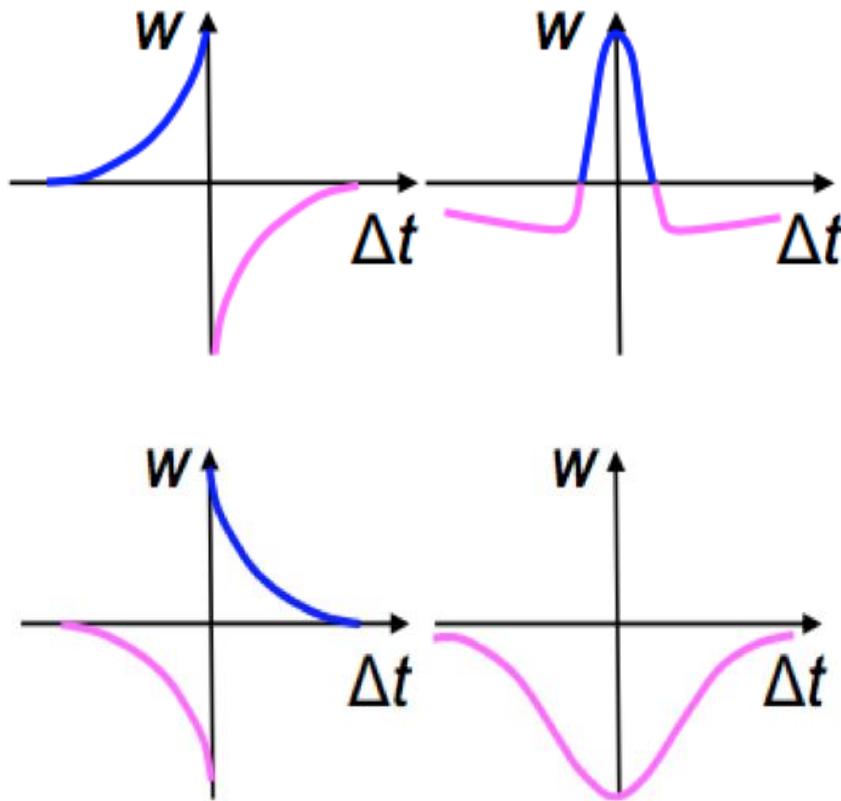
Linear and Symmetric Response

M. Sharbati, ..., F. Xiong, *Adv. Mater.*, 2018



- Long term potentiation (LTP) and depression (LTD)
- Highly linear, symmetric, and reproducible
- > 400 states, i.e. $\Delta G/G < 0.25\%$

