Electrically Controlled Topological States in Bilayer Graphene

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Quantum Hall Effect

In the 2D limit, Landau-level quantization from strong magnetic field leads to quantized Hall conductance --- zero longitudinal resistance.
Edge States of Quantum Hall Effect (QHE)

Back-scattering is forbidden!

Real topological state: Robust against any disorders

Potential application: Zero/low power electronics
The Disadvantage of QHE: Strong B field

QHE: 10000 Gauss
Earth: 0.5 Gauss
Goal of both condensed matter physics and materials physics:

Quantum Hall effect \textit{without magnetic field}

- Quantum anomalous Hall Effect
- Quantum spin Hall Effect
- Quantum valley Hall Effect
- …
Graphene

- thinnest
- mechanical property
- low resistivity
- room temperature QHE

• linear dispersion
• zero gap

Silicon terminator?
Engineering band gaps

How?

Degrees of freedom

Real spin  Valleys  Sublattices  Layers

Real spin

Valleys

Sublattices

Layers

7
Gap opening mechanism (1)

- **Breaking inversion symmetry.**
  
  (a) Placing graphene on top of hexagonal boron nitride:

  G. Giovannetti et al.,
  PRB 76, 073103 (2007)

  (b) Applying an interlayer potential difference in AB-stacking bilayer graphene:

  Y. Zhang et al.,

Supporting quantum valley-Hall state
Gap opening mechanism (2)

- Intervalley scattering.

Doping in 3N*3N supercell of graphene.

J. Ding et al., PRB 84, 195444 (2011)
Z. Qiao, et al., PRB 85, 115439 (2012)
Y. Ren et al, PRB 91, 245415 (2015)
Gap opening mechanism (3)

**Intrinsic spin-orbit coupling**

Kane-Mele model

\[ H = -t \sum_{\langle i,j \rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle i,j \rangle} c_i^\dagger \sigma \cdot (d_{kj} \times d_{ik}) c_j \]

+ \[ i V_r \sum_{\langle i,j \rangle} c_i^\dagger \hat{e}_z \cdot (\sigma \times d_{ij}) c_j \]

**Intrinsic SOC**

**Rashba SOC**

**Quantum spin-Hall effect**

C. Kane et al., *PRL* 95, 146802 (2005)

Y. Yao et al., *PRB* 75, 041401 (2007)

H. Min et al., *PRB* 74, 165310 (2006)

Extremely weak intrinsic SOC!
Gap opening mechanism (4)

Modified Kane-Mele model

\[
H = -t \sum_{\langle ij \rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle ij \rangle} c_i^\dagger \sigma \cdot (d_{kj} \times d_{ik}) c_j
\]

\[
+ i V_r \sum_{\langle ij \rangle} c_i^\dagger \hat{e}_z \cdot (\sigma \times d_{ij}) c_j + \lambda \sum_{i\alpha} c_{i\alpha}^\dagger \sigma_z c_{i\alpha}
\]

Zeeman field

Quantum anomalous-Hall effect
Roadmap of QAHE in graphene

- **Ideal model**
  - Qiao, Yang et al., *PRB* 82, 161414 (2010)

- **Experimental prototype**
  - Periodic adsorption
    - Ding, Qiao et al., *PRB* 84, 195444 (2011)
  - Random adsorption
    - Jiang, Qiao et al., *PRL* 109, 116803 (2012)

- **Improved solution**
  - Magnetic substrate
    - Qiao, Ren et al., *PRL* 112, 116404 (2014)
  - Codoping adatoms
  - Deng, Qi, Xu, and Qiao, *PRB* 95, 121410 (2017)
Engineering topological states using electric means but not spin-related elements
Quantum valley-Hall effect

Monolayer graphene with sublattice potential

Gated bilayer graphene
Quantum valley-Hall effect

Topological order: $C_V = C_K - C_{K'}$.
Quantum valley-Hall effect

1-layer \( C_V = \frac{1}{2} \)

2-layer \( C_V = 1 \)

3-layer \( C_V = \frac{3}{2} \)

4-layer \( C_V = 2 \)

5-layer \( C_V = \frac{5}{2} \)
Quantum valley-Hall effect
Quantum valley-Hall effect

