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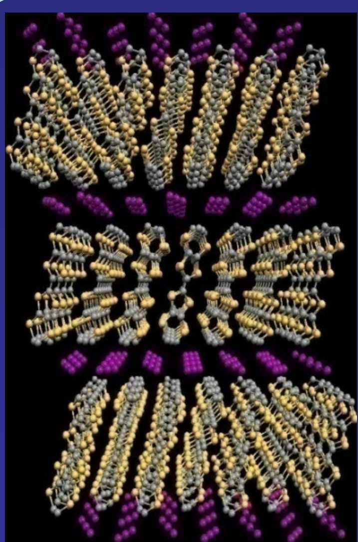
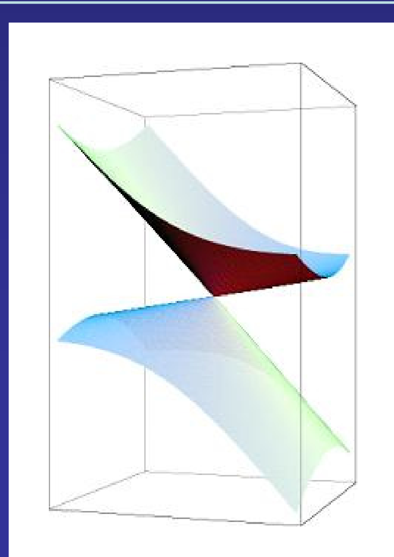
Materials Science-2014 Oct. 6. 2014

Quantum Hall effect in multilayered massless Dirac fermion systems

Toho Univ., N. Tajima





α-$(BEDT\text{-}TTF)_2I_3$ (p>1.5 GPa)

- ✓ Dirac fermion system
- ✓ carriers (holes) doping
- ✓ Quantum transport phenomena
  SdH & QHE

Toho Univ.

:T. Ozawa, T. Yamauchi, Y. Nishio and K. Kajita

RIKEN

:Y. Kawasugi and R. Kato

IMS

:M. Suda and H. M. Yamamoto

Outline

1. Introduction

2. holes-doping: SdH and QHE

3. Conclusions

Outline

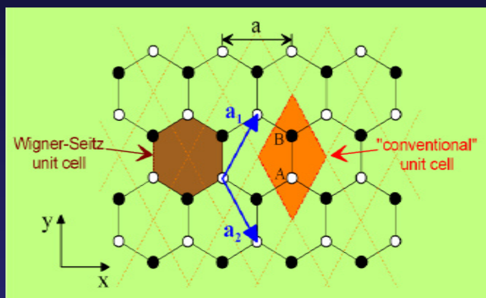
1. Introduction

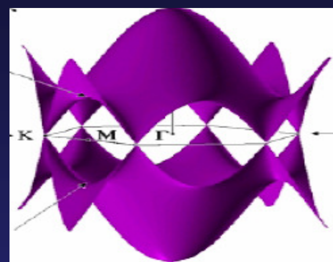
2. holes-doping: SdH and QHE

3. Conclusions

1. Introduction : α-(BEDT-TTF)$_2$I$_3$

Graphene: monolayer of graphite

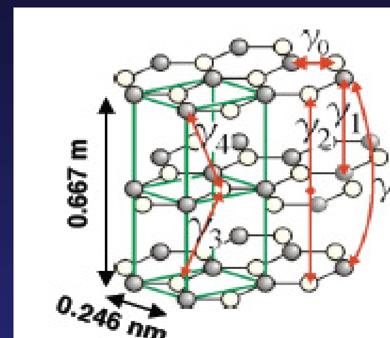




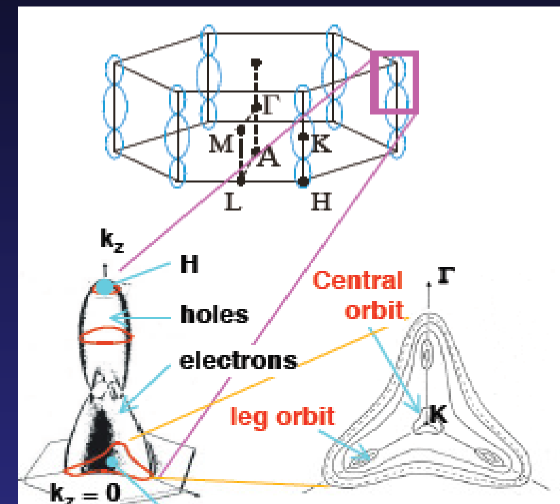
P.R. Wallace, *Phys. Rev. 71, 622 (1947)*

K. S. Novoselov *et al., Nature 438(2005)197.*

Y. Zhang *et al., Nature 438(2005)201.*

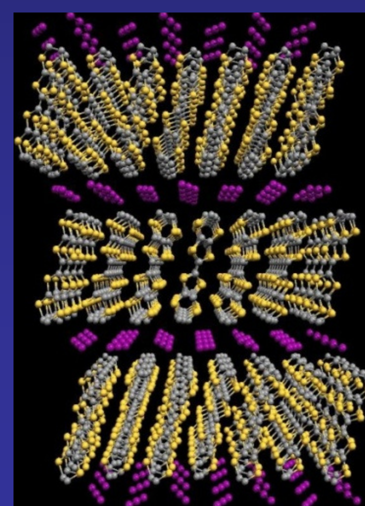


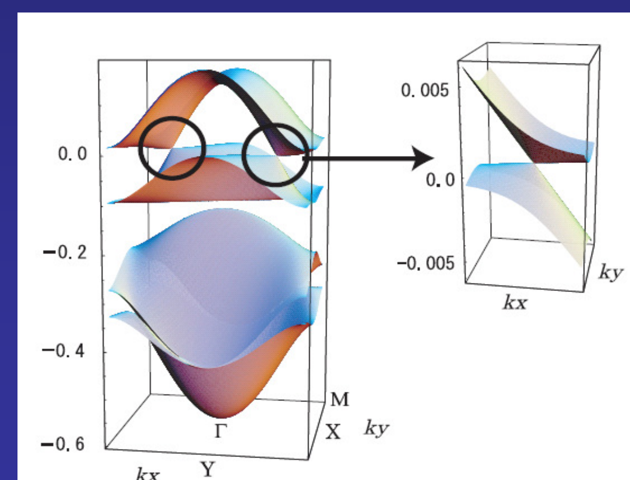
graphite



α-(BEDT-TTF)$_2$I$_3$
(p>1.5GPa)

