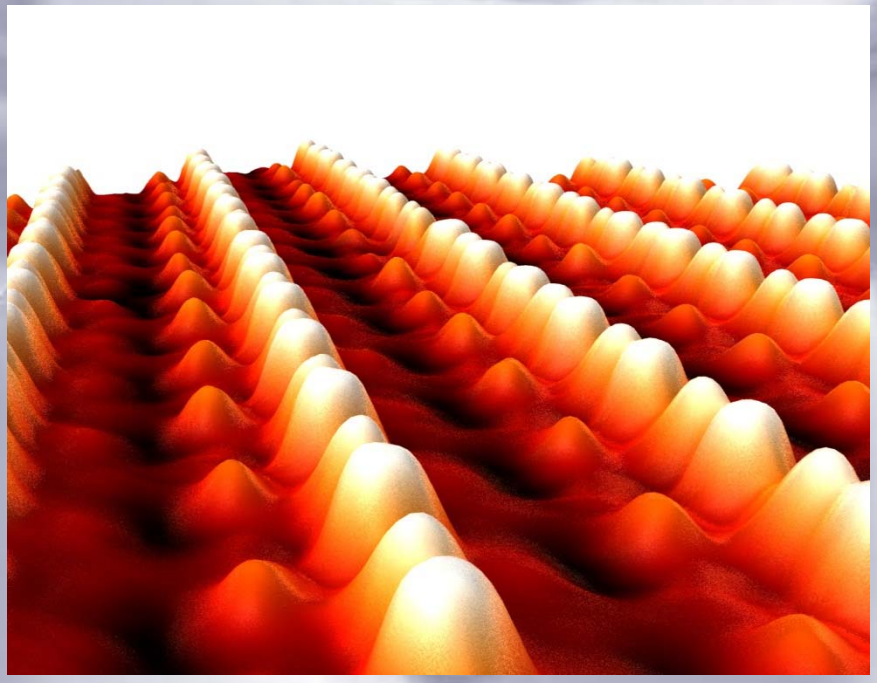
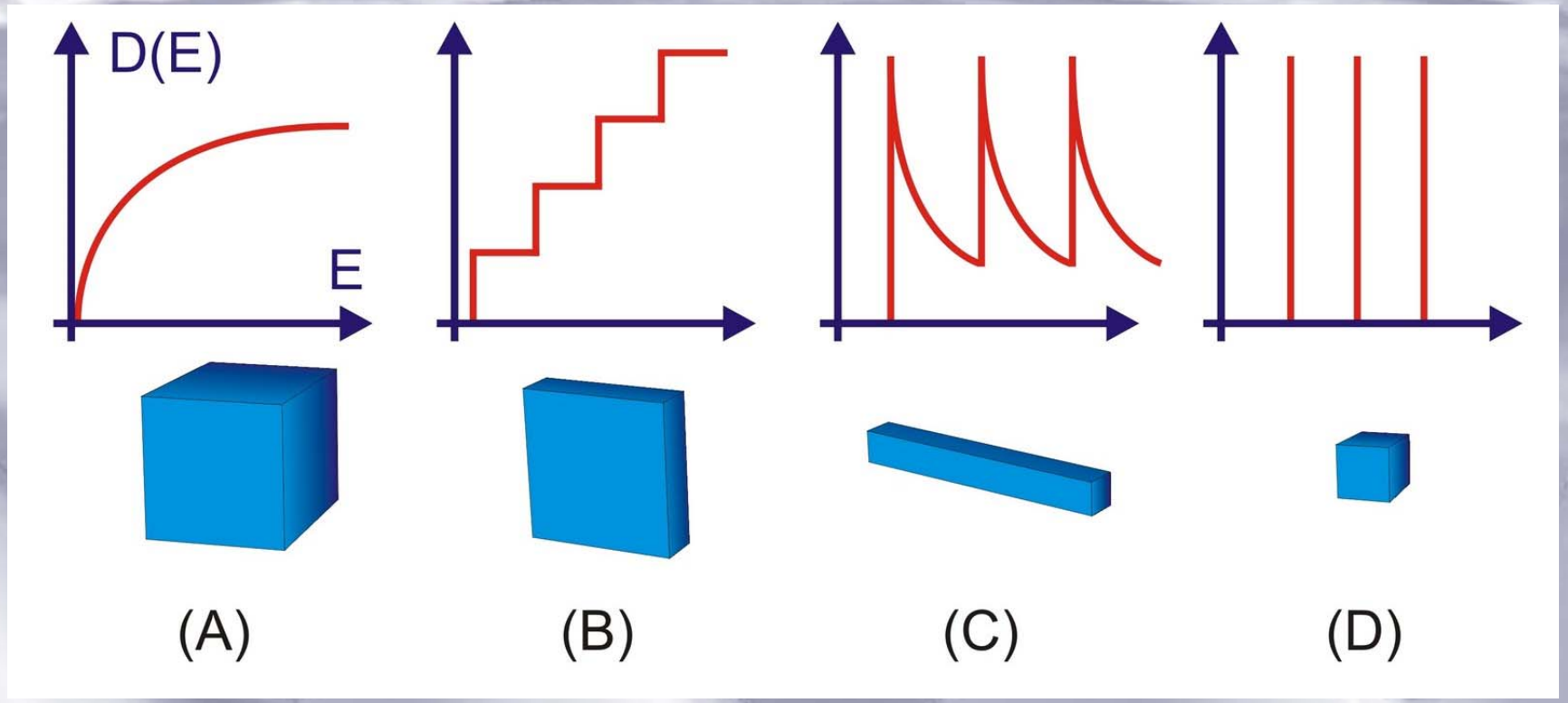
Self-organizing metallic atom chains on semiconductor surfaces

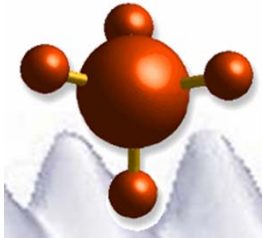
Harold Zandvliet
MESA+ Institute for Nanotechnology, University of Twente



MSU 2014

3D → 2D → 1D → 0D





Physics in 2D

- 2DEG (integer and fractional quantum Hall effect)
- Graphene (E(k)~ k, relativistic electrons, Dirac equation/cones etc.)
- Topological insulators

Physics in 1D

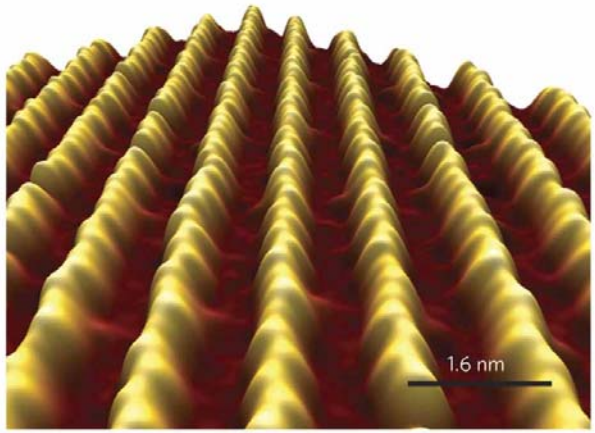
e-e interactions are more important in 1D than in 2D & 3D (Luttinger Liquid Theory)

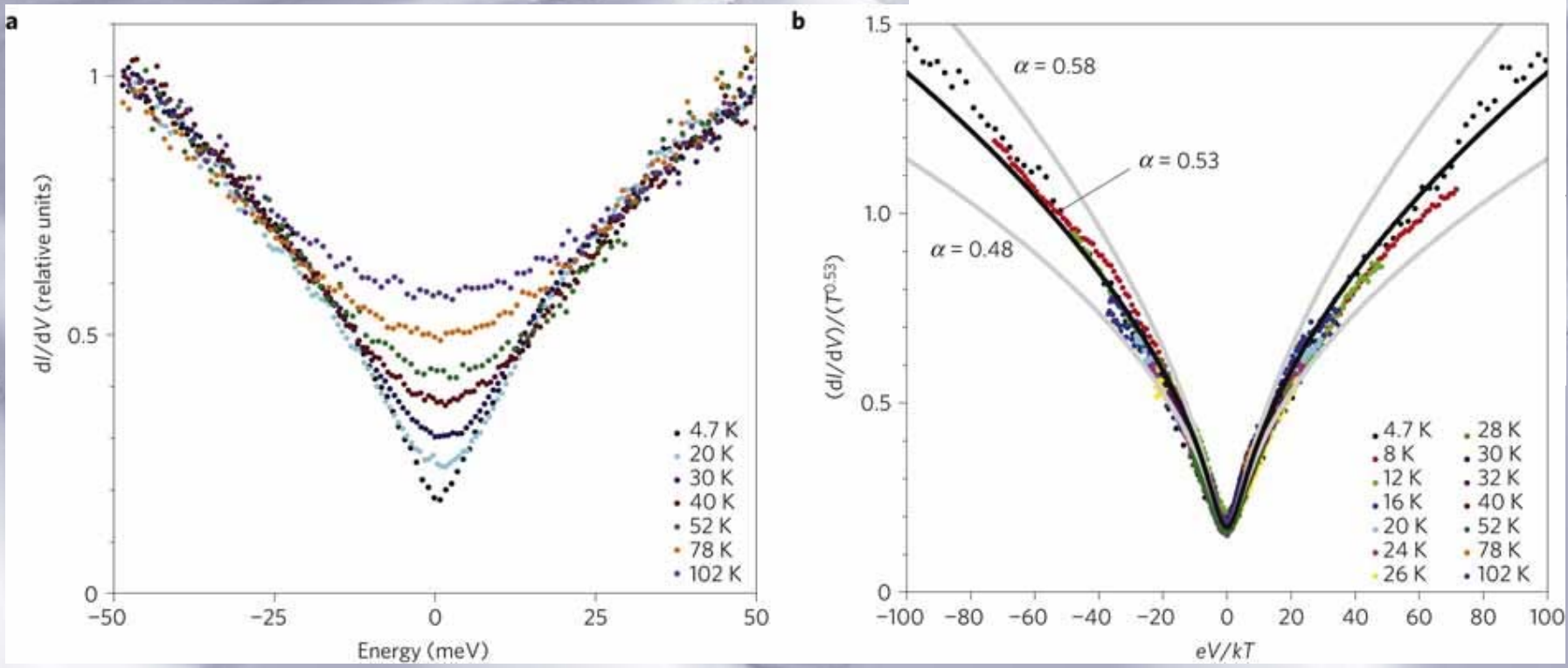
Electron -> spin / charge separation

Linear dispersion relations: E(k) ~k

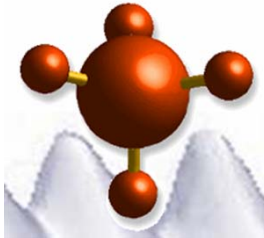
Suppression of DOS near Fermi edge

Au/Ge(001)





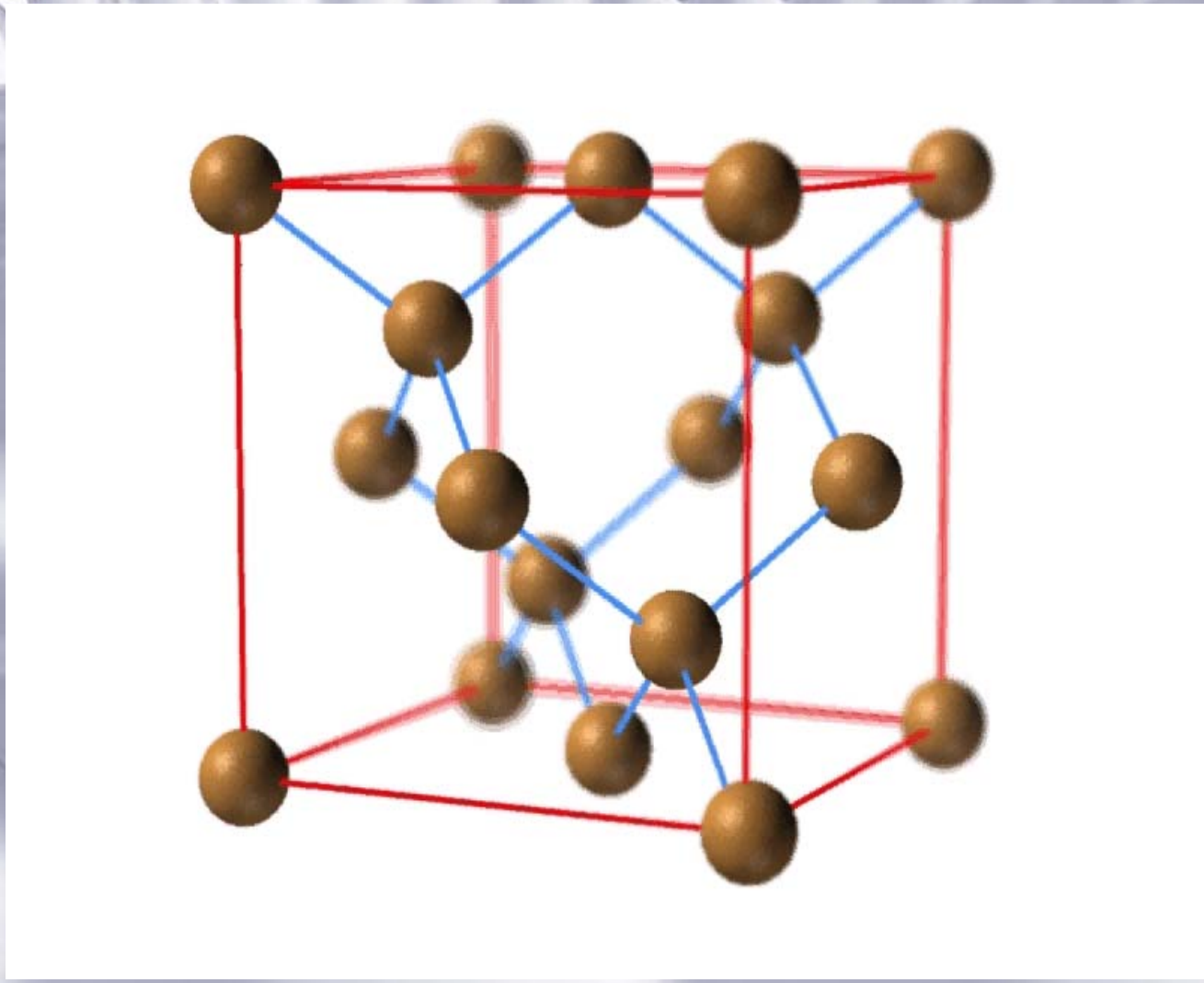
Universal scaling behaviour of D(E)
C. Blumenstein et al. Nature Physics 7, 776 (2011)



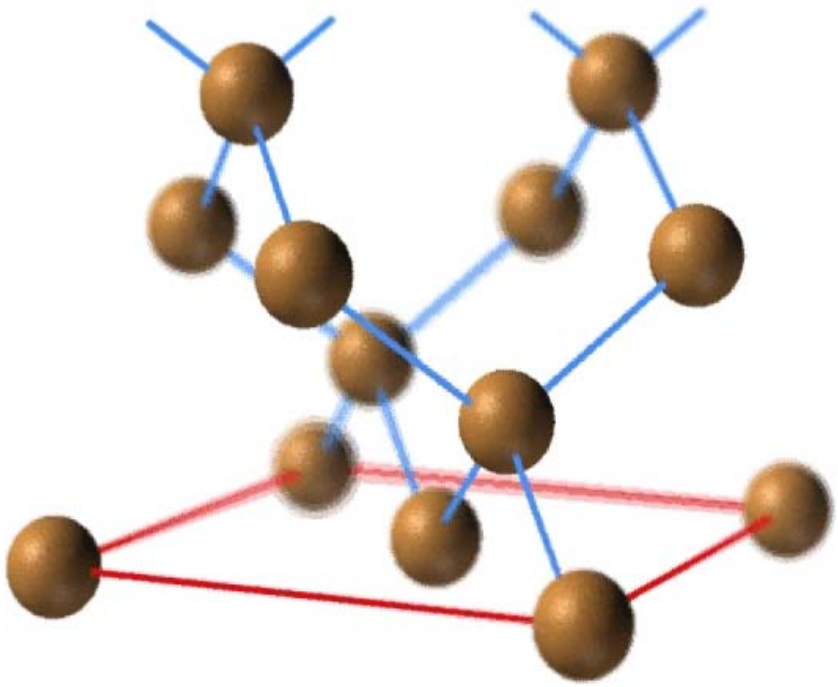
Menu

- 1D systems: Pt/Ge(001), Au/Ge(001) & Ir/Ge(001)
- Physical properties: Quantum confinement & Peierls instability
- Template for molecular electronics

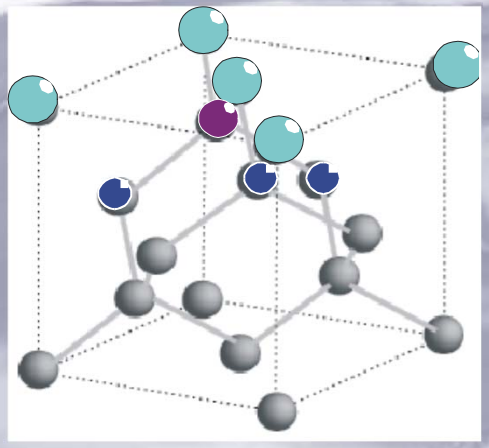
Ge(001) surface



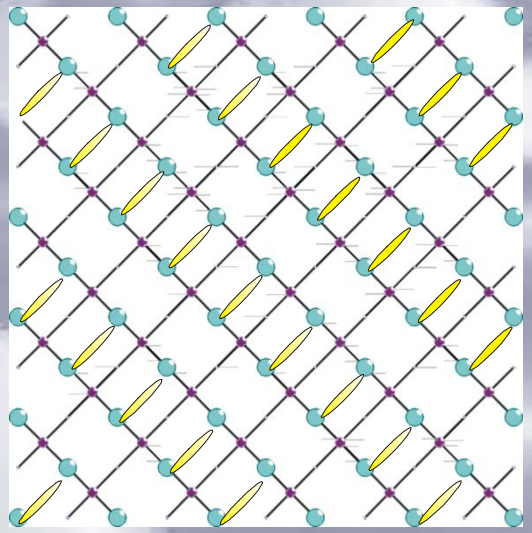
Dimerization



Ge(001)

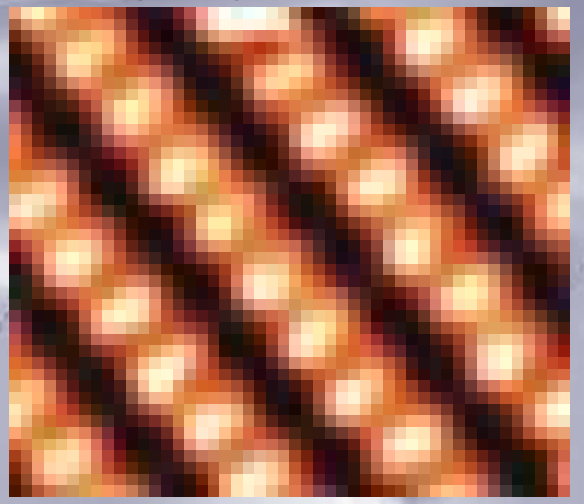


Diamond lattice



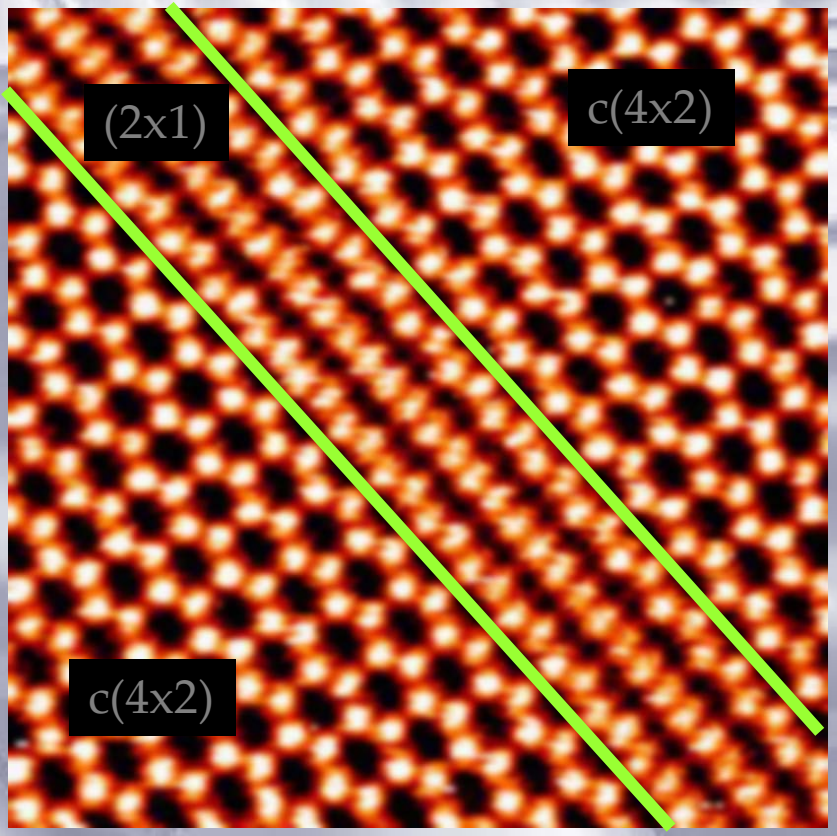
Dimerized(001) surface

Filled state
STM image of the
Ge(001) surface:



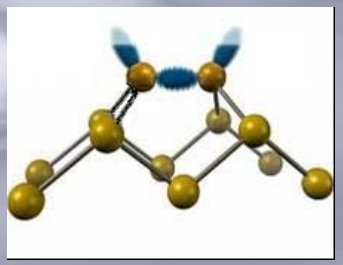
Sample bias = –1.6 V,
Tunneling current = 0.45 nA

Ge(001): symmetric or asymmetric dimers?

