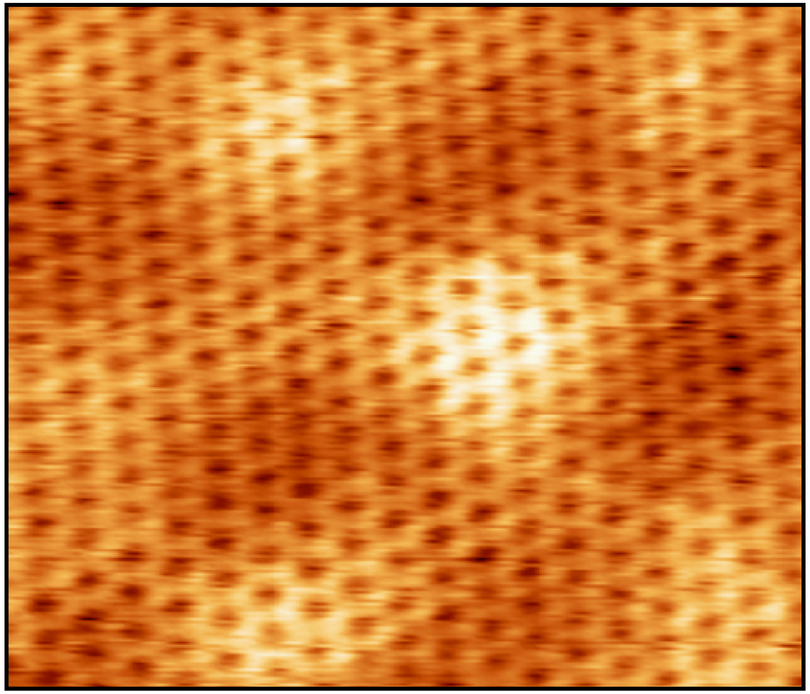
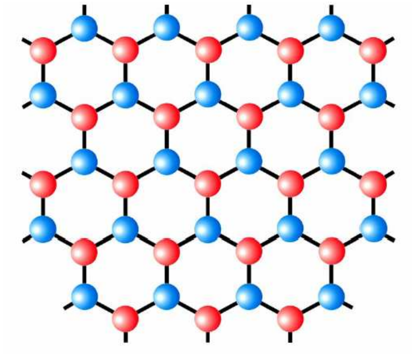
Probing quantum interference effects in epitaxial graphene: STM and magnetotransport studies



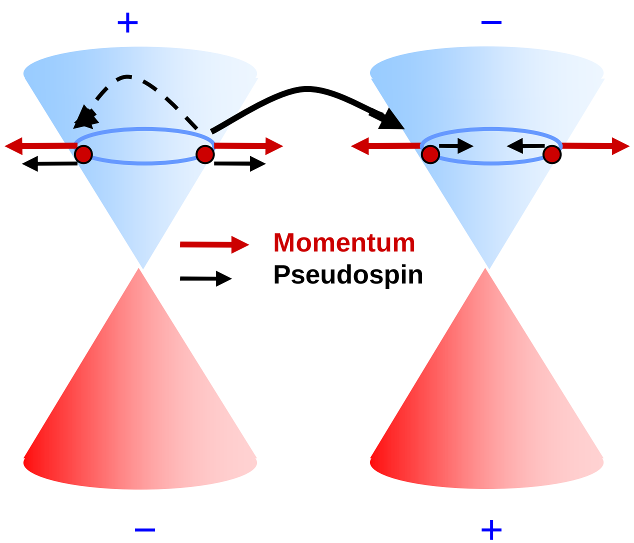
Ather Mahmood, C. Naud, J-Y. Veuillen, P. Mallet, L.P. Lévy

Imagine Nano April 12, 2011

Quasi particle scattering in graphene

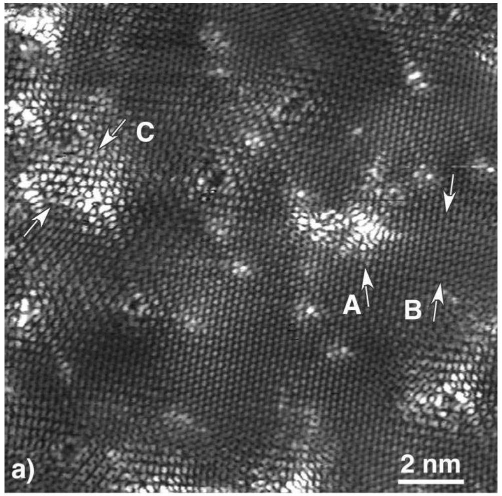


Addl. Quantum numbers:
Pseudospin and Isospin
» intervalley, intra valley scattering

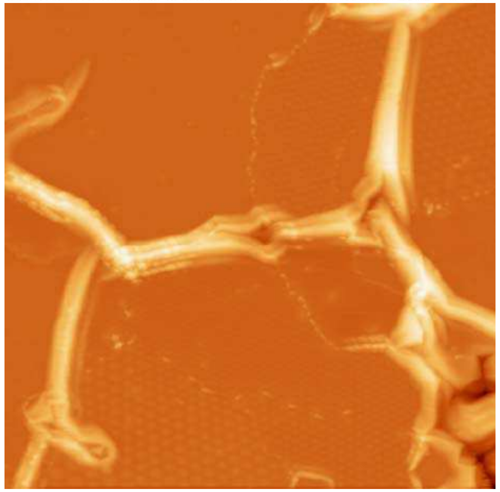


Defects contribute to scattering

Atomically sharp defects



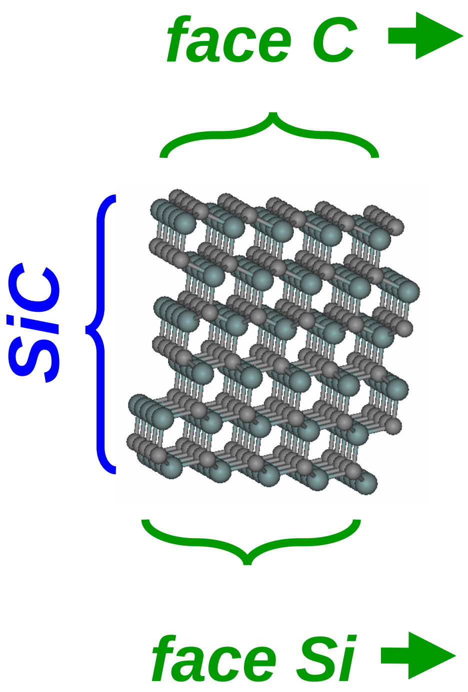
Folds and ripples

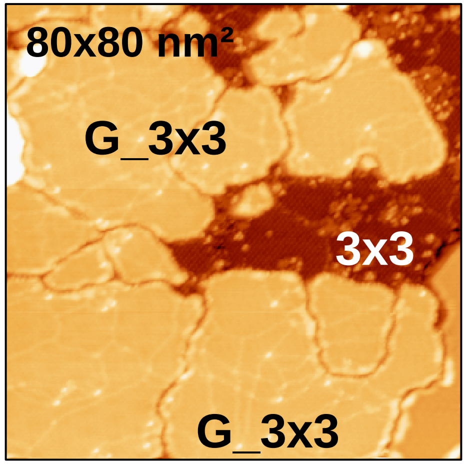


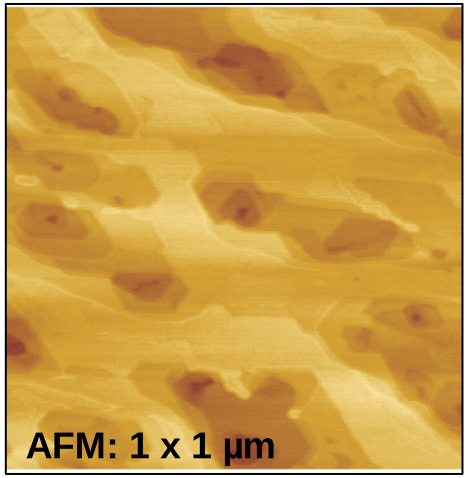
*P. Ruffieux, et al, Phys. Rev. B **71**, 153403 (2005)*