Various bilayer graphene ribbons
# Quantum valley-Hall effect

## Comparison with QHE and Z2 Topological insulator

<table>
<thead>
<tr>
<th></th>
<th>QHE</th>
<th>Z2 TI</th>
<th>QVHE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Topological state</strong></td>
<td>Strong</td>
<td>weak</td>
<td>Weak</td>
</tr>
<tr>
<td><strong>Topological number</strong></td>
<td>Chern number</td>
<td>Z2 number</td>
<td>Valley Chern number</td>
</tr>
<tr>
<td><strong>Robustness</strong></td>
<td>Any kind of disorder</td>
<td>Time-reversal invariance</td>
<td>Without inter-valley mixing</td>
</tr>
</tbody>
</table>
Quantum valley-Hall effect

**Advantage:**
Robust against long-range disorders

**Disadvantages:**
1. Difficult to grow or cut some specific ribbons with gapless edge modes
2. Easy to be destroyed by short-range disorders
From quantum valley-Hall effect to Topological 1D zero-line mode
Topological 1D zero-line mode

Monolayer graphene with alternating sublattice potentials

Semenoff et al., PRL 101, 087204 (2008)
Yao et al., PRL 102, 096801 (2009).

AB stacking bilayer graphene with alternating electric fields

Martin et al., PRL 100, 036804 (2008)

Energy dispersion

\[ K : E = +k \]
\[ K' : E = -k \]

Other names: topological confinement state, kink state, topological zero mode, domain-wall state
Topological 1D zero-line mode

Two representative zero lines (bilayer graphene with varying potential differences):

Zigzag zero line

Armchair zero line

1. Small avoided crossing band gap
2. Easy to be scattered

Gapless mode!

Gapped mode!

Qiao, Jung, Niu, MacDonald, *Nano Lett.* 11, 3453 (2011)
Topological 1D zero line mode

Evolution of band structure from zigzag to armchair zero lines:

Bi, Jung, and Qiao, Phys. Rev. B (Accepted) arXiv:1509.09003
Topological 1D zero line mode

Evolution of band structure from zigzag to armchair zero lines:

Bi, Jung, and Qiao, Phys. Rev. B (Accepted) arXiv:1509.09003
Topological 1D zero line mode

Zero line modes are gapless with distinguishable valleys in any ribbons except armchair ribbon.

Whether such a mode is useful in realistic systems?
Schematic of a 4-terminal device

In a bilayer graphene:

Single 1D zero line can be created by considering different potential profiles:

1. $(+, +, -, -)$
2. $(+, -, +, -)$
3. $(+, +, +, -)$
4. $(+, -, +, +)$
5. $(-, +, +, +)$
6. $(+, +, -, +)$
Transport of single zero line

Conductance from L to R is quantized to $2e^2/h$.

Qiao, Jung, Niu, MacDonald, *Nano Lett.* 11, 3453 (2011)
Conductance from D to U is quantized to $2e^2/h$.

Schematic of zero-line and the mode.

Qiao, Jung, Niu, MacDonald, *Nano Lett.* 11, 3453 (2011)
Transport of single zero line

Transport of single zero line

Numerically obtained local DOS distribution in real space:

Mixed valleys

Schematic of domain wall and its mode.

Conductance from L to U is quantized to $2e^2/h$.

Qiao, Jung, Niu, MacDonald, *Nano Lett.* 11, 3453 (2011)
Transport of single zero line

The conductance along any zero-line is quantized to $2e^2/h$.


Transport of single zero line

1D zero-line state *chirally propagates*;

1D zero-line state exhibits a *zero bend resistance*.

Similar to the quantum Hall effect, except the spatial overlap between the counter-propagating chiral edge modes
Experimental realization of the topological 1D mode
Recent observation of the topological zero-line mode

Feng Wang’s group, Nature 520, 650 (2014)
Experimental Realization (2)

Real bilayer graphene with opposite biases

Experimental Realization (2)

Topological zero-line modes in folded bilayer graphene

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Zero line mode in folded bilayer graphene

COMMUNICATIONS PHYSICS

Experimental Realization

Topological valley transport at the curved boundary of a folded bilayer graphene

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Current partition at a topological intersection

All permitting electronic ways (colors indicate different chiral properties):

Time reversal invariance and zero bend resistance give the relations:

\[
\begin{align*}
G_{RL} &= G_{UD} = 0 \\
G_{UL} + G_{DL} &= G_0 \\
G_{UR} + G_{DR} &= G_0 \\
G_{UL} &= G_{DR} \\
G_{DL} &= G_{UR}
\end{align*}
\]

There is only one independent variable.
Current partition at a topological intersection

Counter-intuitive current partition

$G_{UR} = G_{DR}$

$G_{UR} < G_{DR}$

$G_{UR} > G_{DR}$
Current partition at a topological intersection

Current partition at a topological intersection

\[ G_{UR} = \frac{G_0}{2} [1 - \sin (\alpha + \beta)] \]

\[ G_{DR} = \frac{G_0}{2} [1 + \sin (\alpha + \beta)] \]

Counterintuitive current partition laws

External tunability of current partition

In experiment, the precise control of top/back gates is very difficult. Therefore, it is impossible to design a controllable current splitter by rotating the zero-line angles.