<u>First bulk zero-gap material</u>



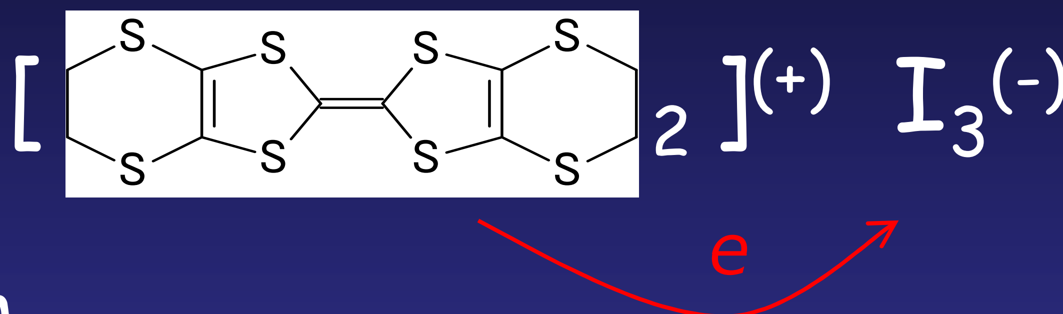


Katayama, et al.,

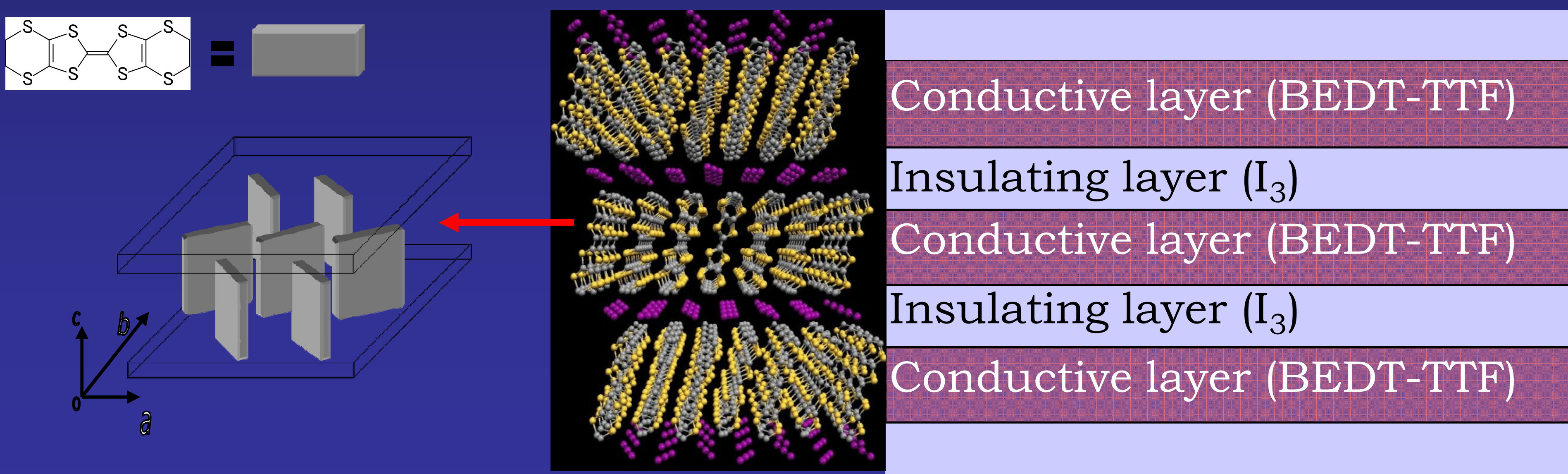
1. Introduction : α-$(BEDT\text{-}TTF)_2I_3$

K.Bender, et al., Mol. Cryst. liq. Cryst., 108 (1984) 359

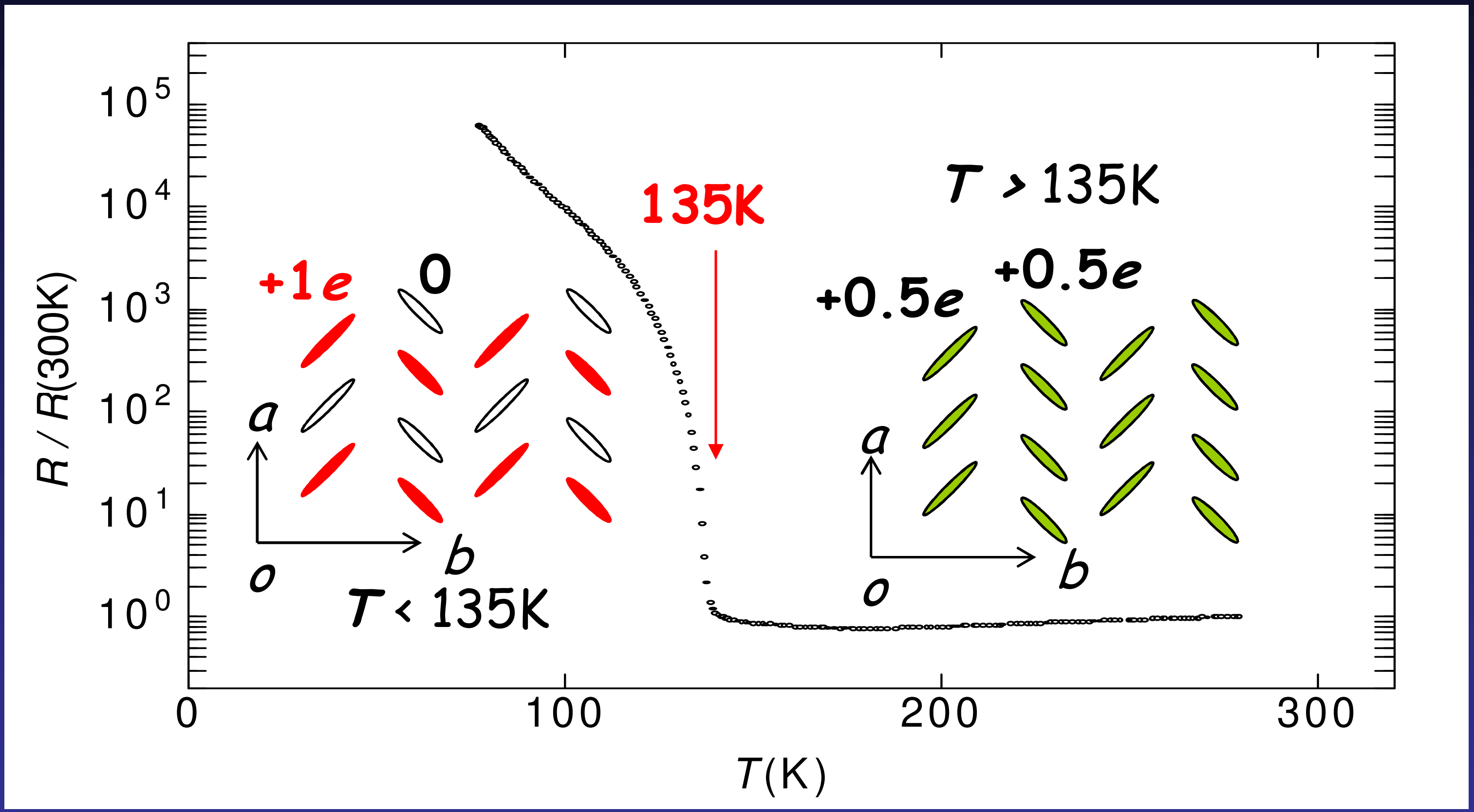
BEDT-TTF



2D-system



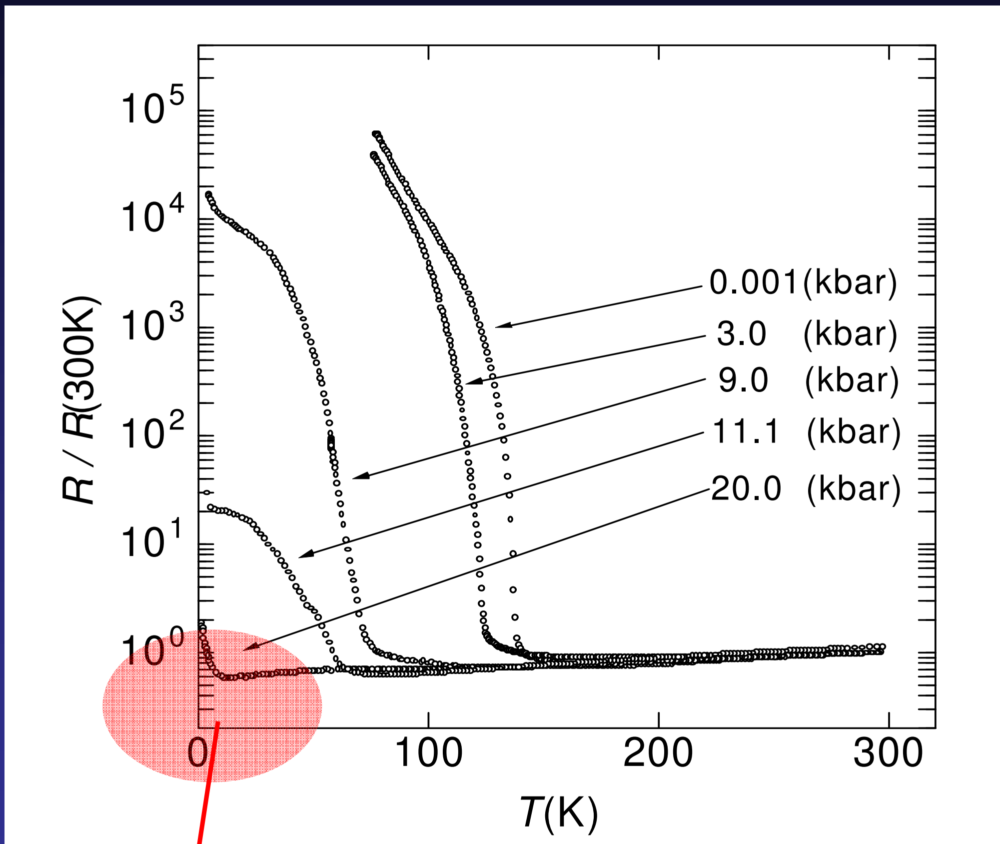
1. Introduction : α-$(BEDT\text{-}TTF)_2I_3$

