Multi-probe scanning tunneling spectroscopy for in-plane electronic transport: theory and experiment

Pedro Brandimarte[1], Marek Kolmer[2,3], Hiroyo Kawai[4], Thomas Frederiksen[1,5],
Aran Garcia-Lekue[1,5], Nicolas Lorente[6], Jakub Lis[2], Rafal Zuzak[2],
Szymon Godlewski[2], Christian Joachim[7], Marek Szymonski[2], Daniel Sánchez-Portal[1,6]

1 *Donostia International Physics Center, Spain*
2 *NANOSAM - Jagiellonian University, Poland*
3 *CNMS – Oak Ridge National Laboratory, USA*
4 *IMRE – National University of Singapore, Singapore*
5 *IKERBASQUE, Basque Foundation for Science, Spain*
6 *Centro de Física de Materiales CSIC-UPV/EHU, Spain*
7 *CEMES-CNRS, France*

October 3, 2019

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1 *Donostia International Physics Center, Spain*
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3 *CNMS – Oak Ridge National Laboratory, USA*
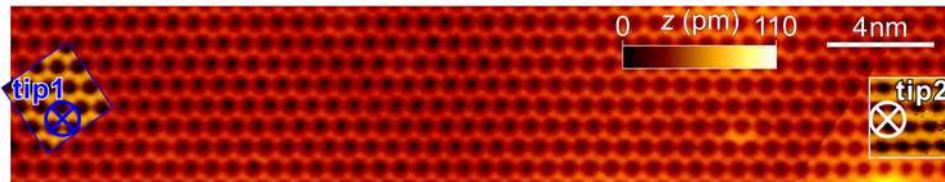4 *IMRE – National University of Singapore, Singapore*
5 *IKERBASQUE, Basque Foundation for Science, Spain*
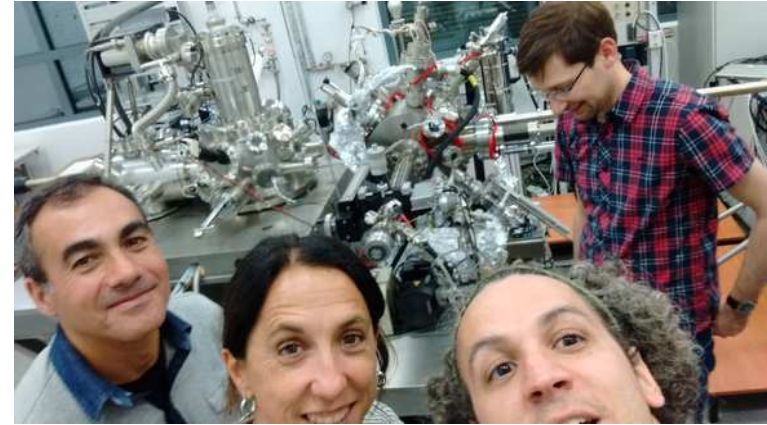6 *Centro de Física de Materiales CSIC-UPV/EHU, Spain*
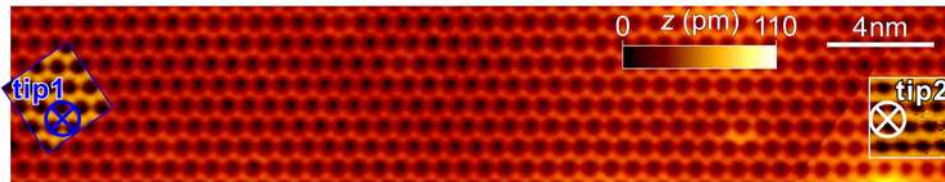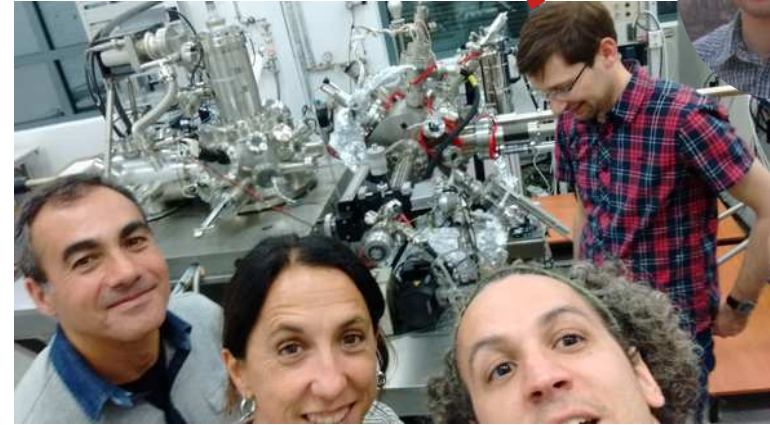7 *CEMES-CNRS, France*

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Two-probe STM at the atomic level

Two-probe STM at the atomic level

V_1

I_1

GND

I_2

GND

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CRACOVIENSIS
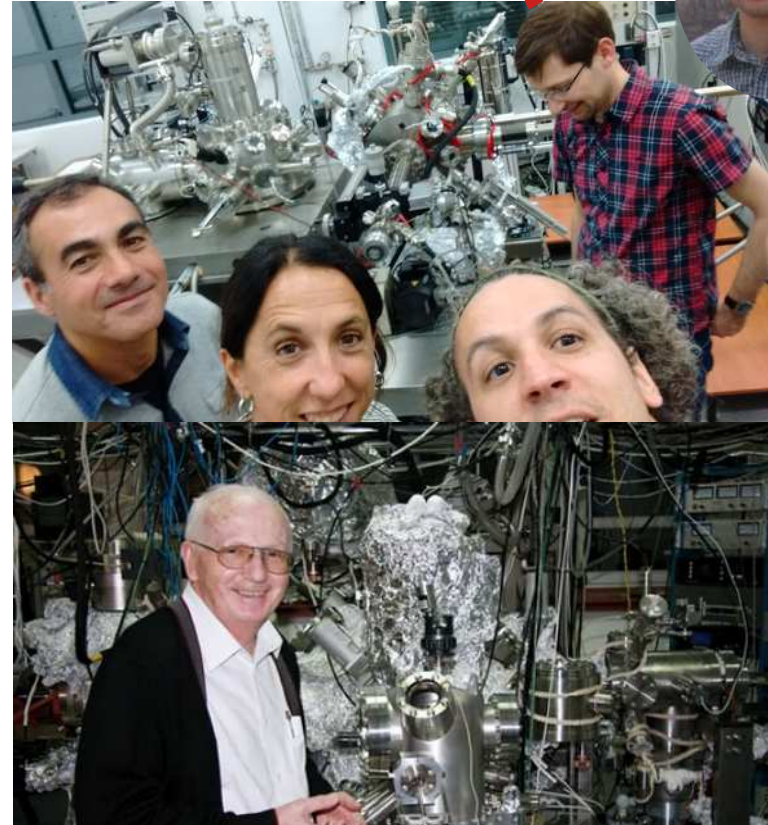
0 z (pm) 110   4nm

tip1

tip2

M. Kolmer *et al*. *J. Phys: Cond. Mat.* **29**, 444004 (2017).

Two-probe STM at the atomic level

M. Kolmer *et al*. *J. Phys: Cond. Mat.* **29**, 444004 (2017).

Two-probe STM at the atomic level
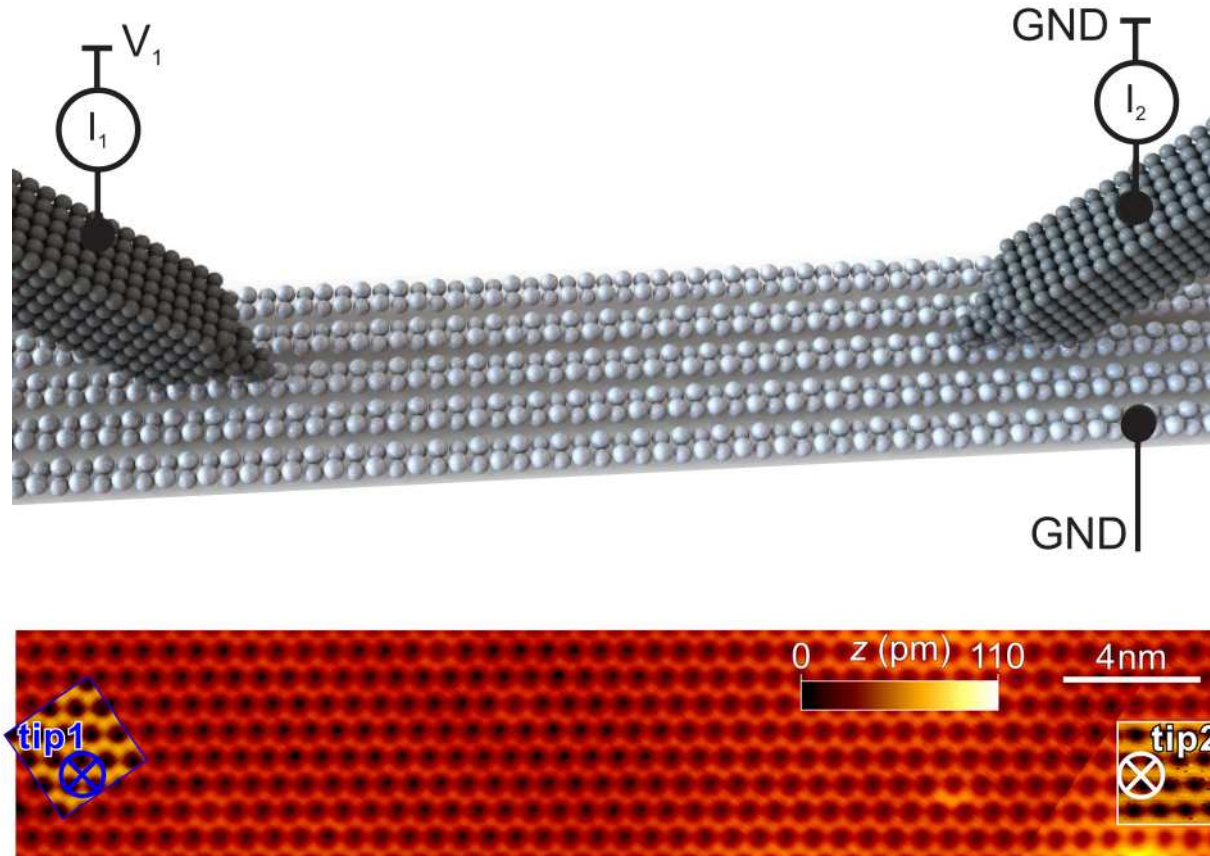
Two-probe STM at the atomic level
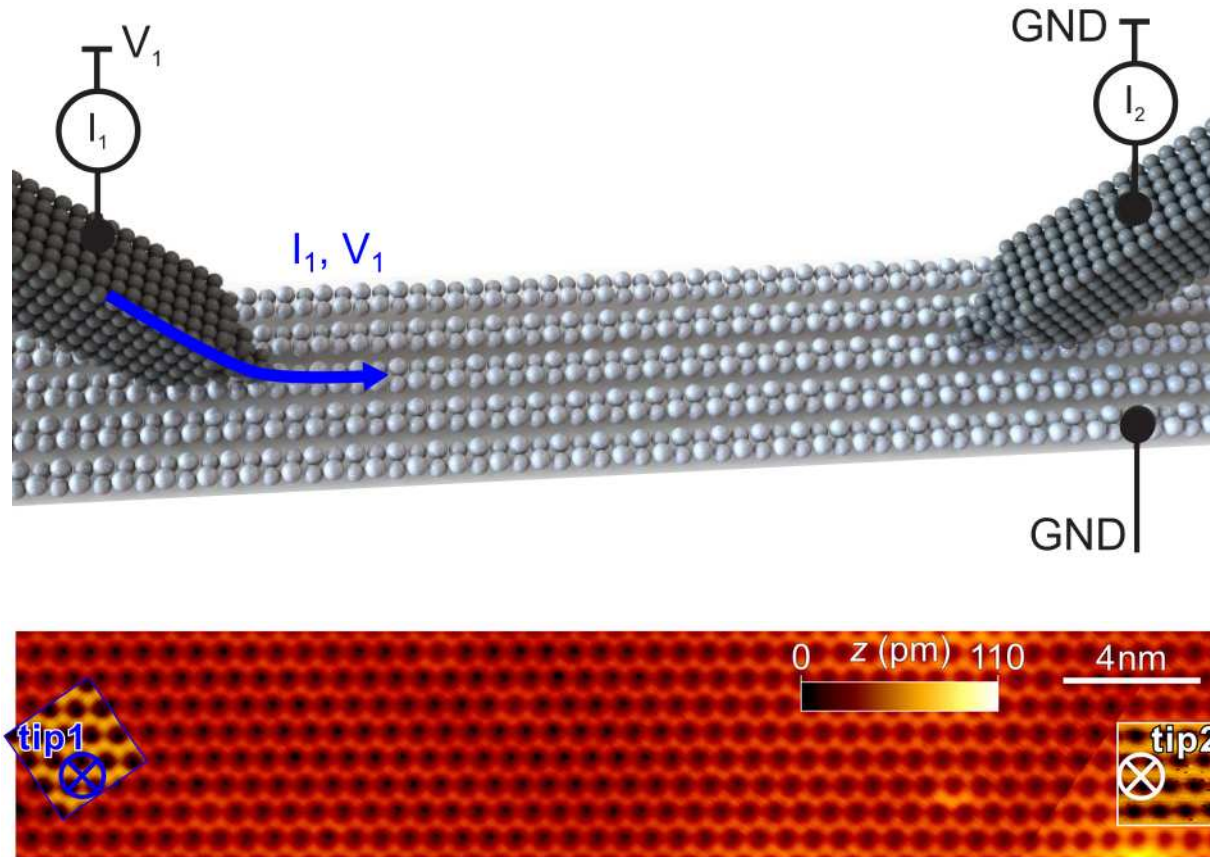
Two-probe STM at the atomic level
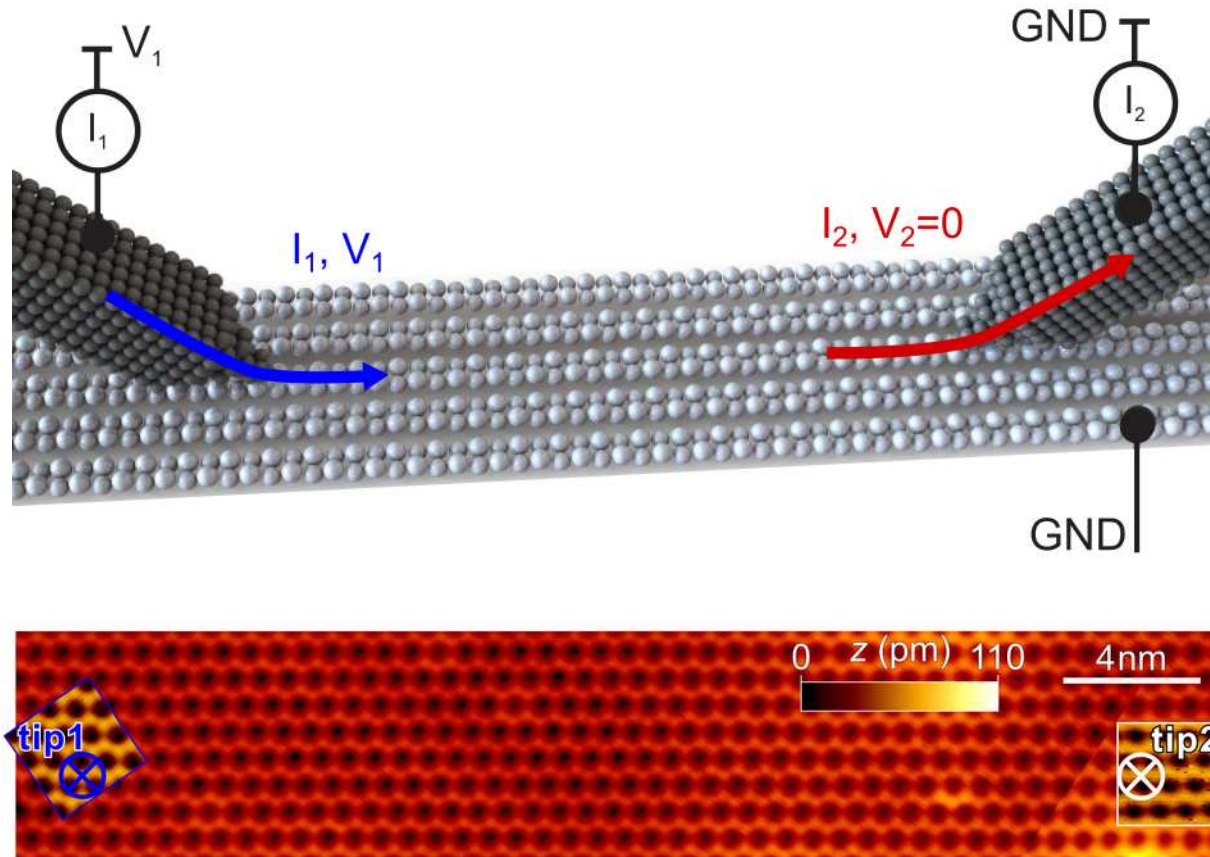
Methods

