Julius-Maximilians-
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Quantum transport measurements on Bi_2Se_3 topological insulators

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26.11.2012

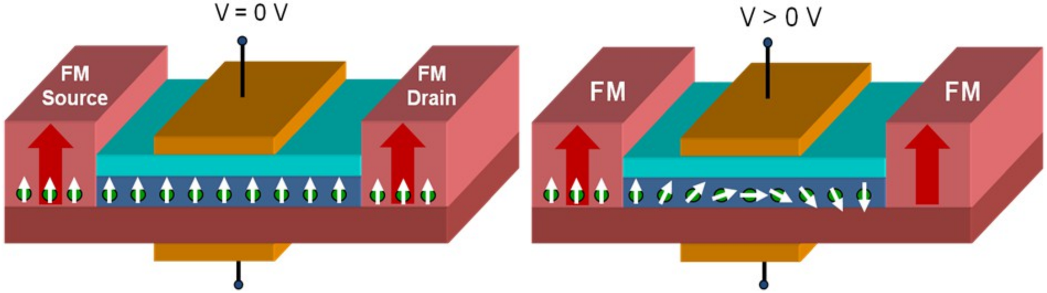
Motivation

Spintronic = Spin based electronics

- „Classical“ Spintronic
  - Use of electron spin in conventional hard disks
  - GMR – Giant Magneto Resistance effect

Conventional Hard disk [CHJ]

- „Modern“ Spintronic
  - Spin currents
  - Spin transistor

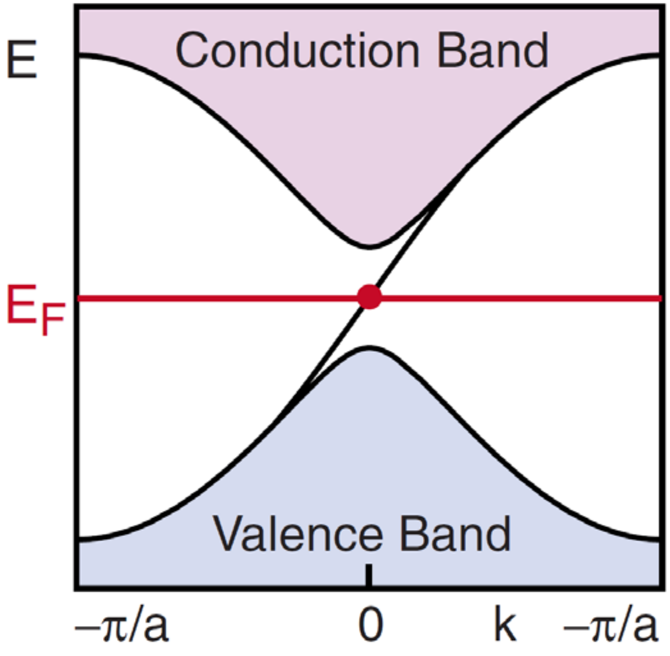


Spin Field Effect transistor [IHT]

Introduction

"Insulator" :	Band gap between valence- and conduction band
"Topological" :	Conducting spin-split 1D (2D) edge states within the band gap

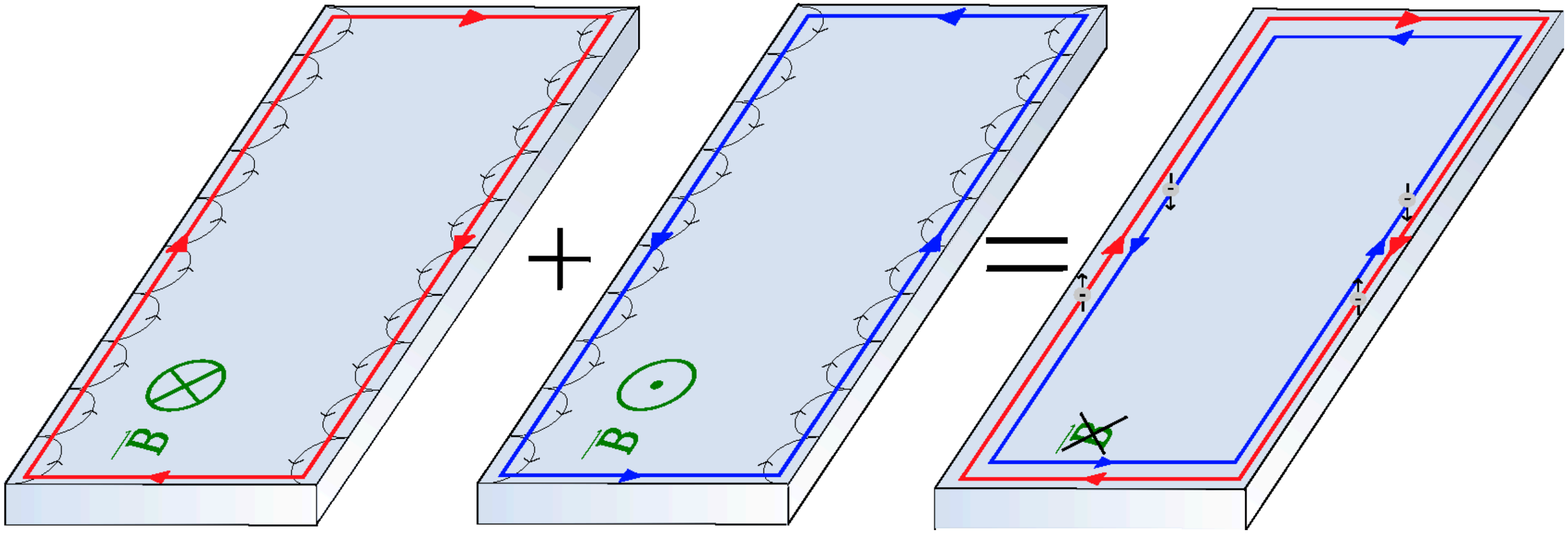
Topological Insulators are conducting!



Simple band structure [HK10]

Topological Insulators

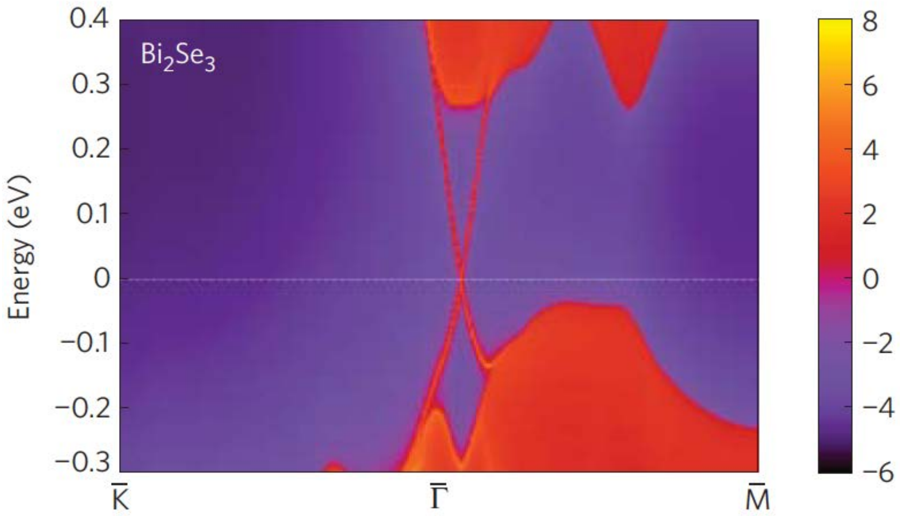
Analogy:
Quantum Spin Hall Effect ≈ superposition of 2 counter-orientated QHE