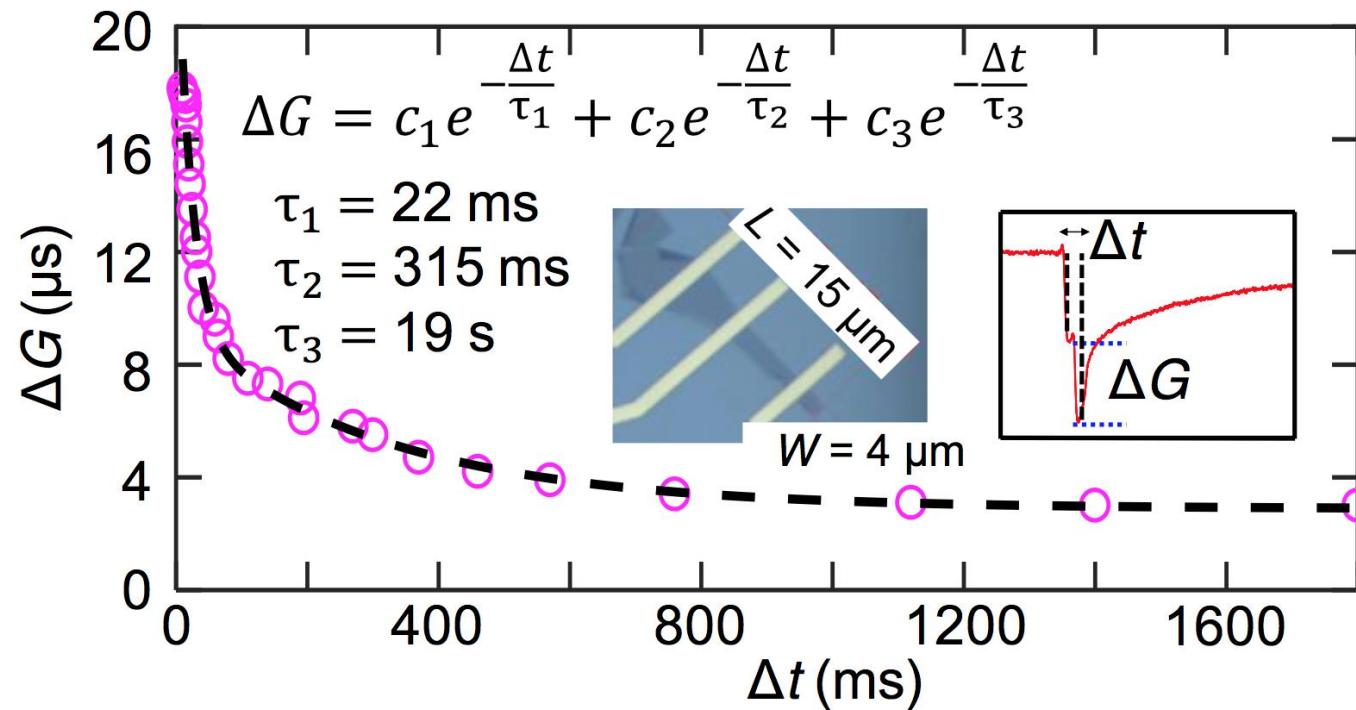
Spike Timing Dependent Plasticity (STDP)



Different forms of STDP in biological synapses

Programmable STDP

M. Sharbati, ..., F. Xiong, *Adv. Mater.*, 2018



$$\tau_D \approx L^2 / 2D$$

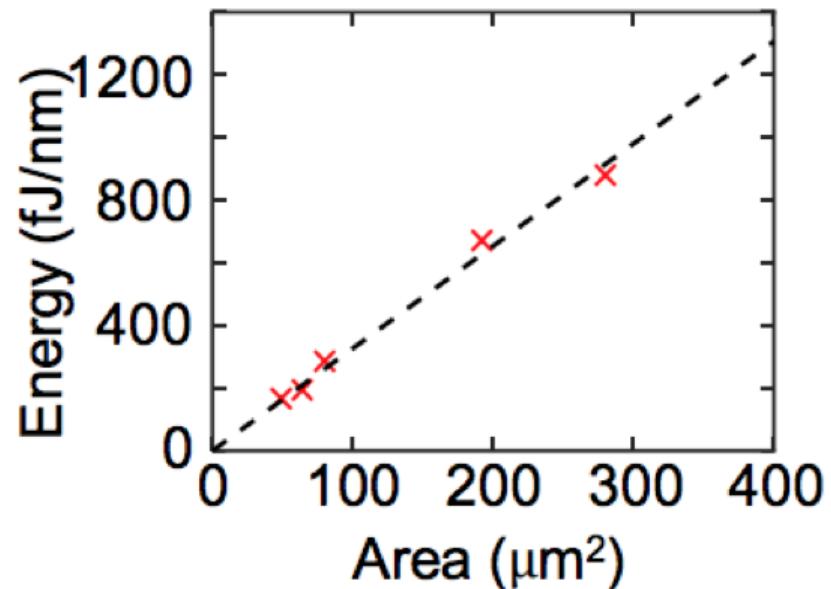
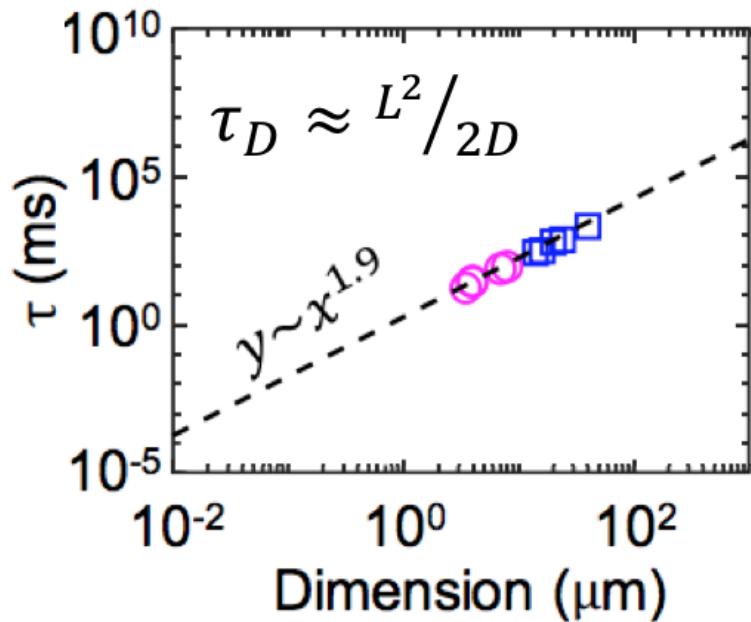
$$\frac{\tau_2}{\tau_1} = 14.5$$