Density-Functional Theory (DFT)

SIESTA

E. Artacho *et al*. *Phys. Stat. Sol.* (b) **215**, 809 (1999).

J. M. Soler *et al*. *J. Phys. Condens. Matter.* **14**, 2745 (2002).

Methods

Density-Functional Theory (DFT)

\+

Non-Equilibrium Green's Function (NEGF)

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M. Brandbyge *et al*. *Phys. Rev. B* **65**, 165401 (2002).

N. Papior *et al*. *Comp. Phys. Comm.* **212**, 8 (2017).

Methods

Density-Functional Theory (DFT)

+

Non-Equilibrium Green's Function (NEGF)

TranSIESTA

Multi-terminal!!!

E. Artacho *et al. Phys. Stat. Sol.* (b) **215**, 809 (1999).

J. M. Soler *et al. J. Phys. Condens. Matter.* **14**, 2745 (2002).

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N. Papior *et al. Comp. Phys. Comm.* **212**, 8 (2017).

Ge(001)x(4x2) surface
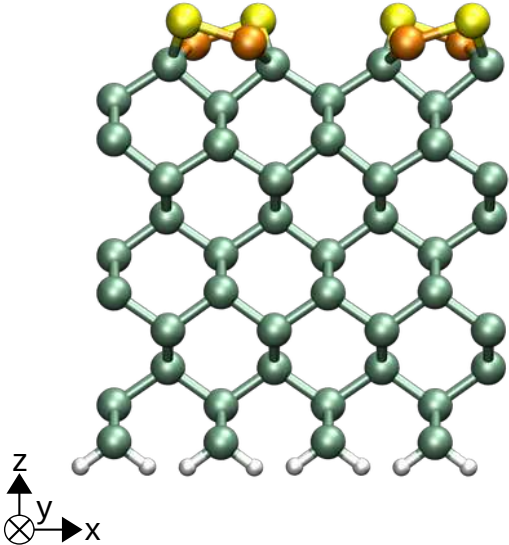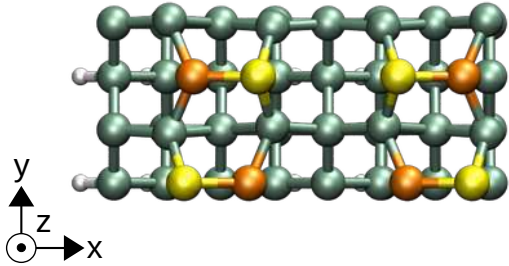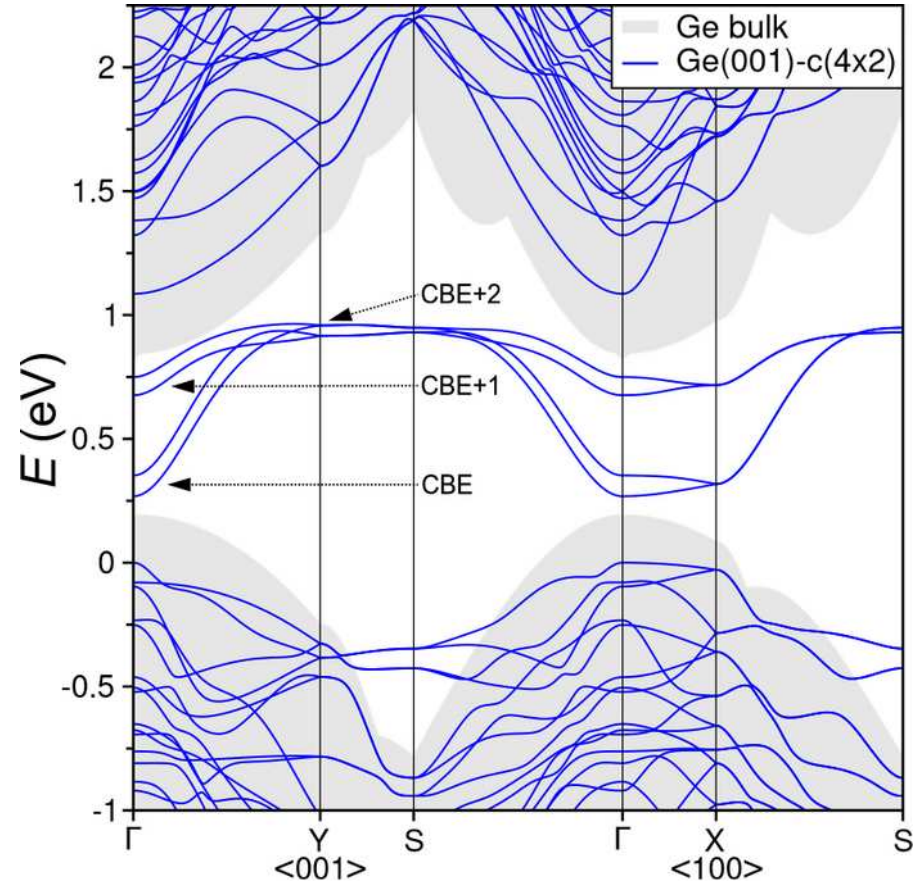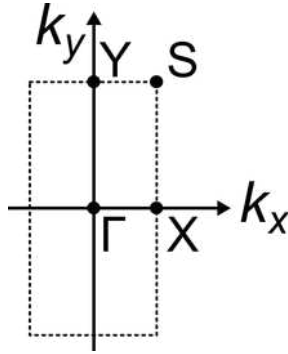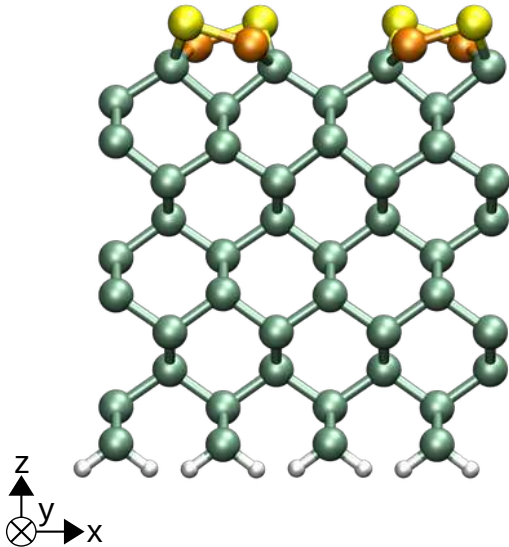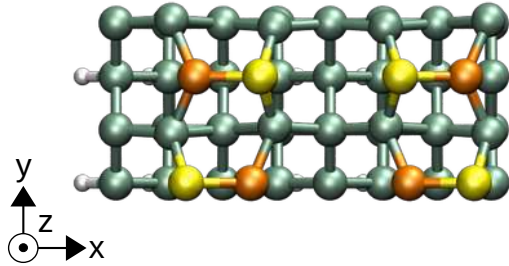
Ge(001)x(4x2) surface
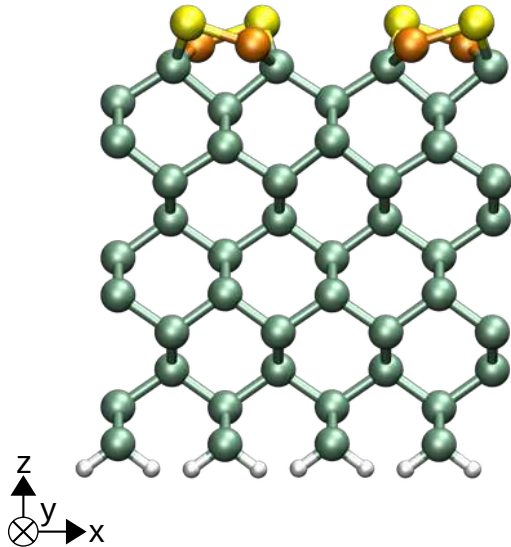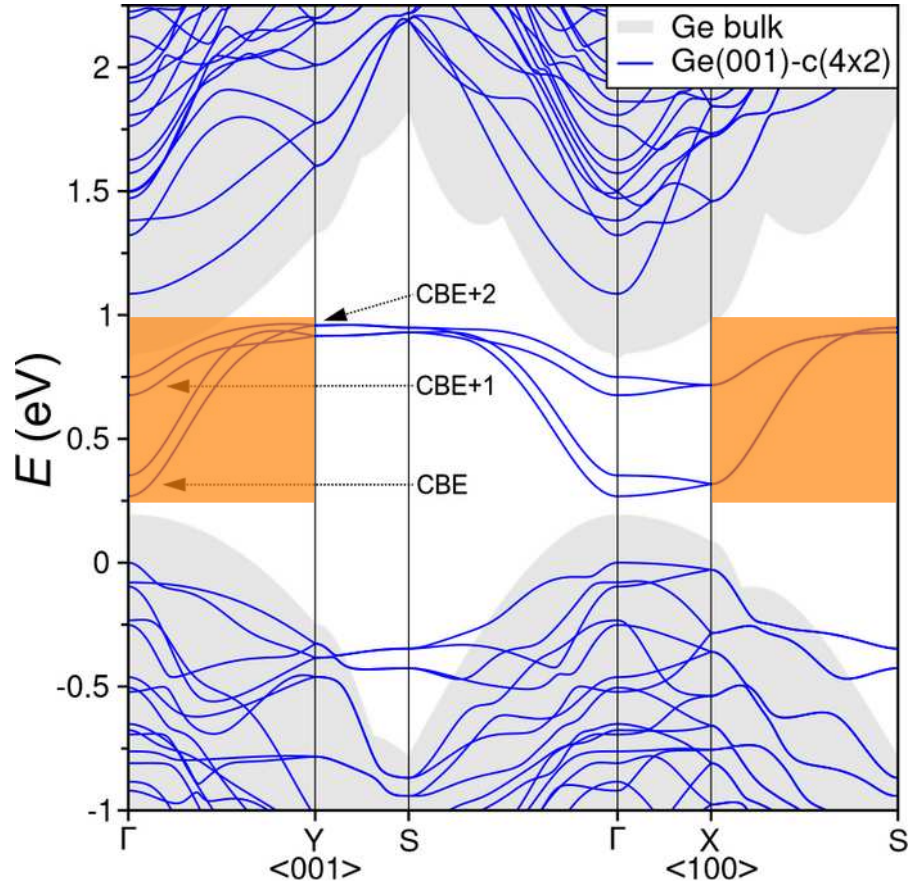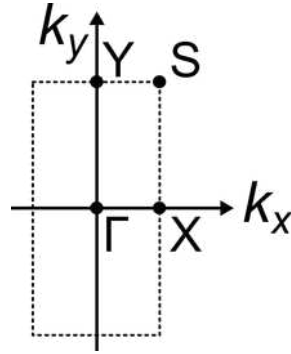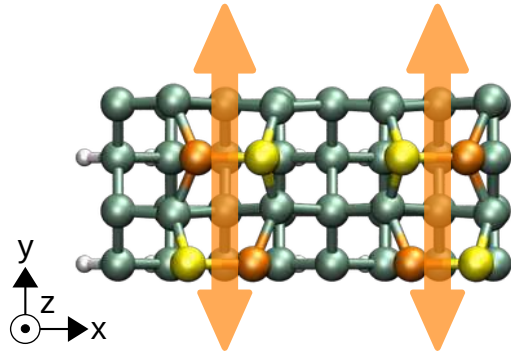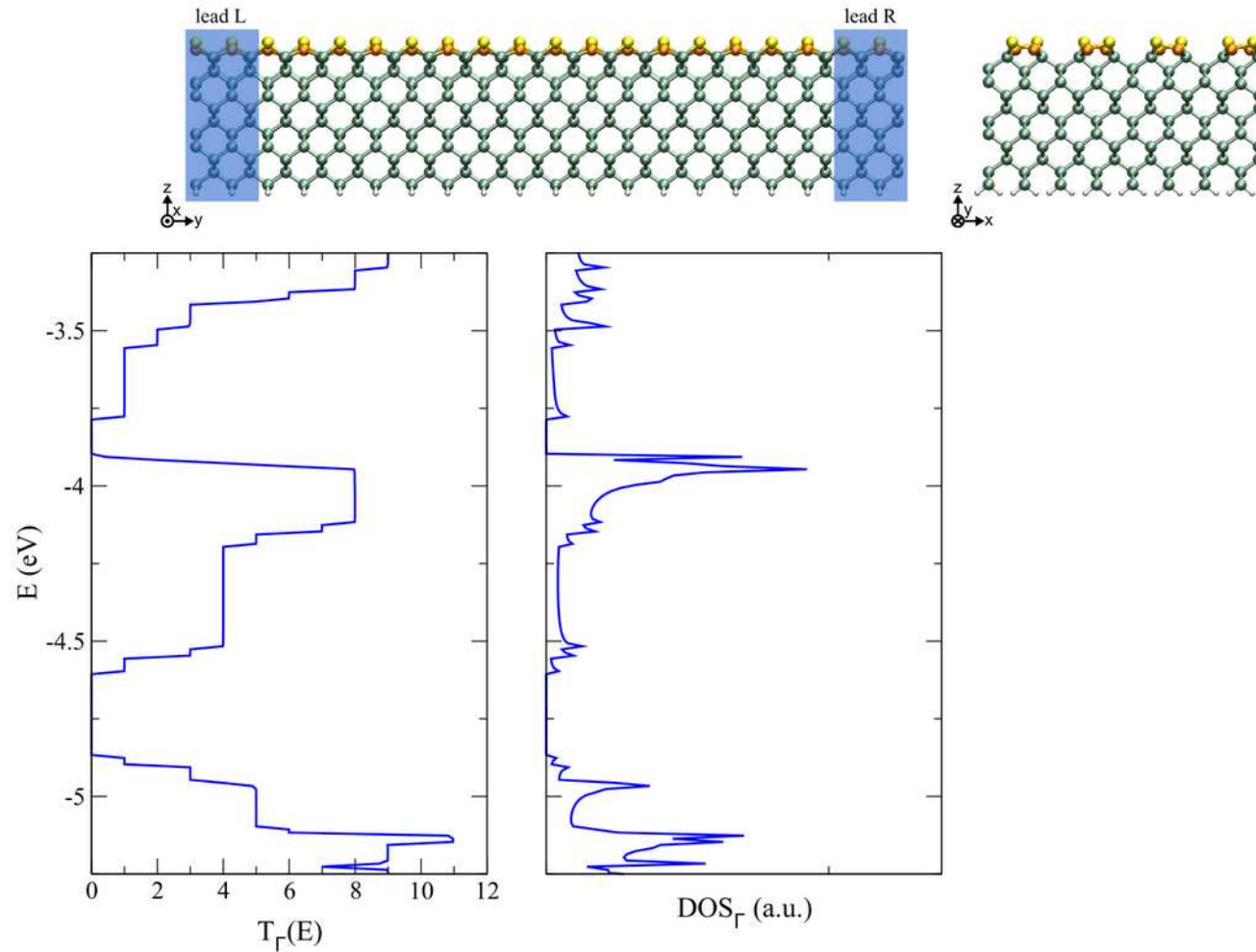
Ge(001)x(4x2) surface

Ge(001)x(4x2) surface
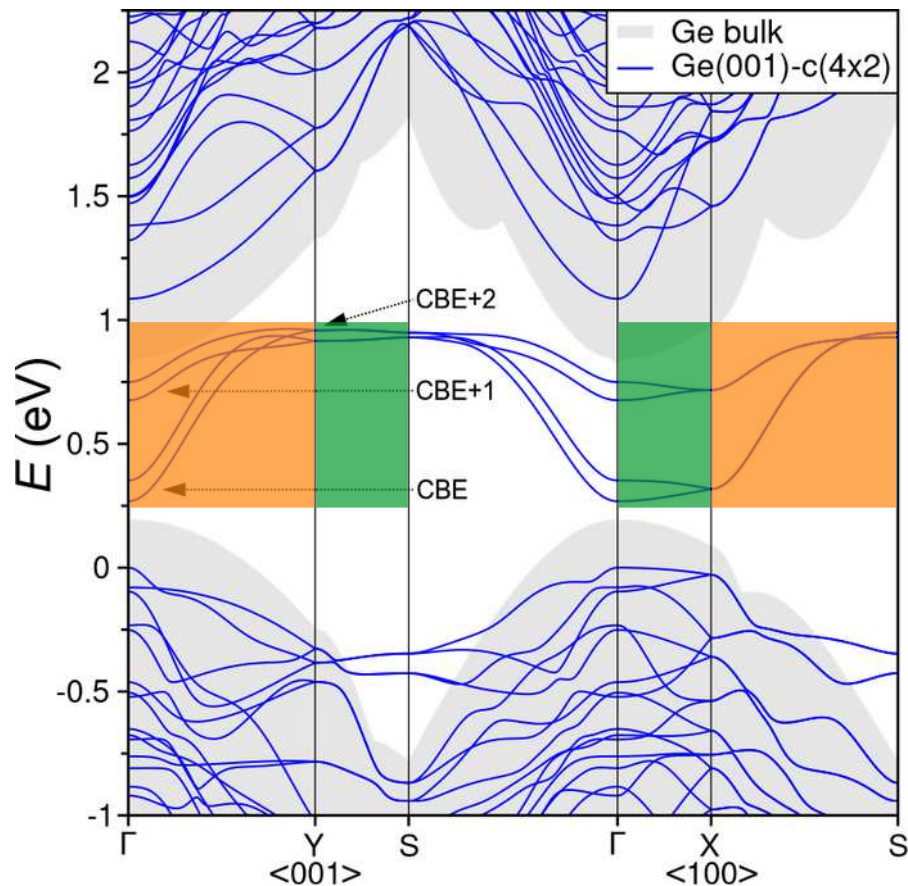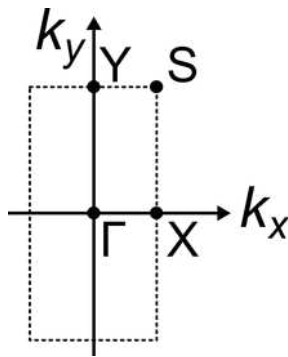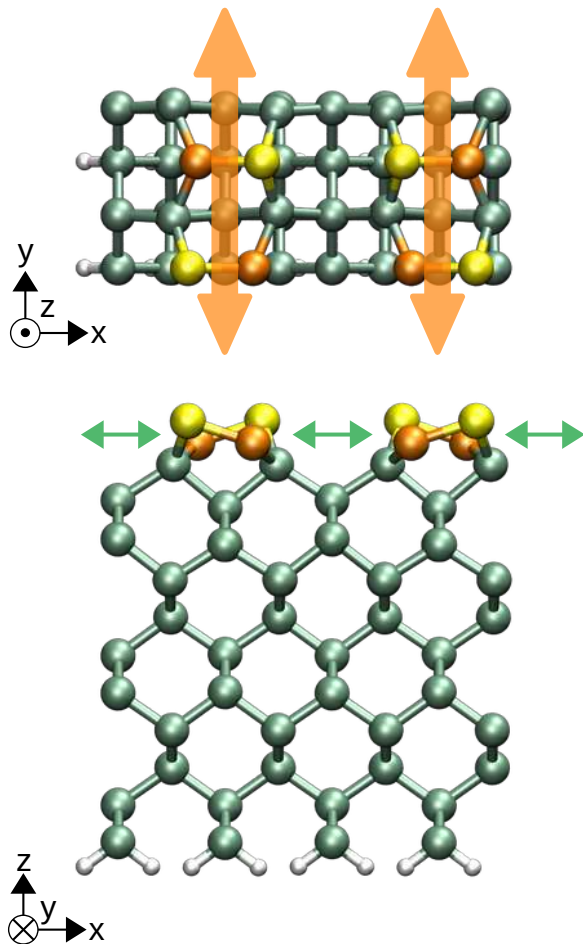
Ge(001) surface: 2-terminal setup
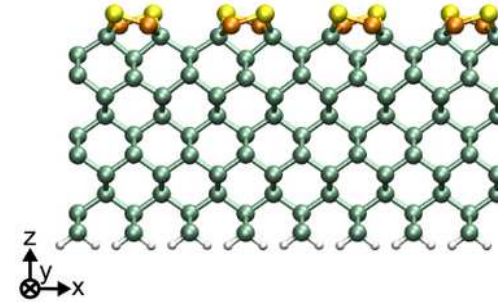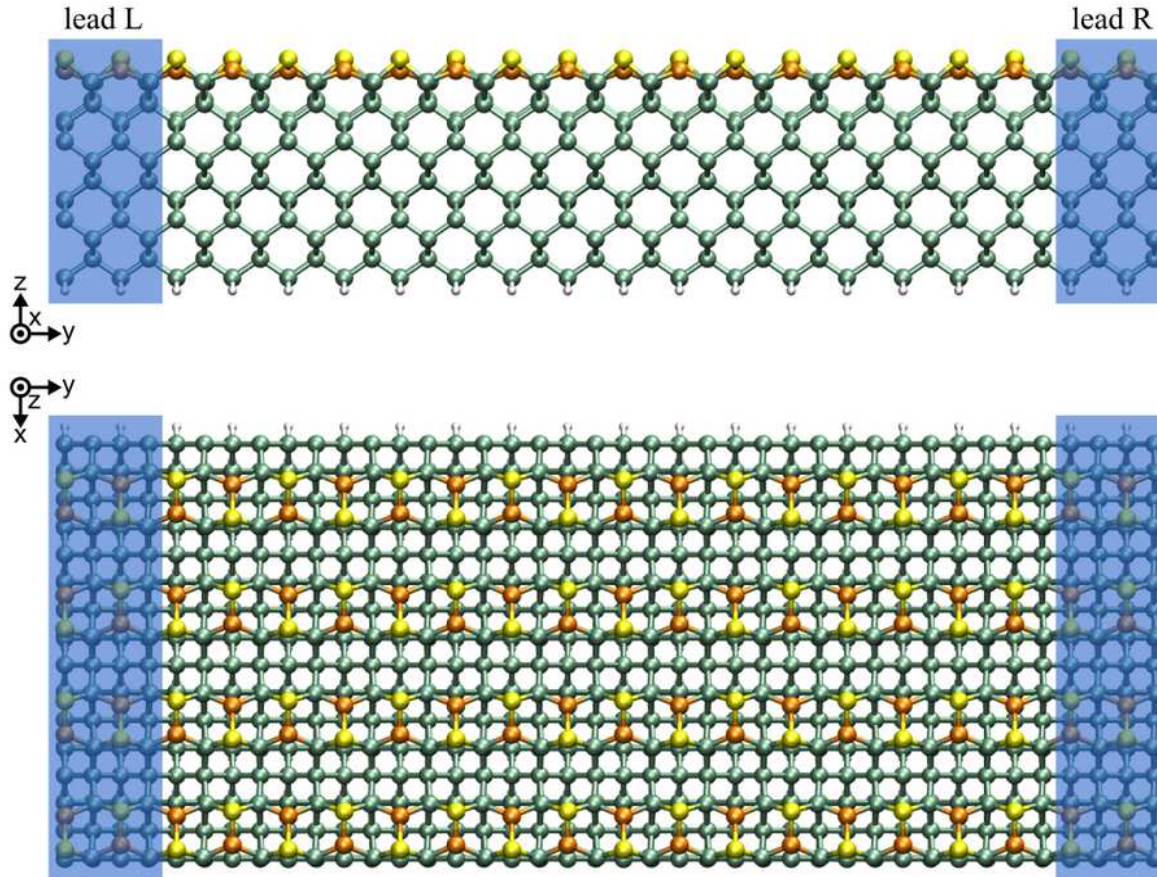
# of atoms/orbitals: **2240/16000**