F. Varchon,, et al, Phys. Rev. B 77, 165415 (2008)

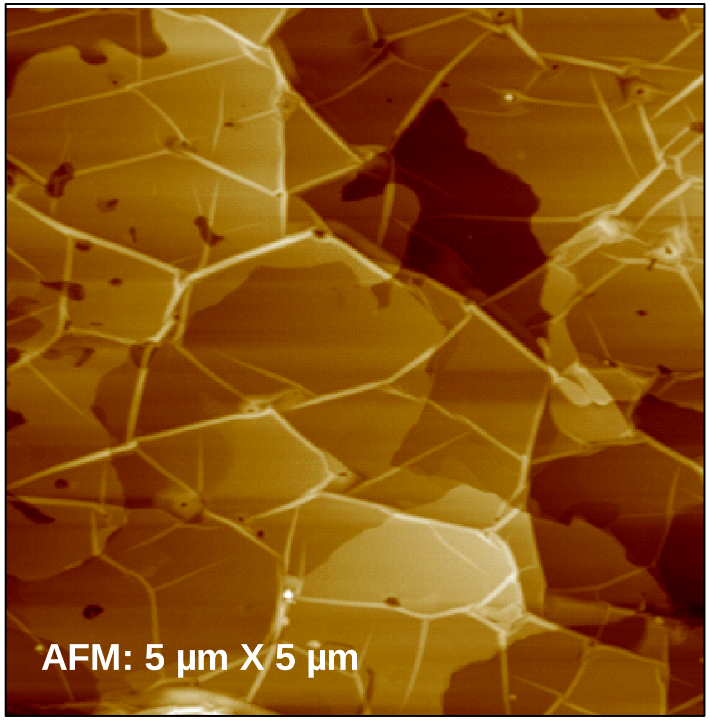
Growth of epitaxial graphene







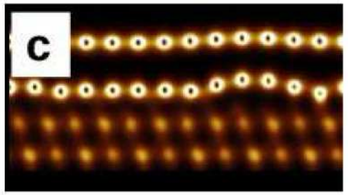
UHV grown
Low temperature ~1300℃
UHV environment
1-2 ML graphene

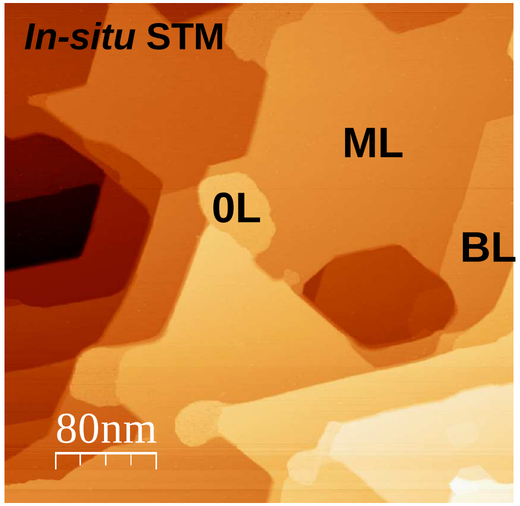


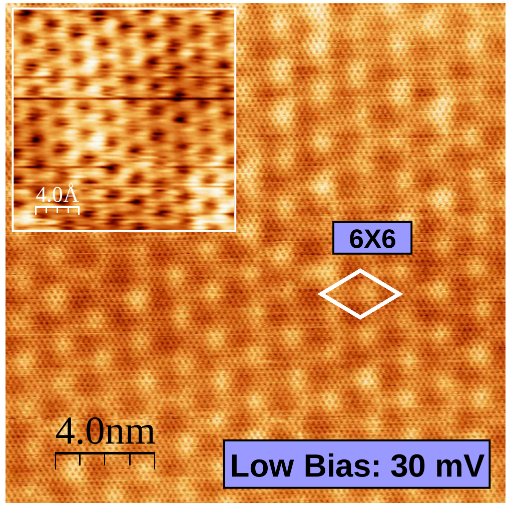
Grown in inert atmosphere
High temperature ~2000℃
Argon atmosphere
Several layers

