Anisotropic conductance oscillations and magnetotransport in Pb films on Si(557)

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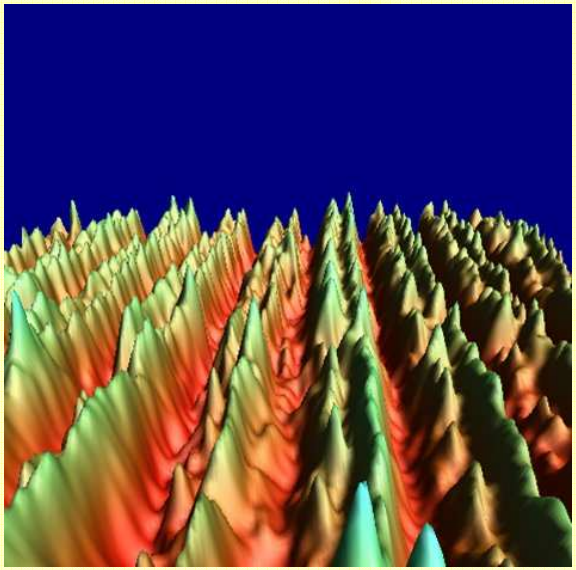


Pb/Si(557)

Motivation

- Correlations between structure, electronic properties and electric transport
- Role of surfaces and interfaces

- Instabilities: charge and spin density waves, Peierls phase transitions

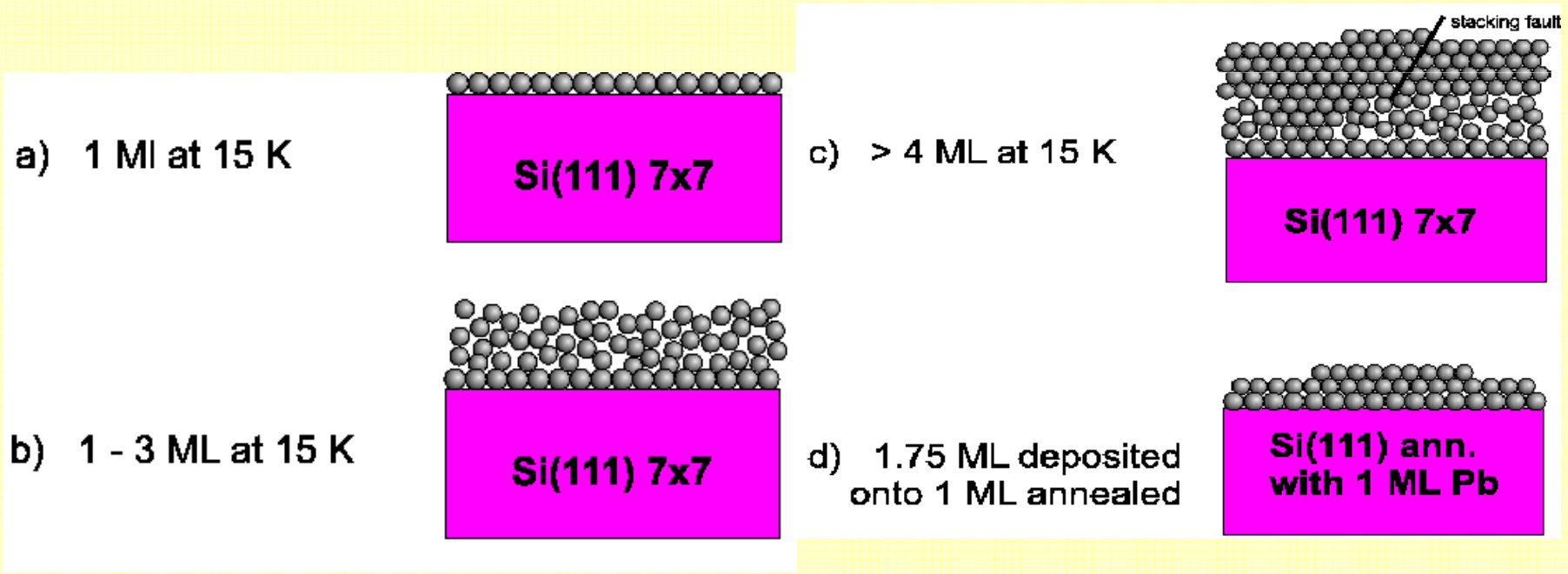
- Quantum confinement vs. „classical“ size effects
- Role of defects (steps, point defects etc.)

➔Elastic, inelastic, spin-orbit scattering

Pb/Si(557): mono- and multilayer growth

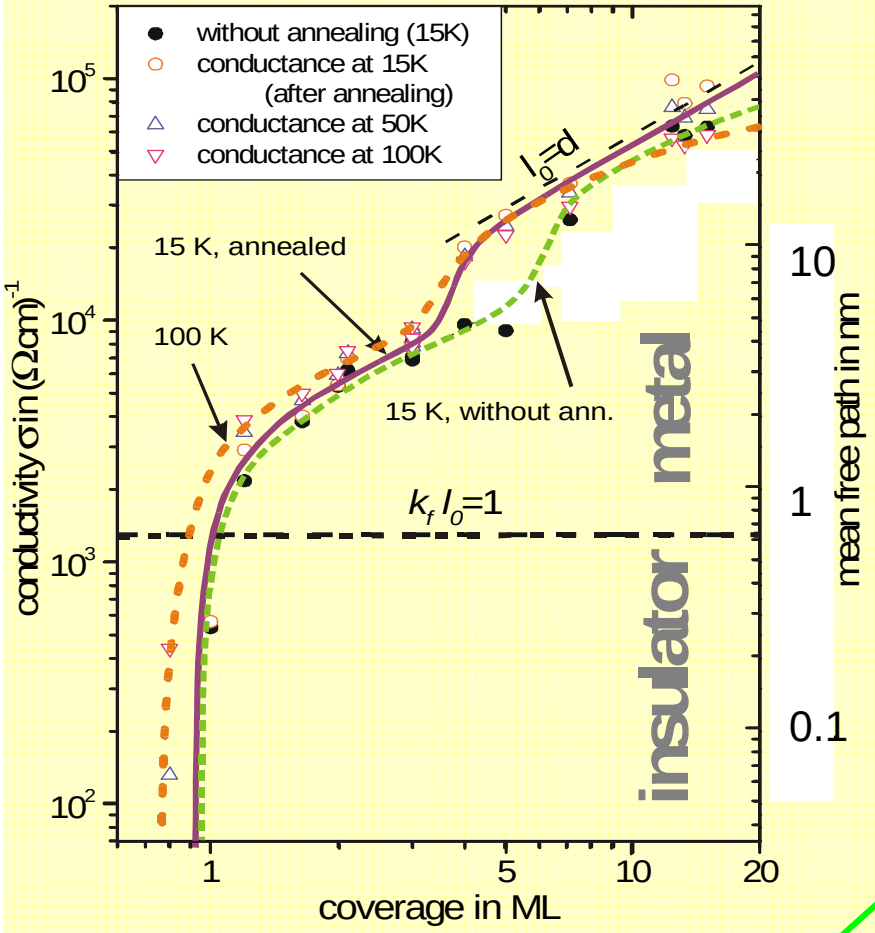
An example of an isotropic 2d metal: Pb/Si(111)

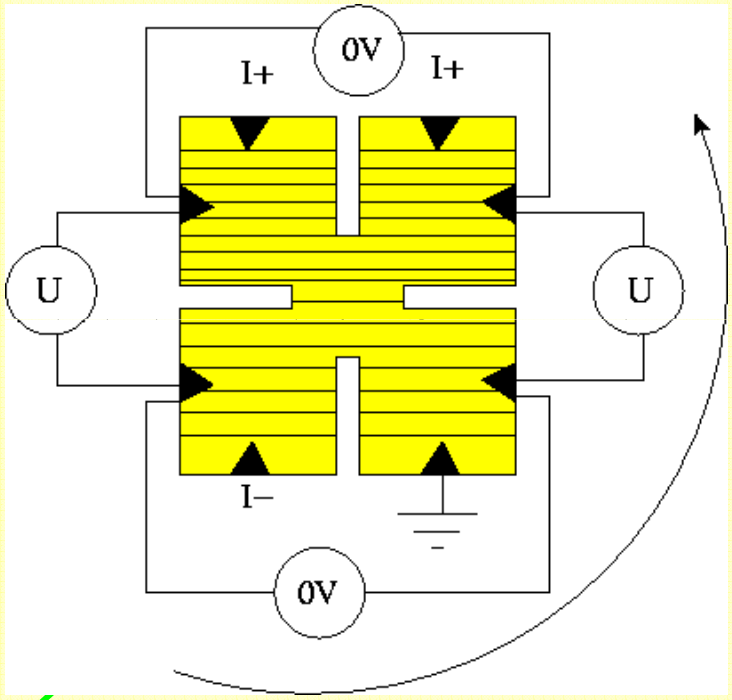
Pb/Si(111): basic growth modes



*A. Petkova, J. Wollschläger, H.-L. Günter, M. Henzler, Surf. Sci.**482-485**, 922 (2001)*

Conductance of Pb films on Si(111) (7 x 7)