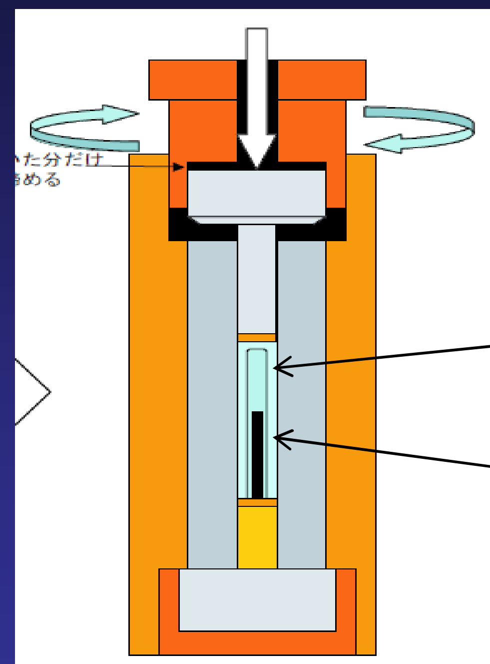


Charge disproportionation

H.Kino and H.Fukuyama (Theory)	*J. Phys. Soc. Jpn. 64(1995)1877.*
H.Seo (Theory)	*J. Phys. Soc. Jpn. 69(2000)805.*
Y.Takano, et.al. (NMR)	*J. Physics and Chemistry. Solid 62(2001) 393.*
R.Wojciechowski, et.al. (Raman)	*Phys.Rev.B 67(2003) 224105.*

1. Introduction : α-$(BEDT\text{-}TTF)_2I_3$



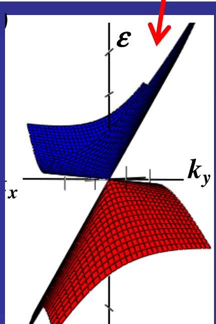


Teflon

Pressure medium: Oil

Sample

※1kbar=0.1GPa= 10,000 atm

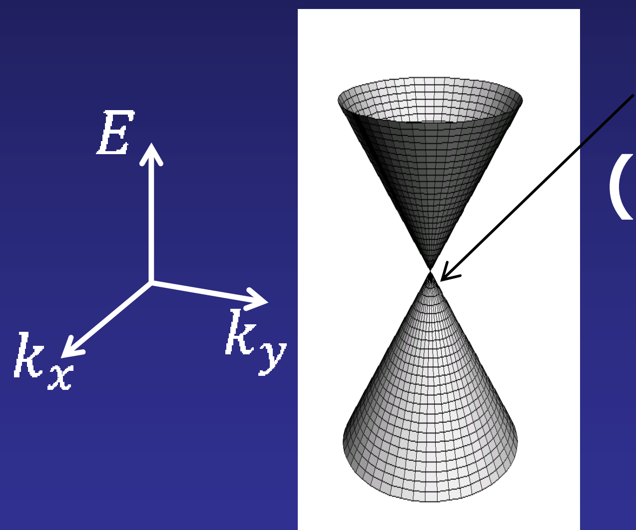


Zero-gap system: Dirac fermion

1. Introduction : α-(BEDT-TTF)$_2$I$_3$

What is interesting?

What is important?



Dirac cone

$$E = \pm \hbar v_F \, |\mathbf{k}|$$

$$E = \frac{\hbar^2}{2m^*} k^2$$:normal-*e*

m^*=0 : massless Dirac electrons

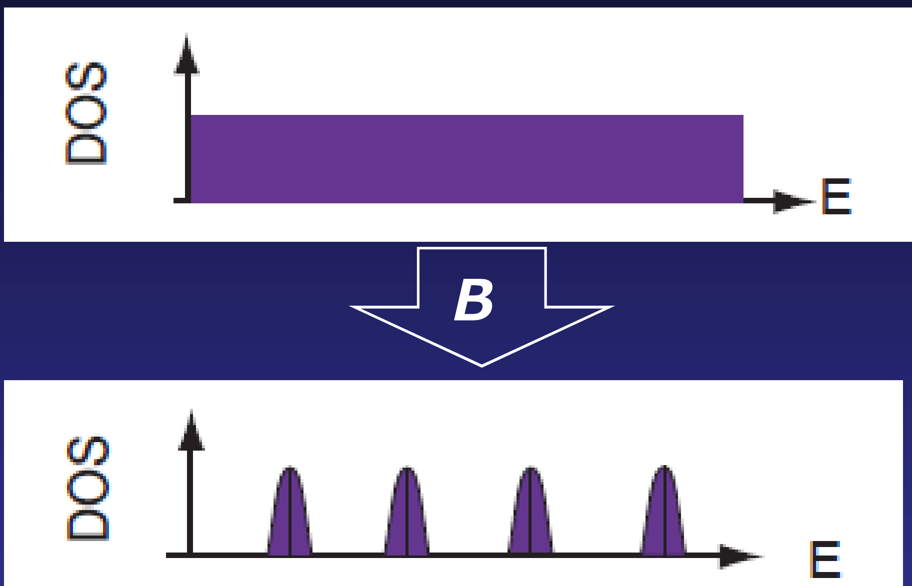
(relativistic electrons)

1. Introduction : Characteristic transport

- ✓ Sheet resistance: $R_s \sim h/e^2$
  - Toho Univ. & RIKEN
- ✓ Carrier density: $n = \int D f dE \propto v_{\mathrm{F}}^{-2} T^2$
  - Toho Univ. & RIKEN
- ✓ Anomalous σ_{xy} due to inter-band effects of B
  - Toho Univ. & RIKEN
  - A. Kobayashi, et al
- ✓ peculiar magnetotransport
  - Toho Univ. & RIKEN

1. Introduction : Landau level

Conventional conductor

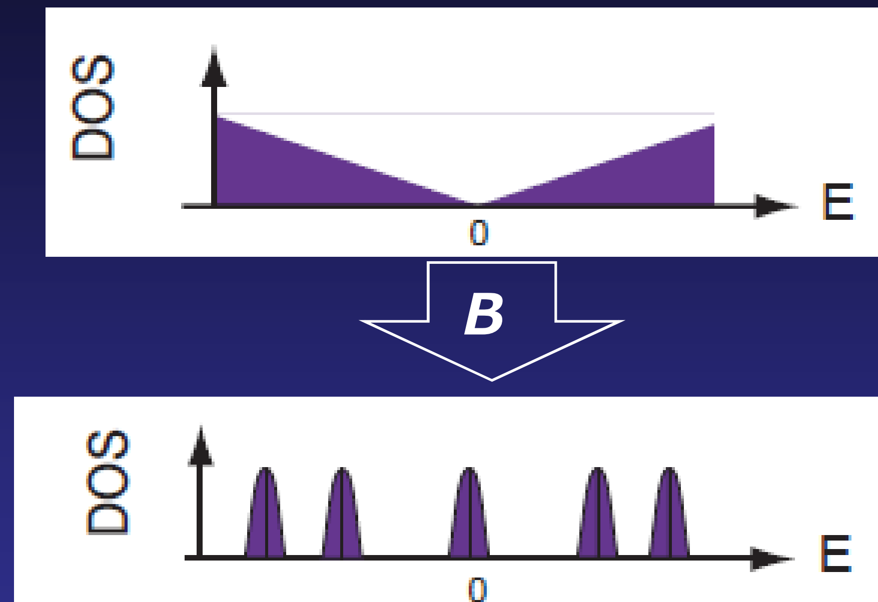


$$H = \frac{1}{2m}(\mathbf{p} + e\mathbf{A})^2$$

$$E_{\mathrm{nLL}} = \hbar\omega_c\left(\mathrm{n} + \frac{1}{2}\right)$$

$$\Delta = \hbar\omega_c$$

Zero-gap structure

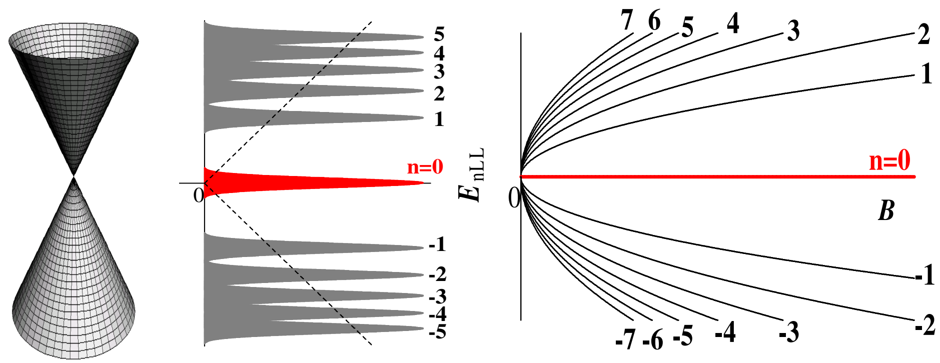


$$H = v_{\mathrm{F}}\boldsymbol{\sigma}\cdot(\mathbf{p} + e\mathbf{A})$$

$$E_{\mathrm{nLL}} = \pm\sqrt{2e\hbar v_{\mathrm{F}}^2 |\,\mathrm{n}\,||\,B\,|}$$

$$\Delta = \sqrt{2e\hbar v_{\mathrm{F}}^2 B}\left(\sqrt{|n|} - \sqrt{|n-1|}\right)$$