$$\left(\frac{L}{W}\right)^2 = 14.1$$

- Assume $D_{coeff} \sim 4 \times 10^{-6} \text{ cm}^2/\text{s}$
→ $\tau_1 \sim 20 \text{ ms}$, $\tau_2 \sim 280 \text{ ms}$ in W and L direction
- τ_3 may rise from diffusion between LFP to Gr
- engineering time constants

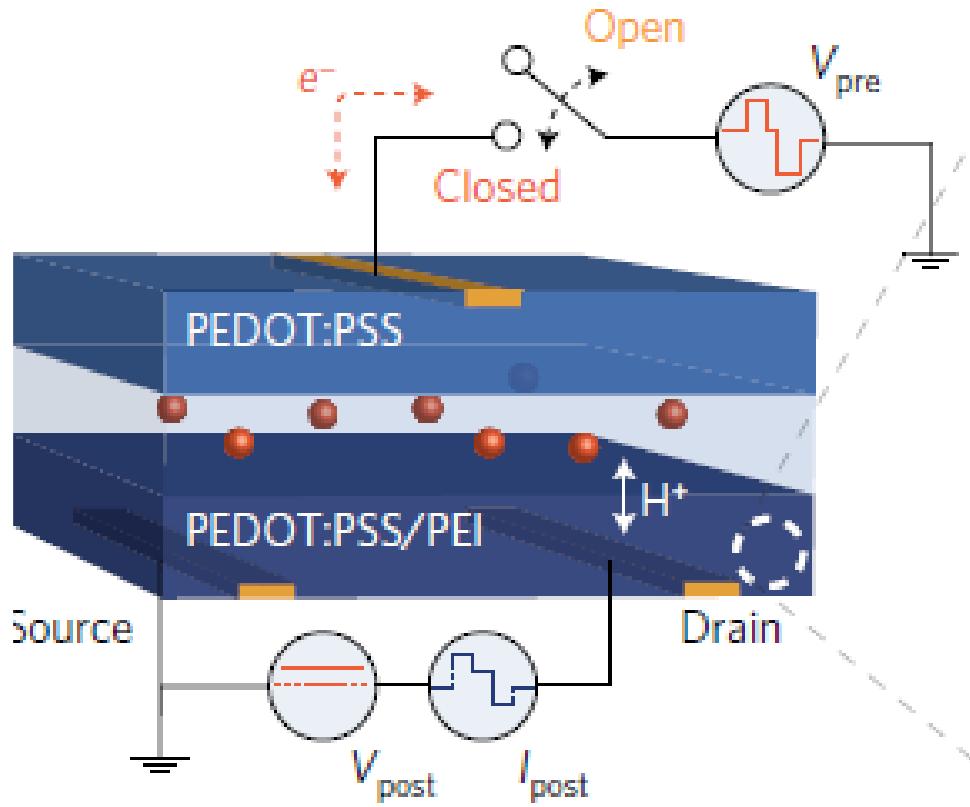
Scaling Analysis

M. Sharbati, ..., F. Xiong, *Adv. Mater.*, 2018



- Scalable in terms of energy and time
- For 30 nm x 30 nm: 100 ns and 5 aJ switching

