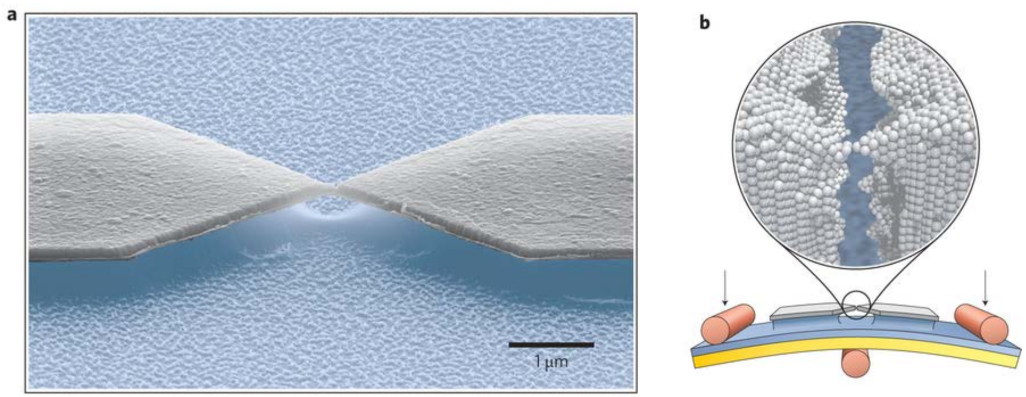
Chapter 12: A current-driven single-atom memory

Exp: C. Schirm , E. Scheer
Theo: M. Matt, J. C. Cuevas (UAMadrid), F. Pauly, P. Nielaba



BADEN-WÜRTTEMBERG STIFTUNG
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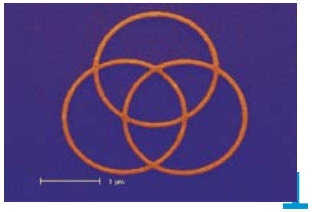
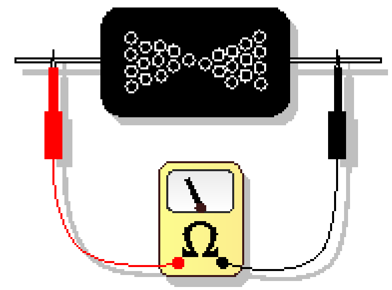
SFB 767



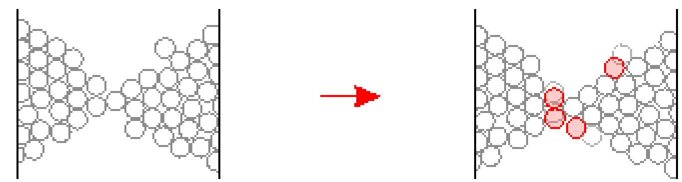
Introduction

Prior realizations of atomic switches



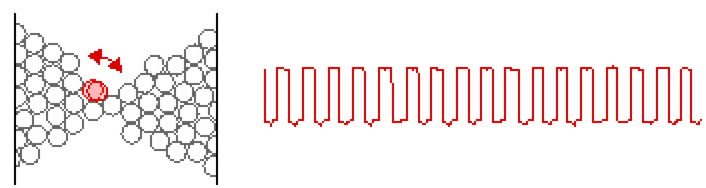
Current-induced rearrangements

Conductance histograms



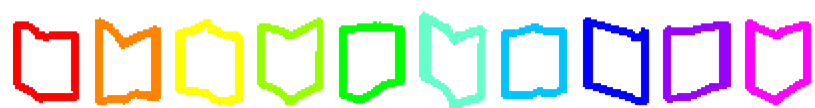
Reversible atomic switches

Individual conductance channels

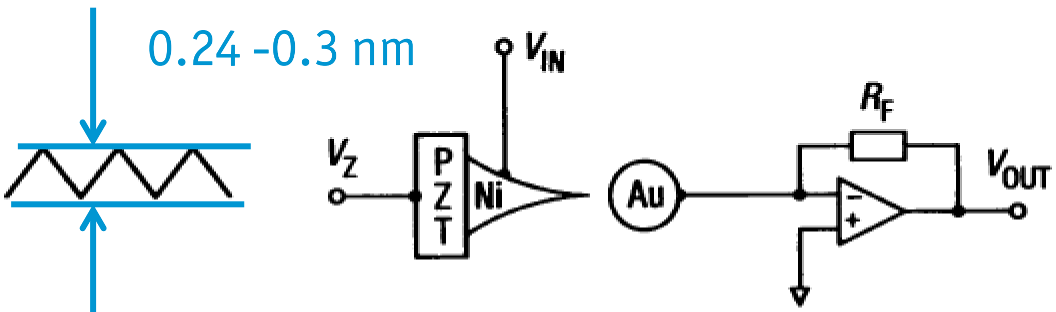


Summary & Outlook

Stability
Hysteresis shapes
and more



Quantum Point Contact Switches

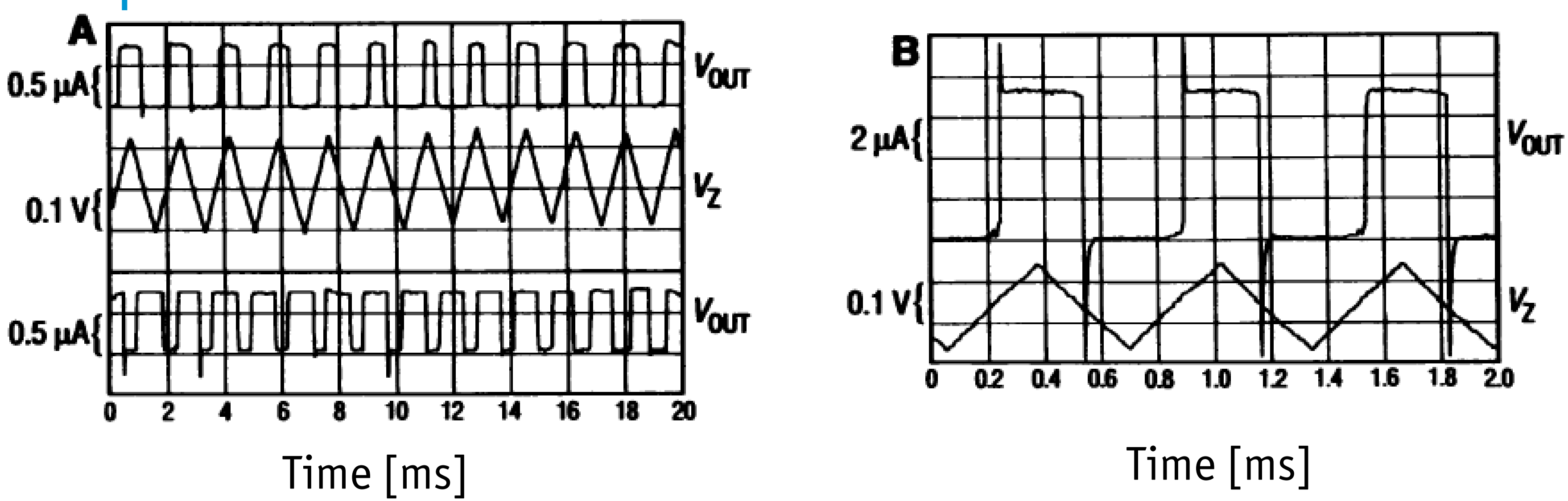


T = 6 K

V_{in} = 10 mV – 100 mV

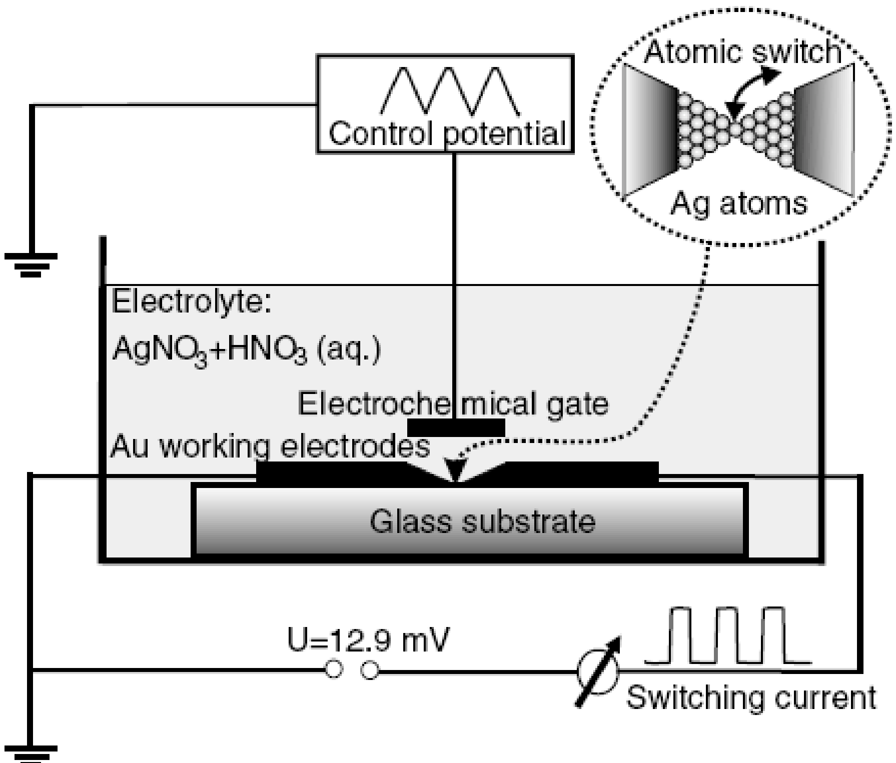
f_{max} = 2kHz

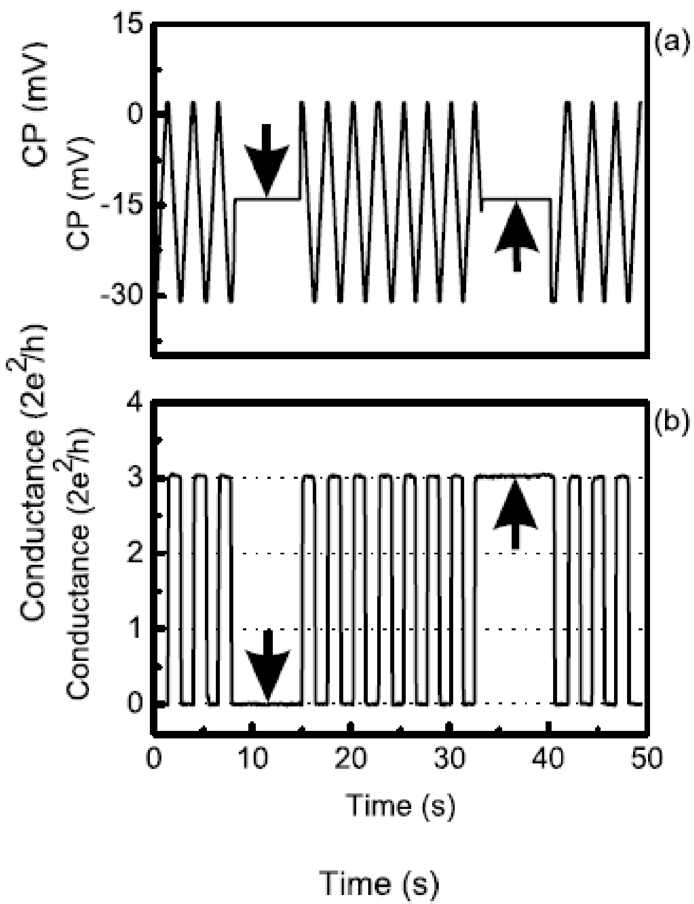
δt = 10 µs



D.P.E. Smith, Science 269, 371 (1995)

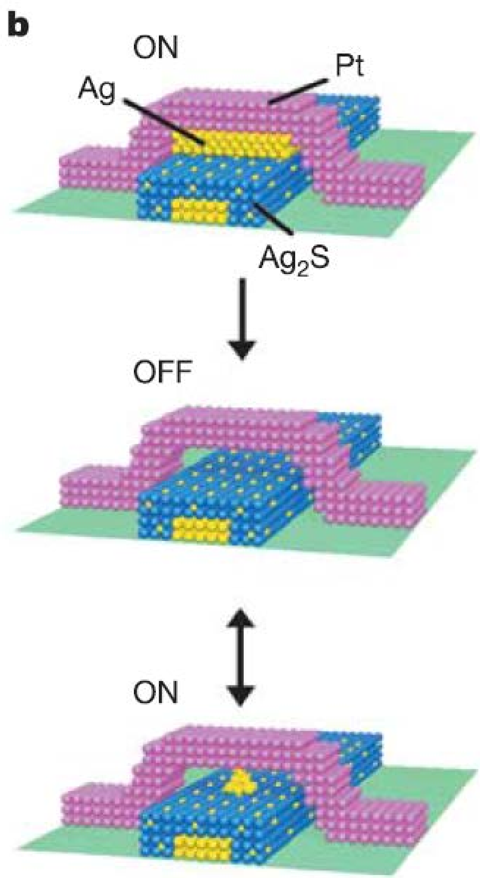
Gate-induced switching of electrochemical contacts

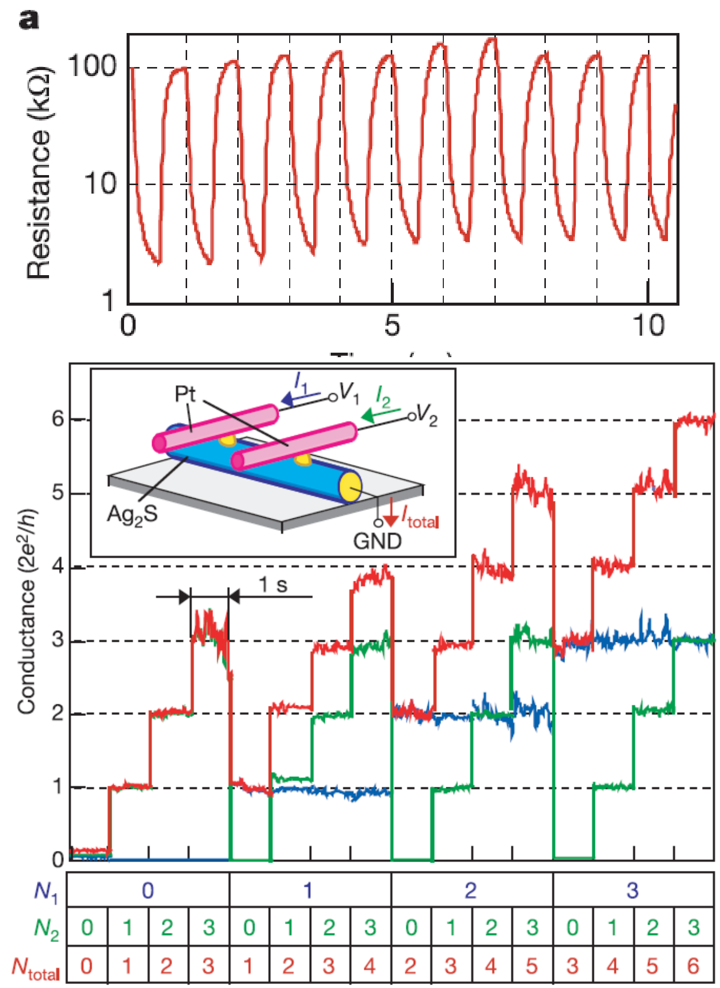




Xie et al, PRL 93, 128303 (2004)

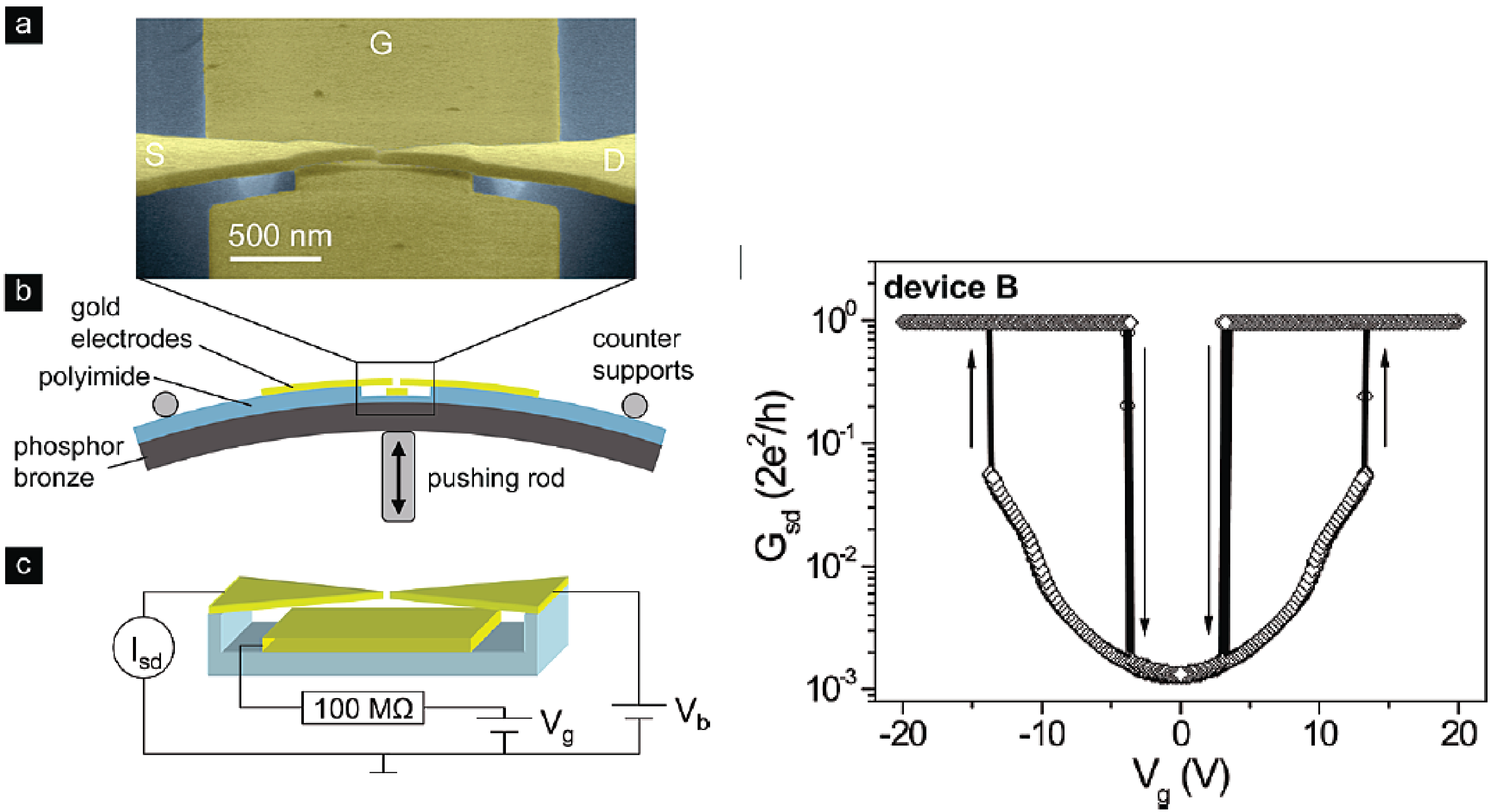
Ion movement controlled memory device





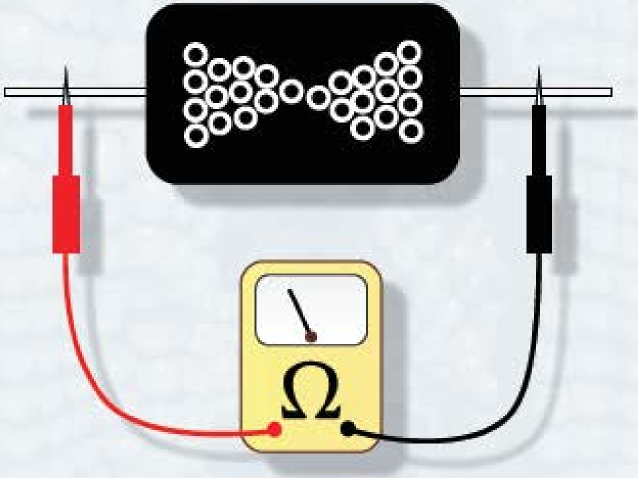
Terabe et al., Nature 433 , 47 (2005)

Nanoelectromechanical single-atom switch

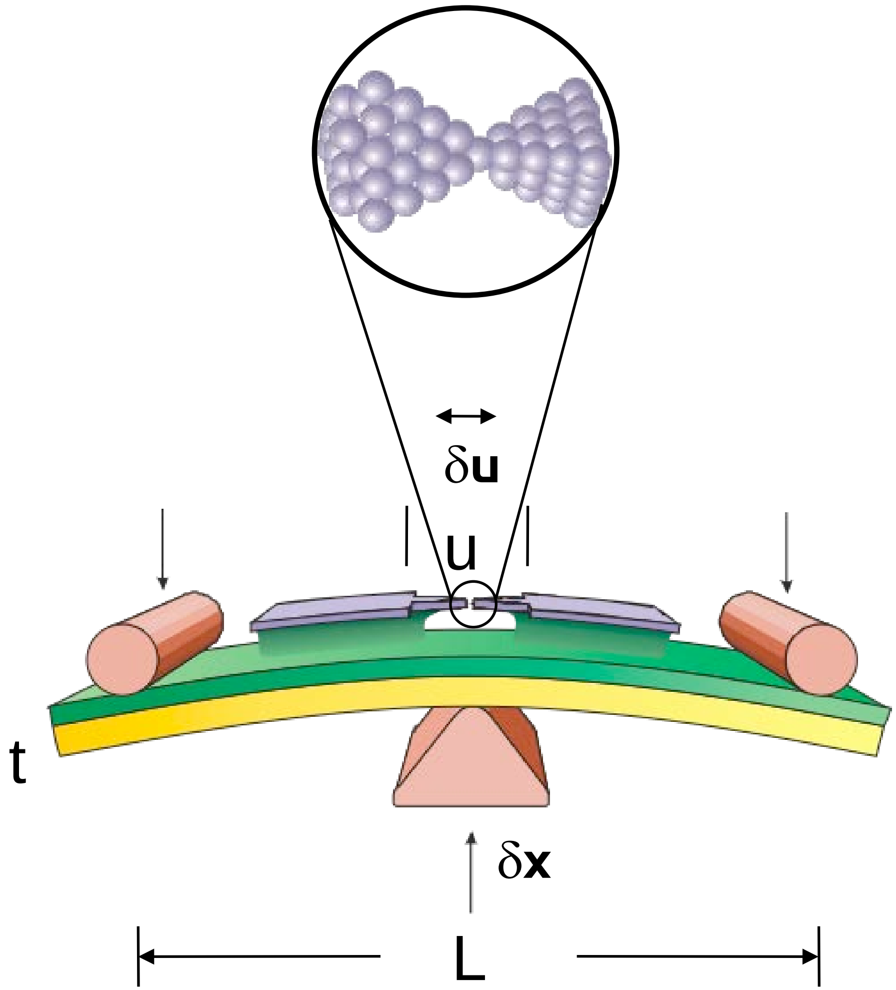


Martin et al., Nano Lett. 9 2940 (2009)