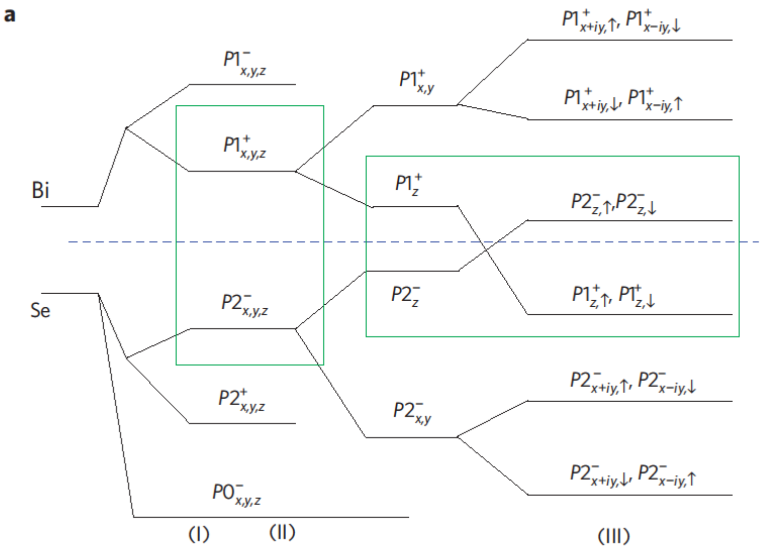
Topological Insulator:
„Internal“ magnetic field caused by spin-orbit interaction!

Band structure Bi_2Se_3

Spin-orbit interaction causes band inversion at the Brillouin zone center Γ



Ab initio calculations of Bi_2Se_3 surface states [SZ09]



Valence- and conduction band at Γ including following effects:

(I) Chemical bonding

(II) Crystal field distortion

(III) Spin-orbit coupling

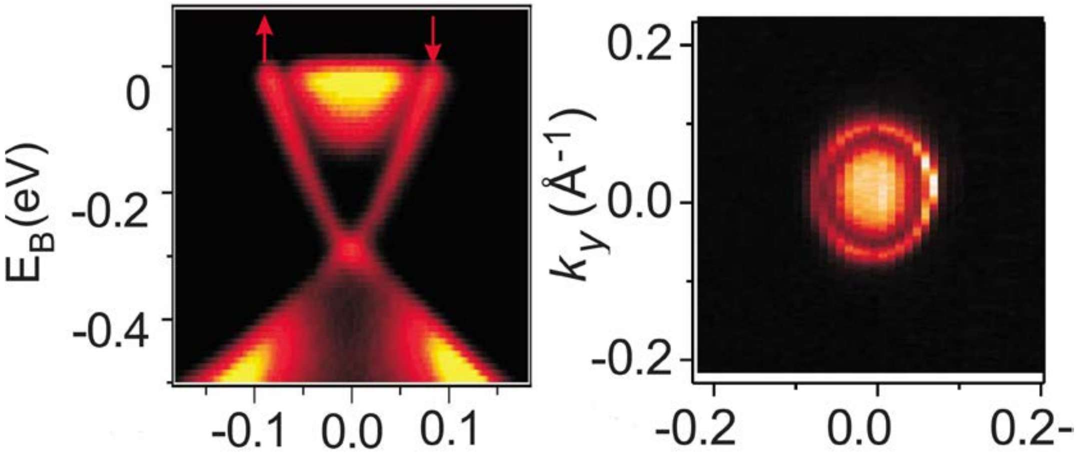
[SZ09]

$\mathrm{Bi_2}Se_3$ ARPES measurements

2009 ARPES measurements:
$\mathrm{Bi_2}Se_3$ is topological insulator!

BUT!

Destinct topological properties not useable!



ARPES data $\mathrm{Bi_2Se_3}$ 2009 [HH09]

Goal:

- Preparation of non (bulk) conducting $\mathrm{Bi_2}Se_3$ crystals
- Quantum transport measurements on surface states

Why $\mathbf{Bi_2Se_3}$?

- Large E_{gap} – Room temperature spintronic applications

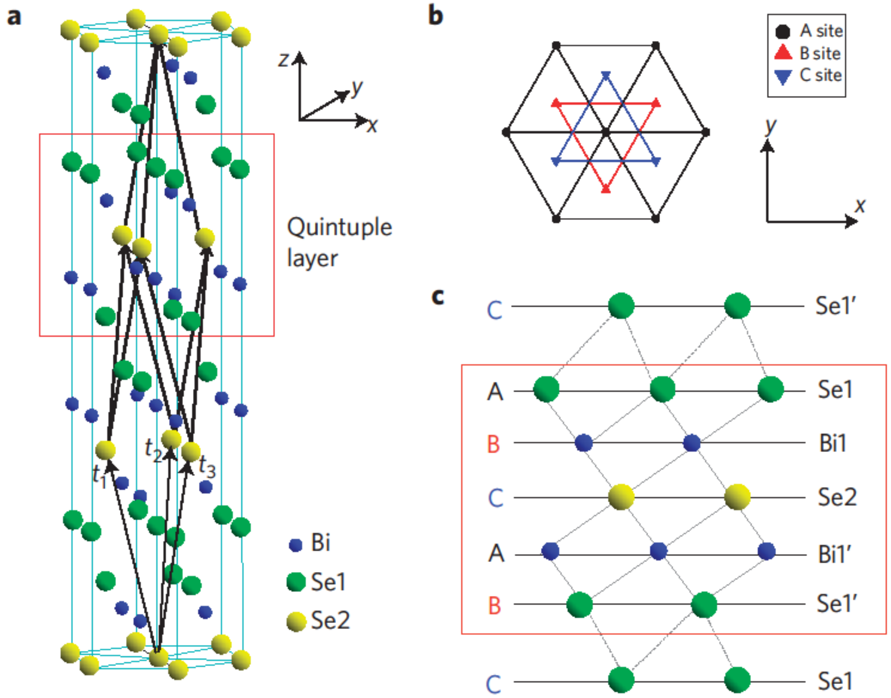
Crystal structure Bi_2Se_3

Problems:

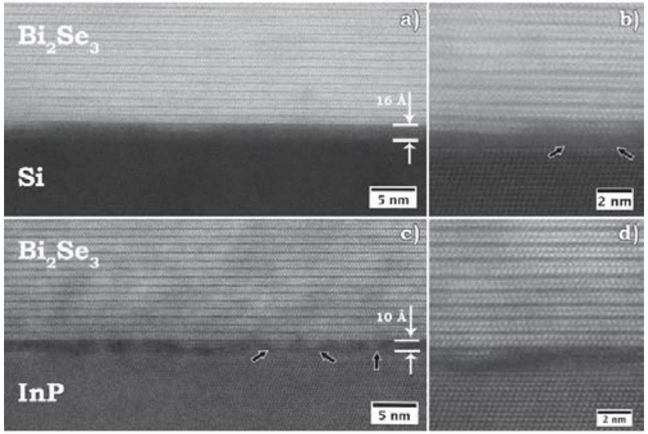
n-type doping by crystal defects

Causes:

- Se vacancies (+2 e-)
- Bad growth start cause layer of poor crystal quality

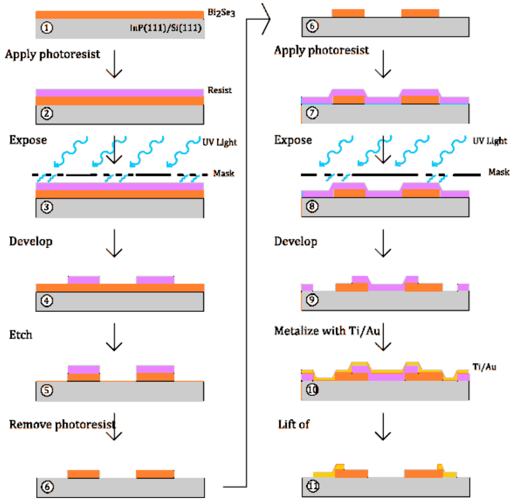


(a) Unit cell Bi_2Se_3 (b) On top view (c) Cross section [SZ09]