Some possible external manipulating methods:

1. The Fermi level;
2. The relative electric field strengths;
3. Weak magnetic field;
4. ......
Two zero line topological intersection

A-B stacked bilayer graphene

phononic crystals


Zero line modes in twisted graphene bilayer

\[ \theta \sim 1^\circ \]

Moiré is different


Three zero line topological intersection

Diameter: 50 nm

T. Hou, Yafei Ren, et al., arXiv: 1904.12826
Three zero line topological intersection

Fermi energy close to the charge-neutrality point

Fermi energy close to band edge

T. Hou, Yafei Ren et al., arXiv: 1904.12826
Three zero line topological intersection

\[ G_{31} = G_{51} = 0, \quad \text{Opposite chirality} \]

\[ G_{21} = G_{61}, \quad \text{Mirror reflection symmetry} \]

\[ G_{tot} = G_{21} + G_{41} + G_{61} = \frac{e^2}{h}. \]

T. Hou, Yafei Ren et al., arXiv: 1904.12826
Three zero line topological intersection

T. Hou, Yafei Ren et al., arXiv: 1904.12826
For each node, it tends to be back, with a tiny part.
For a series of nodes, what happen?

Insulating?
Current routing--- network systems

(a) 

(b) Even partition

(c) Uneven partition

Atomic and electronic reconstruction at van der Waals interface in twisted bilayer graphene

Hyobin Yoo¹, Rebecca Engelke¹, Stephen Carr¹, Shiang Fang¹, Kuan Zhang², Paul Cazeaux³, Suk Hyun Sung⁴, Robert Hovden⁴, Adam W. Tsen⁵, Takashi Taniguchi⁶, Kenji Watanabe⁶, Gyu-Chul Yi⁷, Miyoung Kim⁸, Mitchell Luskin⁹, Ellad B. Tadmor², Efthimios Kaxiras¹,¹⁰, Philip Kim¹

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⁹ School of Mathematics
¹⁰ John A. Paulson Scho

In the twist regime smaller than θc where the atomic and electronic reconstruction become significant, a simple moiré band description breaks down. Upon applying a transverse electric field, we observe electronic transport along the network of one-dimensional (1D) topological channels that surround the alternating triangular gapped domains, providing a new pathway to engineer the system with continuous tunability.
Atomic and electronic reconstruction at the van der Waals interface in twisted bilayer graphene

Hyobin Yoo¹, Rebecca Engelke², Stephen Carr¹, Shiang Fang¹, Kuan Zhang², Paul Cazeaux³, Suk Hyun Sung⁴, Robert Hovden⁴, Adam W. Tsen⁵, Takashi Taniguchi⁶, Kenji Watanabe⁶, Gyu-Chul Yi⁷, Miyoung Kim⁸, Mitchell Luskin⁹, Ellad B. Tadmor², Efthimios Kaxiras¹⁰ and Philip Kim⁰¹∗

In the small twist angle regime ($\theta < \theta_c$), the triangular network of 1D topological channels can be developed by applying a transverse electric field. Figure S10i shows the plot of longitudinal resistance $R_{xx}$ at CNP as a function of transverse electric displacement field. S1-4 show that the channel resistances exhibit an increase and saturate to a value ranging from 1.6 kΩ to 13 kΩ. The value of channel resistances at the saturated regime at high displacement field is of similar order of magnitude to $R_q = \frac{h}{4e^2} \approx 6.4$ kΩ, suggesting electronic transport across the triangular network of 1-D channels. The details of the displacement field dependence on the Dirac peak resistance $R(D)$ of each device can be attributed to many parameters such as device geometry, sample inhomogeneity and different amount of interlayer biasing that is required to create a 1-D conduction channel depending on the twist angle.
Topological network
Topological network
Summary

1、Brief review of topological zero line mode in graphene systems.

2、Recent progress on electronic transport in twisted bilayer graphene systems.