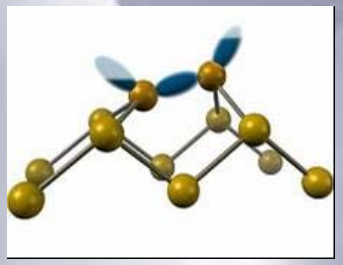


10 x 10 nm² STM image

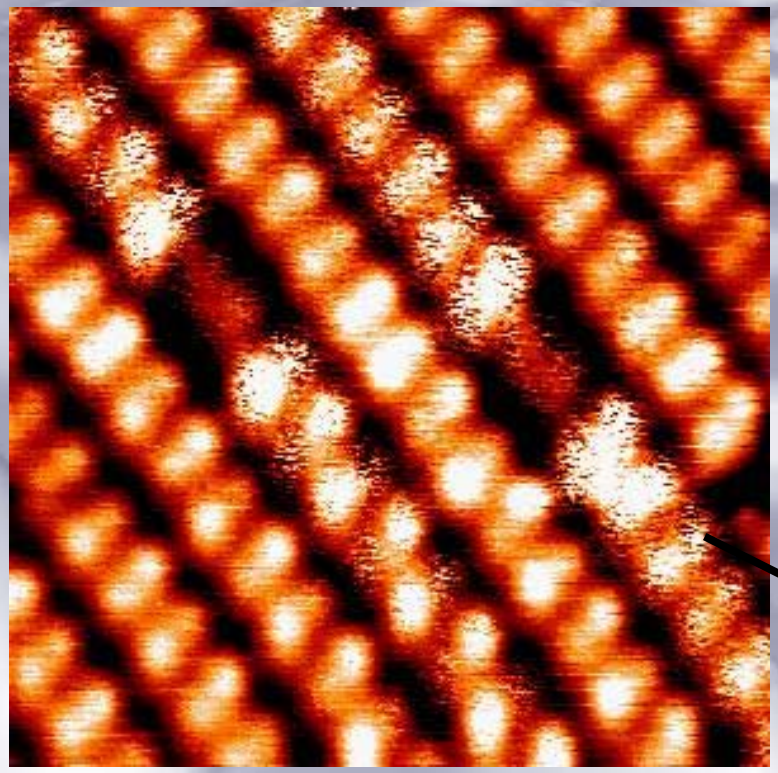
- (2x1) phase: symmetric appearing

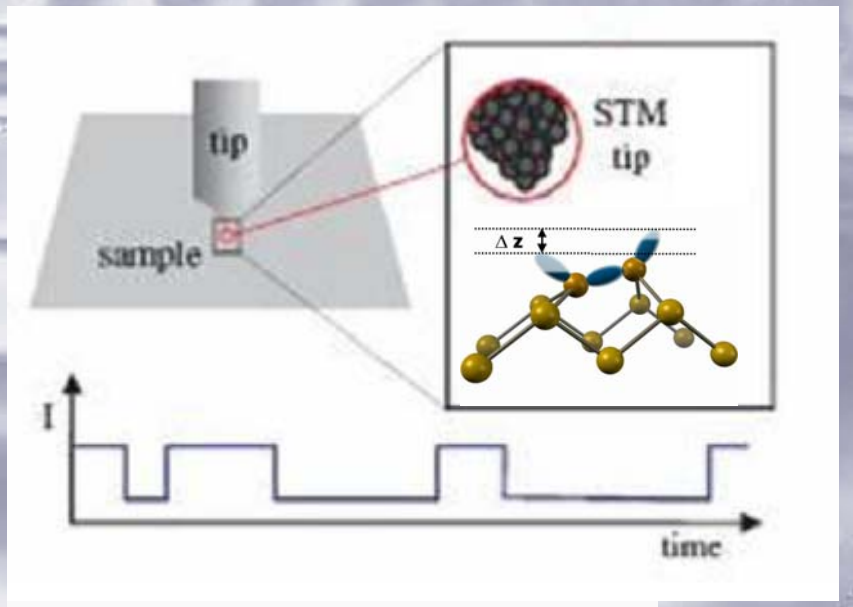


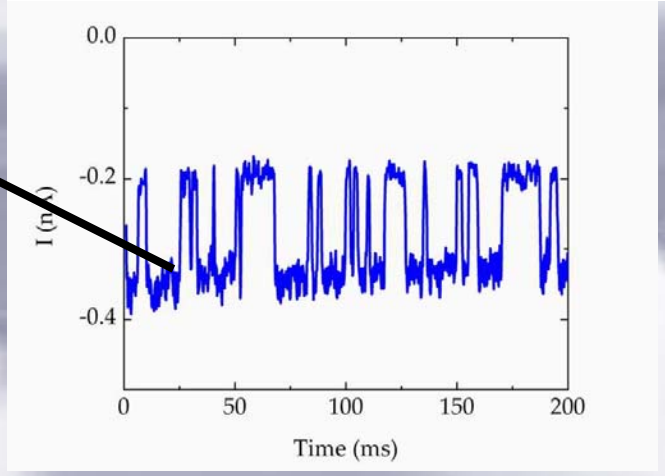
- c(4x2) phase: asymmetric appearing



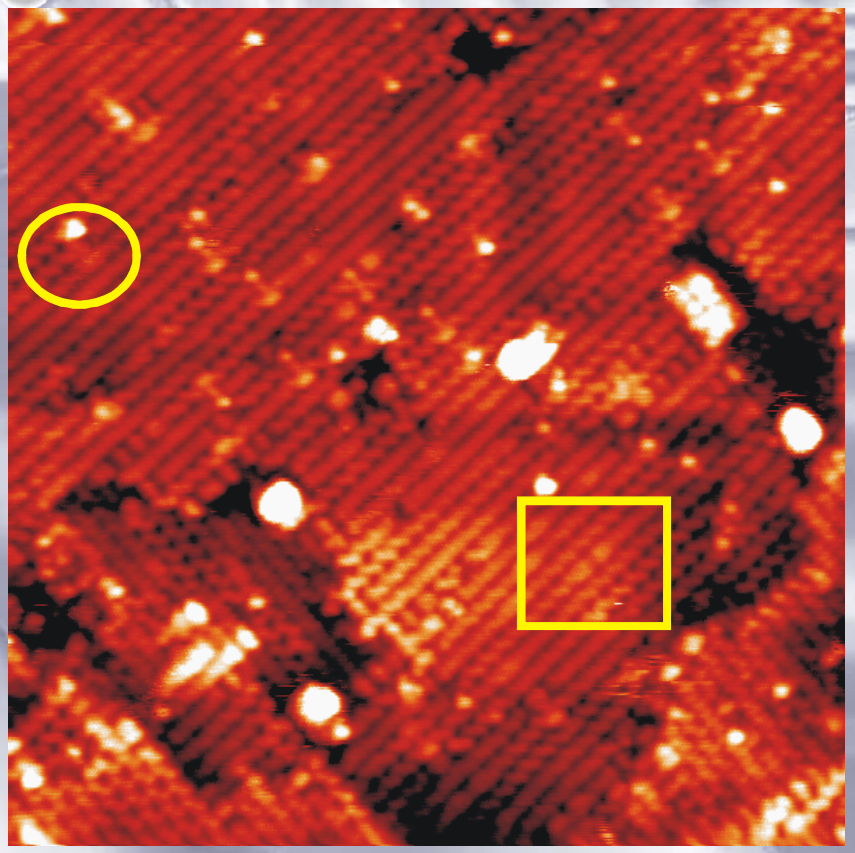
Flip-flopping dimers

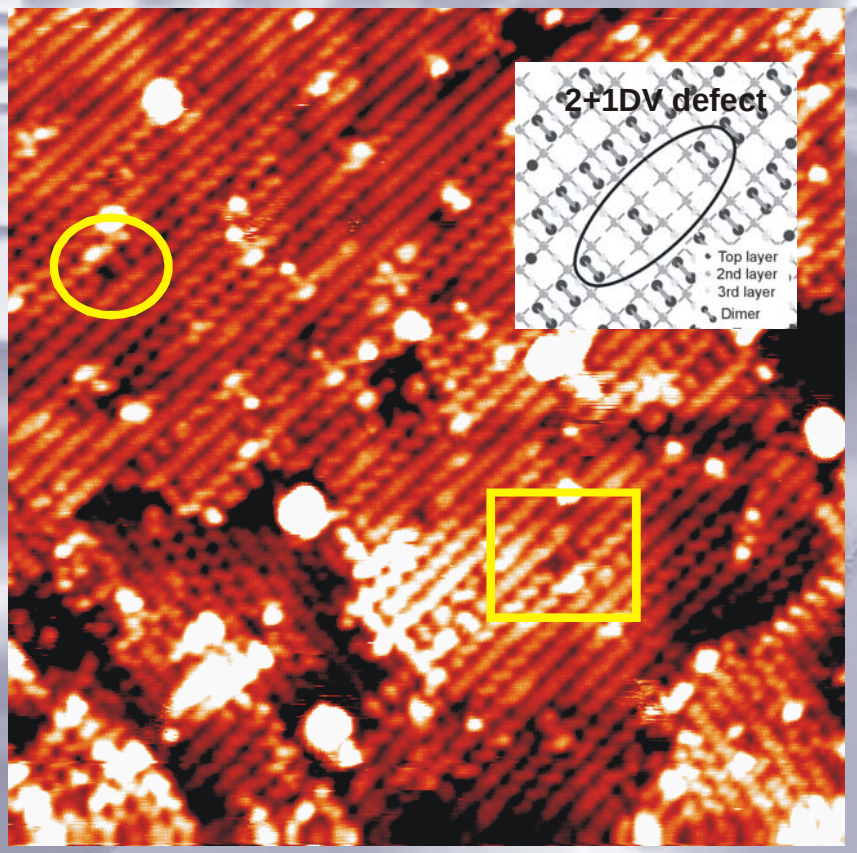




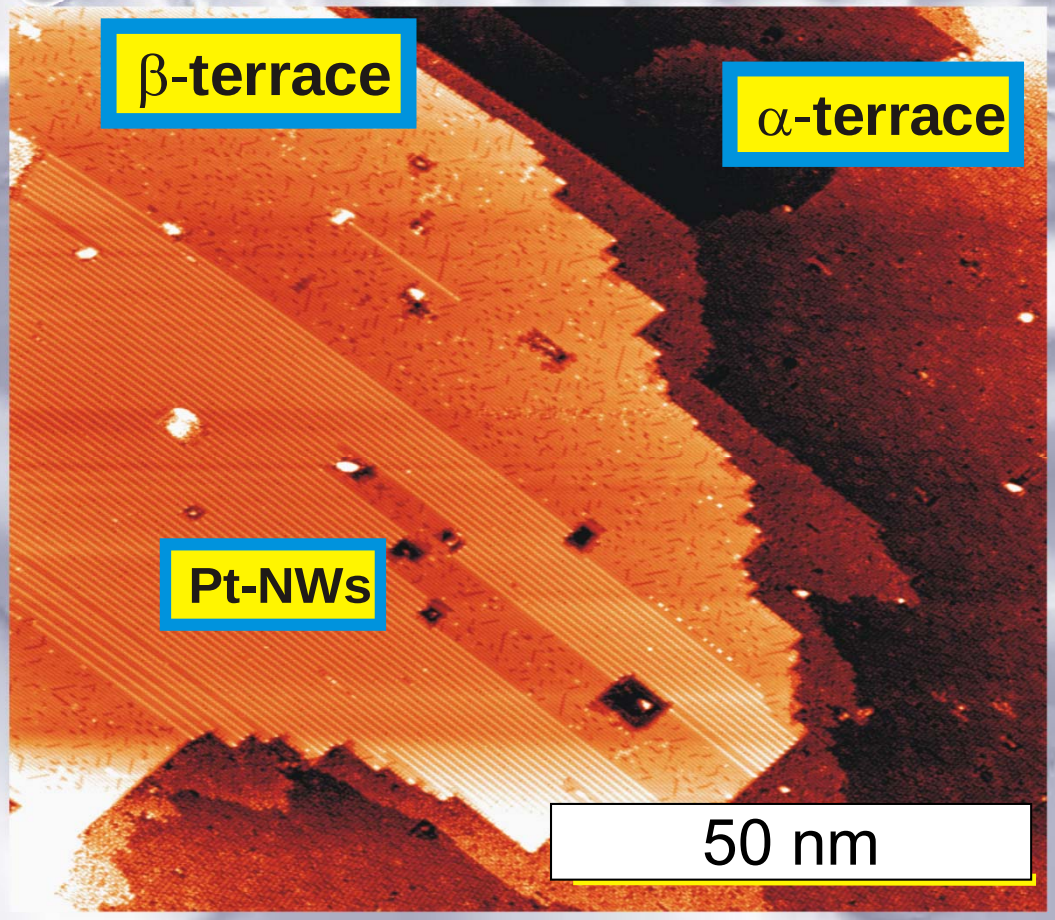


Pt atoms go underground!