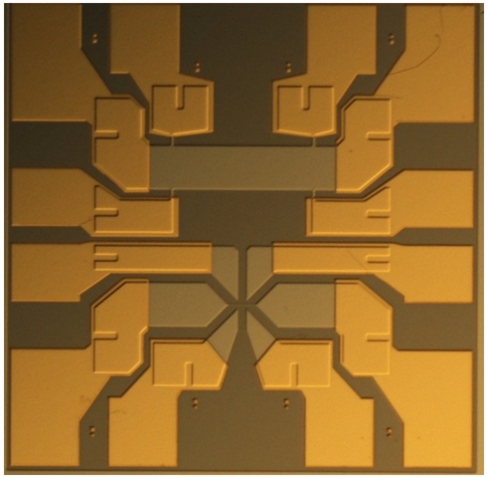


TEM substrate interface [TM12]

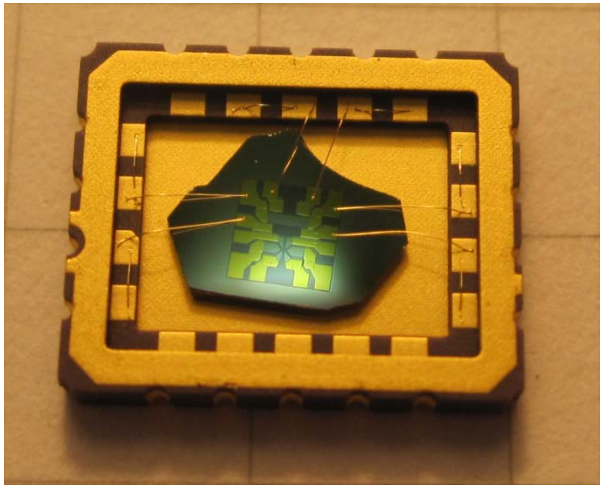
Sample preparation and layout



Lithography process diagram



Top-view without gate



Sample bonded to carrier

Preparation and layout:

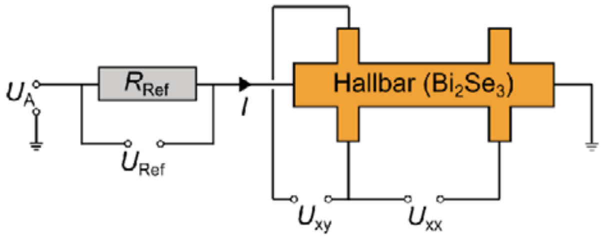
- Made from $\mathrm{Bi_2Se_3}$ (Si/InP substrate) Wafer piece
- Sample preparation by means of photolithography
- 2 Hall bar layout (600 x 200)μm und (10 x 30)μm

Transport setup

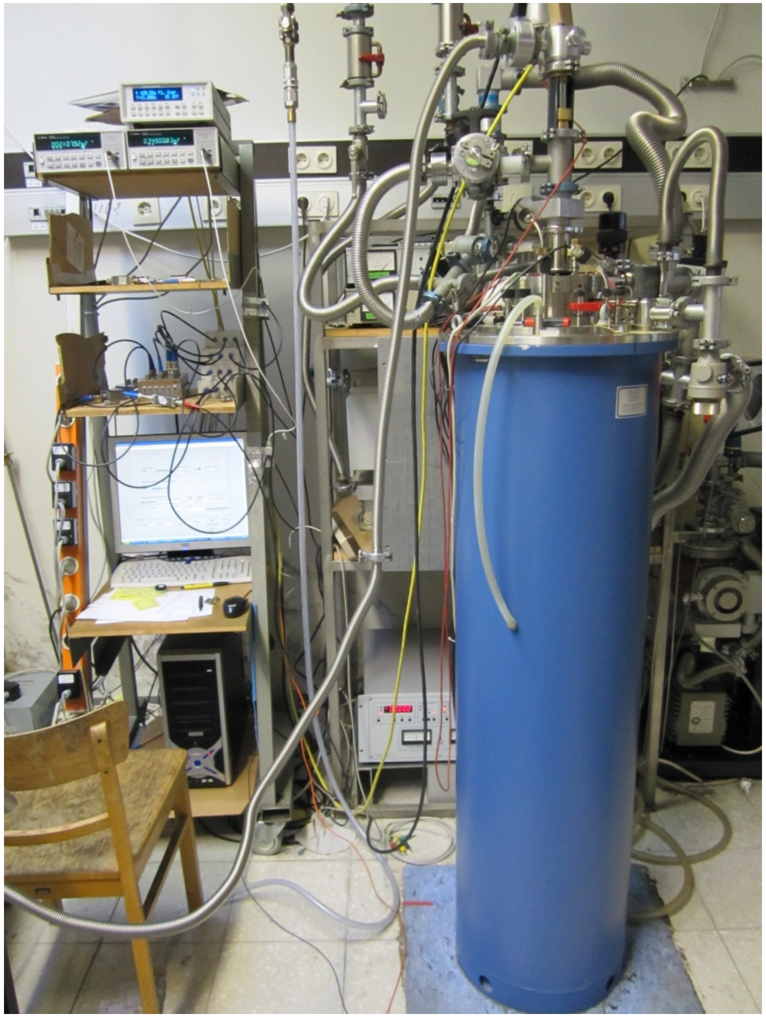
Setup:

- $^{4}\mathrm{He}$ – cryostat
- T = 4.2 K
- Superconducting magnet
- $B_\perp$ – field up to 14 T

- DC – measurements



Circuit diagram [MR11]



“14T”- Setup Ep3 Wuerzburg

Samples on Silicon substrate

Samples on Silicon :

- High densities
- Low mobilities
- Bulk conductance

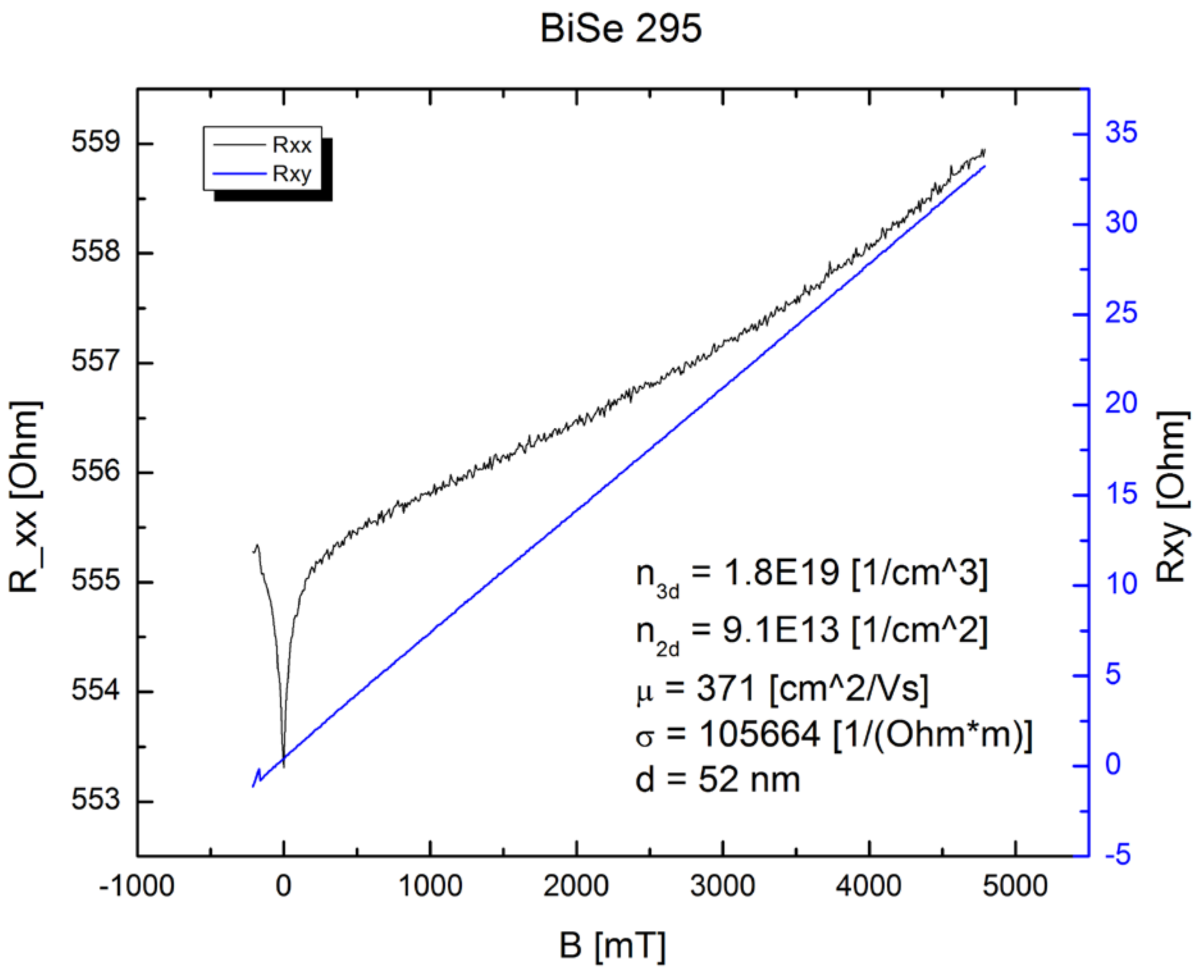
Lattice constants:

- $a_{Si(111)} = 3.84\ \text{Å}$
- $a_{Bi_2Se_3(111)} = 4.14\ \text{Å}$

7%

- $a_{InP(111)} = 4.15\ \text{Å}$

→ InP substrate

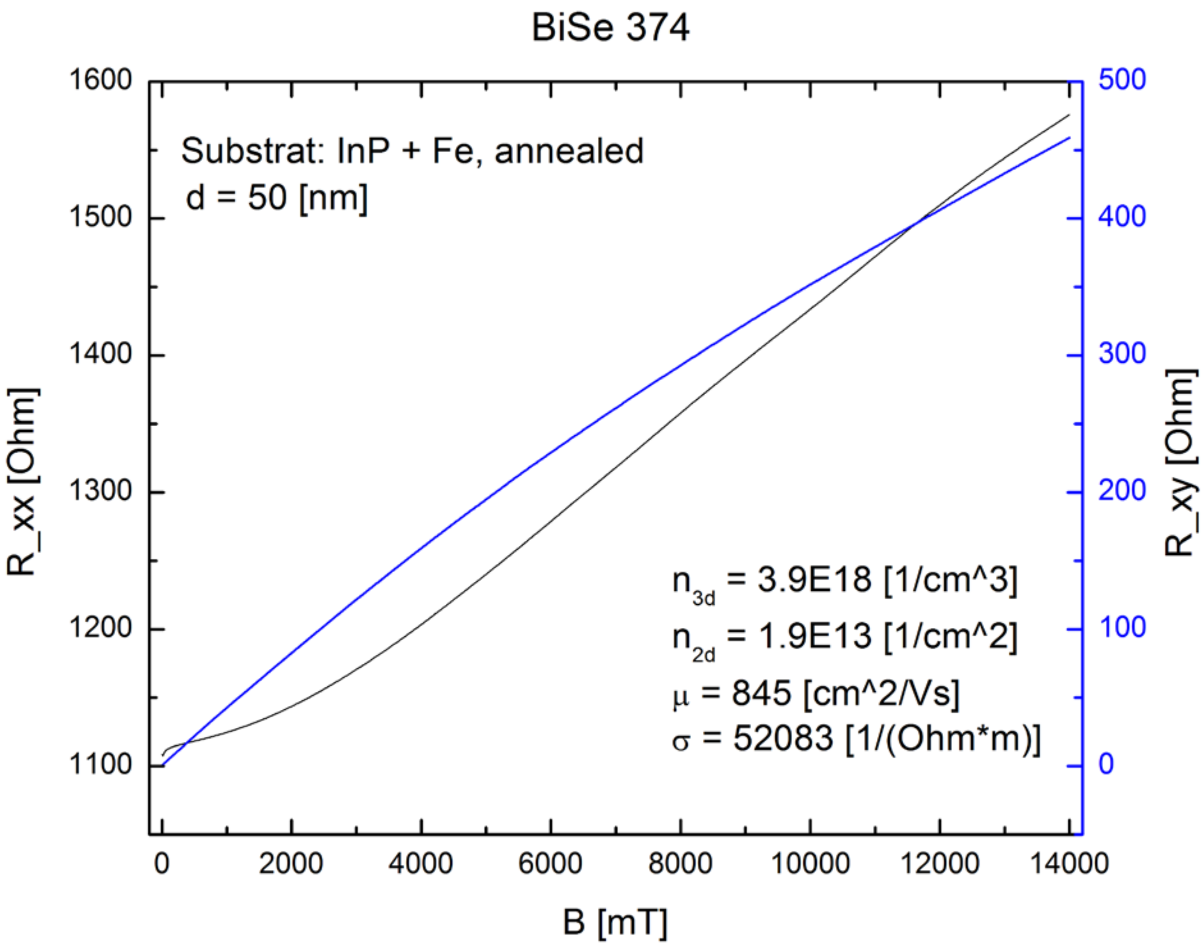


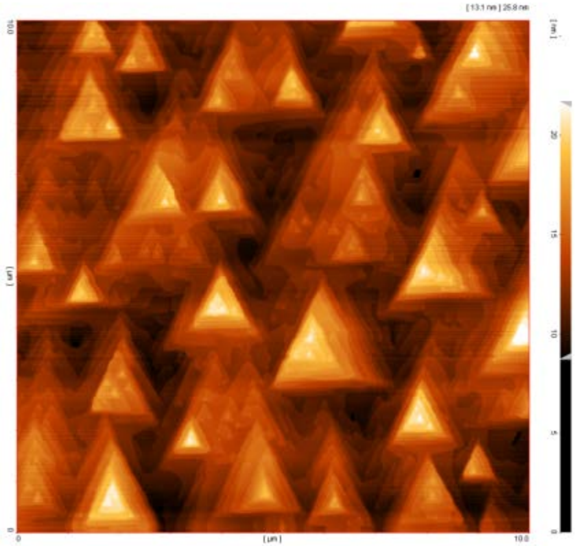
Samples on InP + Fe, annealed

Samples on InP :

