Valley caloritronics by graphene nanoribbons

Xiaobin Chen, Lei Zhang & Hong Guo

Department Of Physics,

McGill University

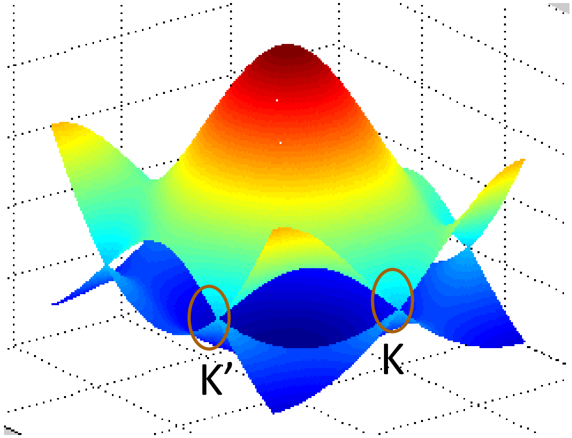
OUTLINE

- Introduction
- General physics of valley caloritronics
- Methods
- Results
- Conclusion

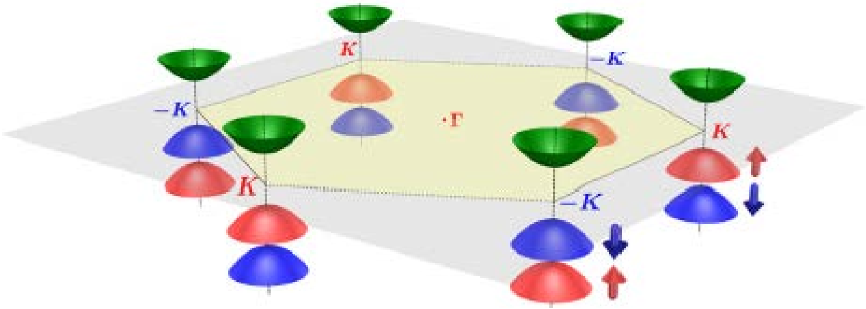
Valley

Another degree of freedom besides spin

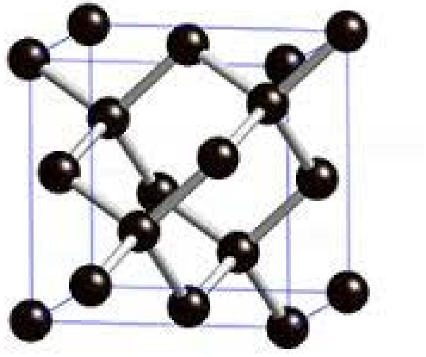
Graphene

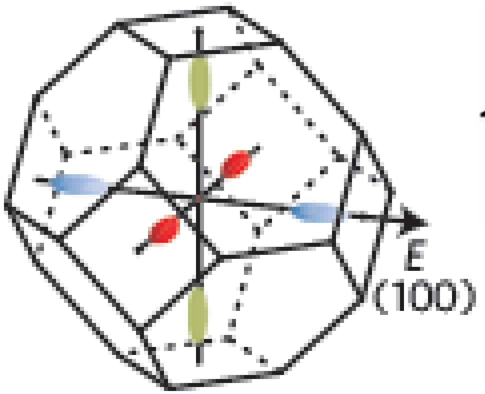


TMDCs--MoS$_2$

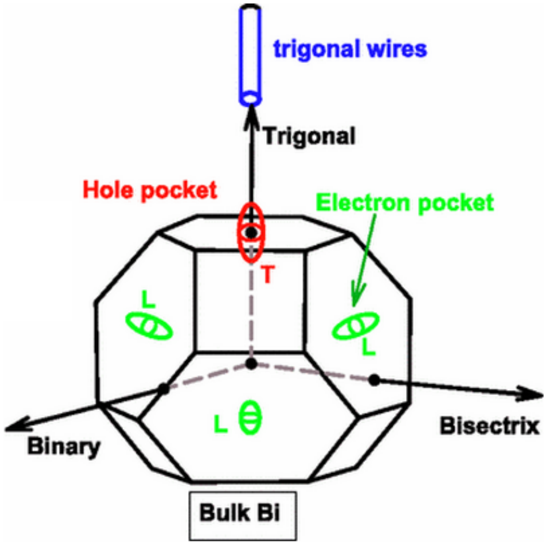


Diamond/Si





Bismuth



Ji Feng, Nat. Commun.(2012), Wang Yao, PRL (2012), Isberg, Nat. Mater.(2013)

Valleytronics

Challenge: achieving valley polarization

Analogous to spintronics

- *Encode information*
- *Make possible devices, such as valley filter and valve, and optoelectronic Hall devices*

  -- J Feng et al. 2012
- *Robust against smooth deformation and low energy phonons because of the large valley separation in momentum space. -- D Xiao et al. 2012*

Realization (expt.)