Multilayered samples:
LMGP Grenoble

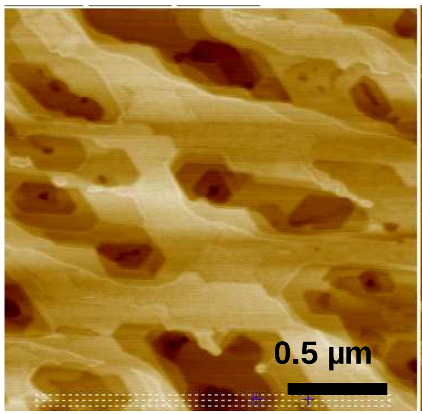
Graphene on Si face SiC



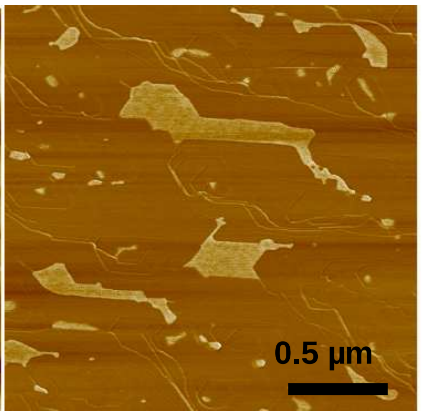




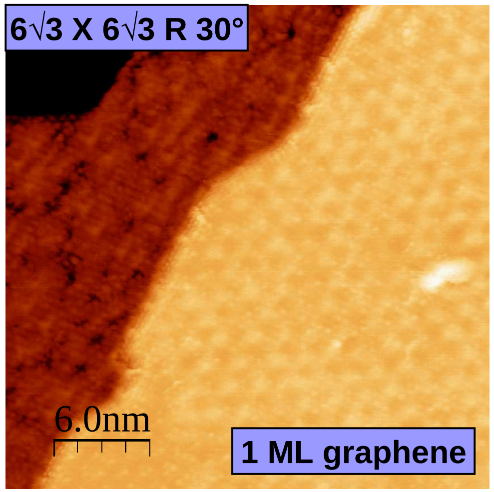
Si face:
Buffer layer coverage



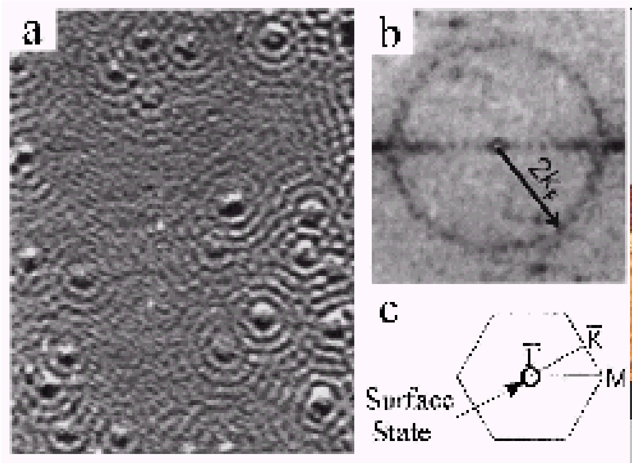
Topography



Phase

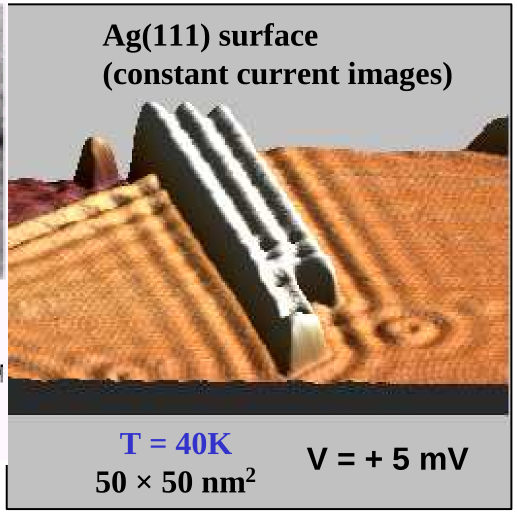


Impurities in a 2-D system

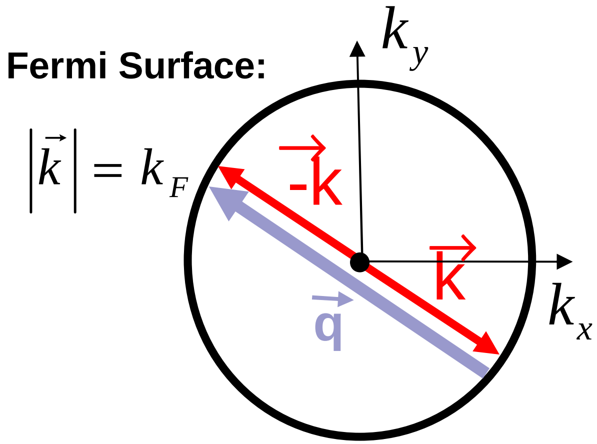


L. Petersen et al., Phys. Rev. B ***57****, R6858 (1998)*

Collection of impurities on Cu(111)



The impurity potential induces quasiparticle interferences



LDOS modulation of

wavevector $q = 2k_F$

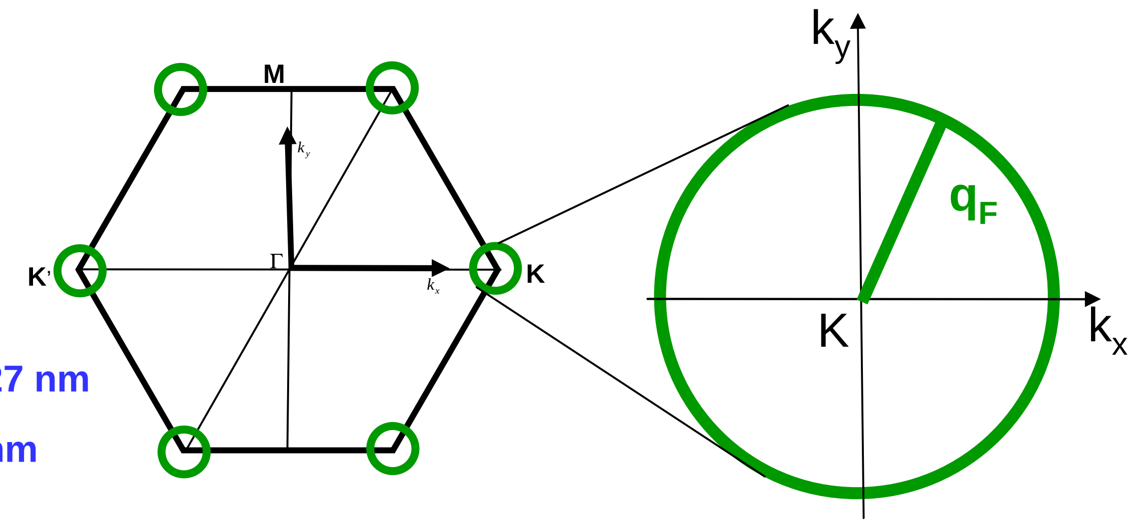
QI in ML and BL epitaxial graphene:

Fermi Surface:
ML and BL

$\Gamma K = k_F$

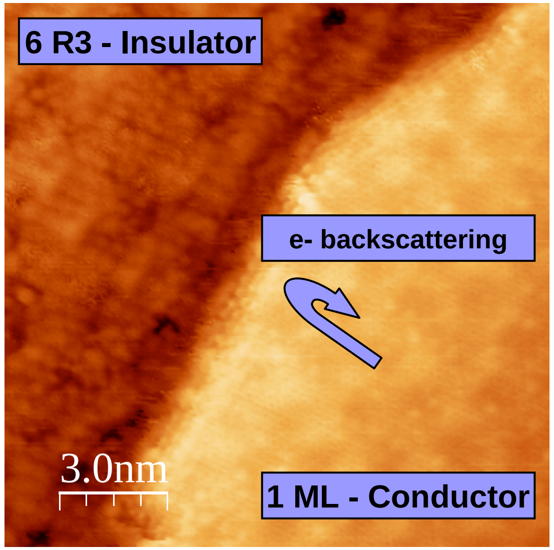
Intervalley scattering: $\lambda_F = 2\pi / k_F = 0.27$ nm

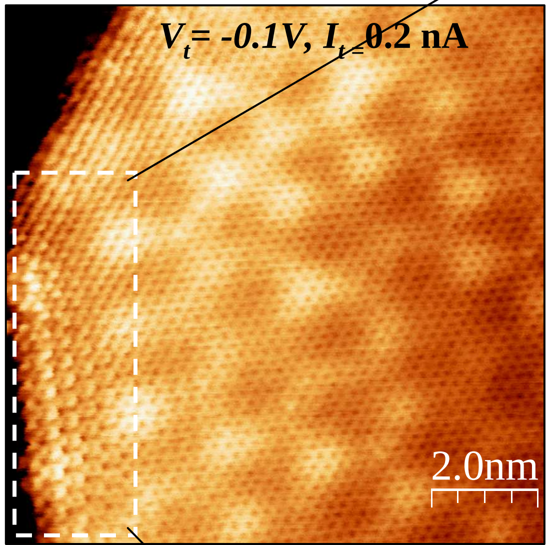
Intravalley scattering: $\lambda_F = \pi / q_F \approx 5.2$ nm