Ge(001) surface: 2-terminal setup

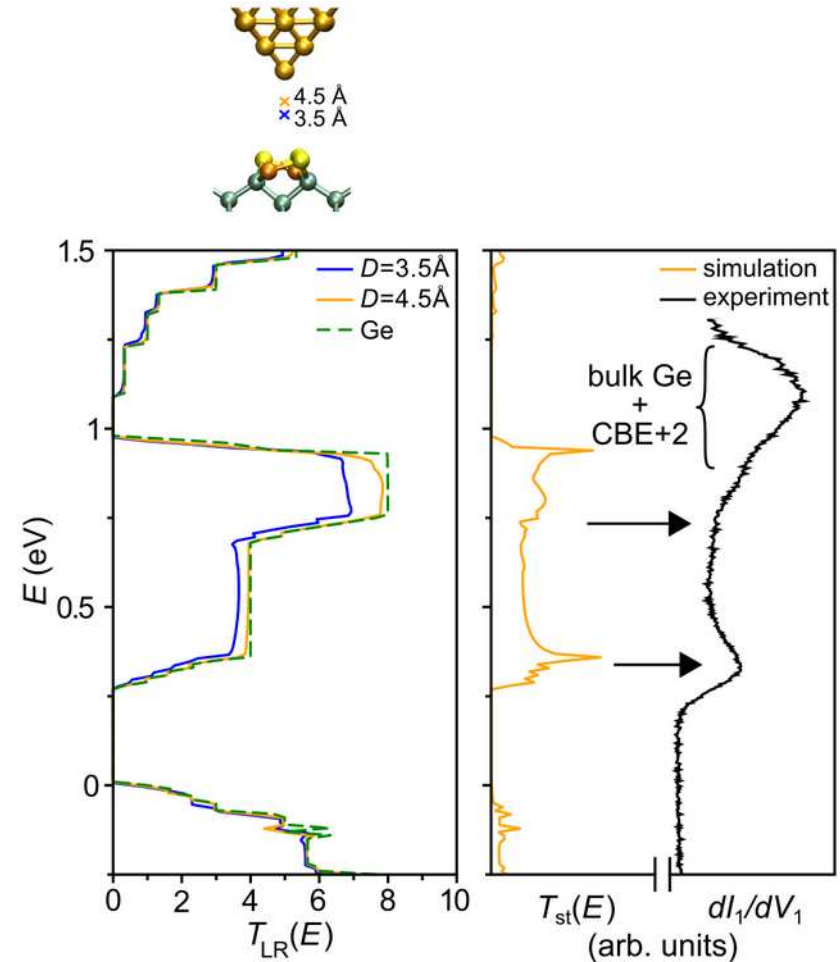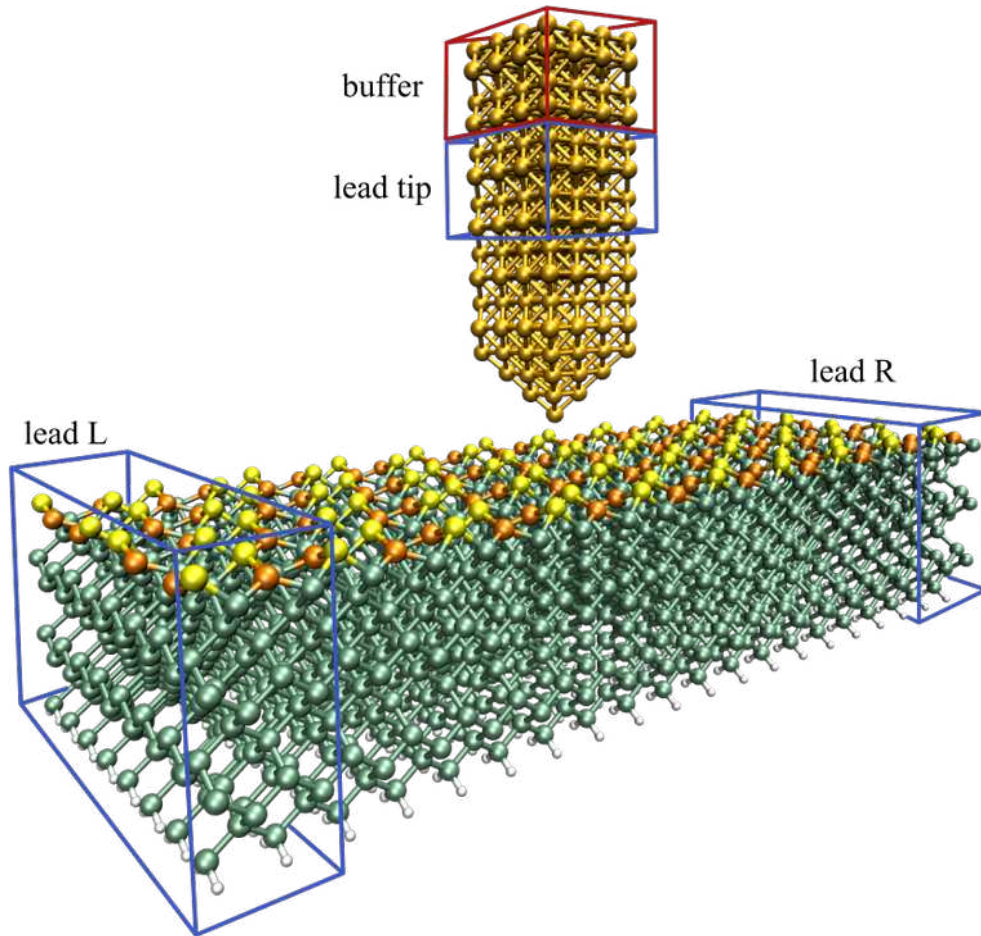## Ge(001) surface: 2-terminal setup
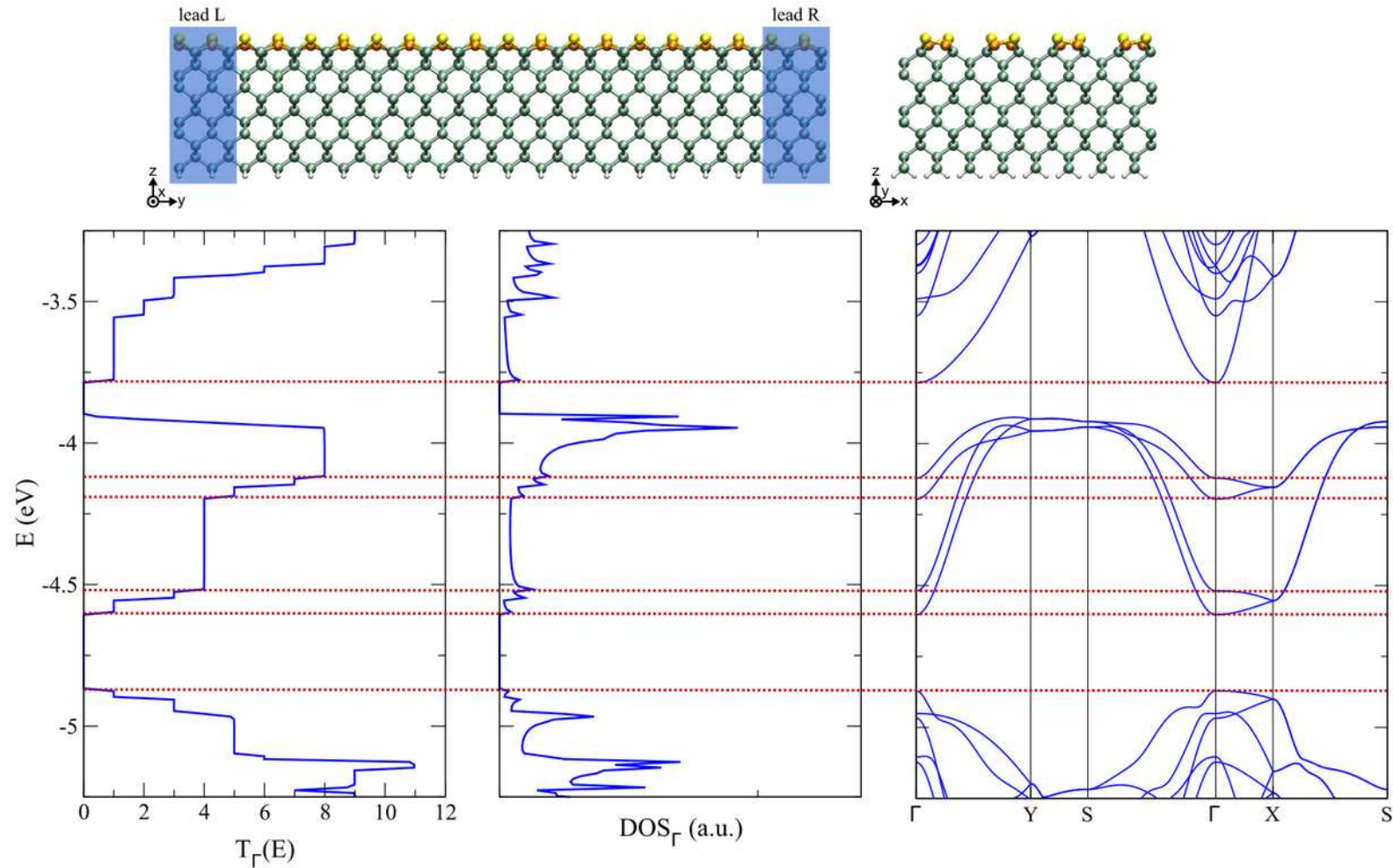
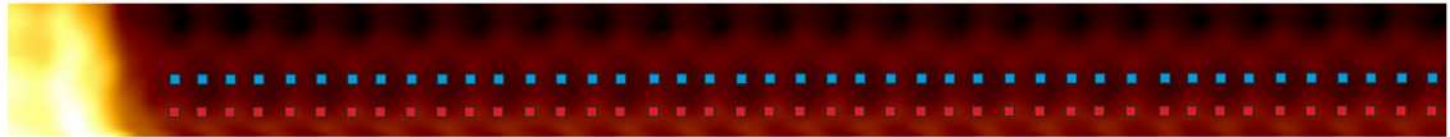## Standard (one probe) Scanning Tunneling Spectroscopy (STS)
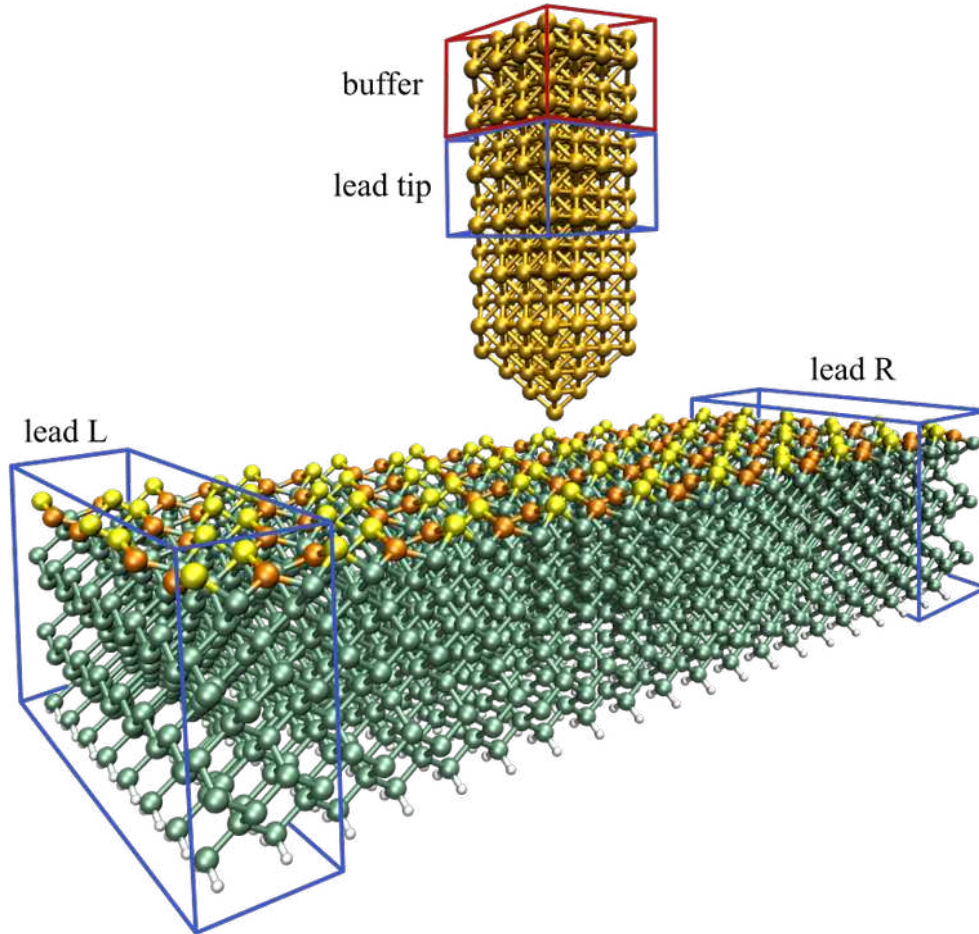
# of atoms/orbitals: **2462/18221**