1. Introduction :   Zero-mode



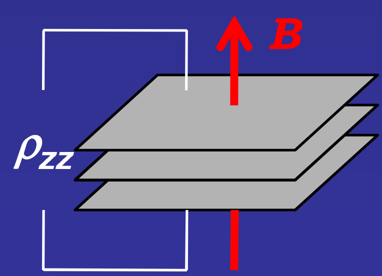
$$E_{\mathrm{nLL}} = \pm\sqrt{2e\hbar v_F^2 |n||B|}$$

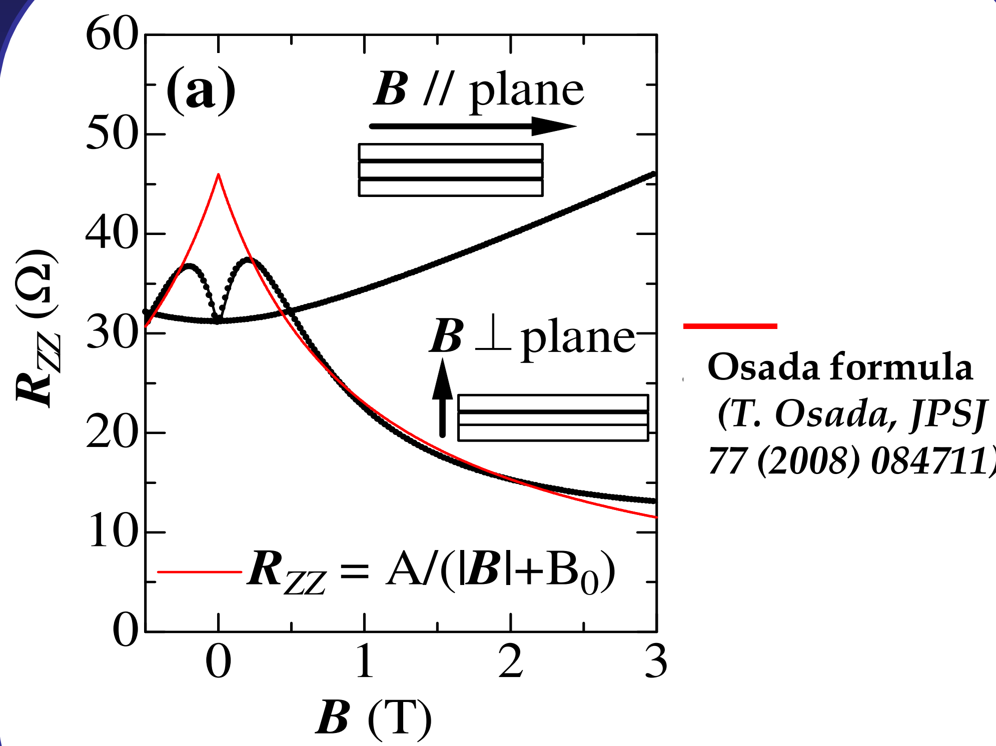
1) $E_{1LL} \gg k_B T$, → quantum limit

2) Degeneracy of zero mode
: $n_{0LL}(B) = B/2\phi_0$, $\phi_0 = h/e$

3) $\sigma_{zz} \propto n_{0LL} \propto B$

$\rho_{zz} \propto 1/B$





N. T, et al., PRL, 102, 176403 (2009).

Outline

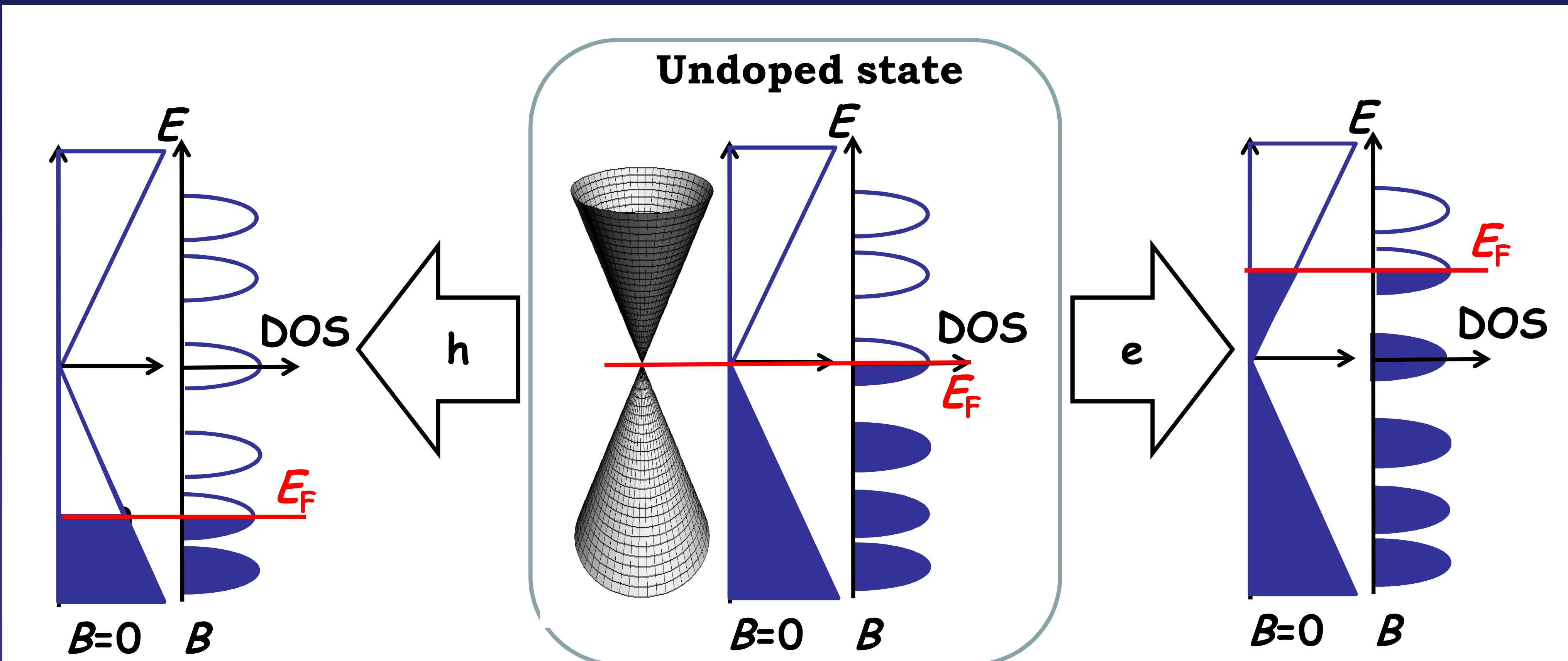
1. Introduction

2. holes-doping: SdH and QHE

3. Conclusions

2. holes-doping : Other Landau level

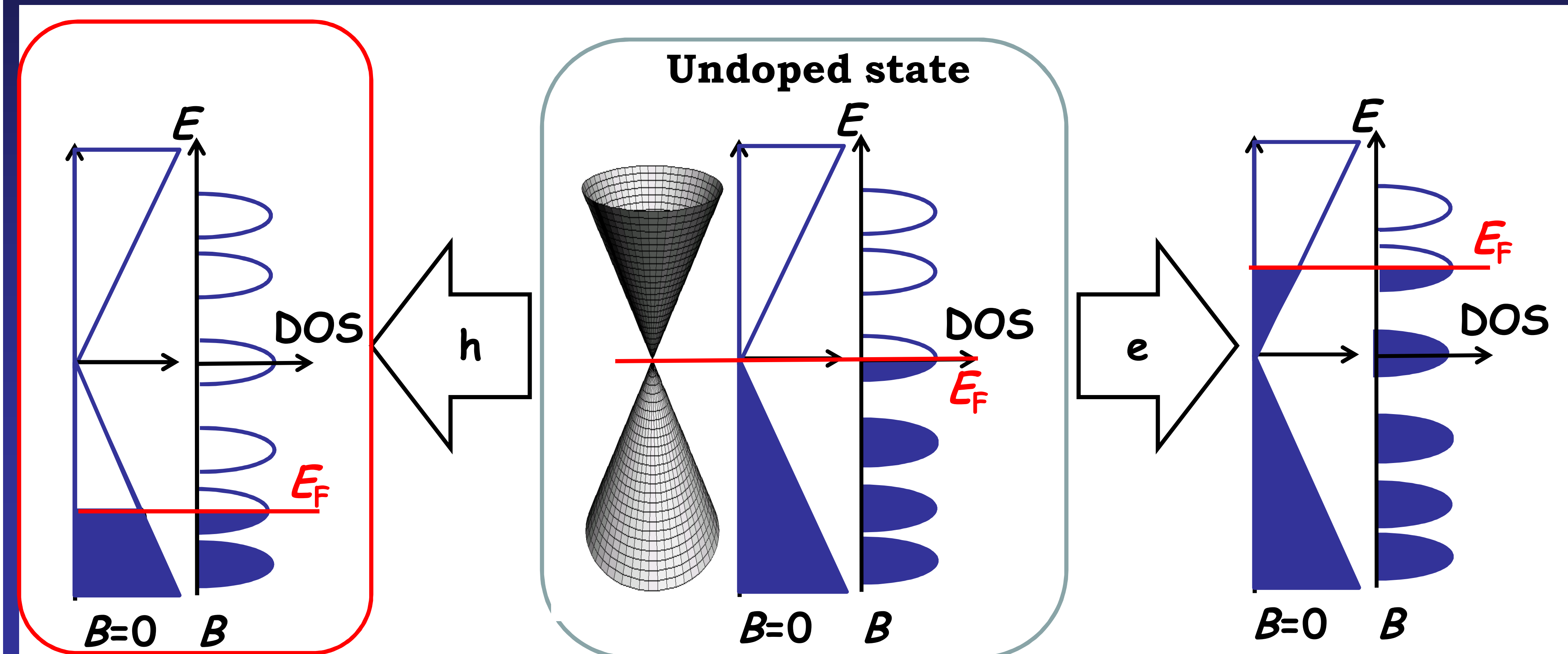
Can we inject the carriers into the sample?