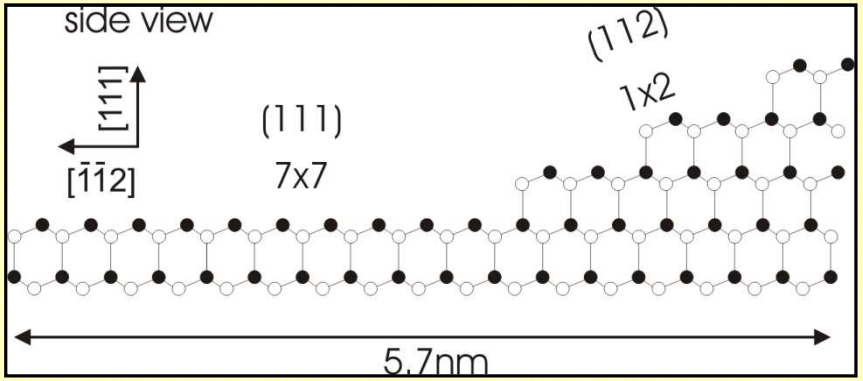
$\sigma \sim d^1$

Dominance of interface scattering
weak dependence on structure

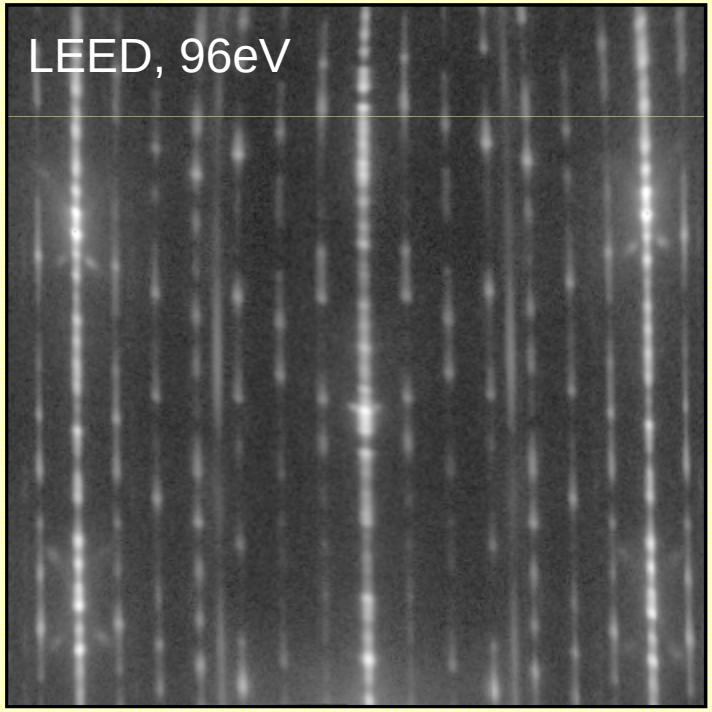
First layer: Mott insulator

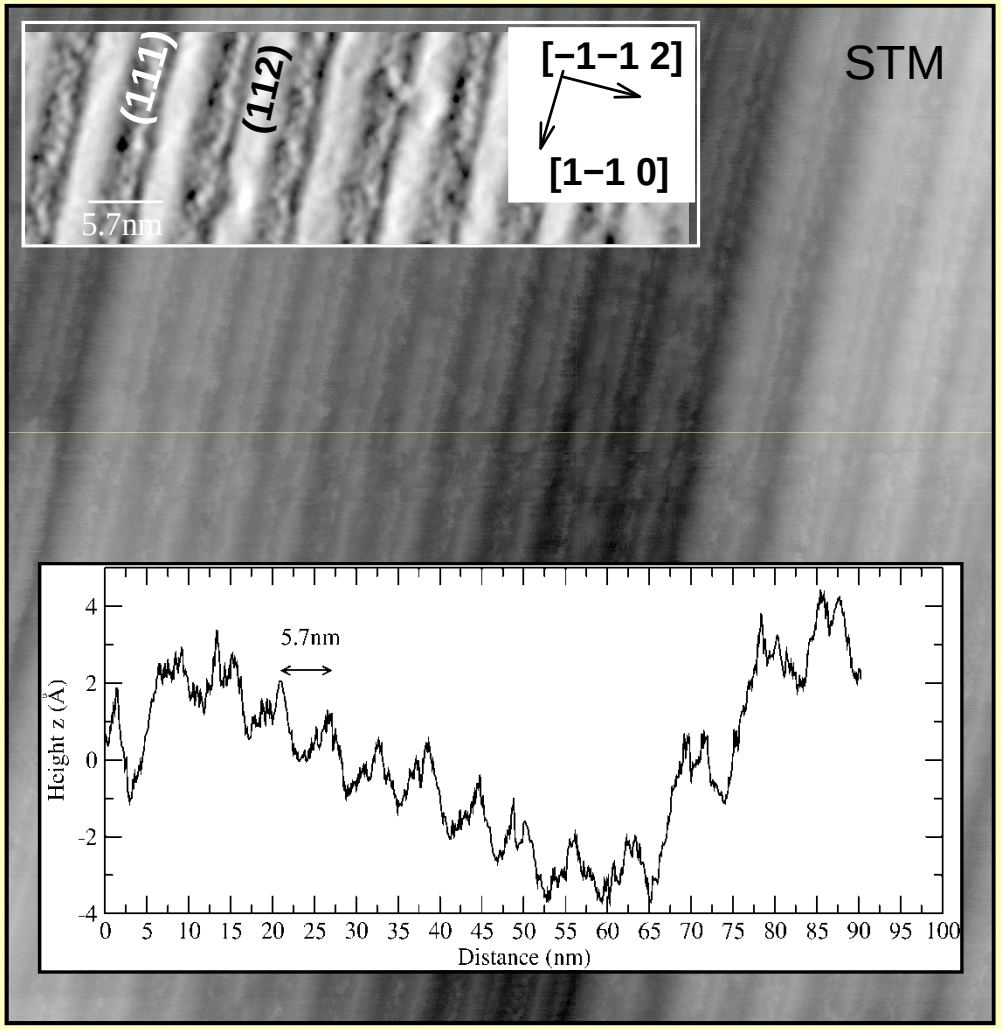
O. Pfennigstorf, A. Petkova, H.-L. Günter, M.Henzler, Phys. Rev. B ***65****, 045412 (2002)*

Clean Si(557) surface



vicinal Si(111)
metastable surface, not equally stepped

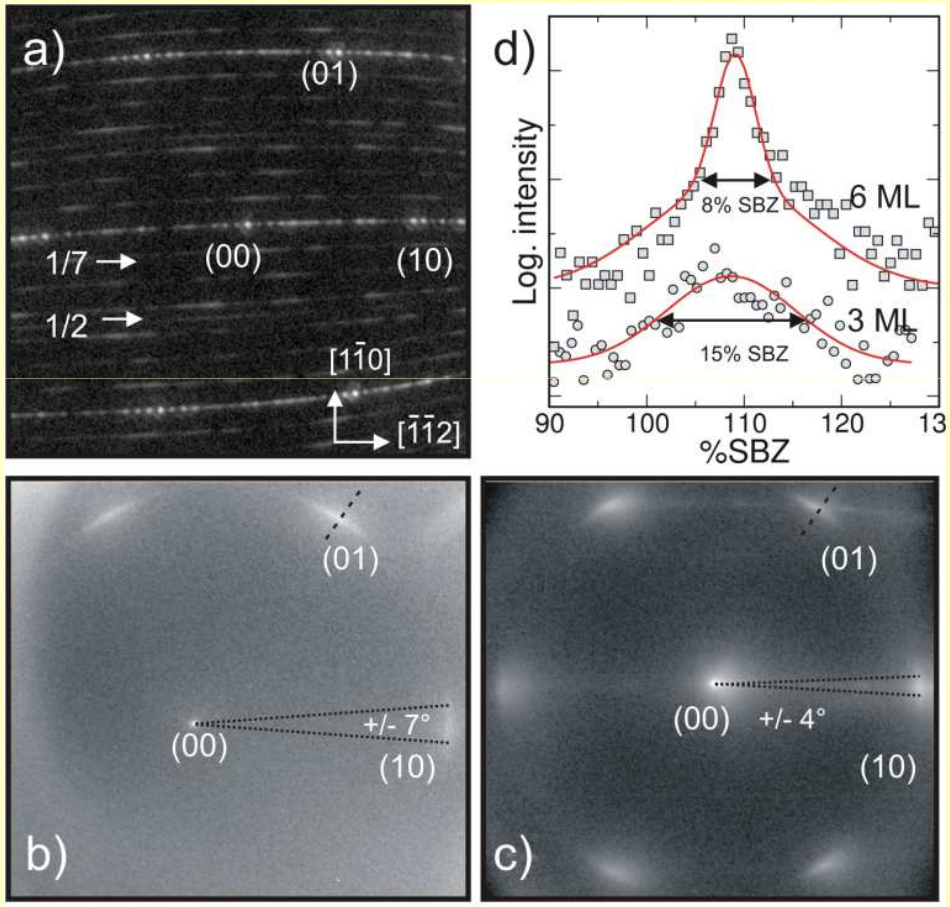




Pb multilayer growth on Si(557): LEED

- Growth at 70 K: (557)-step structure remains as well as (7x7)
- isotropic layer already at 3 ML
- Crystalline growth from the first monolayer
- Nanocrystalline film
- Mismatch of 8.8% compensated by steps within the first few layers