- Strain
  - SiO_2/Si(100)/SiO_2 Quantum Well, 4 K, *K. Takashina, PRL(2006)*
  - AlAs 2D electron gas, 0.3 K, *O. Gunawan, PRL(2006)*
- m^* anisotropy
  - Magnetic field, Bismuth, 40 K, *K. Behnia, Nat. Phys(2012) 80%* σ
  - High Electric field, Diamond, 77K, *J. Isberg Nat. Mater(2013) 98%*
- Optical excitation
  - Monolayer MoS_2,

    J. Feng, Nat. Commun. (2012) 50%, 300 K

    D. Xiao, Nat. Nanotech. (2012) 30%, up to 90 K

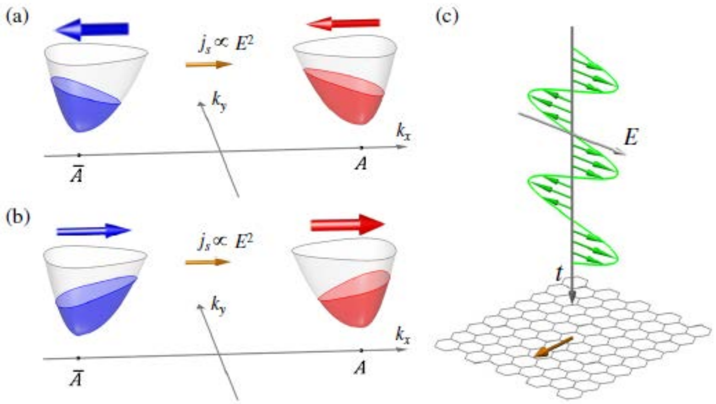
    Mak, Nat. Nanotech. (2012) valley Hall effect

Realization

Thermally generate valley current ?

- Crystal anisotropy
  - Graphene and TMDCs,

    W. Yao, Nat. Commun(2014)



- Valley filters
  - Graphene nanojunctions, *Beenakker, Nat. Phys (2007)*
  - CNT junctions, *H Santos, PRL(2009)*
  - Graphene with grain boundaries, *CT White, PRL (2011)*

Thermal realization?

Valley Caloritronics

- Yes!
  - Crystal anisotropy MoS_2, *Yao et al., Nat. Commun.(2014)*
  - Thermoelectricity   Silicene, *Niu et al., APL(2014)*
- ?
  - Can we have thermal valley filter?
  - Can we have 100% valley-polarized current?
  - Can we have pure thermal valley current?

Yes!

- Another control method

General physics

- Valley-resolved transmission: $\Xi^{1,2}(E)$
- Valley-resolved current

$$J_\eta = \frac{-2e}{h}\int \left(f_L - f_R \right)\cdot \Xi^\eta(E)\,dE, \quad (\eta = 1,2)$$

