Observation of the π-Berry Phase in Nanoribbons of the Topological Insulator Bi_2Se_3

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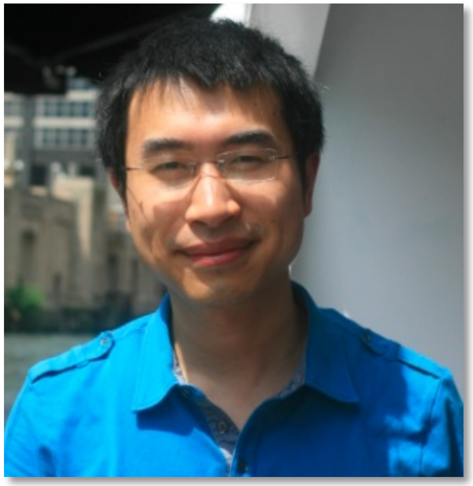
Collaborators



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Outline

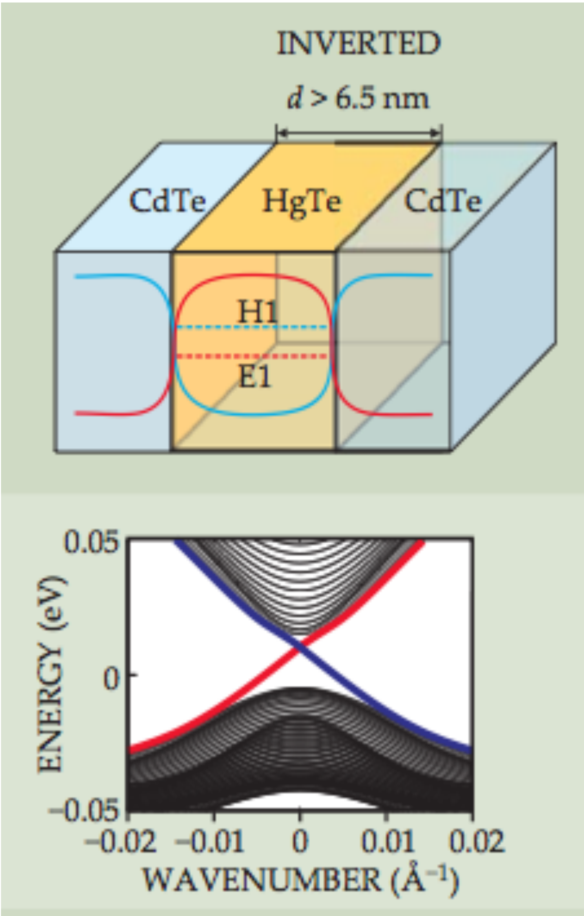
- Shubnikov−de Haas (SdH) quantum oscillations and the Berry phase in topological insulators.

- SdH quantum oscillations on catalyst-free grown topological insulator Bi_2Se_3 nanoribbons

- The determination of π-Berry Phase

- Conclusion

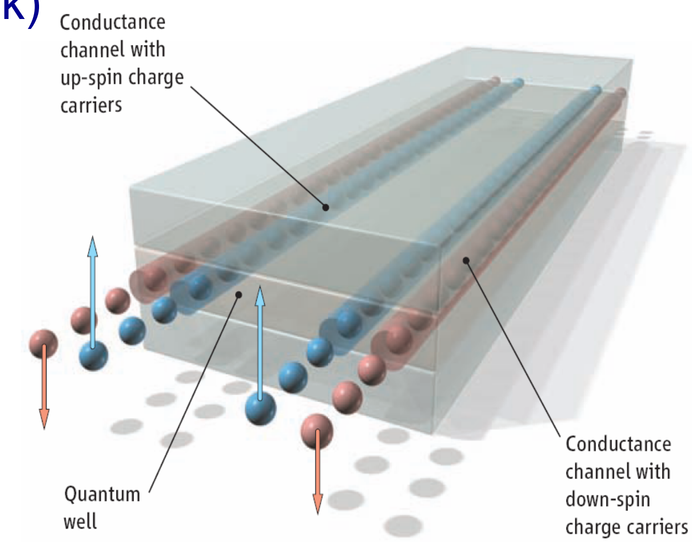
Topological insulator



A novel quantum state
- Insulators with strong spin orbit coupling
- Under protection of time reversal invariance

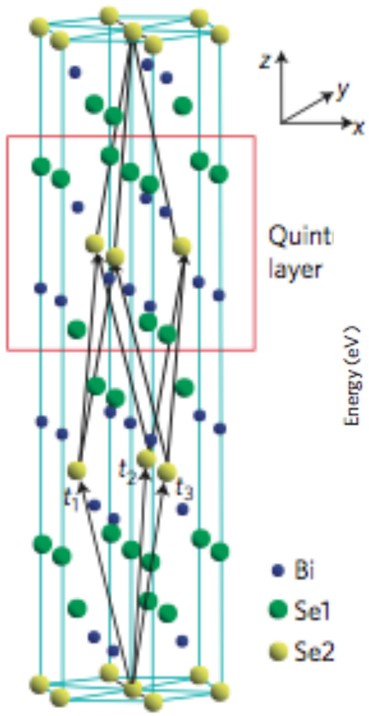
On surfaces
- Conducting electrons with opposite spins
  ---- quantum spin Hall effect
- Immune to impurities or geometric perturbations

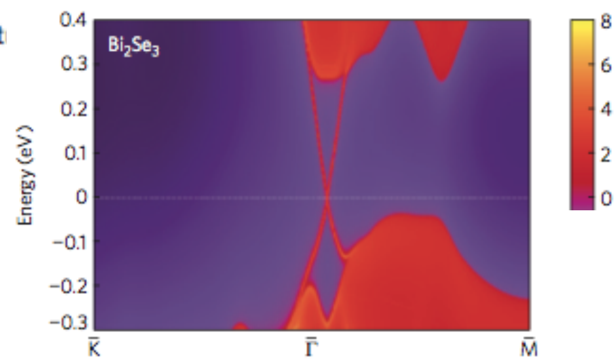
Application potential
- Linear band dispersion ε(k)
  ----Dirac Fermions
- Spin polarized electrons
  ---- spintronics



Theory: Bernevig, Hughes and Zhang, Science **314**, 1757 (2006)
Experiment: Koenig et al, Science **318**, 766 (2007)

3D topological insulator Bi_2Se_3





ARTICLES

PUBLISHED ONLINE: 10 MAY 2009 | DOI: 10.1038/NPHYS1270

nature physics

Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface

Haijun Zhang[1], Chao-Xing Liu[2], Xiao-Liang Qi[3], Xi Dai[1], Zhong Fang[1] and Shou-Cheng Zhang[3]*

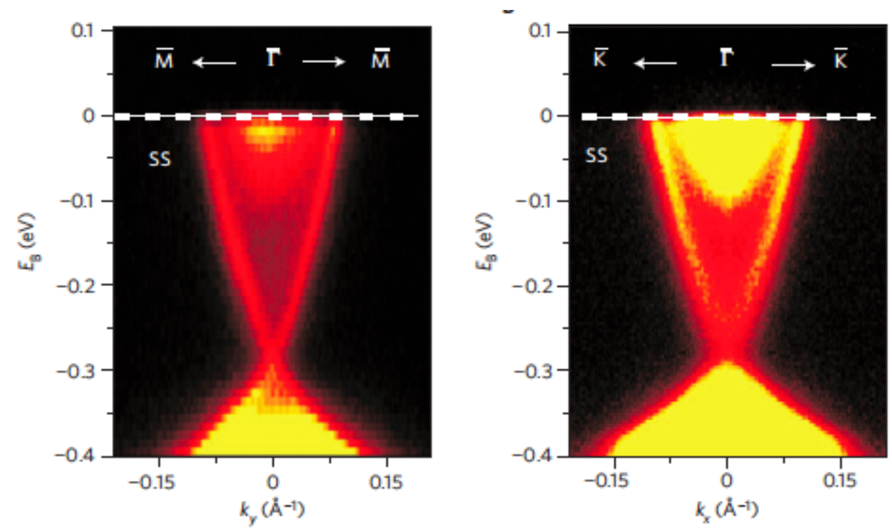
LETTERS

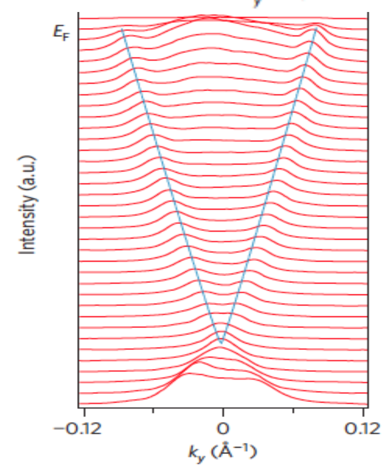
PUBLISHED ONLINE: 10 MAY 2009 | DOI: 10.1038/NPHYS1274

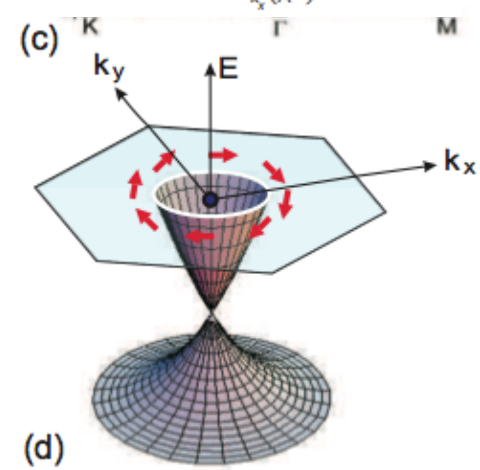
nature physics

Observation of a large-gap topological-insulator class with a single Dirac cone on the surface

Y. Xia[1,2], D. Qian[1,3], D. Hsieh[1,2], L. Wray[1], A. Pal[1], H. Lin[4], A. Bansil[4], D. Grauer[5], Y. S. Hor[5], R. J. Cava[5] and M. Z. Hasan[1,2,6]*







Probe the surface state by electrical transport

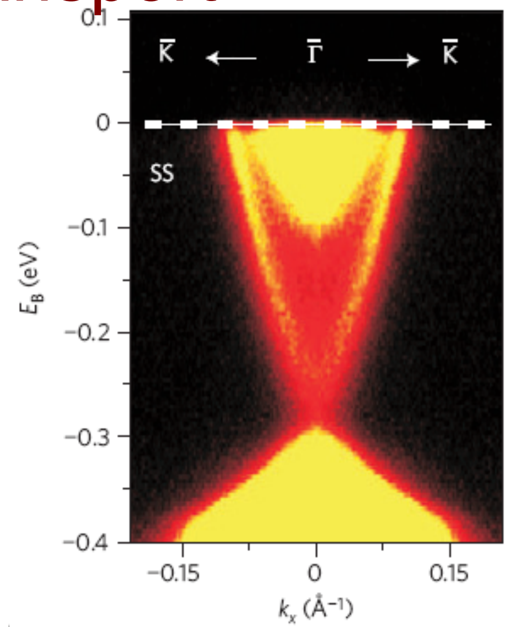
➢ **Barriers**

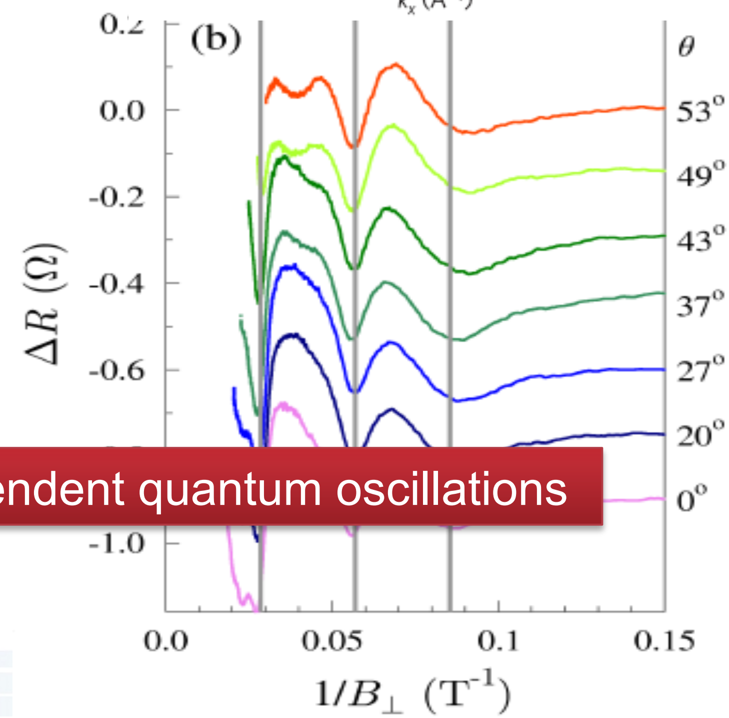
The transport in most cases was dominated by the charge carriers of the bulk.