- Lower densities
- Higher mobilities
- Non linear Hall

→ 2 different carriers





Large domains visible in AFM images

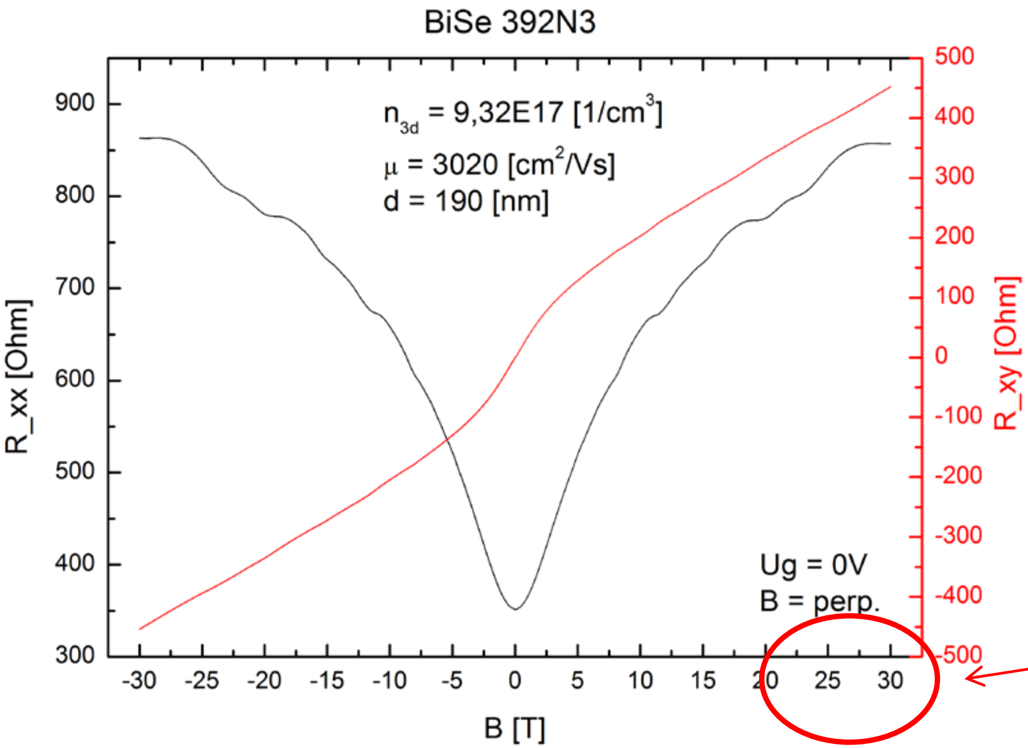
→ High sample quality

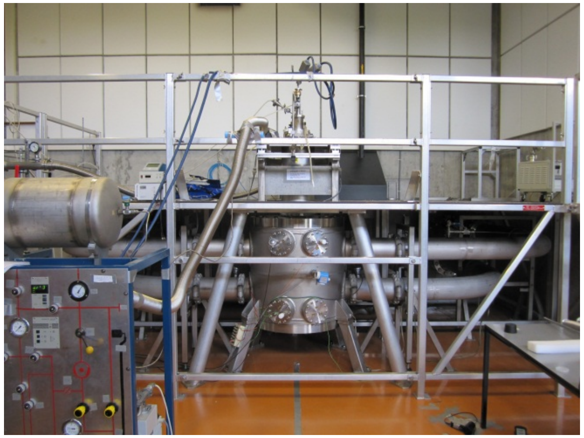
High field measurements

The $\mathrm{Bi_2Se_3}$ thickness of 190 nm is >> 2D system, therefore:

If Quantum Hall Effect

- ➡ 2D System
- ➡ Conduction via surface states
- ➡ Topological insulator





Bitter-magnet HMFL Nijmegen

Magnetic field rotation

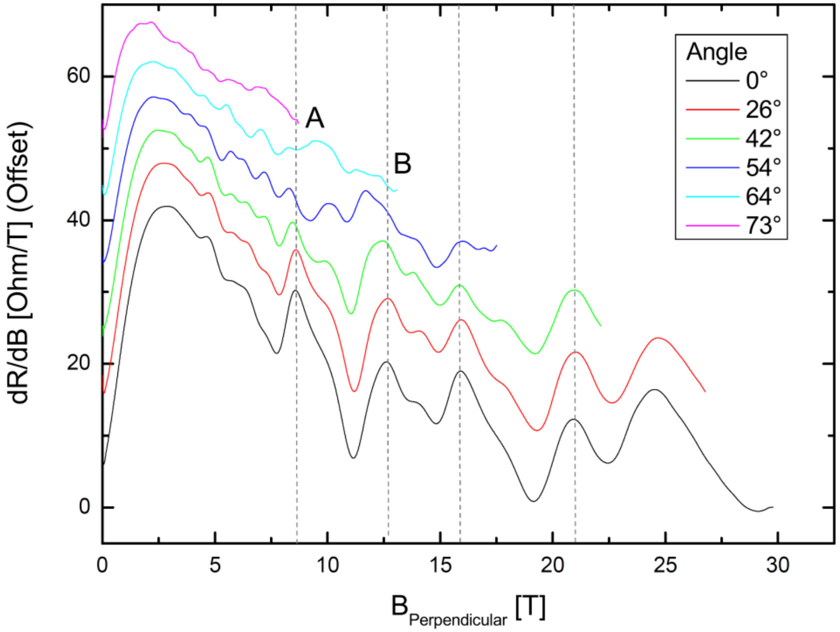
True 2D electron gas:

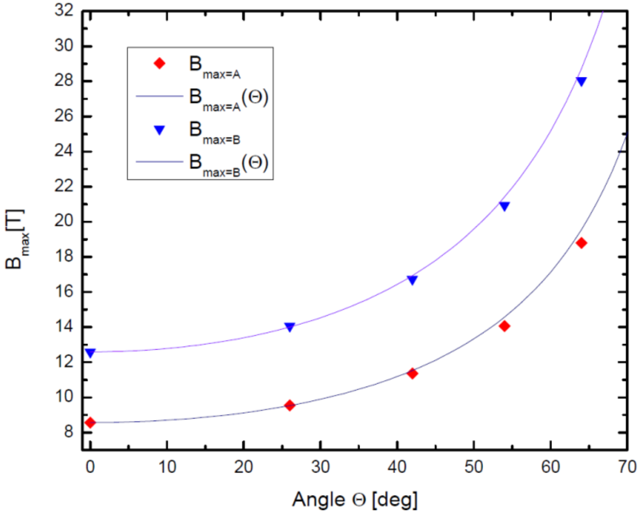
- Oscillations independent of $B_{||}$ component!
- Oscillations periodic in 1/B

Only holds up to 50^{o}

Oscillations only in some cases periodic in 1/B

- Oscillations caused by other effects?
- Multiple oscillation frequencies?





Summary

Goals:

- Growth of bulk insulating Bi_2Se_3
- Quantum transport measurements of 3D TI surface states

Results:

- Improvement of carrier density and carrier mobility
- Established growth on InP substrates
- High field measurements: Surface states or bulk oscillations (!?)

Thank you for your kind attention!

Sources

[HK10] Z. Hasan, L. Kane. *Colloquium: Topological Insulators,* Review of modern physics, vol. 82, 2010

[SZ09] S. C. Zhang et al. *Topological insulators in Bi2Se3, Bi2Te3 and Sb2Te3 with a single Dirac cone on the surface*. Nature Physics, 5:438, 2009.

[MR11] M. Reuß. *Transporteigenschaften dreidimensionaler topologischer Isolatoren*, Diplomarbeit, Physikalische Fakultät Universität Würzburg, 2011.