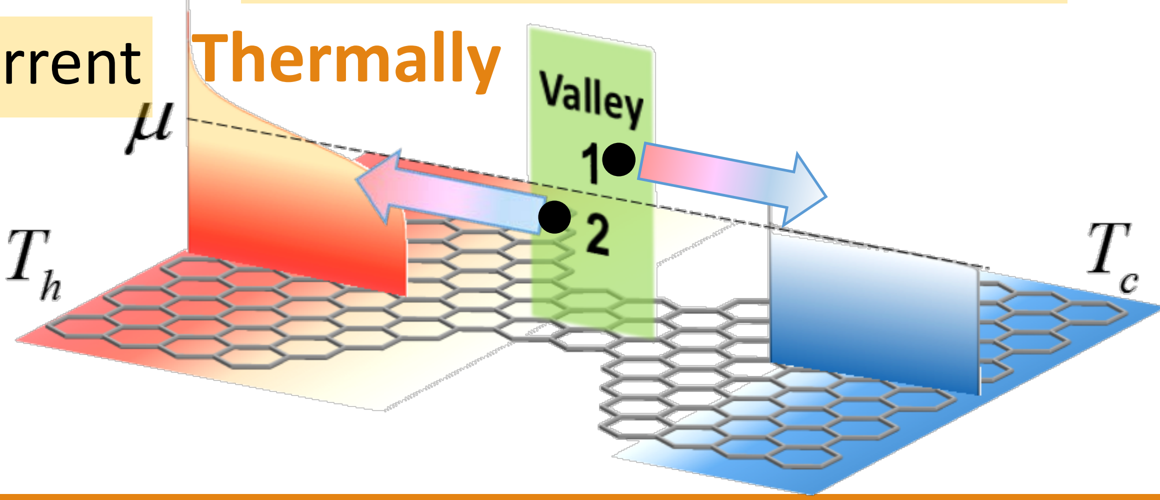
  - Charge current $J_c = J_1 + J_2,$
  - Valley current $J_v = J_1 - J_2,$

J₁ + *J₂* =0 ➔ Pure valley current

Electrically or thermally

J_1=0, J_2≠0 ➔ 100% valley-polarized current

Thermally



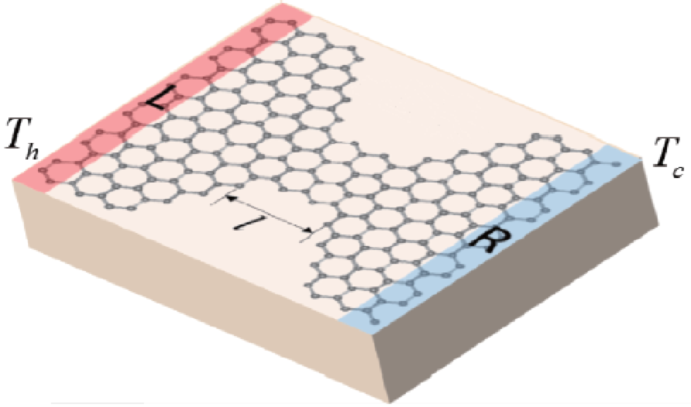
- Linear response

$$J_\eta = \underbrace{G_\eta}_{>0}\Delta V + \underbrace{G_\eta S_\eta}_{>=<\,0}\Delta T,$$

Method

12/4/12 wedge-shaped GNR

$\approx$ 12-ZGNR/4-ZGNR/12-ZGNR



- ✓ Valley filters
- ✓ Simple
- ✓ Thermal stability
- ✓ Easily integrated to carbon circuits

- Nearest-neighbor tight-binding

$$H = \gamma \sum_{\langle i,j \rangle} c_i^+ c_j + \sum_i U_i c_i^+ c_i, \gamma = -2.6 \text{ eV}$$