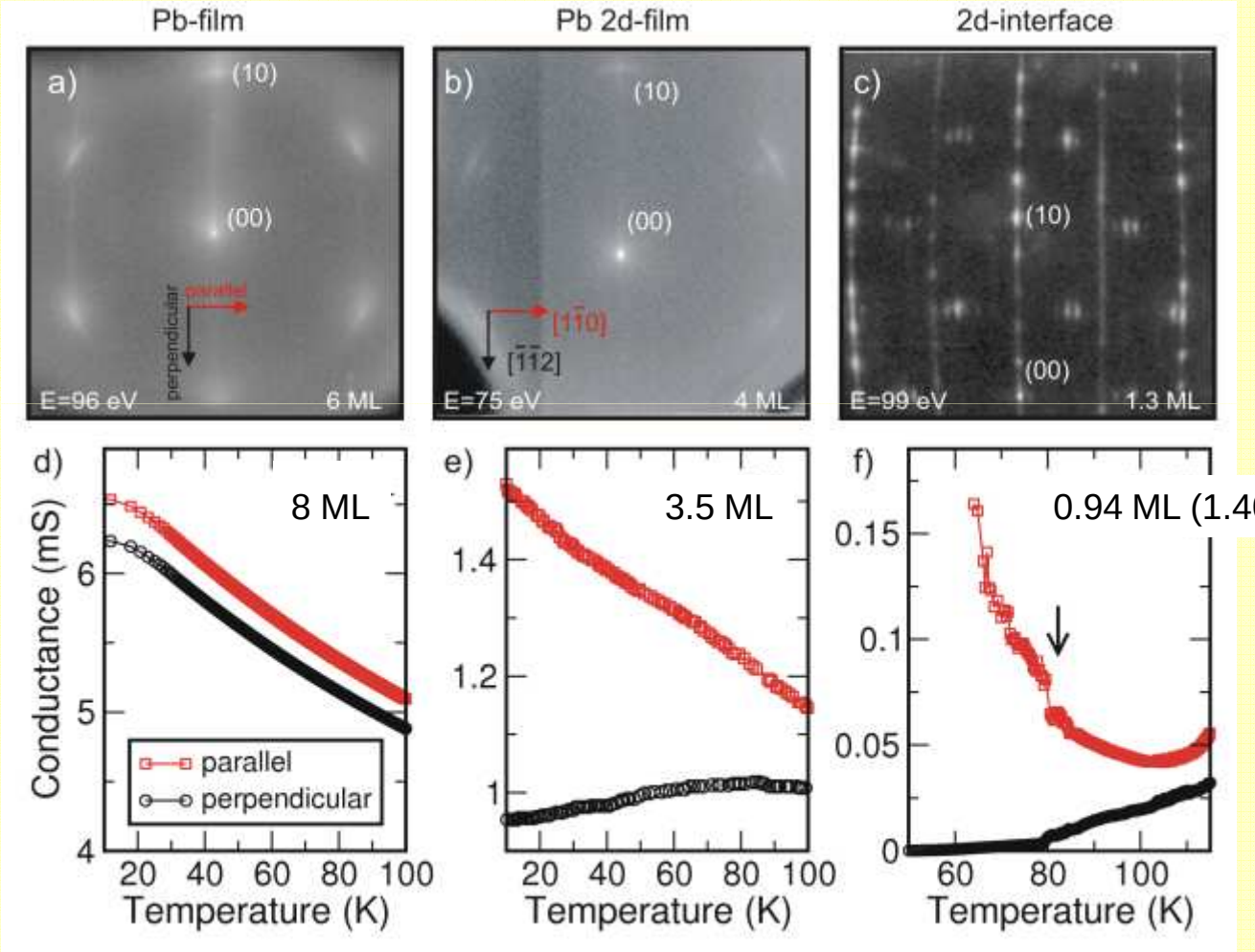
clean



3ML

6ML

Pb multilayer growth on Si(557): conductance



Metallic,
small anisotropy

Semi-metallic
Strong anisotropy

Transition 1d -2d
metallic-> activated

Continuous adsorption 70 K

(a)

Percolation threshold close to 0.5 ML

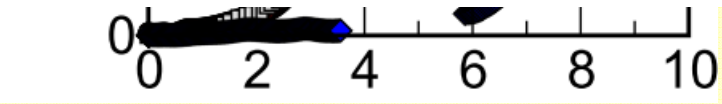
Layer-by-layer growth starting with the first monolayer

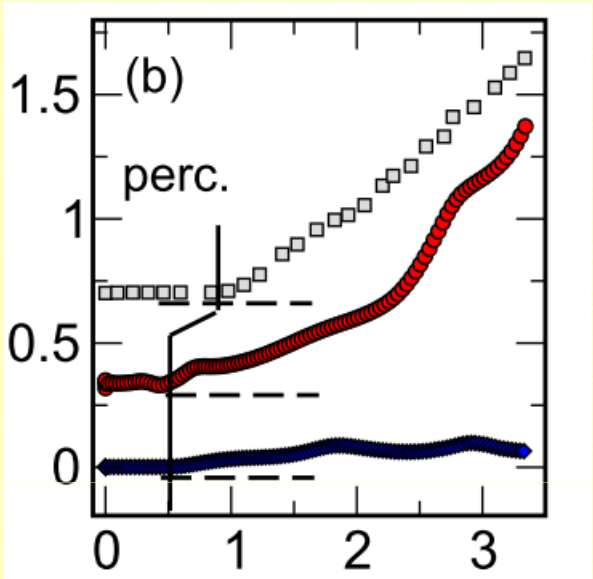
Parallel to steps: power law $G_{\parallel} \sim d^{x}$
$x \approx 3$ up to 5 ML, $x \approx 2$ up to 10 ML

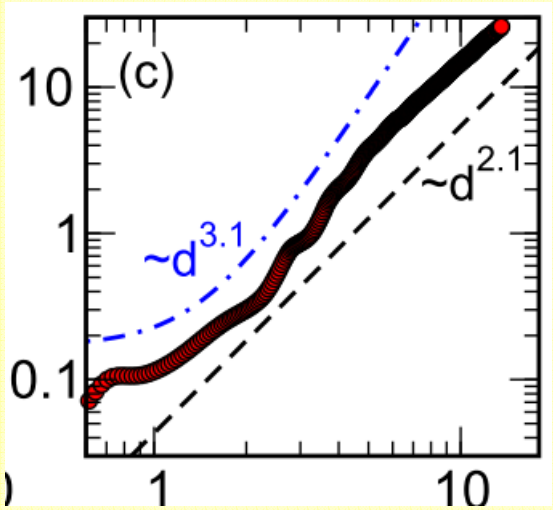
Perpendicular to steps: $G_{\perp} \sim d$

Characteristic oscillations with Monolayer period in both directions

Increment in G isotropic above 7 ML







Classical size effects

- From photoemission + magnetoconductance:
  mean free path $\lambda \approx 5\text{nm} >> d$ in all cases investigated

➔ Interface scattering important

$G_{\parallel}$:

Diffuse scattering at interface: $\sigma \sim d^{2.1}$

Correction by increase of Fermi surface, i.e. DOS with d: $\sigma \sim d^{1}$

➔ $G_{\parallel} \sim d^{2}$ correct for d > 5ML

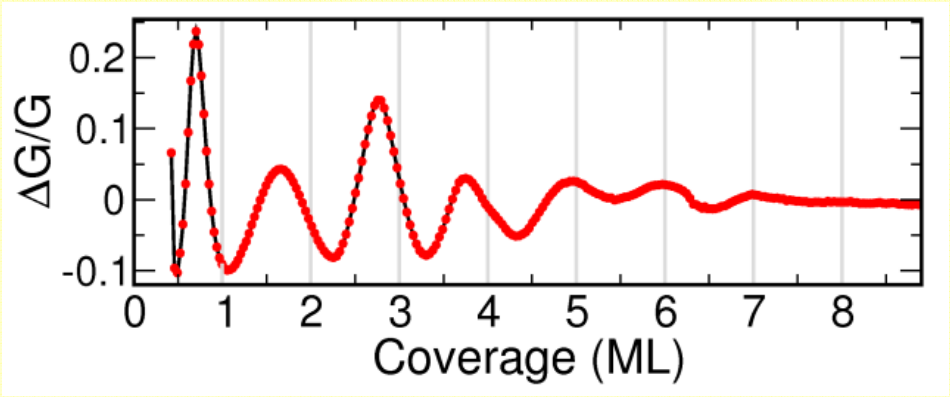
Small d ➔ small number of subbands ➔ x>2 (Calecki et al.)

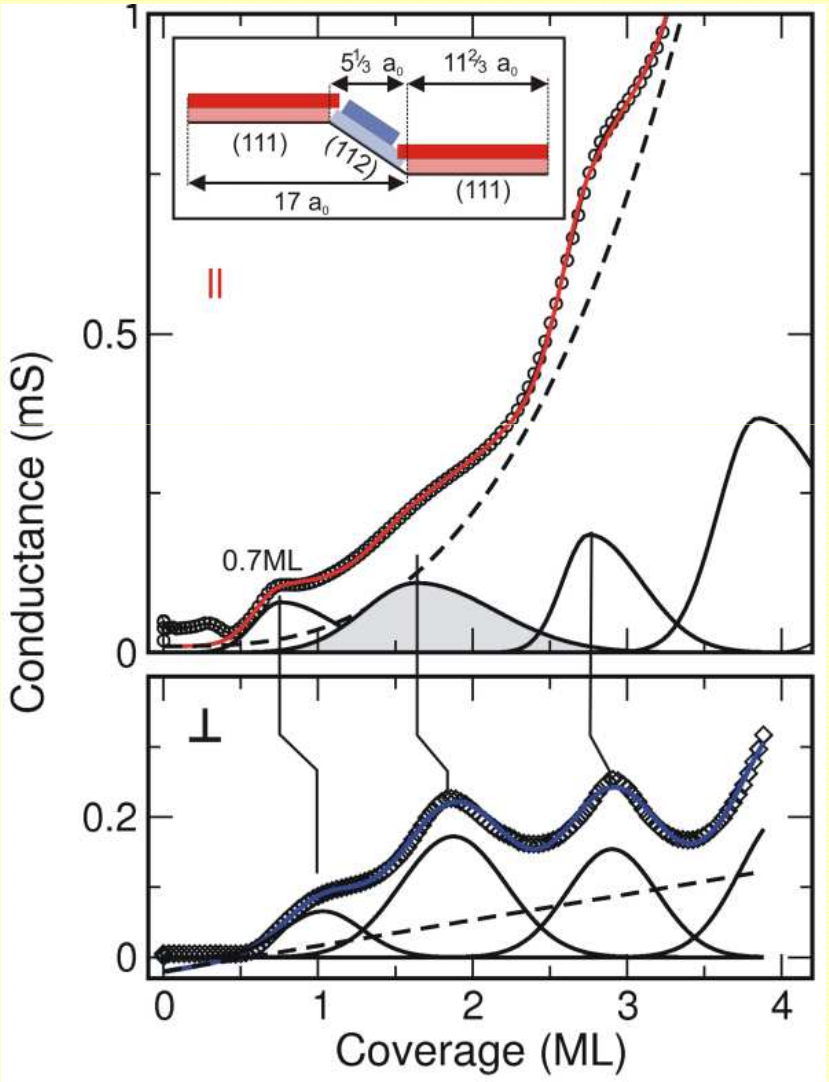
Overall behavior of $G_{\parallel}$ explainable by diffuse inferface scattering (without oscillations)