2. holes-doping :

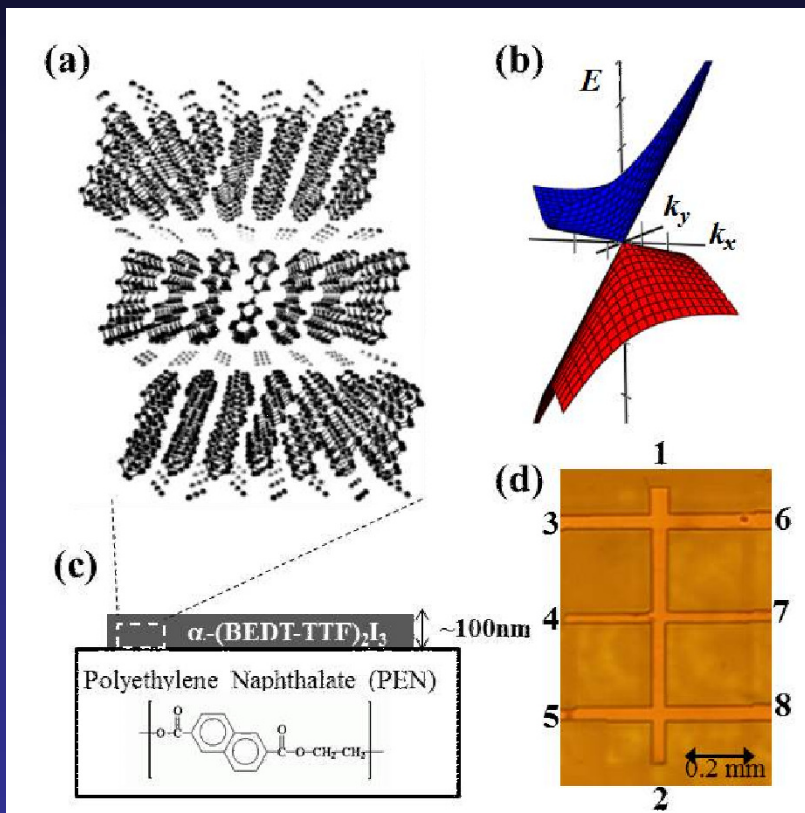
Can we inject the carriers into the sample?

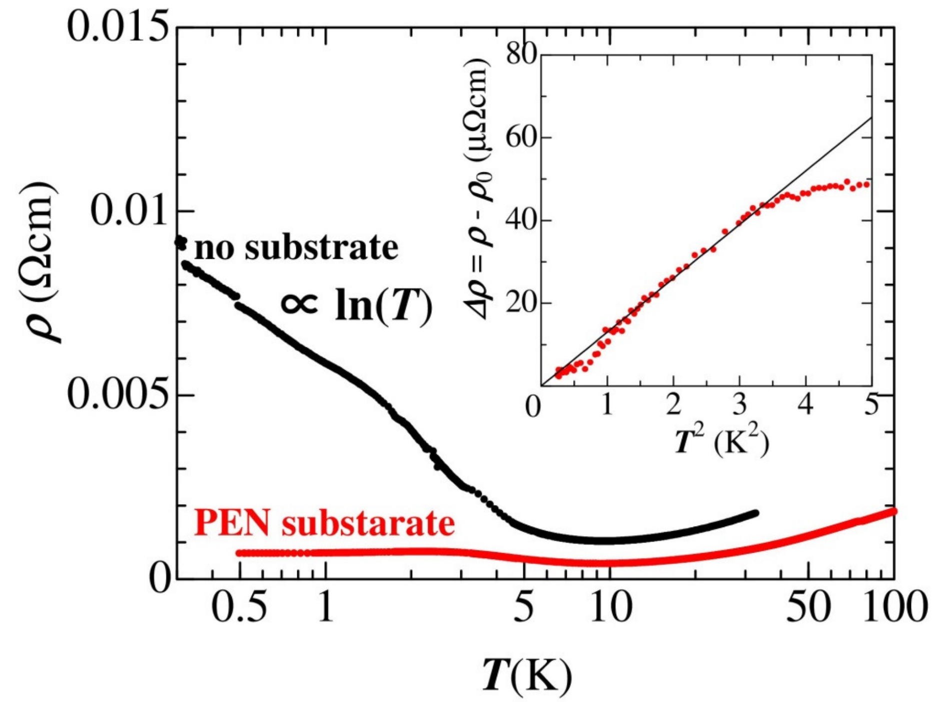
Yes → Breakthrough



2. holes-doping: resistivity

N. T, et al., PRB, 88, 075315 (2013).





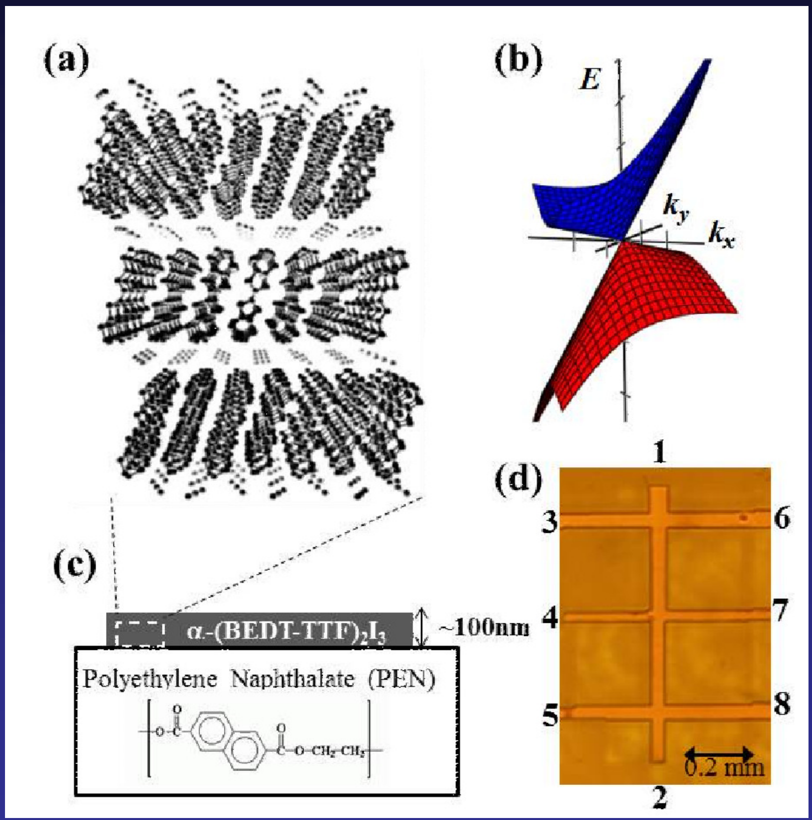
1. PEN is slightly charged in negative.
2. n~10^8 cm^{-2}/layer at low-T