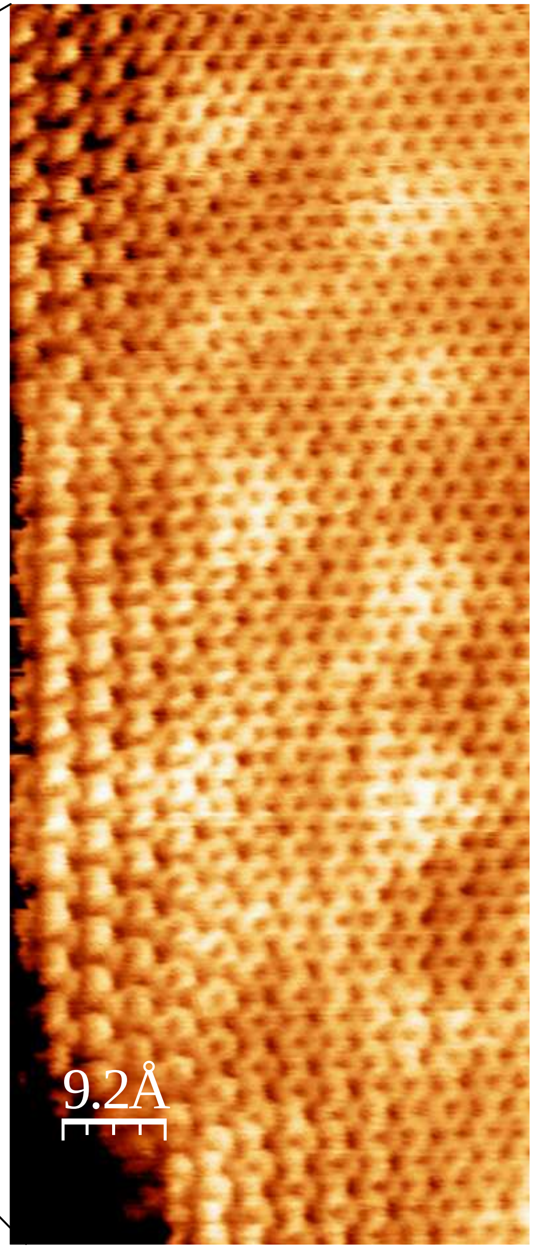


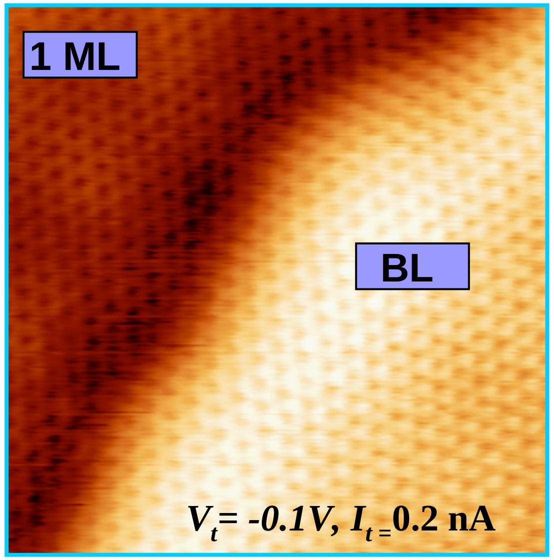
Interferences at the edges

✓Controlled growth
✓Junction between 1 ML and buffer layer



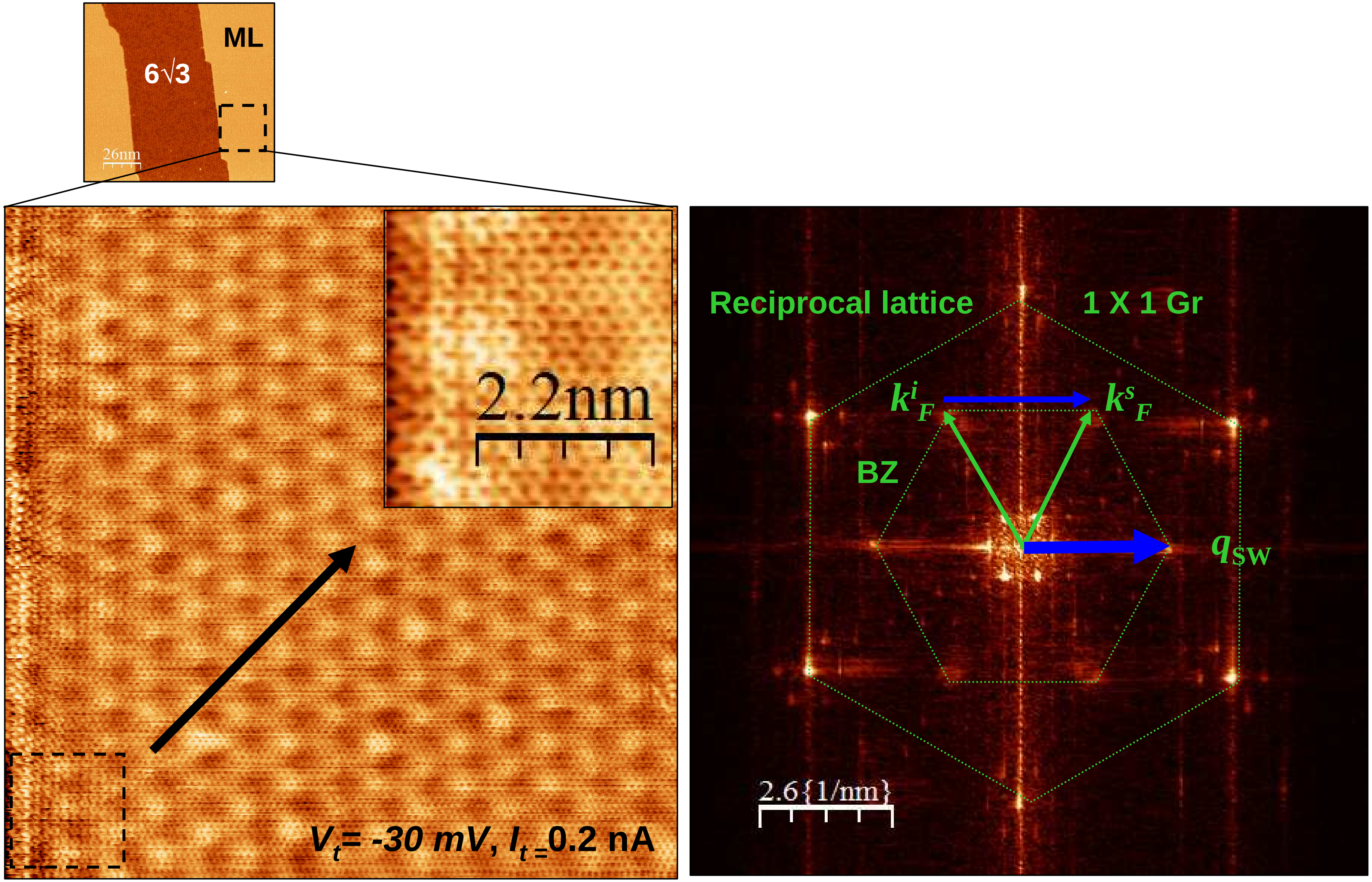




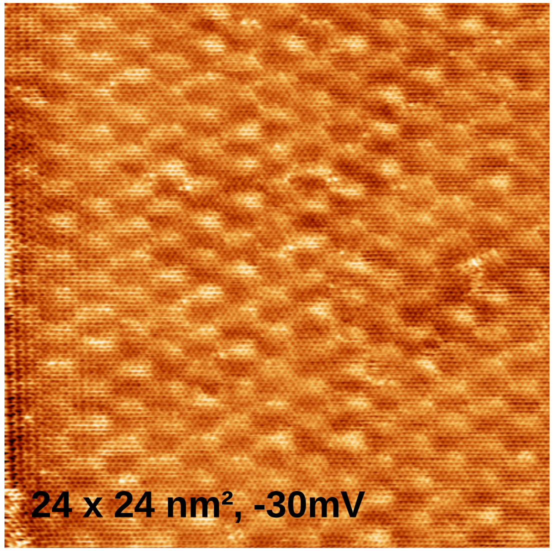


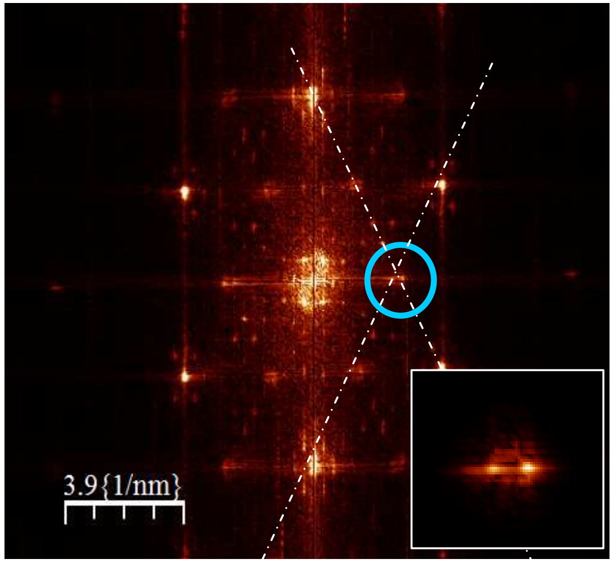
✓ No backscattering at ML/BL junction

Interferences at the edges II

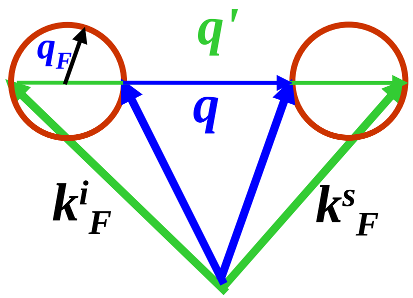


Interferences: Effect of doping



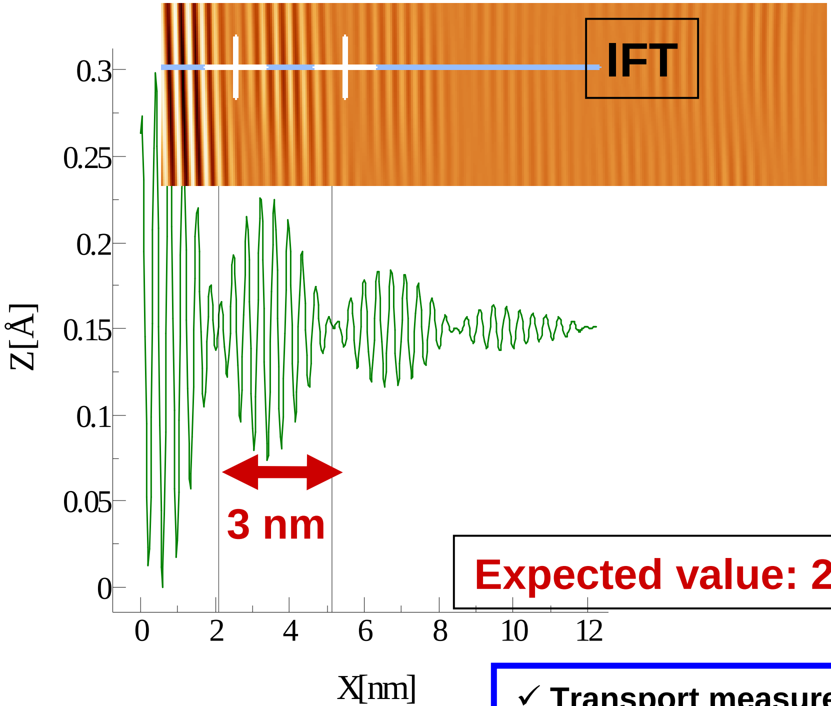


Fermi surface > finite size



$q' - q = 4\ q_F$

Similar results:
H. Yang, et al, Nanolett. . Advanced online



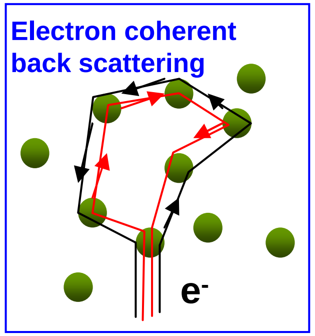
- Beating of different periods for intervalley scattering due to finite radius q_F of the Fermi surface (doping): $\Gamma K \pm 2q_F$ (q_F = 0.06 Å^{-1})