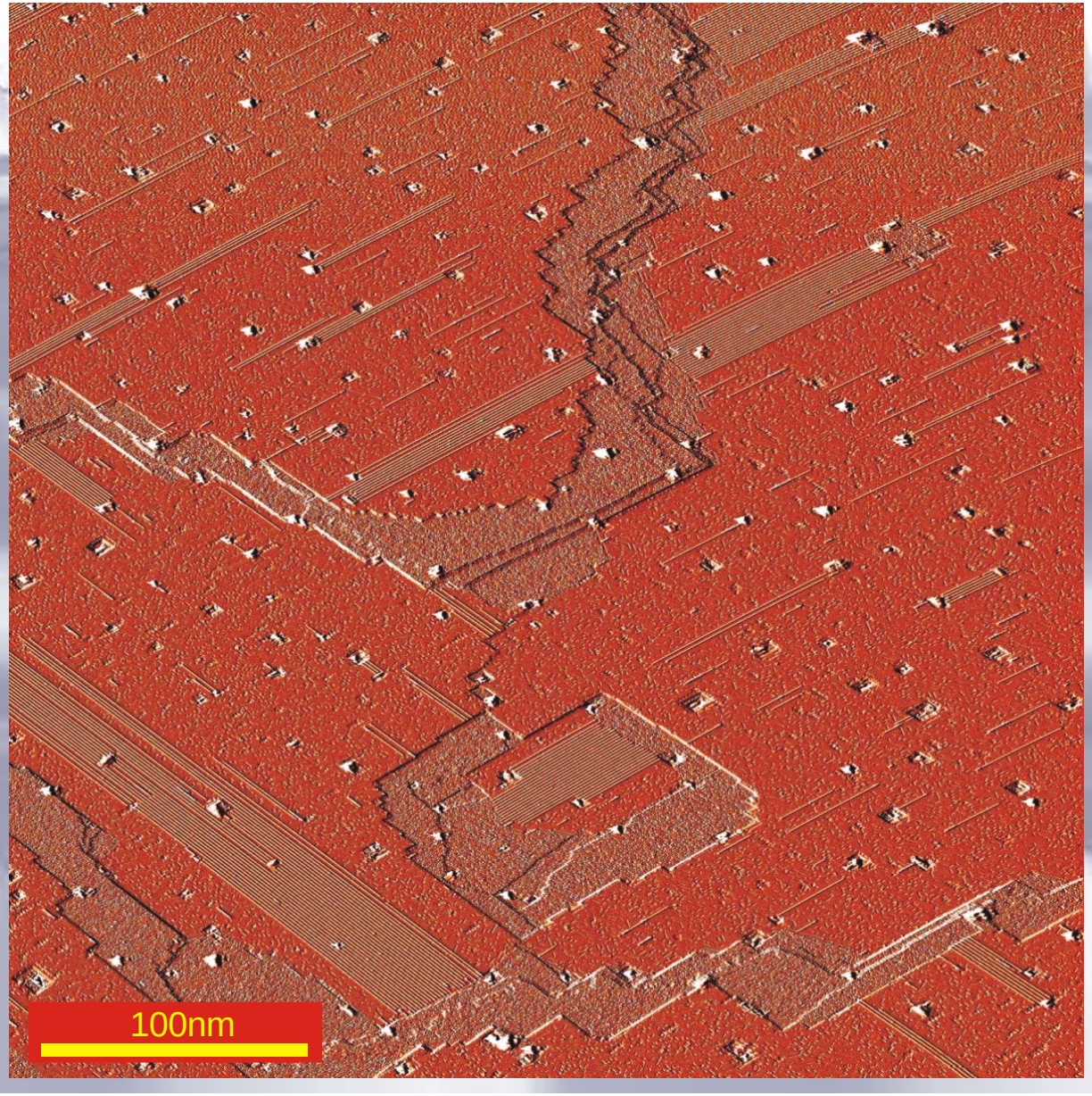


Annealing at 1000 K

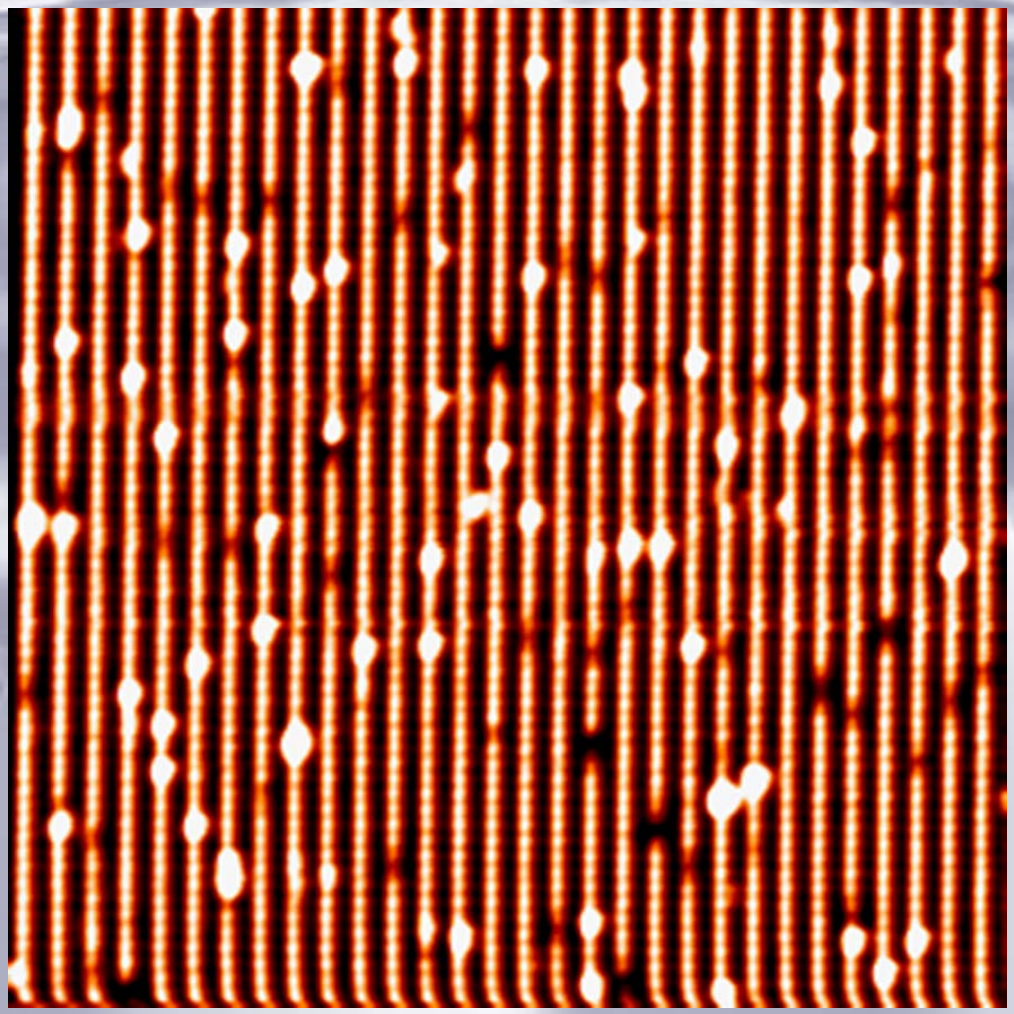


Pt/Ge(001)
Self-lacing
nanowires

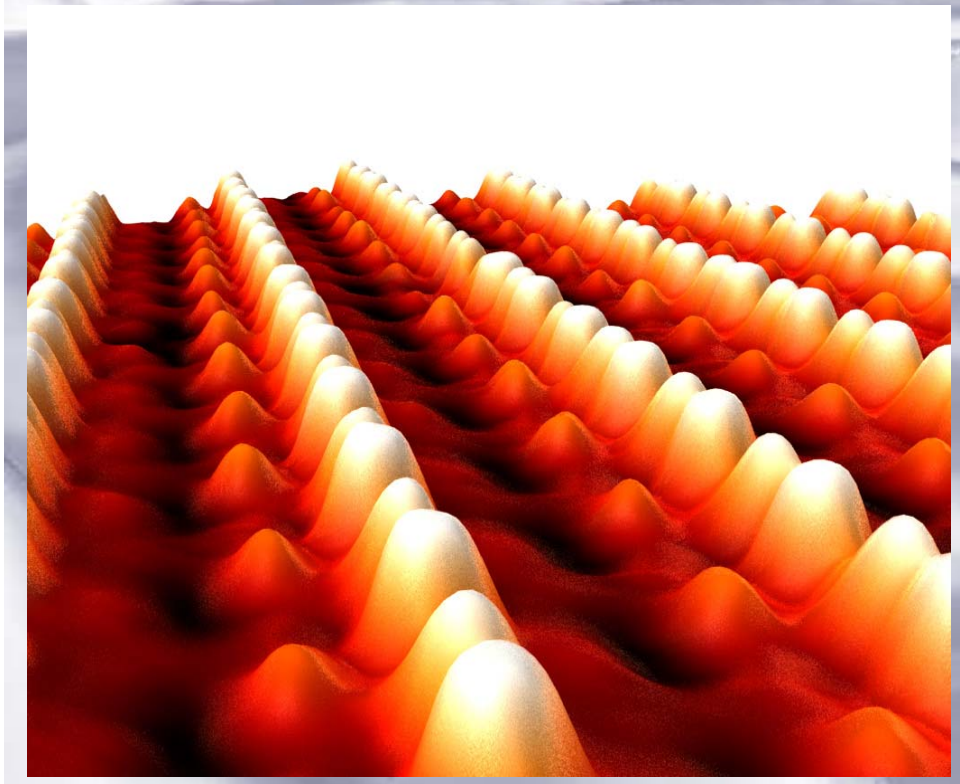
Large view

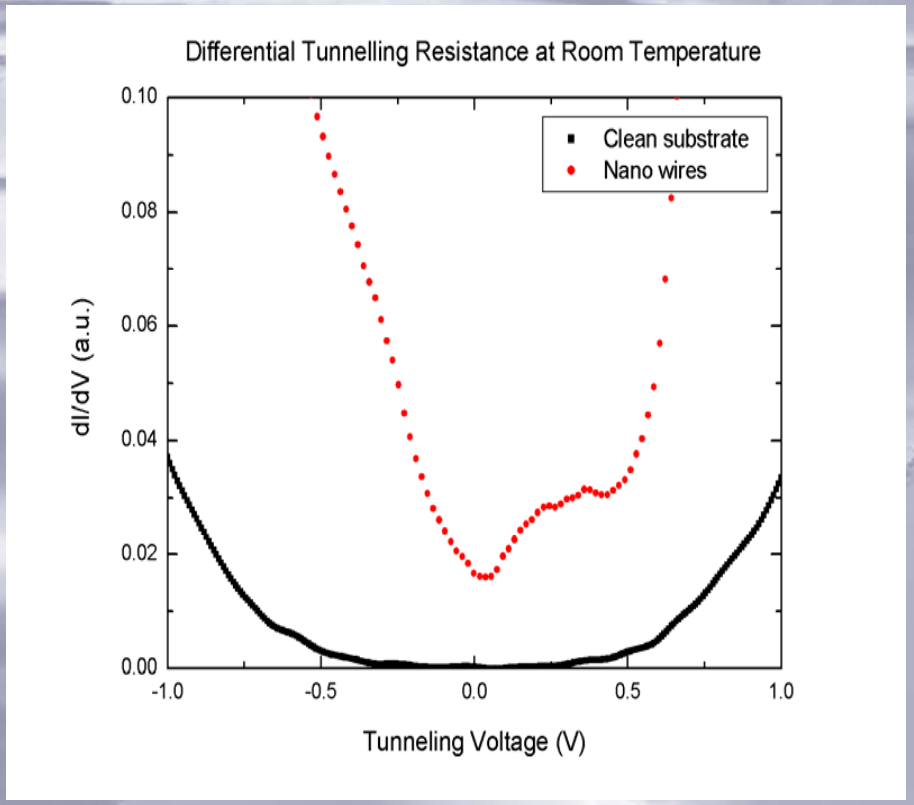


Pt or Ge chains?.....CO adsorption

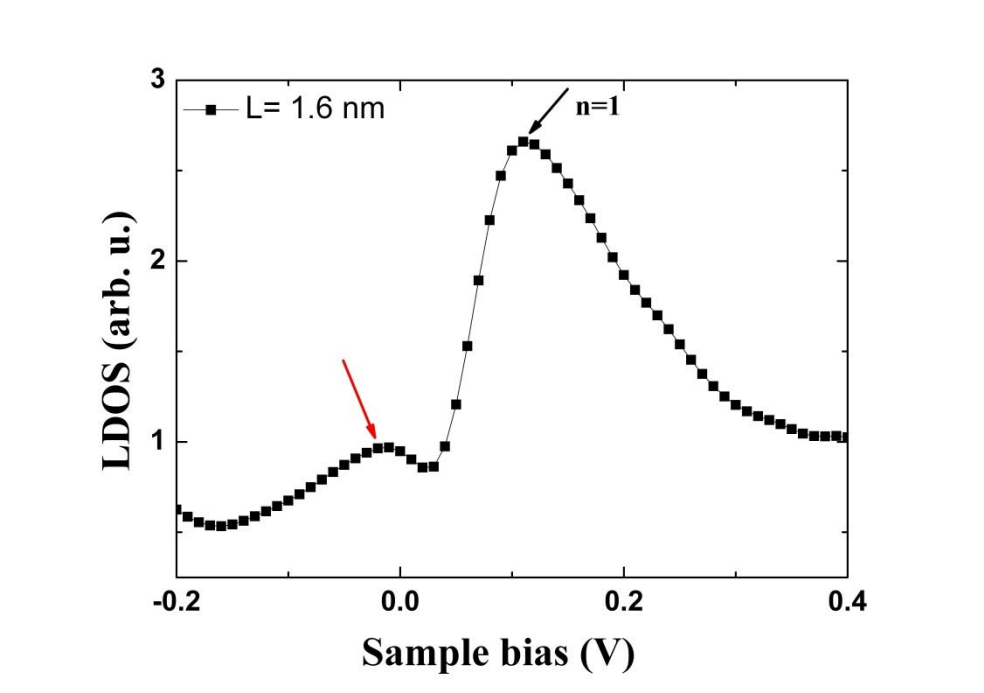


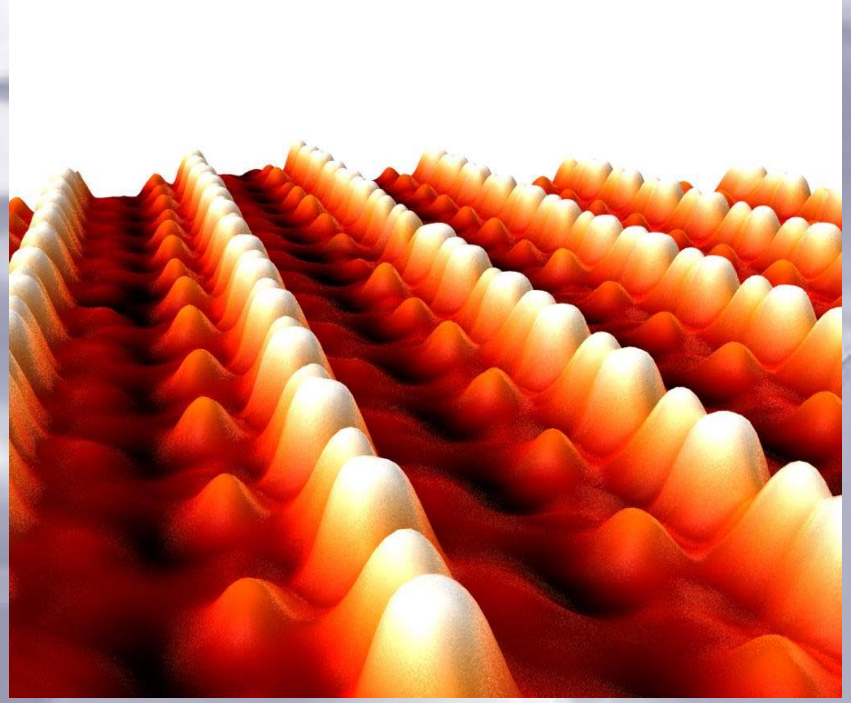
Metallic at RT



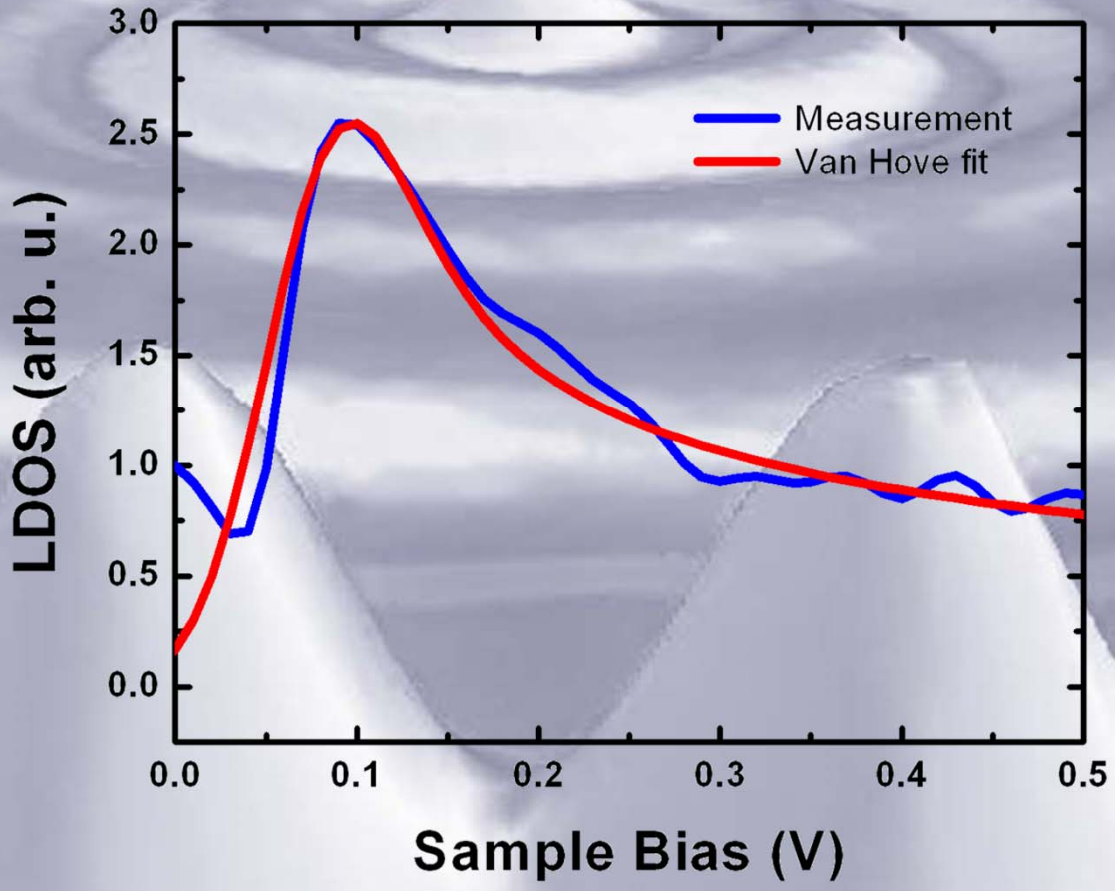


Pt/Ge(001): STS at 77 K

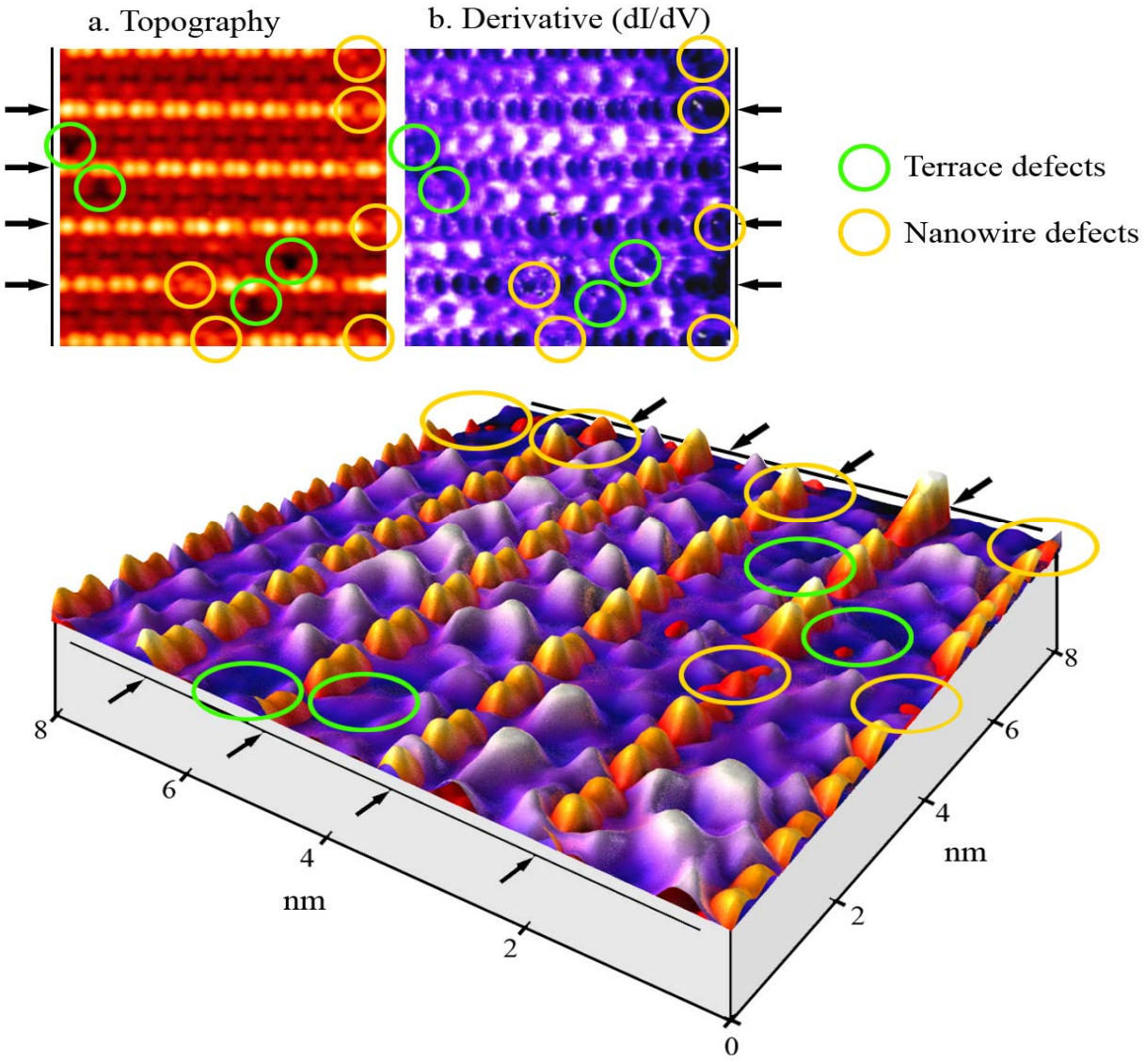




LDOS of 1D electronic state

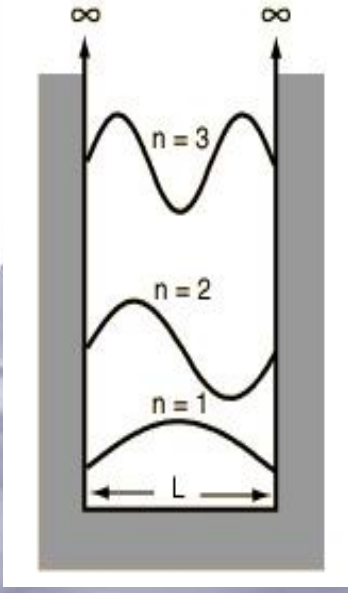


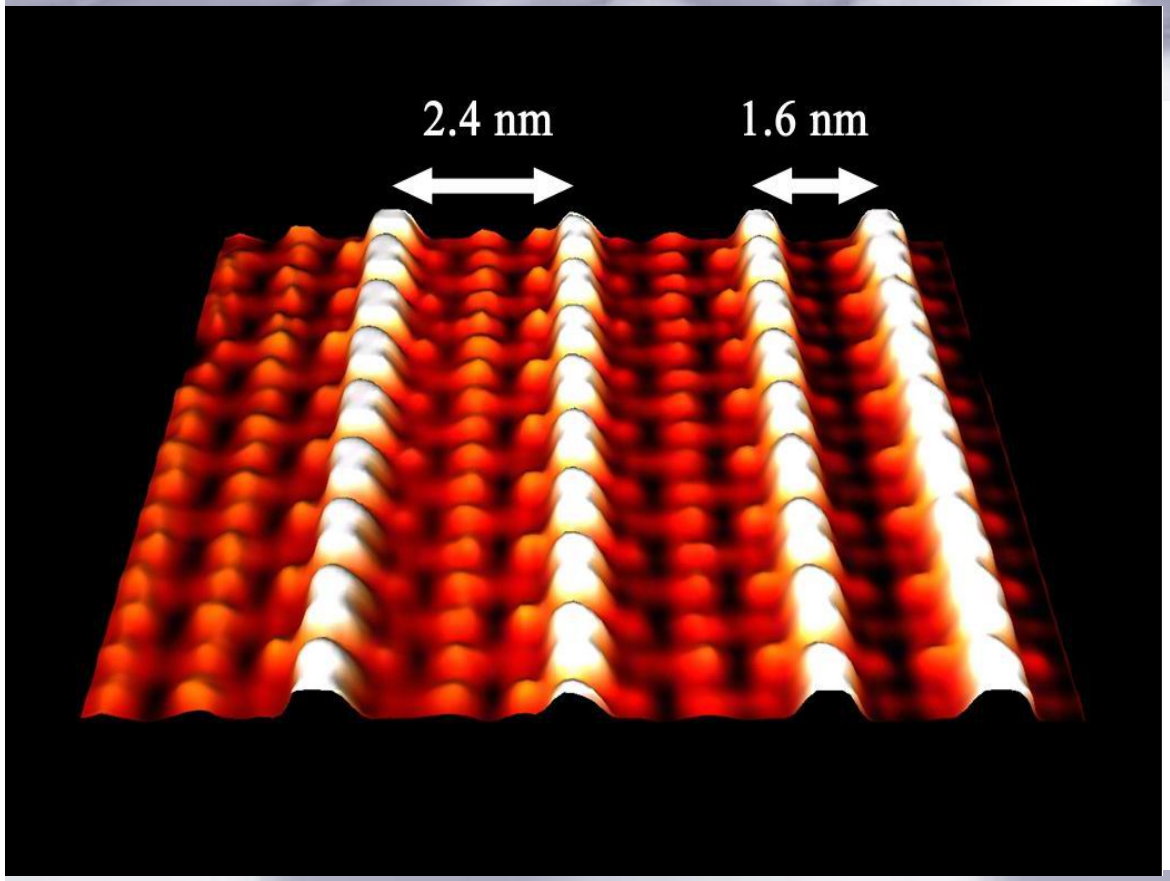
Spatial Mapping of the 1D state
2008 National Physics Exam (VWO)

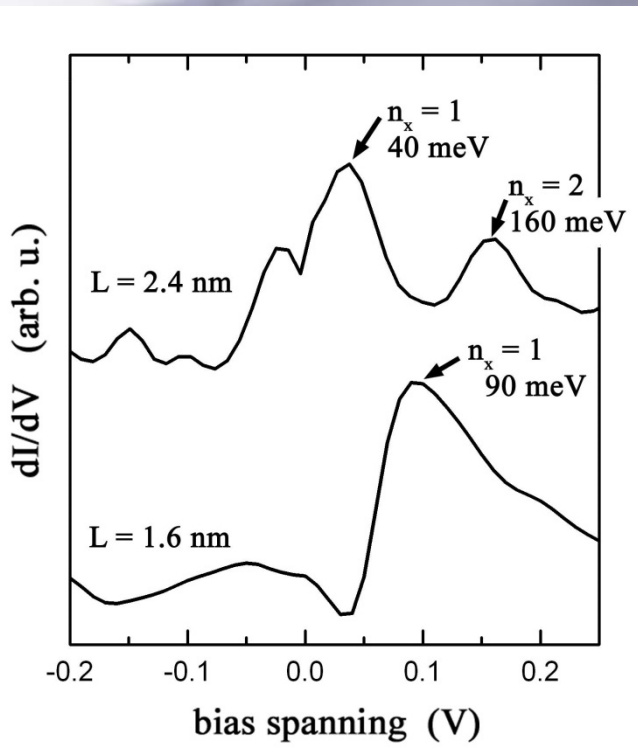


Pt nanowires

$$E_n = \frac{n^2 h^2}{8mL^2}$$

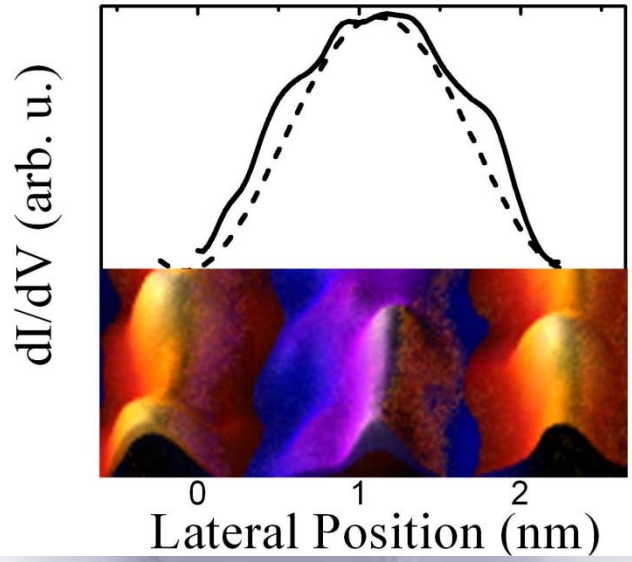


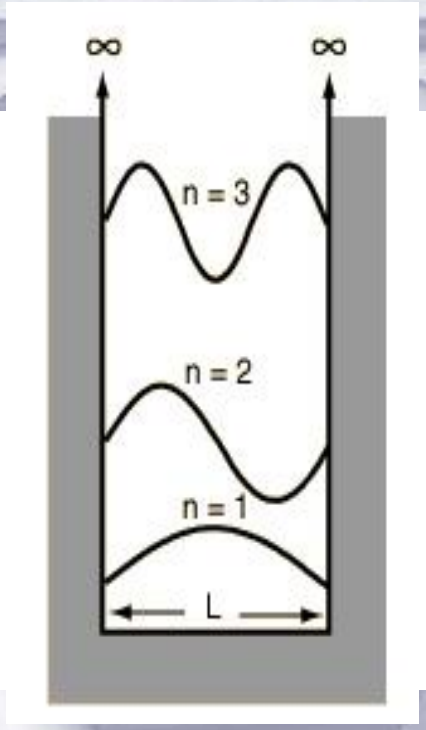




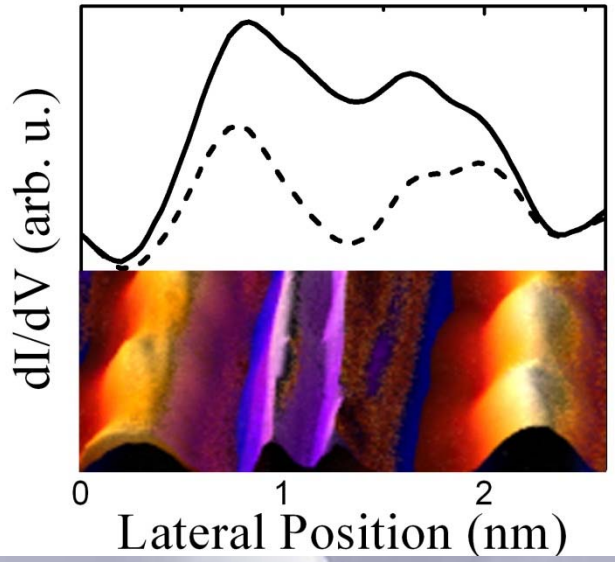
QM particle in a box (n=1,2)