Experimental Setup



Mechanically controlled break junctions



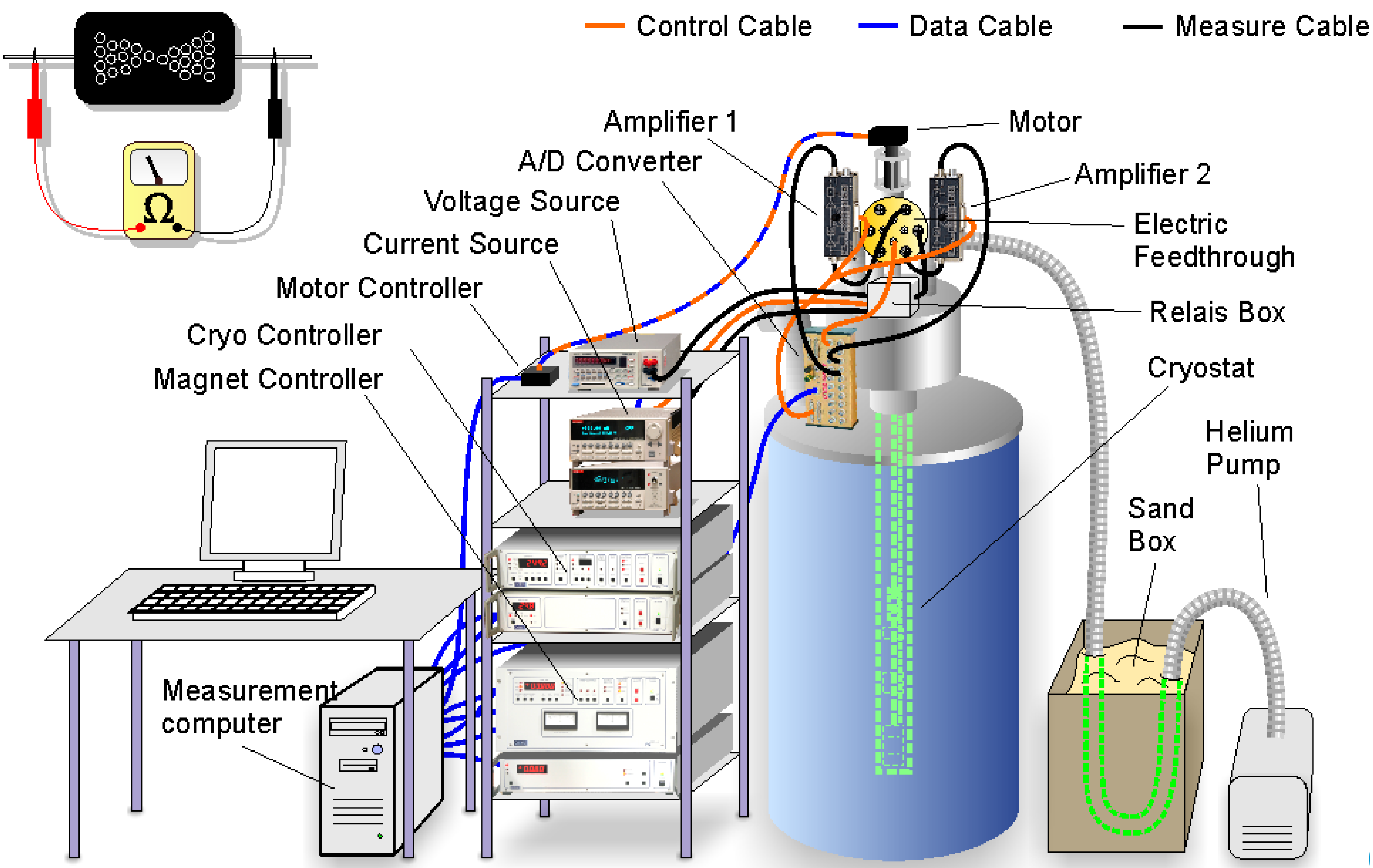
Realization of single-atom contact:

Bending by δx results in a lateral stretching of δu = r δx, where

$$r = \frac{6tu}{L^2}$$

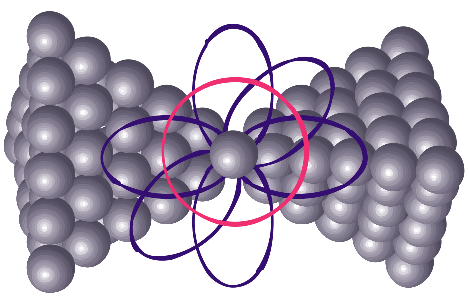
$$r \approx 10^{-4} \dots 10^{-5}$$

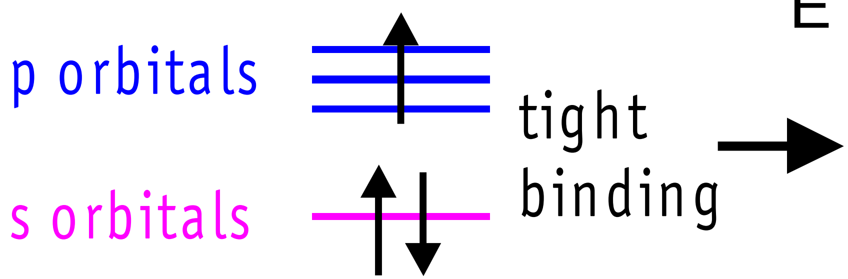
⇒ Atomic resolution possible with "simple" mechanics

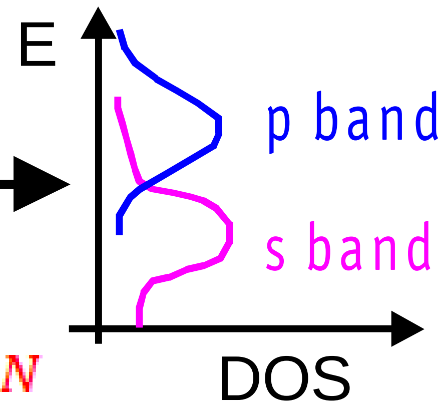


C. Schirm, H.F. Pernau, and E. Scheer, Rev. Sci. Instrum. **80** 024704 (2009)

Conductance of atomic-size contacts







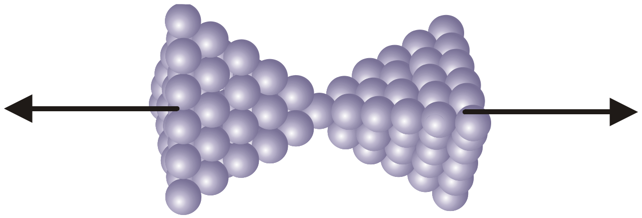
Landauer Formula:

$$G = \frac{2e^2}{h}\sum_{i=1}^{N}\tau_i$$

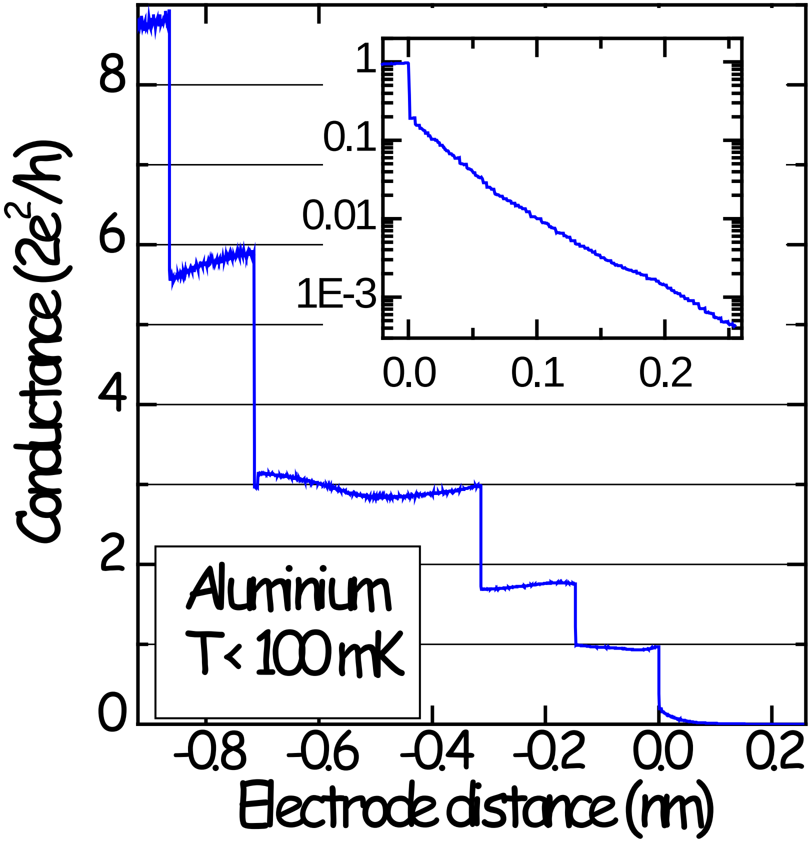
Conductance strongly depends on

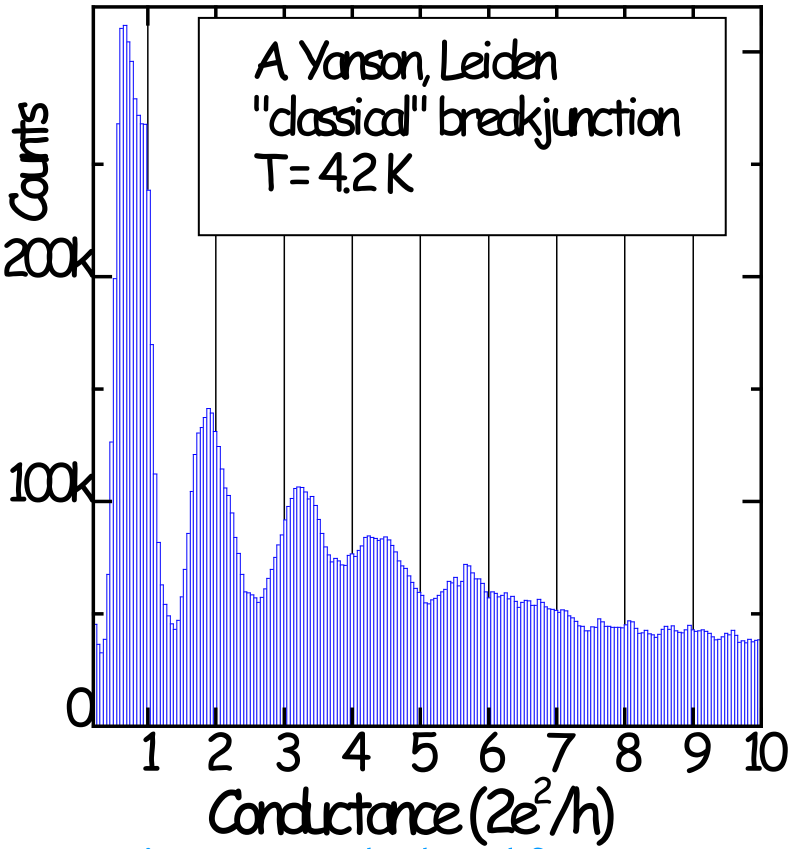
- chemical valence
- position of Fermi level
- precise atomic arrangement