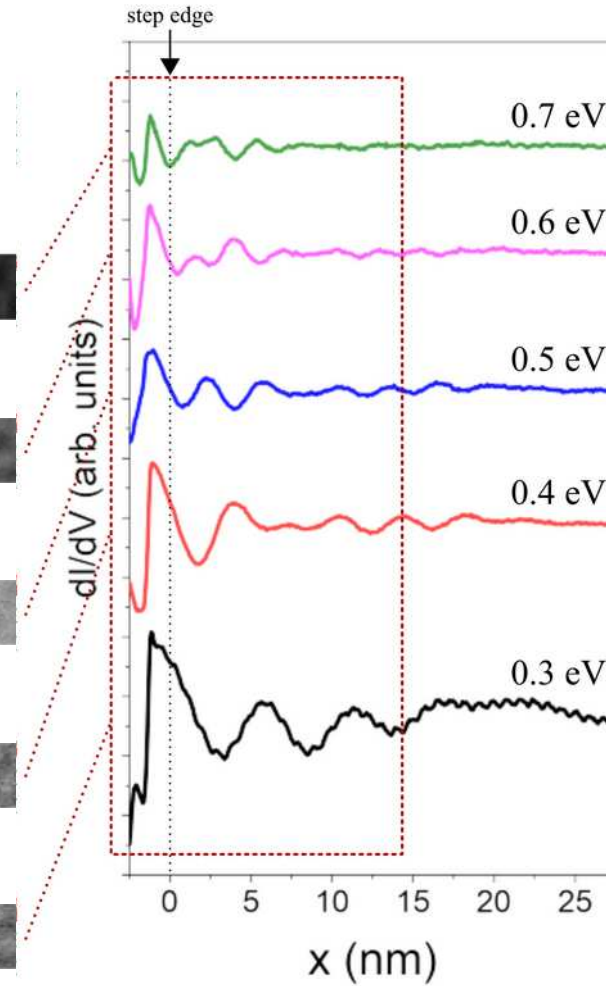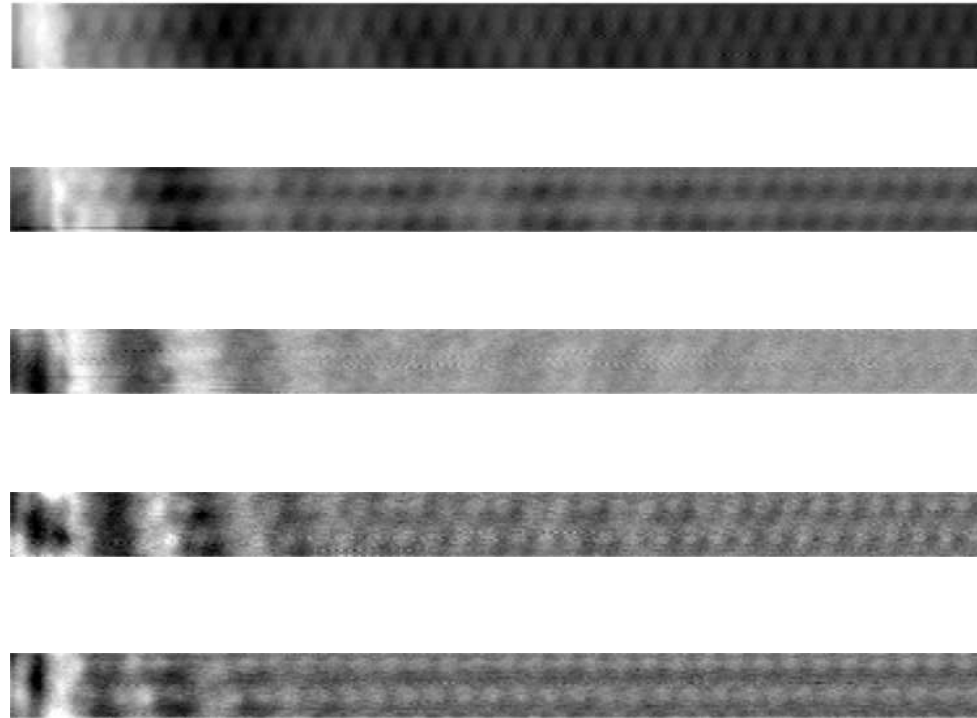## Standard (one probe) Scanning Tunneling Spectroscopy (STS)
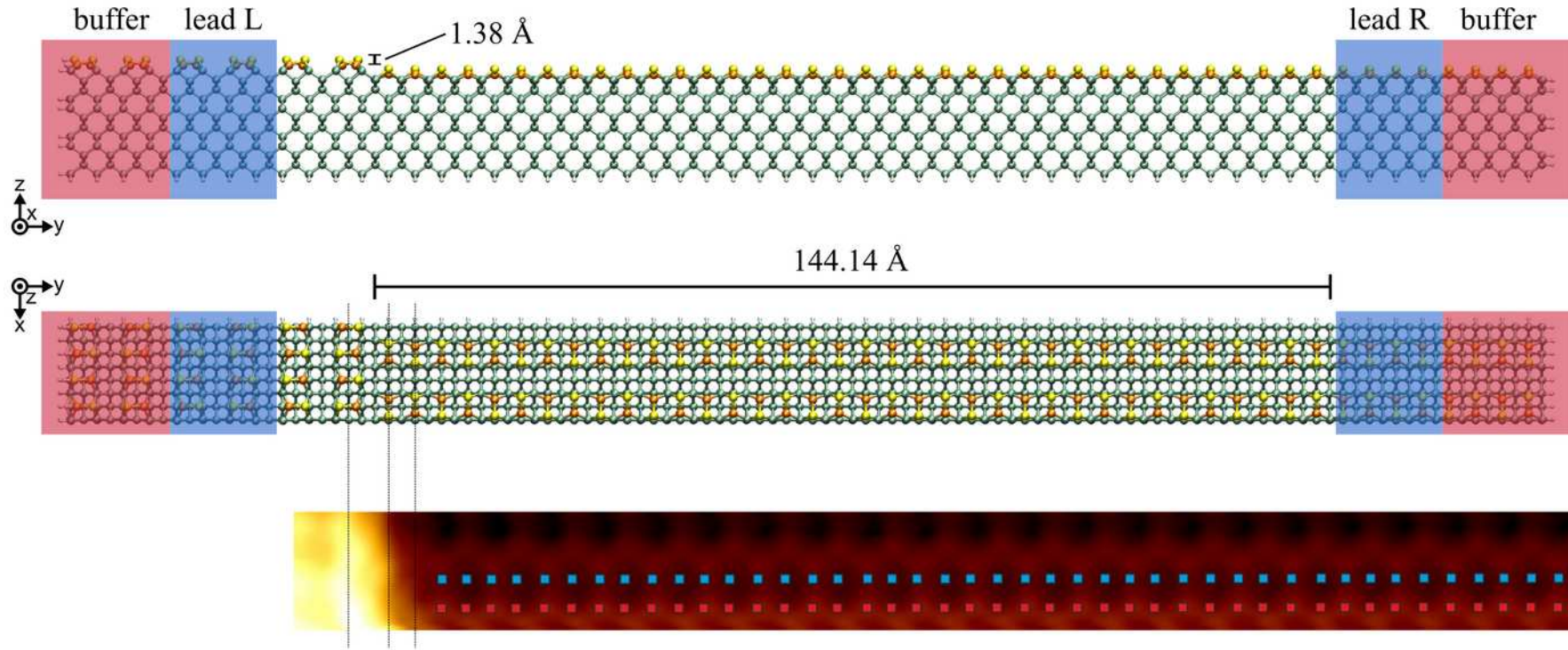