n=1



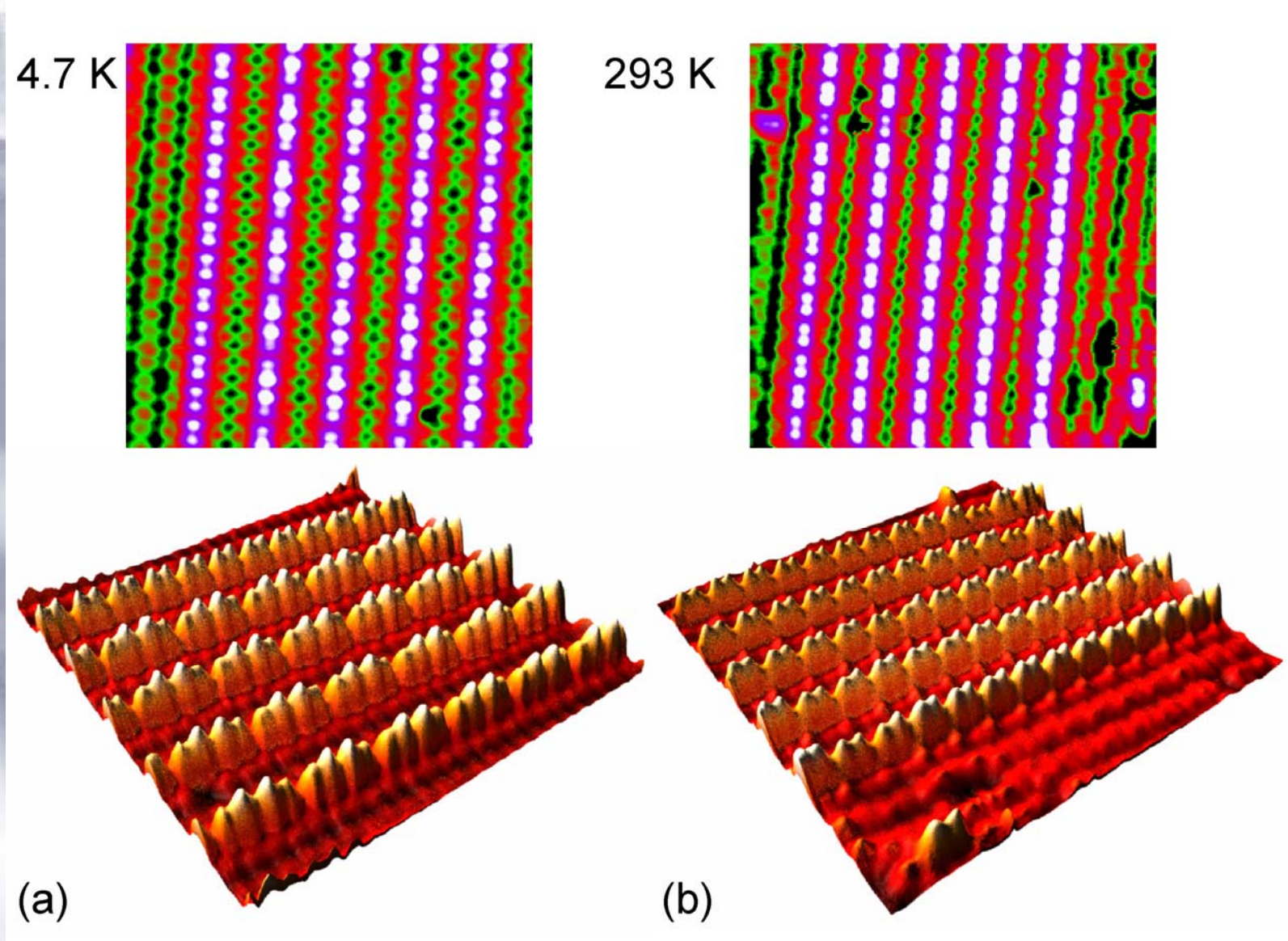


n=2

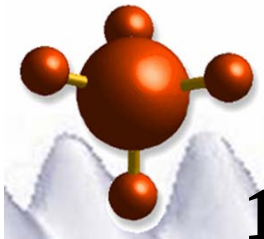


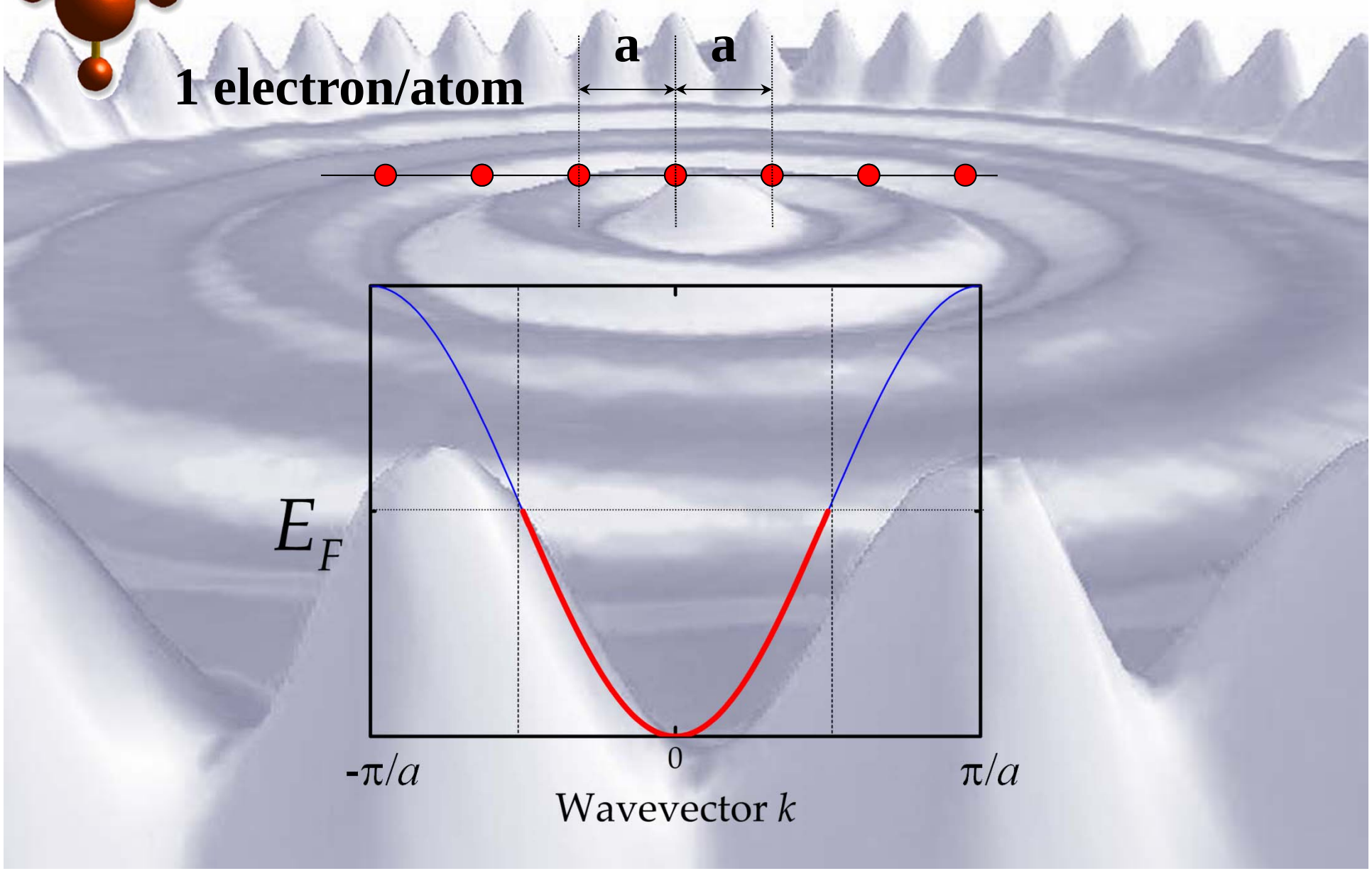
$$E_n = \frac{n^2 h^2}{8mL^2}$$

Doubling of the Periodicity at 4 K

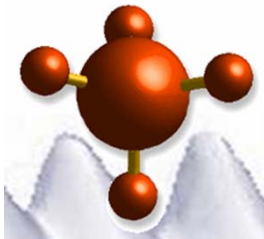


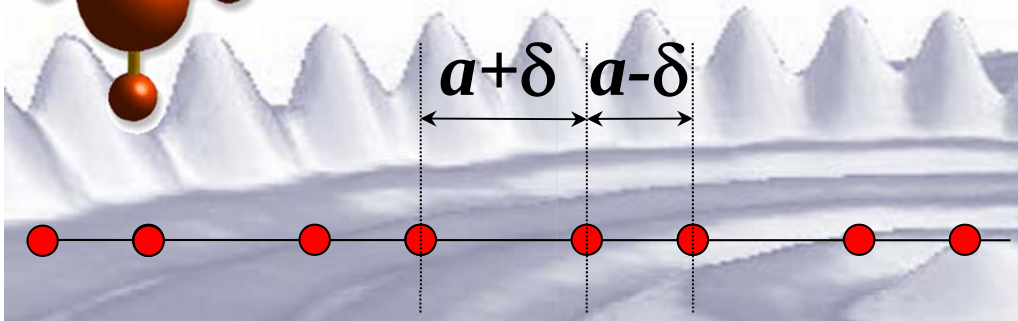
Peierls instability

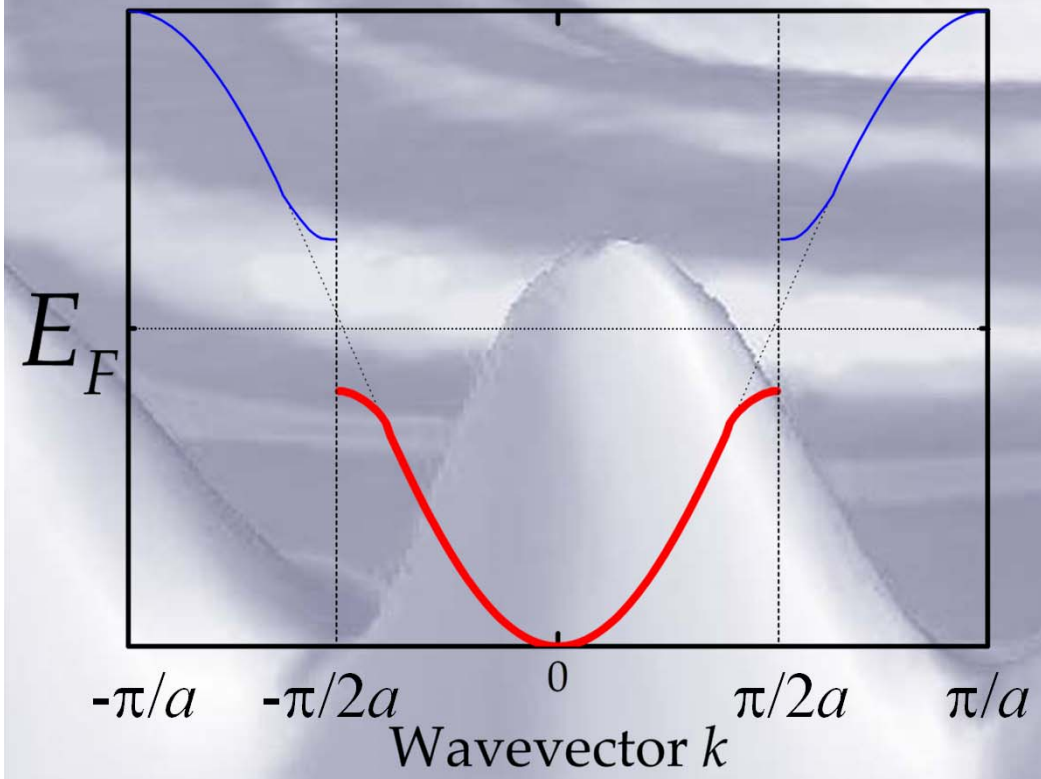




Peierls instability





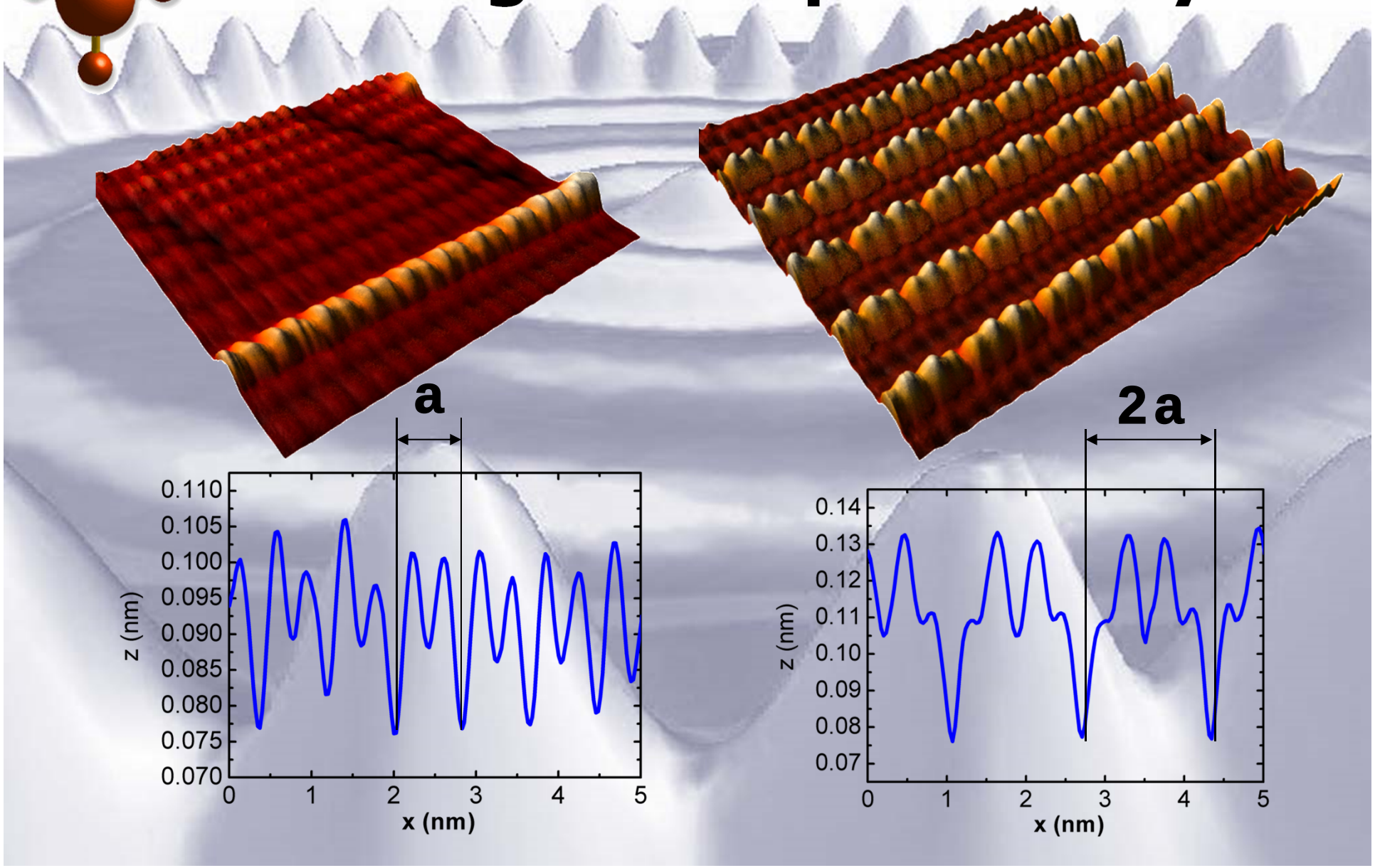


Peierls transition temperature

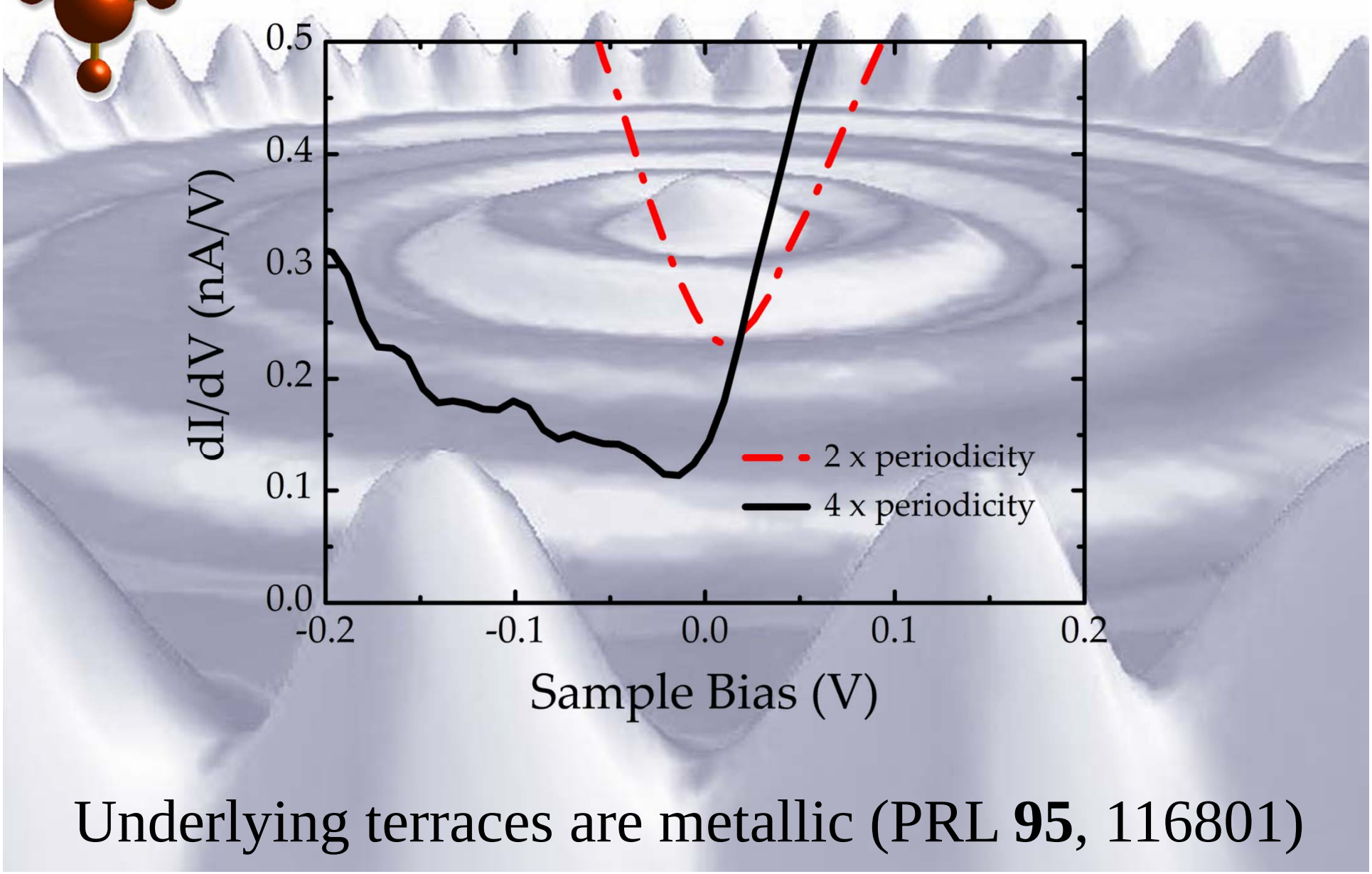
Ideal one-dimensional system: 0 K

Quasi one-dimensional system: > 0 K

Doubling of the periodicity



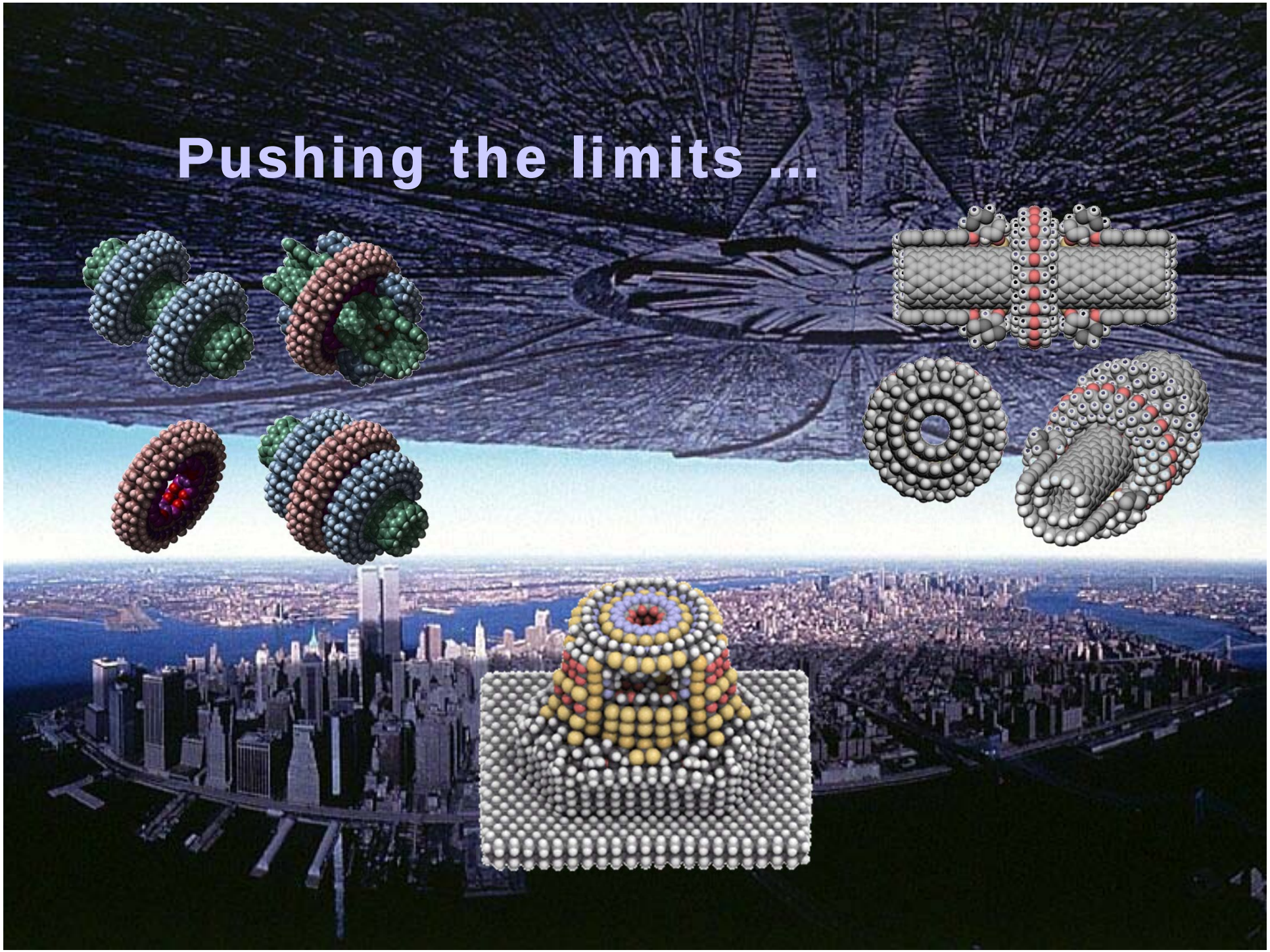
Density of states at E_F



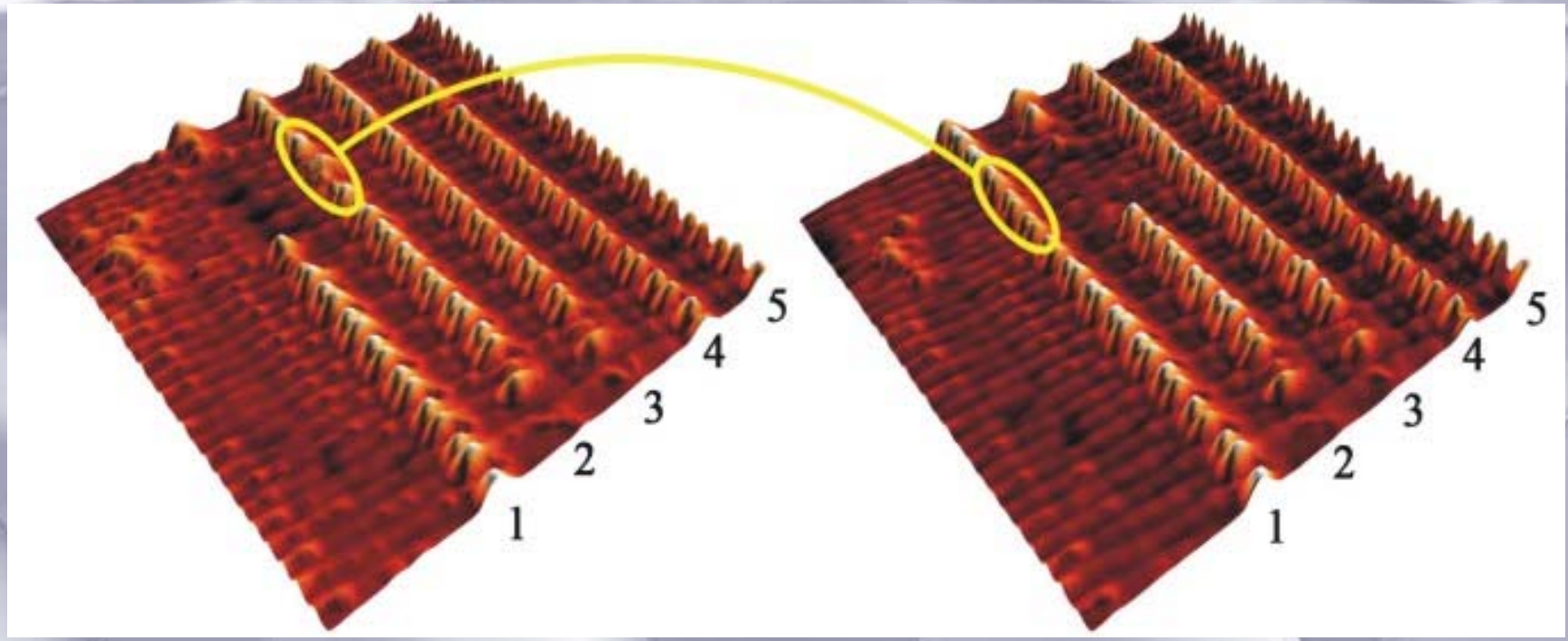
Underlying terraces are metallic (PRL **95**, 116801)

Machines: Range of length

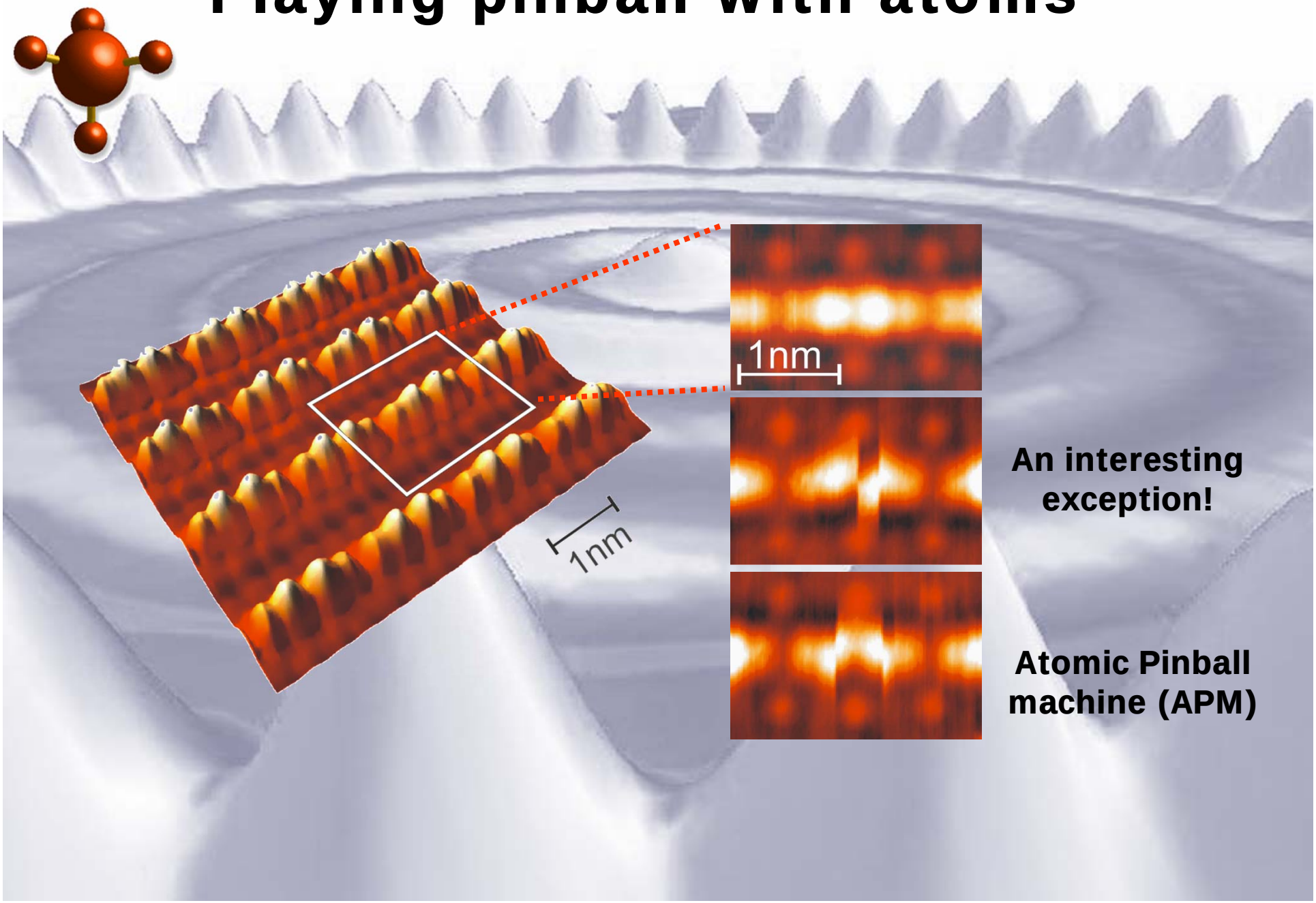
Pushing the limits ...