- $\Xi^{1,2}(E)$ Wave-matching method

  S. Savito PRB(1999)

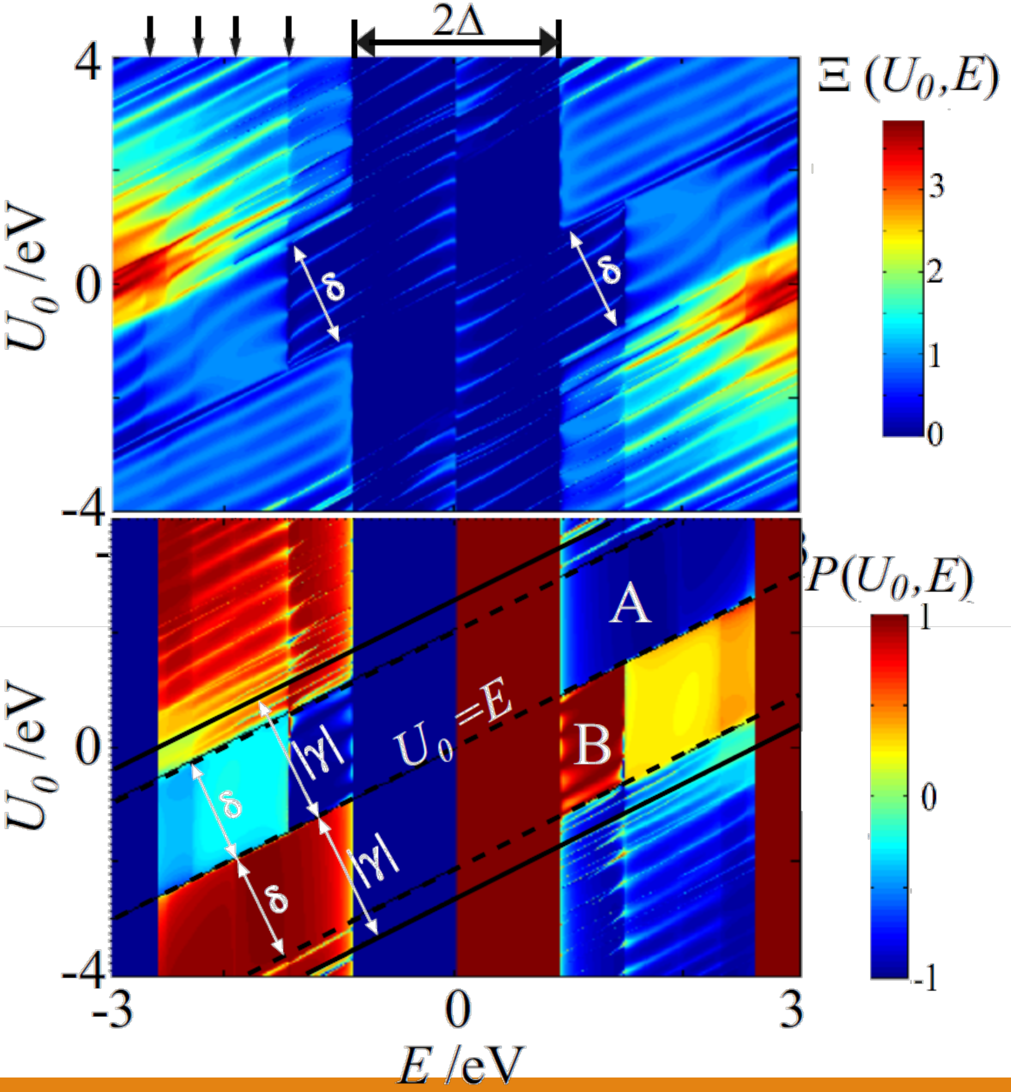
  P.J. Kelly PRB(2005)

- Landauer formulism

$$J_\eta = \frac{-2e}{h} \int (f_L - f_R) \cdot \Xi^\eta (E) dE, \ (\eta = 1, 2)$$