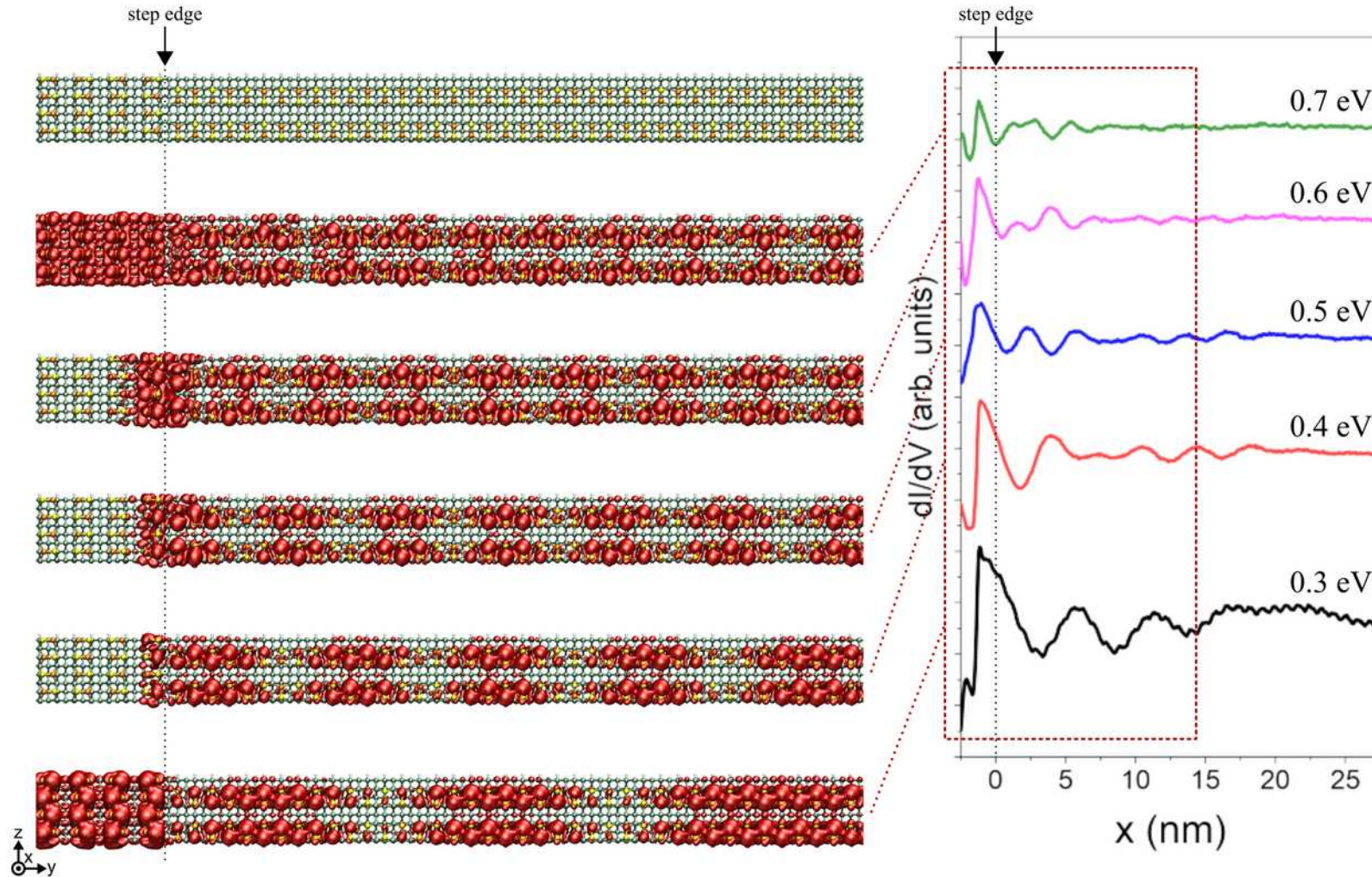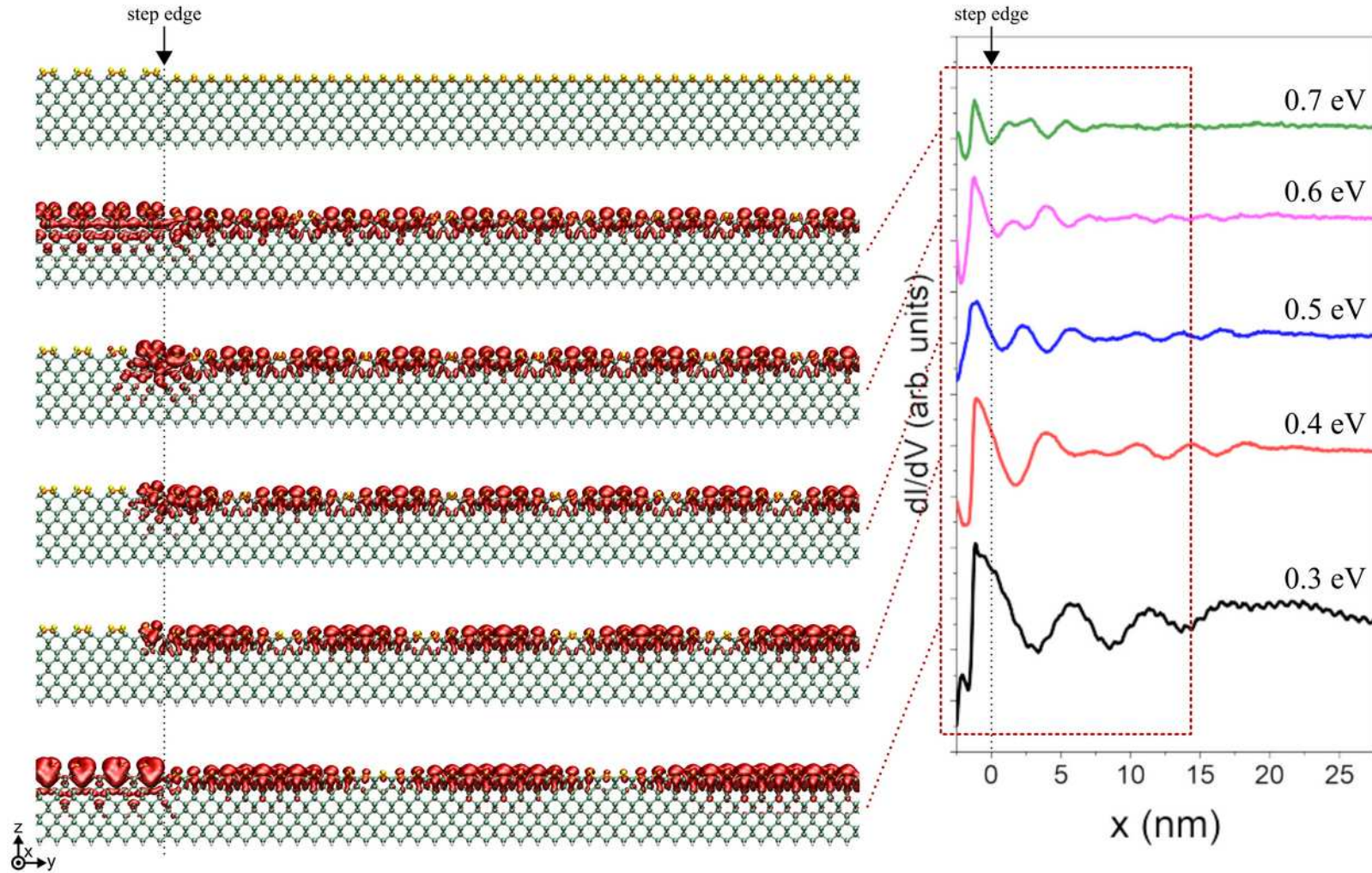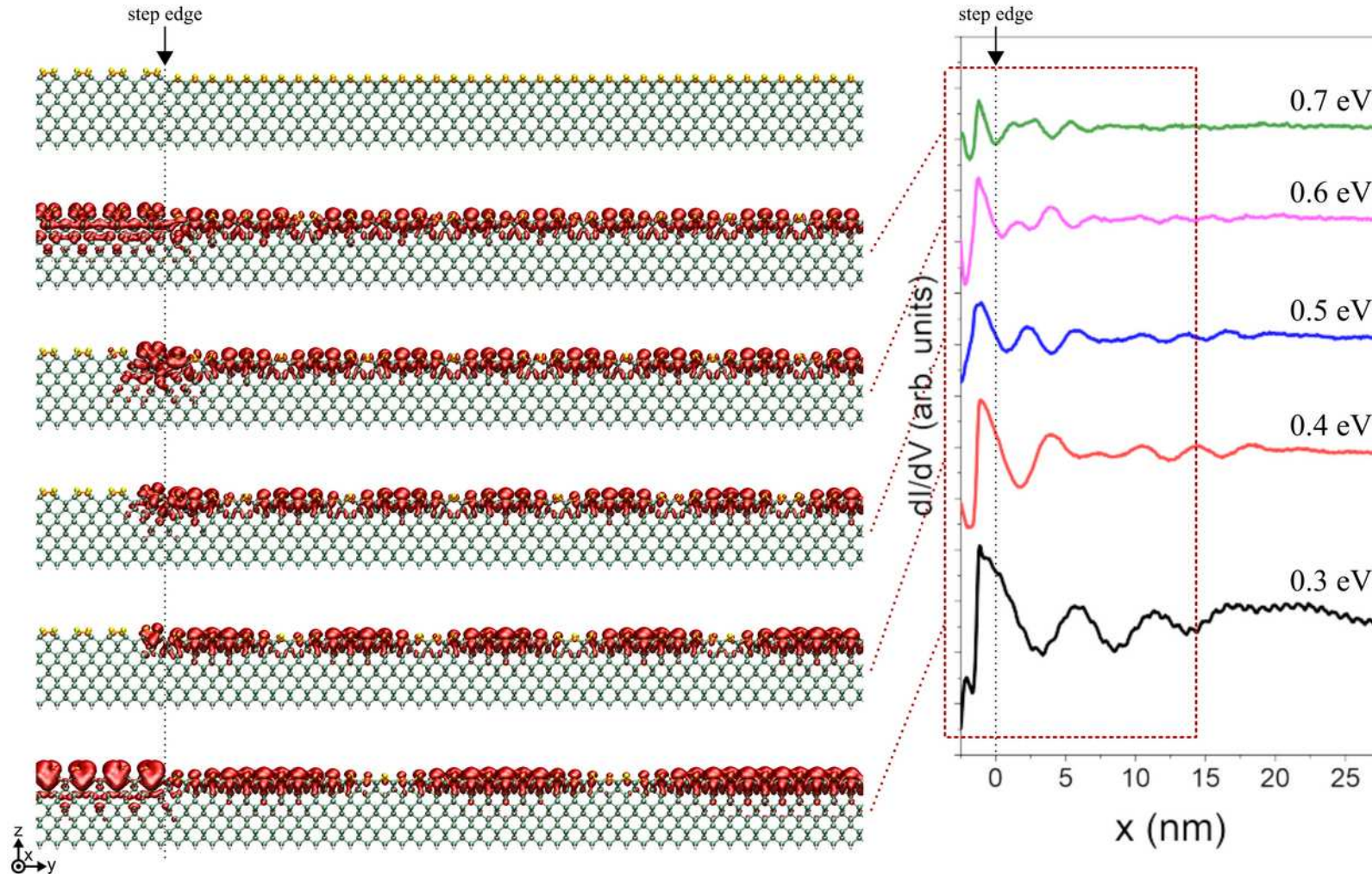# Proof of ballistic transport