➢ **Electrons on surfaces**

- High electron mobility
  Immune against back-scattering by impurities.
  Mobility of bulk electrons is heavily influenced by impurities.

- Two dimensional behavior
  3D behavior of bulk electrons



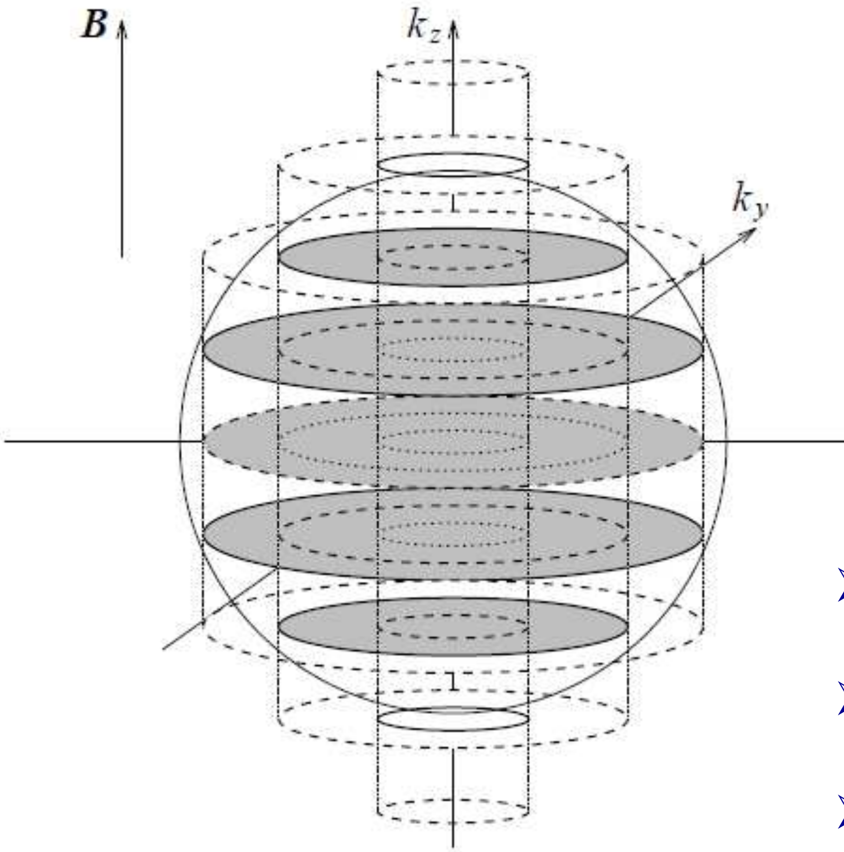


Surface state can be probed by angular dependent quantum oscillations

Analytis et al. Nat. Phys 2010

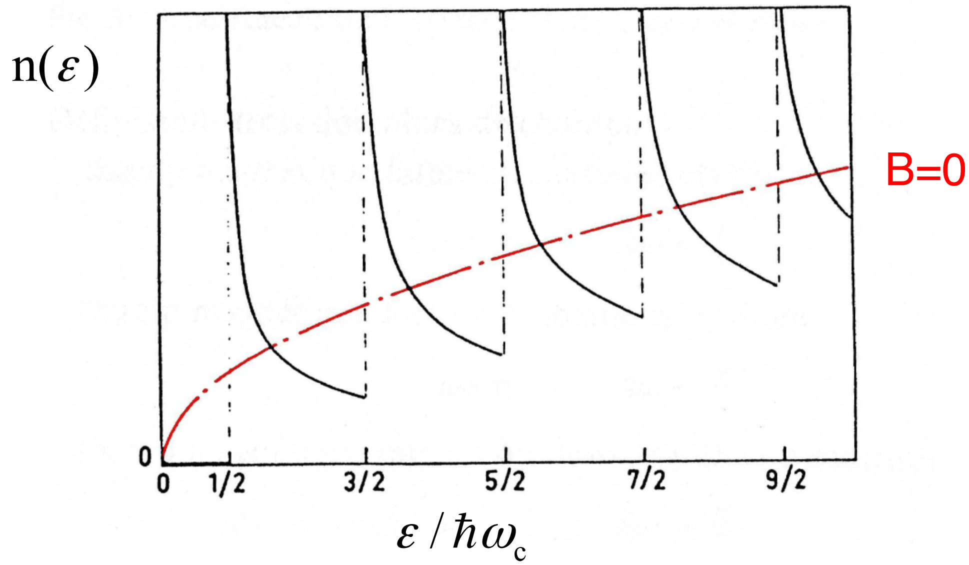
Quantization with magnetic field

Landau tubes



The motion parallel to B is unaffected.

Density of states



In the plane of perpendicular to B

- The energy of electron's motion is quantized ---Landau levels.
- The density of state is quantized into Landau levels.
- The k-space areas of orbits are quantized ----Landau tubes.

$$A_N = \frac{2\pi e}{\hbar} B(N + \gamma),$$

Quantum Oscillations

Landau quantization will occur when a Landau tube crosses an extremal cross-section of Fermi surface

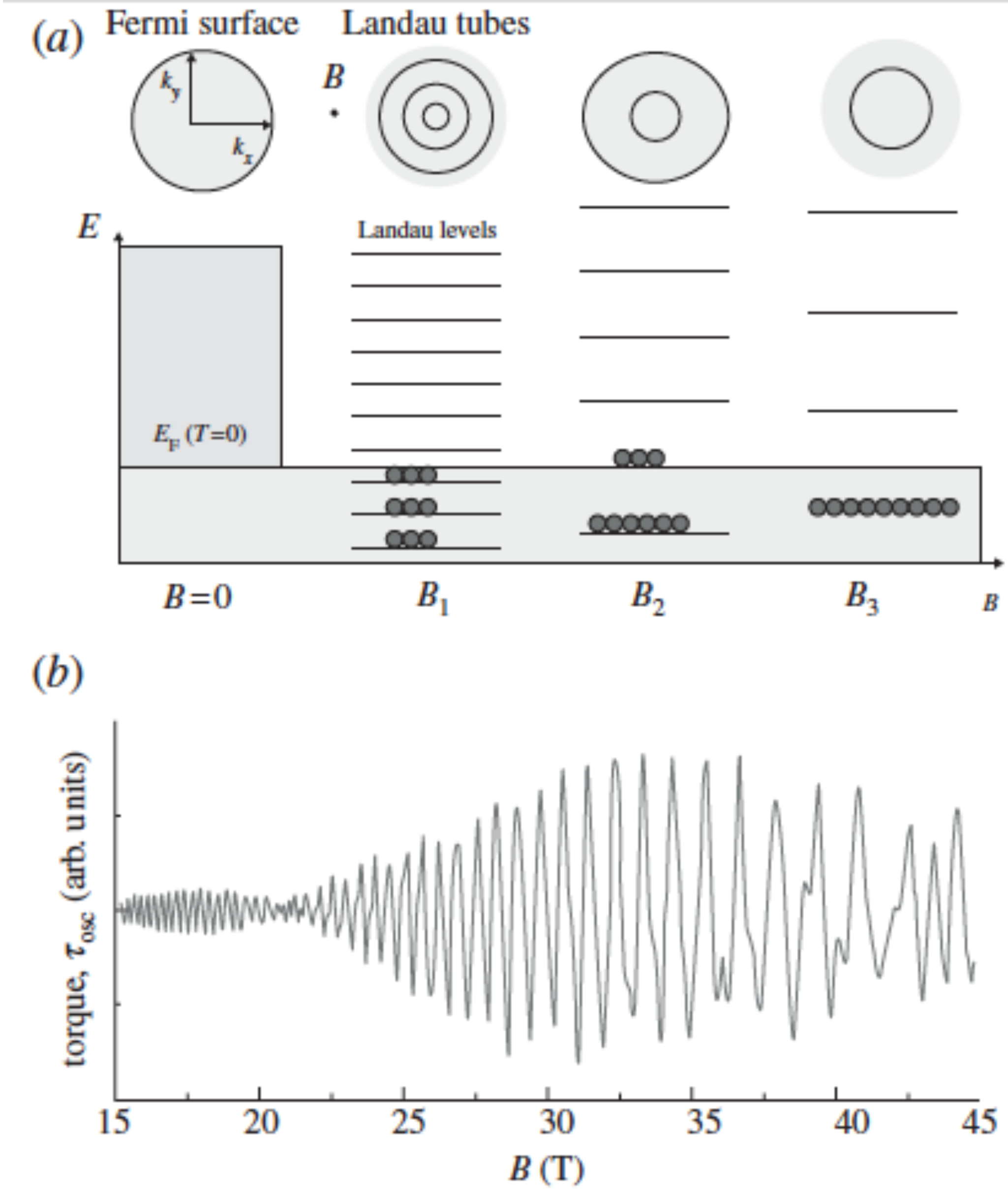
$$A_F = A_N = \frac{2\pi e}{\hbar} B(N + \gamma),$$

Magnetization:
de Hass-van Alphen (dHvA)
Resistance:
Shubnikov-de Hass (SdH)

$$1/B = (2\pi e/\hbar A_F)\ (N+\gamma)$$

Onsager relation:

$$F = (\Delta(1/B))^{-1} = (\hbar/2\pi e) A_F$$



Lifshitz-Kosevich theory

Lifshitz-Kosevich theory (1956)

T≠0

p=1

$$\Delta R, \Delta M \propto R_T \, R_D \, R_S \, sin\left[2\pi\left(\frac{F}{B} - \gamma\right)\right]$$

$$\frac{F}{B} = \frac{\hbar}{2\pi q}\frac{A_F}{B}$$ Onsager relation $\Rightarrow$ A_F Extremal area

$$R_T = \frac{X}{sh(X)} \quad \text{where } X = 14.694 \times T m_c / B$$ $\Rightarrow$ m^* Cyclotron mass

$$R_D = \exp\left(-\frac{14.694 \times T_D m_c}{B}\right) = \exp\left(-\frac{\pi}{\mu B}\right)$$ $\Rightarrow$ $T_D = \frac{\hbar}{2\pi k_B \tau}$ Dingle temperature (mean free path)