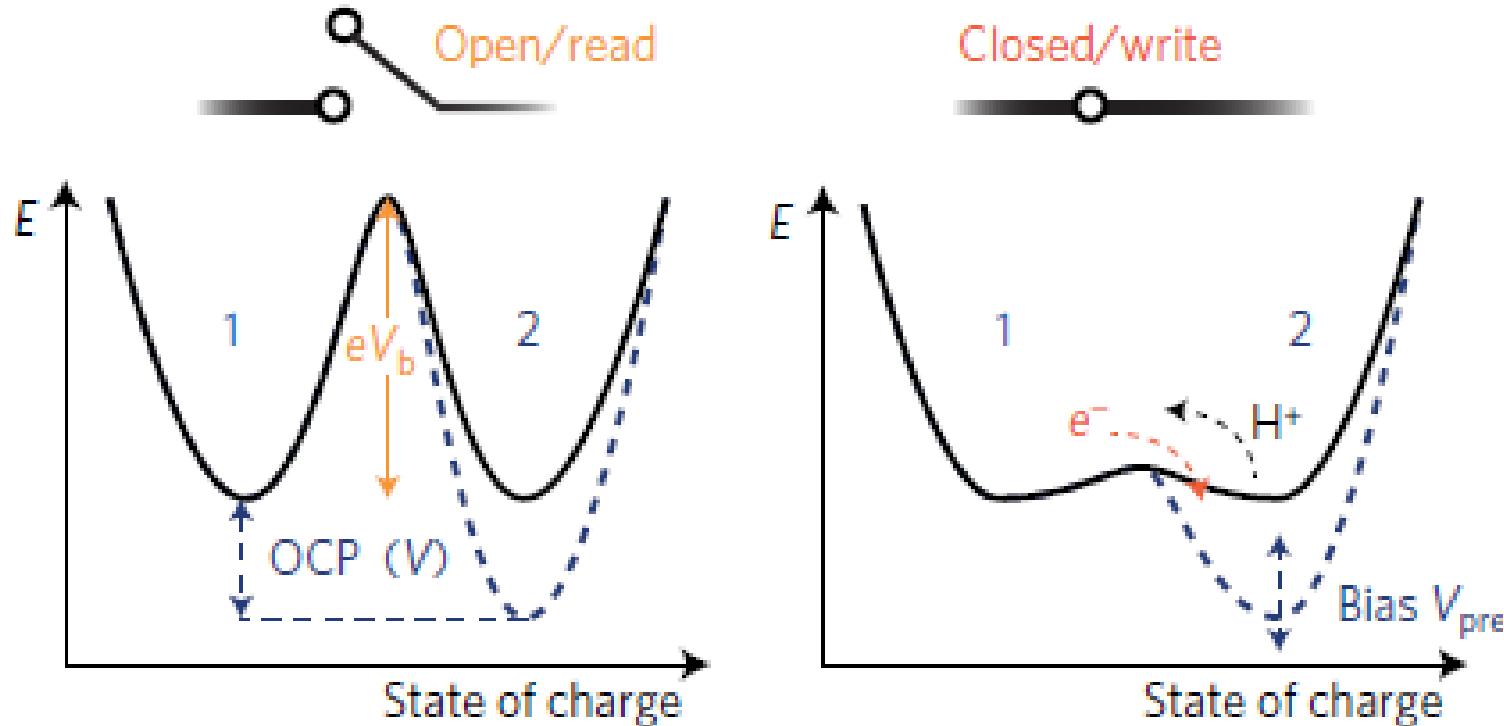
Redox Synapse



- Synapse weight is channel conductance
- Programming through electrochemical reaction – adding H^+ ions into the conduction channel