C. W. J. Beenakker, *et al*, *Nat. Phys.* **3**, 172 (2007)

Transmission and Polarization

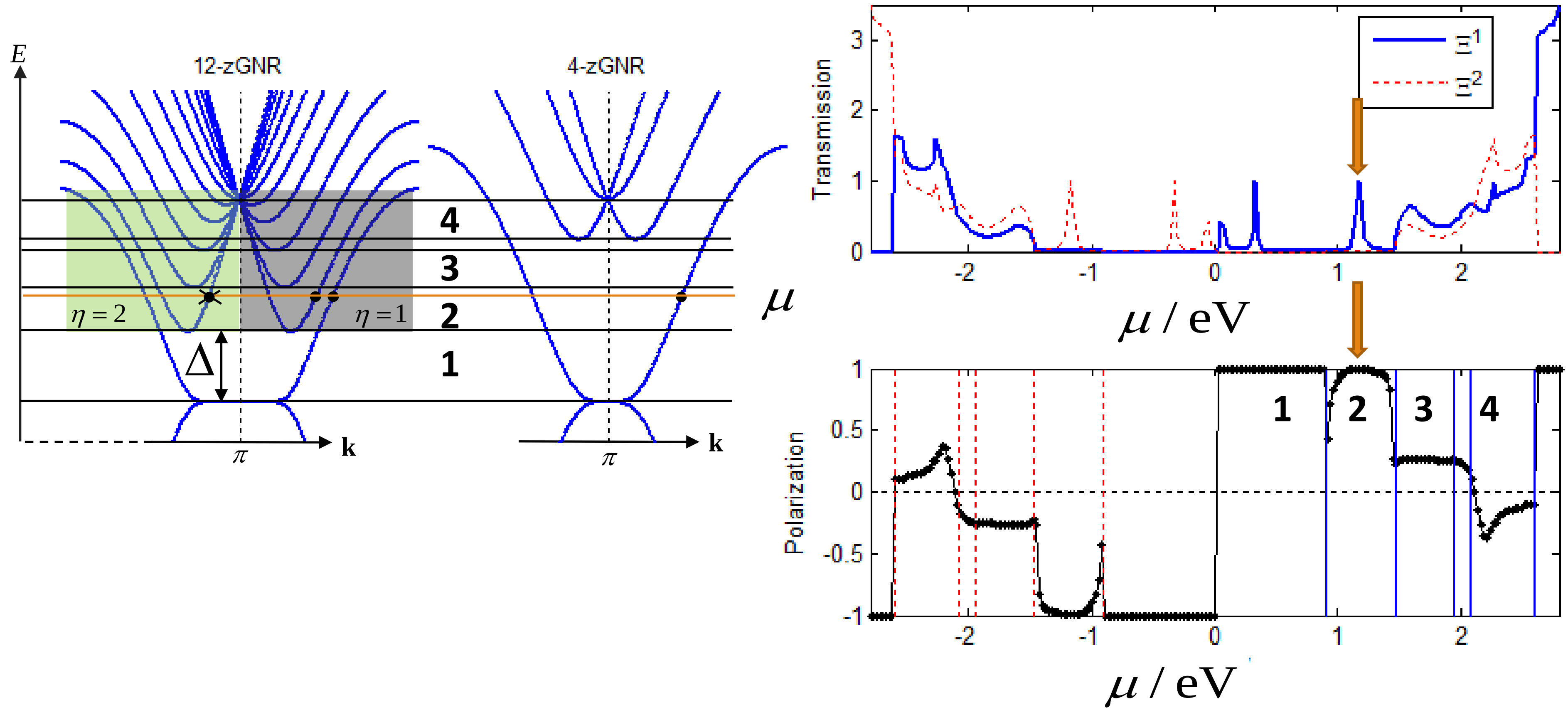


- Spiky structure
  - Resonant tunneling
- e-h symmetry
- Band structure

$$P(E)=\frac{\Xi^1(E)-\Xi^2(E)}{\Xi^1(E)+\Xi^2(E)}.$$

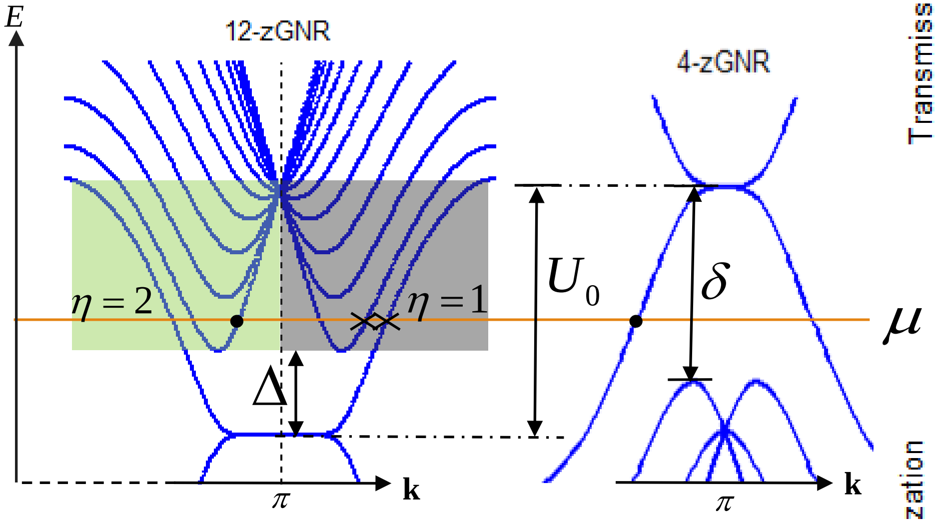
- Excellent Valley filtering
- Related to transmission