- Pseudo-period of beating events ~2.9 nm
- Beat period 3 nm from IFT

Expected value: 2*π/(0.22 Å^{-1})=29 Å

✓ Transport measurements will complement the microscopic backscattering studies

Weak localization for a 2 DEG

A sensitive tool for QI effects



$$A_p = |A_p| \exp(iS_p)$$

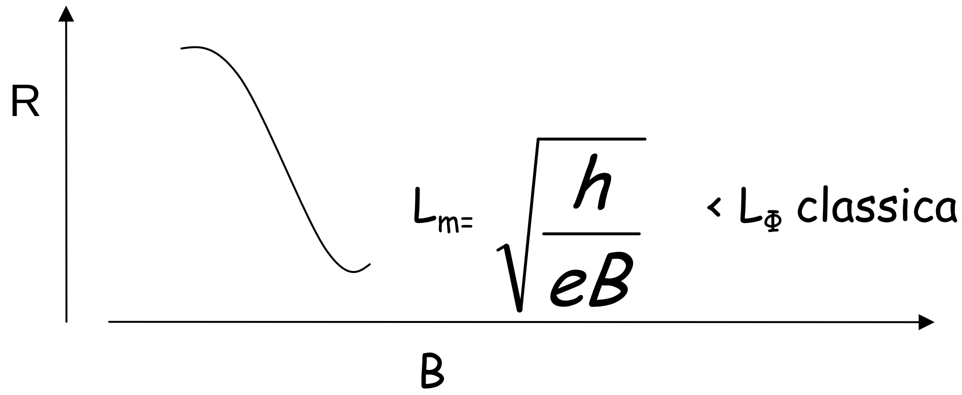
$$S_p = \int_p \vec{k} \cdot d\vec{r}$$

$$A_p A_q^* \mapsto \Delta\Phi = S_p - S_q = \int_p \vec{k} \cdot d\vec{r} - \int_q \vec{k} \cdot d\vec{r}$$

Probability of backscattering

$$P(\vec{R},\vec{R}) = |A_p + A_{-p}|^2 = |A_p|^2 + |A_{-p}|^2 + A_p A_{-p}^* + A_p^* A_{-p}$$

Conventional systems:
inelastic / magnetic impurities



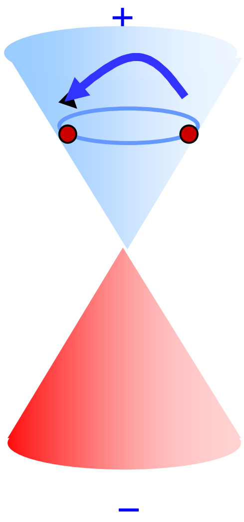
$$L_m = \sqrt{\frac{h}{eB}} < L_\Phi \text{ classical value}$$