Berry phase revealed by quantum oscillations

VOLUME 82, NUMBER 10 PHYSICAL REVIEW LETTERS 8 MARCH 1999

Manifestation of Berry's Phase in Metal Physics

G. P. Mikitik and Yu. V. Sharlai

$$\Delta R, \Delta M \propto R_T R_D R_S \sin\left[2\pi\left(\frac{F}{B} - \gamma\right)\right]$$

$2\pi\gamma$ represents the Berry phase in metal

$\gamma = 0$ for electrons in bands with parabolic dispersion

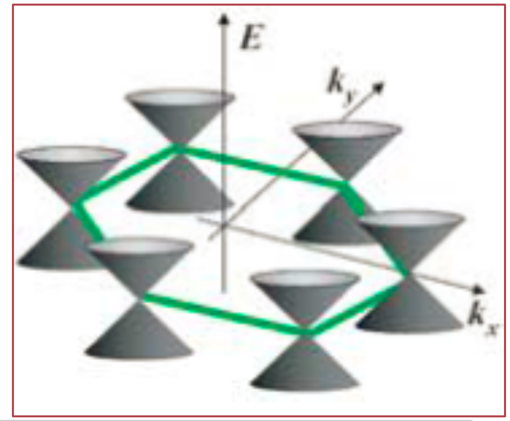
$\gamma = 1/2$ for electrons with linear linear dispersion ----Dirac fermions

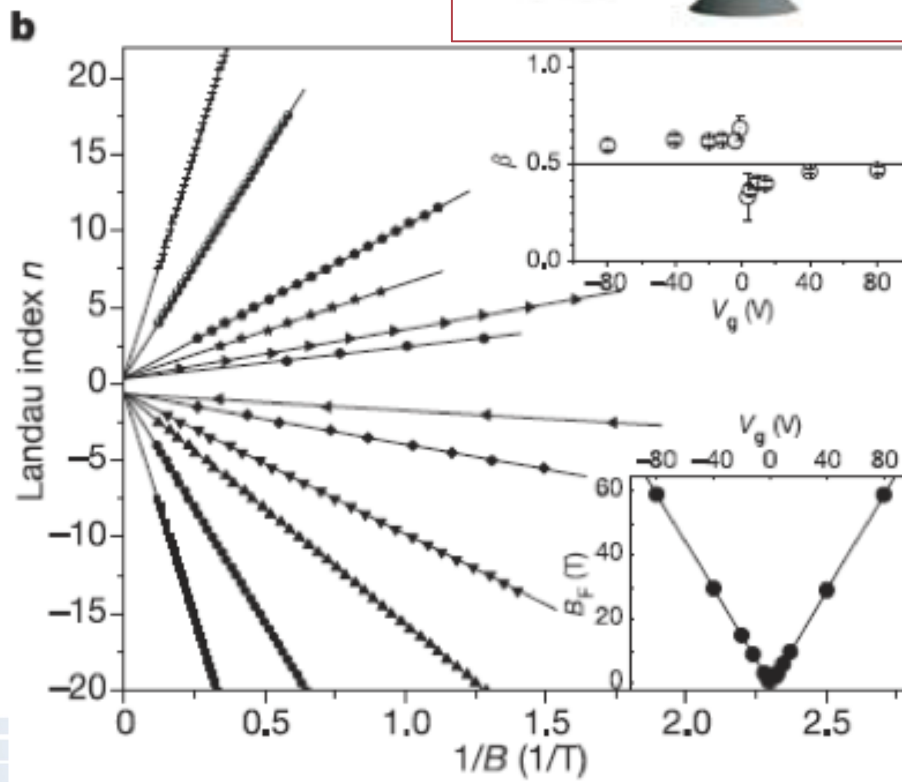
$$A_F = \frac{2\pi e}{\hbar} B(N + \gamma),$$

Fan diagram of Landau levels

$1/B = (2\pi e/\hbar A_F)\ (n+\gamma)$

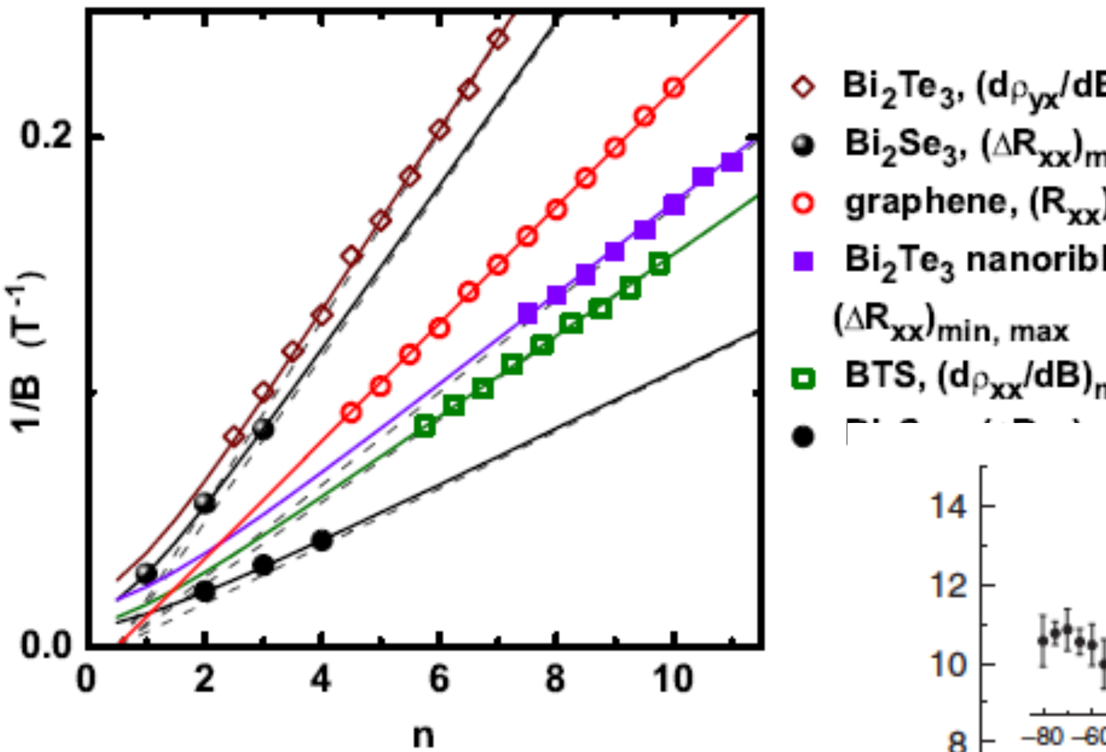
Graphene:

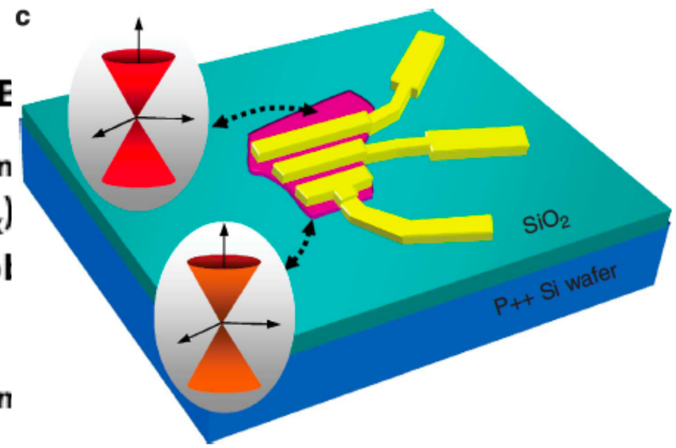


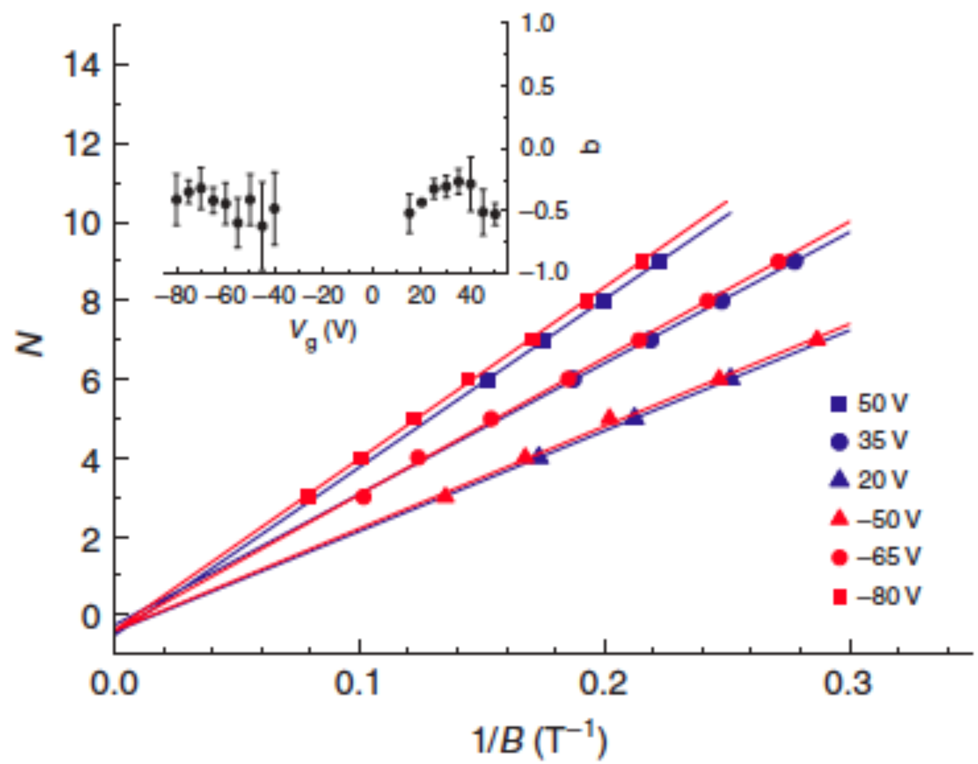


Nature, Vol. 438, 201-204 (2005)

Berry phase in topological insulators







$0.44\ \pi$ for Bi_2Te_2Se by Z. Ren et al.,
$(1.62\pm0.02)\pi$ for Bi_2Se_3 nanoribbons by H. Tang et al.,
…..