STM manipulation @RT



Playing pinball with atoms

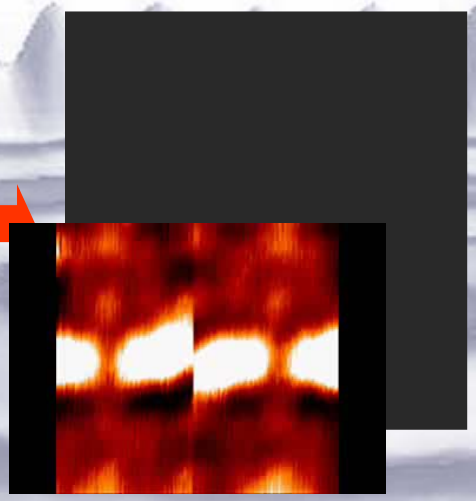


An interesting exception!

Atomic Pinball machine (APM)

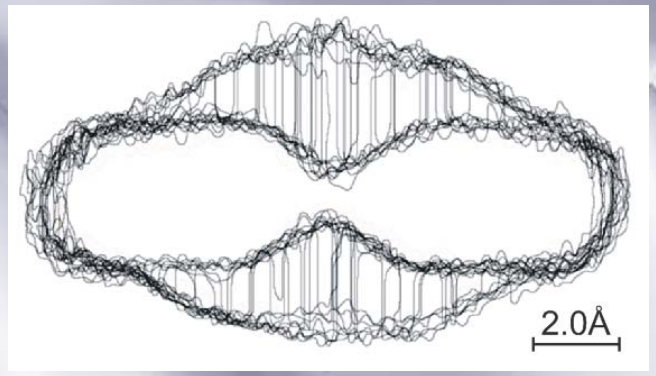
Playing pinball with atoms

Making a sequence of topography images from APM

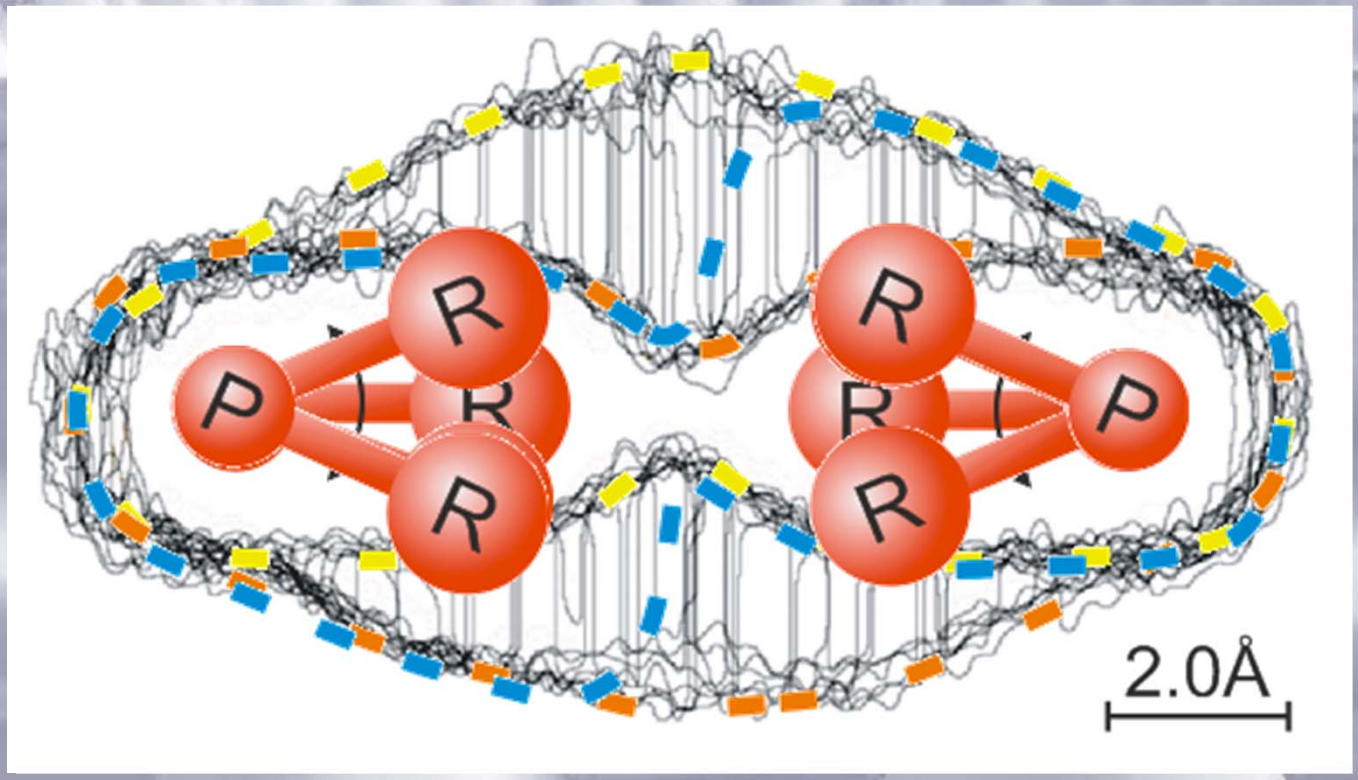


Extracting the boundaries of APM

Superposition of the boundaries

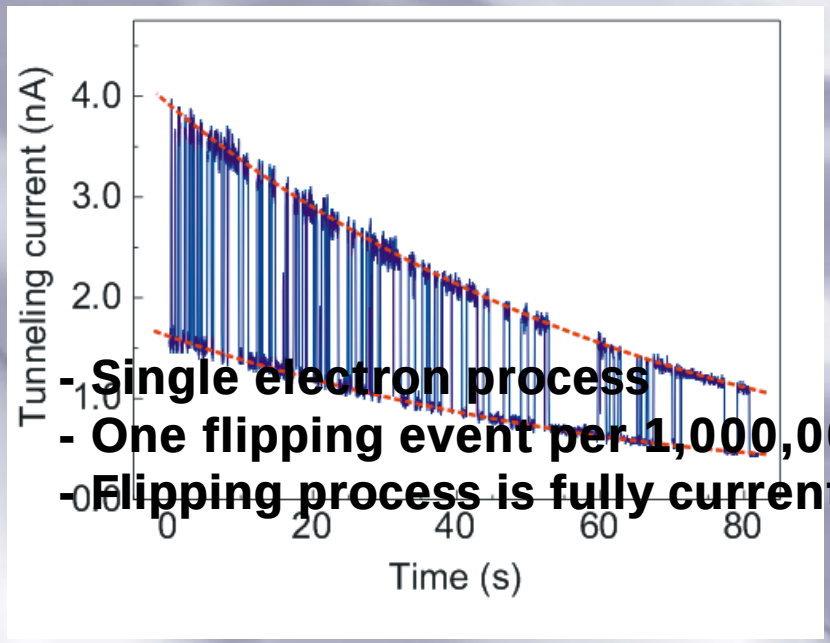


Atomic Pinball Machine

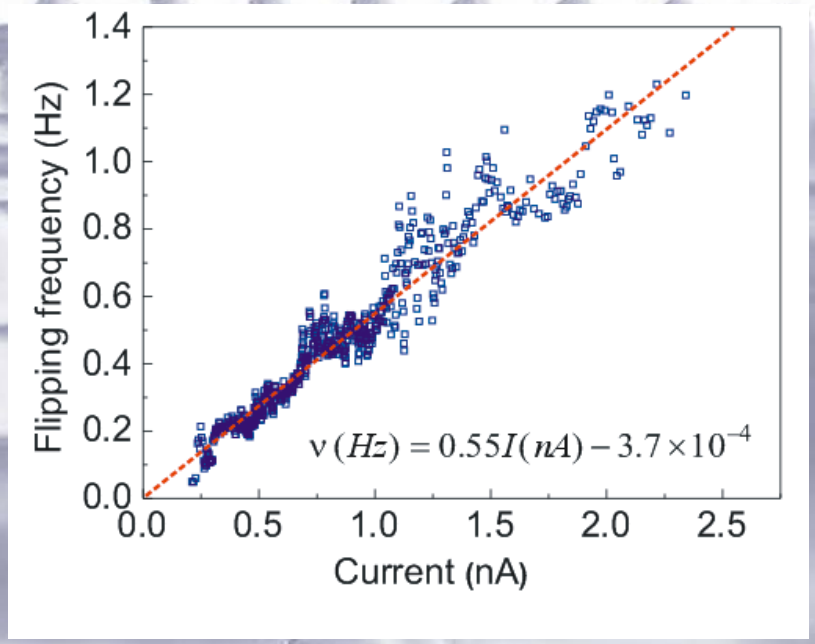


I(t) spectroscopy

Open-loop I(t)

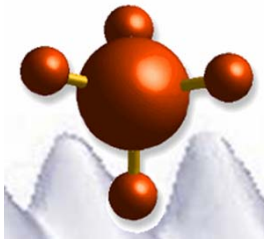


- Single electron process
- One flipping event per 1,000,000,000 electrons!
- Flipping process is fully current induced



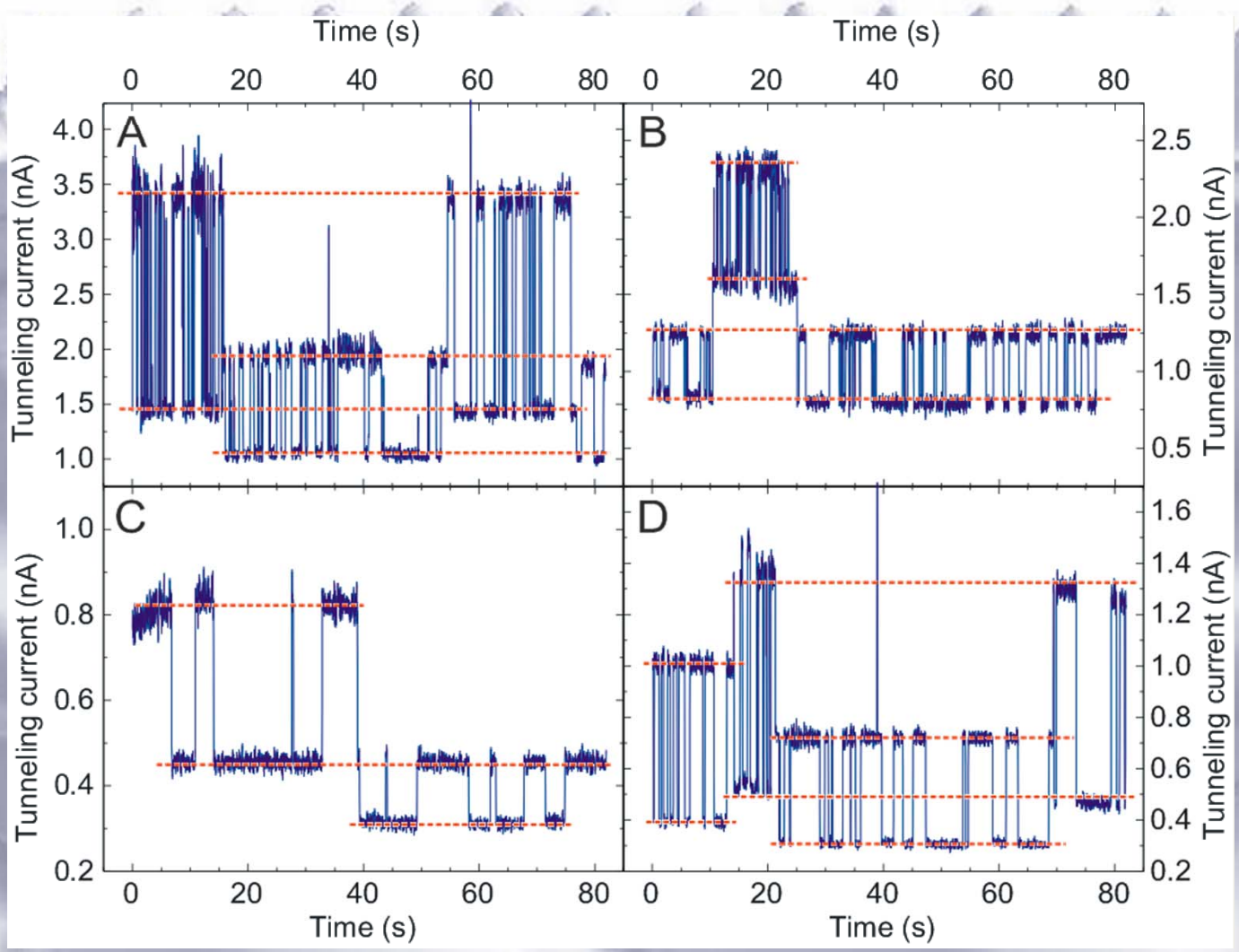
Flipping frequency versus tunneling current