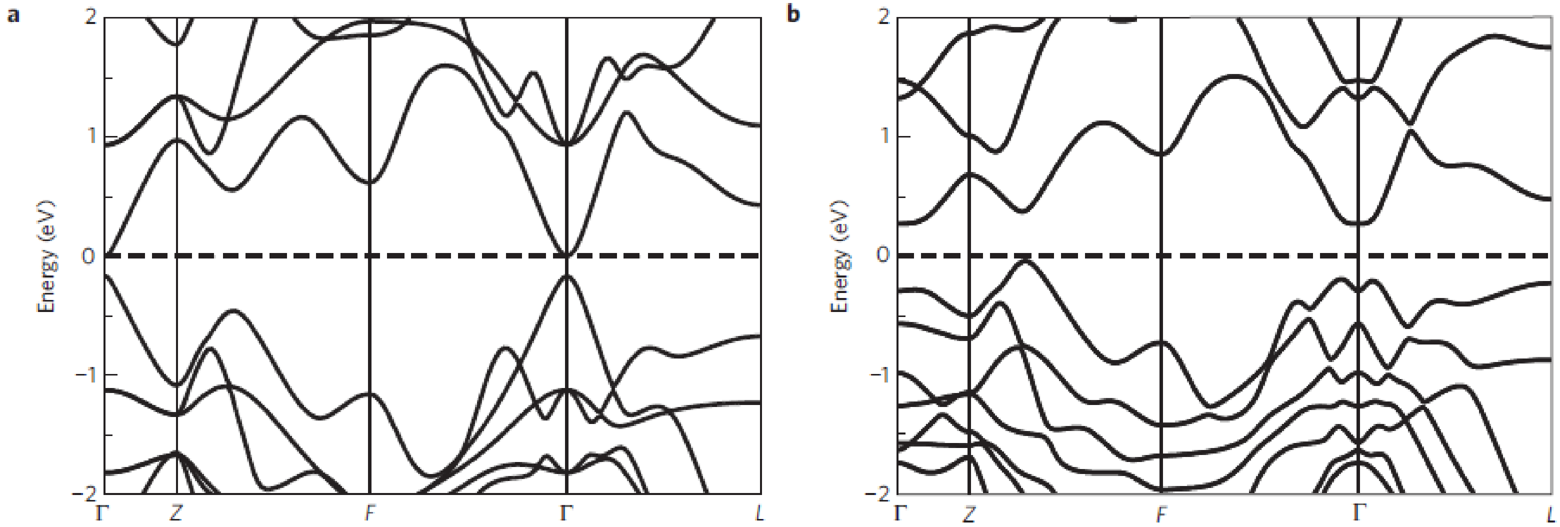
[HH09] M. Hasan, D. Hsieh et al. *A tunable topological insulator in the spin helical Dirac transport regime,* Nature vol. 460, 2009

[TM12] N. Tarakina, L. Molenkamp et al. *Comparative Study of the Microstructure of Bi2Se3 Thin Films Grown on Si(111) and InP(111) Substrates,* Crystal Growth and Design, 2012

[CHJ] C. Jansky, public domain, wikipedia.org/festplatte.

[IHT] Institut für Halbleitertechnik, Universität Köln, iht.uni-stuttgart.de/forschung/spinplasm

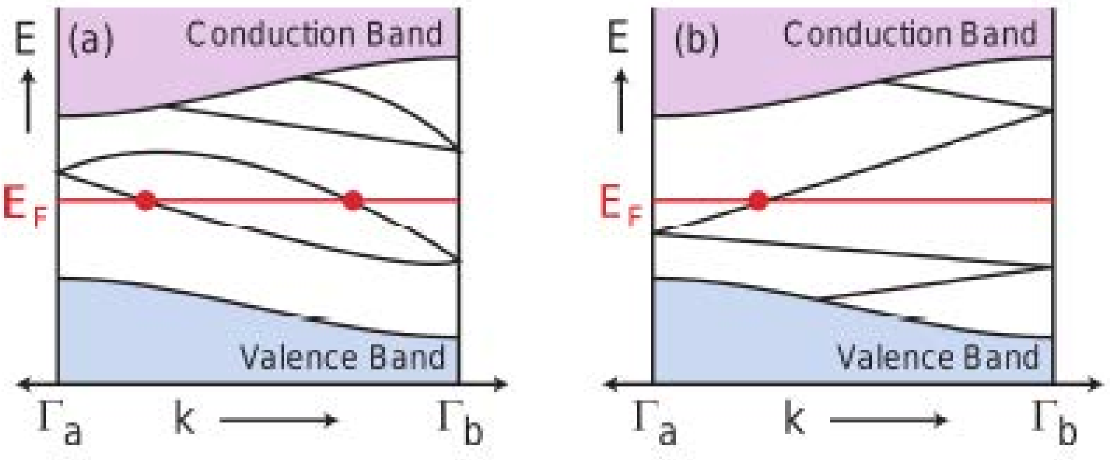
Band structure $\mathrm{Bi_2}Se_3$

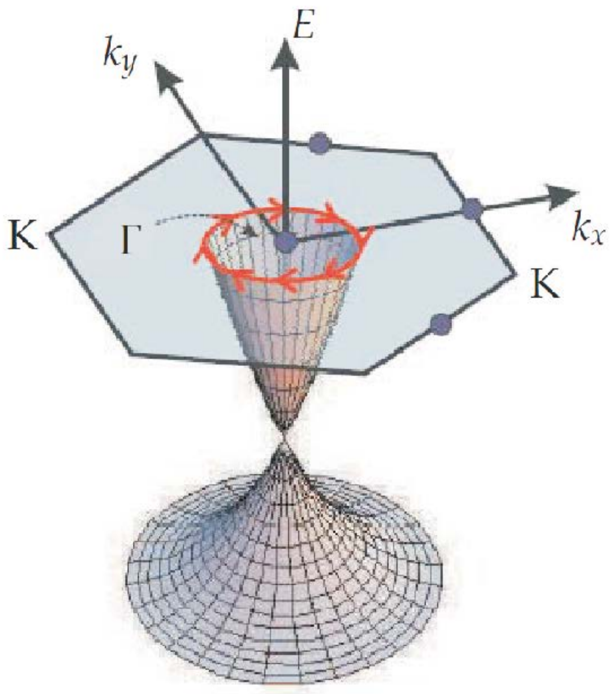


Ab initio band simulations: (a) without SOC (b) with SOC

Topological Insulators

Time reversal symmetry maintained since $\mathrm{B}_{Total} = 0$!





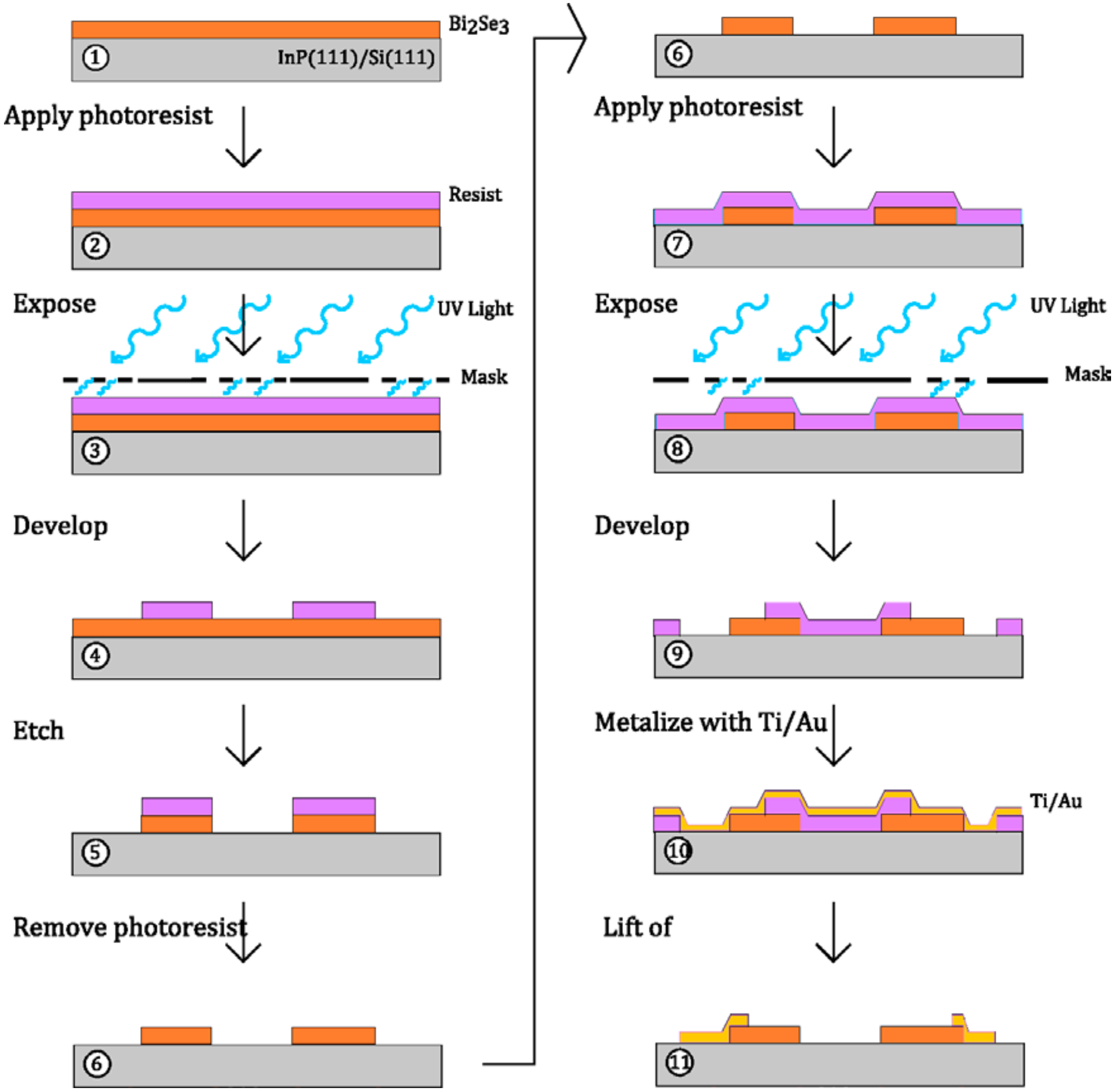
[HK10]