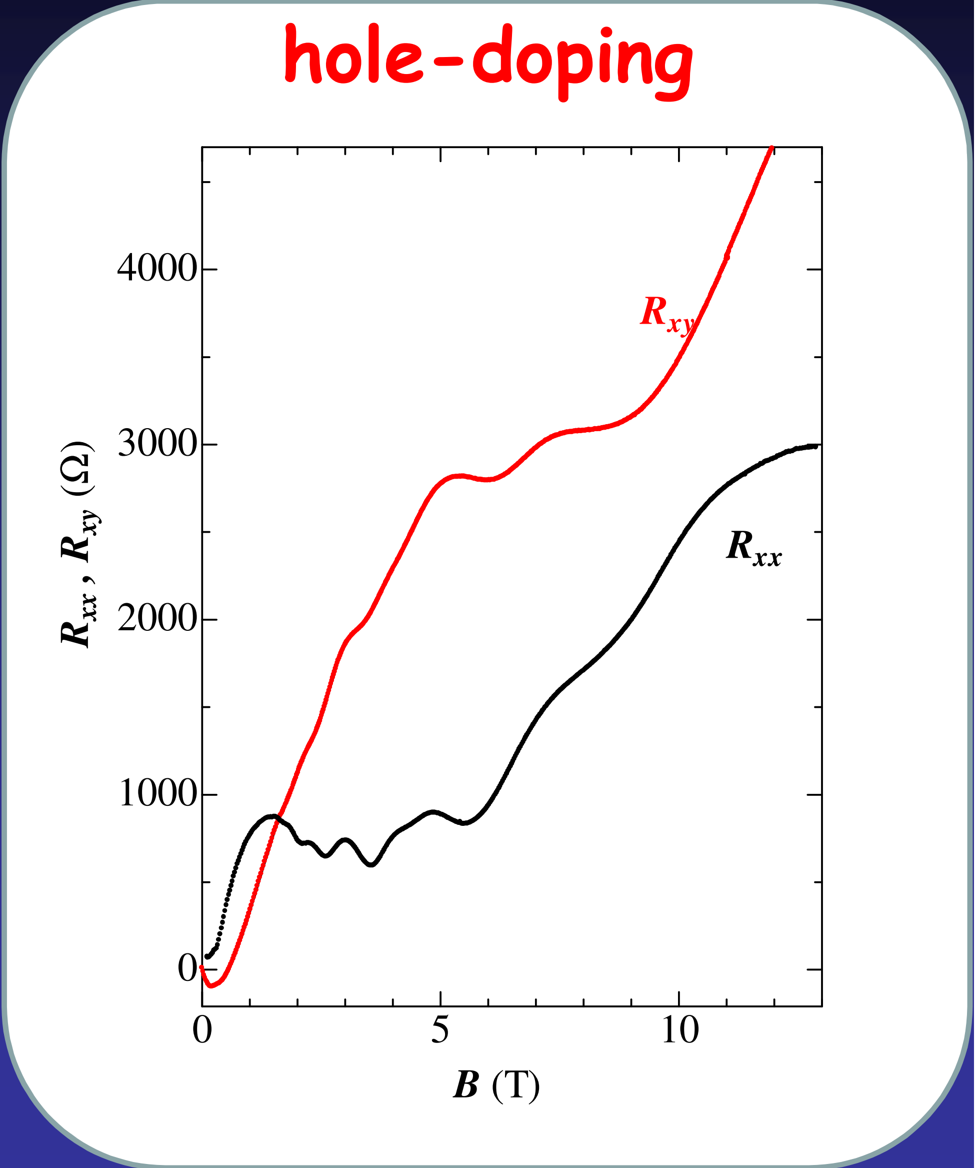
Fermi-liquid sate

$\rho \propto T^2$

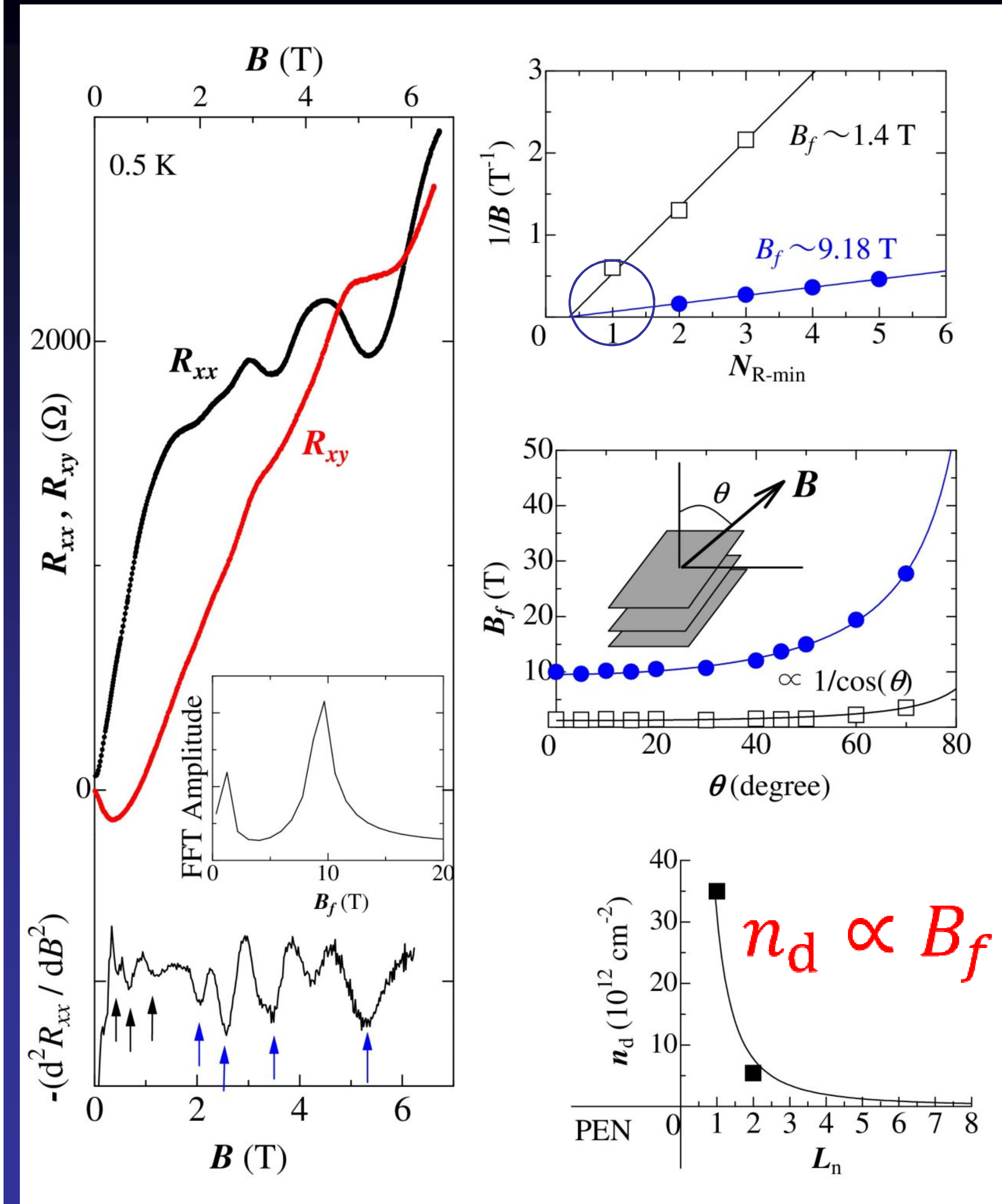
2. holes-doping: SdH & QHE

N. T, et al., PRB, 88, 075315 (2013).





1. PEN is slightly charged in negative.
2. $n \sim 10^8$ cm^{-2}/layer at low-T



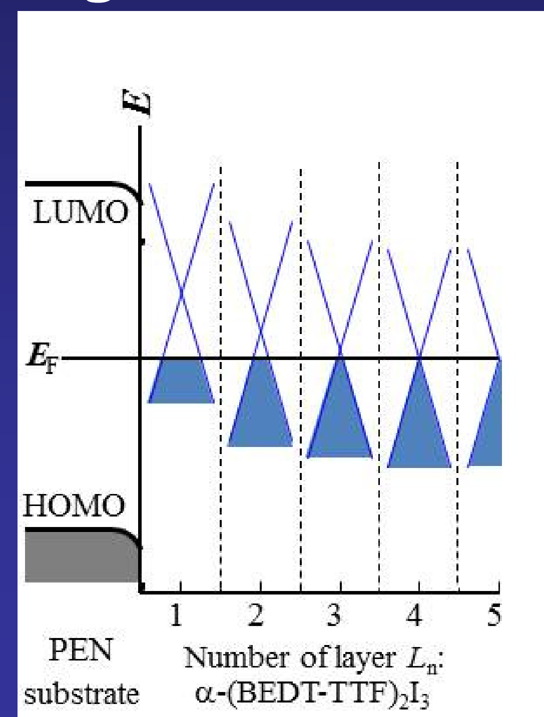
N. T, et al., PRB, 88, 075315 (2013).