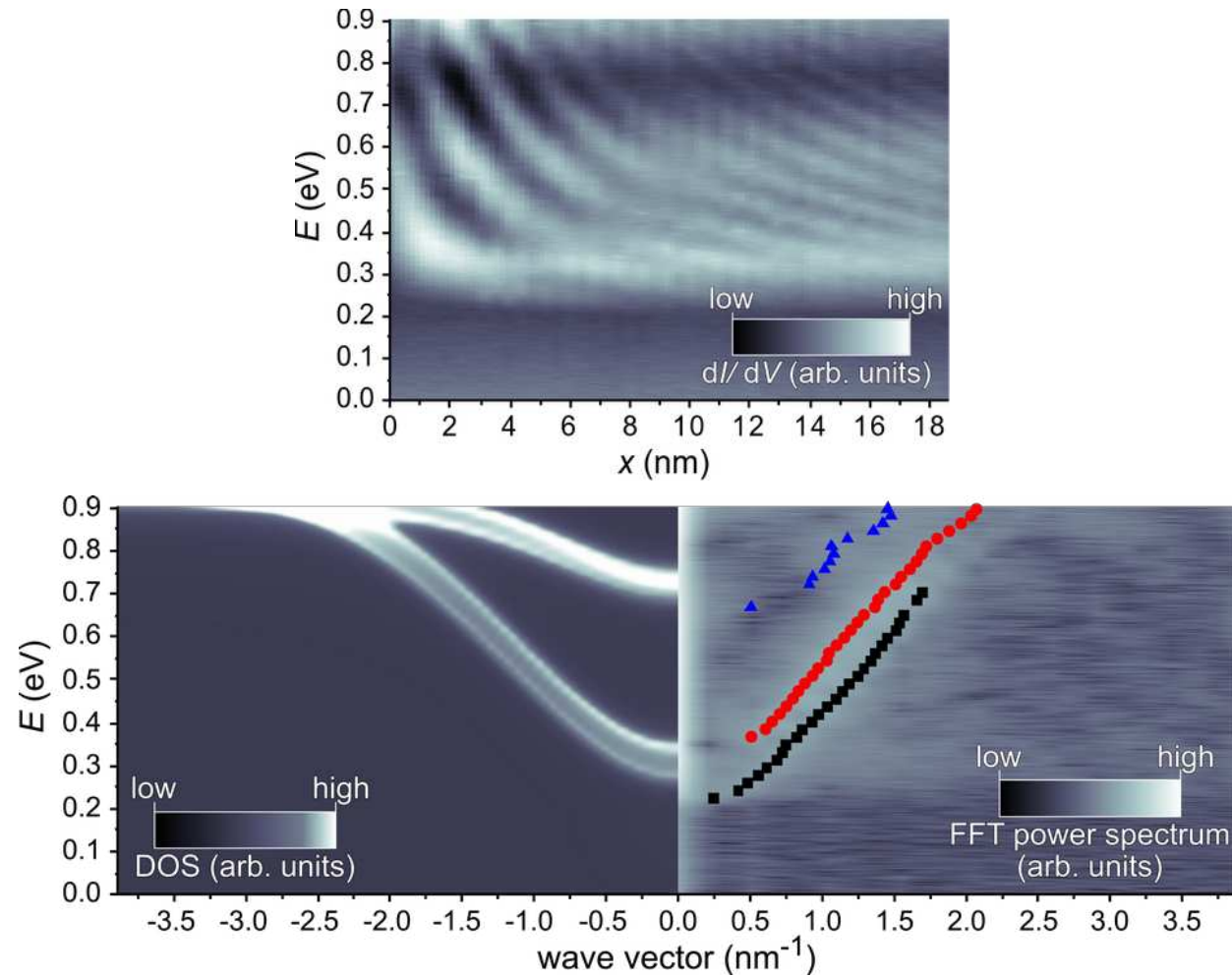## Proof of ballistic transport

Proof of ballistic transport

Proof of ballistic transport

Proof of ballistic transport

Proof of ballistic transport

Coherence length
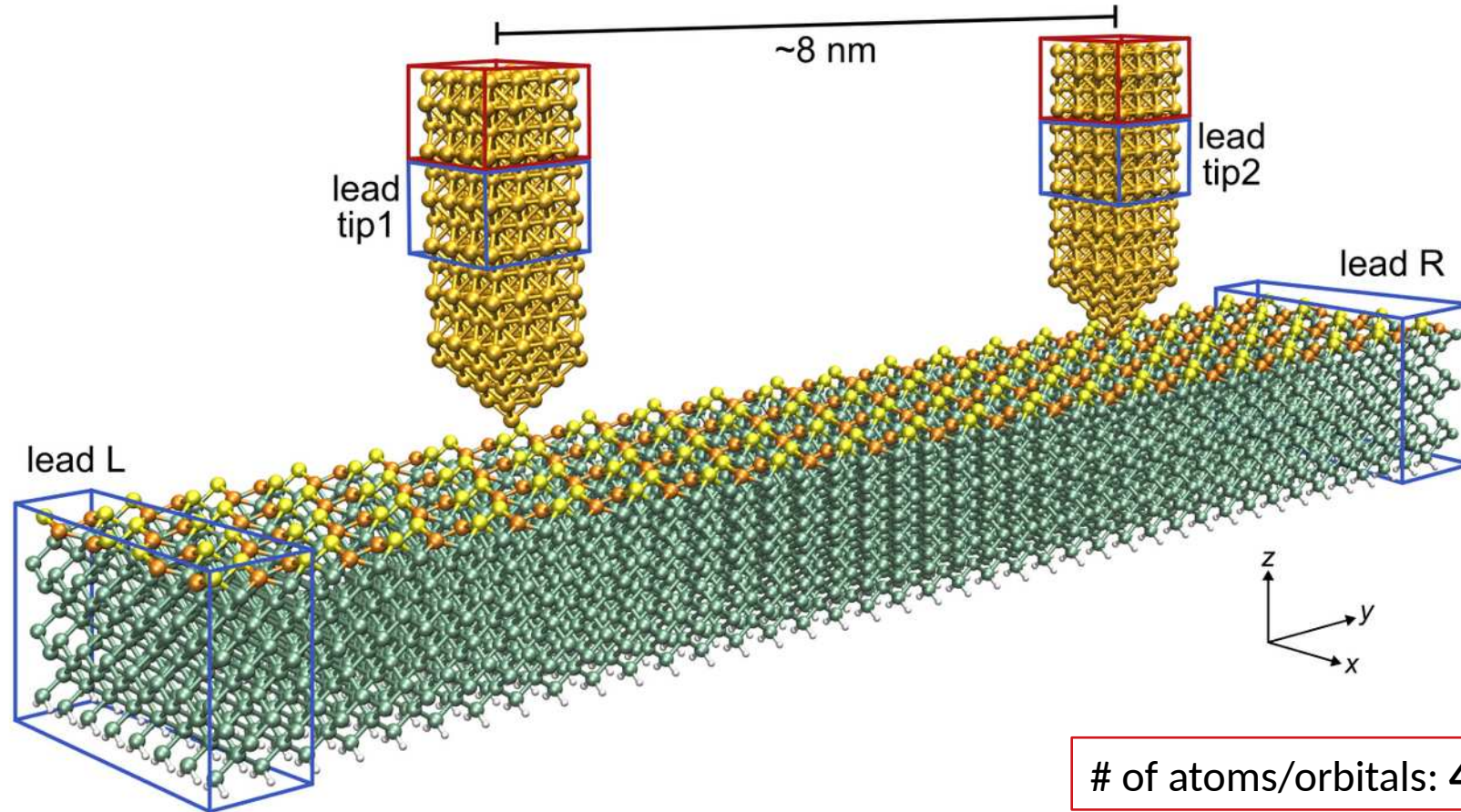up to **50 nm**!!!

Proof of ballistic transport

Coherence length up to **50 nm**!!!

Ge(001) surface addressed by two tips: 4-terminal setup
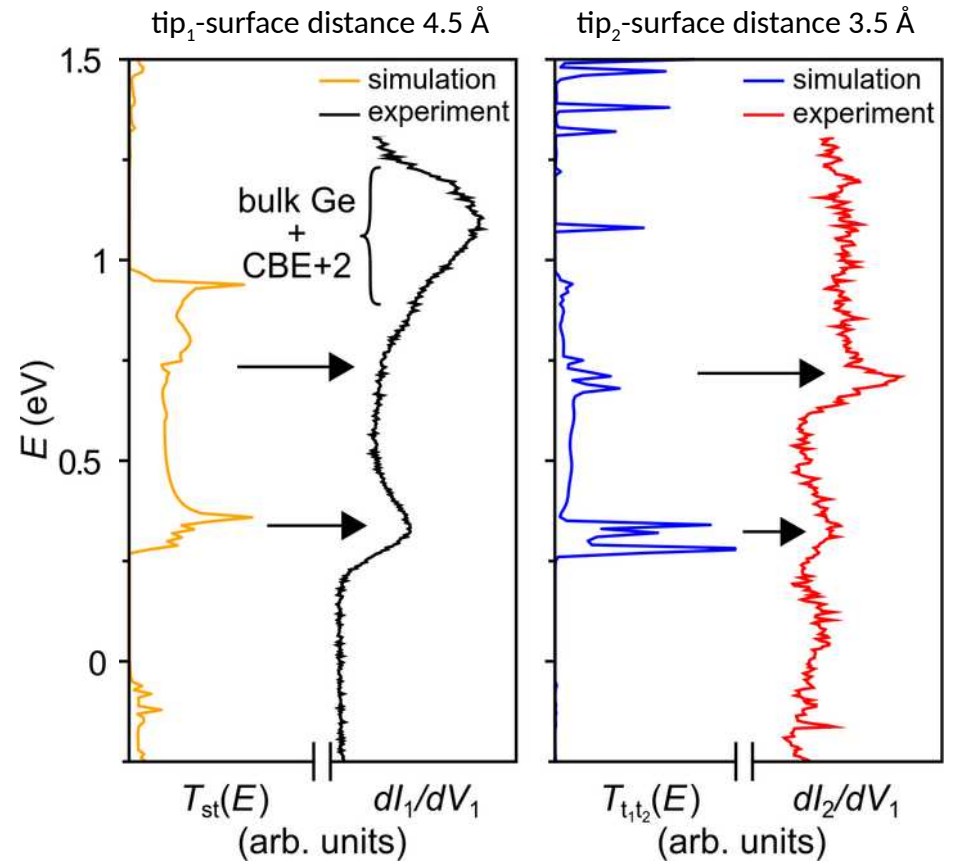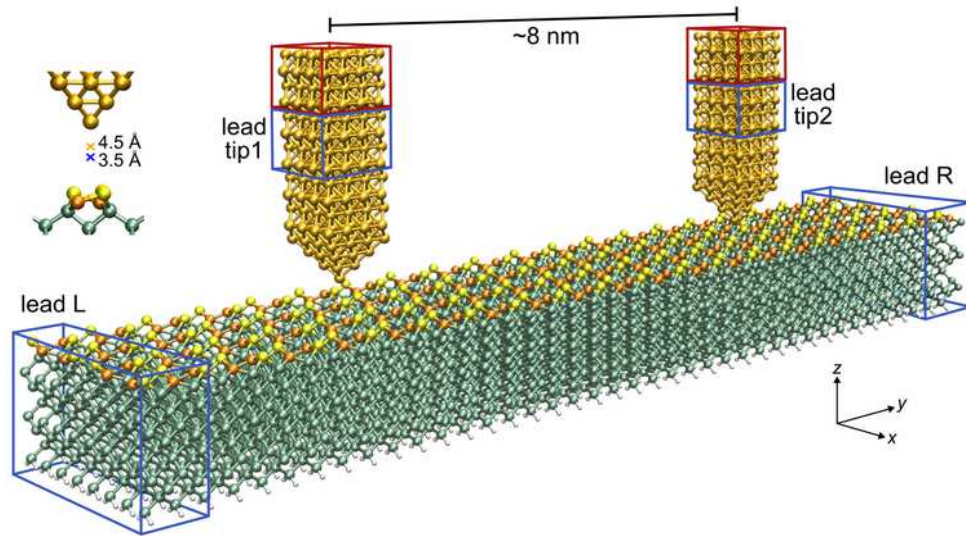

~8 nm

lead tip1

lead tip2

lead R

lead L

# of atoms/orbitals: **4924/36442**
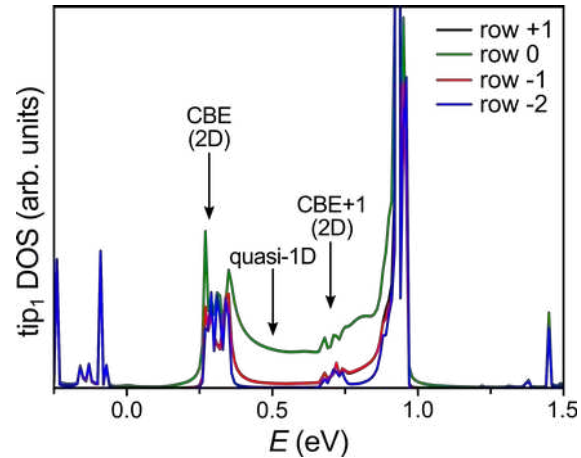
Ge(001) surface addressed by two tips: 4-terminal setup