Levy Yeyati et al., PRB 1997;
Cuevas et al., PRL 1998;
Häfner et al., PRB 2004



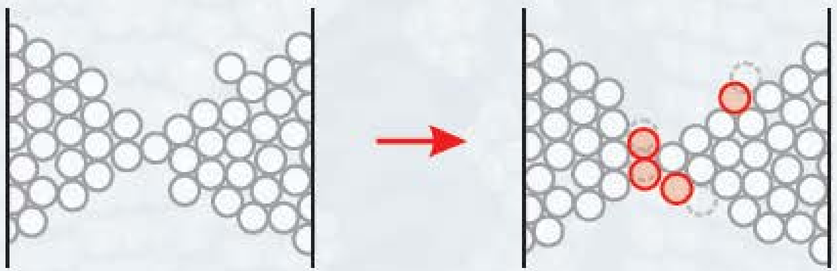
ALUMINUM FEW-ATOMS CONTACTS



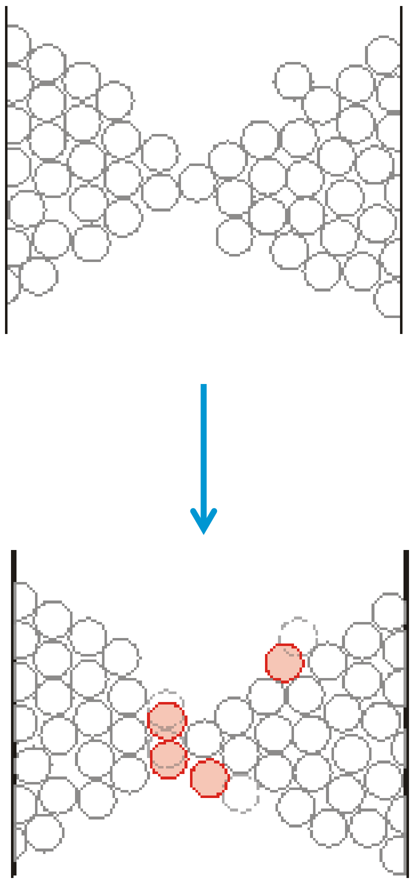


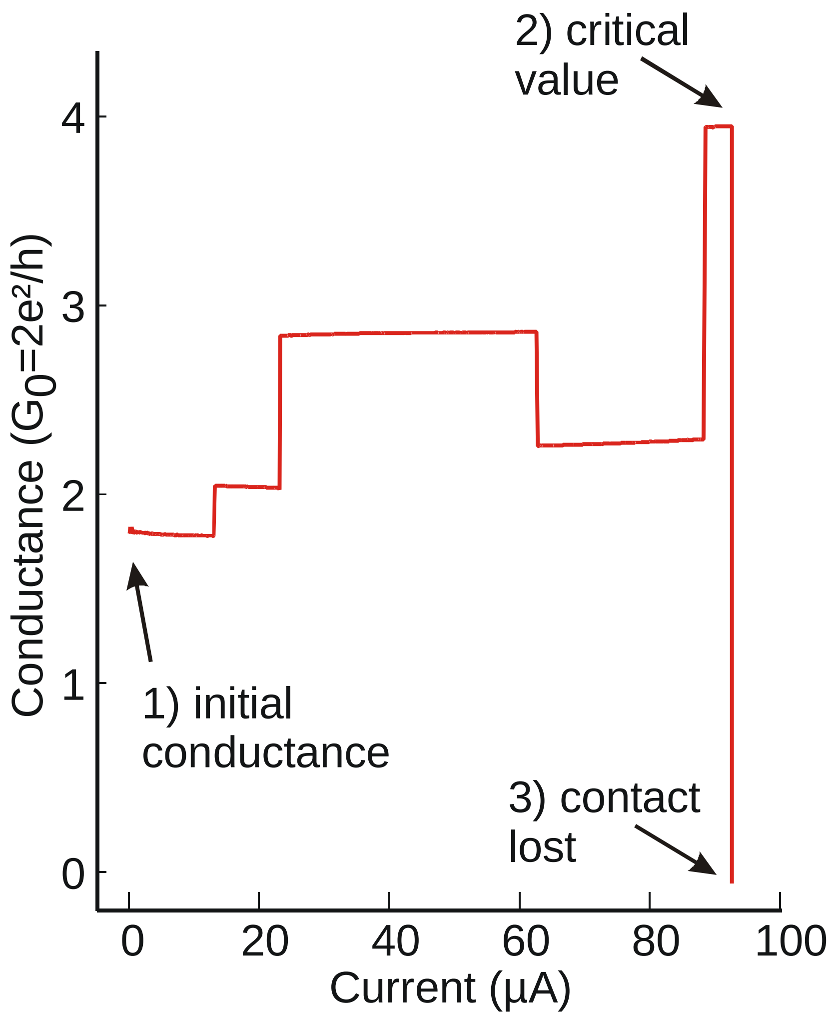
Histogram calculated from >6200 scans

Current-induced rearrangements



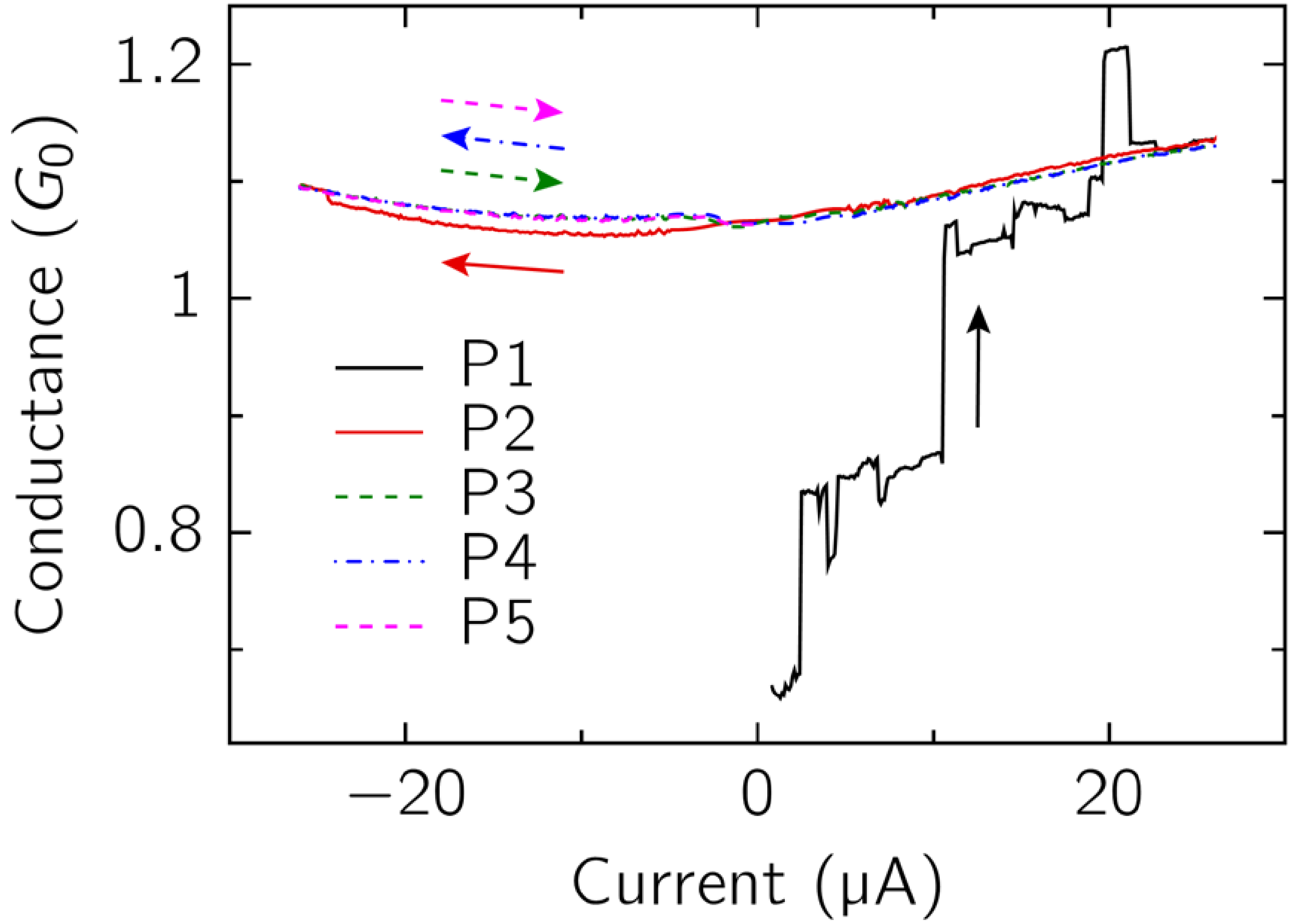
Current-induced rearrangements





Aluminum, 1.4 K

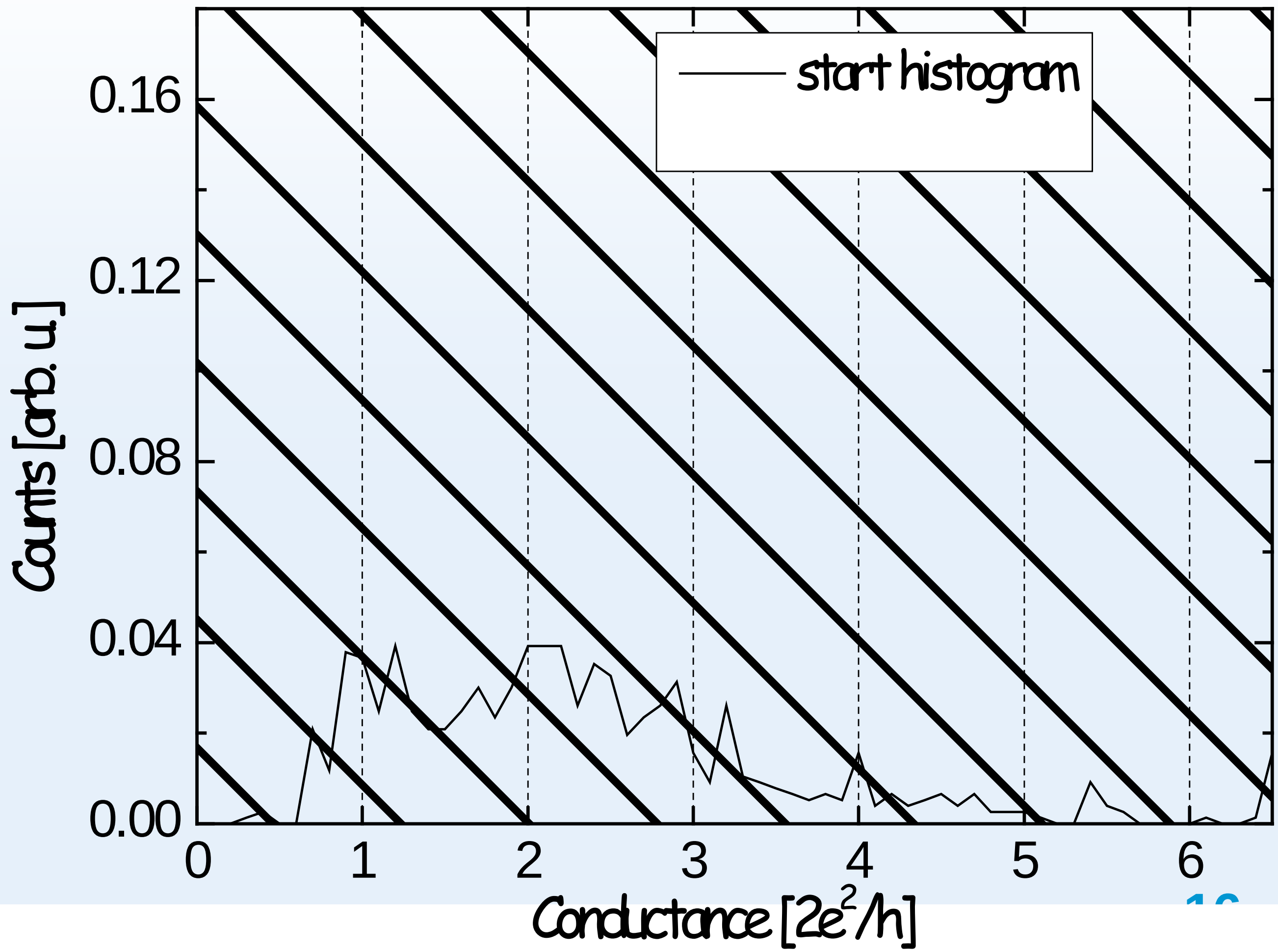
Current-induced rearrangements



-> Rearrangements result in more stable configurations

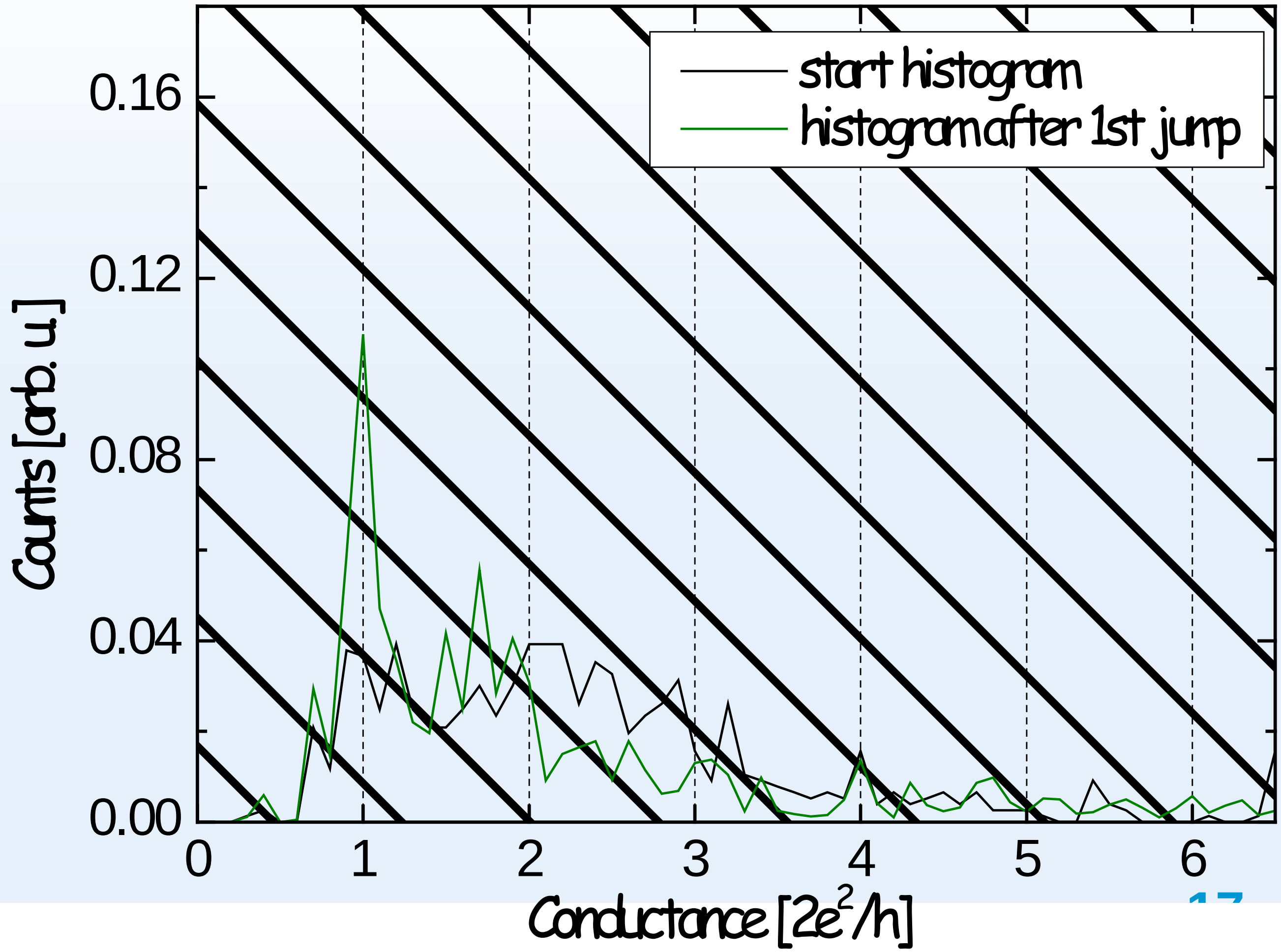
Aluminum,1.4 K

Current-induced rearrangements



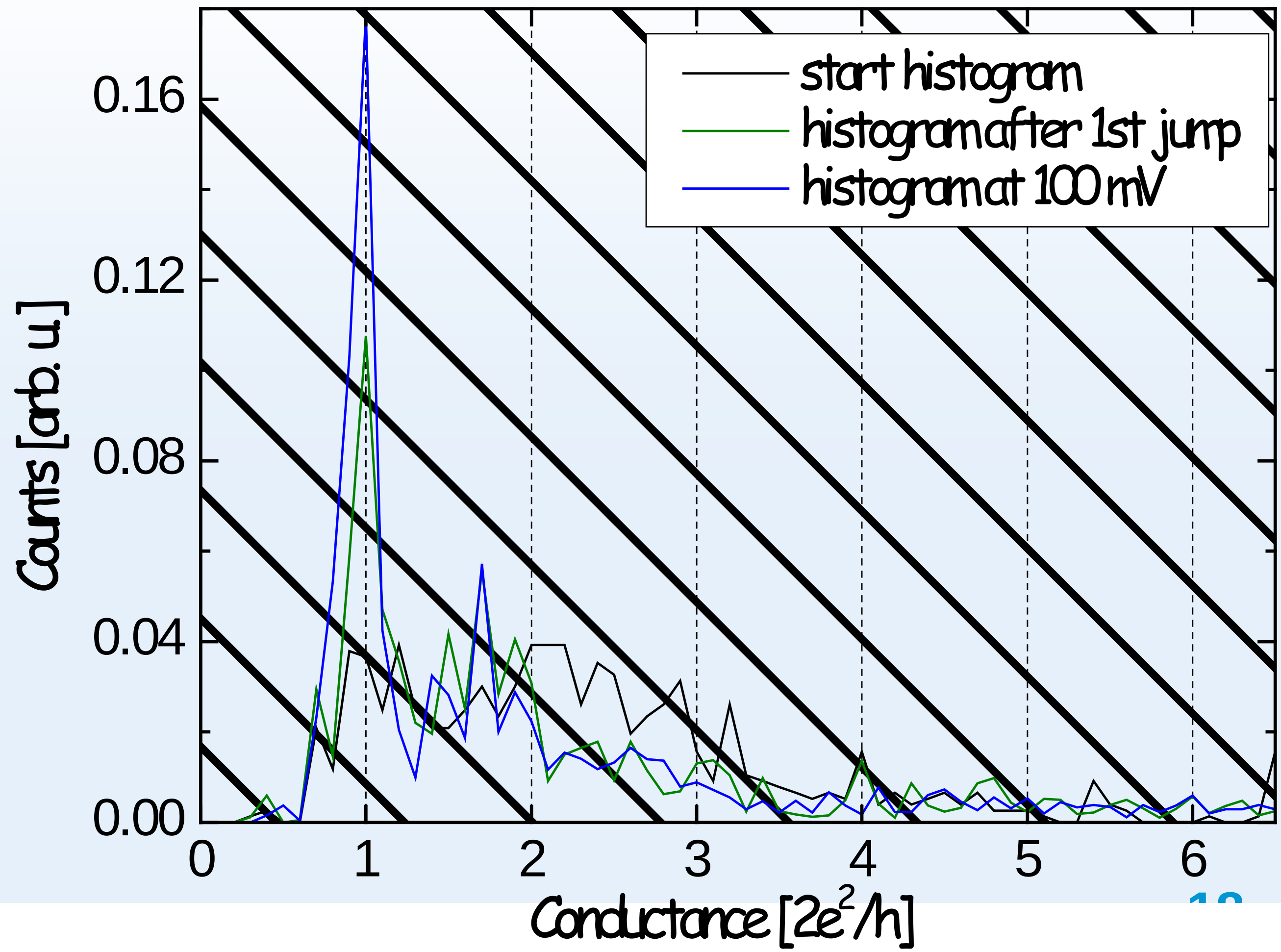
Gold, 1.4 K

Current-induced rearrangements



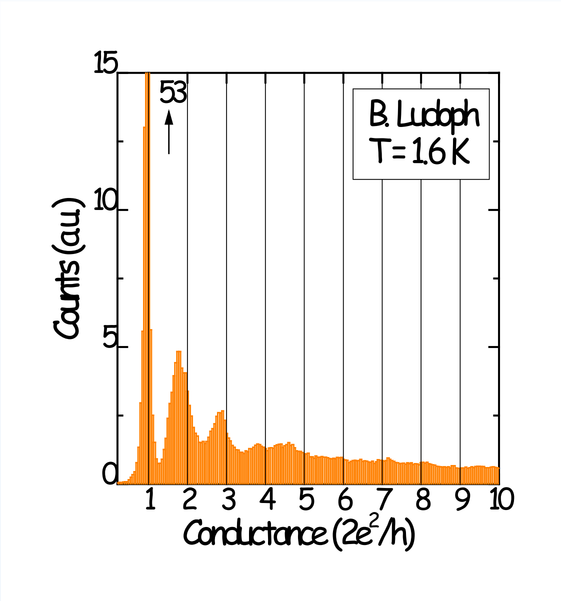
Gold, 1.4 K

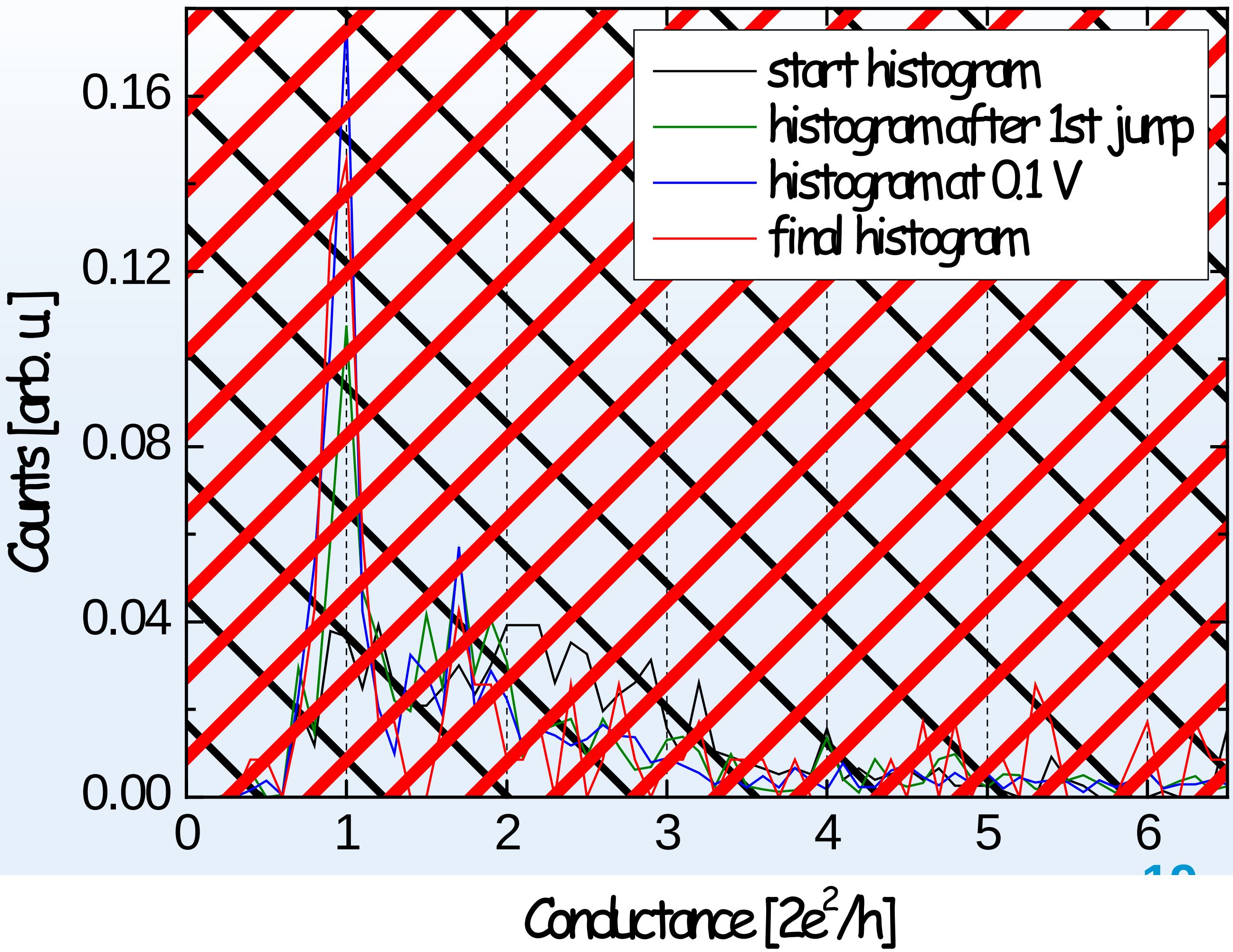
Current-induced rearrangements



Gold, 1.4 K

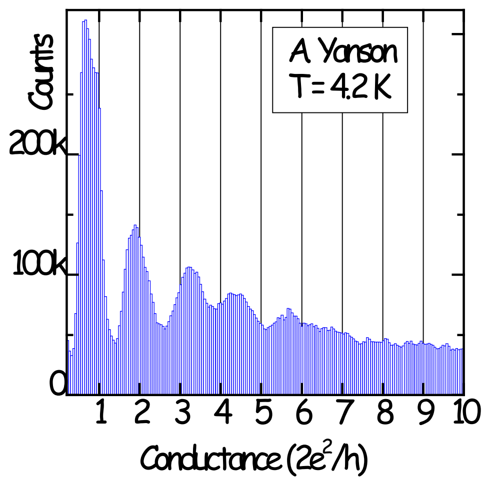
Current-induced rearrangements

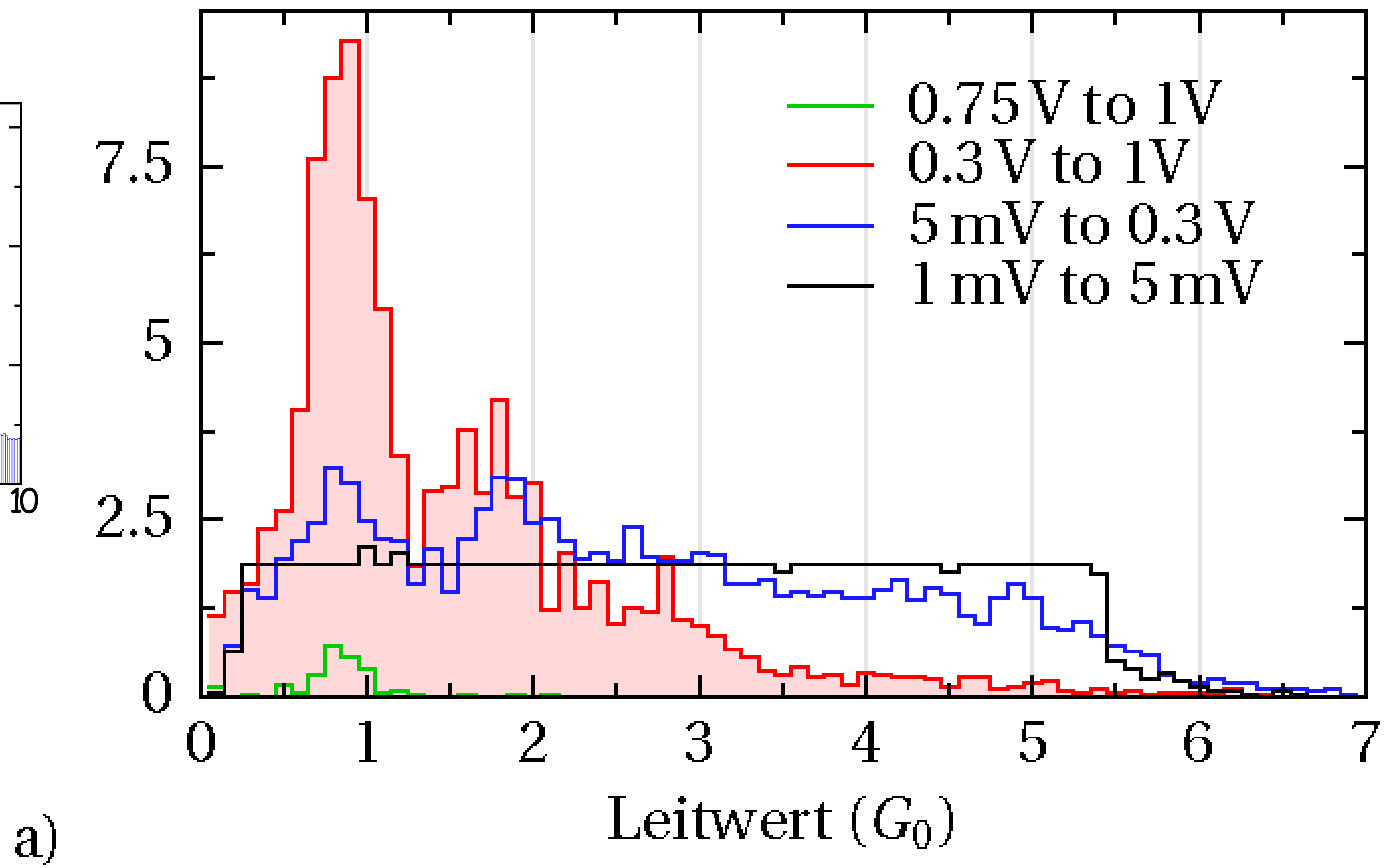




Gold, 1.4 K

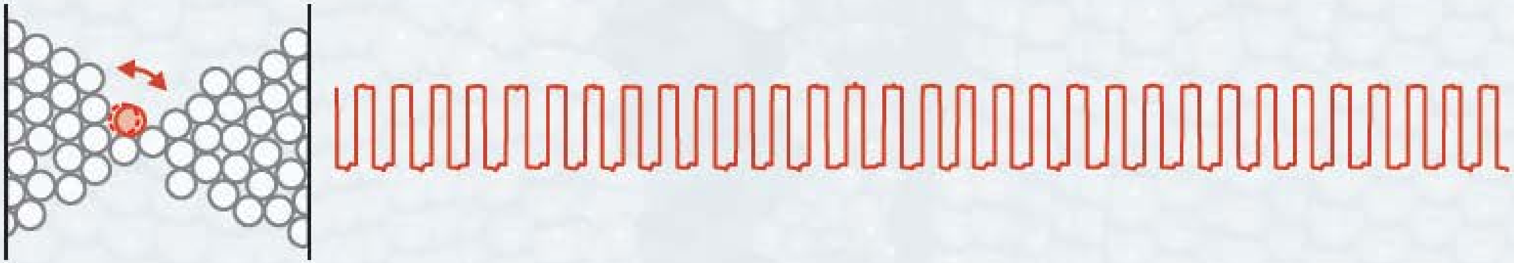
Current-induced rearrangements



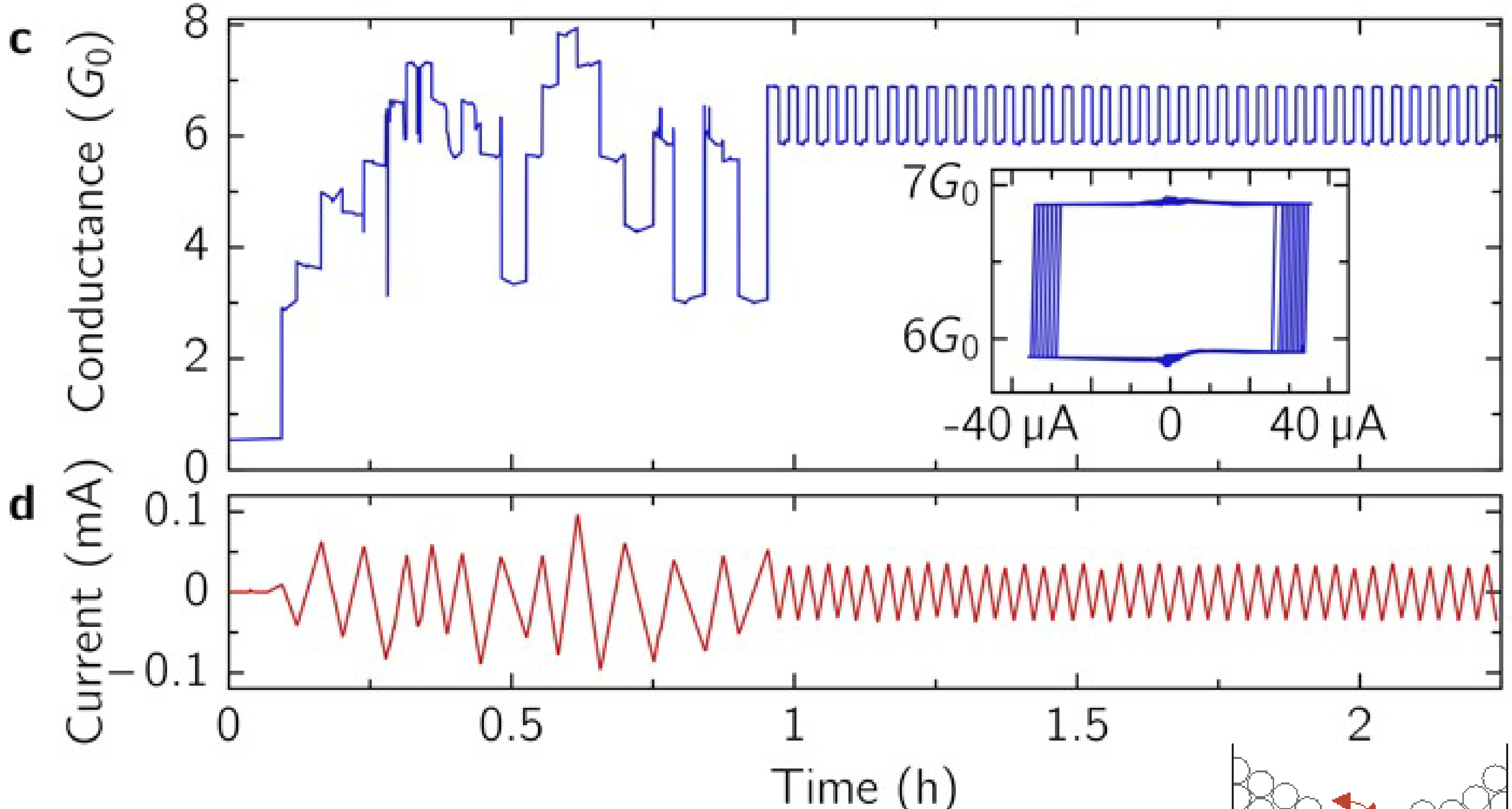


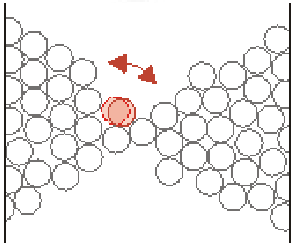
Aluminum, 1.4 K

Reversible Atomic Switches



