Topological Valleytronics in Bilayer Graphene

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Electronic degrees of freedom

- **Charge**
  - electric field, magnet field

- **Spin**
  - magnetic field, spin-orbit coupling

- **Valley**
  - Valley-(controlled) (elec)tronics
Two-dimensional layered materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Graphene and bilayer graphene</th>
<th>hBN</th>
<th>MoS$_2$</th>
<th>WSe$_2$</th>
<th>Fluorographene</th>
</tr>
</thead>
</table>

- h-BN, graphene fluoride, MoS$_2$, WSe$_2$, graphene, NbSe$_2$,
- Germanene, Silicene, Stanene, hexagonal GaN ...
h-BN/bilayer graphene/h-BN

- High sample quality
- Sophisticated nanostructures
Crystal structure of conventional semiconductor: Si

Multi-valleys but they are equivalent.
Monolayer graphene: two inequivalent valleys

The unusual band structure of a single layer of graphene, shown in Fig. 3, has been known for 60 years. The Dirac points, illustrated by C. Jozsa and B. J. van Wees, are connected by reciprocal-lattice vectors, so they are equivalent. Likewise, the three corners marked by a black dot are equivalent. The two components of the wave vector are denoted by \( k_x \) and \( k_y \). The two-dimensional Brillouin zone is indicated. The conduction band points \( K \) and \( K' \) are the Dirac points. Illustration by C. Jozsa and B. J. van Wees.

The energy excitations \( E(k) = \pm v_F |k| \) have a conical dependence on \( k \), with the Fermi velocity \( v_F \) of \( 10^6 \) m/s proportional to \( k^2 \) on the honeycomb lattice. This two-dimensional Dirac Hamiltonian is expressed in terms of the two-component spinor \( \psi(k) \) as

\[
\begin{align*}
H(k) &= \left( \begin{array}{cc}
-\frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2}
\end{array} \right) \cdot \left( \begin{array}{c}
k_x + ik_y \\
k_x - ik_y
\end{array} \right) \\
&= \frac{1}{2} v_F \left( \begin{array}{cc}
-\frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & \frac{1}{2}
\end{array} \right) \cdot \left( \begin{array}{c}
k_x + ik_y \\
k_x - ik_y
\end{array} \right)
\end{align*}
\]

The energy \( E(k) = \pm \frac{1}{2} v_F |k| \) is proportional to \( k^2 \). The two components of the wave vector are denoted by \( k_x \) and \( k_y \). The two-dimensional Brillouin zone is indicated. The conduction band points \( K \) and \( K' \) are the Dirac points. Illustration by C. Jozsa and B. J. van Wees.

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Sublattice inversion symmetry

\[ \hat{H} = v_F \left( \xi p_x \hat{\sigma}_x + p_y \hat{\sigma}_y \right) \]

\[ \xi = \pm 1 \text{ for K and K' valley} \]

\[ E_{\pm} = \pm v_F p \]

\[ \psi_{\pm} = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = \frac{e^{i p \hat{r}/\hbar}}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm \xi e^{i \theta} \end{pmatrix} \]

\[ \theta_p = \tan^{-1} \left( \frac{p_y}{p_x} \right) \]

Zero band gap comes from A/B inversion symmetry
Lattice inversion symmetry broken

A band gap opens!

Also graphene on a Moire lattice and gated bilayer graphene

Bernal (AB)-stacked bilayer graphene

Li, ... J.Z. PRB 94, 161406(R) (2016)
Zou, ... J.Z. PRB 84, 085408 (2011)
Electric field induced band gap in bilayer graphene


Zhu lab

Δ up to 200 meV

F. Wang group, IR absorption
Self-consistent tight-binding
DFT calculation

Δ

Zou, ... J. Z. PRB 82, 081407(R)(2010)
Li, ... J. Z. aXiv:1708.03644v1
In a gapped two-dimensional hexagonal lattice,

What are the valley-contrasting properties? How do we control and detect them?
Orbital magnetic moment and optical selection rules

\[ m(k) = r_z \frac{3e a^2 \Delta t^2}{4\hbar(\Delta^2 + 3q^2 a^2 t^2)}. \]

\[ m_j = -\frac{3}{2} \]
\[ m_j = -\frac{1}{2} \]
\[ m_j = -\frac{1}{2} \]
\[ m_j = +\frac{1}{2} \]
\[ m_j = +\frac{1}{2} \]