Quantum size effect: appearance of new subbands

- Responsible for oscillations
- Onset of plateaus by appearance of new subbands
- Non-monotonous variation of amplitudes and halfwidths
- Peaks in $G_{\parallel}$ appear before completion of layers

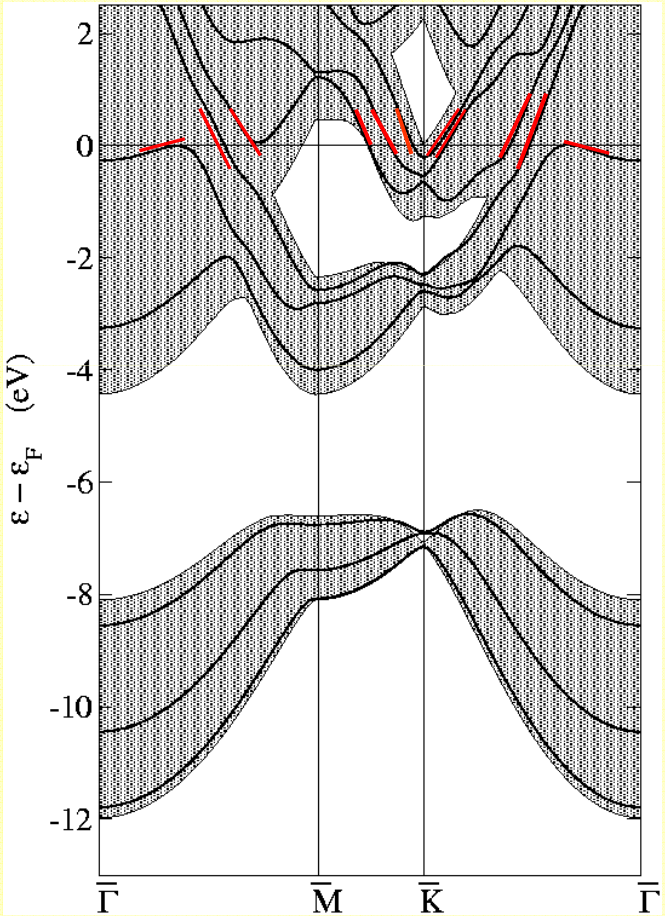
  ➔„chemical“ quantum effect



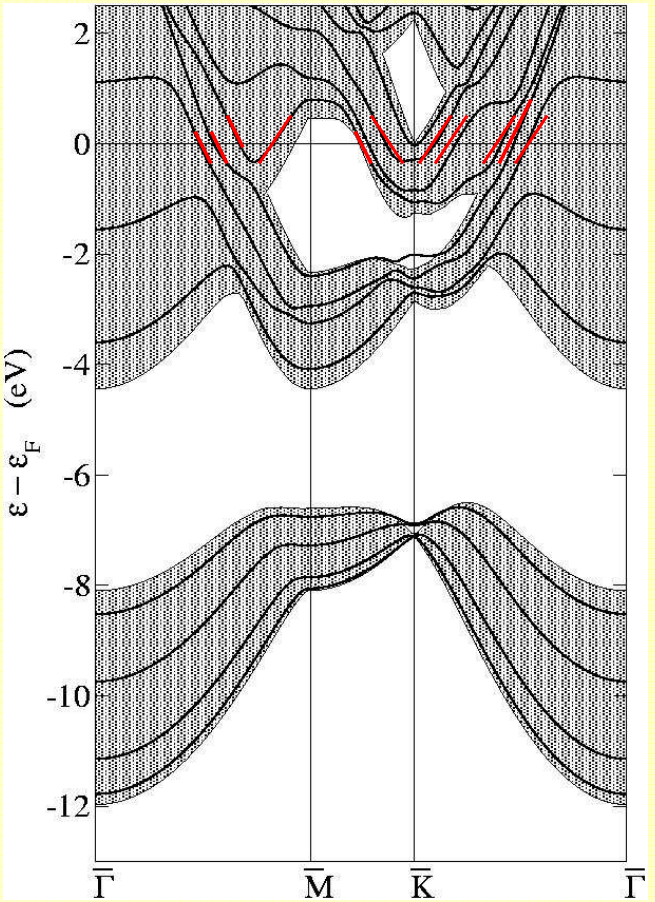


Pb-Band structure from DFT

3ML

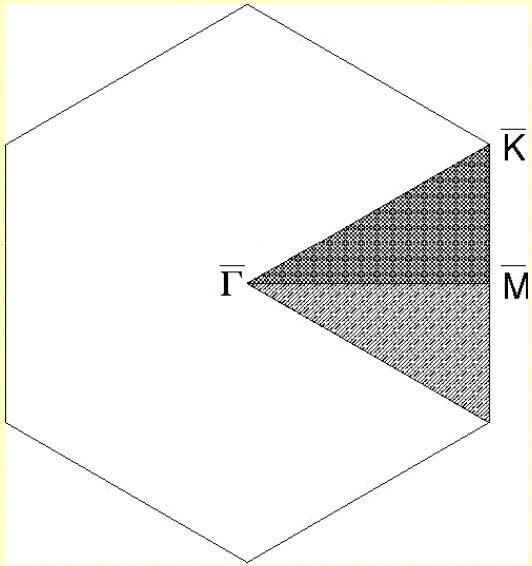


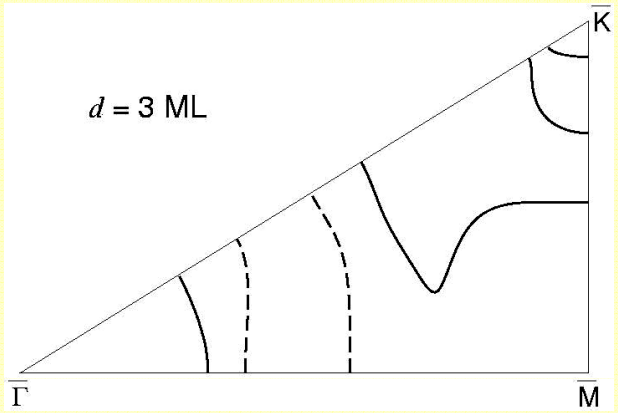
4 ML

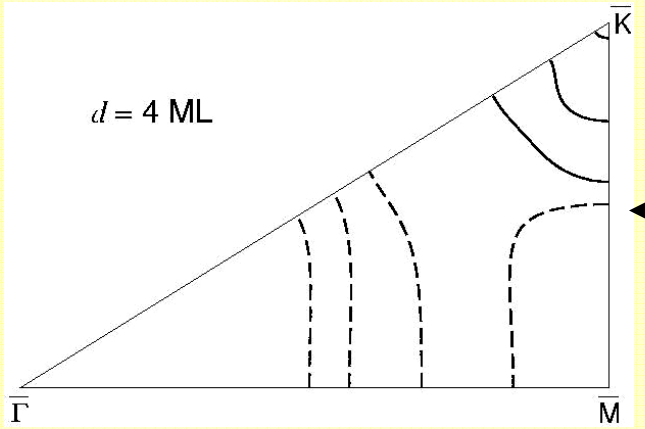


Calculations with free-standing Pb films

Fermi surface







← electron states

⟵ hole states

Quantum size effect: appearance of new subbands

- Responsible for oscillations
- Onset of plateaus by appearance of new subbands
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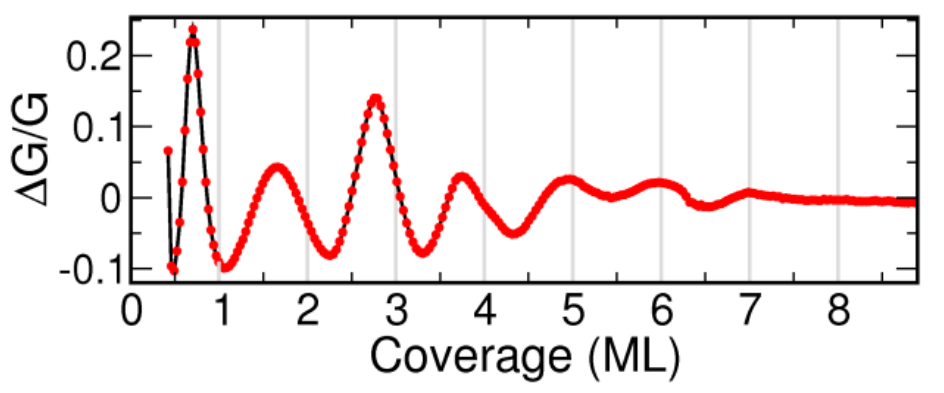
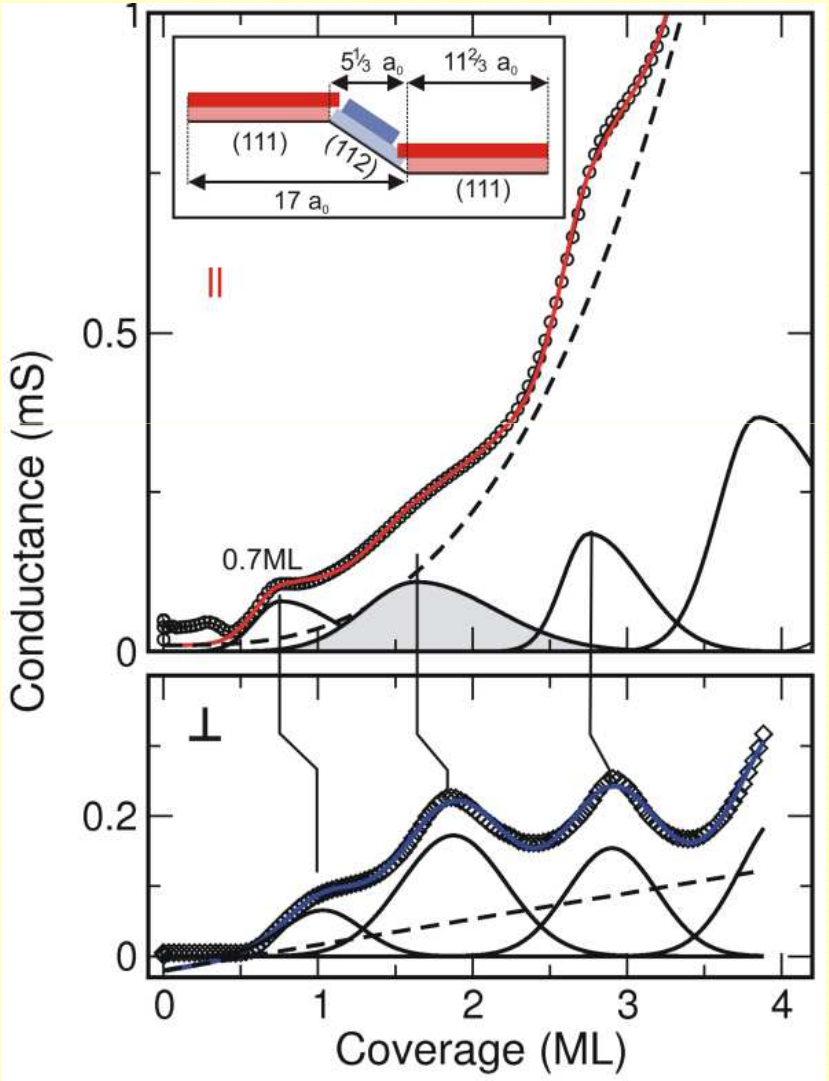
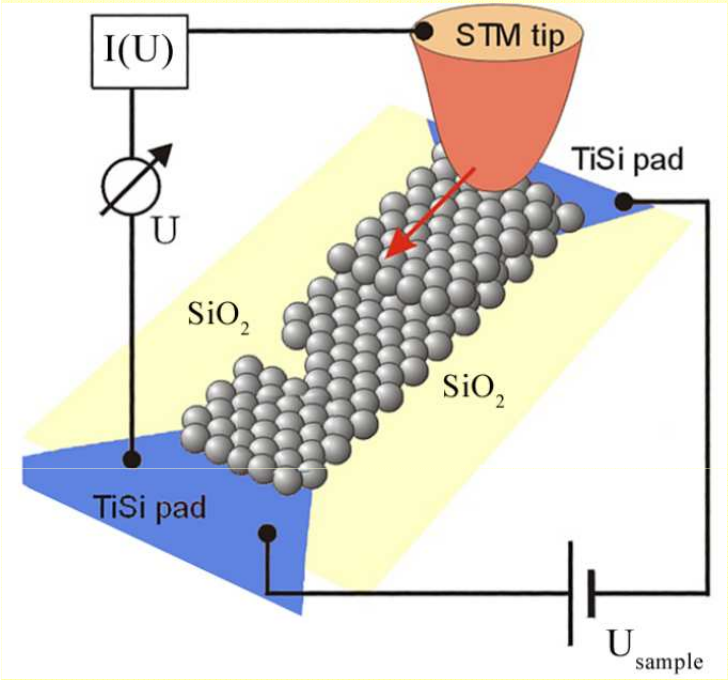
  ➔„chemical“ quantum effect