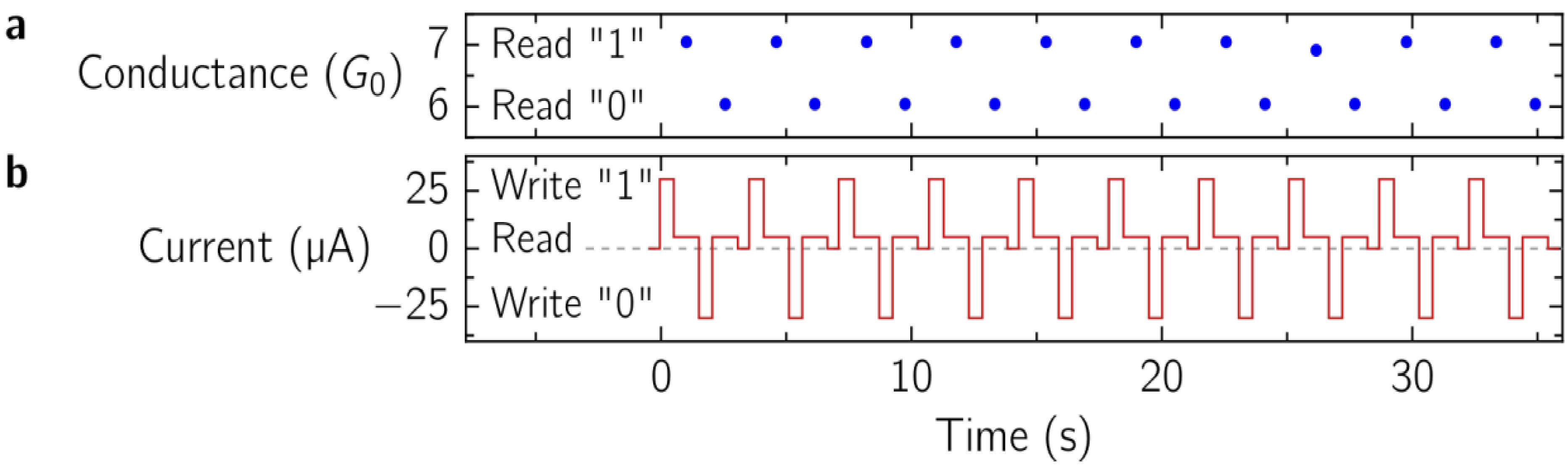
Training of bistable switch





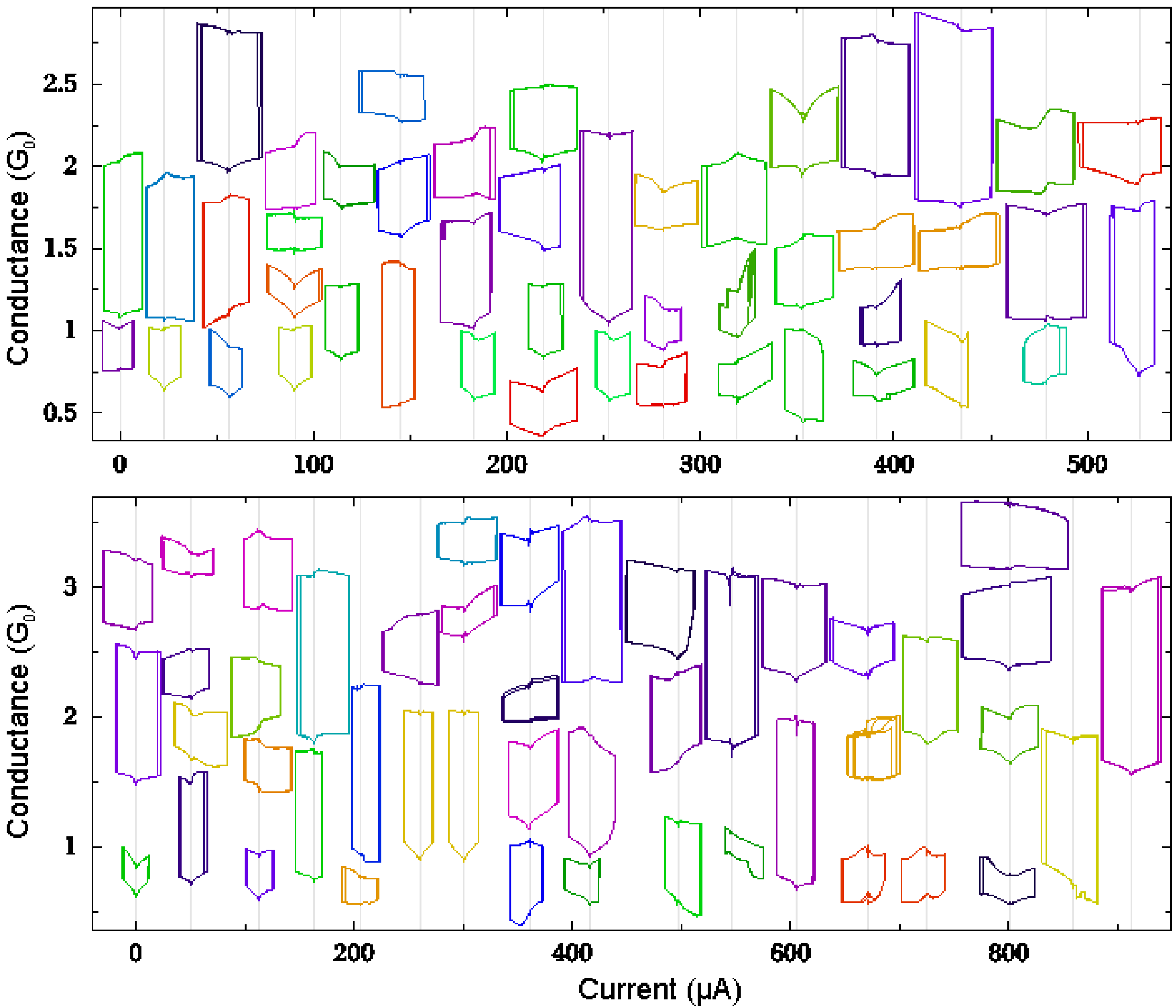
Aluminum, 1.4 K

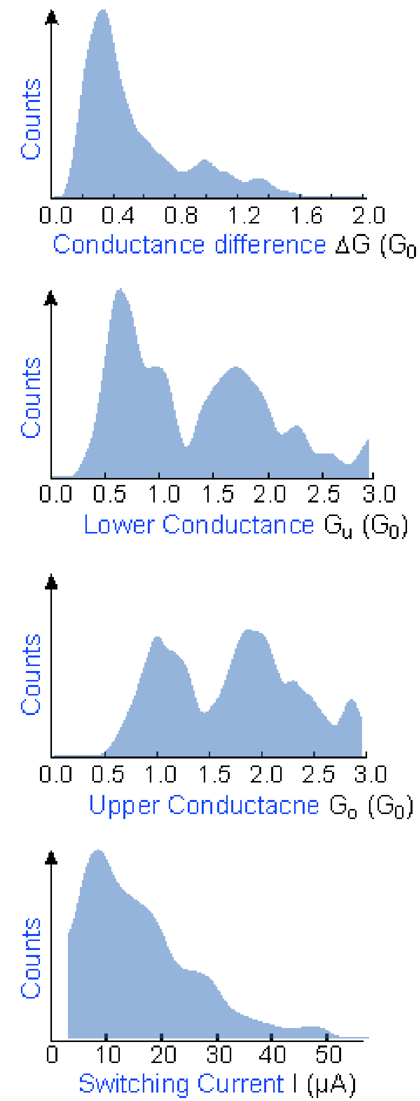
Hysteretic switching: Atomic memory device



Aluminum, 1.4 K

Hysteresis shapes





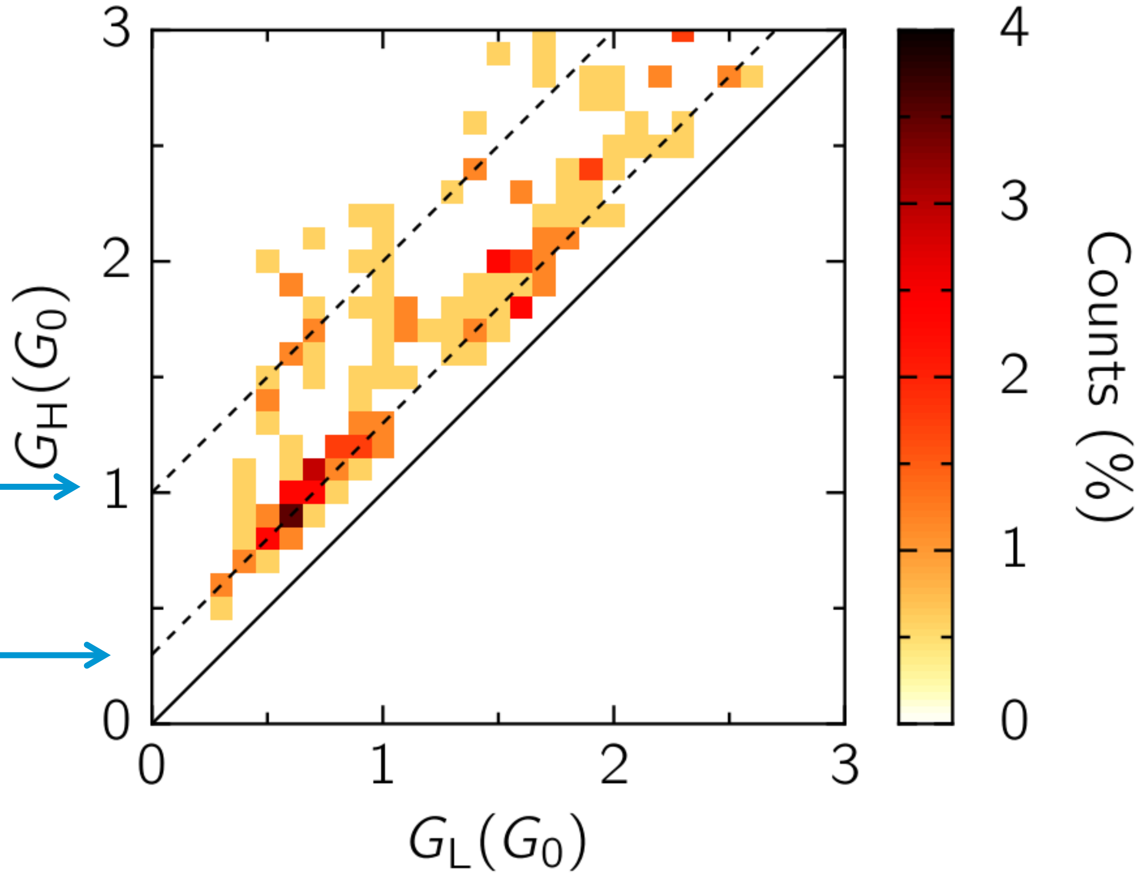
Preferred switching height?

Analysis of > 150 bistable switches

$\Delta G = G_H - G_L$

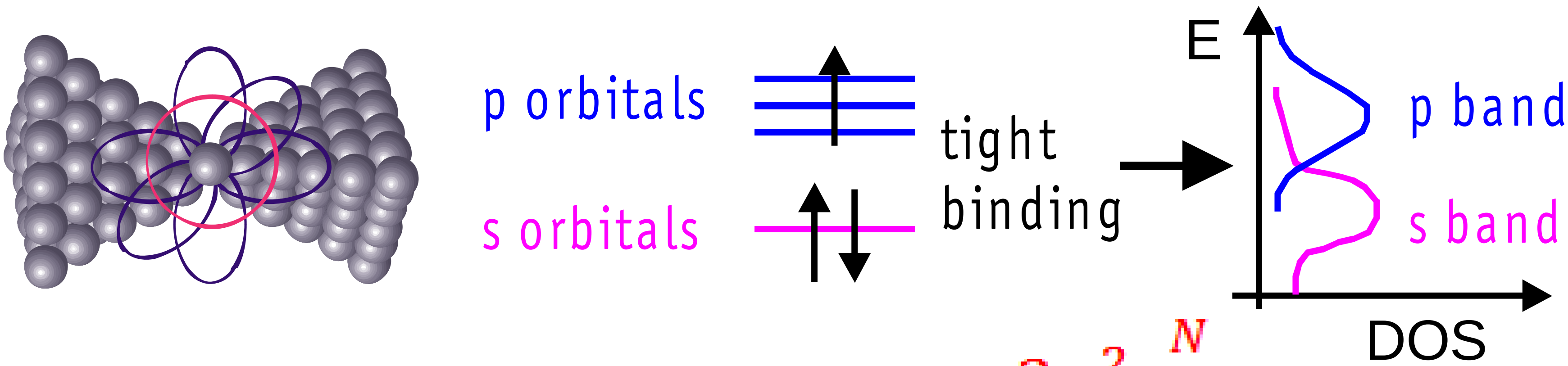
$\Delta G = 1\ G_0$

$\Delta G = 0.3\ G_0$



-> no indication for conductance quantization

Conductance of atomic-size contacts



Landauer Formula:

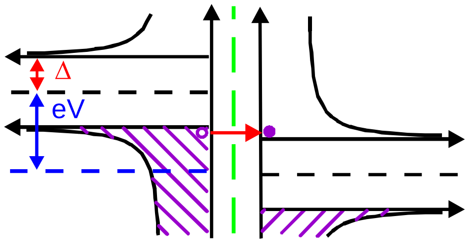
$$G = \frac{2e^2}{h} \sum_{i=1}^{N} \tau_i$$

Conductance strongly depends on
- chemical valence
- position of Fermi level
- precise atomic arrangement

Levy Yeyati et al., PRB 1997;
Cuevas et al., PRL 1998;
Häfner et al., PRB 2004

Superconductivity:
Nonlinear IV characteristics by MAR

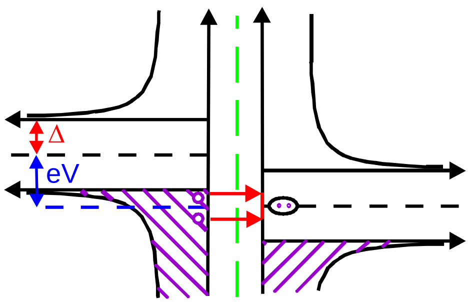
single-electron transport



eV ≥ 2Δ/1

P ∝ τ^1

2 electrons:

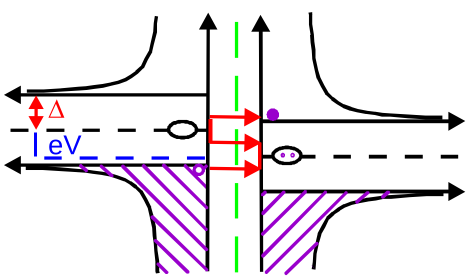


eV ≥ 2Δ/2

P ∝ τ^2

Andreev reflection

3 electrons:



eV ≥ 2Δ/3

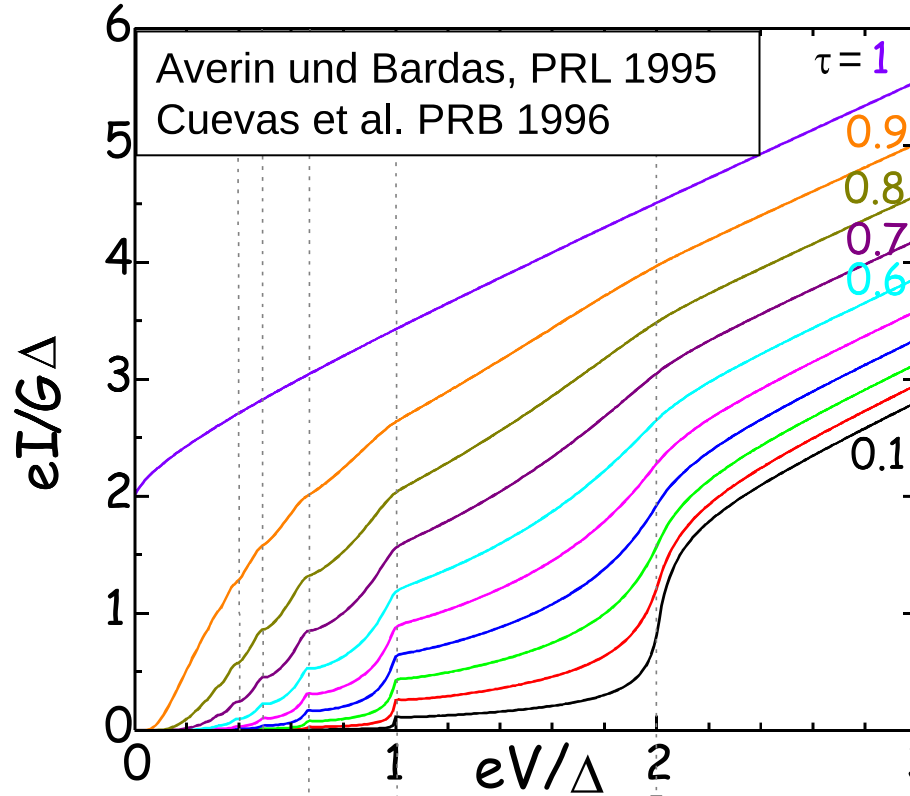
P ∝ τ^3

multiple Andreev reflection (MAR)

m electrons:

eV ≥ 2Δ/m

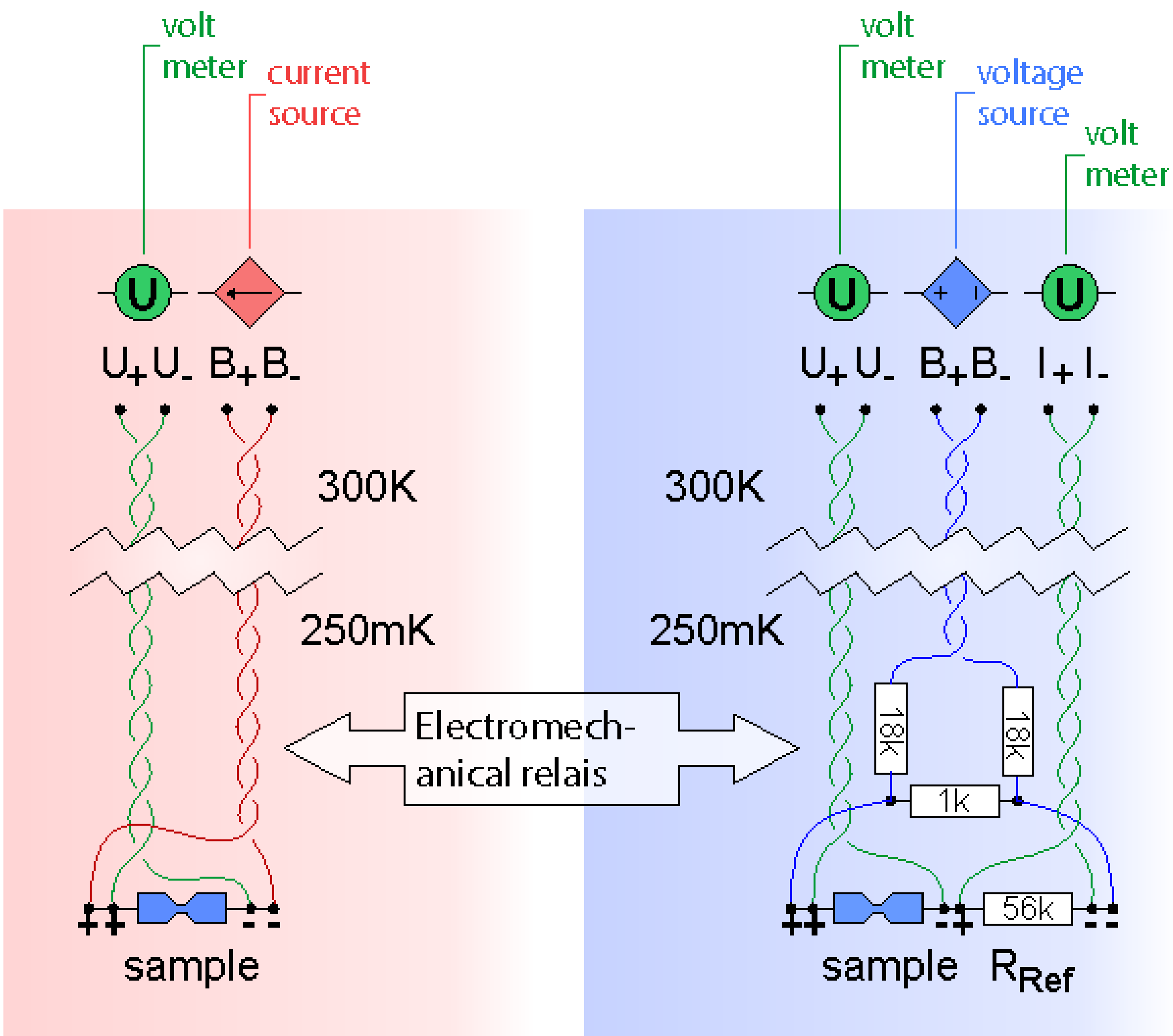
P ∝ τ^m

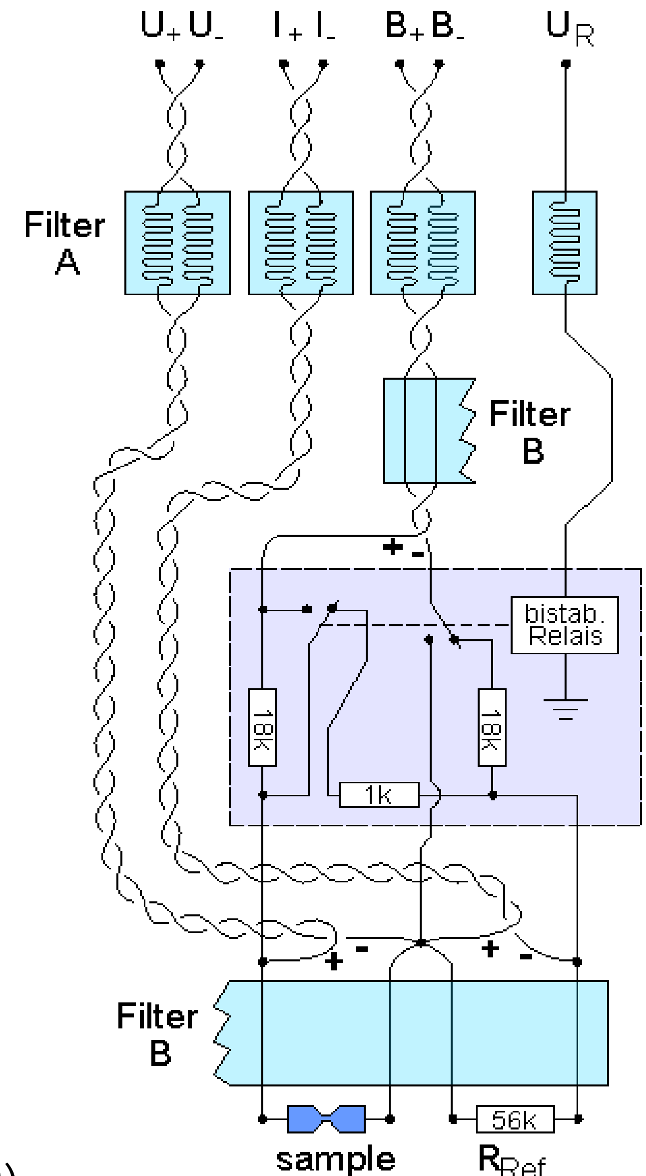


3 e⁻ transfered
2 qp created
eV > 2Δ/3
P ∝ τ^3

2 e⁻ transfered
2 qp created
eV > 2Δ/2
P ∝ τ^2

1 e⁻ transfered
2 qp created
eV > 2Δ/1
P ∝ τ





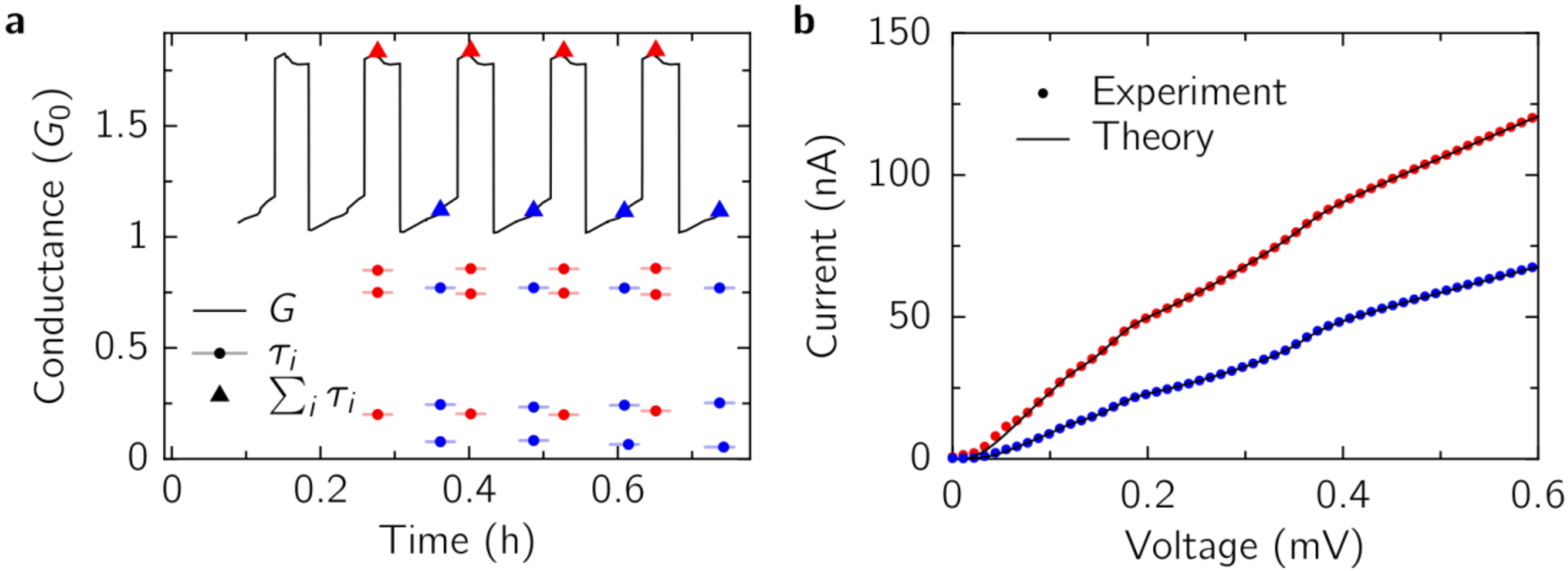
Relais switch off 1: high current

Relais switch on: low noise

C. Schirm, H.F. Pernau, and E. Scheer, Rev. Sci. Instrum. **80** 024704 (2009)

Bistable switching: Conduction channels

Determination of atomic configuration



$G_H = 1.84\ G_0$
3 channels
$\tau_1 = 0.87$
$\tau_2 = 0.76$
$\tau_3 = 0.21$

$G_L = 1.12\ G_0$
3 channels
$\tau_1 = 0.78$
$\tau_2 = 0.25$
$\tau_3 = 0.08$

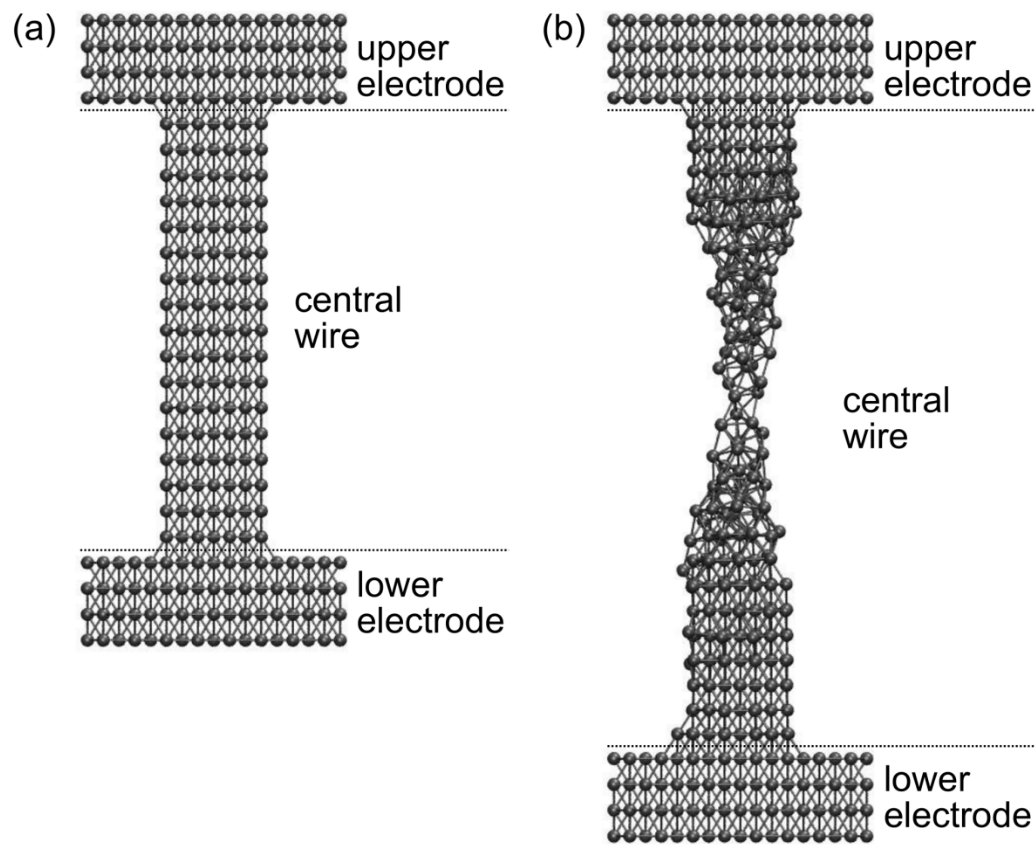
Aluminum, 250 mK

Revealing the structures: Molecular Dynamics

Stretching simulation of a nanowire

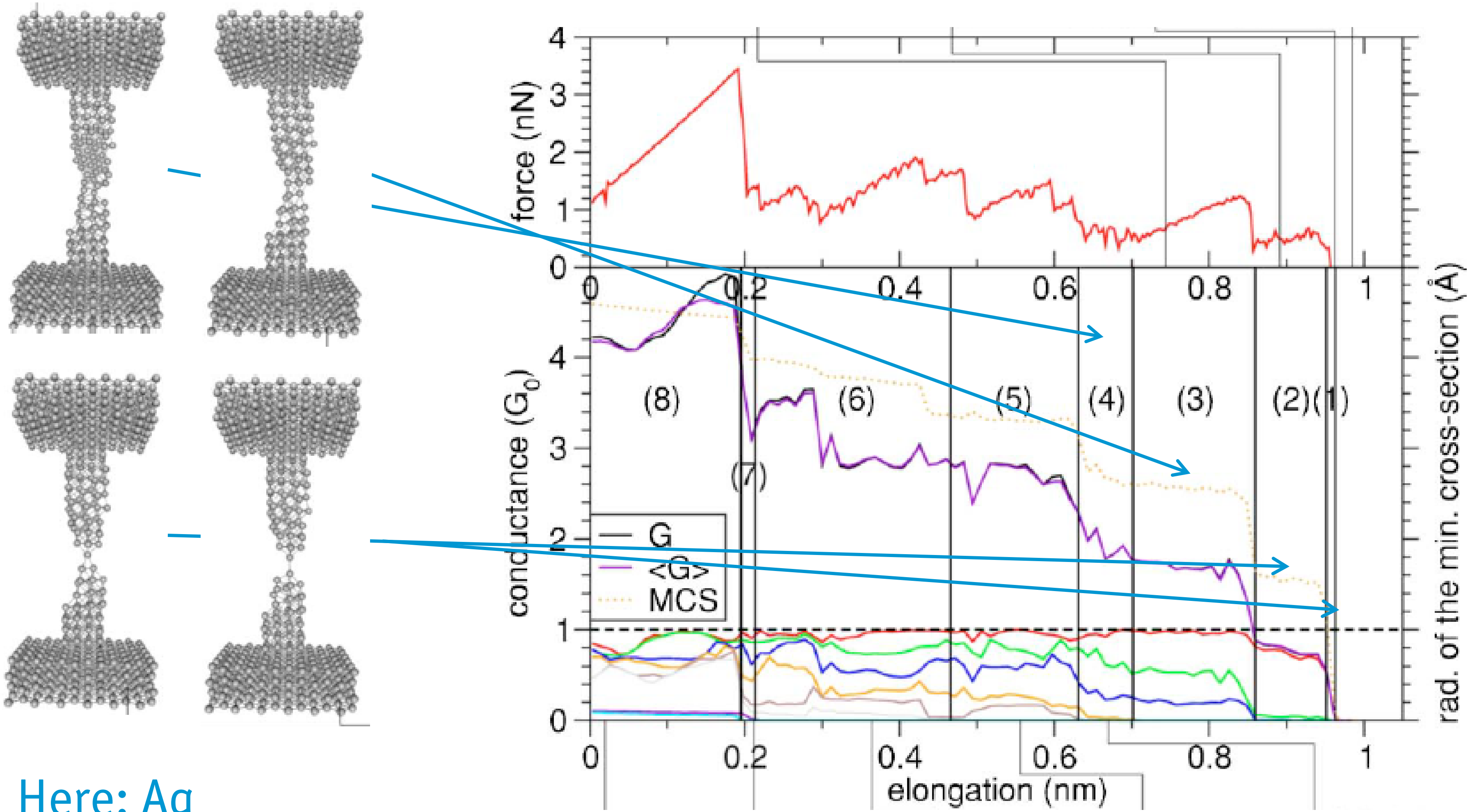
Embedded-atom potential
T = 1.4 K (Hoover thermostat)

Transport calculation using
Tight binding & NEGF



F. Pauly et al., *Phys. Rev. B* **74**, 235106 (2006)

Simulated breaking curves

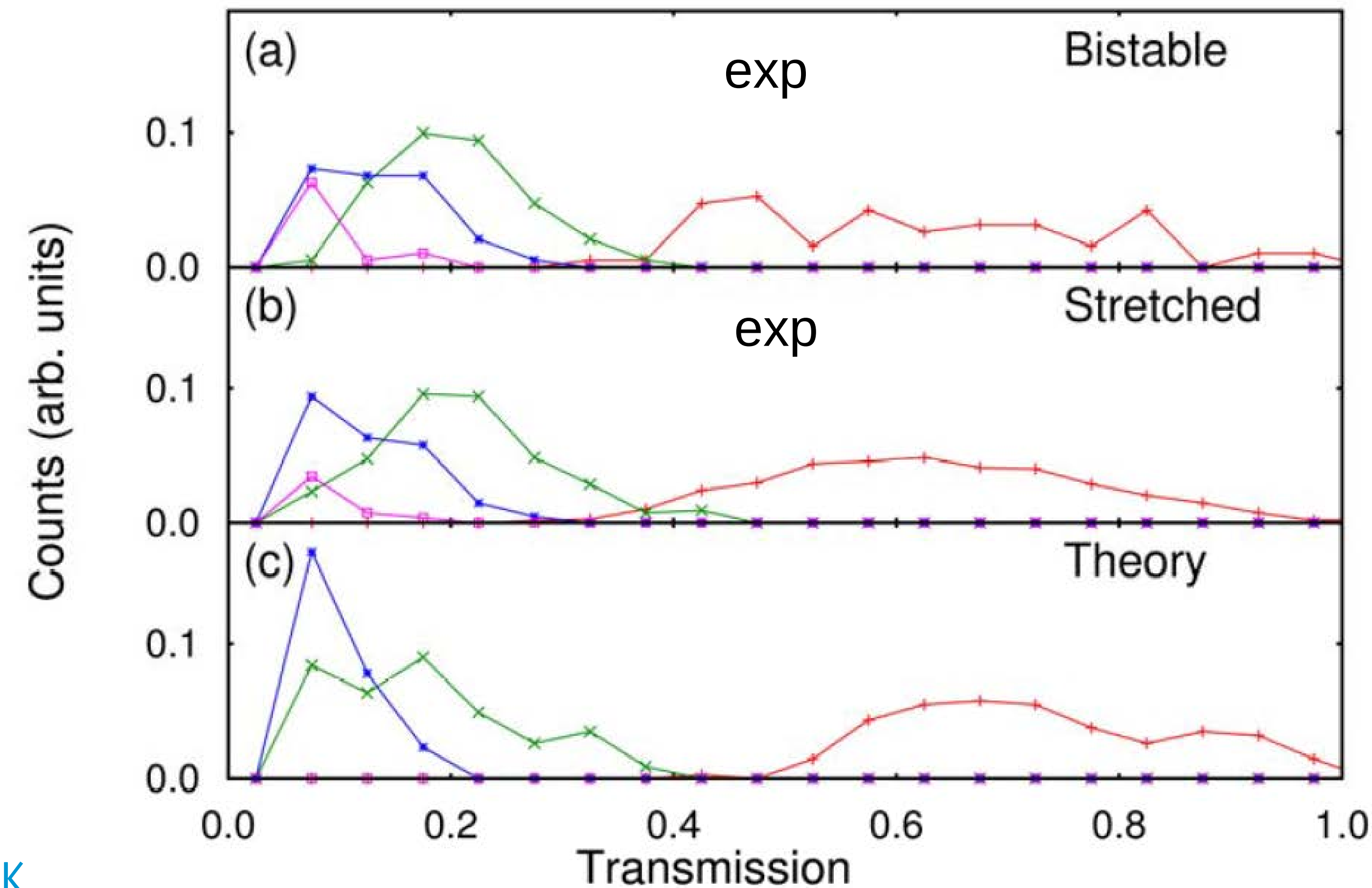


Here: Ag

F. Pauly et al., *Phys. Rev. B* **74,** 235106 (2006)

Statistical comparison of experiment and theory: Stretching curve

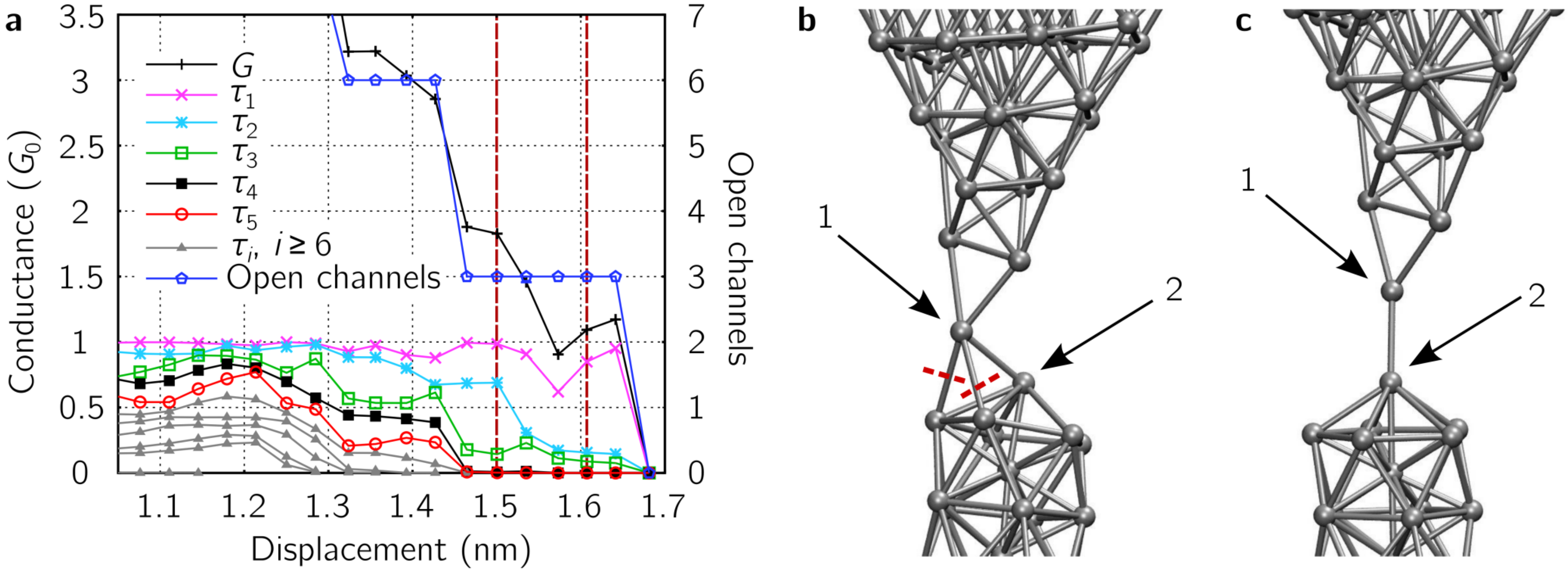
Transmission histograms of single-atom contacts



Aluminum, 250 mK

Single-atom switch

Two bonds break at same atom

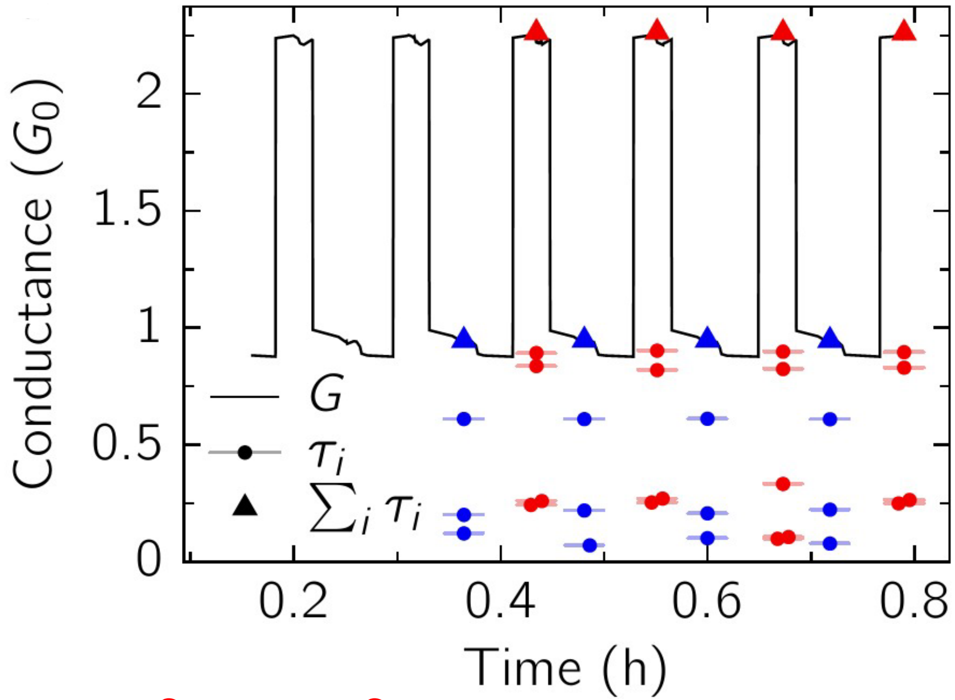


$G_H = 1.84\ G_0$	$G_L = 1.12\ G_0$
3 channels	3 channels
$\tau_1 = 0.87$	$\tau_1 = 0.78$
$\tau_2 = 0.76$	$\tau_2 = 0.25$
$\tau_3 = 0.21$	$\tau_3 = 0.08$