Γ_i : Kramers degenerate points [HK10]

3D: $(-1)^{\nu 0} = \prod_{i=1}^{8} \delta(\Gamma_i)$

(a) No topological insulator at even number of intersections
(b) $\mathbb{Z}_2$topological insulator at $\Delta\upsilon_0 = N mod 2 = 1$

Photolithography



Lithography process diagram

Transport measurements

1 Carrier model:

$$A_H = \frac{1}{nq} \qquad n = \frac{1}{ed}\frac{I}{U_H}B = \frac{1}{ed}\frac{B}{R_H} \qquad \mu = \frac{\sigma}{ne} = \frac{l}{R_{xx}b}\frac{R_H}{B}$$

2 Carrier model:

$$A_H = \mp e^{-1}\frac{(\mu_1^2 n_1 + \mu_2^2 n_2) + (\mu_1\mu_2 B)^2(n_1 + n_2)}{(\mu_1|n_1| + |n_2|)^2 + (\mu_1\mu_2 B)^2(n_1 + n_2)^2}$$

- Determination of transport parameters via Hall measurements
- Fit 1 or 2 carrier model to data

Topological Insulators

Quantum Hall Effect:

$$\varepsilon_m = \hbar\omega_c\left(\mathrm{m} + \frac{1}{2}\right)$$

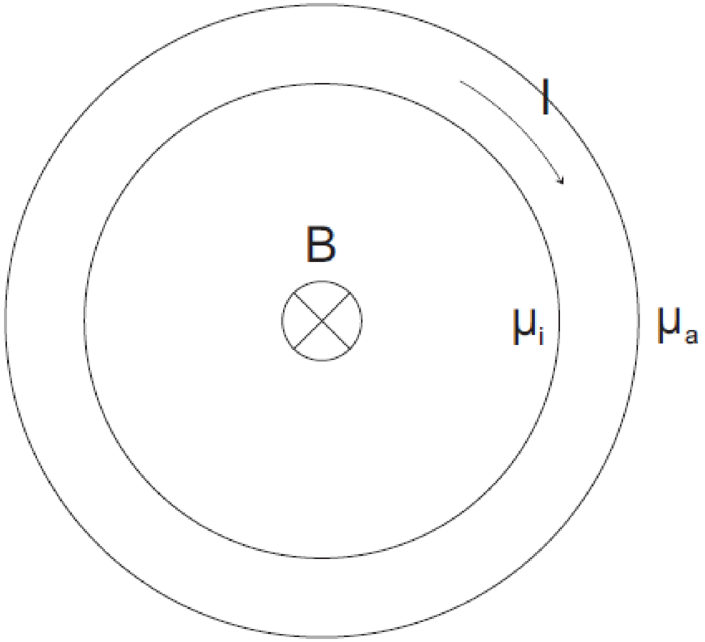
$$\sigma_{xy} = N\,\frac{e^2}{h}$$

Hall constant can be calculated
From the Berry flux

$$N = \sum_m n_m$$

$$n_m = \int d^2\boldsymbol{k}\,(\nabla \times (\mathrm{i}\langle u_m|\nabla_k|u_m\rangle))$$

Laughlin Picture:



[SG10]

$$I = \frac{\Delta F}{\Delta\Phi} = \frac{ne(\mu_a - \mu_i)}{h} \qquad G = \frac{I}{U} = n\frac{e^2}{h}$$

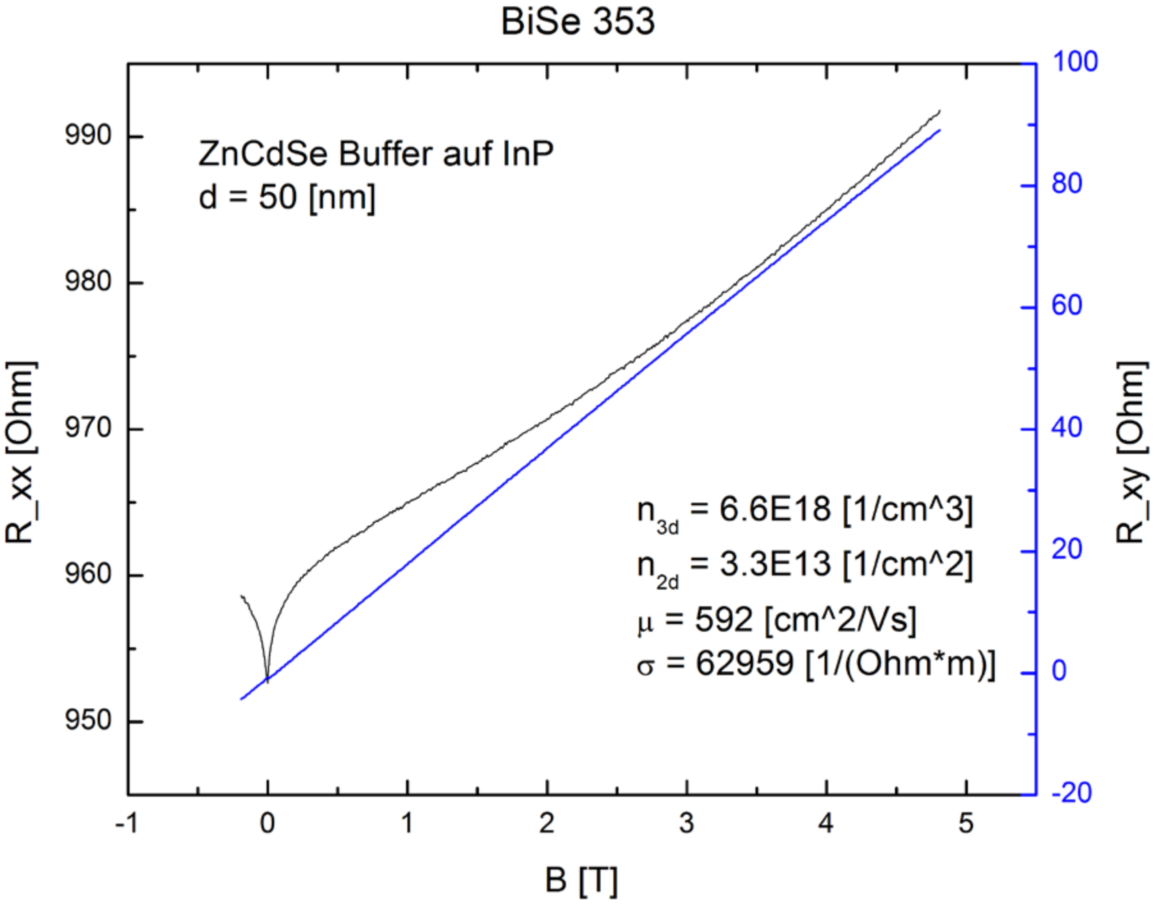
Samples on ZnCdSe buffer

Samples with ZnCdSe buffer:

- Better densities
- Higher mobilities

Draw backs:

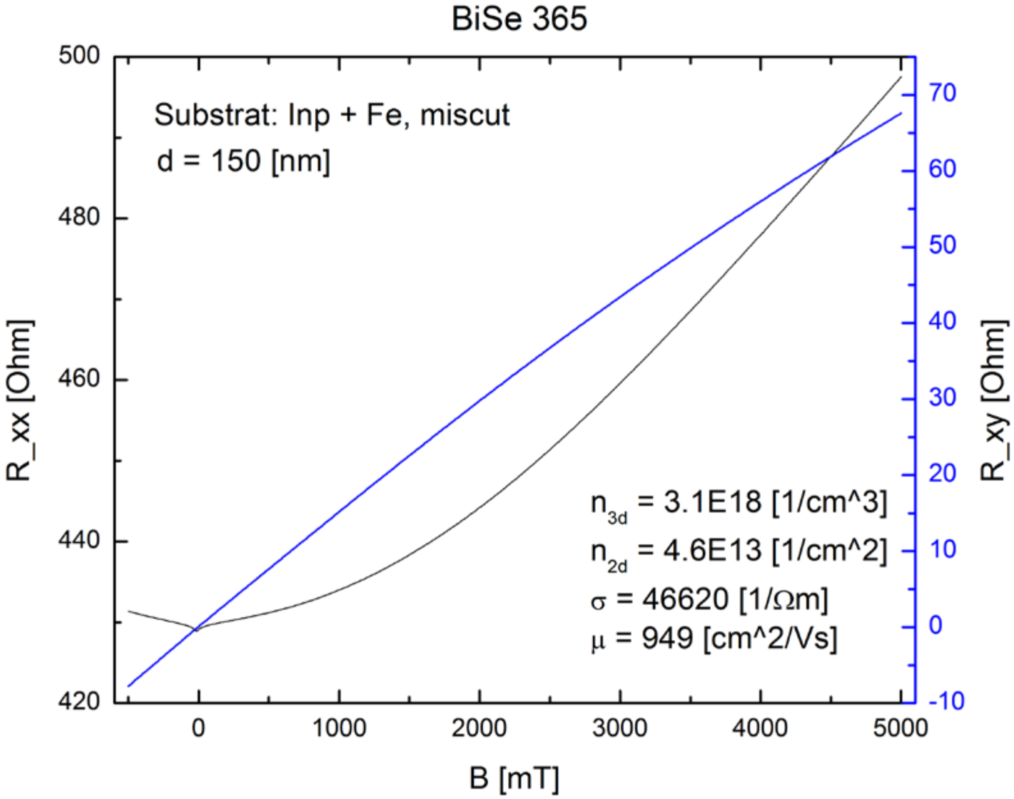
- Difficult growth
- New error types



Samples on InP + Fe, miscut

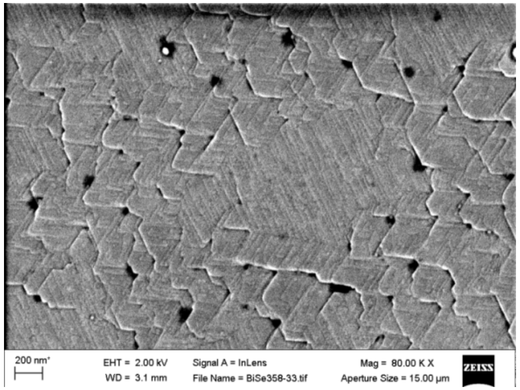
Iron doped InP substrate:

- InP insulating
- Better carrier densities
- Higher mobilities (compared to Si(111))



Miscut:

- Surface miscut relative to InP(111)
- Idea: stepwise growth

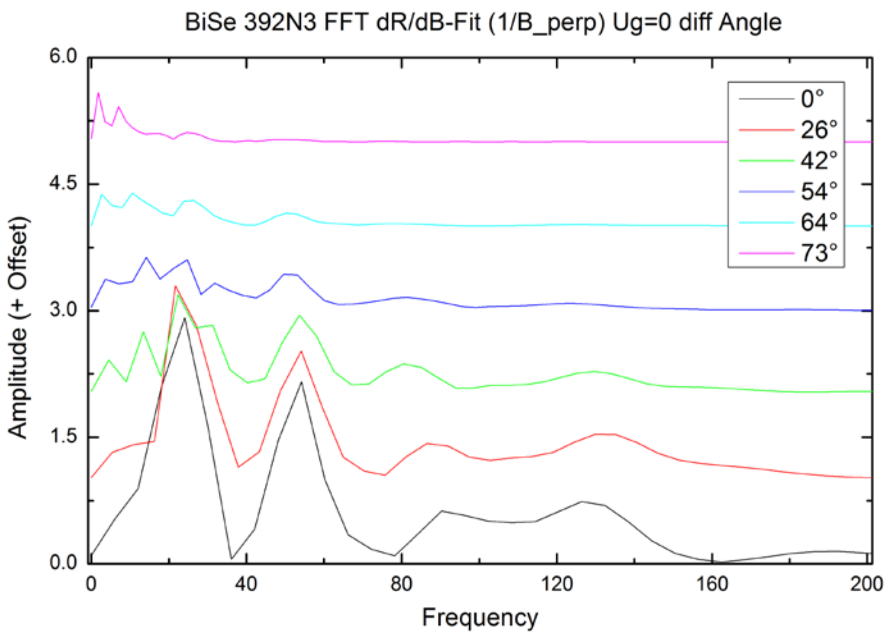


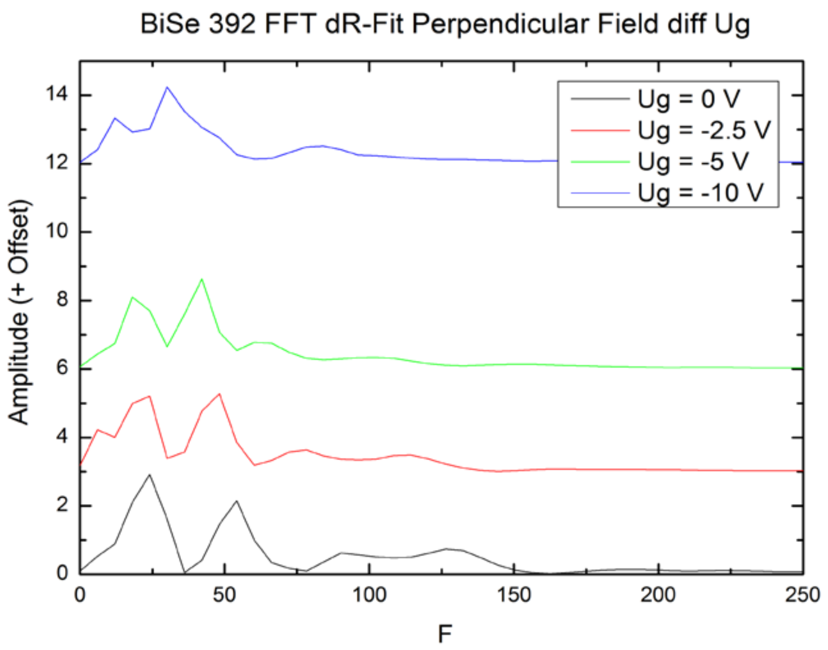
[TM12]

Fourier transformation

2 frequencies = 2 surface states ?

- Hard to get carrier densities from few oscillations
- Signal to weak for FFT


BiSe 392N3 FFT dR/dB-Fit (1/B_perp) Ug=0 diff Angle


BiSe 392 FFT dR-Fit Perpendicular Field diff Ug

Temperature dependence