$$\Delta R_{xx} = A(B)\cos\left[2\pi\left(\frac{B_0}{B}+\frac{1}{2}+\gamma\right)\right]$$

$\gamma = 0$: normal -e

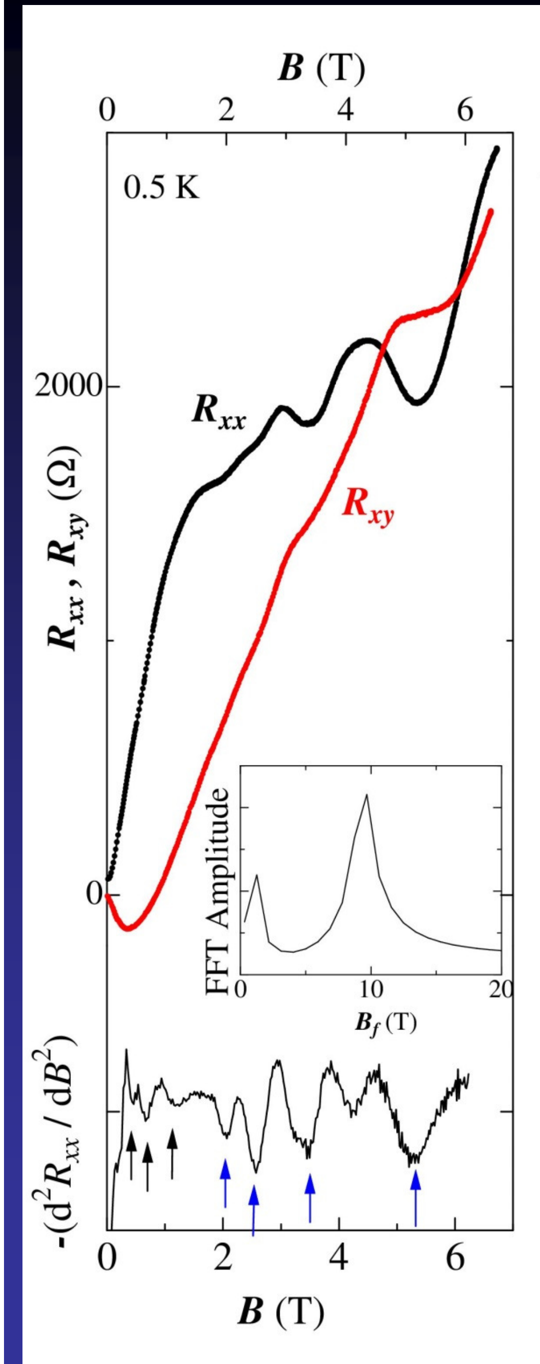
$\gamma = 1/2$: Dirac -e

Energy diagram



...oping

N. T, et al., PRB, 88, 075315 (2013).

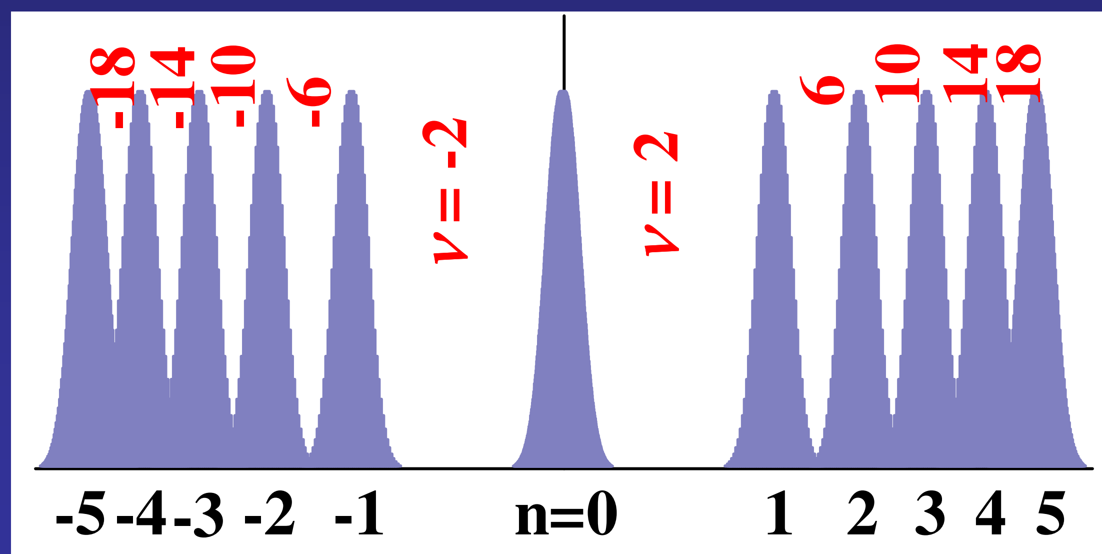


QHE in 2D Dirac system

$$R_{xy}^{-1} = \nu e^2/h$$

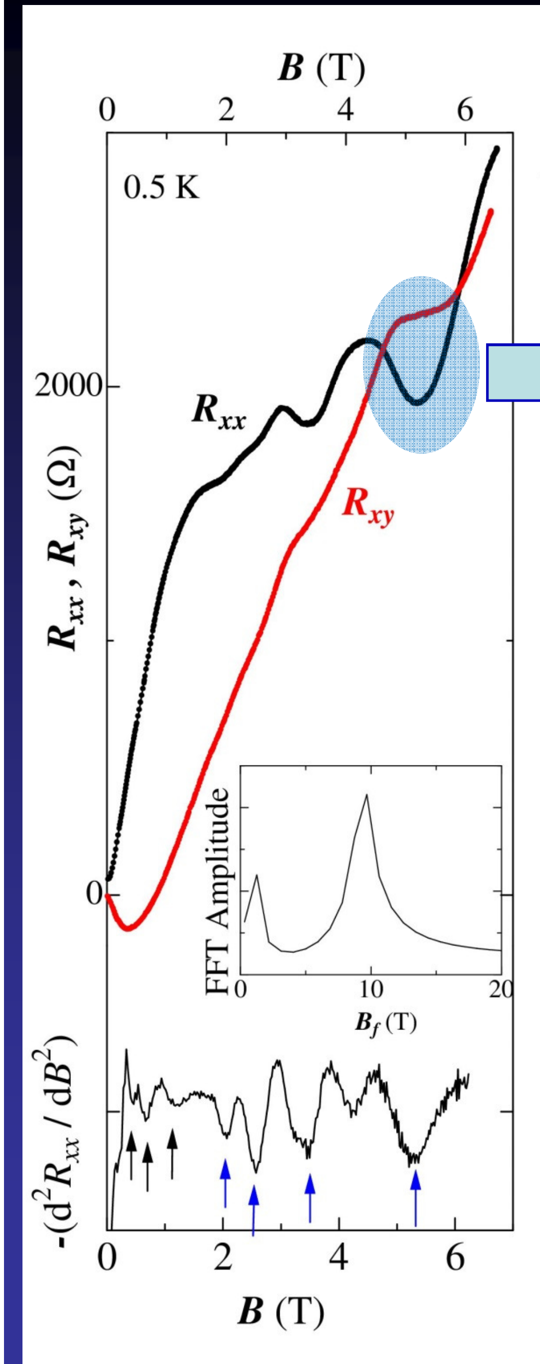
$$\nu = \pm 4(n + 1/2)$$

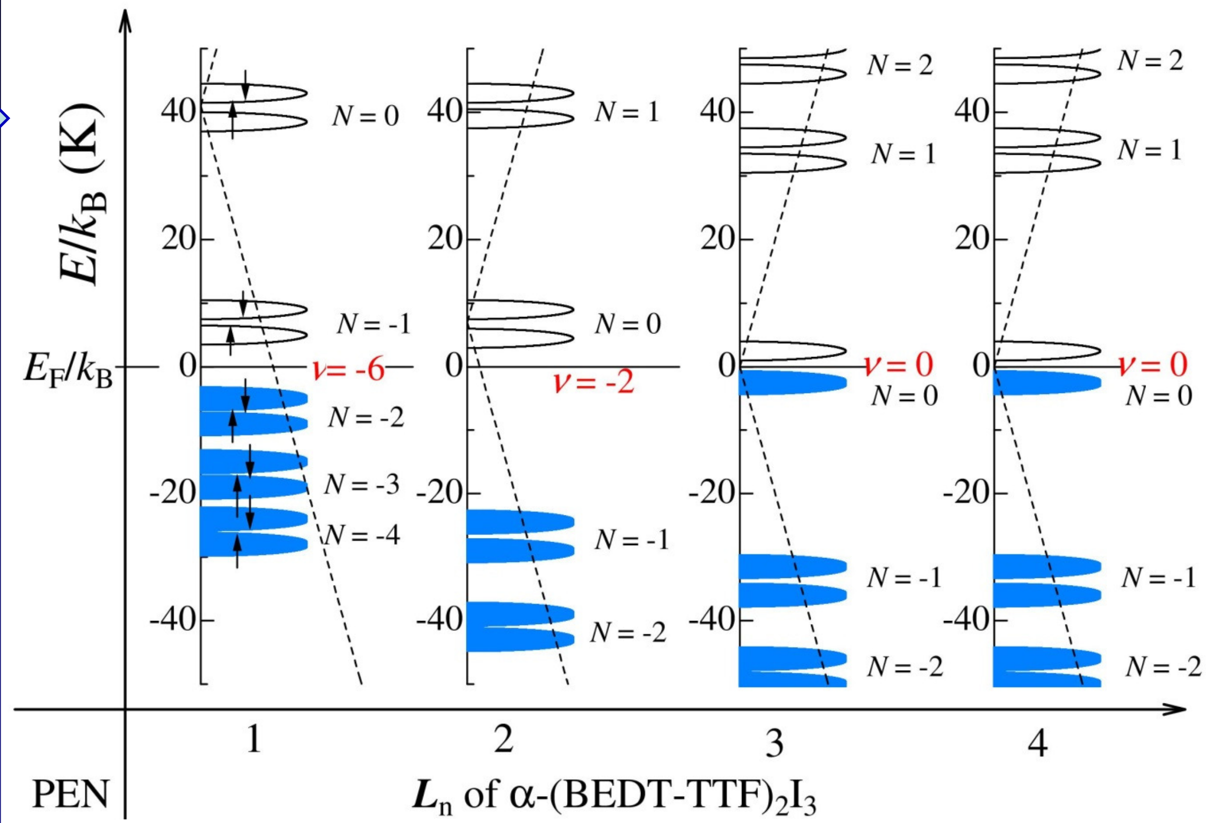
$$|\nu| = 2, 6, 10, 14, 18, \cdots$$



oping: QHE at 5.5 T

<ins>*N. T, et al., PRB, 88, 075315 (2013).*</ins>





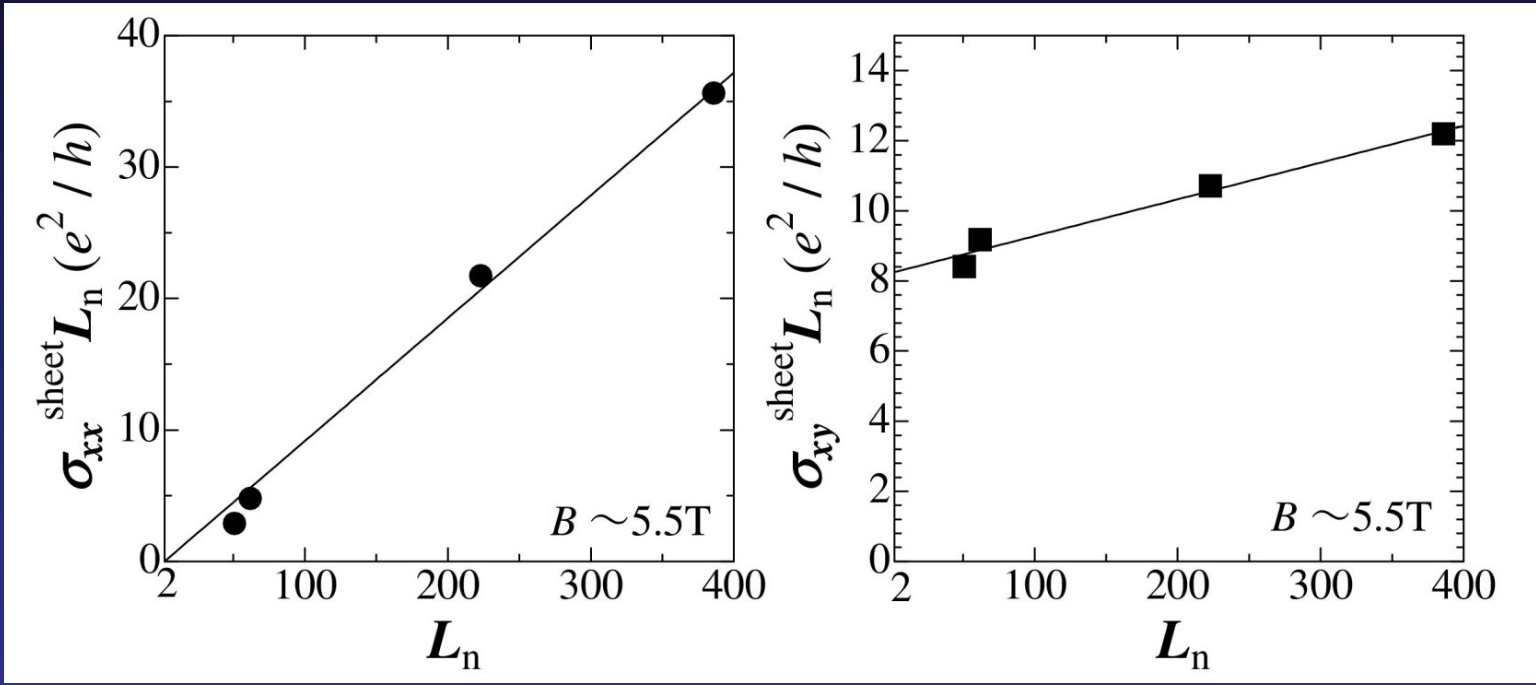