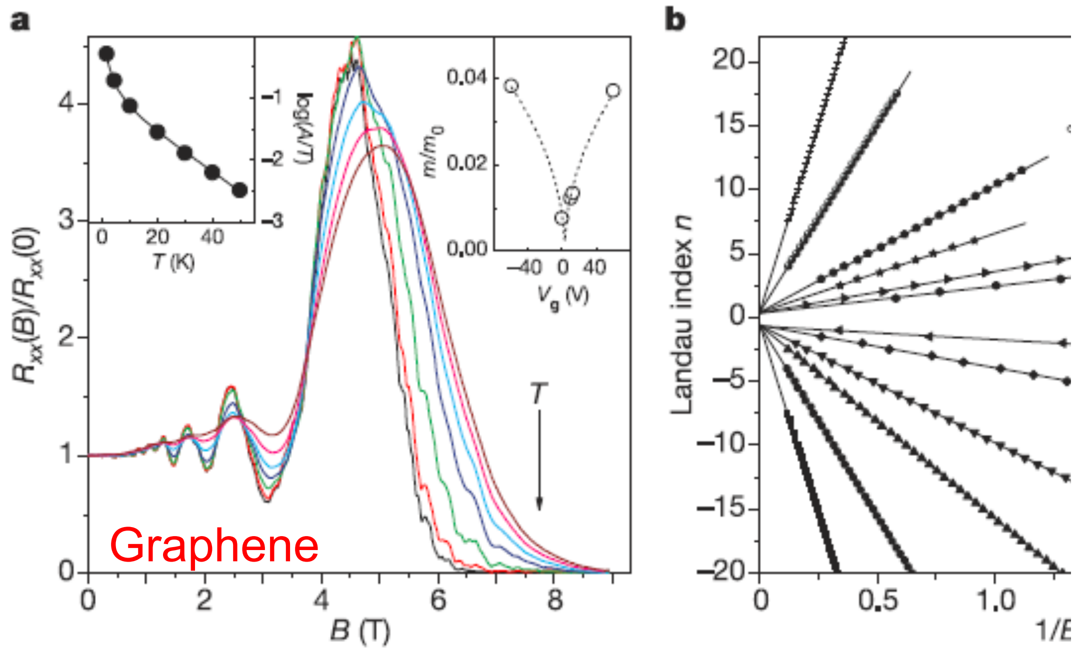
Zeeman splitting in high magnetic fields
Non linear band dispersion at Dirac cone

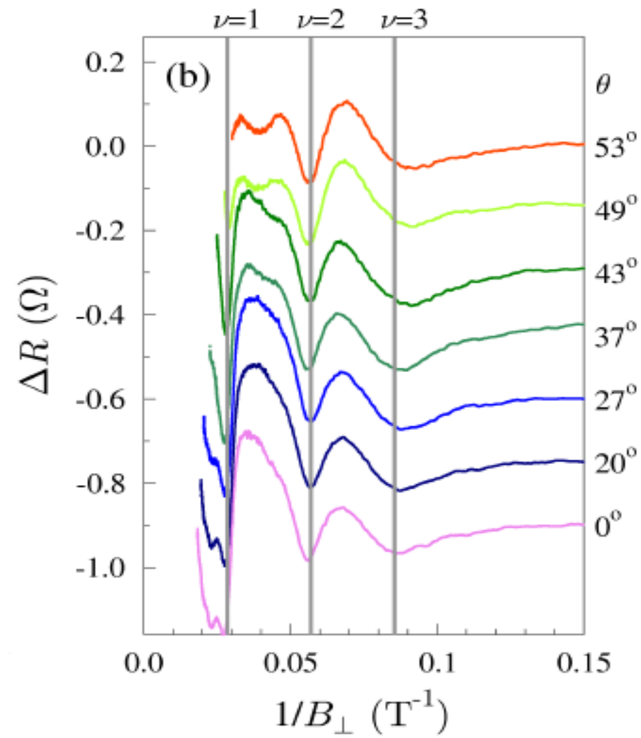
Nature Phys. **2010**, *10*, 960 PRB **84, 035301 (2011)** Nature Commun.2, 575 (2011)

Approach to reveal π Berry phase in topological insulators

- Large number of oscillation cycles for precise determination of Berry phase

- 2D quantum oscillation from surface states

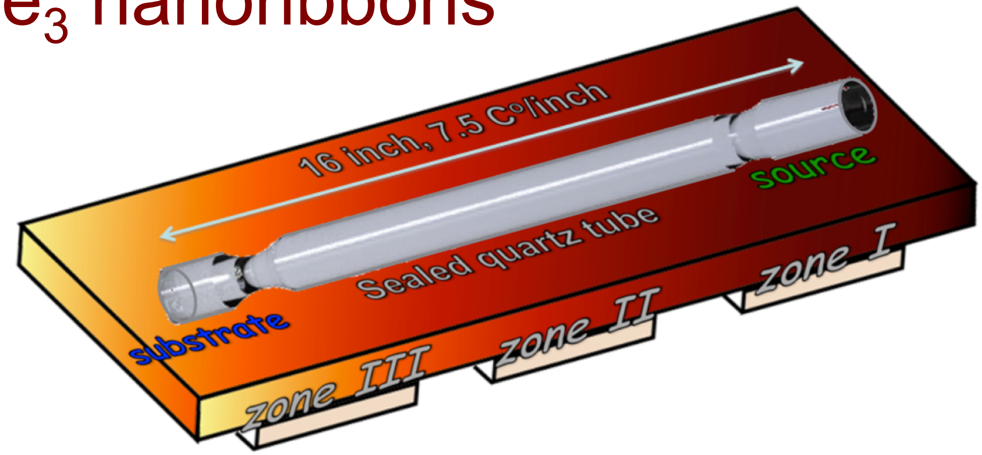




Material solution
1) nanostructure ----- to enhance the ratio of surface contribution
2) catalyst free growth ---- to avoid incorporation of metal catalysts

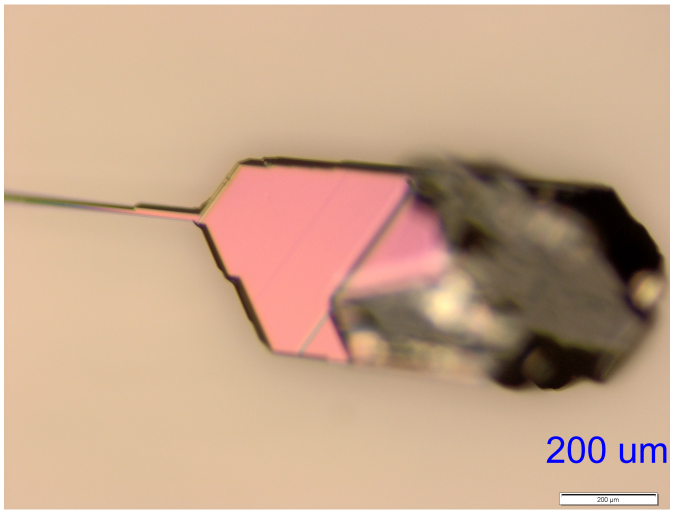
Nature, Vol. 438, 201-204 (2005)   Analytis et al. Nat. Phys 2010

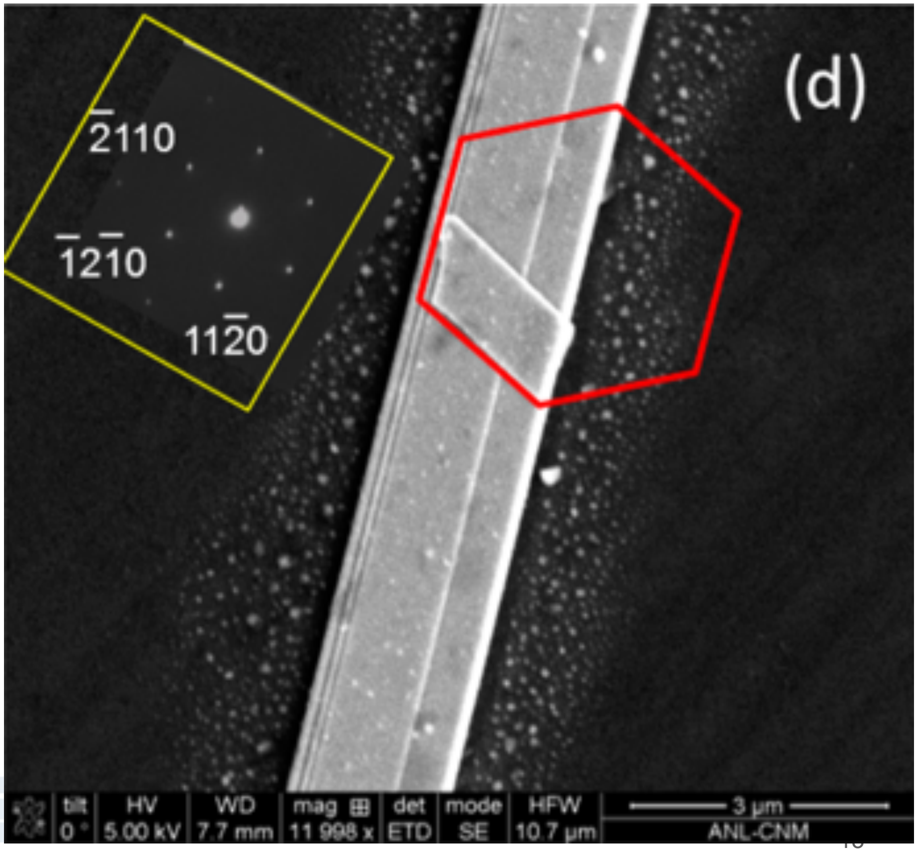
Catalyst-free growth of Bi_2Se_3 nanoribbons