Burgt et al., Nat. Mater, 2017

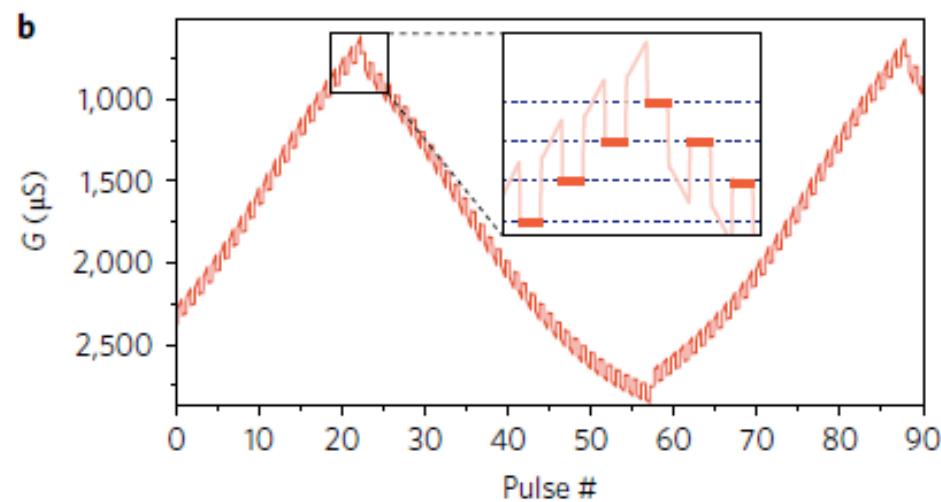
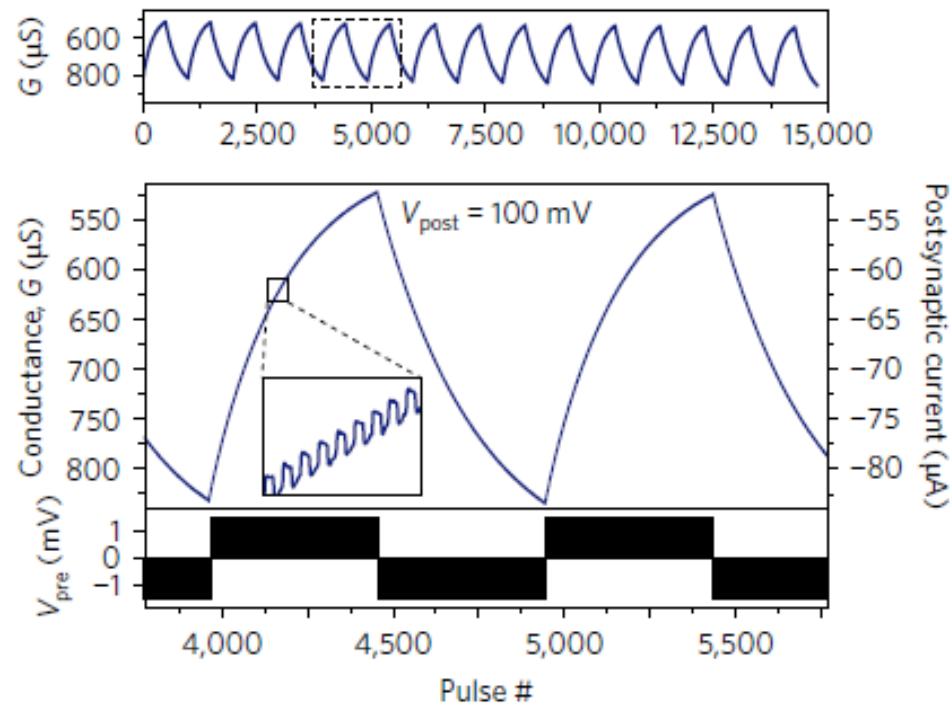
Retention and Power Consumption



- Typically, retention and power consumption are coupled
- Better retention \rightarrow large barrier \rightarrow high power
- Here: retention (electrochemical reaction) and programming (conduction) are de-coupled
- Good retention AND low power