The pinball wizard…..more surprises



Four levels

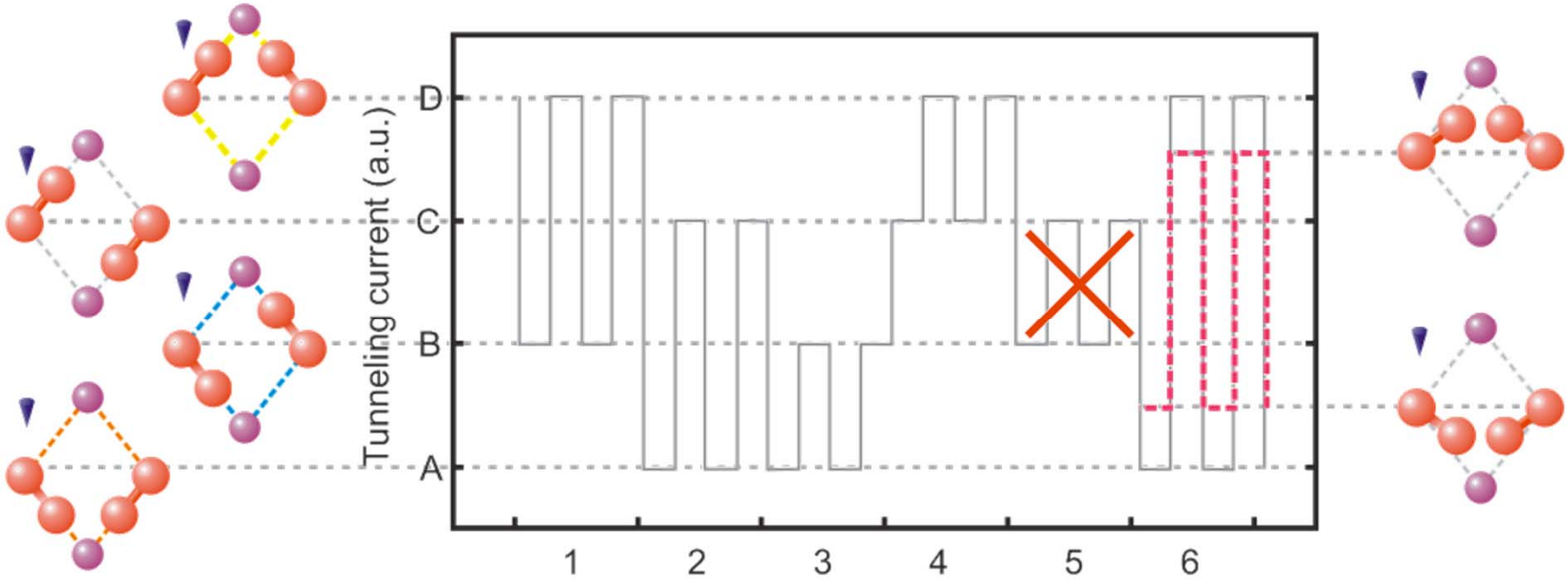
Three levels

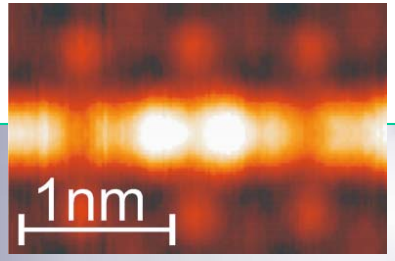


Four levels

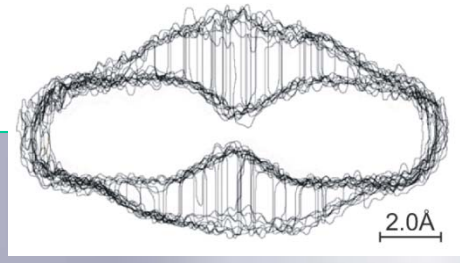
Six levels

Constructing a model





Flipping mode



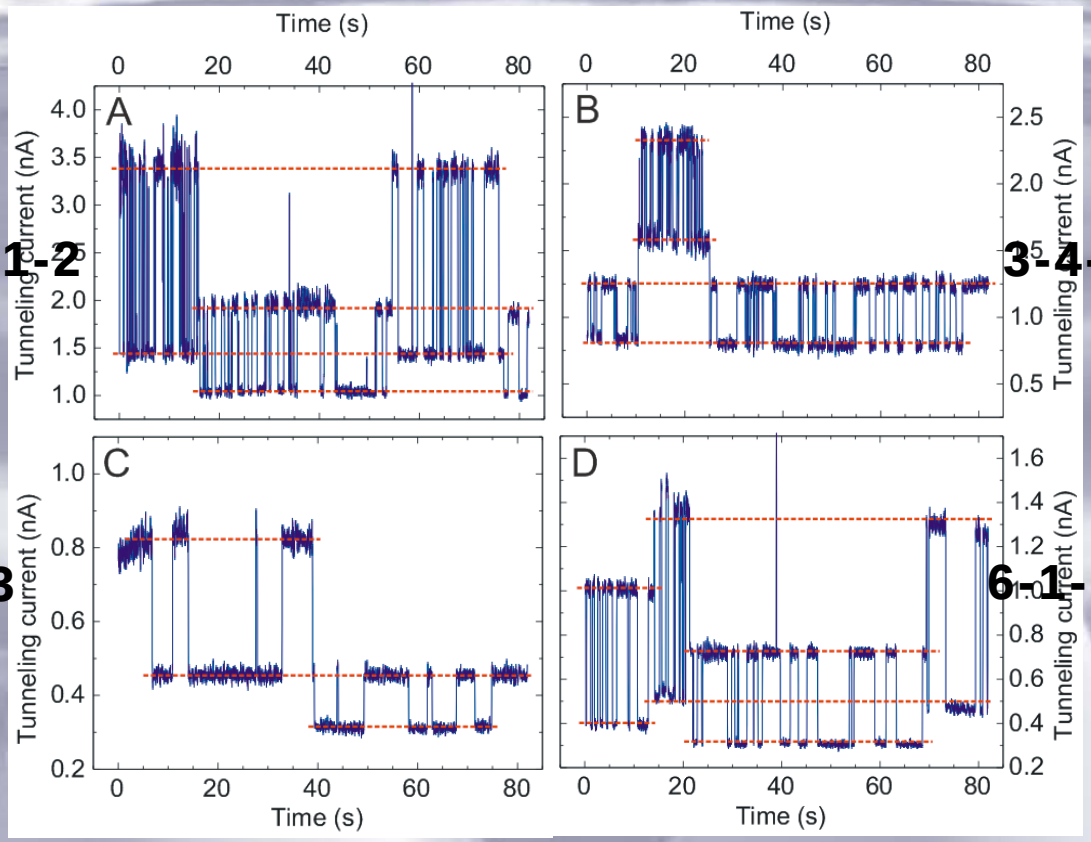
Comparison of model with results

1-2-1-2

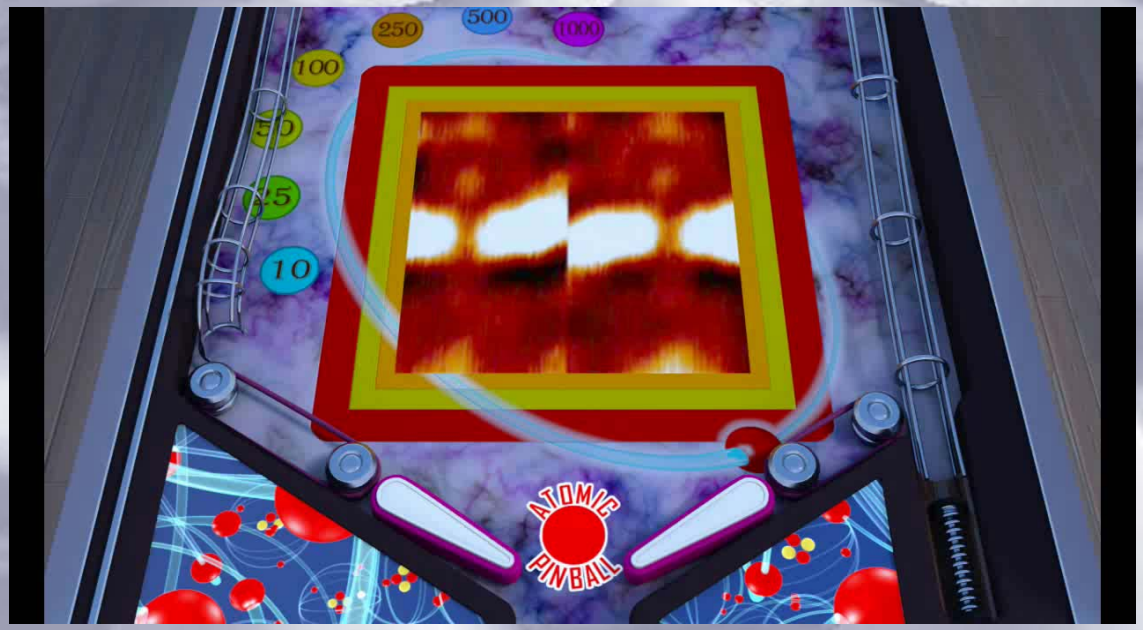
3-4-3

1-3

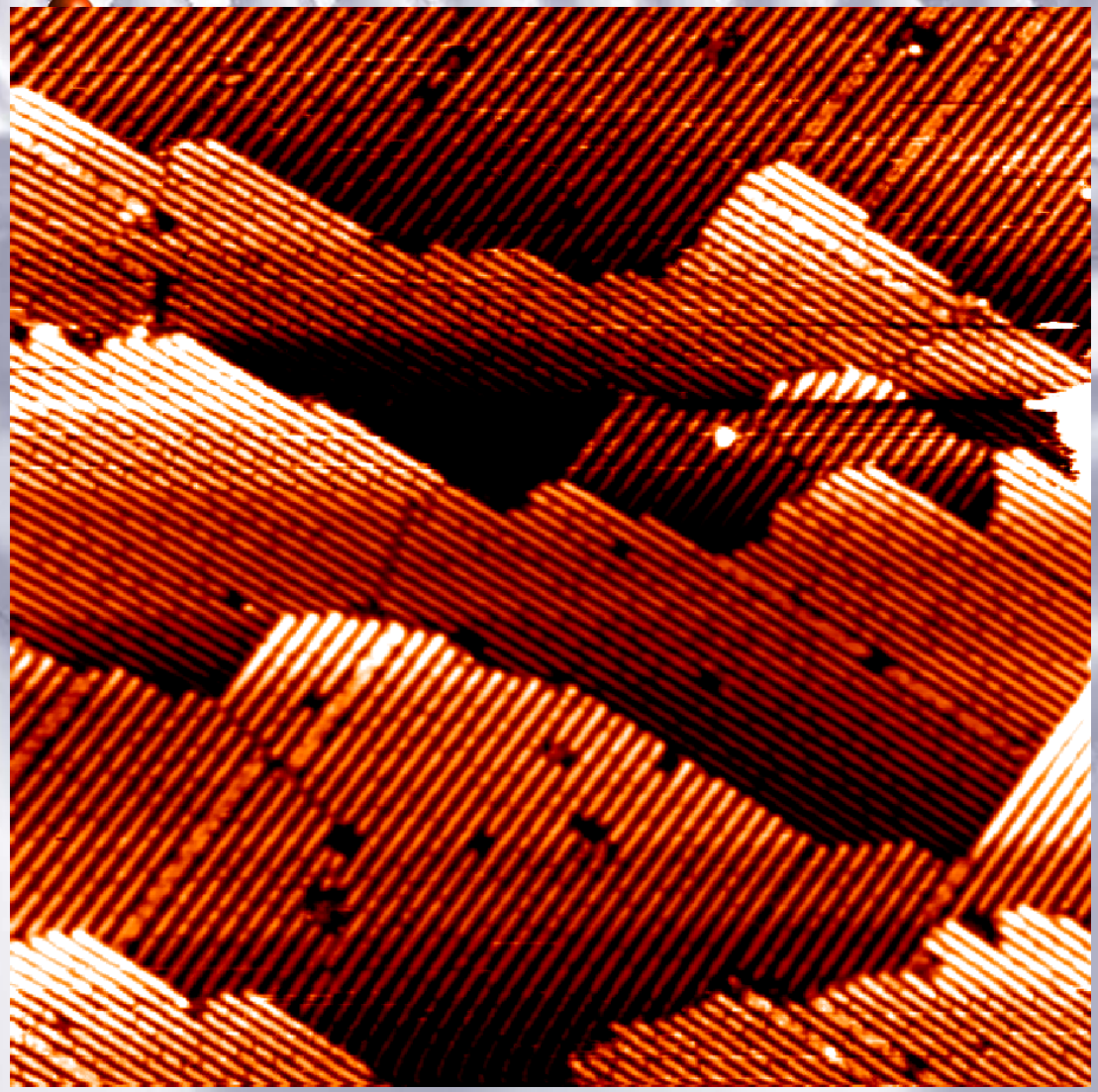
6-1-2-6

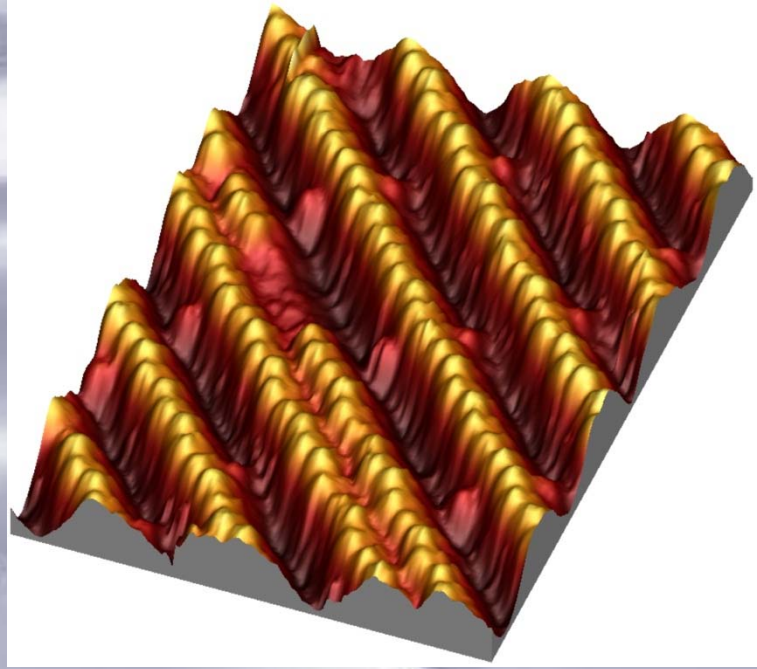


An Atomic Pinball Machine

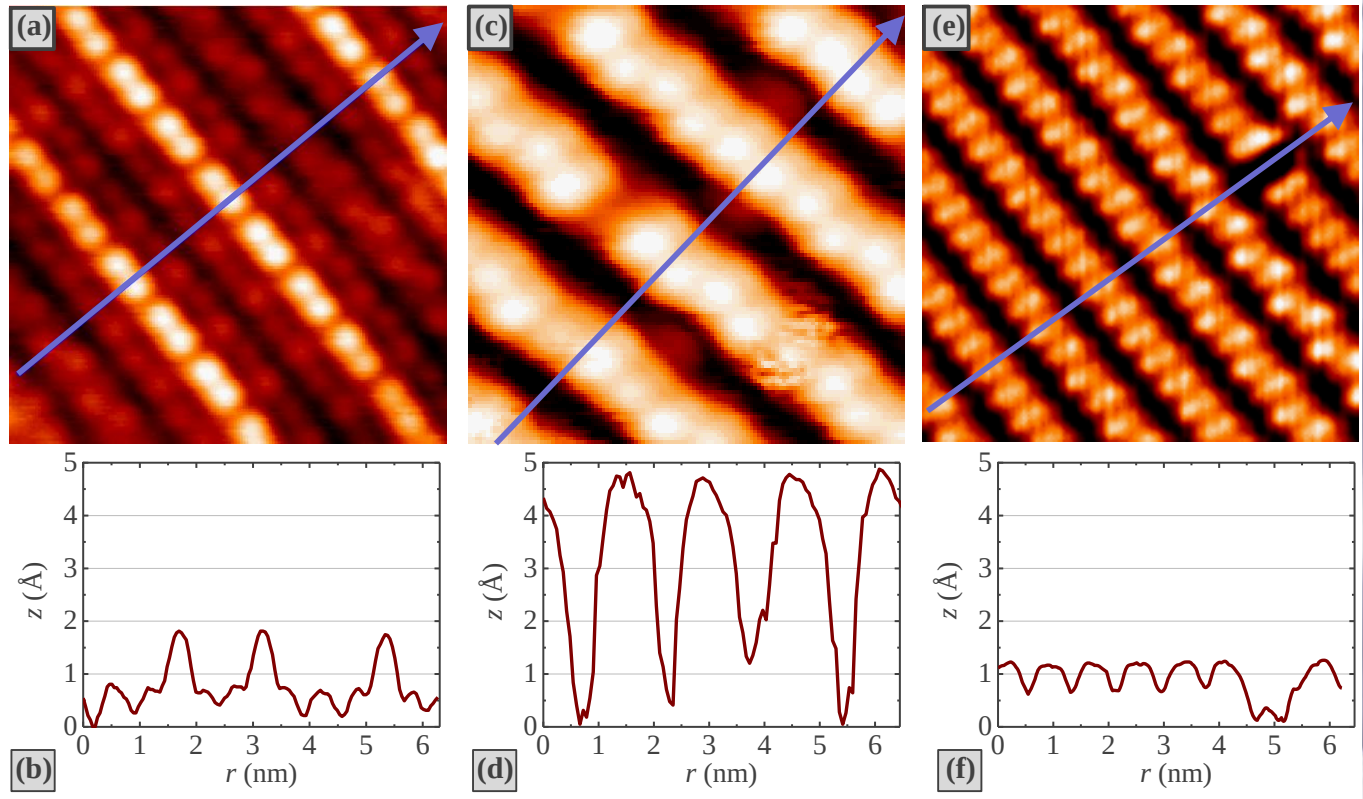


Au/Ge(001)



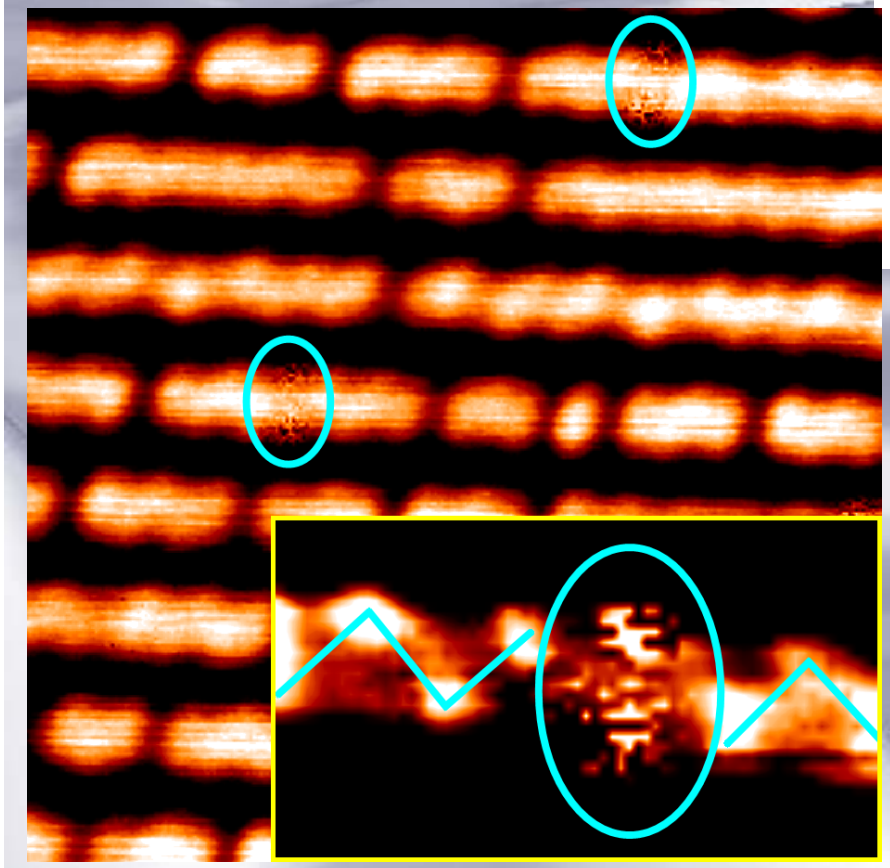


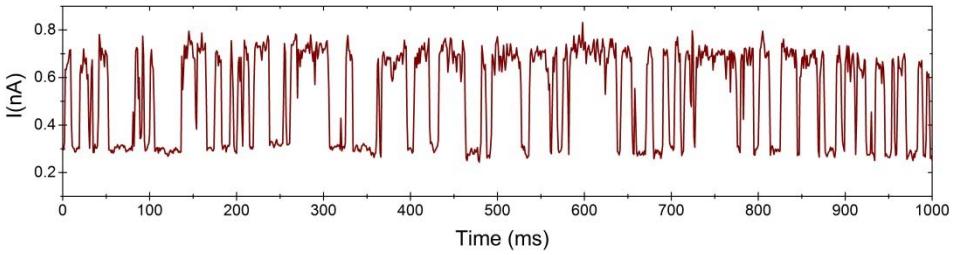
Au/Ge(001) vs Pt/Ge(001)

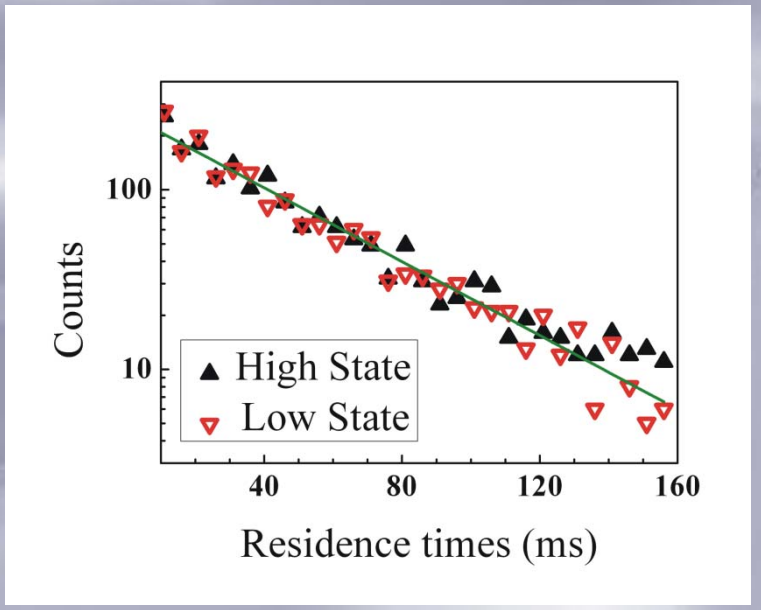


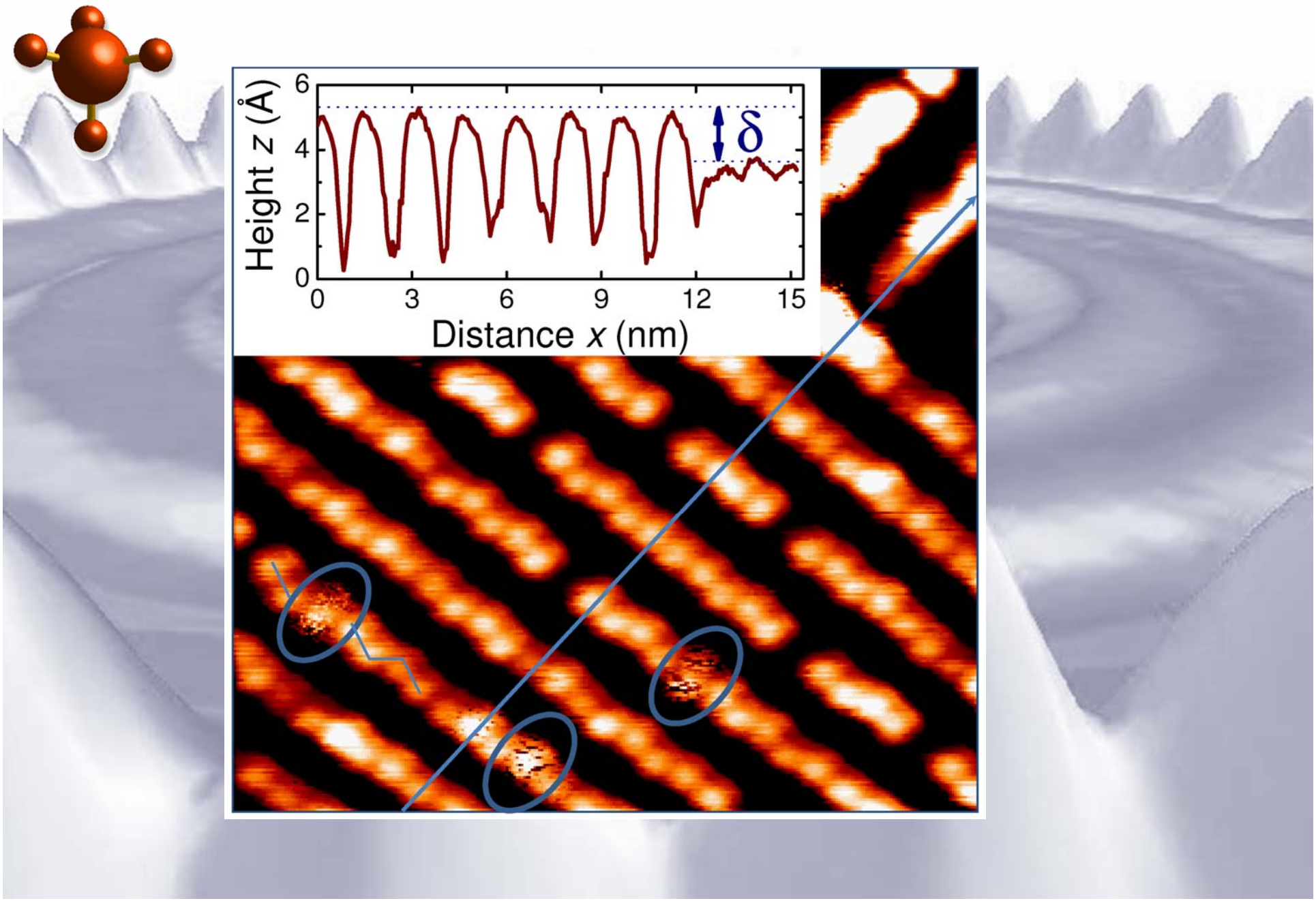
Pt/Ge(001) Au/Ge(001) clean Ge(001)

Dynamics

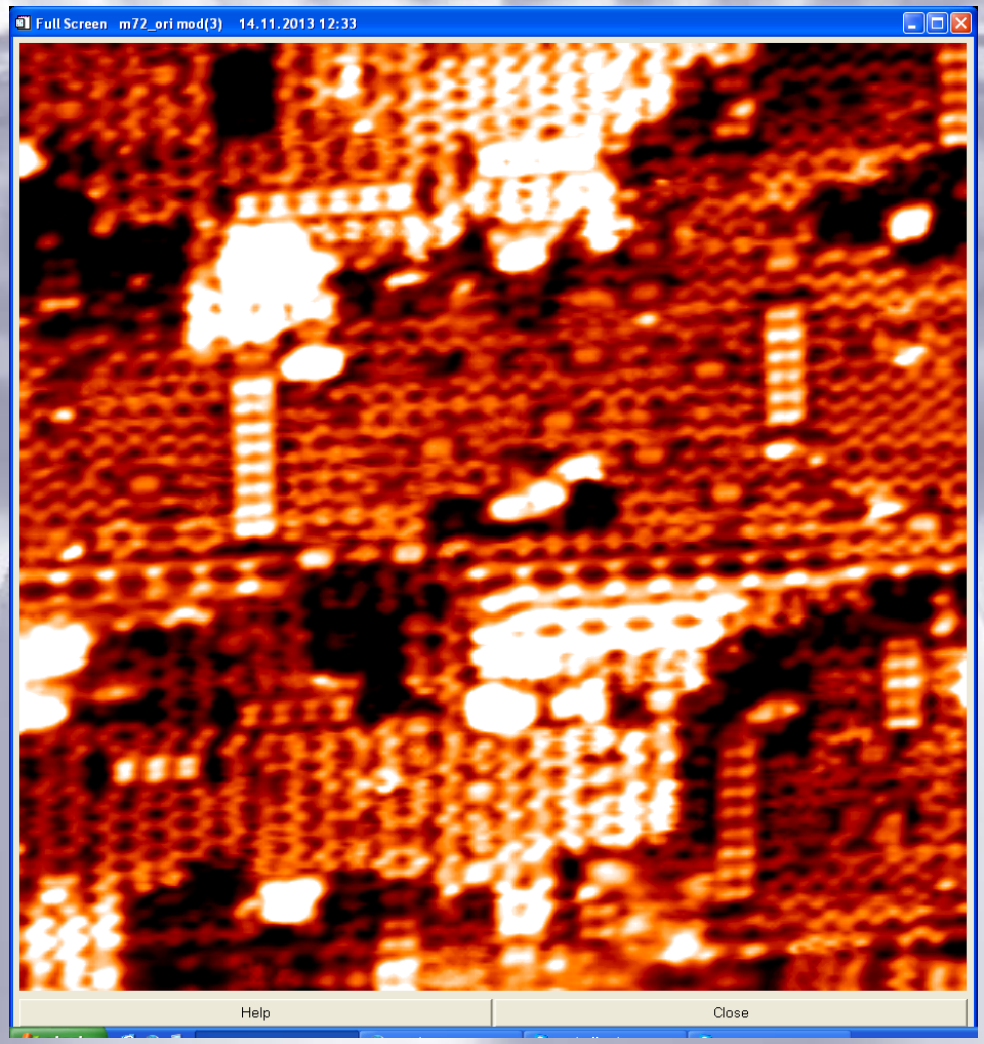



I(nA)
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
800
900
1000
Time (ms)

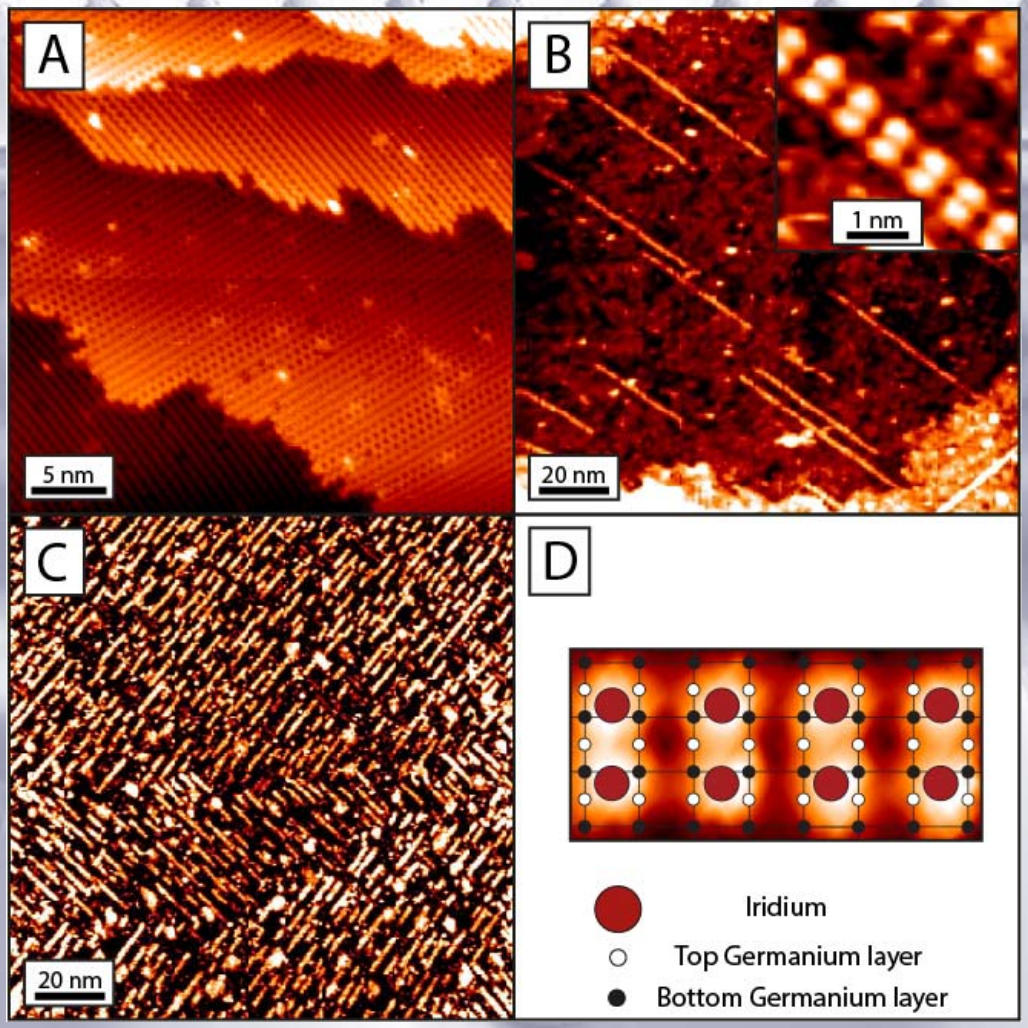

Counts
100
10
High State
Low State
40
80
120
160
Residence times (ms)