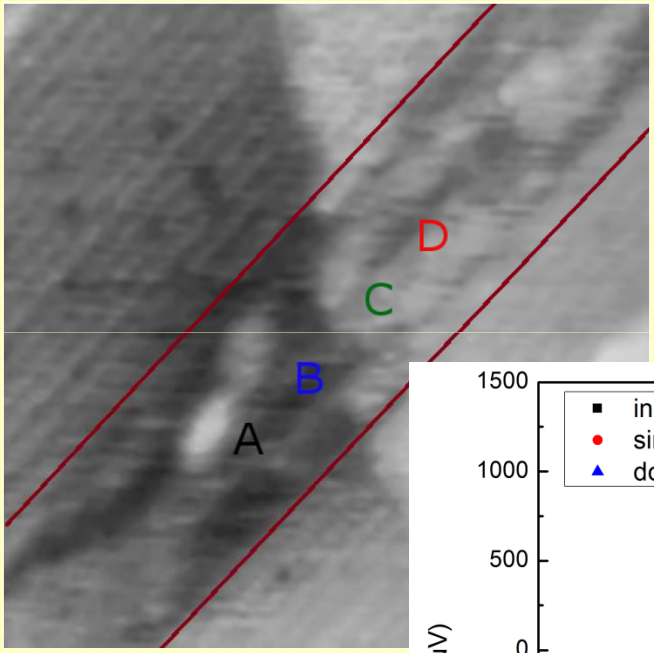


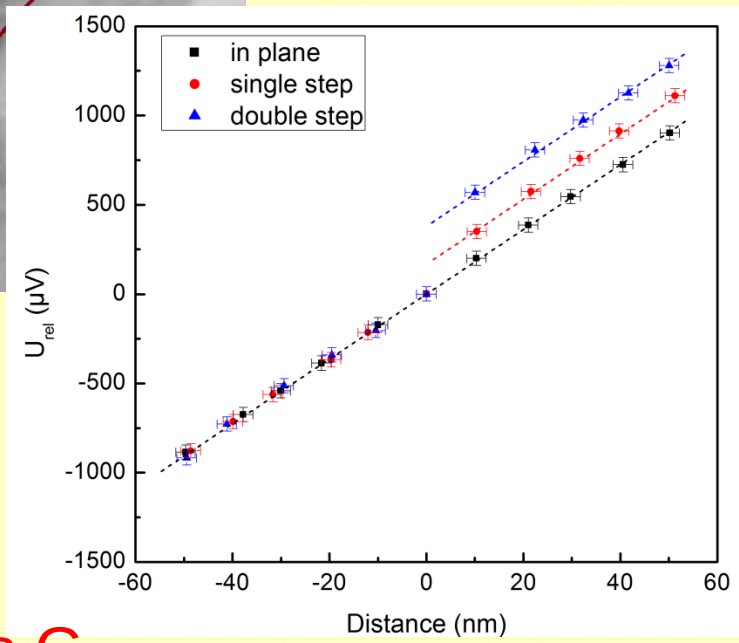
Parallel to steps



$G_\perp \sim d$: the resistance of single steps







Strip width 50 nm

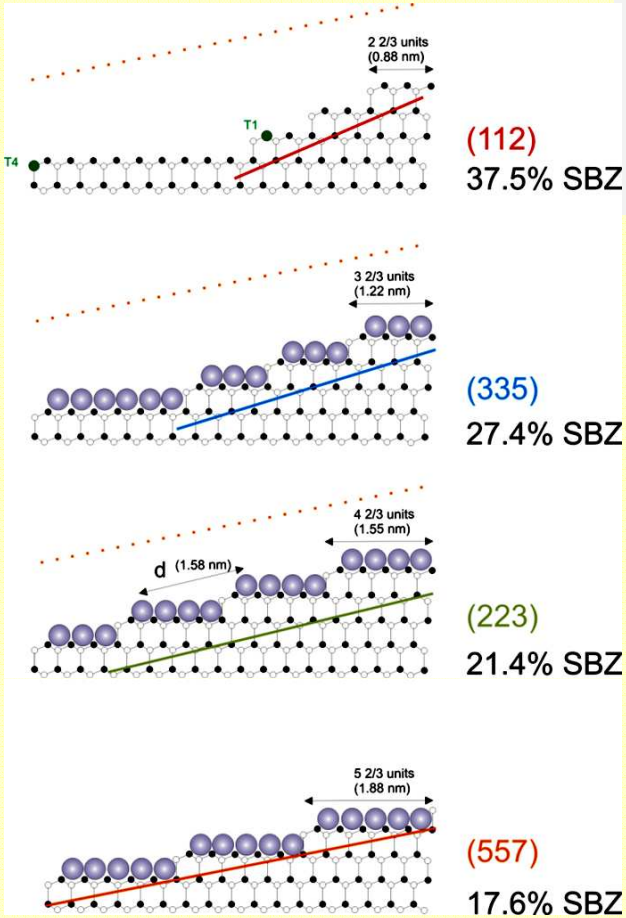
$\Theta_{Pb} \approx 1.7$ ML

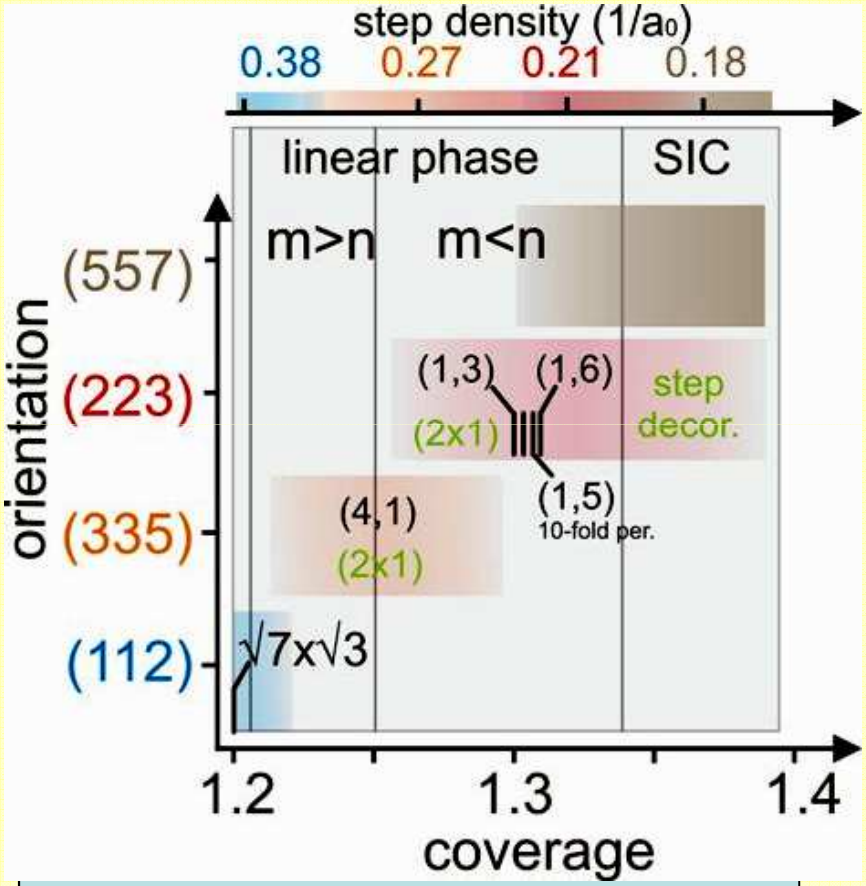
Constant resistivity ρ 13.4 Ω/nm

Double step (h = 3.14 Å): ~ 10-fold increase of ρ

Transmission through step determines $G_\perp$

High T-annealed first monolayer: re-facetting of Si(557)





Model ($1.20 < \Theta < 1.33$):

- **Steps stabilized by Pb**