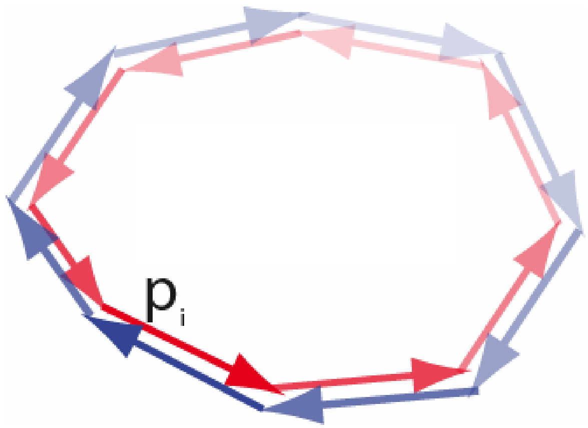
Localization for graphene

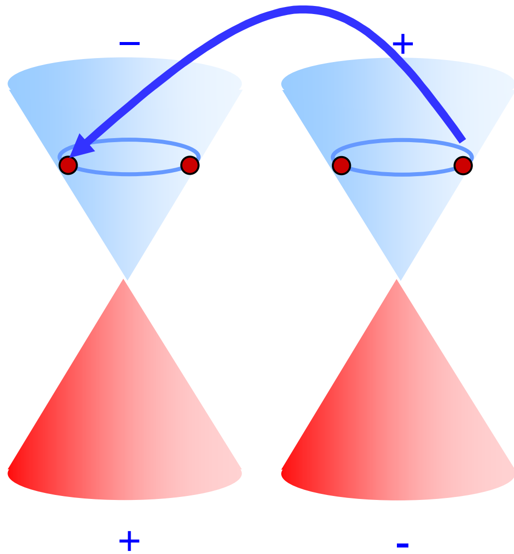
Graphene:

Inelastic / Elastic

Berry's phase➔ antiphase







For an intra-valley scattering :

The isospin stays linked to the momemtum direction.

2π rotation changes the sign of wavefn

ANTI-LOCALIZATION

For an inter-valley scattering :

The isospin is averaging to zero

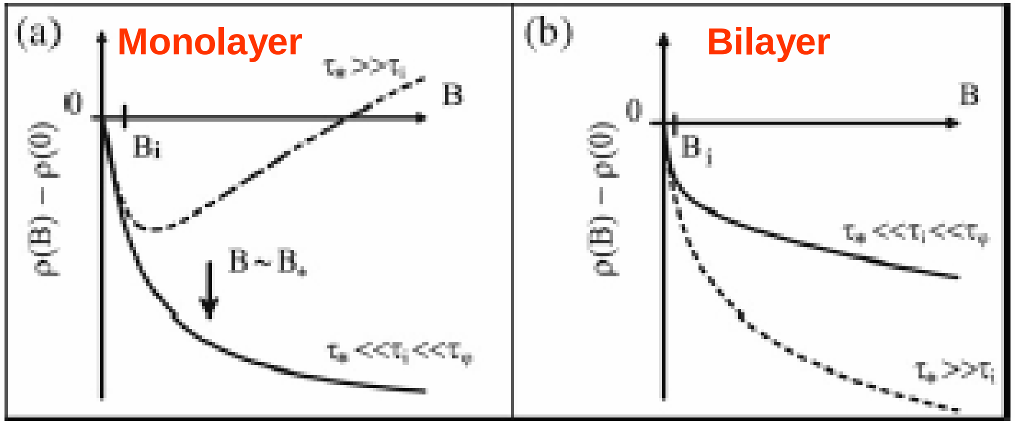
LOCALIZATION

Intervalley

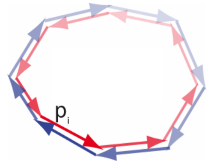
$$\Delta\sigma(B) = \frac{e^2}{\pi h}\left(F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1}}\right) - F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + 2\tau_i^{-1}}\right) - 2F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + \tau_i^{-1} + \tau_*^{-1}}\right)\right)$$

Intravalley

$$F(z) = \ln z + \psi\left(\frac{1}{2} + \frac{1}{z}\right),\ B_{\varphi,\mathrm{i},*} = \frac{\hbar c}{4De}\tau^{-1}_{\varphi,\mathrm{i},*}.$$



E. McCann, et al., Phys. Rev. Lett. ***97****, 146805 (2006).*
*V. I. Falko, K. et al., SolidState Comm****143****, 33 (2007).*
K. Kechedzhi, et al., Eur. Phys. J. Spec. Topics, 148, 39 (2008).



Scattering mechanisms

Inelastic: Phase breaking, τ^{-1}_φ

Elastic: Chirality breaking, τ^{-1}_s ➔ Sharp defects, dislocations

Intravalley, τ^{-1}_i ➔ Lattice spacing sized

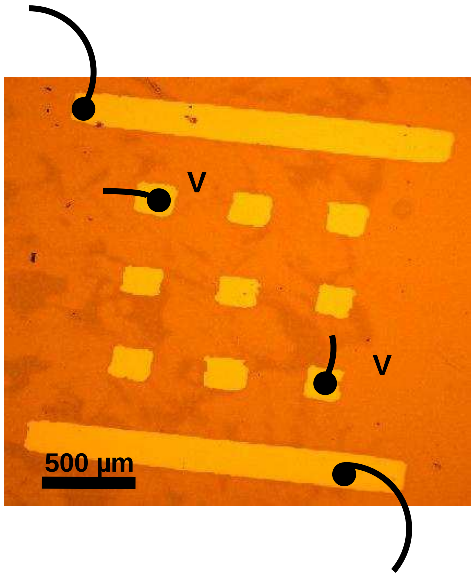
Interplay restores or supresses WL

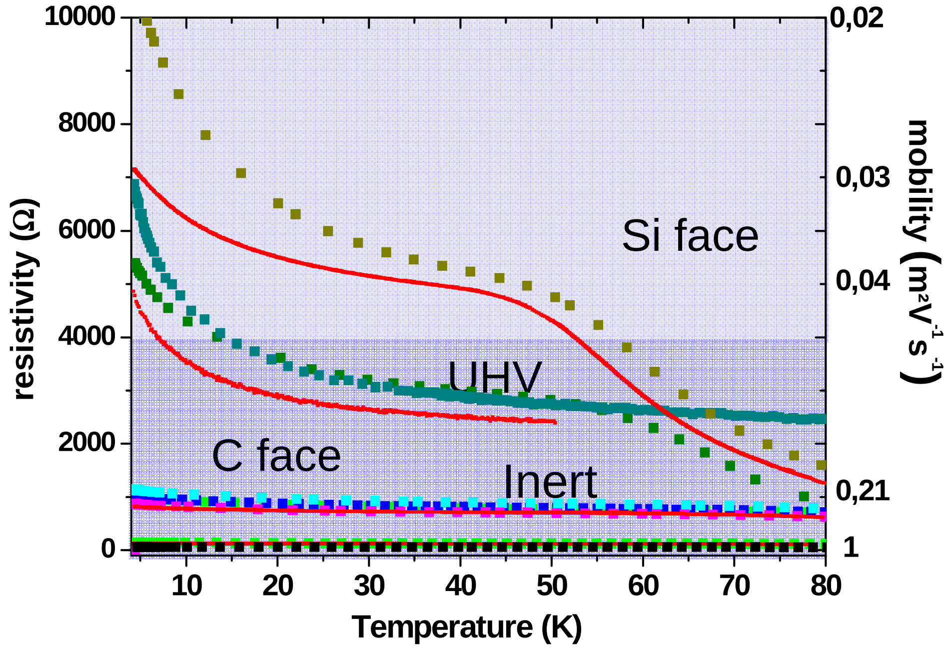
Can we observe different regimes versus the growth conditions ?

