Thermoelectric Transport in Bilayer Graphene

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Outline

- Introduction
  - Thermoelectric power (TEP)
  - TEP in monolayer graphene
  - TEP in bilayer graphene

- Results and Discussion – studies on bilayer
  - Gate-voltage and temperature dependence
  - Deviation from Mott’s relation
  - Magneto-thermoelectric power

- Conclusion
Thermoelectric Power

\[ \Delta V = -S\Delta T \quad (\Delta T = T_h - T_c) \]

- Mott relation; valid for TEP generated by diffusive carriers
**Mott Relation of TEP**

\[
S = -\frac{\pi^2 k_B^2 T}{3|e|} \left. \frac{\partial \ln \sigma(E)}{\partial E} \right|_{E_F}
\]

\[
S = -\frac{\pi^2 k_B^2 T}{3|e|} \frac{1}{\sigma} \left. \frac{d\sigma}{dV_{BG}} \frac{dV_{BG}}{dE} \right|_{E_F}
\]

Compare

\[
TEP(S) = -\frac{\Delta V}{\Delta T}
\]

For weak e-p interaction in graphene;
- TEP linearly depends on \( T \)
- Phonon-drag component \( \rightarrow \) nonlinear \( T \) dependence

\[
\frac{dV_{BG}}{dE} \bigg|_{E=E_F} = \frac{1}{\alpha} \left. \frac{dn}{dE} \right|_{E=E_F}
\]

\( E_F(n) \)

TEP \( \rightarrow \) details of \( E_F(n) \),
band structure of graphene near \( E_F \)
- Gate dependent TEP and sign changes at CNP
- Linear dispersion relation
- TEP increases linearly with $T$ – weak e-p interaction
How do thermoelectric properties change in bilayer graphene?

At intermediate energy ($u \ll |E| < \gamma_1$)

$$E = \pm \frac{1}{2} \gamma_1 \left[ \sqrt{1 + 4v_F^2 \hbar^2 k^2 / \gamma_1^2} - 1 \right]$$

At very low energy ($u \ll |E| \ll \gamma_1$)

$$E = \frac{\hbar^2 k^2}{2m^*} = \frac{\hbar^2 \pi n}{2m^*}$$

$\gamma_1 \sim 0.39$ eV (graphite)

McCann and Fal'ko, PRL 96, 086805(2006)
- **Introduction**
  - Thermoelectric effect
  - TEP in monolayer graphene
  - TEP in bilayer graphene

- **Results and Discussion**
  - Gate-voltage and temperature dependence
  - Deviation from Mott’s relation
  - Magneto-thermoelectric effect

- **Conclusion**
**Measurement Configuration**

\[ I_{\text{heat}} @ f_{\text{heat}} \]

- Ti/Au (3-17 nm)

\[ \Delta V @ 2f_{\text{heat}} \]

\[ R_{\text{Th1}}(T_{\text{base}}, I_{\text{heat}}) \rightarrow \Delta T \]

\[ R_{\text{Th2}}(T_{\text{base}}, I_{\text{heat}}) \rightarrow \Delta T \]

\[ S = -\frac{\Delta V}{\Delta T} \]
Main Results

Resistance

- Resistance near the CNP is $T$-dependent
- Insulating behavior due to thermally excited carriers
- Low e-p scattering rate in bilayer graphene

Thermoelectric power

- Sign changes in TEP @ CNP – ambipolar nature of carriers

mobility = 2000 ~ 4000 cm^2/Vs
Comparison to Monolayer Graphene

Monolayer graphene

Zuev et al.
PRL 102, 096807 (2009)

Bilayer graphene

$R(T)$ changes
thermally activated carriers

general trends are similar
Fit of TEP at Low Temperatures

\[ S = -\frac{\pi^2 k_B^2 T}{3|e|} \frac{\partial \ln \sigma(E)}{\partial E} = -\frac{\pi^2 k_B^2 T}{3|e|} \frac{1}{\sigma} \frac{d\sigma}{dV_{BG}} \frac{dV_{BG}}{dE} \]

\[ E = \pm \frac{1}{2} \gamma_1 \left[ \sqrt{1 + 4v_F^2 \hbar^2 k^2 / \gamma_1^2} - 1 \right] \]

\[ \gamma_1 = 0.39eV \]
\[ v_F = 0.93 \times 10^6 \text{ m/s} \]

TEP is consistent with the hyperbolic band structure of bilayer graphene.

Nam et al., PRB 82, 245416 (2010)
**Fit at Different Temperatures**

- For $T$ up to 50 K; semiclassical Boltzmann theory valid
- Deviation above 140 K – in contrast to monolayer graphene

Fixed parameters;

$$\gamma_1 = 0.39 eV$$

$$v_F = 0.93 \times 10^6 \text{ m/s}$$

At high $T$ and low carrier density, a deviation appears.