Burgt et al., Nat. Mater, 2017

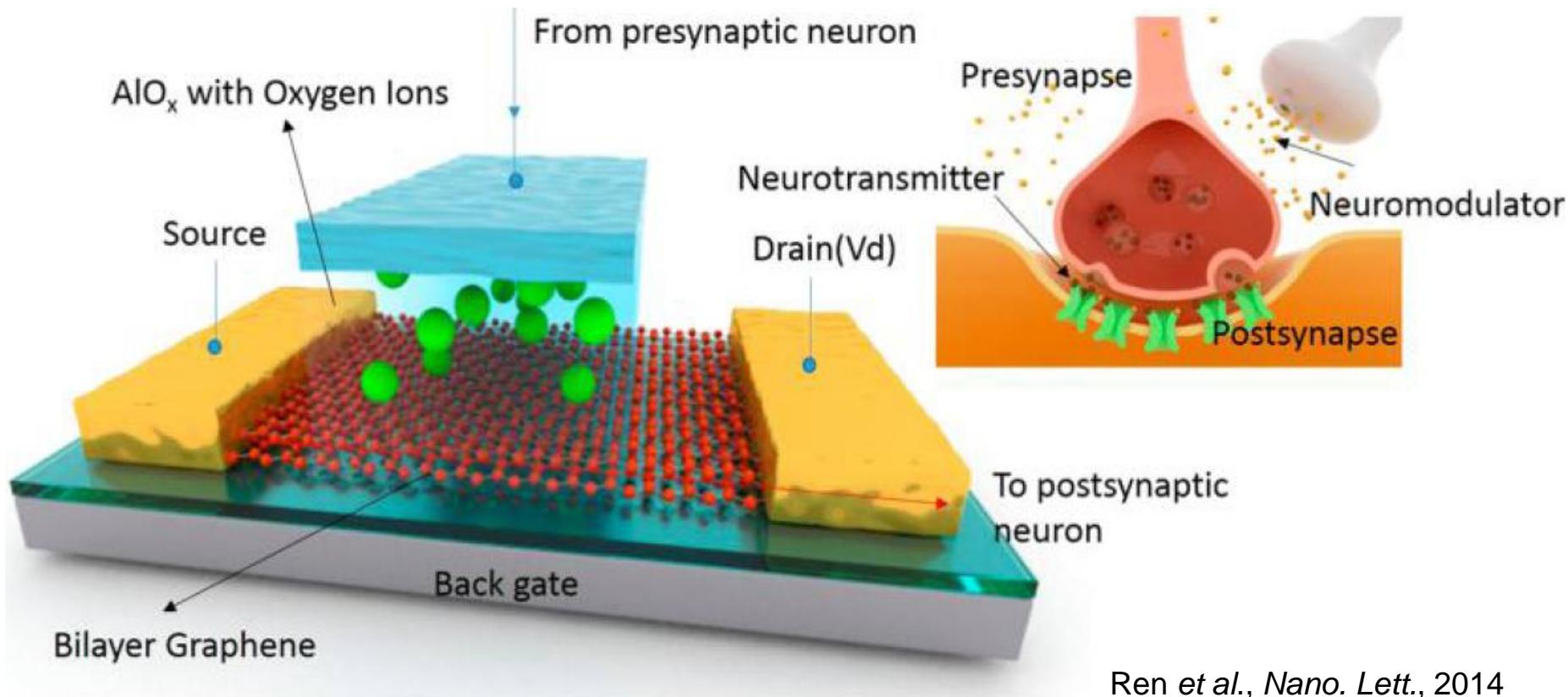
LTP and LTD



- Fine control over conductance
- Stable operation with good endurance

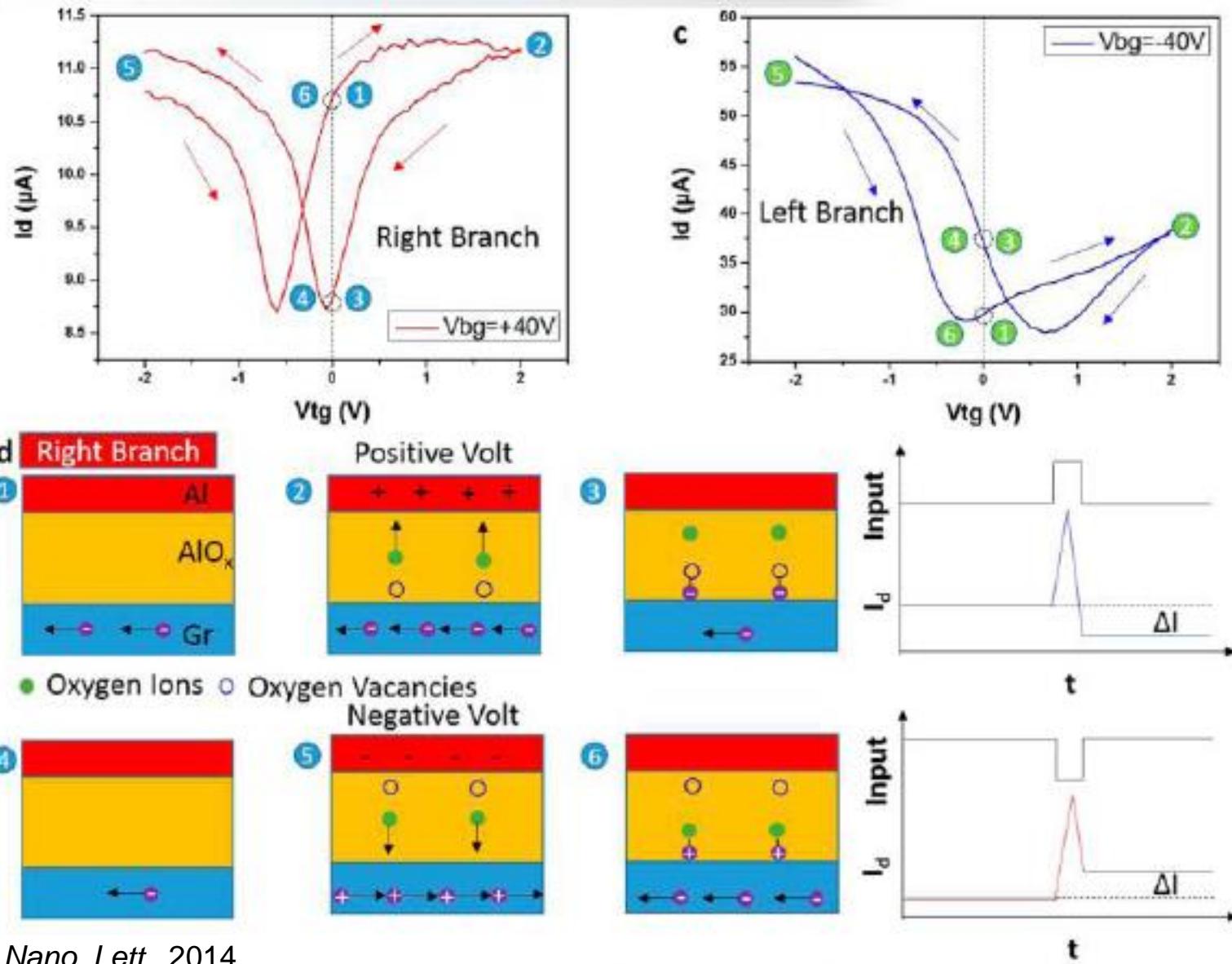