T-reversal

K and K' couple to light of opposite circular polarizations.
Berry curvature $\Omega(k)$: magnetic field in momentum space

Non-zero Berry curvature

$$\Omega(k) = \tau_z \frac{2\hbar^2 v_F^2 \Delta}{(\Delta^2 + 4k^2\hbar^2 v_F^2)^{3/2}}$$
Hall effect (from real magnetic field)

\[ \dot{k} = -\dot{r} \times B \]

Valley Hall effect (from Berry curvature)

\[ \dot{r} = -\dot{k} \times \Omega \]

How to detect valley polarization?
Detection of valley Hall effect

- Optical pumping, electrical detection

- Faraday rotation

Mak et al, Science 344, 1489(2014)

Detection of valley Hall effect

- Electrically pumped, electrically detected

net valley polarization is small

on gapped graphene and bilayer graphene

Generating valley polarization is hard!

I wish I had a valley magnet...

A valley filter proposal uses a short and narrow constriction with zigzag edges...


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Valley-coded electron highways and traffic control at a 4-way junction

Quantum valley Hall effect

- Valley-momentum locked 1D channels
- Conductance quantization at $4e^2/h$

Topological valleytronics

- Valley valve
- A tunable electron beam splitter


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From spin Hall effect to quantum spin Hall effect

- CdTe/HgCdTe/CdTe QW
- InAs/GaSb bilayer
- spin-momentum locked edge states
- ballistic conduction


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https://www.scienecenews.org/article/physics-edge

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Inverting the band gap of bilayer graphene is easy

\[ E \rightarrow -E \]

\[ \Delta \rightarrow -\Delta \]
Quantum valley Hall effect in bilayer graphene

Theoretical proposal:

- 4 pairs of counter-propagating metallic 1D modes in the junction
- Valley-momentum locked – “quantum valley Hall kink states”

Topological origin: Valley Chern number change

Quantum spin Hall effect

- $C_s = \pm 1$
- $C_s$ changes by -1
- $C_s$ changes by +1
- 1 mode per spin
- spin-momentum locked

Quantum valley Hall effect

- $\Delta > 0$
  - $C_k = +1$
  - $C_{k'} = -1$
- $\Delta < 0$
  - $C_k = -1$
  - $C_{k'} = +1$

- $K$: $C_k$ changes by +2
- $K'$: $C_{k'}$ changes by -2

- 2 modes per valley
  - x2 for spin
    - 4 modes per valley
- valley-momentum locked

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Jung et al PRB 84, 075418 (2011), Li et al, PRB 82, 245404 (2010)  
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Band structure of a smooth junction

- Chiral in each valley
- Ballistic conductance $4e^2/h$ in the absence of inter-valley scattering

Zhenhua Qiao Group, USTC
“odd” vs “even” configuration: built-in control

\[ \Delta > 0 \quad \Delta > 0 \quad \Delta < 0 \quad \Delta > 0 \]

\[ \Delta > 0 \quad \Delta > 0 \quad \Delta < 0 \quad \Delta > 0 \]

Potential (a.u.)

Distance (nm)

Potential (a.u.)

Distance (nm)

E (meV)

\[ \Delta' \]

\[ \Delta \]
Kink states in bilayer graphene: two helicities

\[ h = +1 \quad h = -1 \]
A valley valve of kink states

Valve “on” state

Valley index aligned

Valve “off” state

Valley index anti-aligned

A spin valve

https://commons.wikimedia.org/wiki/File:Spin-valve_GMR.svg
Outline

• The valley degree of freedom in hexagonal lattices
  Valley, Berry curvature, valley Hall effect and topological kink states

• Quantum valley Hall kink states in bilayer graphene
  ➢ Precision lithography
  ➢ Transport properties
  ➢ Valley valve and electron beam splitter

• Summary
A dual-split gated bilayer graphene device

1. Use the four split gates to gap both sides
2. Measure transport along the junction
3. Use the doped Si backgate to control $E_F$ in the junction
A high-quality GaAs 2D electron gas

The highest quality two-dimensional electron system
Devices dimensions cannot be made too small

μ \sim 3 \times 10^7 \text{cm}^2\text{V/s}
\lambda \sim 0.1 \text{mm}
Van der Waals Transfer Method

Enable heterostructures of different 2D materials...