$G_H = 1.83\ G_0$	$G_L = 1.09\ G_0$
3 channels	3 channels
$\tau_1 = 0.99$	$\tau_1 = 0.85$
$\tau_2 = 0.69$	$\tau_2 = 0.16$
$\tau_3 = 0.14$	$\tau_3 = 0.09$

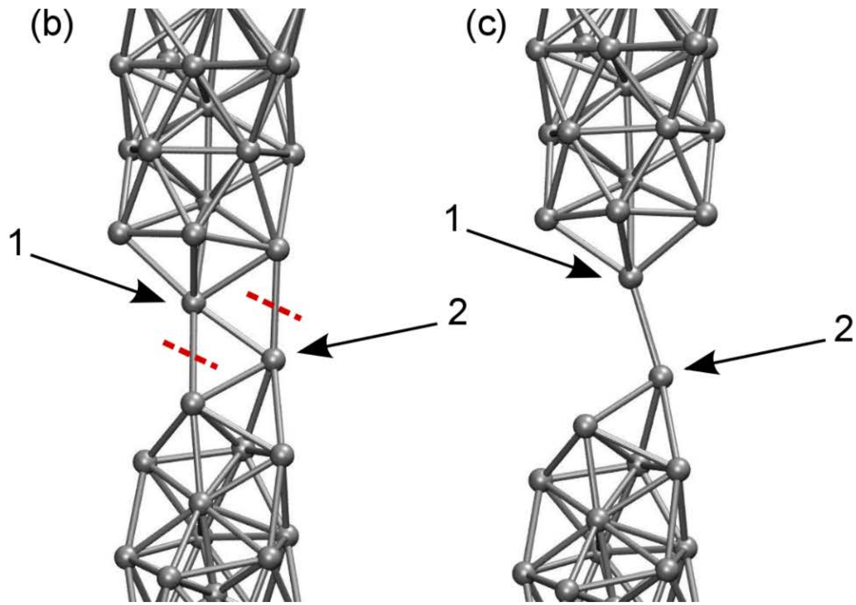
Two-atom switch

Switch from 2 atom contact to dimer



$G_H = 2.23\ G_0$
4 channels
$\tau_1 = 0.89$
$\tau_2 = 0.84$
$\tau_3 = 0.26$
$\tau_4 = 0.24$

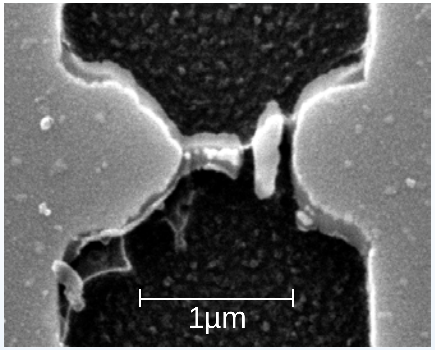
$G_L = 0.93\ G_0$
3 channels
$\tau_1 = 0.61$
$\tau_2 = 0.20$
$\tau_3 = 0.12$



$G_H = 2.17\ G_0$
4 channels
$\tau_1 = 0.97$
$\tau_2 = 0.73$
$\tau_3 = 0.26$
$\tau_4 = 0.18$

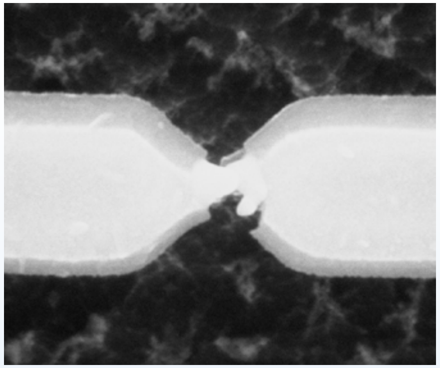
$G_L = 0.91\ G_0$
3 channels
$\tau_1 = 0.62$
$\tau_2 = 0.20$
$\tau_3 = 0.09$

Summary & Outlook



Au,
after DC electromigration

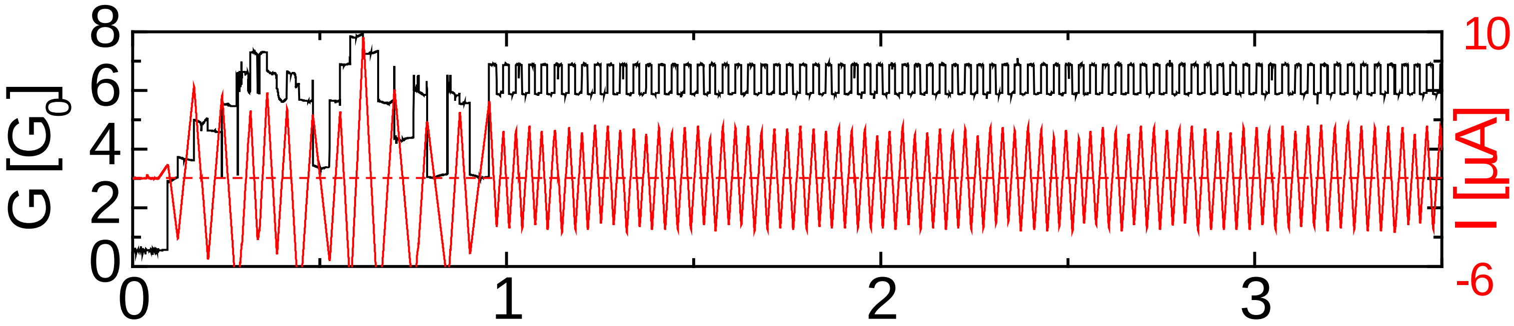
Au,
after AC elecromigration



- Atomic configuration of bistable positions revealed
- Bistable contacts selected by atomic configuation, not by preference of particular transmission values
- Bistable switching: „atomic memory device“
- Long time stability? Initialization process?

C. Schirm, H.F. Pernau, E. Scheer, Rev. Sci. Instrum. **80** 024704 (2009)
C. Schirm , M. Matt, F. Pauly, J. C. Cuevas, P. Nielaba, E. Scheer, Nature Nanotech. **8,** 645 (2013)

Long-time stability

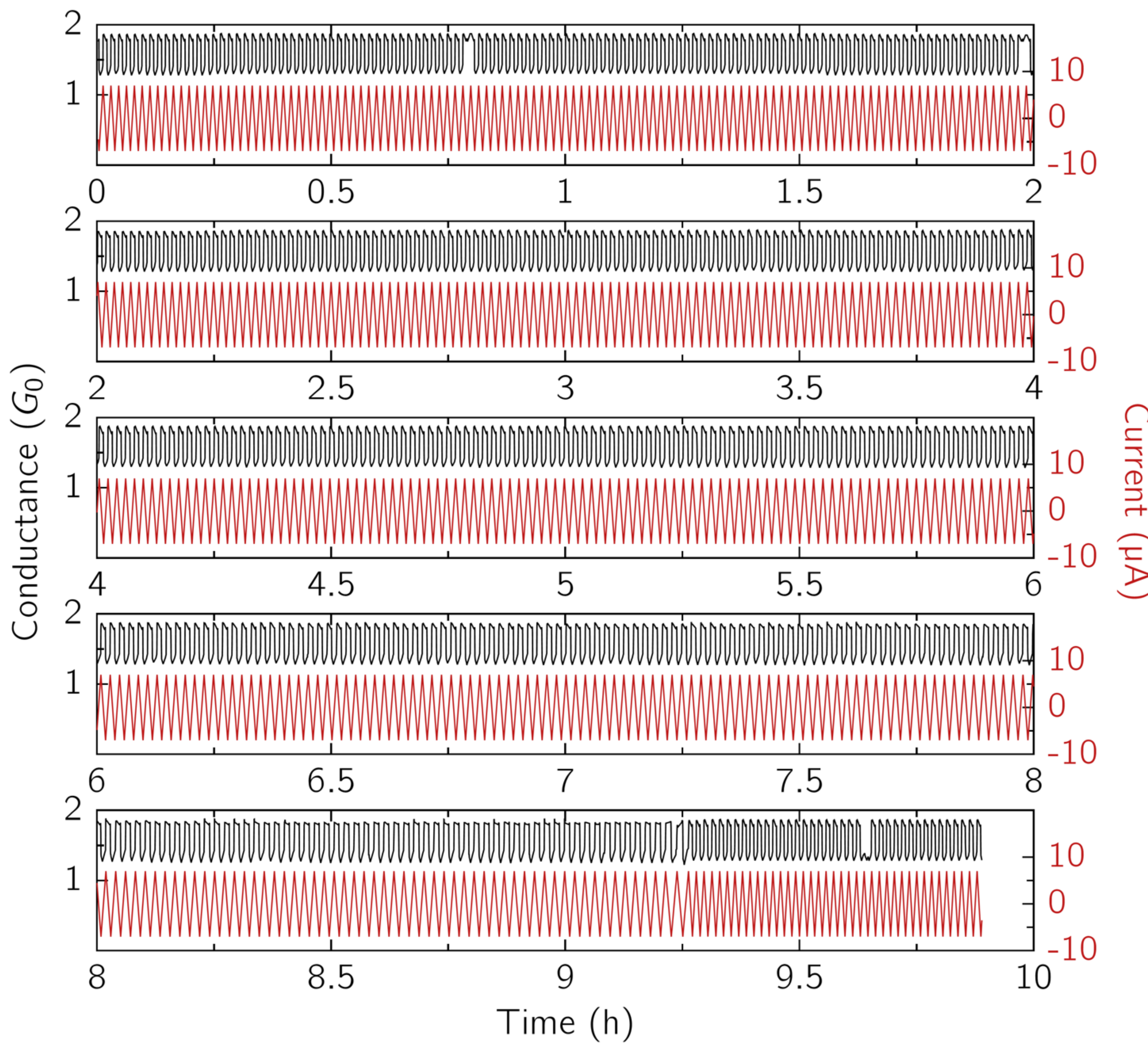


time [h]

Aluminum, 1.4 K

Long-lived single-atom switch

> 500 repetitions

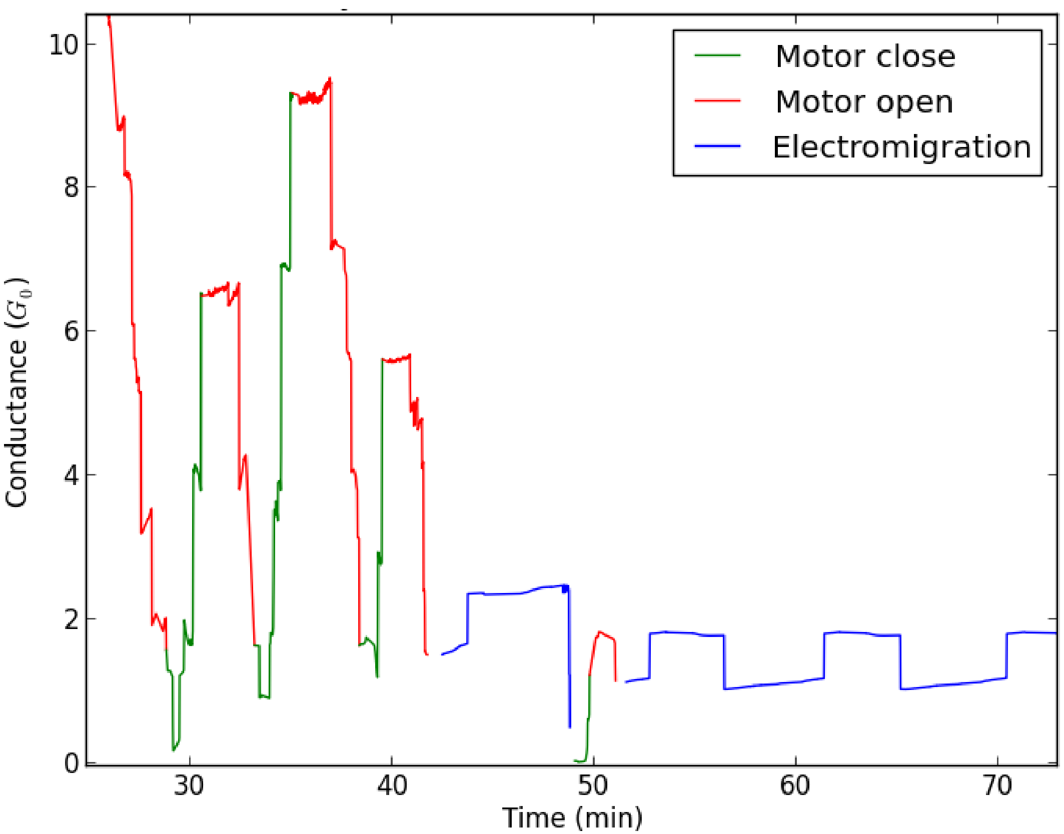


Aluminum, 1.4 K

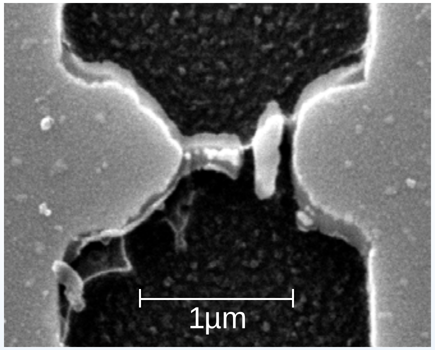
Work hardening and training period

Average number of electromigration training steps before bistable state is reached: 3.2

Dependence on work-hardening and history?

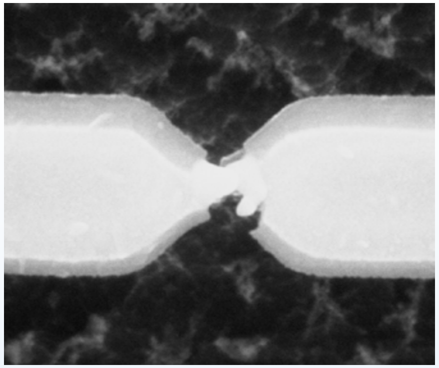


Single atom switch



Au,
after DC electromigration

Au,
after AC elecromigration



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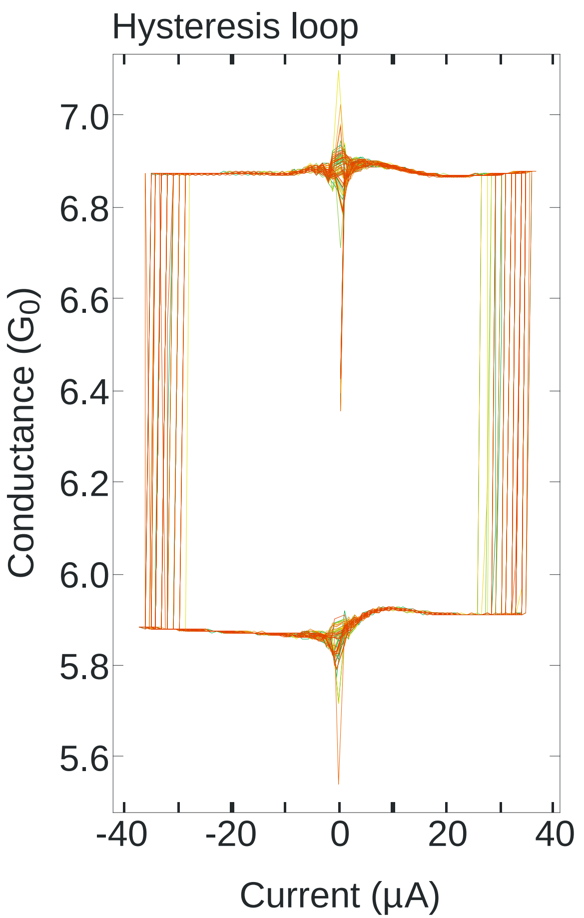
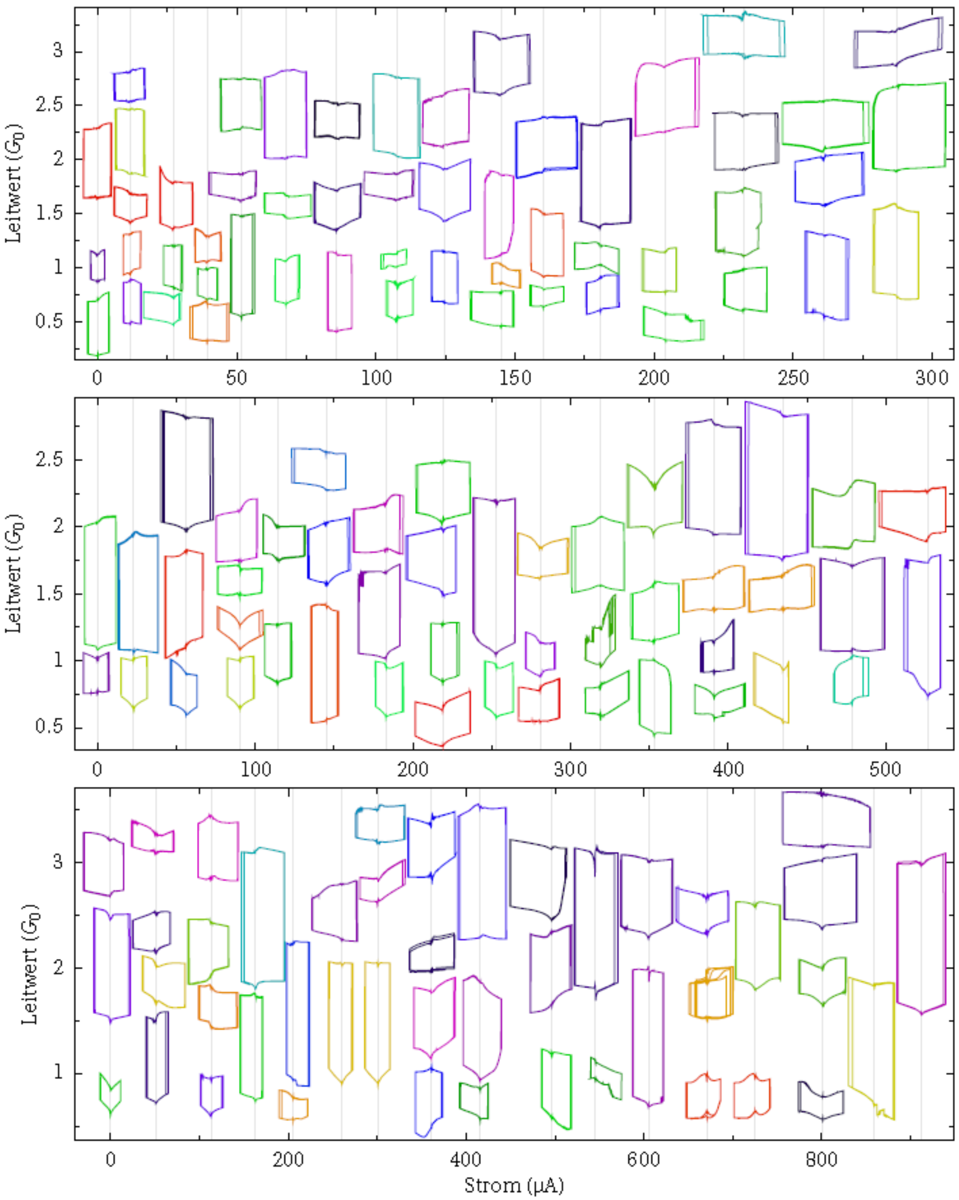
C. Schirm, H.F. Pernau, E. Scheer, Rev. Sci. Instrum. **80** 024704 (2009)
C. Schirm , M. Matt, F. Pauly, J. C. Cuevas, P. Nielaba, E. Scheer, Nature Nanotech. **8**, 645 (2013)