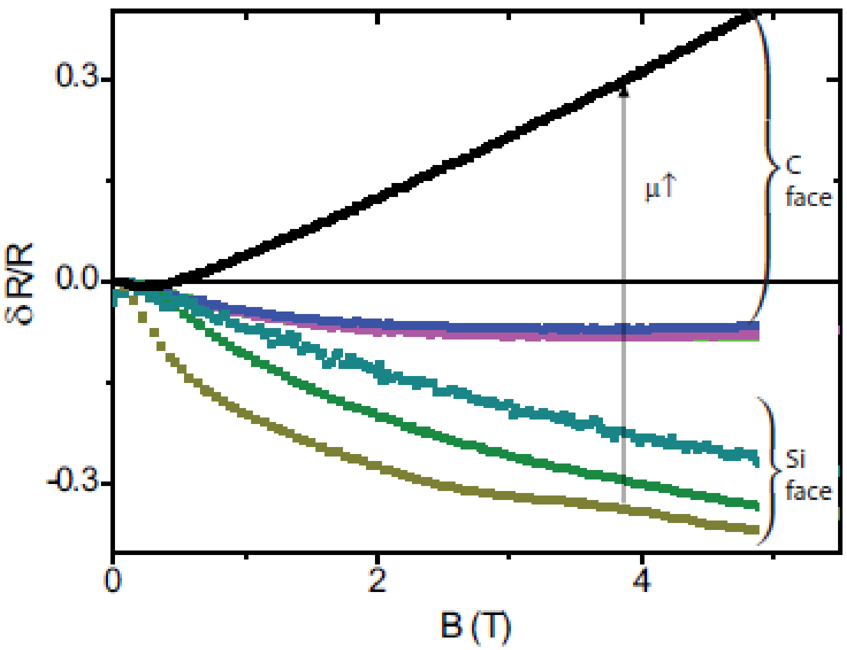
2D Transport properties

Sample conditions:

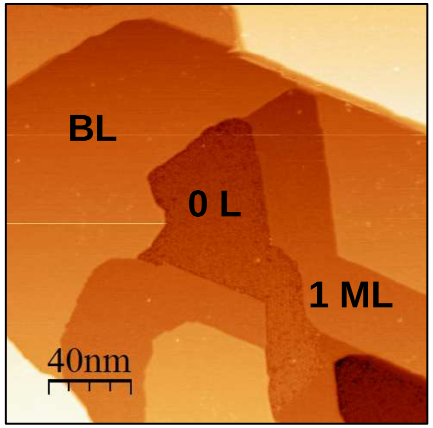
✓Contact on large area 2 mm X 2 mm
✓Metal pads by shadow mask
✓ Resist free deposition



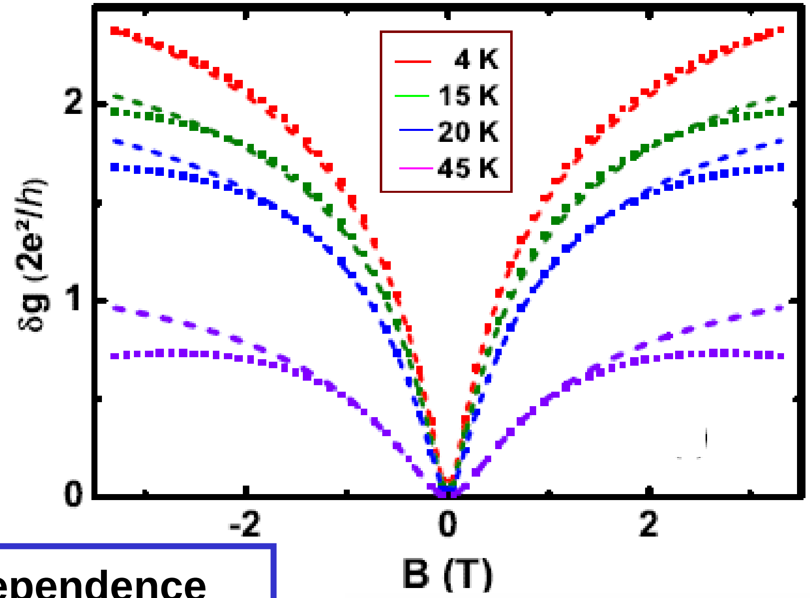




Localization on Si face



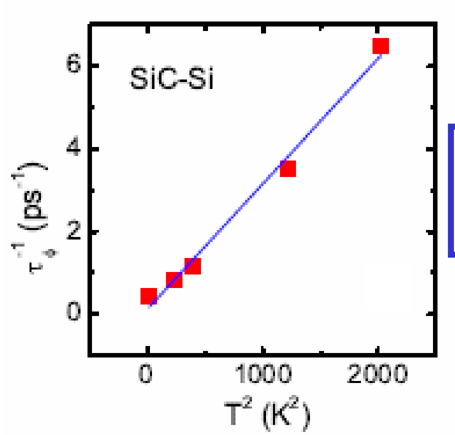
$B_\Phi = \Phi_o / L^2_\Phi$



Lφ = 70 nm

Lφ = 64.4 nm

Lφ = 57 nm

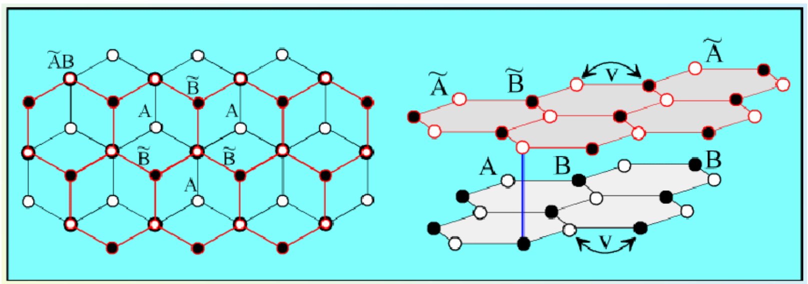


T² dependence
e-ph scattering ?

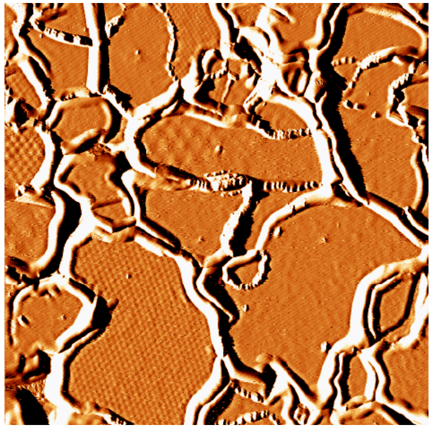
$$\Delta\sigma(B) = \frac{e^2}{\pi h}\left(F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1}}\right) - F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + 2\tau_i^{-1}}\right)\right.$$

Opposite sign → $$\left. + 2F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + \tau_i^{-1} + \tau_*^{-1}}\right)\right).$$

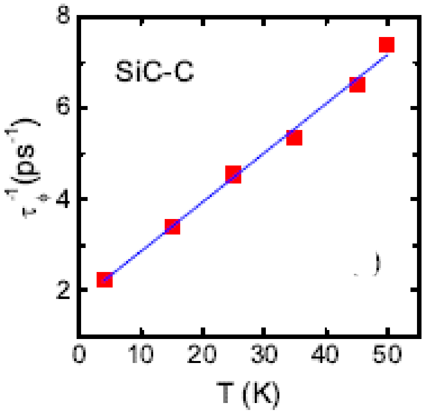
$\tau_i^{-1} = 1.02*10^{13}\ s^{-1}$
$\tau_w^{-1} = 1.63*10^{13}\ s^{-1}$
$\tau^{*-1} = 2.65*10^{13} s^{-1}$