Li et al, Nat. Phys. 13, 751 (2017)
Generation I: one kink channel device

Layer by layer stacking of graphite/h-BN/bilayer graphene/h-BN
Generation II: 4-way junction

- 4 pairs of split gates
- Global Si back gate
- Dry van der Waals transfer
- 1D side contact
- 4 channels: 300 nm (L) x 70 nm (W)
Generation II: 4-way junction
All the fun we (Jing) had since 2012...

graphite bottom gates

Au top gates

Au top gates

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Alignment of the top and bottom gates is critical

- Center alignment better than 10nm.
- Dimension control better than 5nm.
Evidence of the kink states: generation I

Kink states present only in the “+-” and “-+” configurations

Evidence of the kink states: generation I

Kink states present only in the “+-” and “-+” configurations

Also Lee et al, Scientific Reports 7, 6466(2017) (Hu-Jong Lee group)
Generation II: 4-way junctions

- $R_{13}$ can measure north, south or both channels
- $R_c \sim$ hundreds of $\Omega$ (metal interface + access region)
Band structure of the kink states in a magnetic field

➢ Landau levels in the conduction and valence bands of the junction
➢ The increase of gap makes the kink states more robust

Nearly ballistic conduction in individual channels
Nearly ballistic conduction in individual channels

\[ R_{2-4} \text{ (Ω)} \]

\[ V_S i \text{ (V)} \]

\[ h / 4e^2 \]

\[ + R_C \]

Kink states + hopping in the gapped quadrants

\[ E_F \]
Nearly ballistic conduction in individual channels

Magnetic field suppresses hopping conduction

\[ R_{24} (\Omega) \]

\[ \frac{h}{4e^2} + R_C \]

\[ \text{E}_F \]
Nearly ballistic conduction in individual channels

\[ R_{\text{kink}} \sim 7 \text{k}\Omega \text{ at zero magnetic field} \]

\[ \frac{h}{4e^2} = 6.45 \text{k}\Omega \]

- L = 300 nm
- T = 1.5 K

\( R_{\text{kink}} \sim 7 \text{k}\Omega \) at zero magnetic field
A valley valve of kink states

Valve “on” state

Valve “off” state

Valley index aligned

Valley index anti-aligned
A valley valve and beam splitter

Video courtesy of Ivar Martin

Magnetic field: wave function control

\[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} \]

A tunable electron beam splitter based on the chirality of the kink states


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“On” State of the valley valve

**Diagram:**
- **North kink regime:**
  - **$R_{1\rightarrow3}$ (Ω):**
    - 9k
    - 8k
    - 7k
    - 6k
    - 5k
    - 4k
    - 3k
    - 2k
- **Voltage ($V$):**
  - Range from -40 to 40

**Label:**
- **B=6T**
- **D**
- **S**

**Legend:**
- **Red arrows:**
  - **D**
  - **S**
“On” State of the valley valve

$kink\ regime\ B=6T$

North kink
South kink

$R_{1-3}(\Omega)$

$VS\ i\ (V)$
“On” State of the valley valve

Perfect transmission through the intersection
“On” State of the valley valve

Transmission coefficient $\tau_i$ of the junction

\[ \begin{array}{c}
\tau_i \\
B (T)
\end{array} \]

- $\tau_i$ vs $B$ (T)
- $R^N_{\text{para}}$, $R^S_{\text{para}}$
- $N^k_{\text{kink}}$, $S^k_{\text{kink}}$
- $R_C$
A reconfigurable waveguide

Kink states can go around a bend!
Valley valve and electron beam splitter

- The valley valve works in the entire $E_F$ range
- $E_F$ controls splitting ratio between West and East terminals
On/off ratio of the valley valve

- ON/OFF ratio 800% at B=0, more than 100 at high field.
A tunable electron beam splitter

- Current partition ratio tunable from 0 to close to 100%.

Ren et al, arXiv: 1702.00089v1

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An S-Matrix model

S-matrix model
+ Landauer Buttker

➤ Excellent agreement between model and data

Jason Liu
(Penn State)
Summary

Experimental realization of quantum valley Hall kink states

- Valley-momentum locked topological channel
- Gate-defined and scalable

Outlook:
- Larger on/off ratio of the valley valve
- Beam splitter in the absence of a magnetic field
- Operation at higher temperature

Valleytronics

- Valley valve
- Tunable beam splitter
Acknowledgement

The Zhu lab

- Quantum valley Hall kink states
- Quantum Hall and quantum spin Hall effect
- Edge state tunneling and interferometry
- Atomically thin 2D semiconductors

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Thank you!