$$\nu_{\text{total}} = \nu_{\text{first}} + \nu_{\text{second}} + \sum \nu_{\text{undoped}}$$

$$= -6 - 2 + 0 = -8$$

2. holes-doping: QHE at 5.5 T

N. T, et al., PRB, 88, 075315 (2013).

Thickness dependence of conductivity



✓ QHE around 5.5 T

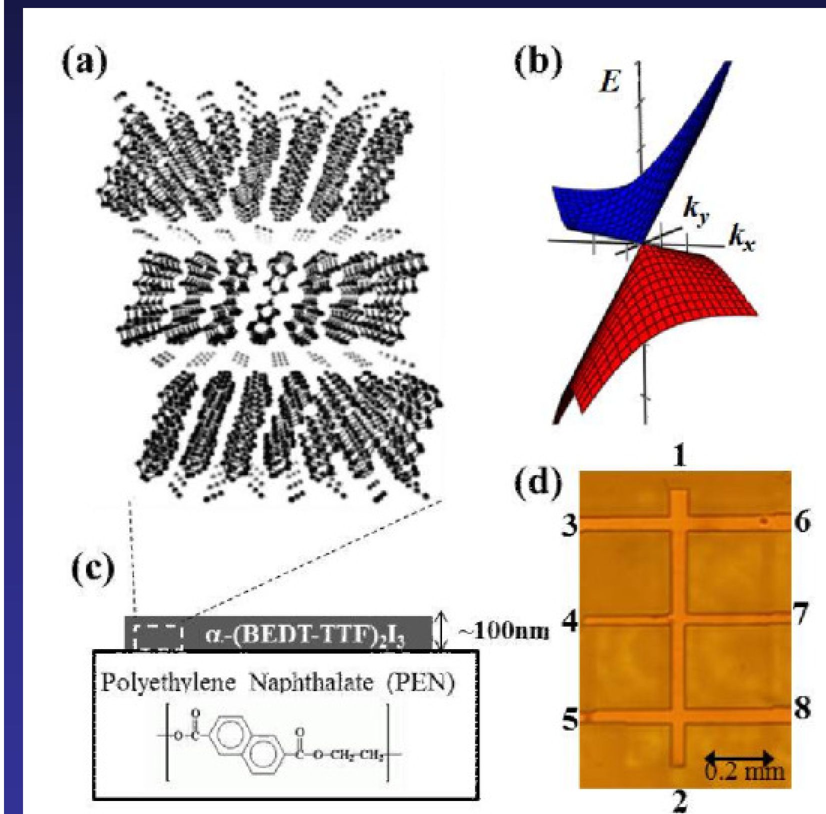
$$\text{At } L_n \to 2, \ \ \nu_{\text{total}} = -8$$

✓ Undoped layer

$$\sigma_{xx} \sim 0.07 e^2/h, \qquad \sigma_{xy} \sim 0.008 e^2/h$$

3. Conclusions

Crystals on PEN



- holes doping
- Fermi liquid state
- First observation of SdH & QHE
- Direct evidence of Dirac system

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