Θ = 1.2 ML: (112) facets

- **Local Θ almost constant at all coverages**

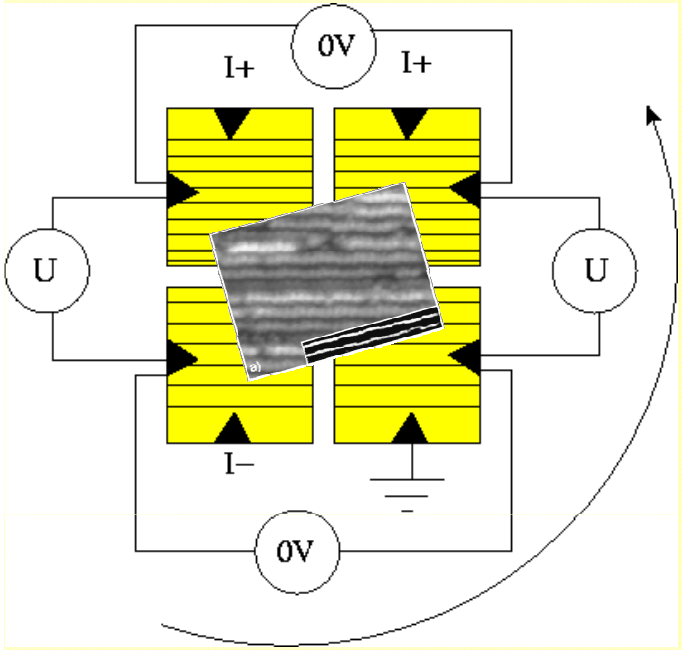
but:

- **Steps not covered by Pb**

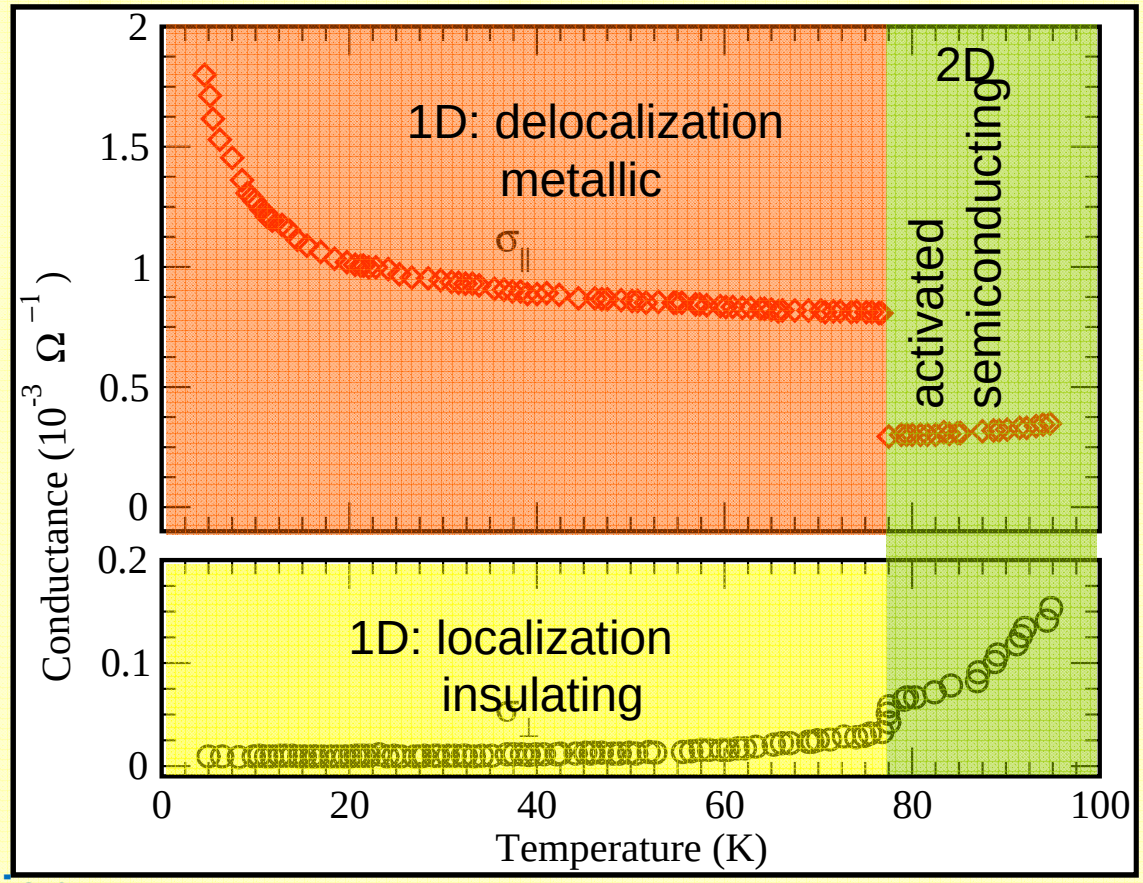
Increasing coverage:

Annihilation of steps more favorable than step decoration

One (1.3) ML of Pb on Si(557): Quasi-1D conductance



after removal of (7x7)



$T>T_C$: Anisotropic 2D behavior

$T<T_C$:

$\sigma_{||}$ metallic / delocalization

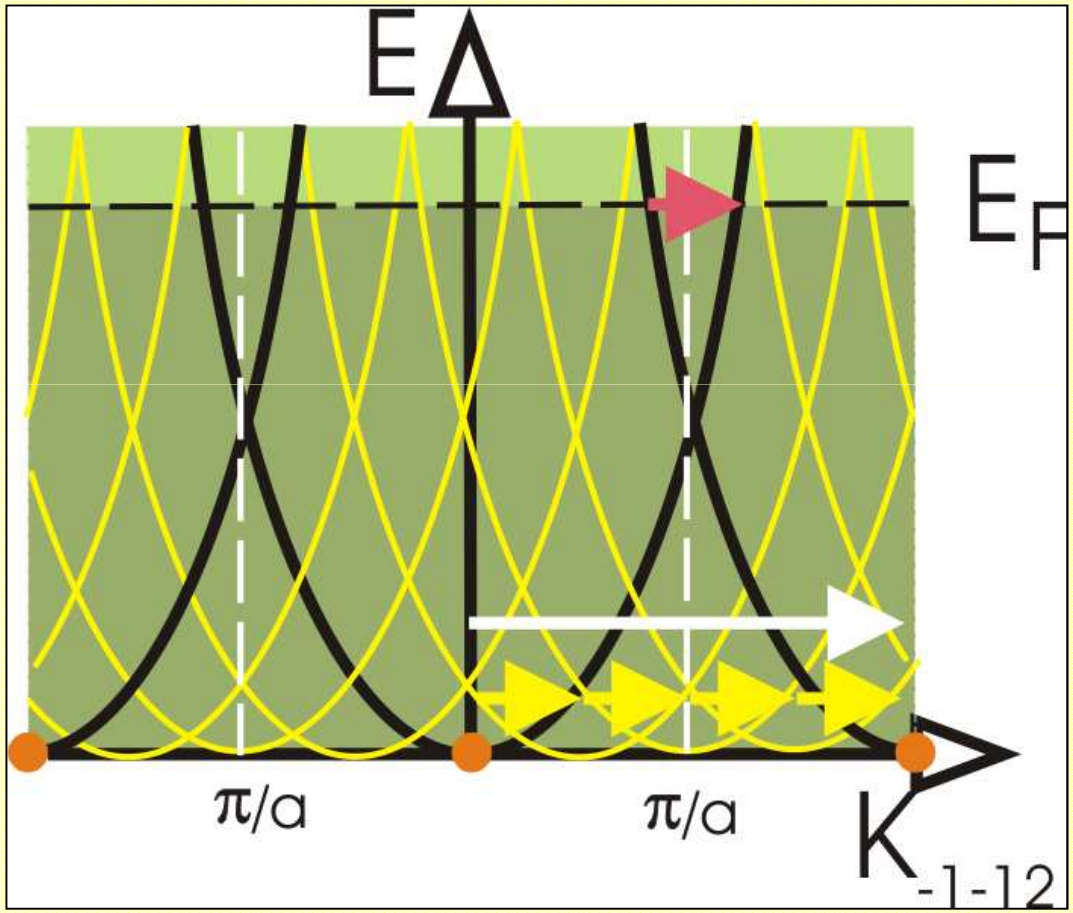
$\sigma_{\perp}$ insulating

Reversible !