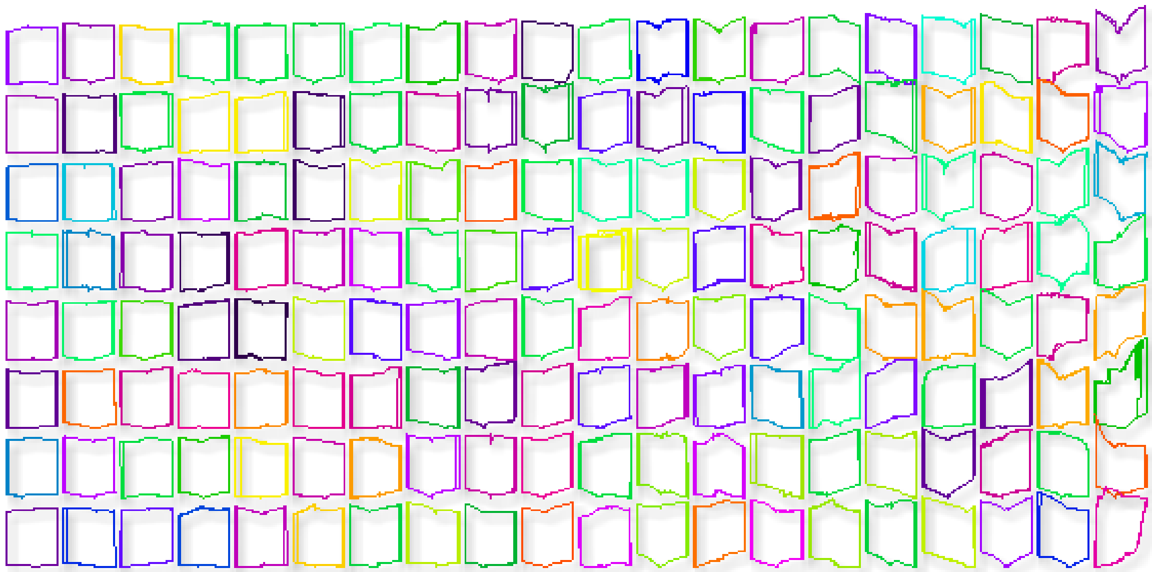
Bistable switching



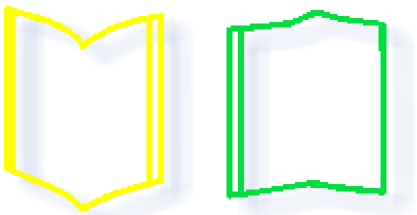


Aluminum, 1.4 K

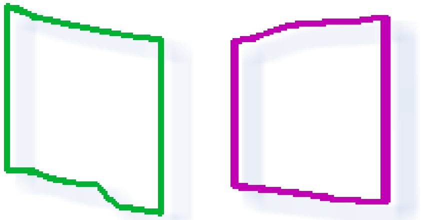
Hysteresis: Comparison of the shapes



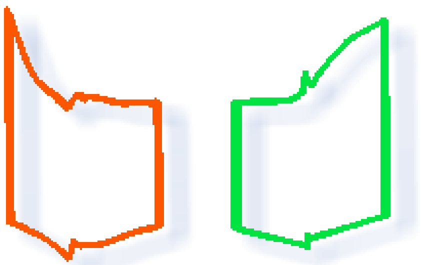
Kink on top and bottom

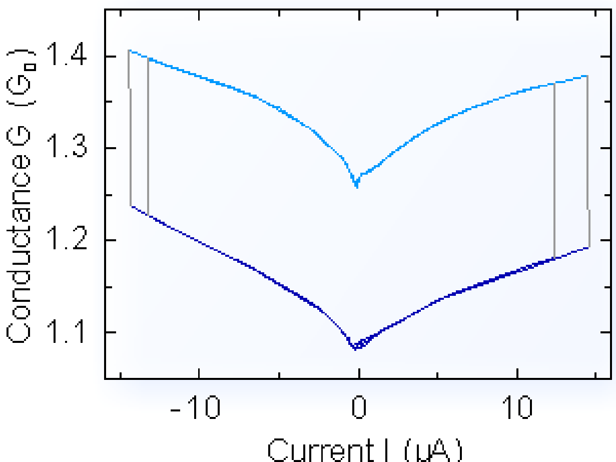


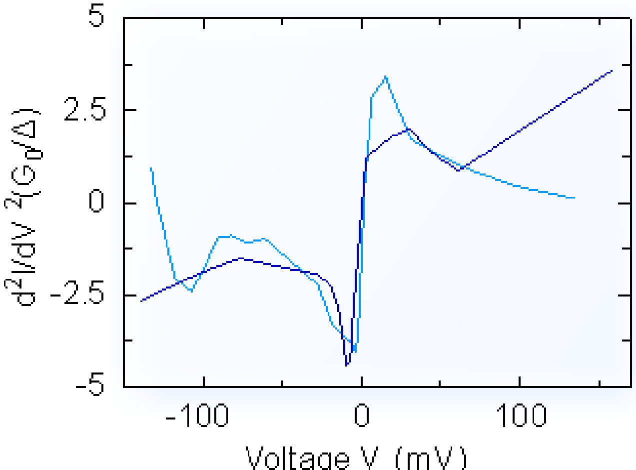
rare case: without kink



asymmetric

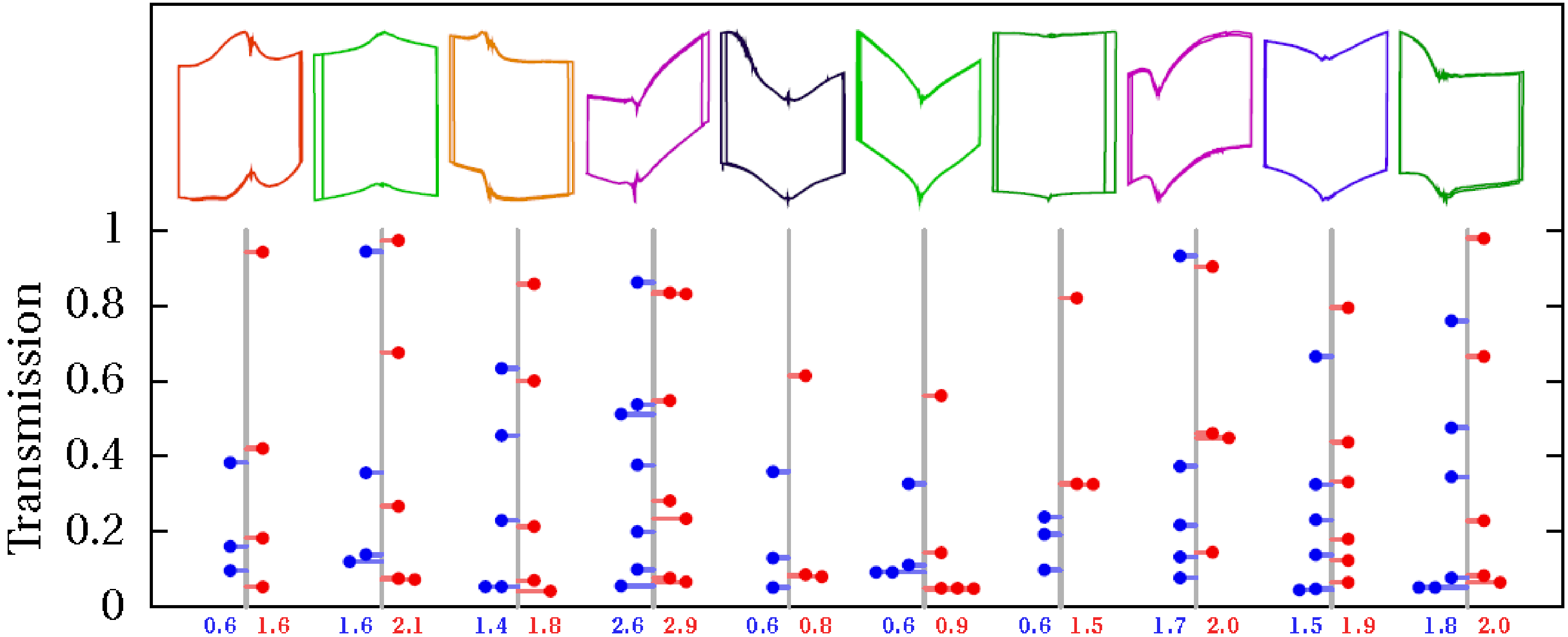




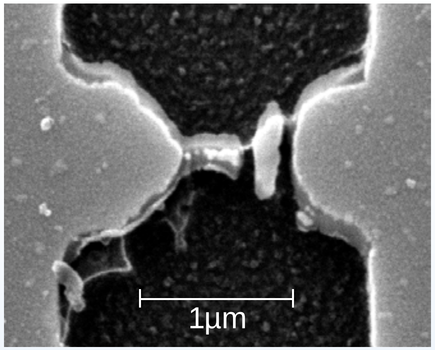


Shape of the spectra

Examples with similar spectra in both states



-> shape determined by environment: conductance fluctuations



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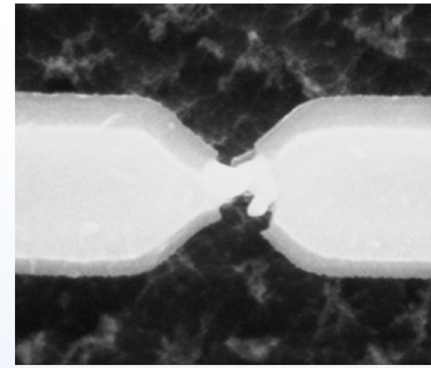

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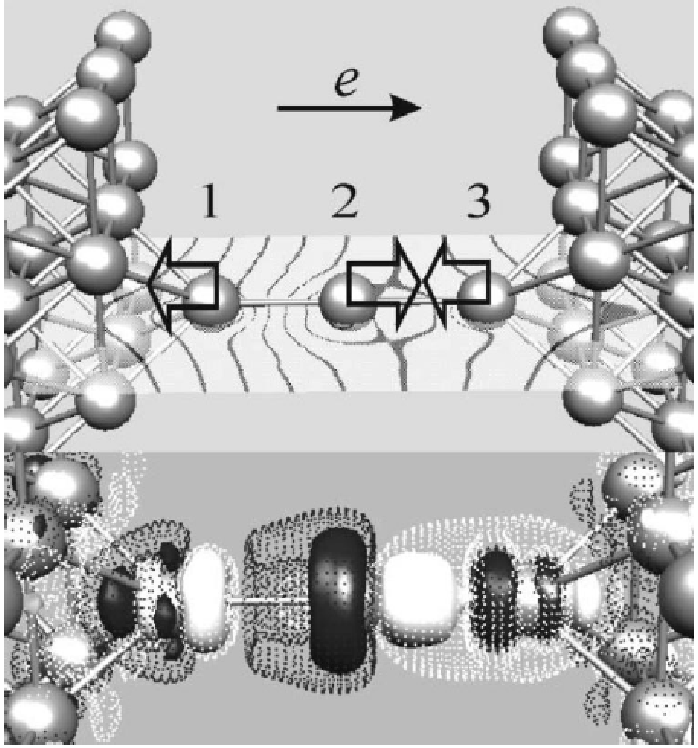
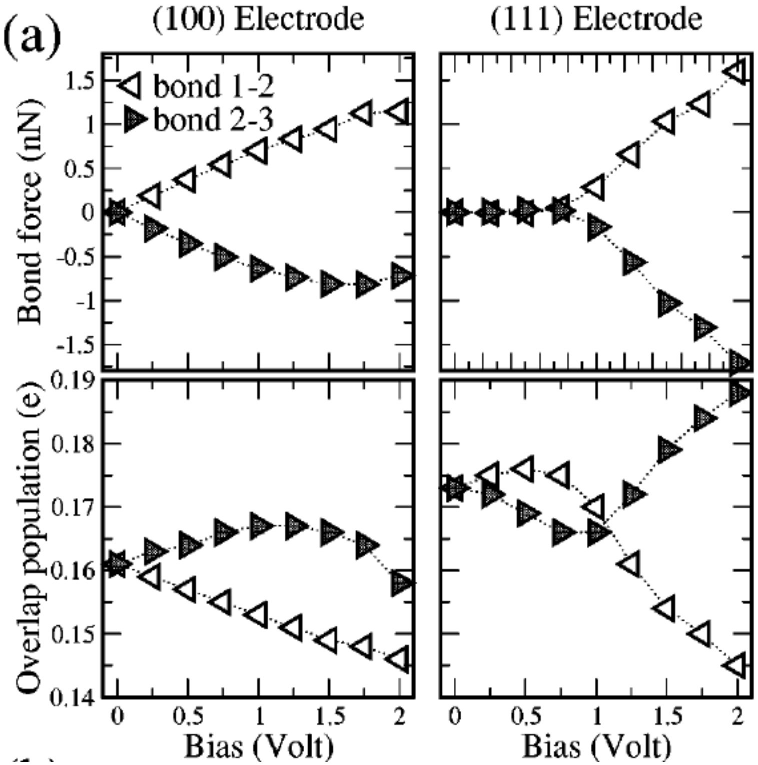
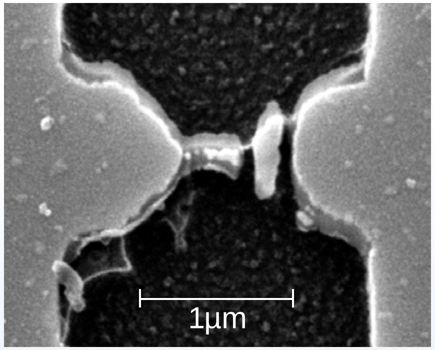
Electro-migration: microscopic approach





Brandbyge et al., Origin of current-induced forces in an atomic gold wire: a first-principles study. Phys. Rev. B **67**, 193104 (2003).



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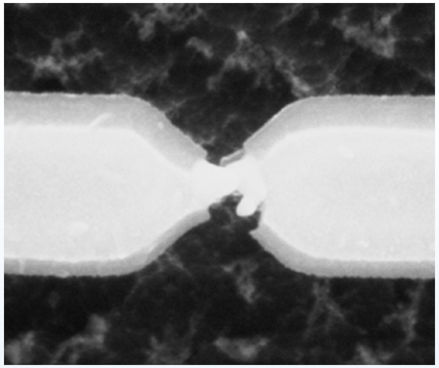

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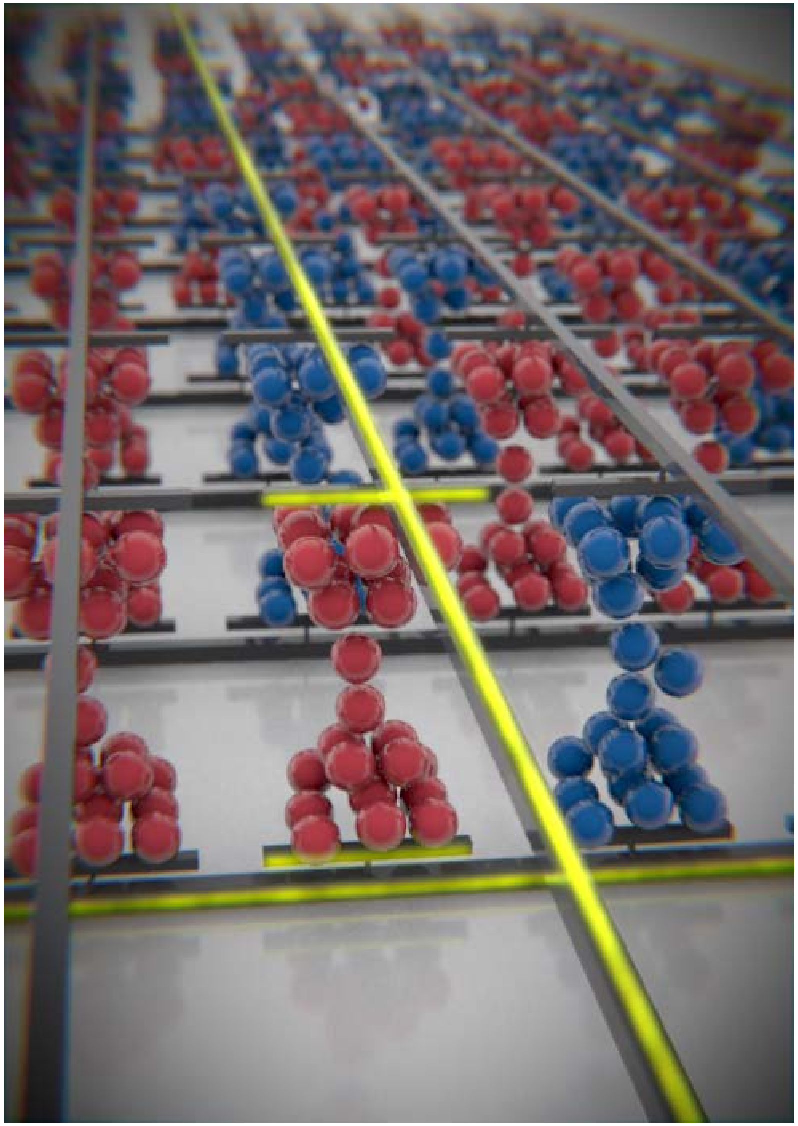
Thank you!



Electro-migration in a nutshell

Ion flux $$\mathbf{J}_m = -L_{m,m}\nabla\left(\frac{\mu_{ec}^m}{T}\right) - L_{m,e}\nabla\left(\frac{\mu_{ec}^e}{T}\right) - L_{m,u}\left(\frac{\nabla T}{T^2}\right)$$

Electron flux $$\mathbf{J}_e = -L_{e,m}\nabla\left(\frac{\mu_{ec}^m}{T}\right) - L_{e,e}\nabla\left(\frac{\mu_{ec}^e}{T}\right) - L_{e,u}\left(\frac{\nabla T}{T^2}\right)$$

Energy flux $$\mathbf{J}_u = -L_{u,m}\nabla\left(\frac{\mu_{ec}^m}{T}\right) - L_{u,e}\nabla\left(\frac{\mu_{ec}^e}{T}\right) - L_{u,u}\left(\frac{\nabla T}{T^2}\right)$$

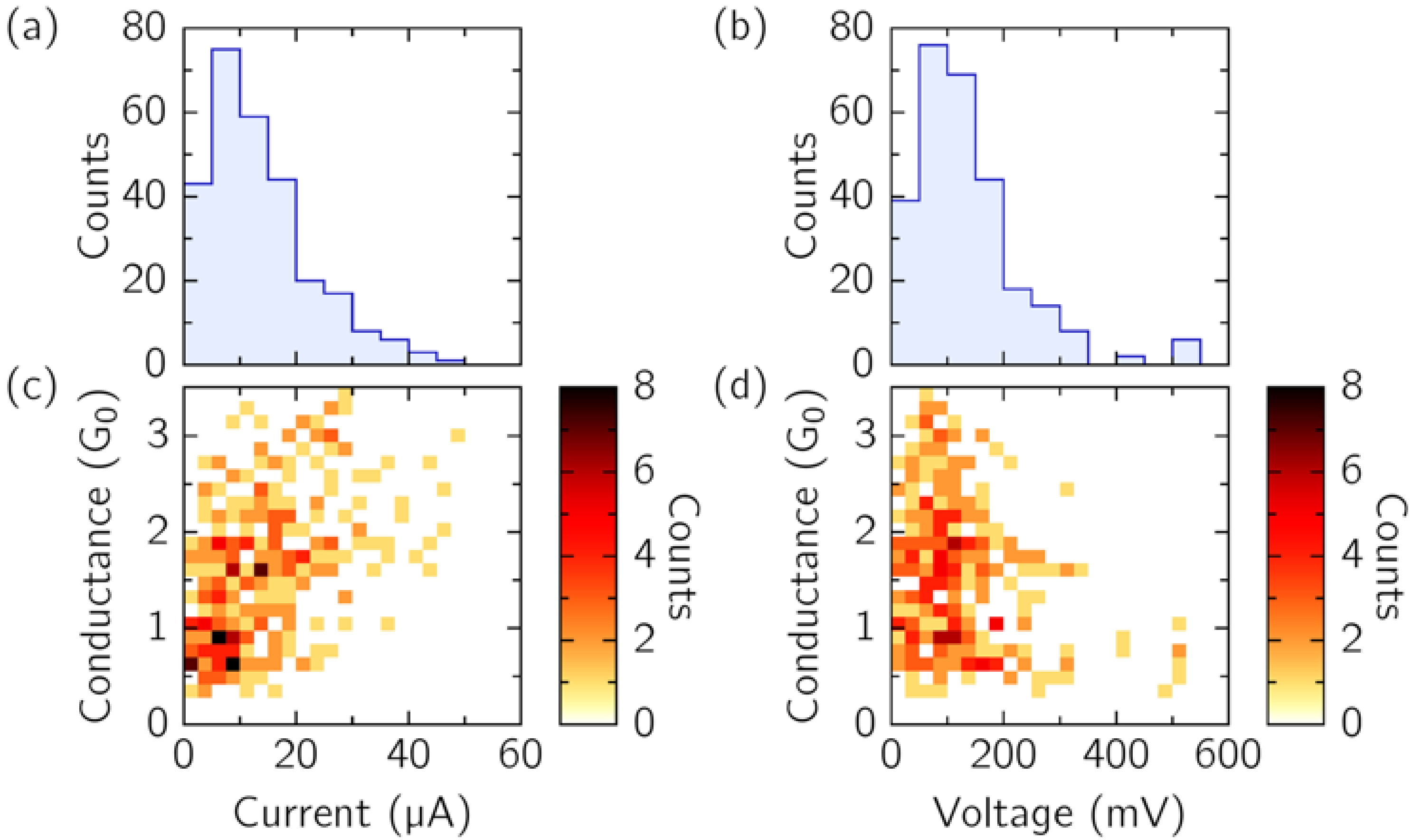
with the electrochemical potential $\mu_{ec} = \mu + Zej$

For metals this reduces to: $$\mathbf{J}_m = -L^*_{m,m}(\nabla\mu^m - Z^* e\rho j)$$

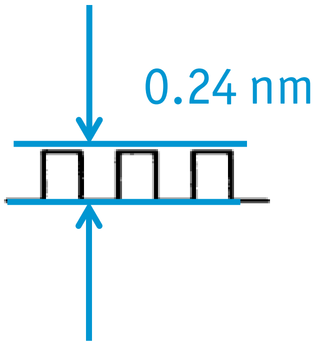
where $L^*_{m,m} = L_{m,m}/T$ and $Z^* = Z - L^*_{m,e}/L^*_{m,m}$

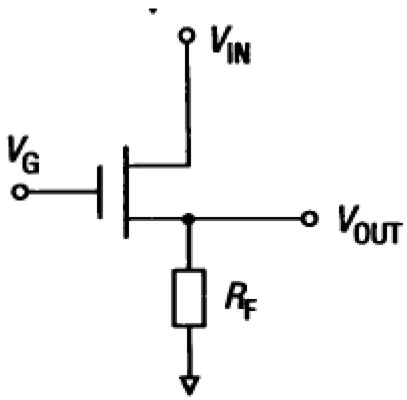
Z* < 0 for most metals: net force follows direction of electron flow.