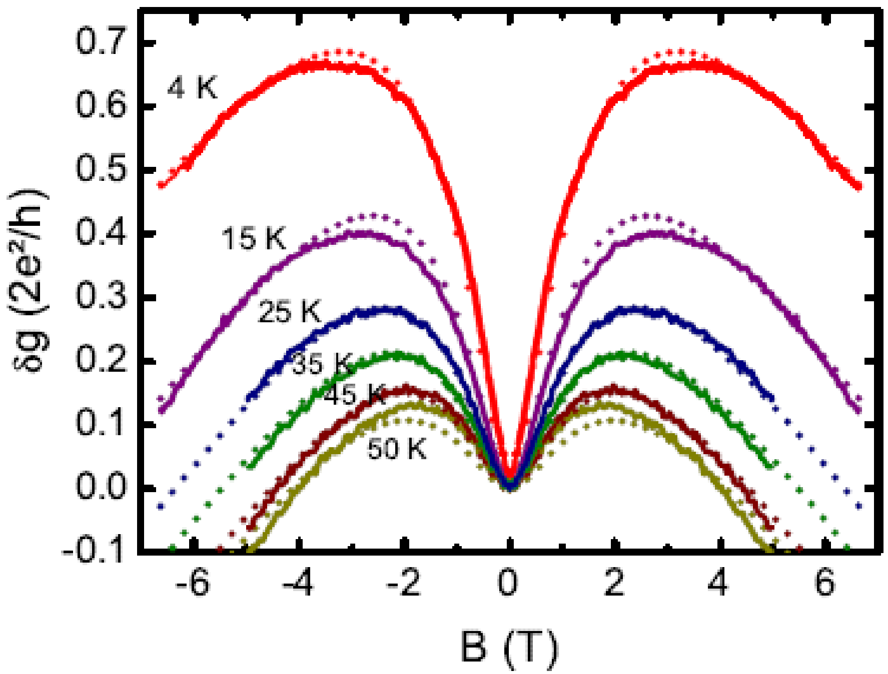
Anti-localization on the C face



150 x 150 nm²



$B_\Phi = \Phi_o / L^2_\Phi$



Lφ = 33 nm

Lφ = 28 nm

Lφ = 25 nm

$$\Delta\sigma(B) = \frac{e^2}{\pi h}\left(F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1}}\right) - F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + 2\tau_i^{-1}}\right) - 2F\left(\frac{\tau_B^{-1}}{\tau_\phi^{-1} + \tau_i^{-1} + \tau_*^{-1}}\right)\right).$$

$\tau_i^{-1} = 6.6 \cdot 10^{12}\ s^{-1}$

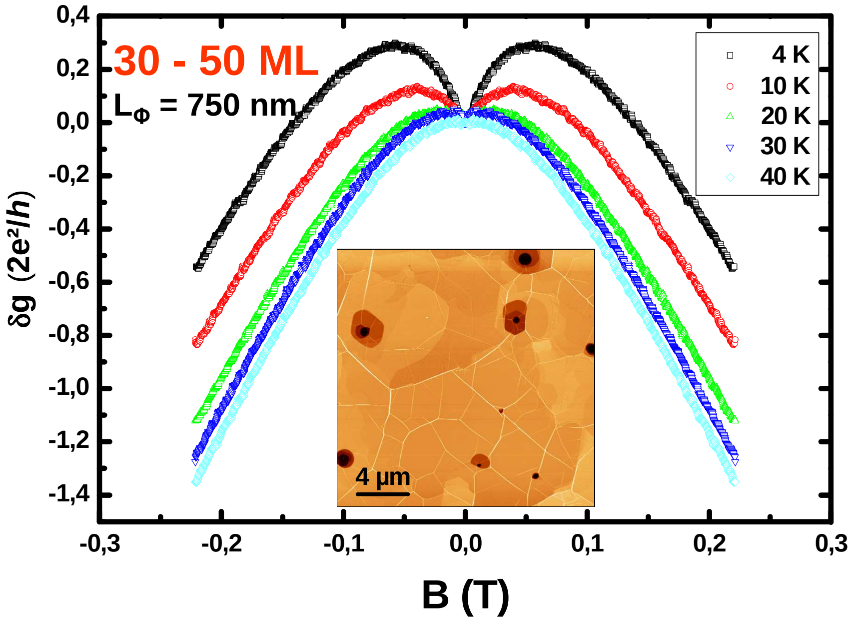
$\tau_w^{-1} = 7.4 \cdot 10^{12}\ s^{-1}$

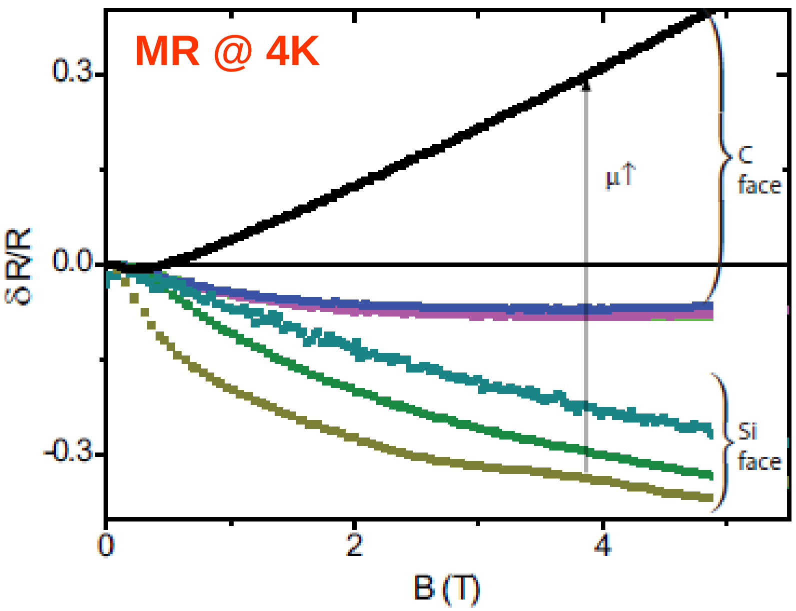
$\tau^{*-1} = 6.6 \cdot 10^{12} + 7.4 \cdot 10^{12} = 1.4 \cdot 10^{13} s^{-1}$

τ_φ / τ_i and τ_φ / τ^* relatively small

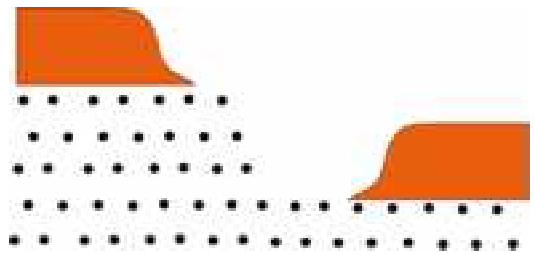
Linear dependence
Altshular-Aronov prediction for e-e

Multilayers: deviation from true WAL





- ✓ Large localization amplitude > e^2/h
- ✓ Weak interlayer coupling
- ✓ Large l_e ~300 nm
- ✓ D dependent on B ➡ linear positive MR
- ✓ Other contributions to WAL slope (Coulomb scattering, tunneling)?



Conclusions

- Morphology (STM, AFM)- QI at step edges
- 2D transport properties.
- Form WAL to conventional WL
- Importance of stacking