- **Peierls transition only in direction normal to steps**
- **ideal 1d conductor**

Tegenkamp et.al. PRL **95**, 176804 (2005)

Nesting and transport:

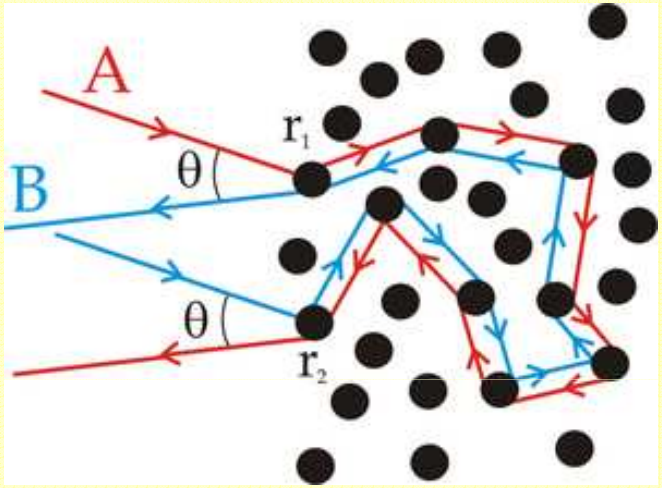


→ = →

$2\pi/d = 2k_F$

-> localization

Magnetoconductance:
Weak localization



Medium with (mainly elastically) scattering defects for electrons close to E_F

If Θ = 0°: constructive interference due to time reversal symmetry fo r paths A and B

➔Enhanced resistance

B-field destroys time reversal symmetry ➔ positive magnetoconductance

If contribution of spin orbit scattering is dominant:

(4π-symmetry of spin wave functions!) **Weak anti-localization**

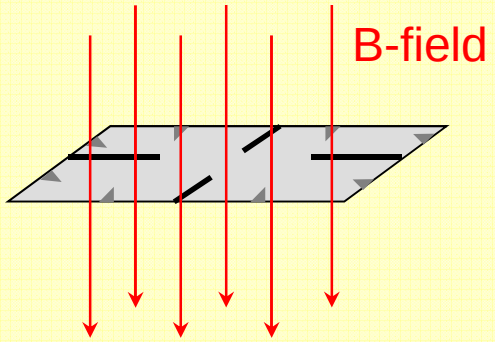
Electronic transport beyond the Drude model

Manipulation of Weak Localization by B-fields

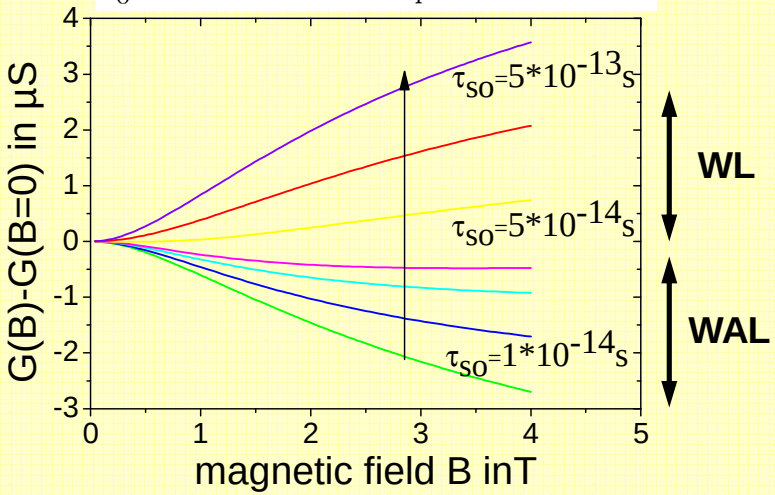
- Phase coherence at the origin is disturbed by external magnetic fields
- Phase shift of the partial waves $\Delta\varphi = \frac{2e}{\hbar}\Phi$

→ „*Hikami-theory*[1]“ of weak localization:

- Conductance depends on magnetic field B
- ΔG depends implicitly on 3 scattering times



$\tau_0 = 2 \cdot 10^{-14}\mathrm{s} \quad \tau_i = 5 \cdot 10^{-14}\mathrm{s}$



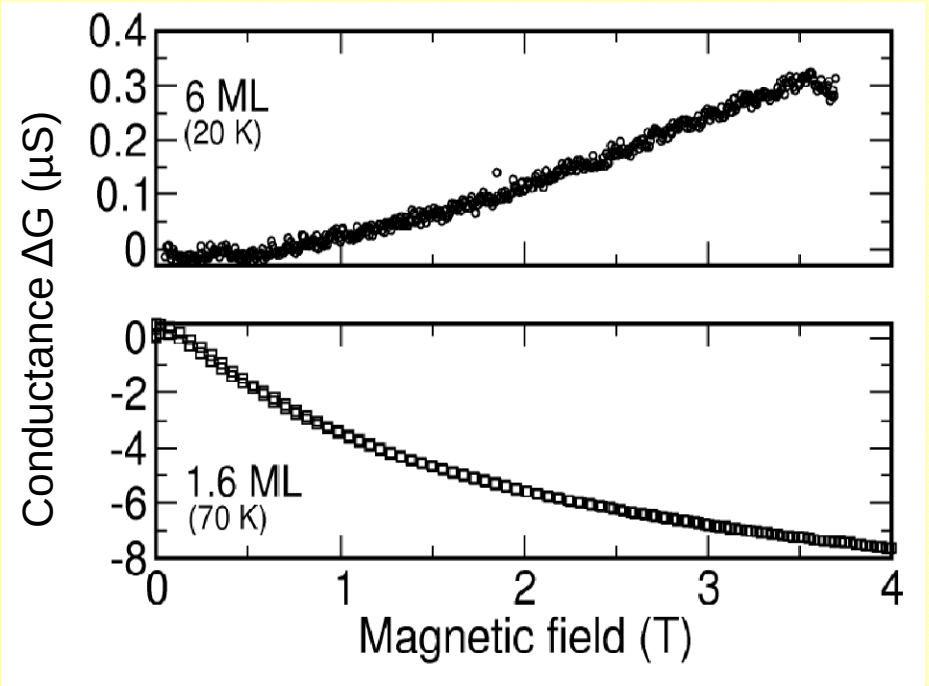
τ_0 : elastic scattering time
τ_i : inelastic scattering time
τ_{so} : spin-orbit scattering time

$$\Delta G(B) = G(B) - G(B=0) = -G_{00} \cdot [f_1(B, \tau_0, \tau_{so}) + f_2(B, \tau_0, \tau_i, \tau_{so}) + f_3(B, \tau_0, \tau_i)]$$

$$G_{00} = \frac{e^2}{2\pi^2\hbar} = 0,123 \cdot 10^{-4} S$$

1) Hikami et al., Prog. Theor. Phys. Vol. 63 (1980)

Magnetoconductance - Pb films vs. monolayers



multilayers

monolayers

Conductance change ΔG vs. magnetic field B:

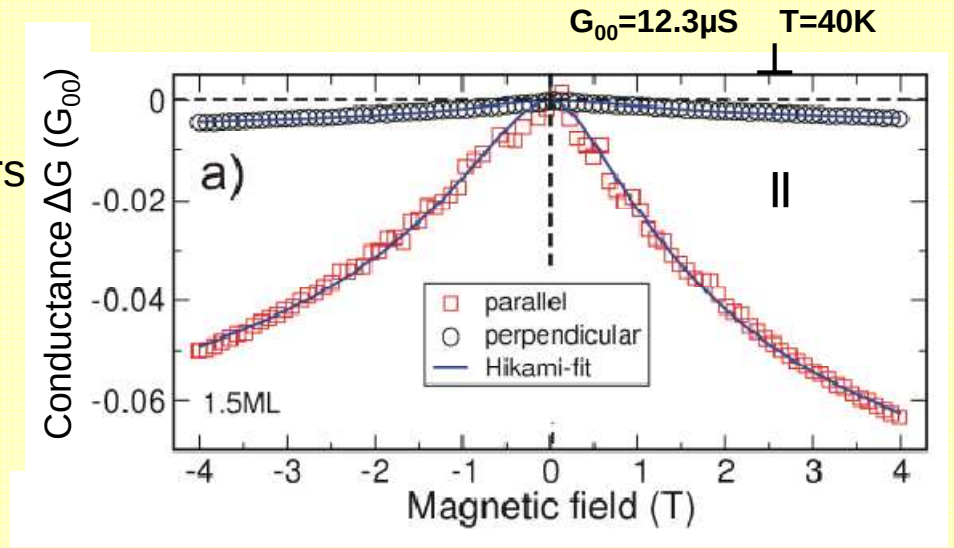
- multilayers → **Weak Localization**
- monolayer → **Weak Anti-Localization**
- **spin-orbit and elastic scattering strong for monolayers**
- **band structure/Fermi surface is different to Pb films**

From: D. Lükermann et al., Phys. Rev. B 81 (2010)