Statistics of switching currents and voltages



Quantum Point Contact Switches: FET analogue





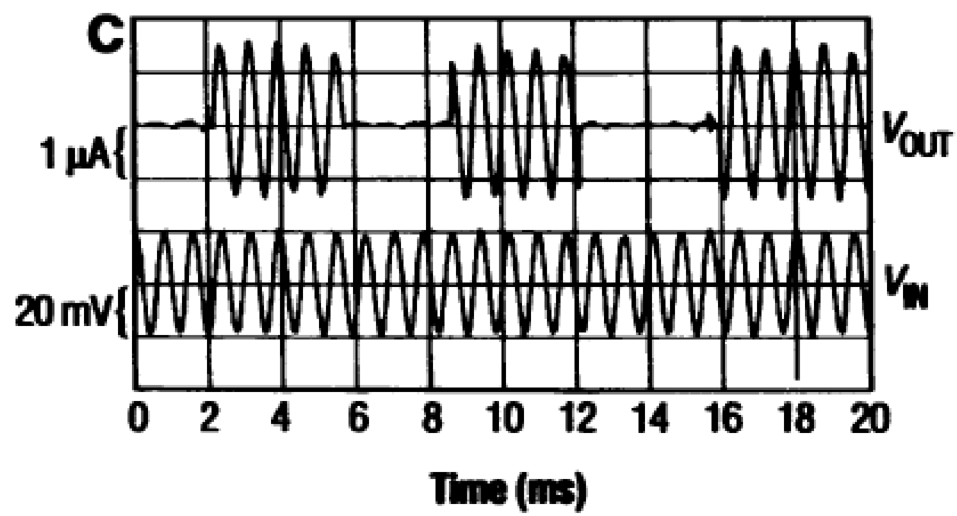
$T = 6$ K

$V_{in} = 10$ mV – 100 mV

$f_{max} = 2$kHz

$\delta t = 10$ µs

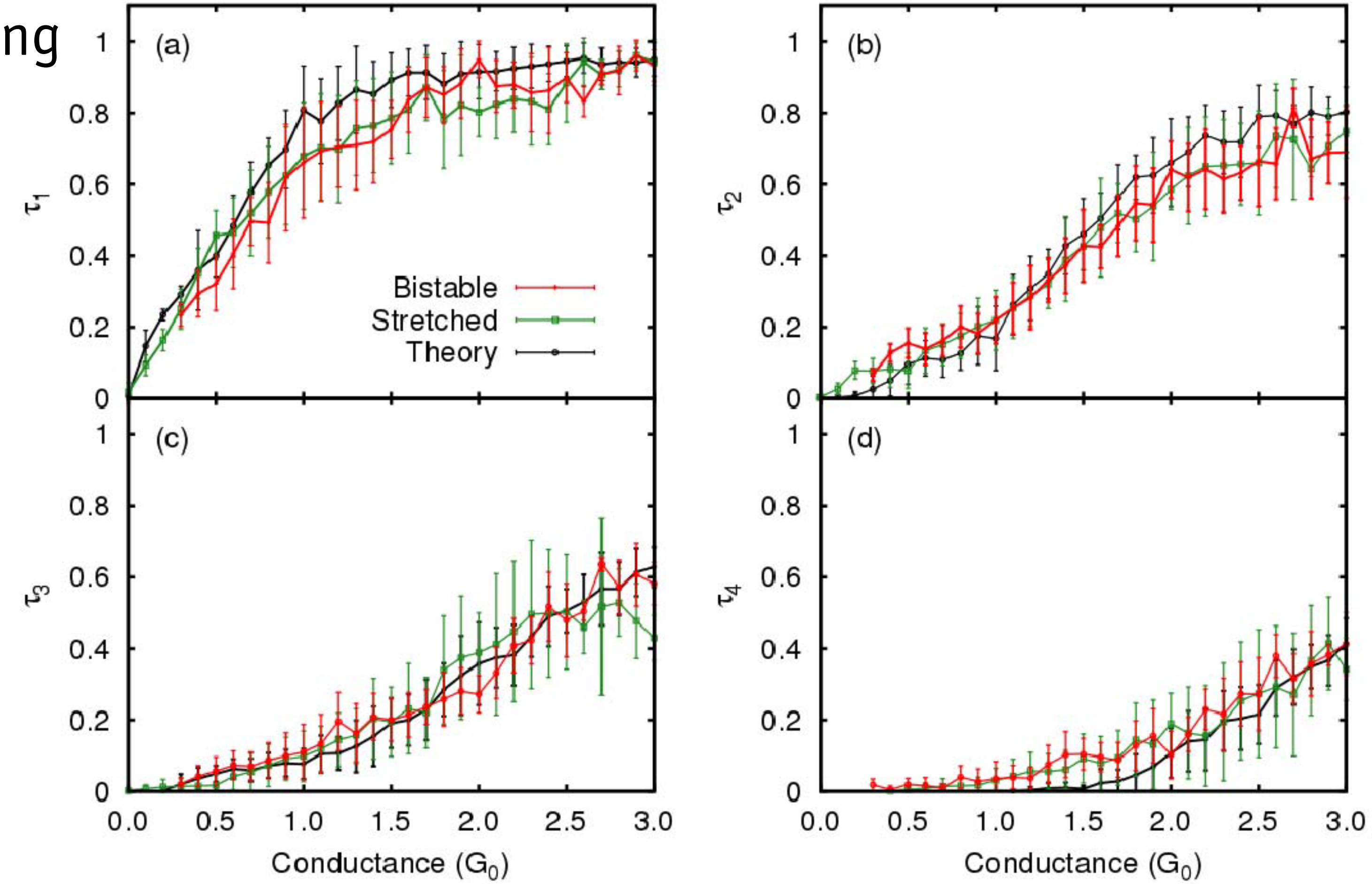
V_z -> V_{gate}



D.P.E. Smith, Science 269, 371 (1995)

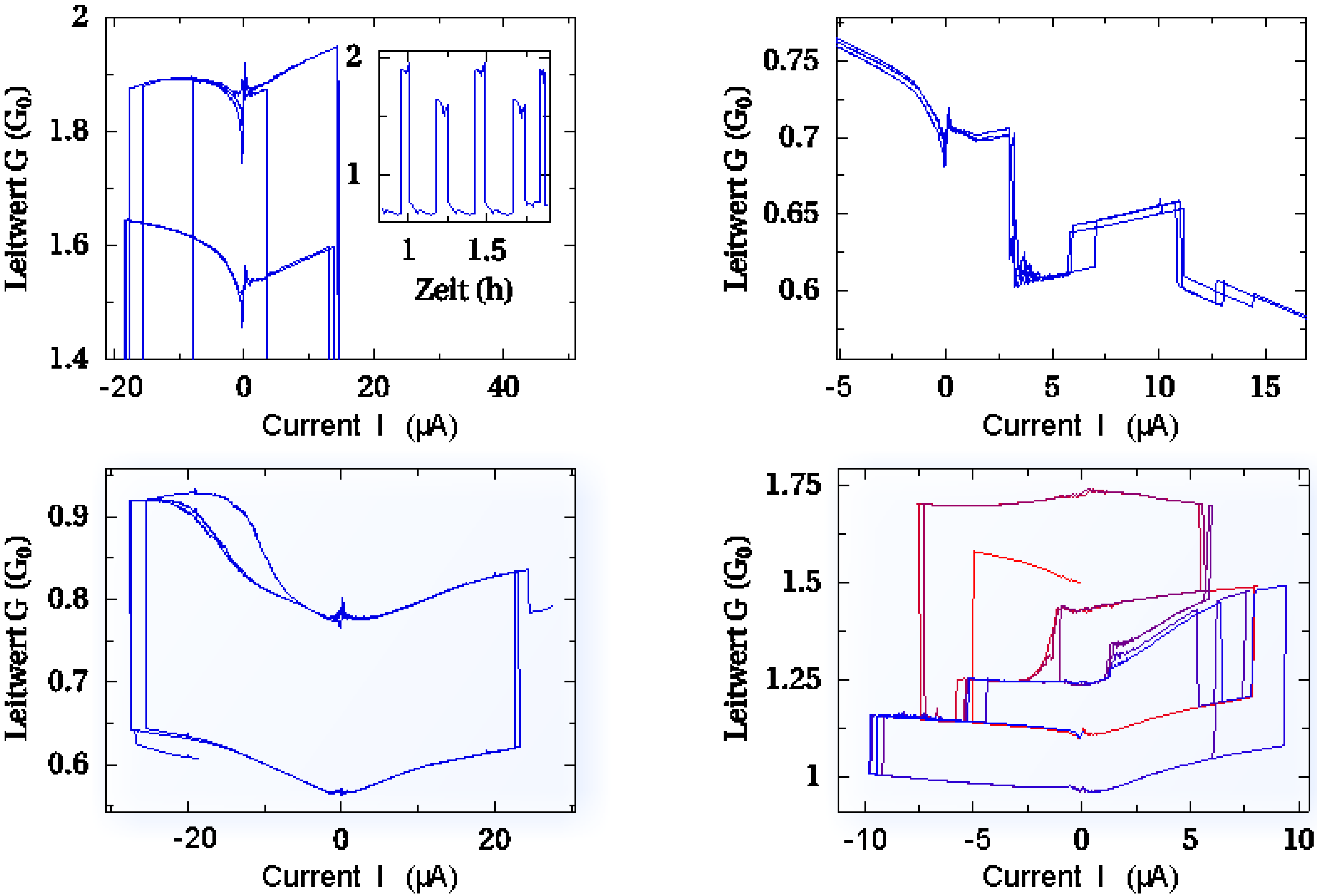
Statistical comparison of experiment and theory: Channel distribution

Channel opening



Aluminum, 250 mK

Complex Switching



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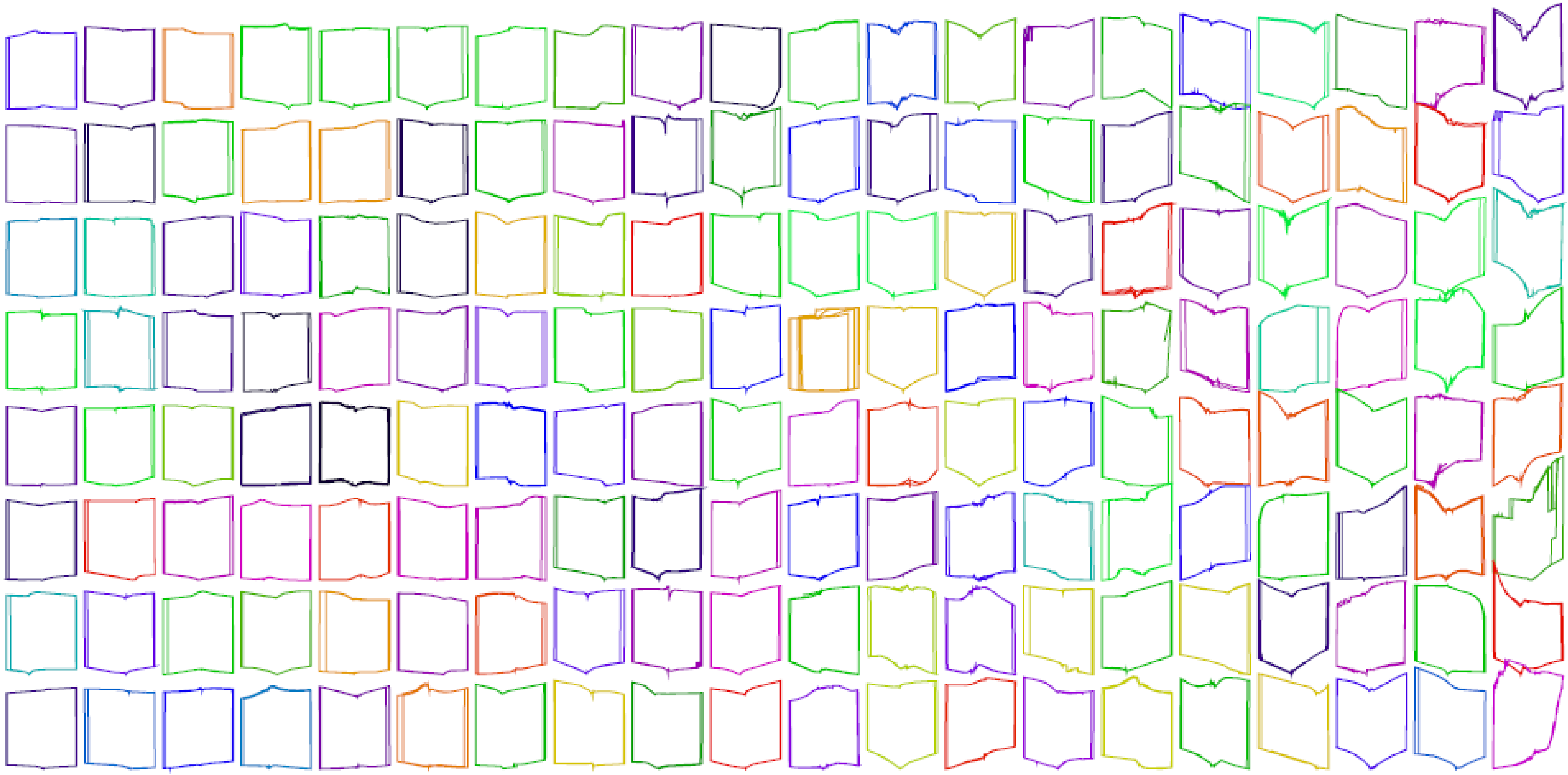
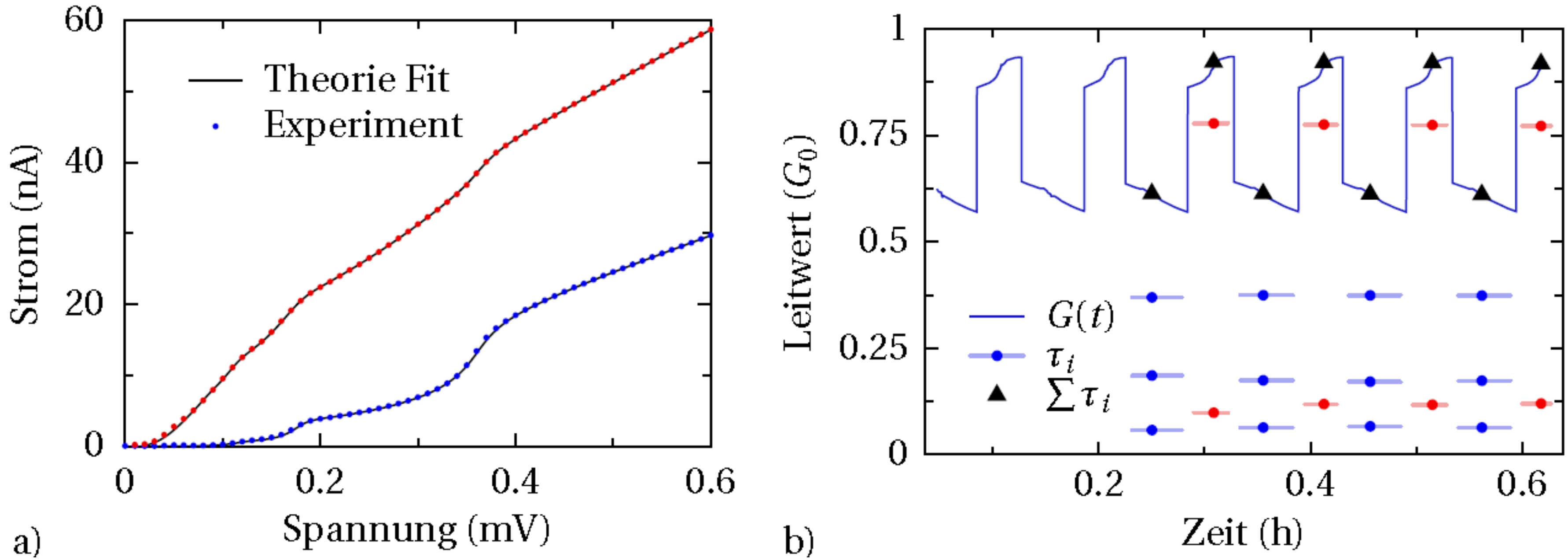
Normalized shape of the hysteresis loops



Bistable switching: conductance channels

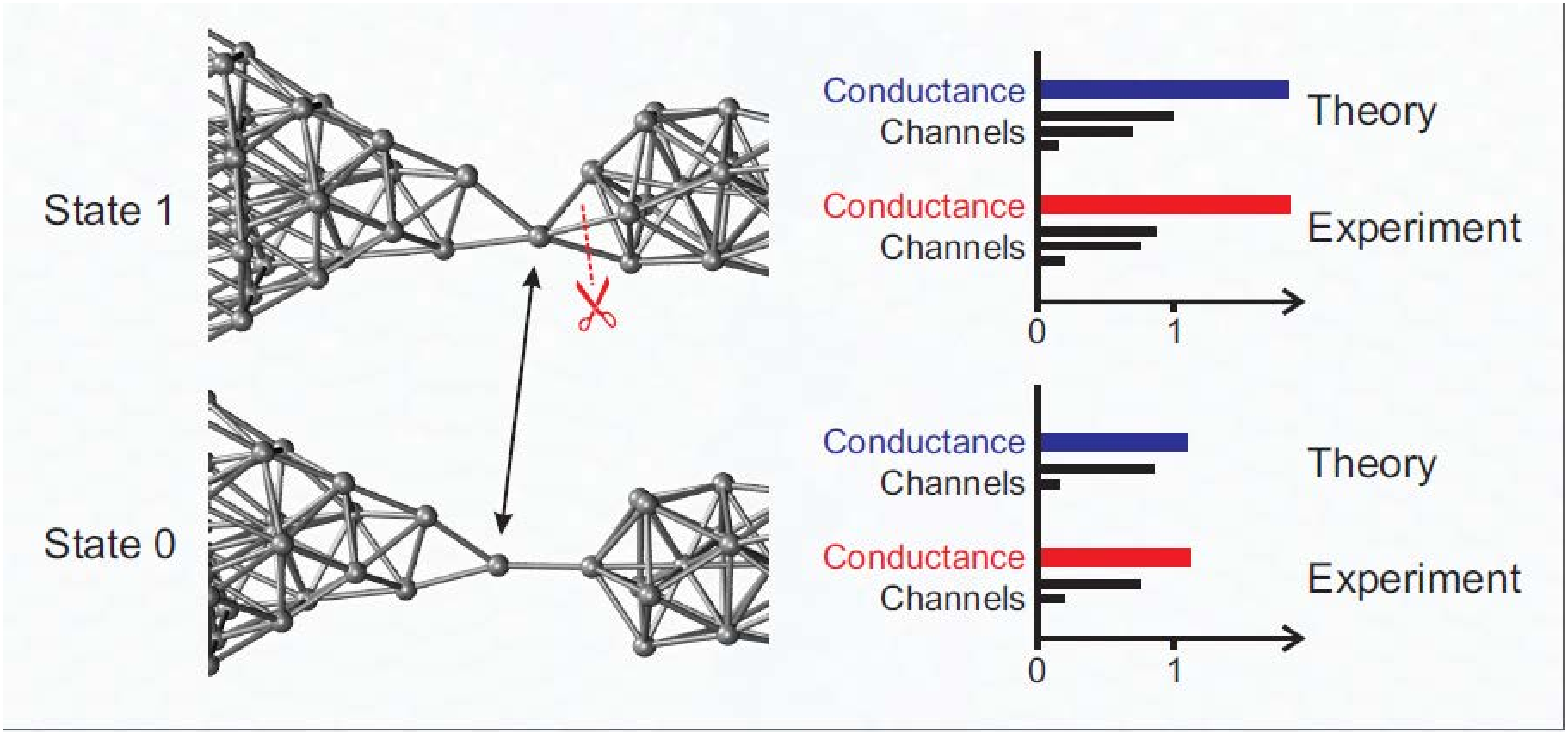


$G_H = 0.89\ G_0$
2 channels
$\tau_1 = 0.77$
$\tau_2 = 0.12$

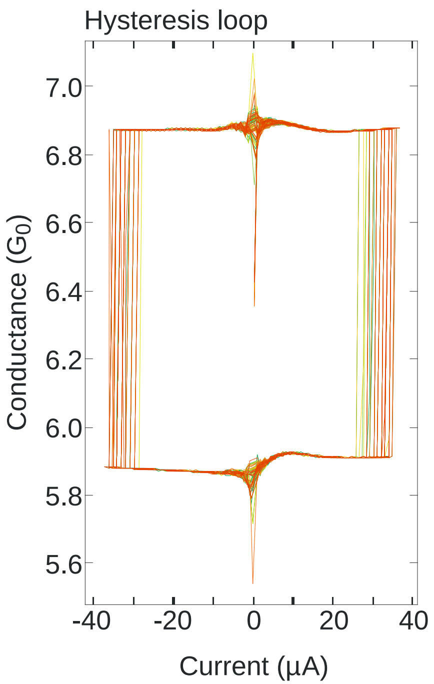
$G_L = 0.63\ G_0$
3 channels
$\tau_1 = 0.37$
$\tau_2 = 0.19$
$\tau_3 = 0.07$

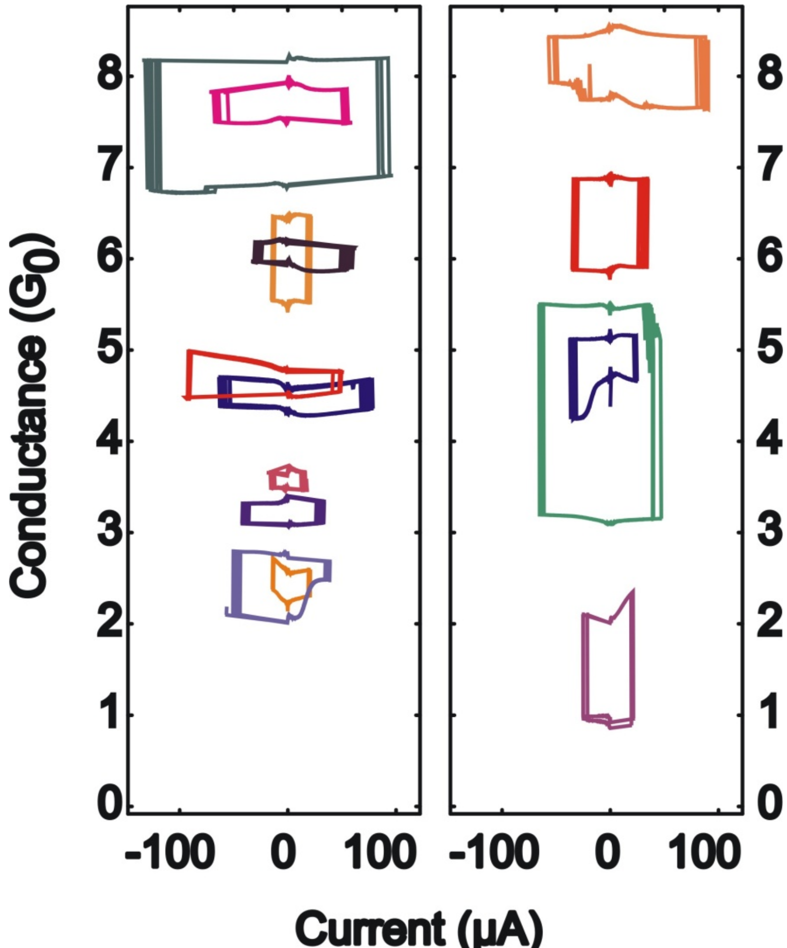
Single-atom switch?

Aluminum, 250 mK


State 1
State 0
Conductance
Channels
Theory
Conductance
Channels
Experiment
0
1
Conductance
Channels
Theory
Conductance
Channels
Experiment
0
1

Bistable switching: Statistical behavior





Aluminum, 1.4 K