•Physical vapor deposition controlled by temperature gradient

•Nanoribbons grow along the $(11\bar{2}0)$ direction



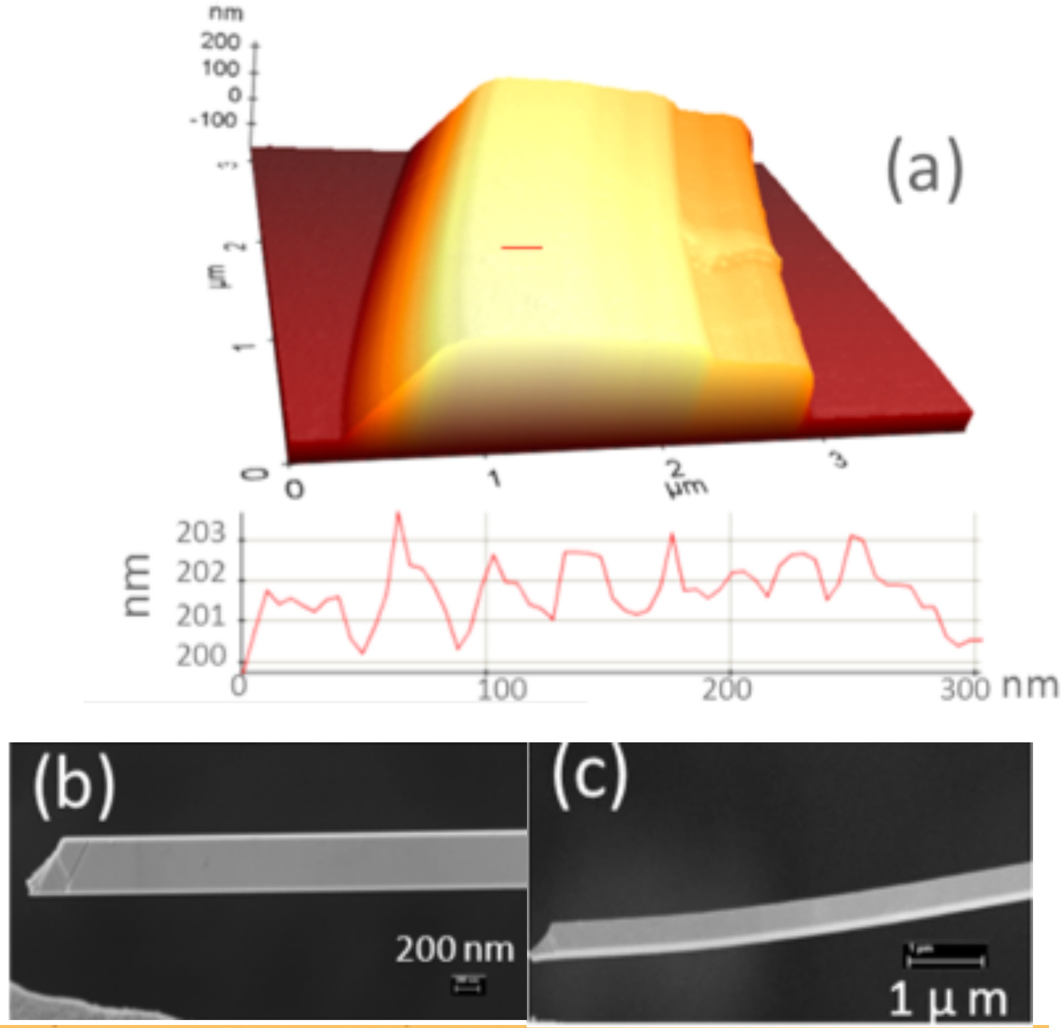


The Bi_2Se_3 nanoribbons

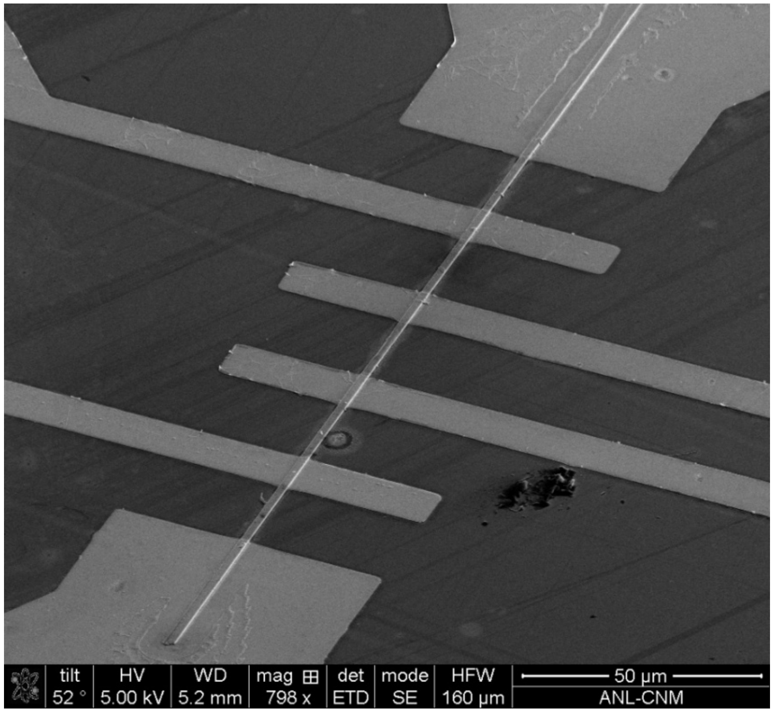
- Roughness: < 3nm
  the c-axis lattice constant 28.6 Å

- Width: 200 nm ~ 3 µm
  Thickness: 100 ~300 nm

- Ultra-long (~mm) nanoribbons can be synthesized provided adequate time and temperature gradient



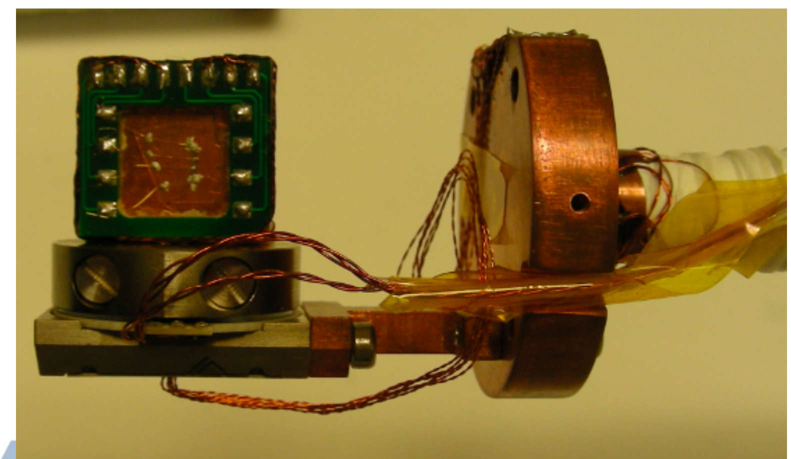
Experiment set-up

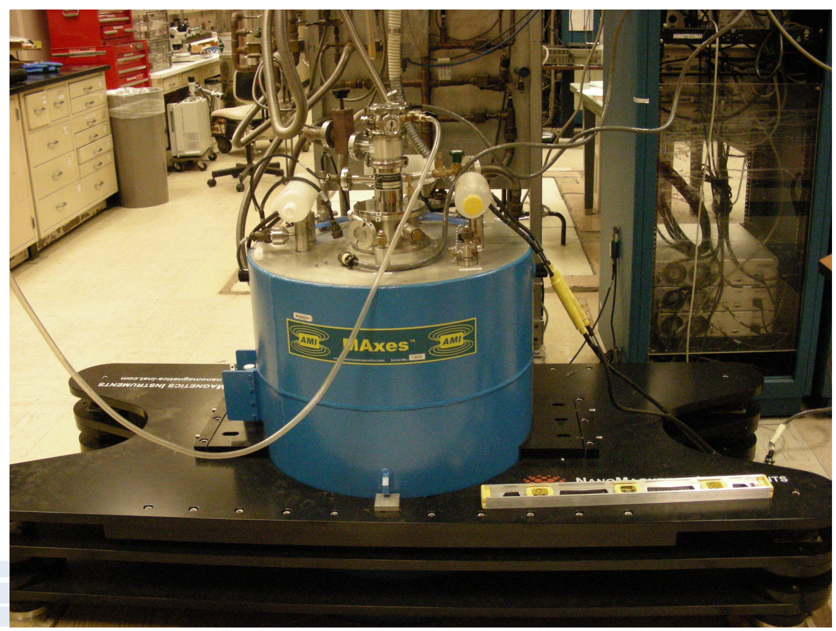


- Au/Ti electrical contacts patterned by photolithograph and lift-off process

- Multi-voltage pairs to detect the homogeneity of the nanoribbons

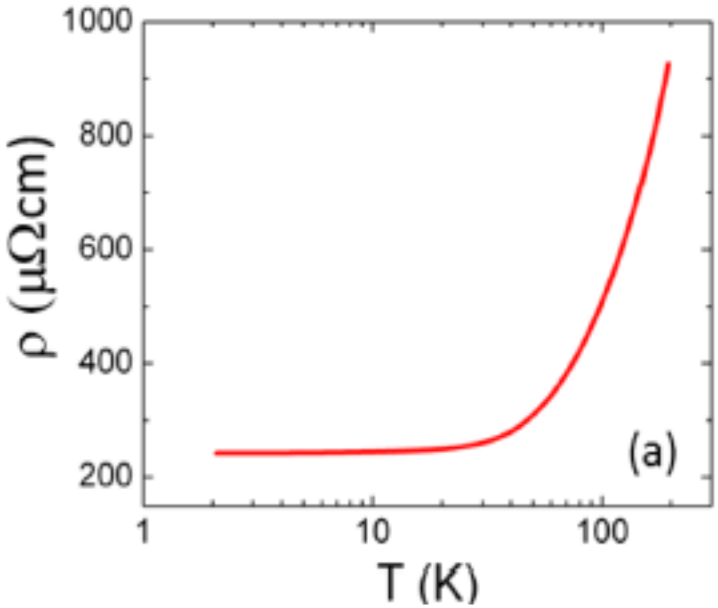
- attocube® piezo-rotator for precise position control