Burgt et al., Nat. Mater, 2017

Graphene FET with Top AlO_x Gate



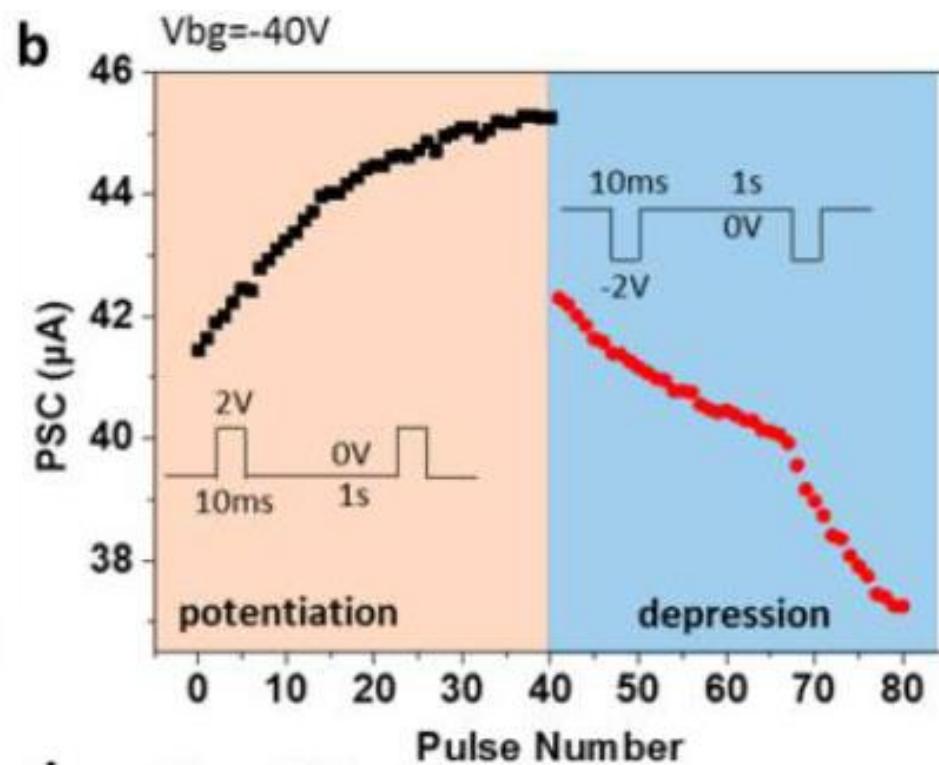
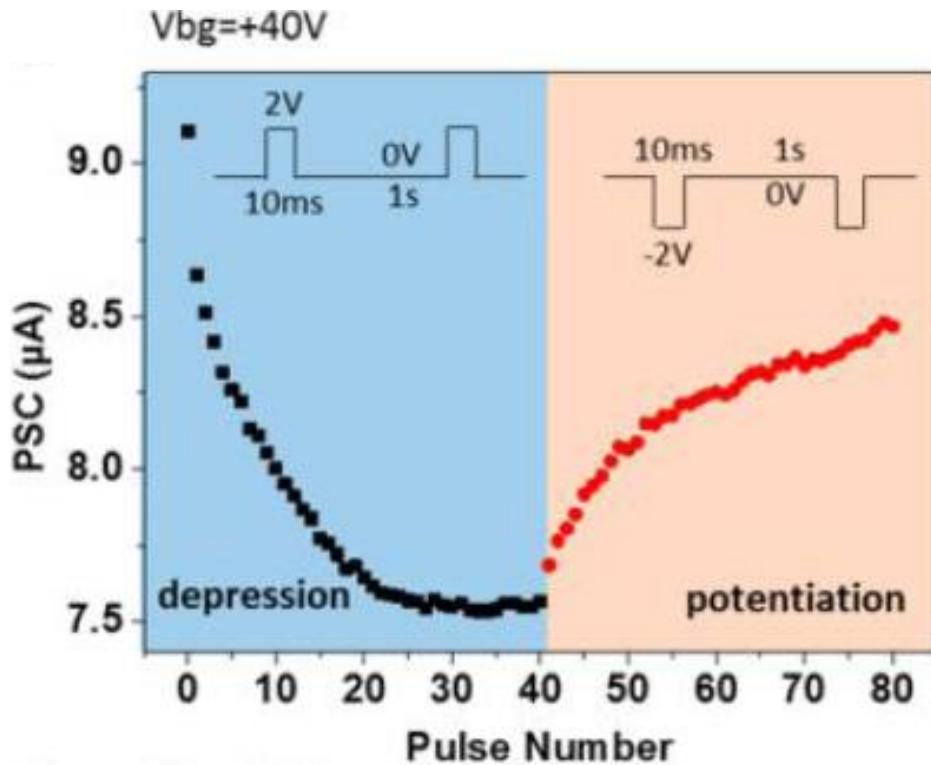
- Graphene field effect transistor
- Back-gate: electron or hole
- Top-gate: AlO_x

Charge Trapping in AlO_x



Ren et al., *Nano. Lett.*, 2014

Long Term Potentiation and Depression



Ren et al., *Nano. Lett.*, 2014

- Continuous change via pulse trains