Height z (Å)
0
2
4
6
0
3
6
9
12
15
Distance x (nm)
δ

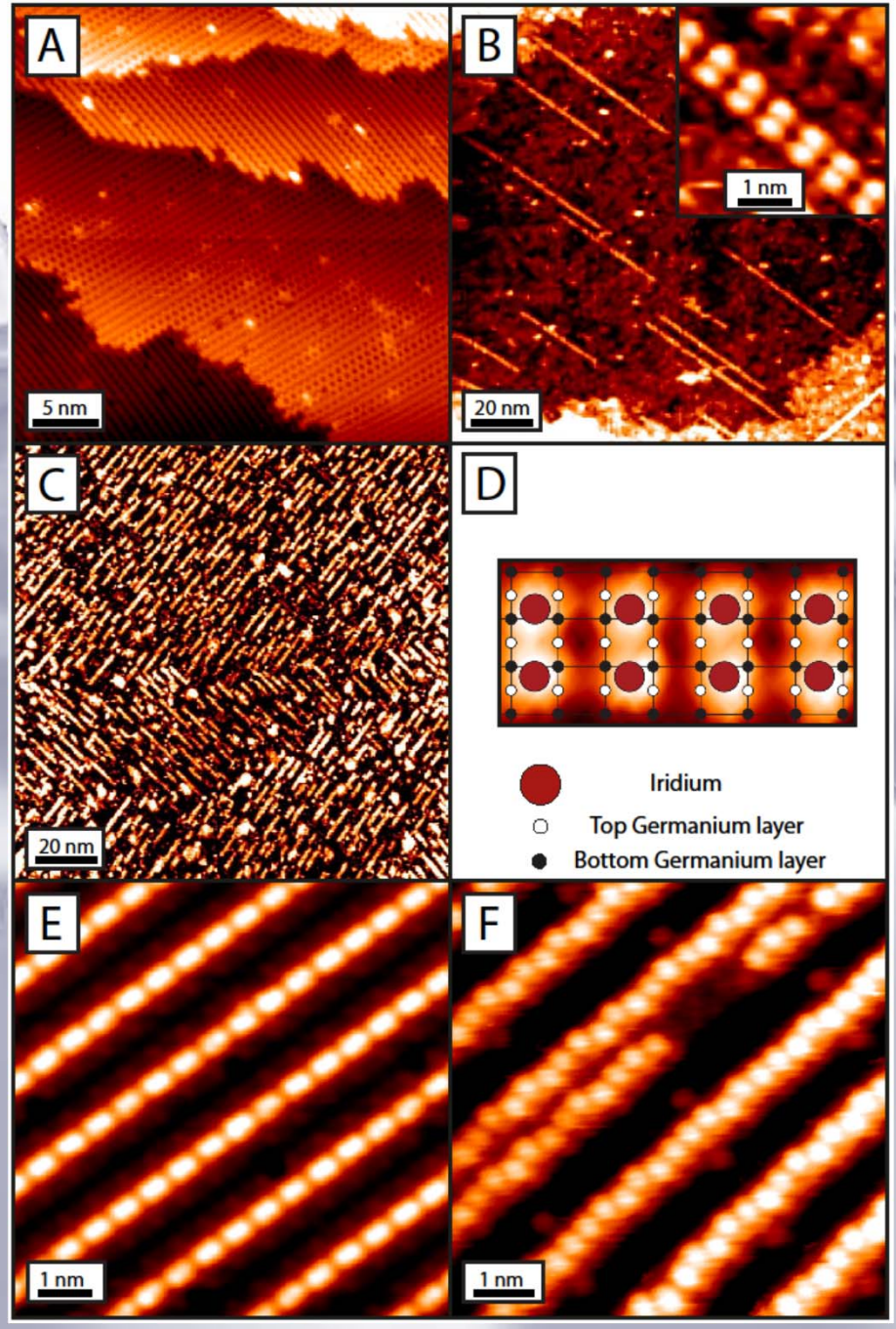
Ir quantum wires



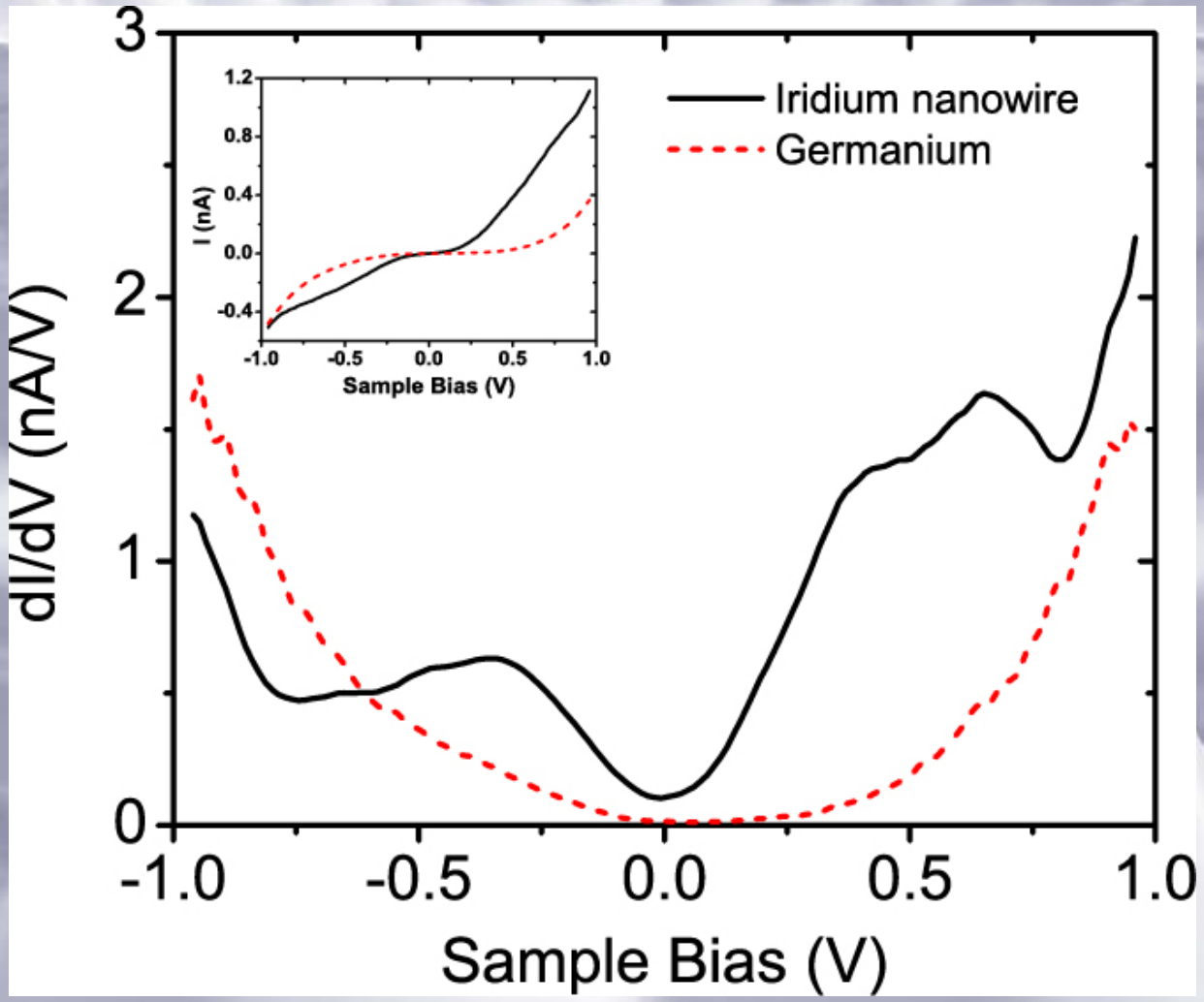
Ir nanowires on Ge(001)



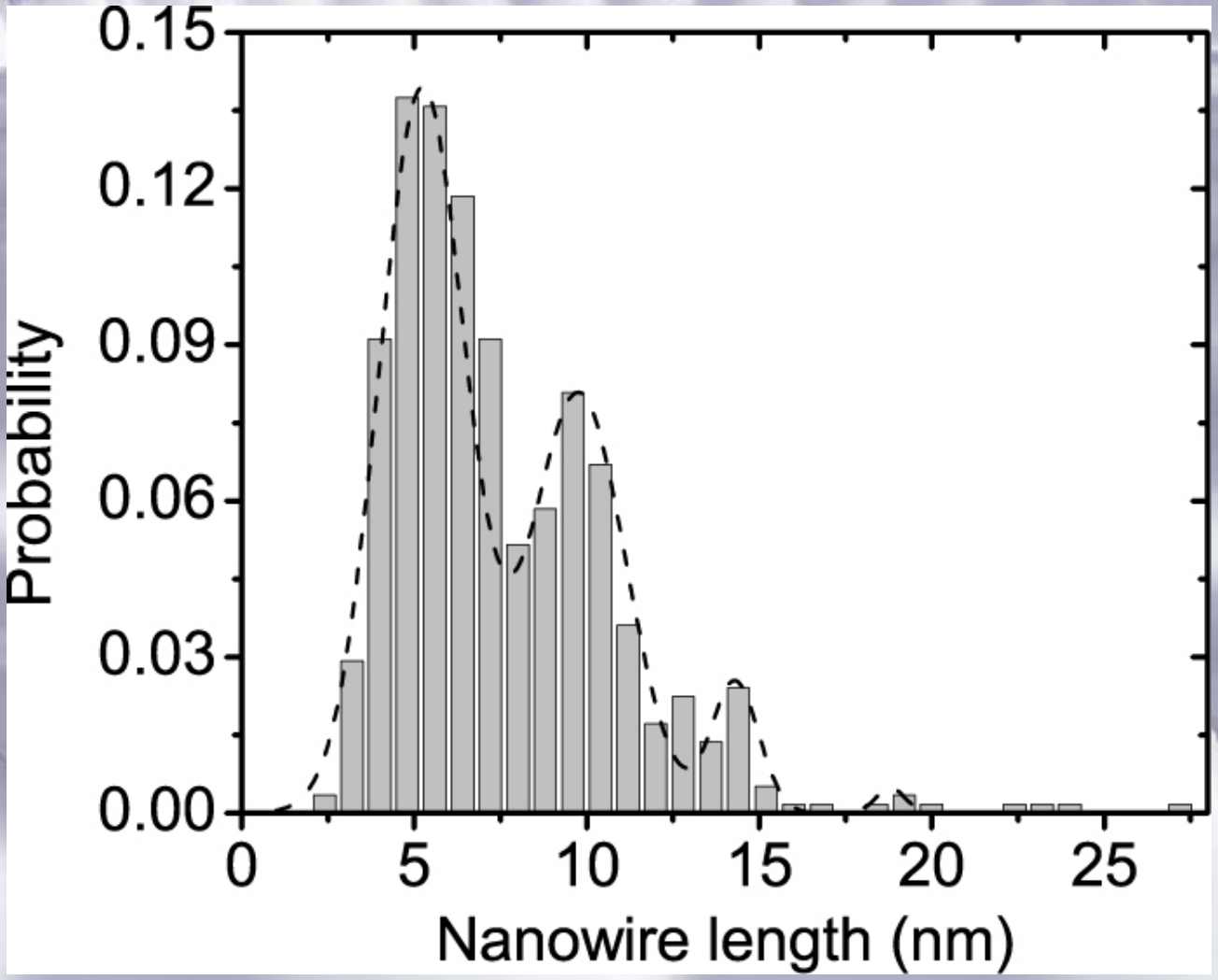
Nikolay Kabanov (MSU) July 2013


A
5 nm
B
1 nm
20 nm
C
20 nm
D
Iridium
Top Germanium layer
Bottom Germanium layer
E
1 nm
F
1 nm

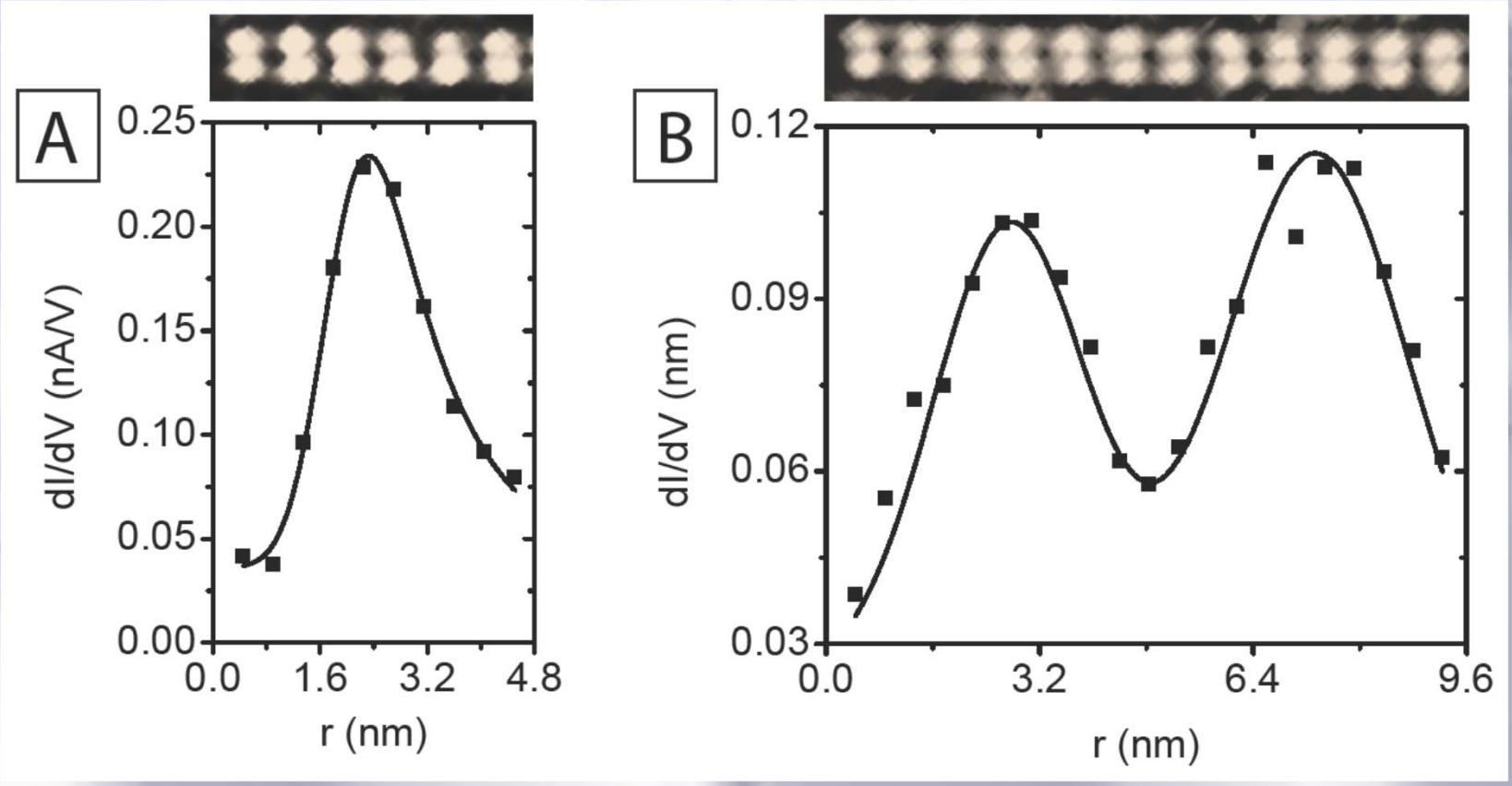
Spectroscopy



Length quantization

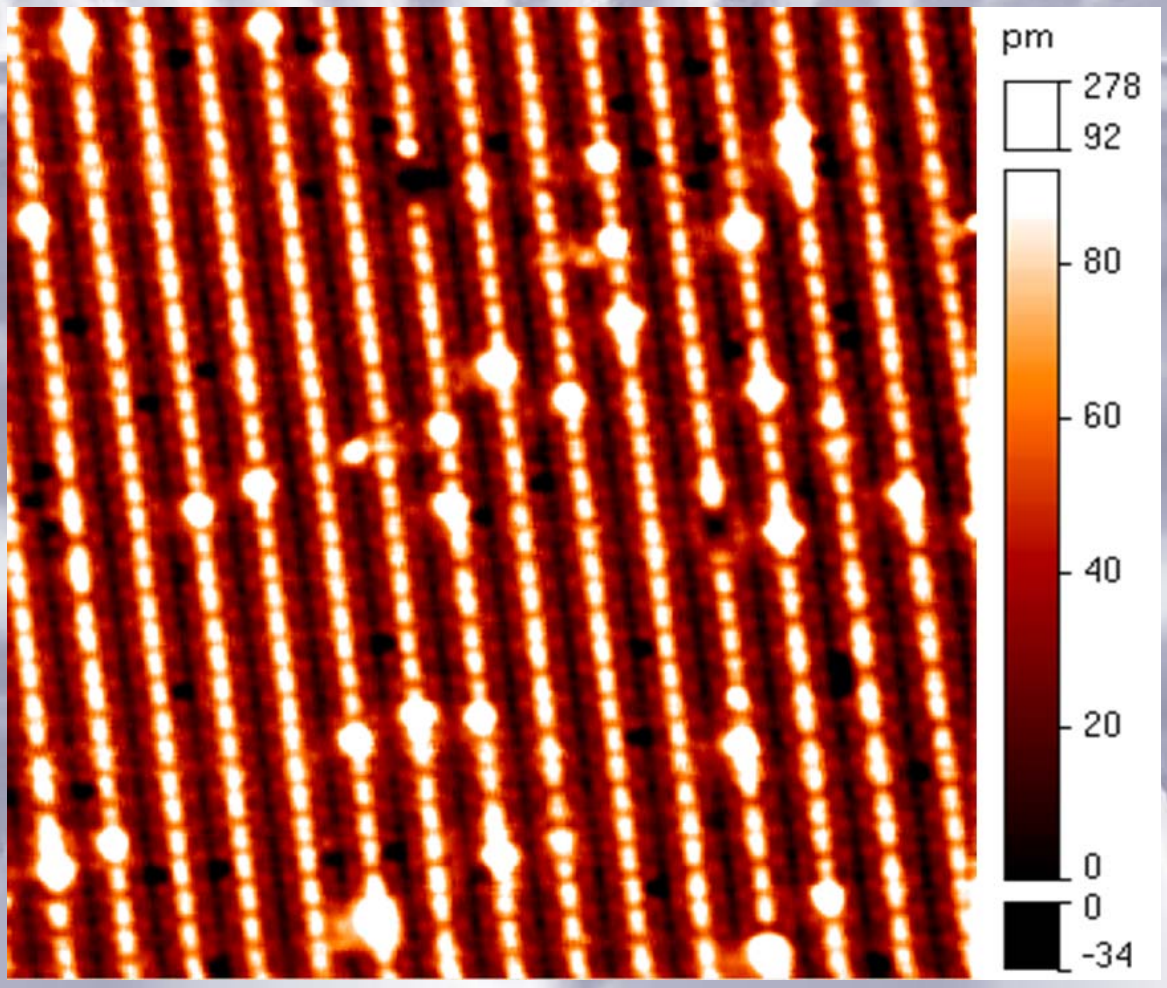


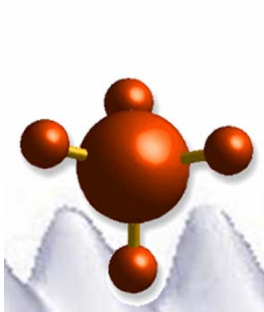
Standing wave patterns

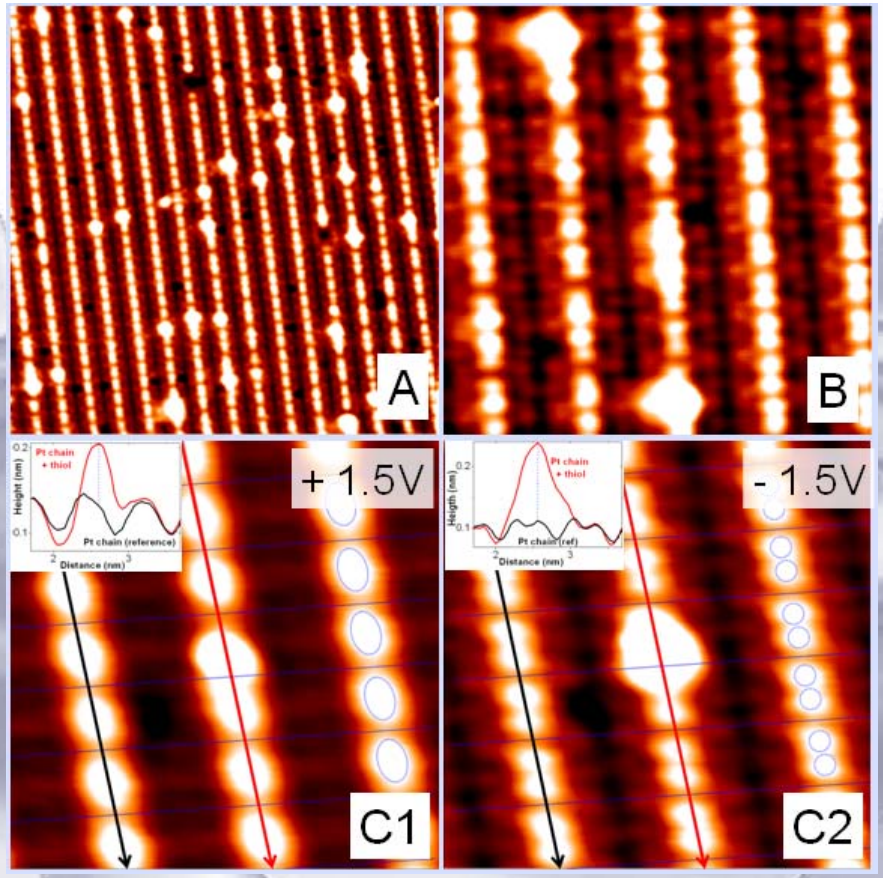


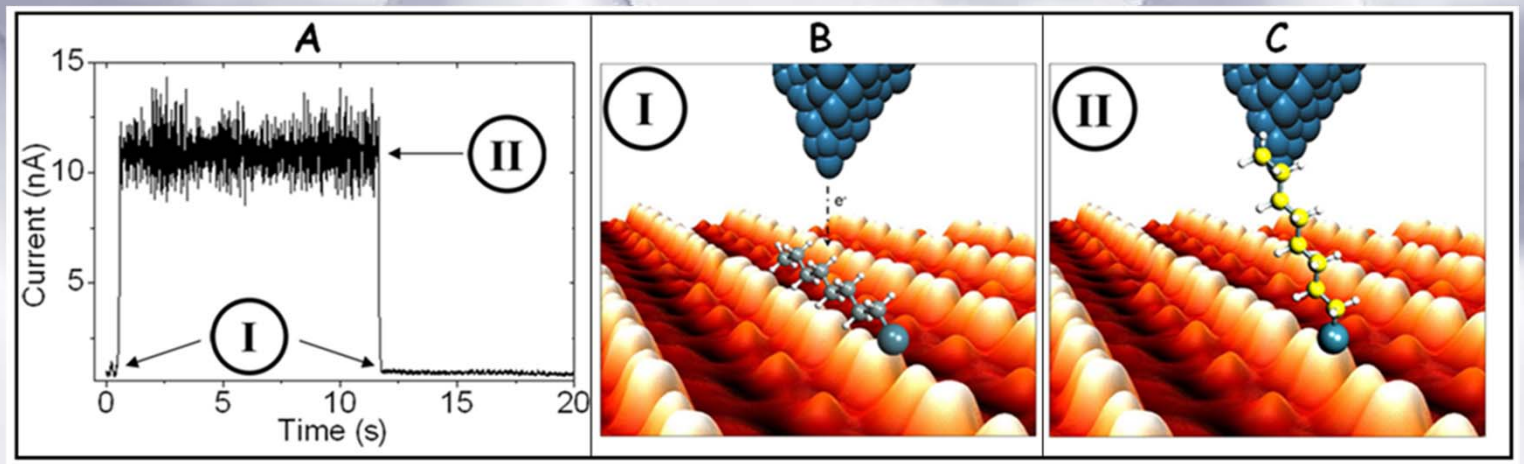
Single Molecule Switch

Octanethiols T = 77 K



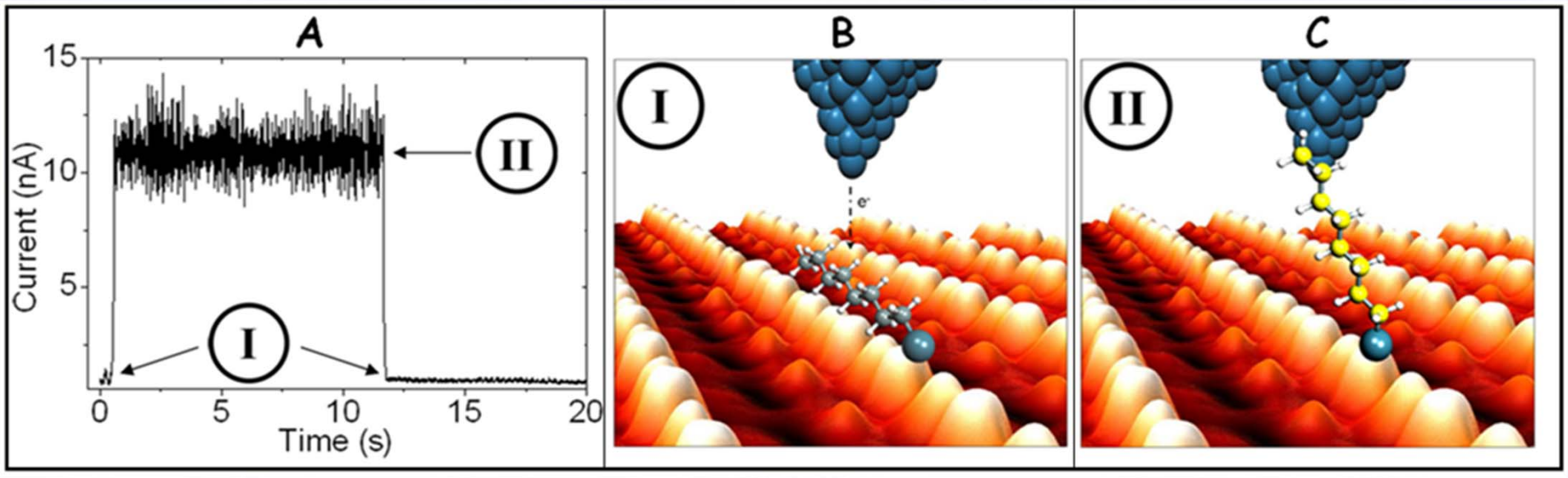



A
B
+ 1.5V
- 1.5V
C1
C2
Pt chain + thiol
Pt chain (reference)
Pt chain (ref)
Height (nm)
Distance (nm)