Monolayers: anisotropic magnetotransport

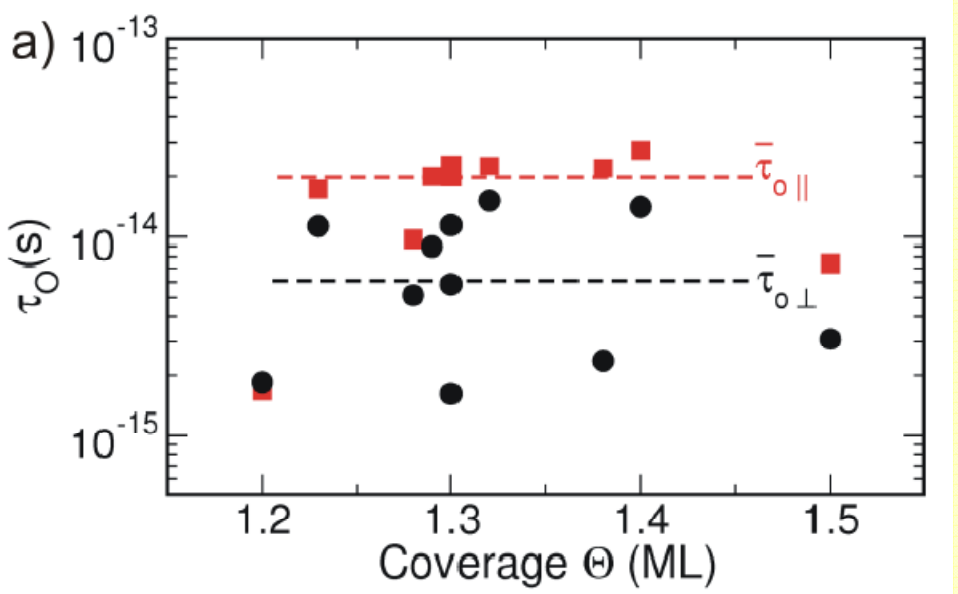
- anisotropy of Pb/Si(557) surface is reflected in magnetotransport of monolayers
- Hikami theory fits the data accurately

→ scattering times can be determined



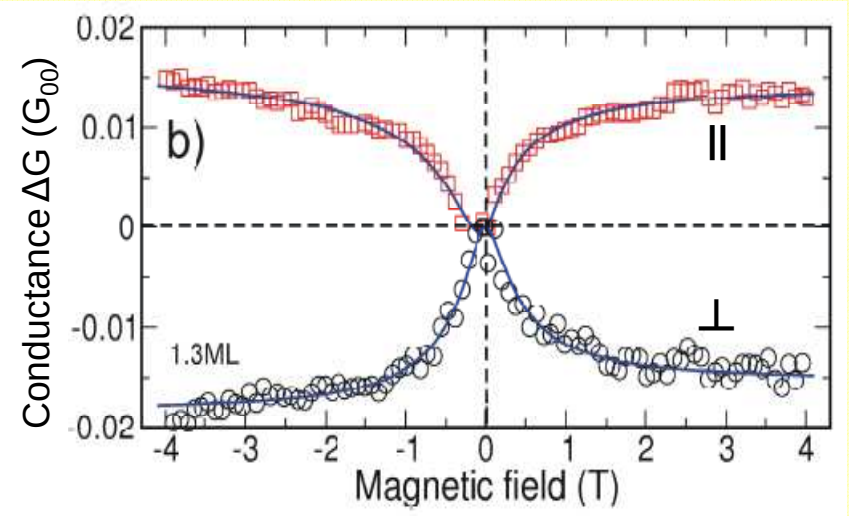
- elastic scattering time is shorter perpendicular to the steps

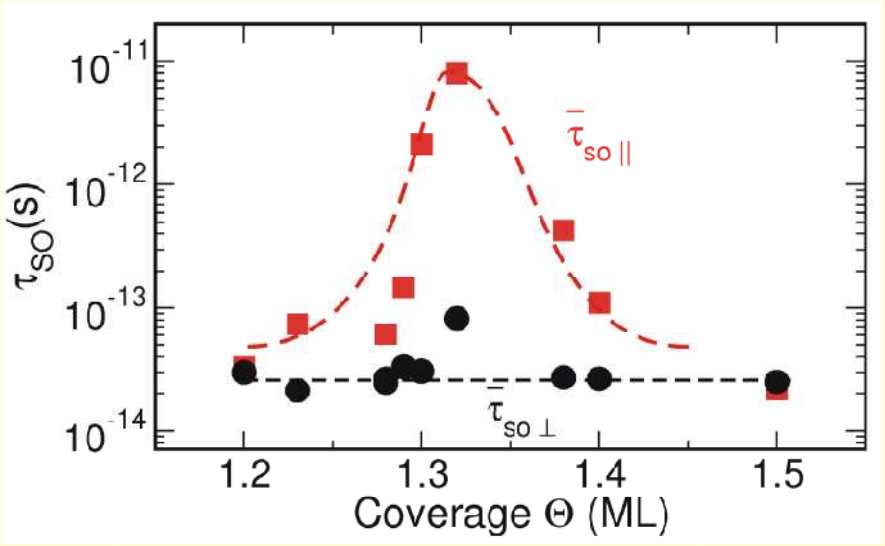
→ **steps act as scatterers**



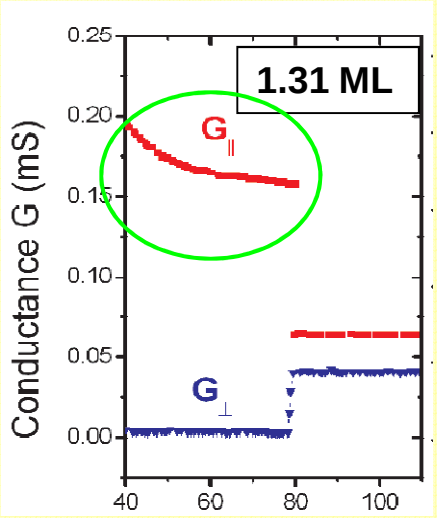
D. Lükermann et al.Phys. Rev. B 81 (2010)

Suppressed spin-orbit scattering





- peculiar behavior for 1.3 ML:
- **WL in parallel ↔ WAL in perp. direction**

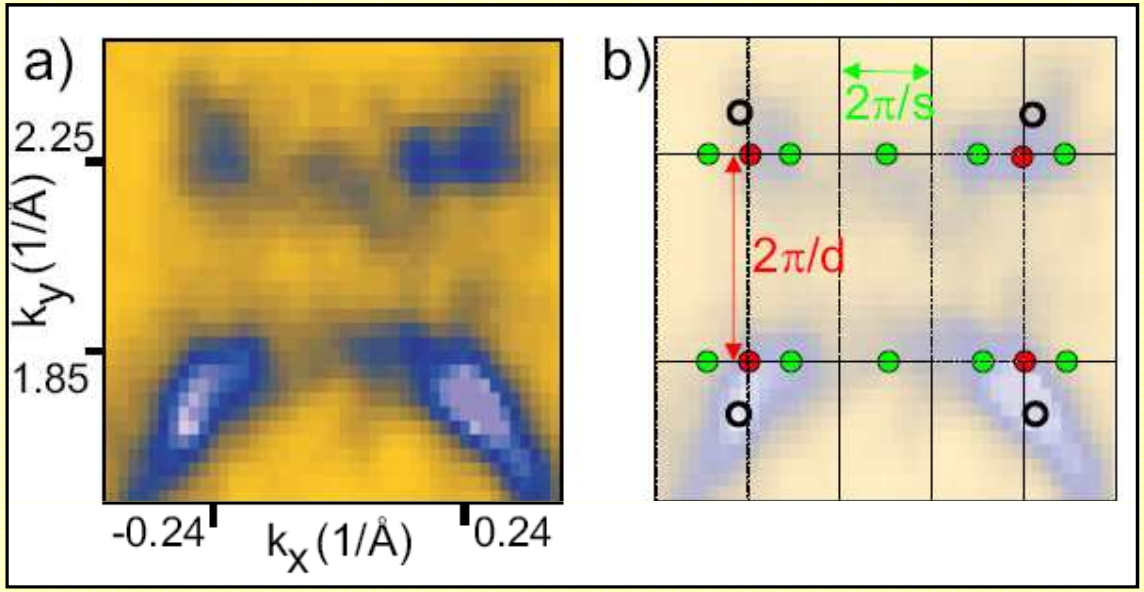


- reduced spin-orbit-scattering in parallel
- maximum @ 1.3 ML, 3 orders of magnitude

→ **reason for metallic conductivity in 1D-regime?**

D. Lükermann et al.,

Phys. Rev. B 81 (2010)



Tentative explanation:

If bands marked by green dots are spin polarized: Spin Umklapp forbidden

Strictly fulfilled only at 1.3 ML

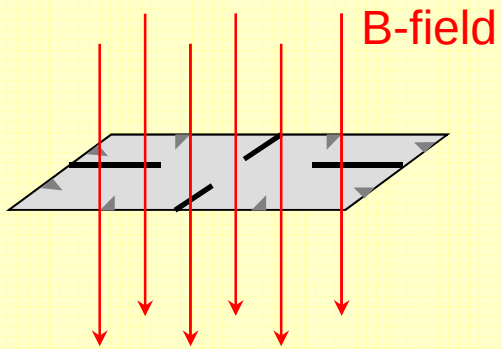
Outside this coverage:

- Other periodicities along the terraces
- Thermal activation to other bands

Summary

Dc-conductance:

- Steps very effective for strain accomodation
- Conductance measurements very sensitive to anisotropic layer distortions
- Classical
- Quantum size effects for very thin layers



Magnetotransport of Pb/Si(557)

- Hikami-theory describes the data very well
- **WL** for Pb films, **WAL** for Pb monolayers
- **anisotropy** of surface visible in conductance and deduced scattering times
- peculiar behavior of spin-orbit scattering time around **1.3 ML (0.85 PML)**
  → **spin-orbit scattering strongly suppressed**
  → possibly due to **spin polarized** split-off **bands**