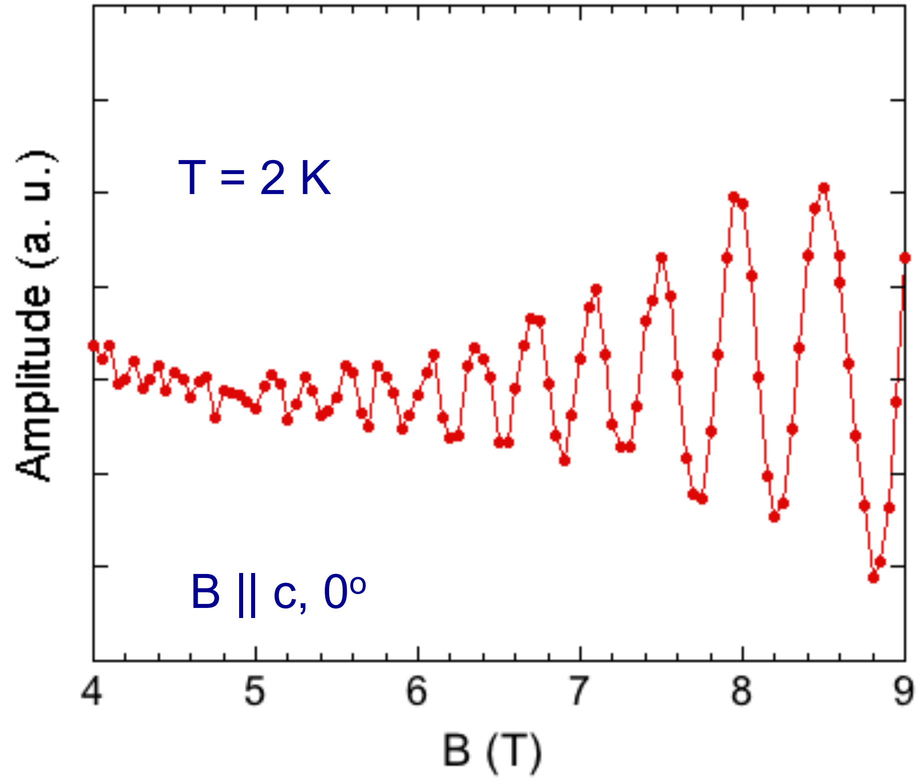


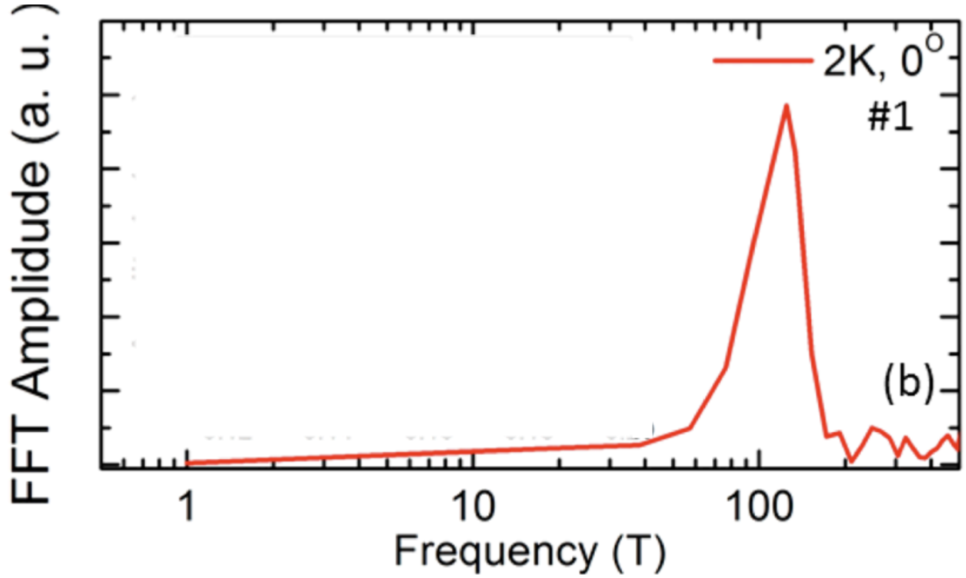


SdH quantum oscillations

Sample #1

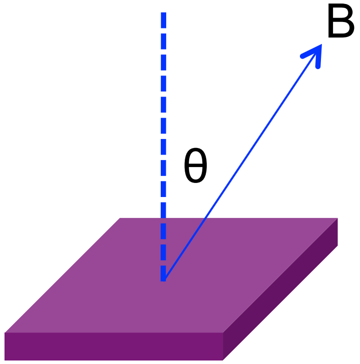


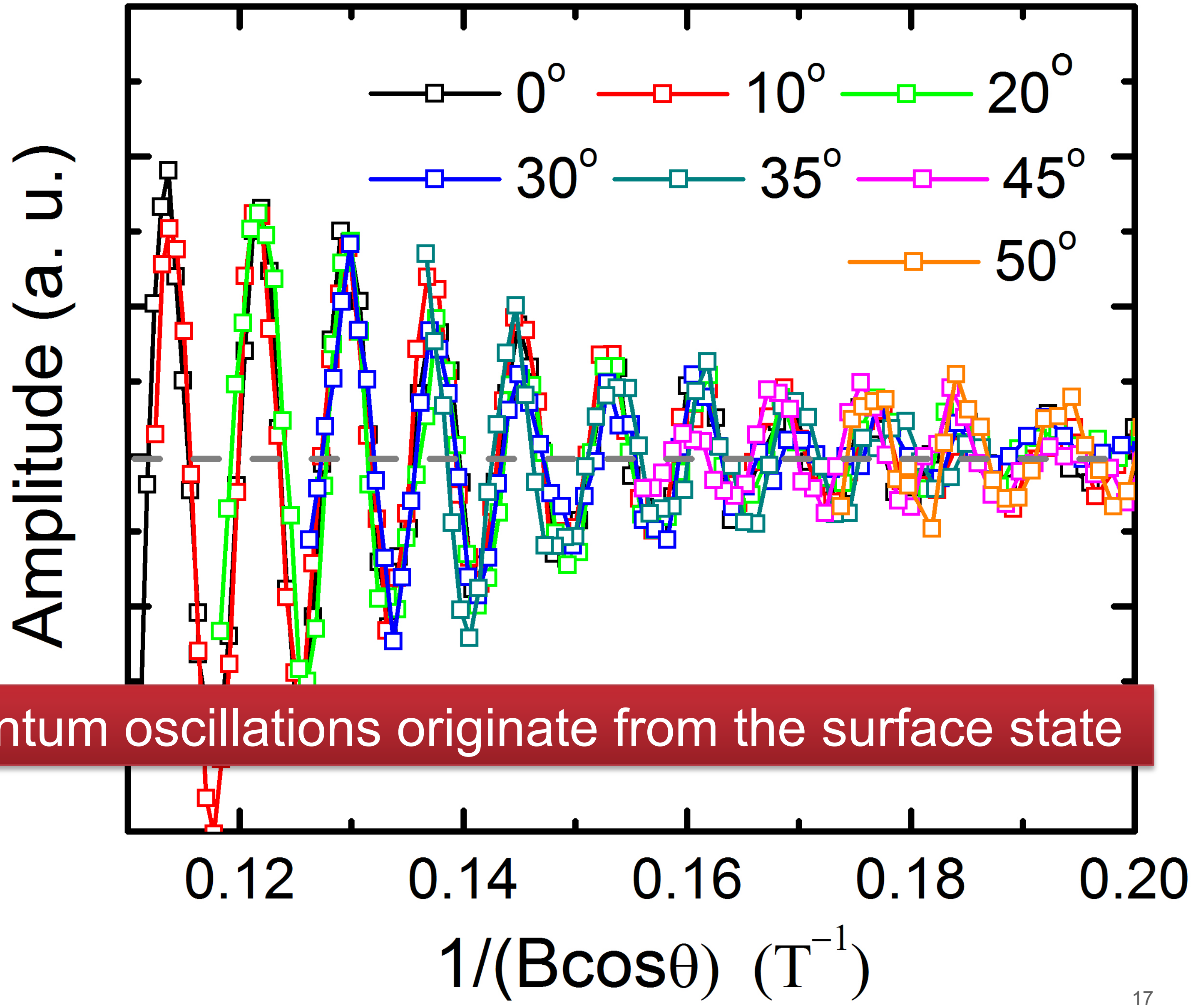




- 11 oscillation periods are observed within magnetic field of 9T
- Single oscillation frequency