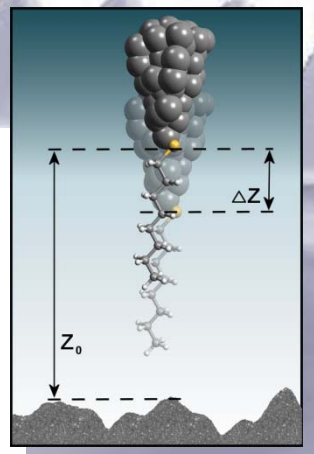

A
B
C
Current (nA)
Time (s)
I
II
e⁻

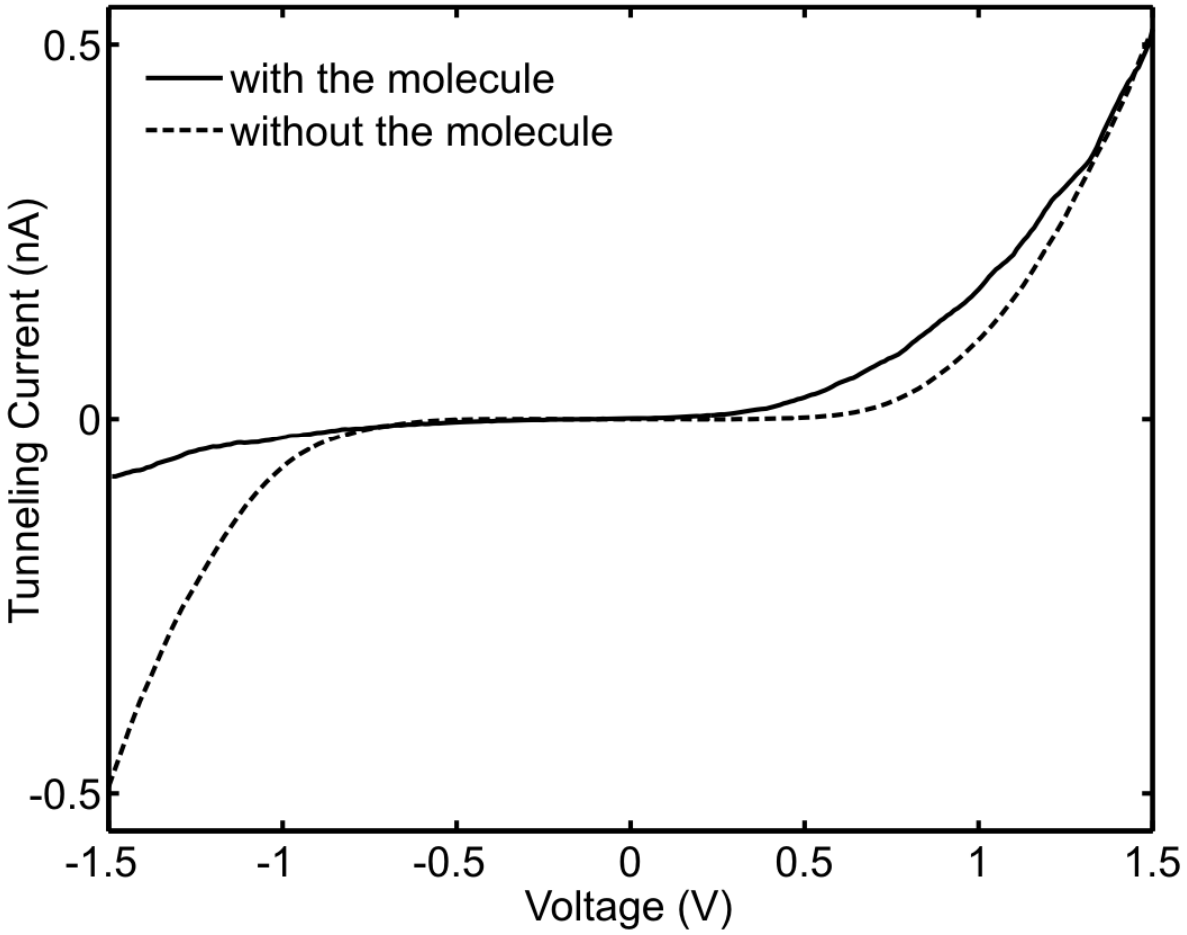
No control!

- Jump into contact occurs randomly
- High-current state is noisy

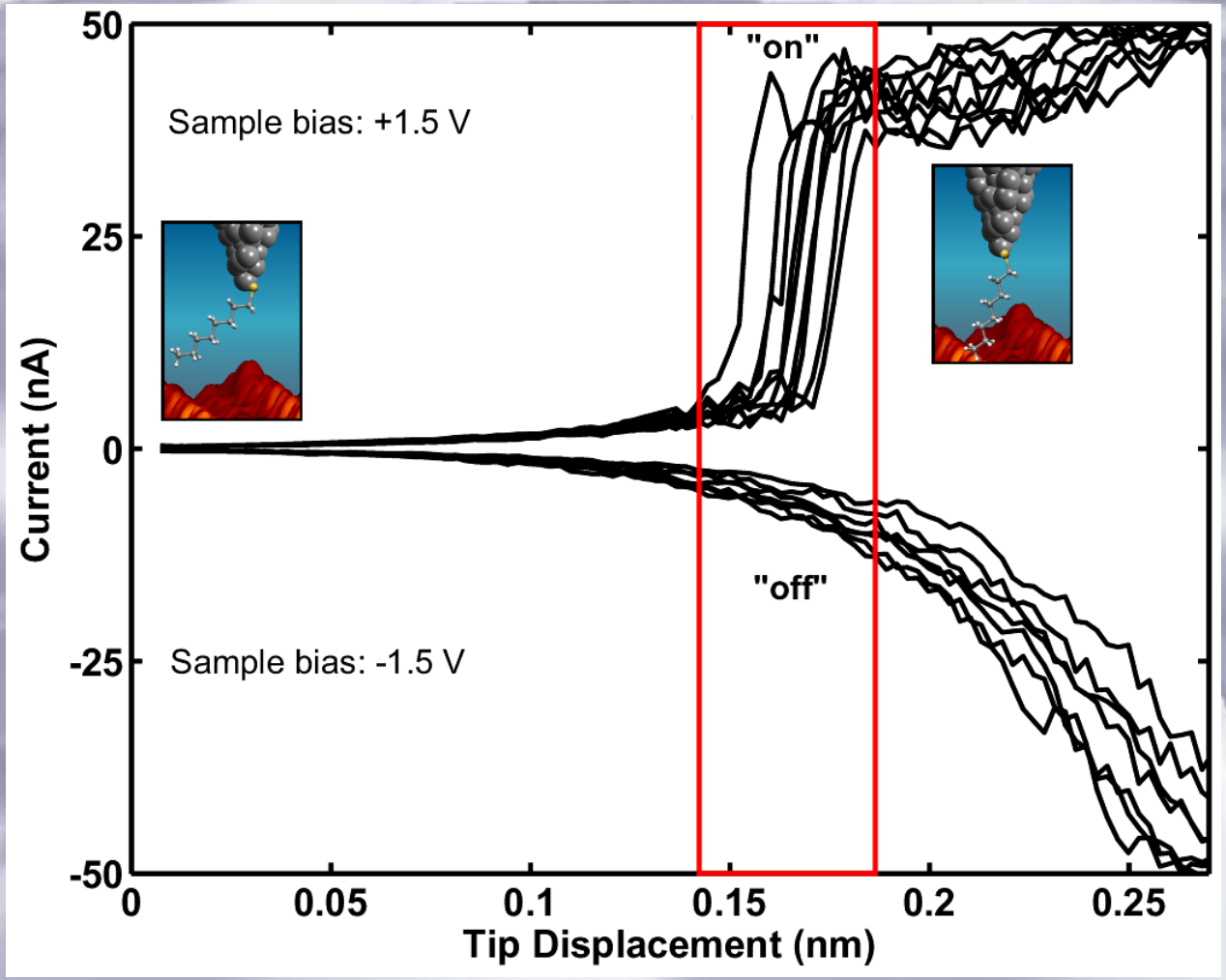


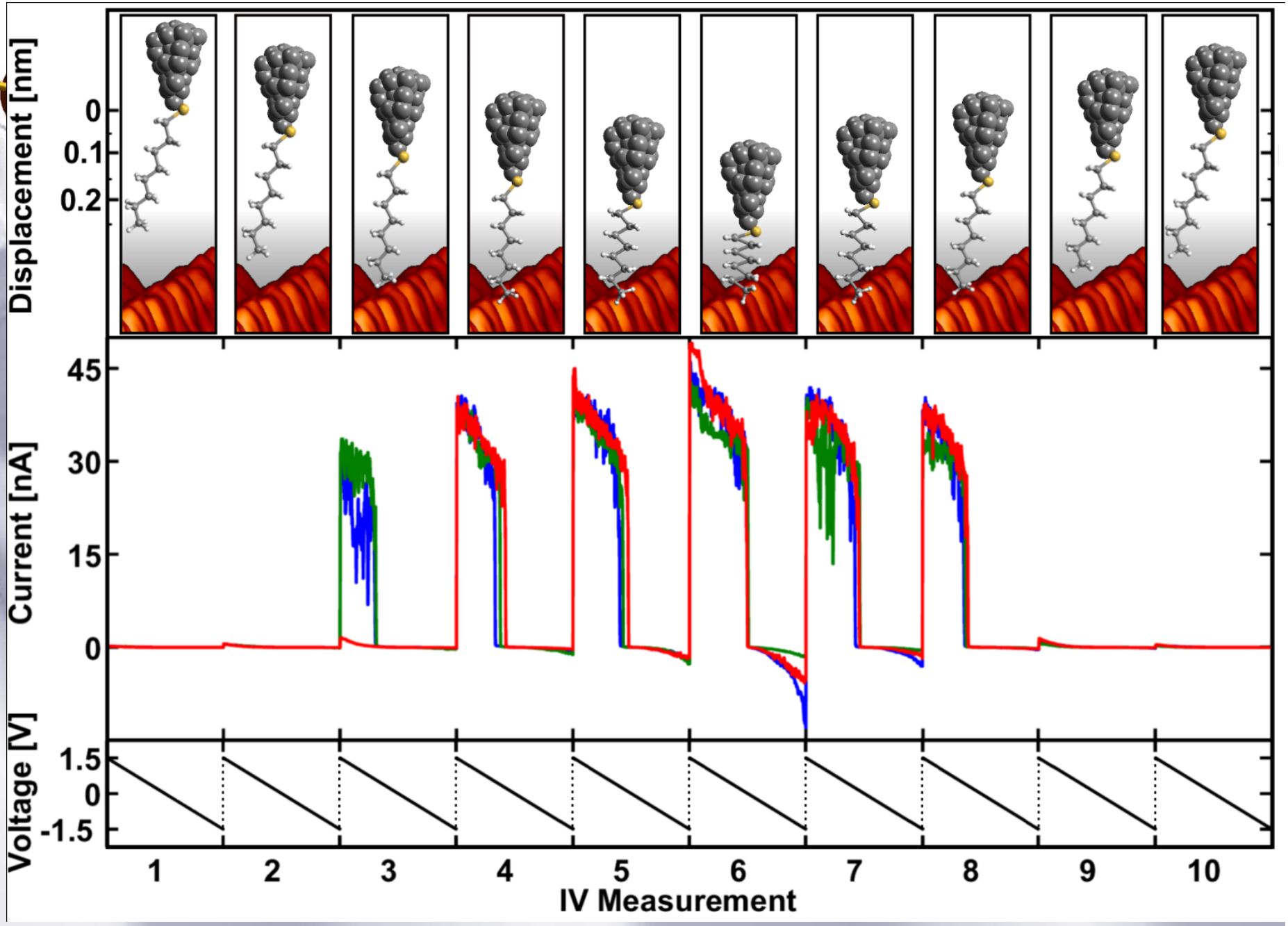
Thiol decorated STM tip



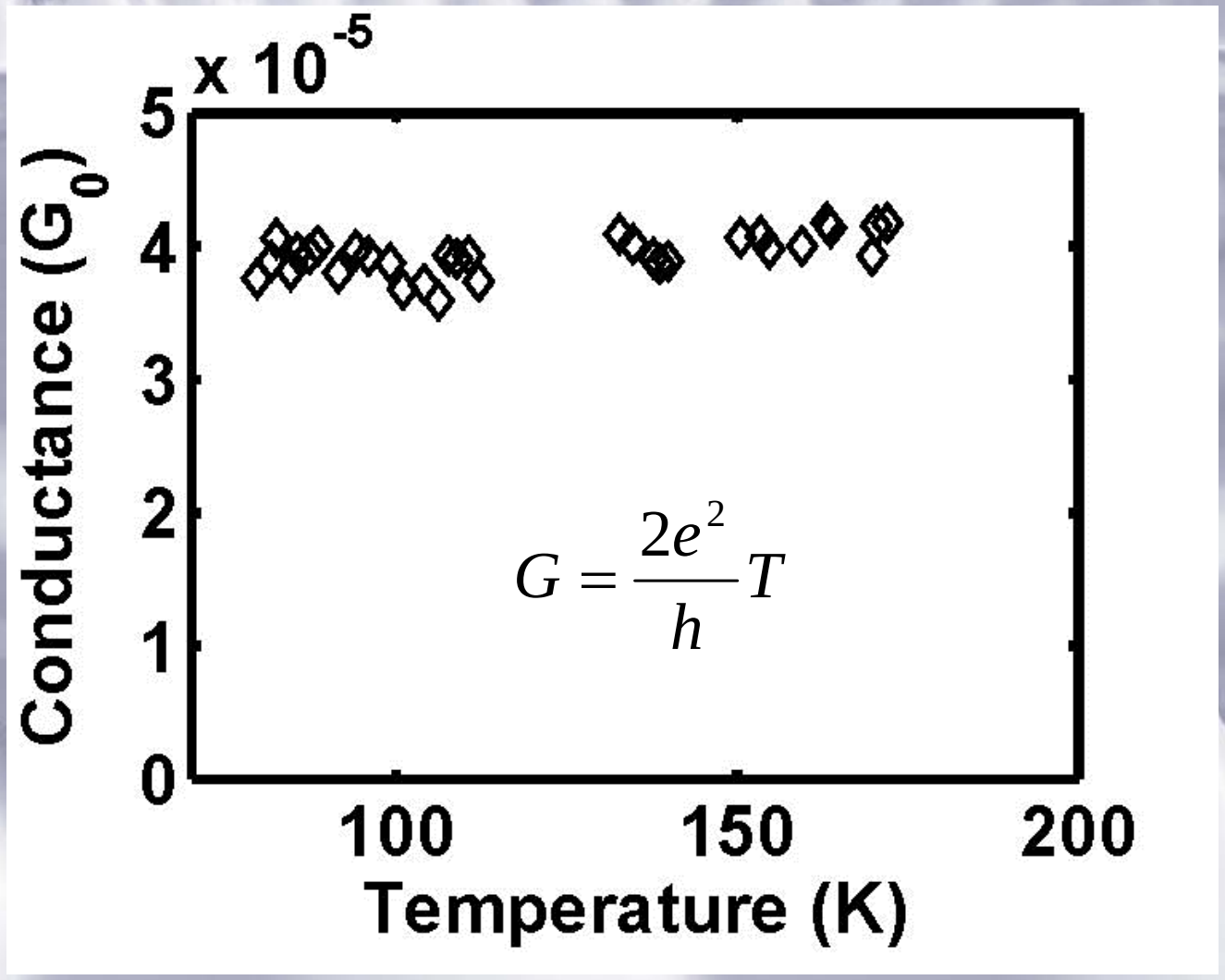


The Molecular Switch

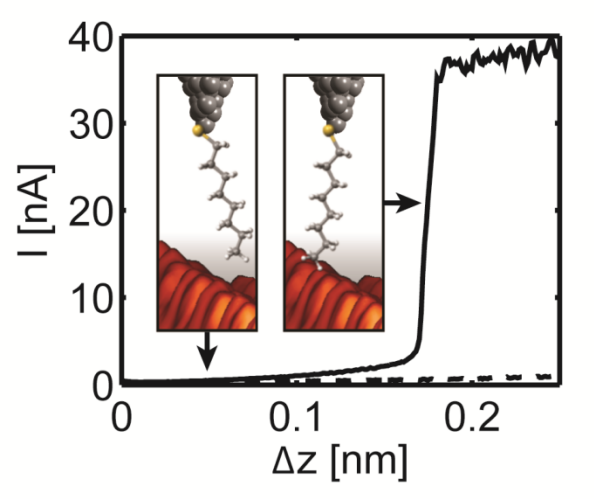


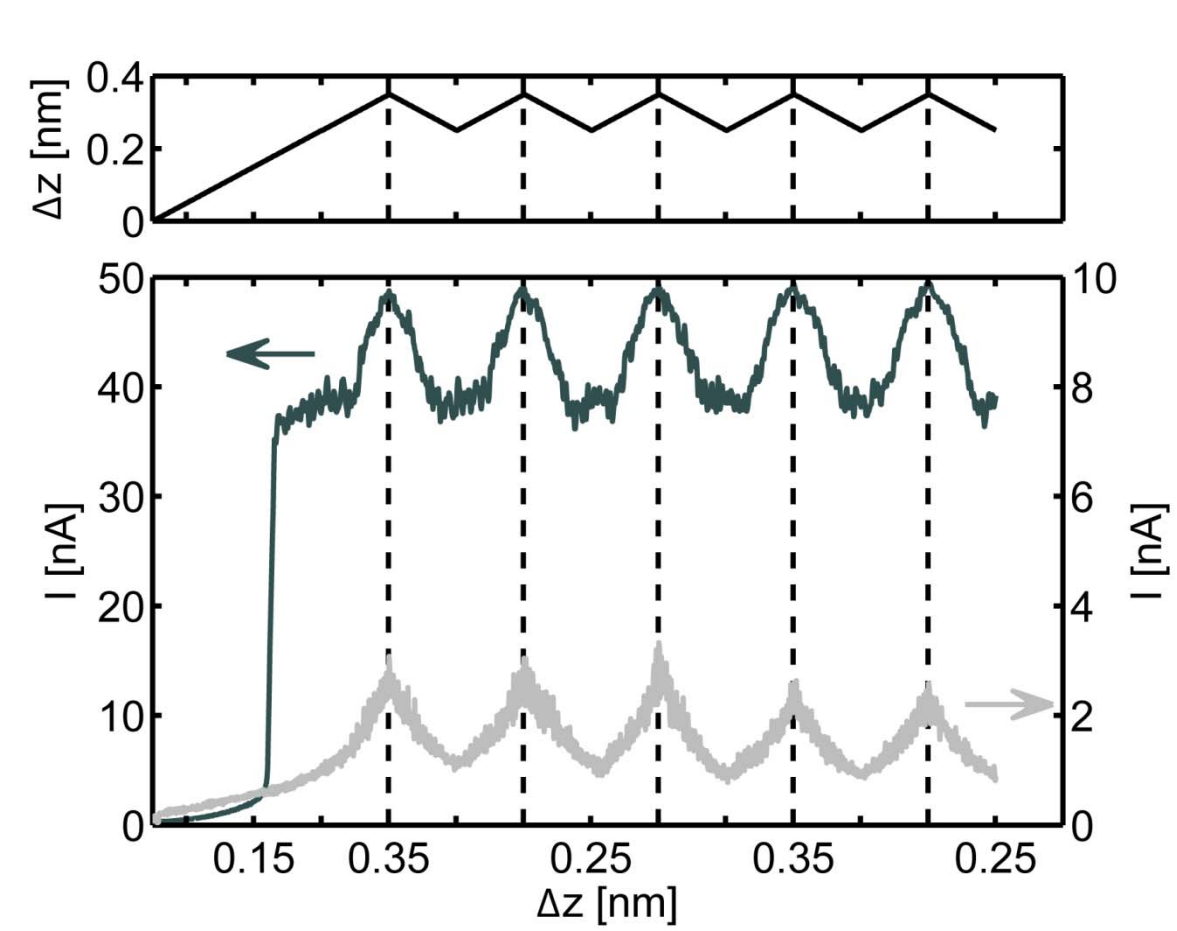

Displacement [nm]
0
0.1
0.2
Current [nA]
45
30
15
0
Voltage [V]
1.5
0
-1.5
1
2
3
4
5
6
7
8
9
10
IV Measurement

T-dependence conductance

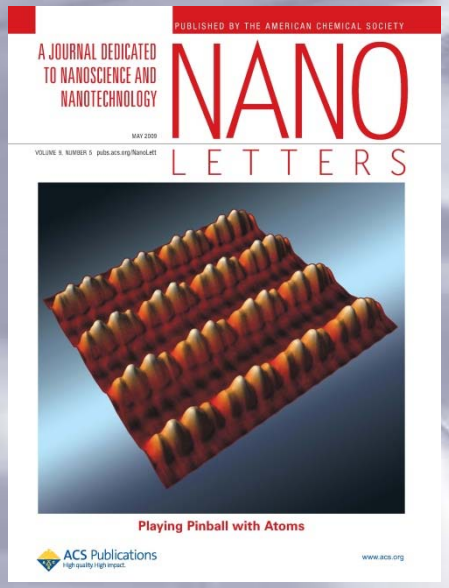


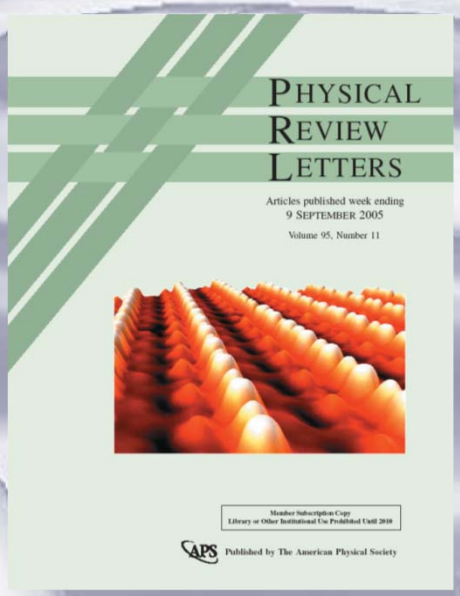
2-terminal single molecule transistor

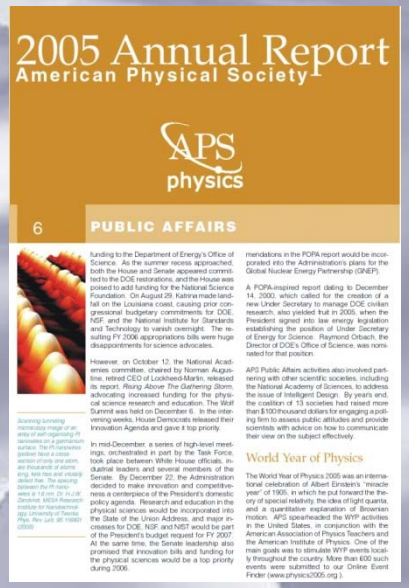




That's all folks







Acknowledgements

Arie van Houselt, Amir Saedi, Nuri Oncel, Oguzhan Gurlu, Daan Kockmann, Avijit Kumar, René Heimbuch, Tijs Mocking, Pantelis Bampoulis & Nikolay Kabanov (MSU)