~8 nm

lead tip1

lead tip2

× 4.5 Å
× 3.5 Å

lead R

lead L

z
y
x

# of atoms/orbitals: **4924/36442**

Ge(001) surface addressed by two tips: 4-terminal setup

Ge(001) surface addressed by two tips: 4-terminal setup
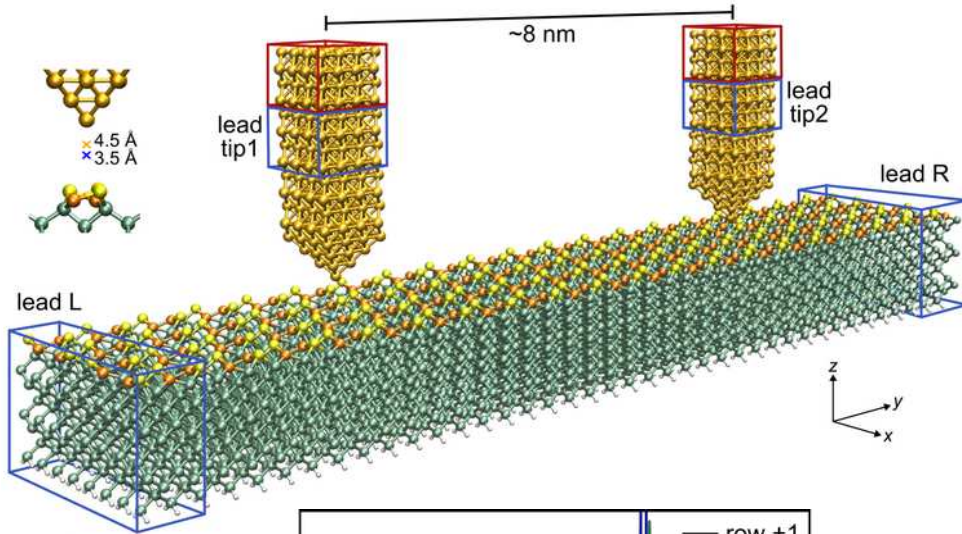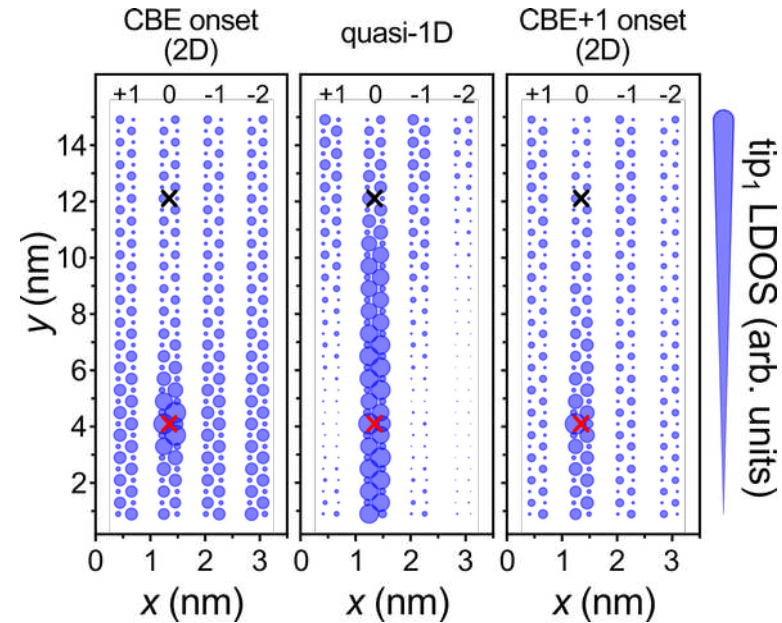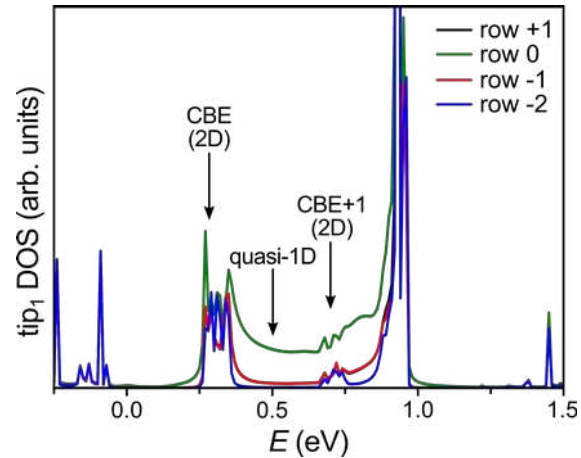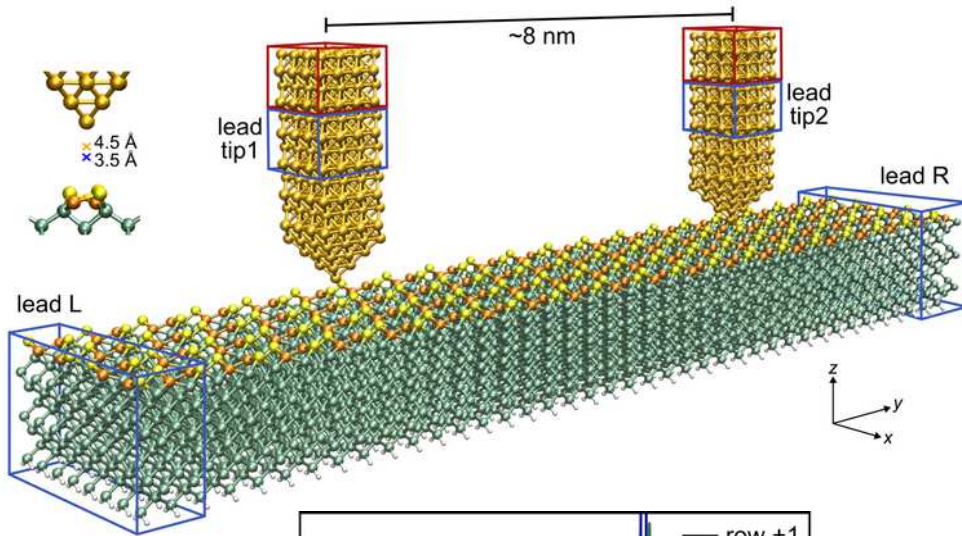
Ge(001) surface addressed by two tips: 4-terminal setup

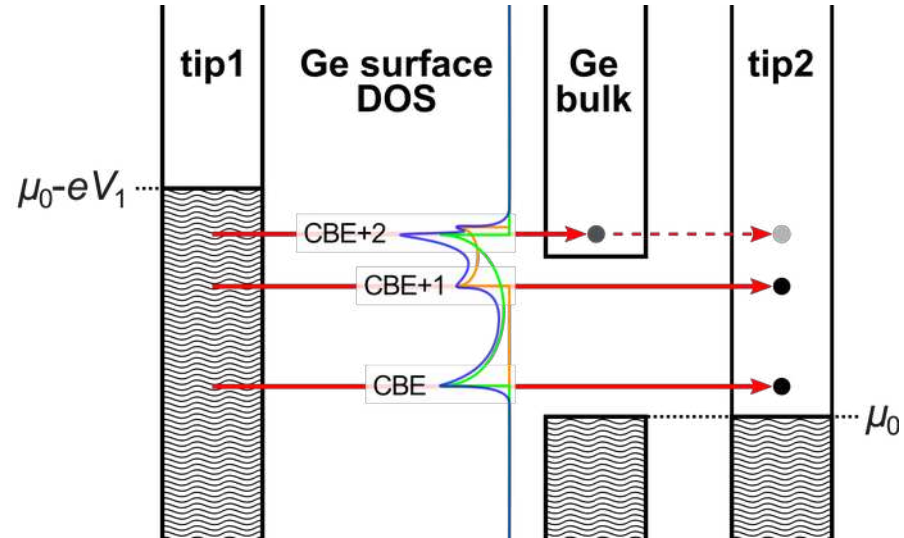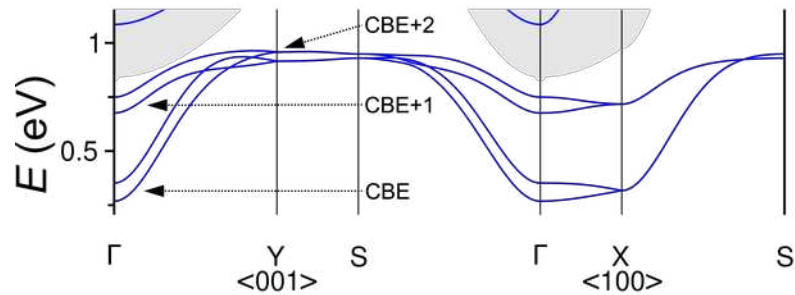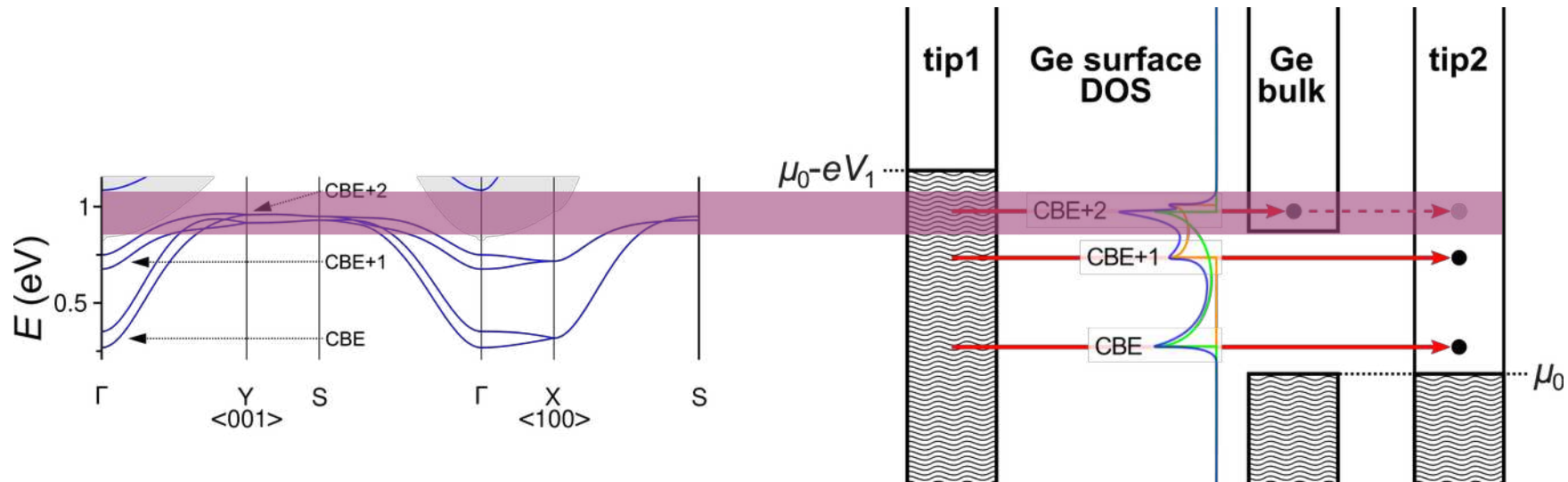# Ge(001) surface addressed by two tips: 4-terminal setup

Ge(001) surface addressed by two tips: 4-terminal setup

Conclusions

- Identification and characterization of the quasi 1D transport surface channels along a single dimer row on bare Ge(001)-c(4×2) surface;

- SP-STM/STS and calculated eigenchannels on a step-edge confirms a coherent transport length up to 50nm;

- TP-STS planar transconductance resonances measured with a tip-to-tip distance down to 30nm and confirmed by multi-terminal DFT-NEGF simulations.
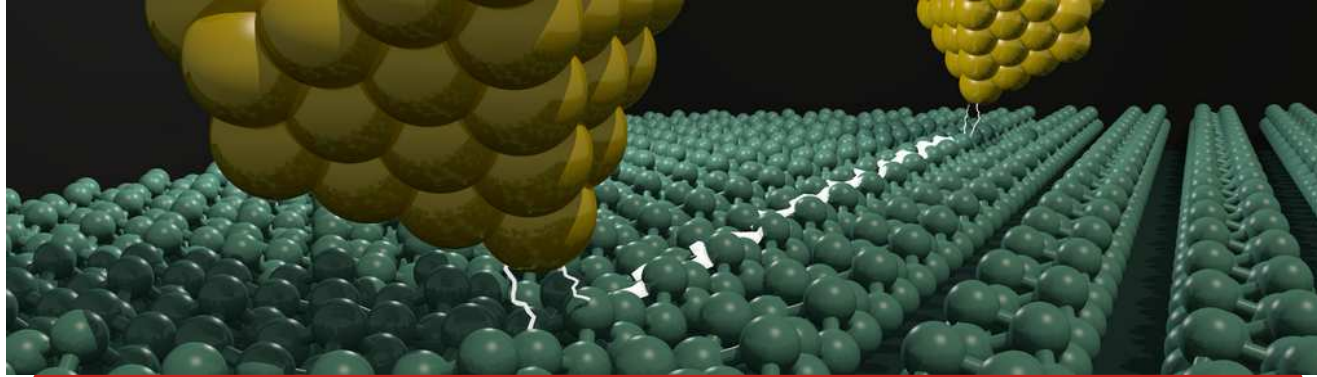
M. Kolmer, P. Brandimarte* *et al. Nature Communications* **10**, 1573 (2019)