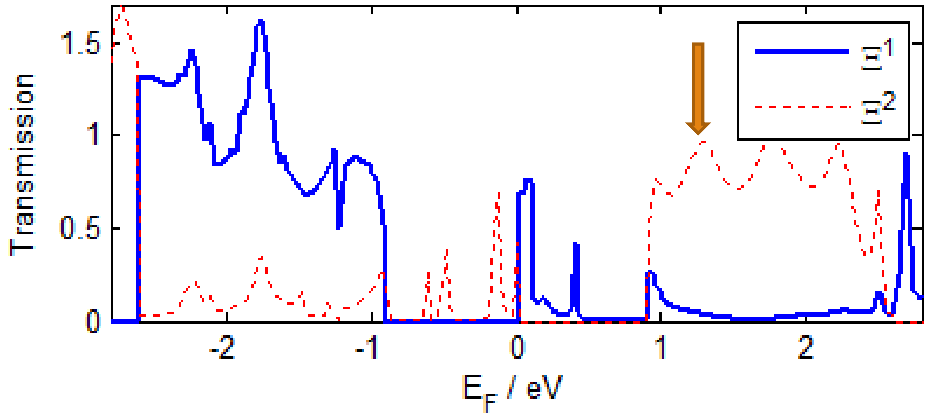
$U_0 = 0$ (B region)

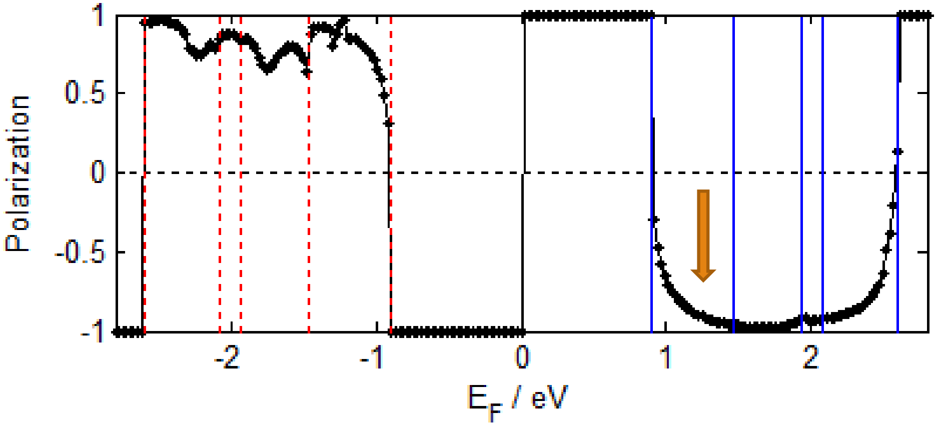


E
12-zGNR
4-zGNR
4
3
2
1
$\eta = 2$
$\eta = 1$
Δ
π
k
π
k
μ
Transmission
3
2
1
0
-2
-1
0
1
2
Ξ^1
Ξ^2
μ / eV
Polarization
1
0.5
0
-0.5
-1
-2
-1
0
1
2
1
2
3
4
μ / eV

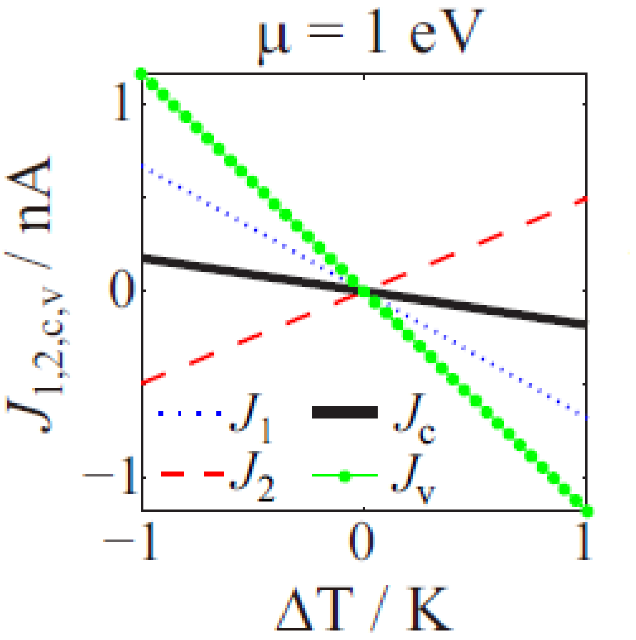
U_0=2.6 eV (A region)