2D behavior of SdH oscillations



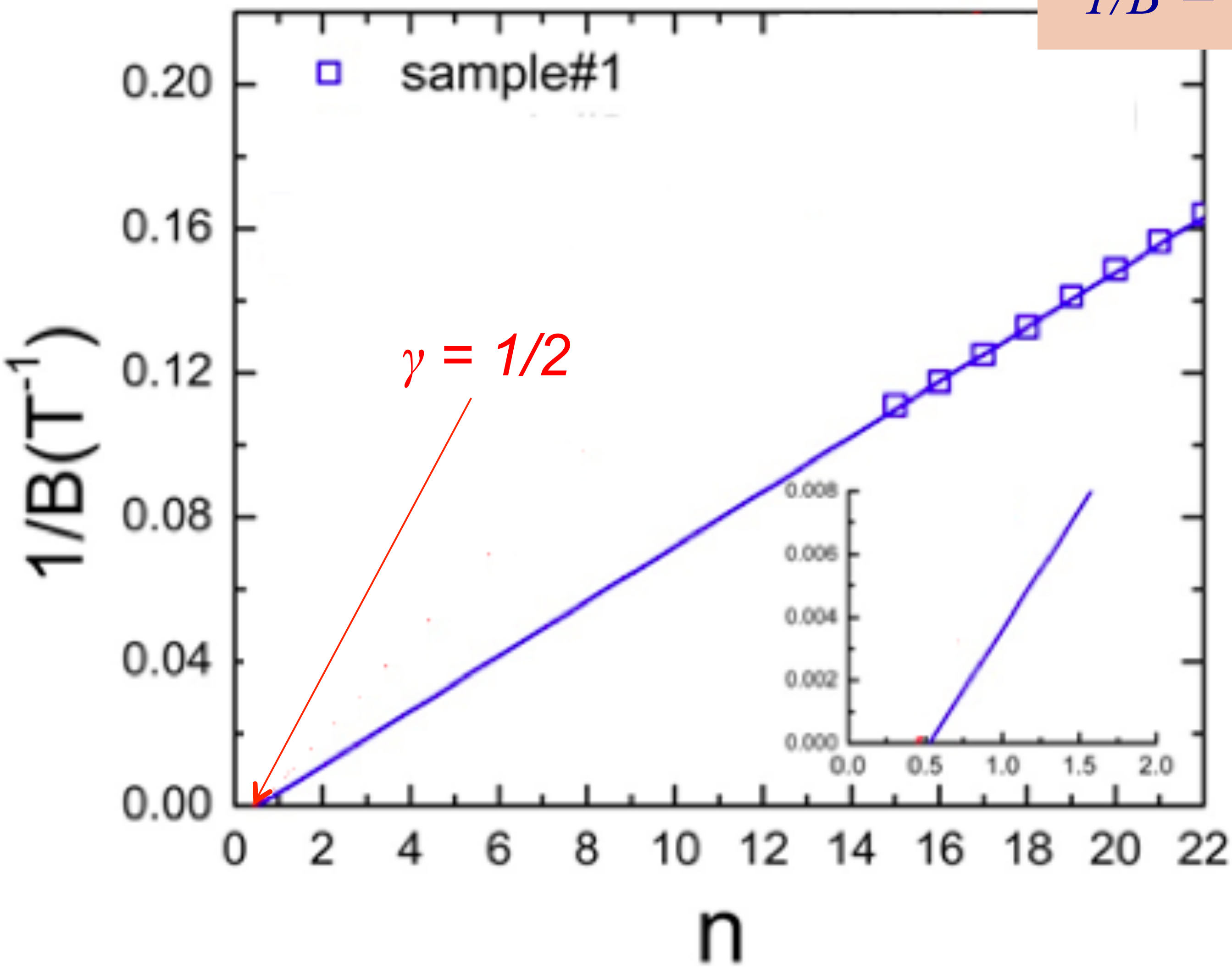


The SdH quantum oscillations originate from the surface state

Berry phase of surface electrons

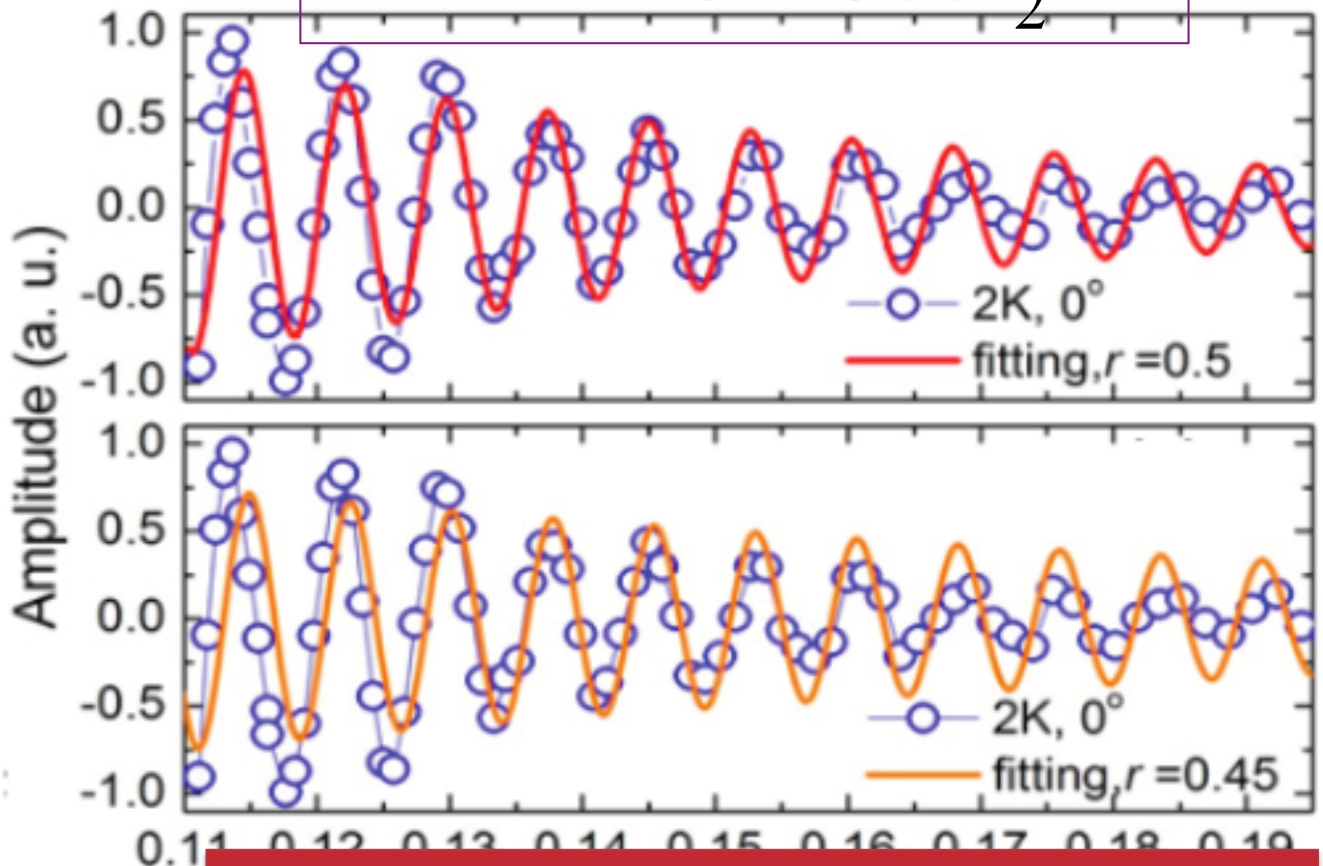
Fan diagram of Landau levels

$$1/B = (2\pi e/\hbar A_F)\ (n+\gamma)$$



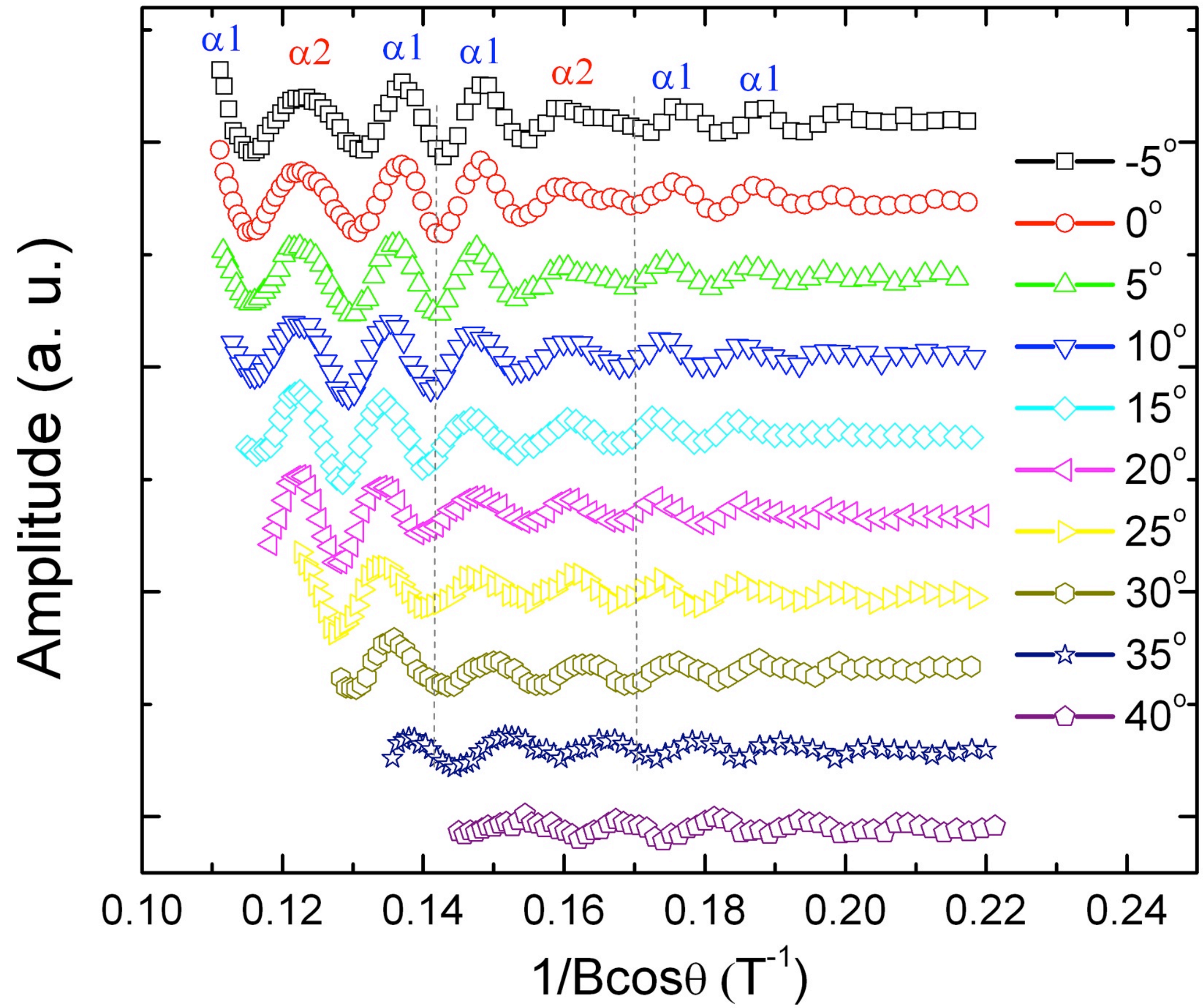
Berry phase determined by LK theory

$$\Delta R \propto R_T R_D \cos[2\pi(F/B + \frac{1}{2} + r)]$$



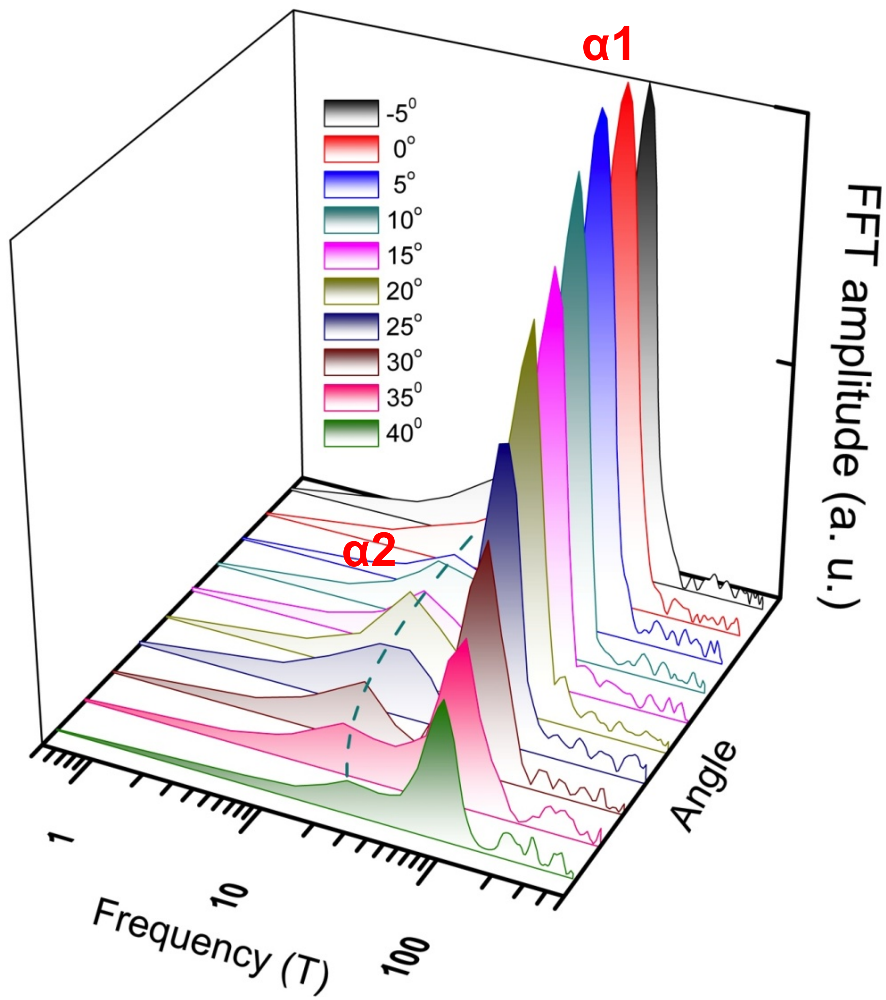
Berry phase of surface electrons = (1 ± 0.1) π

SdH oscillations on the 2nd sample



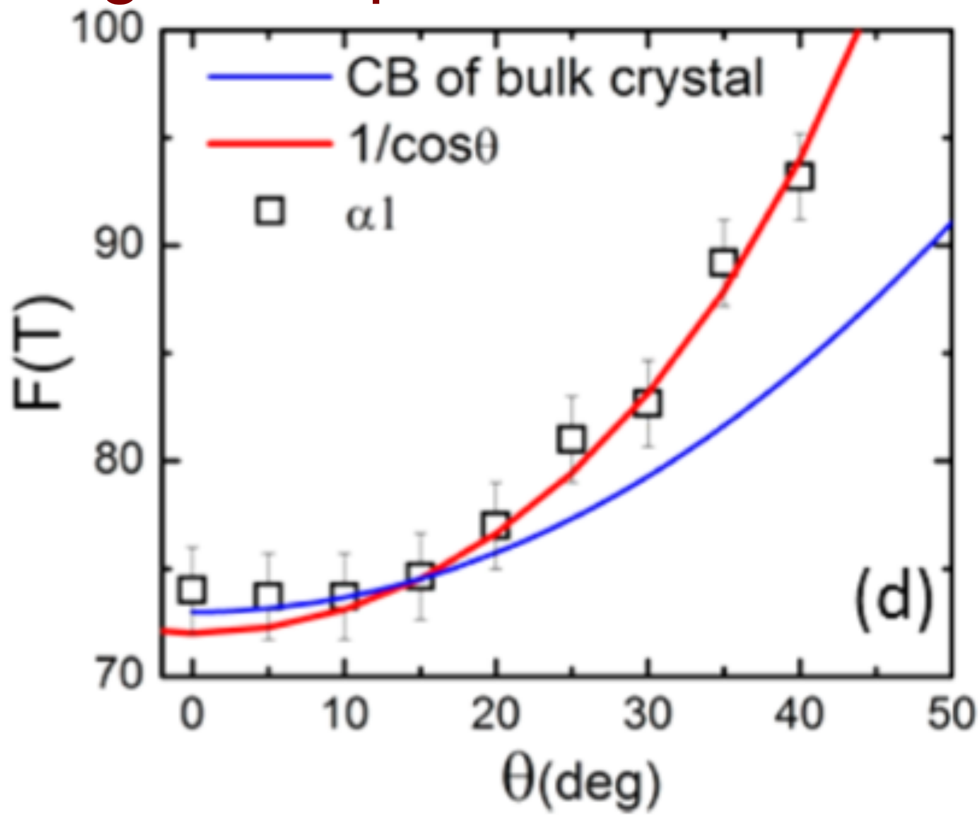
Two different shapes of harmonics appeared periodically

Oscillation frequencies



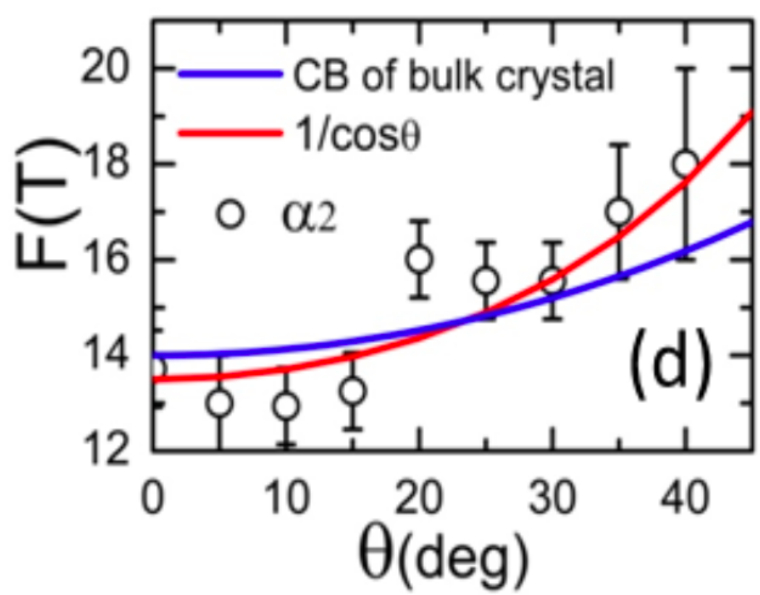
- **Two oscillation frequencies: α1 & α2**

Angular dependence



Angular dependence of α1 frequency follows 1/cosθ rule

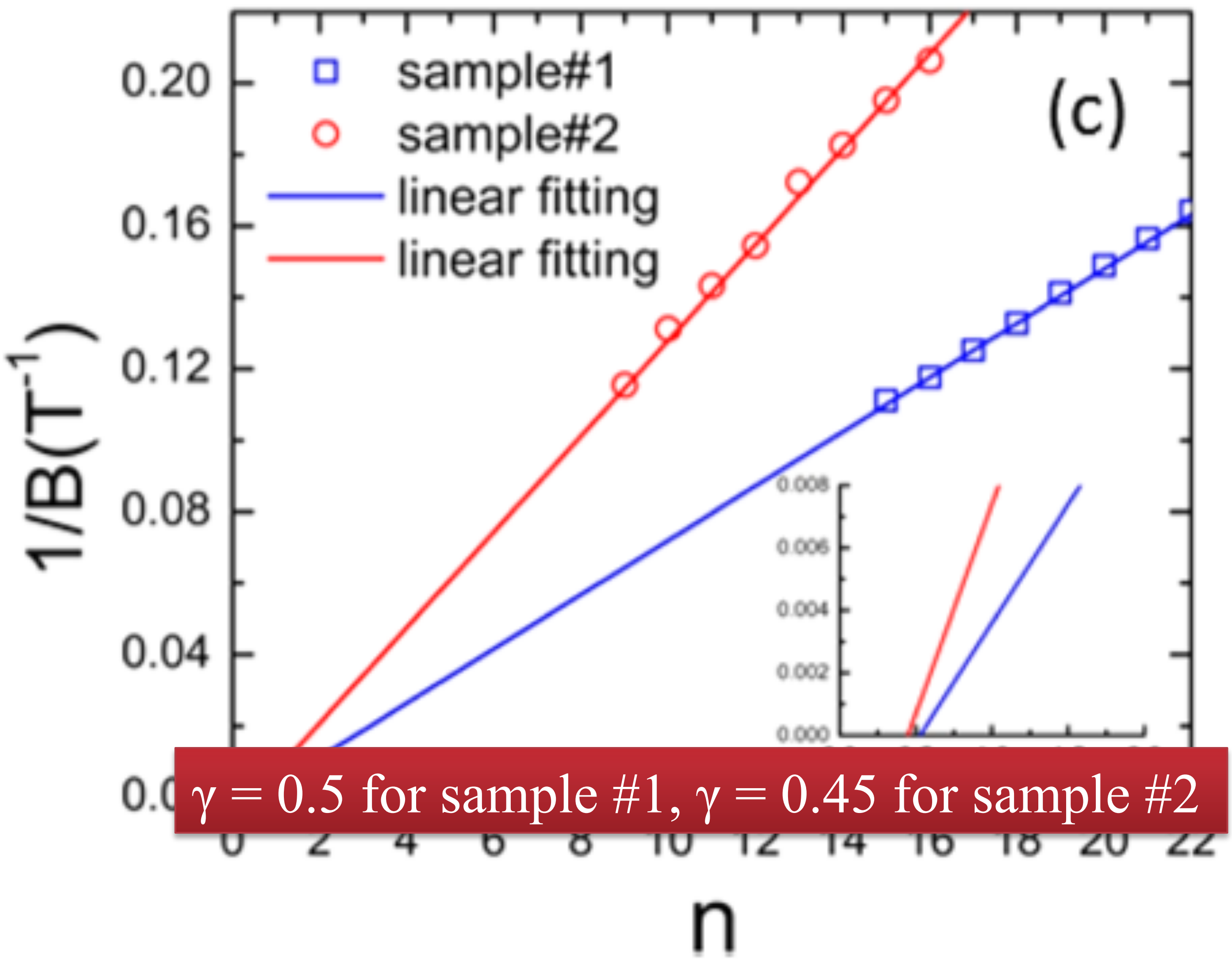
Clearly derivates from the angular dependence of bulk state



Large frequency uncertainties inhibit the dimensionality of the α2 frequency

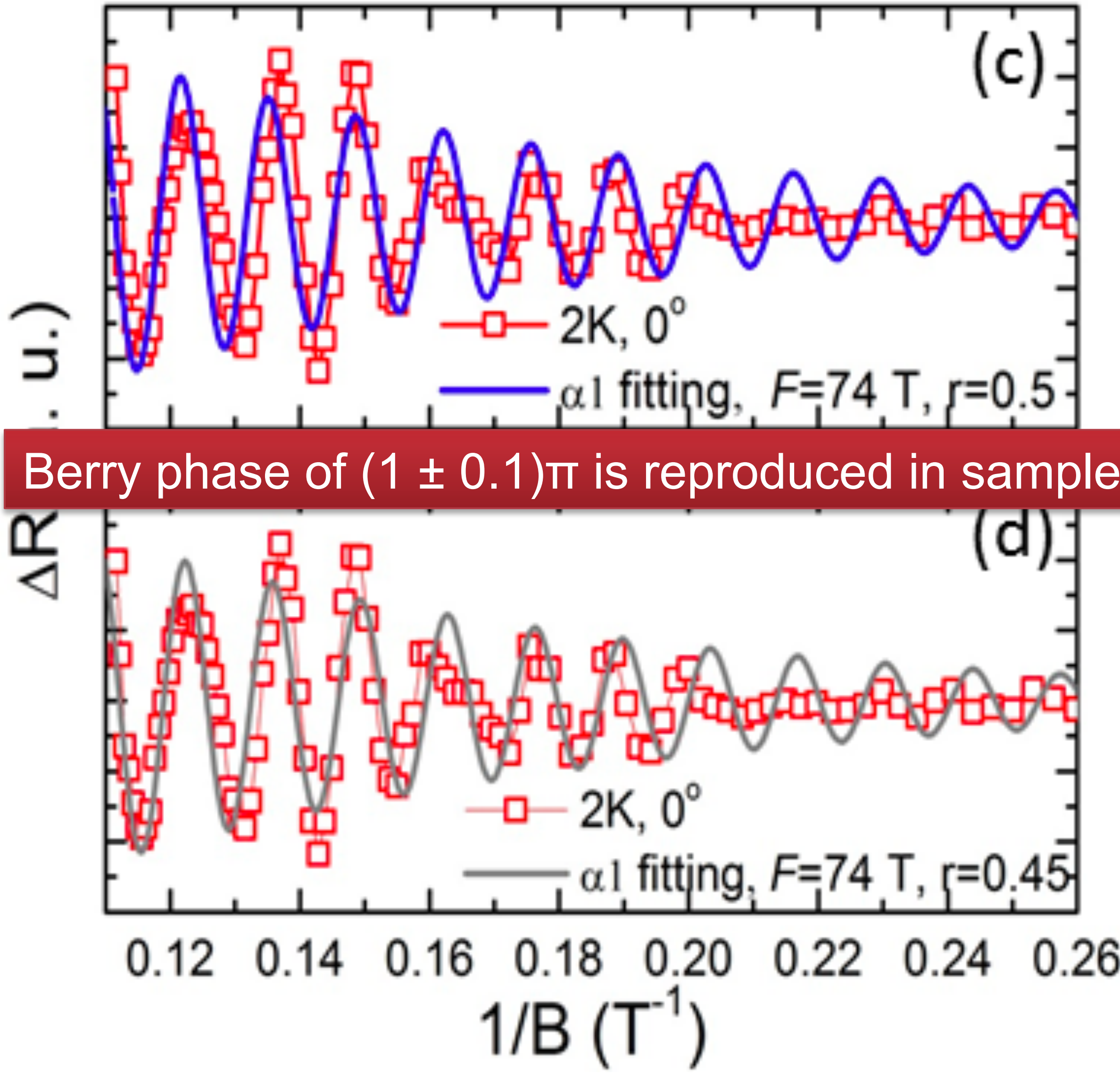
Phys. Rev. B **2010**, *81*, 195309

Berry phases



γ = 0.5 for sample #1, γ = 0.45 for sample #2

Berry phase determined by LK theory



Berry phase of (1 ± 0.1)π is reproduced in sample #2

Physical parameters of the surface electrons

$F = (\Delta(1/B))^{-1} = (\hbar/2\pi e)A_F$

$A_F = \pi k_F^2$

$R_T = \alpha T m_c^* / B \sinh[\alpha T m_c^* / B]$

$E_F = v_F \hbar k_F$

$v_F = \frac{(2e\hbar F)^{1/2}}{m_e m_c^*}$

$R_D = \exp\left(-\frac{14.694 \times T_D m_c}{B}\right) = \exp\left(-\frac{\pi}{\mu B}\right)$

$T_D = \hbar / 2\pi k_B \tau$

sample	F (T)	k_F (nm^{-1})	n_{2D} (10^{12} cm^{-2})	m_c^* (m_e)
1	131	0.63	3.16	0.18 ± 0.1
2	74	0.47	1.786	0.14 ± 0.1

v_F (10^5 m/s)	E_F (meV)	τ (10^{-13} s)	l (nm)	μ (m^2/(V s))
3.96	176	4	161.7	0.3926
3.8	128	2.4	92.6	0.302

Au-catalyzed VLS grown nanoribbons (ACS Nano 5, 7510-7516 (2011))
F = 86 T, n_{2D} = 1.3 x10^{12}/cm^2, m_c^* = 0.12m_e, k_F = 0.41 nm^{-1}, and μ = 0.12 m^2/Vs

Conclusion

- Topological Insulator Bi_2Se_3 nanoribbons were grown by a *catalyst-free* physical vapor deposition method

- Shubnikov de-Hass quantum oscillations were observed in magnetoresistance. Magnetic field orientation dependent measurements enabled us to identify the topological surface states as the dominant contributor to the SdH quantum oscillations

- The fan diagram of the Landau levels and in particular, the fitting of the oscillatory resistance with the Lifshitz-Kosevich theory yield a Berry phase with a phase quantity (1±0.1) π, indicating the existence of ideal Dirac fermions in the topological insulator Bi_2Se_3

NANO LETTERS Letter

pubs.acs.org/NanoLett

Catalyst-Free Growth of Millimeter-Long Topological Insulator Bi_2Se_3 Nanoribbons and the Observation of the π-Berry Phase

L. Fang,[*,†] Y. Jia,[†] D. J. Miller,[†] M. L. Latimer,[†,‡] Z. L. Xiao,[*,†,‡] U. Welp,[†] G. W. Crabtree,[†] and W.-K. Kwok[†]