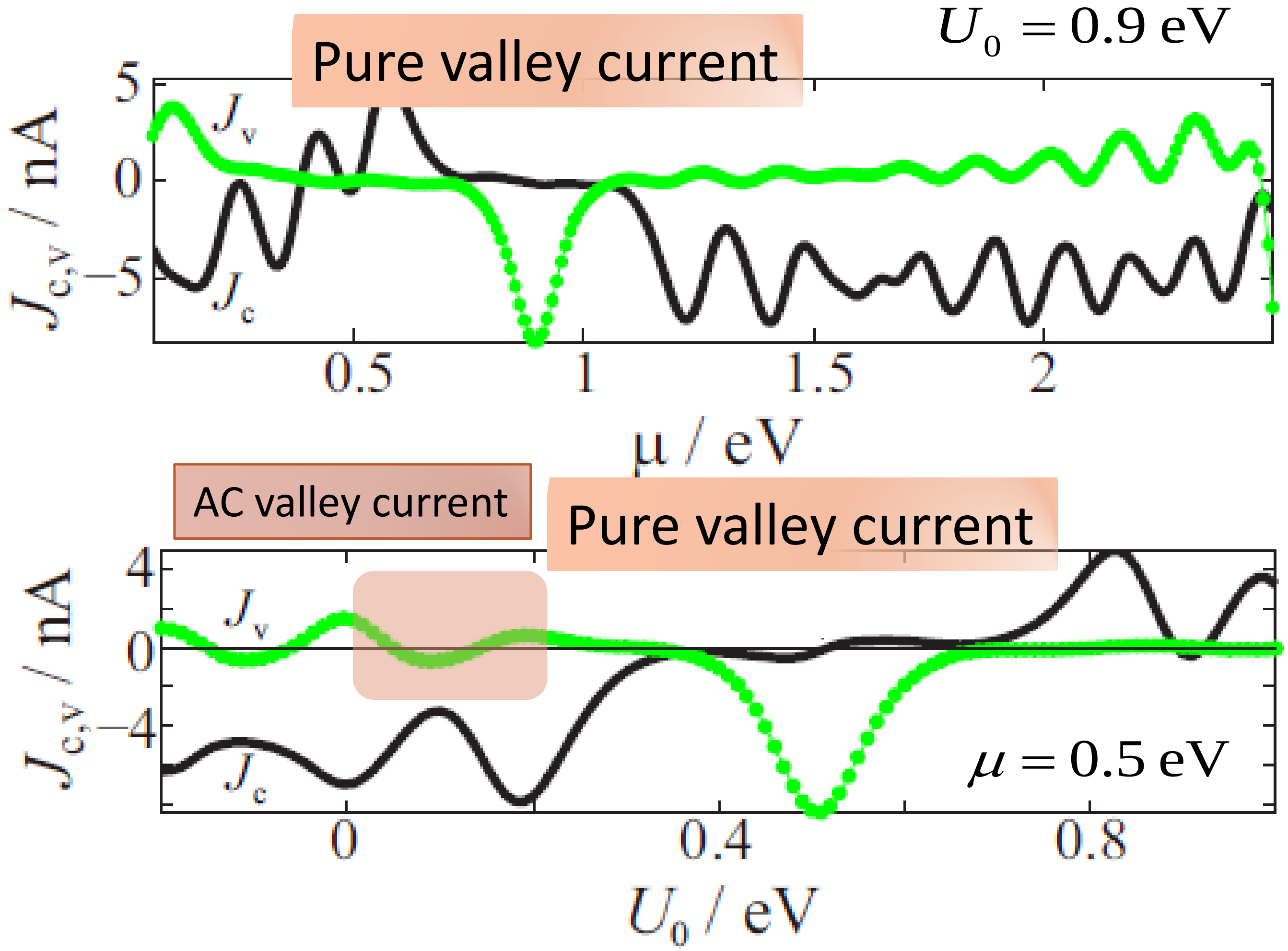


Thermal valley current



- □ ΔT
- J_1 , J_2 in different directions
- nA: Strong output due to first-order response
- Variational J_v: Depends on chemical potential

μ and gate control



Pure valley current

AC valley current

Pure valley current

140/40/140 wedge-shaped GNR

Conclusion

- A general picture for valley caloritornics
- Thermally driven nearly 100% valley-polarized and pure valley current can be obtained, with linearity maintained to large temperature difference.
- AC valley current can be obtained by varying the gate voltage without changing its polarity.

Acknowledgement

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Thank you!