P. Wei, *et. al.*

*PRL* **102**, 166808 (2009)
Temperature Dependence for Different $V_{BG}$

Y. M. Zuev, et. al.,
PRL 102, 096807 (2009)
Deviation from Mott’s Formula

- Deviation from Mott’s relation at an onset temp. $T^*$ (gate-dependent) – due to failure of Sommerfeld expansion at high $T$
- TEP saturates near the onset temp. $T^*$

E. H. Hwang, et. al., PRB 80, 235415 (2009)

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Mott’s relation; valid only at low $T \ll T_F$ ($\sim 0.2T_F$)

**Monolayer**

$$T_F = \frac{\hbar v_F \sqrt{\pi n}}{k_B} \approx 363 \times \sqrt{\Delta V(V)} \, K$$

($T_F \sim 1150 \, K$ at $\Delta V = 10 \, V$)

**Bilayer**

$$T_F = \frac{\pi \hbar^2 n}{2 k_B m^*} \approx 33.3 \times \Delta V(V) \, K$$

($T_F \sim 330 \, K$ at $\Delta V = 10 \, V$)
Temperature Dependence

Nam et al., PRB 82, 245416 (2010)

- upswing of $T/T_F$ potentially leads to new physics
- further clarified with cleaner graphene by overcoming the effect of electron-hole puddles.

consistent with theoretical prediction
Hwang, et. al., PRB 2009
$S_{xx}$ in High Magnetic Field

$T = 15 \text{ K, } B = 7 \text{ T}$

Graphene

$E_F$ 8-fold degeneracy

$S = -\frac{\pi^2 k_B^2 T}{3|e|} \left. \frac{\partial \ln \sigma(E)}{\partial E} \right|_{E_F}$
$S_{xx}$ in Magnetic Field

$S_{xx,n}^{\text{max}} = - \frac{E_x}{|\nabla T|} = \frac{k_B \ln 2}{e} \times \frac{1}{\sum_m^n f_0(E_m)} = \frac{k_B \ln 2}{e} \times \left\{ \begin{array}{ll}
\frac{1}{n} & ; \text{monolayer} \\
\frac{1}{n + \frac{1}{2}} & ; \text{bilayer}
\end{array} \right.$

$\frac{k_B}{2e} \approx 59.6 \mu \text{V/K}$

- thermal broadening of Landau levels
- disorder
Conclusion

1. Mott relation; valid in bilayer graphene at low temperatures

- Hyperbolic dispersion relation
- Interlayer hopping term $\gamma_1$

2. Deviation from Mott’s behavior;

- Saturation of TEP at high T
- Saturation T is gate-dependent
- Validity of Mott’s formula $T_F$ of bilayer $\ll T_F$ of monolayer
3. In high magnetic field, oscillatory behavior of TEP is observed

Reduction of maximum of $S_{xx}$ - disorder effect?
$S_{xy}$ in Magnetic Field – Nernst Effect

P. Wei, et. al.
PRL 102, 166808 (2009)

$S_{xy} = -E_y / |\nabla T|$

Z. Zhu, et. al., Nature
Phys. 6, 26 (2010)

$T = 15 \text{ K}, B = 7 \text{ T}$

Two dimensional band

graphite 2D(graphene)
\[ (\ln 2) (k_B / e) \sim 60 \ \mu V/K \]

- \(1/(m+1/2)\) dependence 보이지만 값은 작은데 disorder가 있을 때 \(S_{xx}\)는 이론값보다 줄어들 수 있습니다.

Increasing disorder
3. In high magnetic field, oscillatory behaviors of TEP and the Nernst signals are also observed

No anomalous sign change of TEP near CNP in bilayer graphene
Nernst signal points to 2D nature of the bilayer graphene

Conclusion
Collaborators

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Monolayer Graphene

\[ \sum_{N} f_0(E_N) = m \]

\[ S_{xx} = \frac{k_B}{e} \frac{\ln 2}{m} \]

Bilayer Graphene

\[ \sum_{N} f_0(E_N) = m + 1/2 \]

\[ S_{xx} = \frac{k_B}{e} \frac{\ln 2}{m + 1/2} \]
\[ S_{xx} = \frac{1}{eT} \sum_{N}^{\infty} \int_{E_N} dE \left( E - \mu \right) \frac{df_0}{dE} \]

\[ = \frac{k_B \ln 2}{e} \times \frac{1}{\sum_{N} f_0(E_N)} \]

\[ \sum_{N} f_0(E_N) = m + 1/2 \]

\[ S_{xx} = \frac{k_B}{e} \frac{\ln 2}{m + 1/2} \]
$S_{xx}$ in High Magnetic Field

Checkelsky and Ong, PRB 80, 081413(R) (2009)

Zuev, Chang, & Kim, PRL 102, 096807 (2009)

No anomalous sign change near the CNP
ΔR, ΔV ∝ ΔT ∝ Power ∝ V^2_{heat}

\[ TEP(S) = -\frac{ΔV}{ΔT} \]
Saturation of TEP

- Deviation from Mott’s relation at a certain onset $T$, (gate-dependent)
- TEP saturates near the onset $T$.

Why is it saturated?

- Scattering due to unscreened charged impurities
- Further theoretical work is required
Comparison to Monolayer Graphene

Finite DOS at CNP

Monolayer

\[ \Delta n_T \approx \frac{1}{\pi} \left( \frac{k_B T}{\hbar v_F} \right)^2 \]

\[ \approx 5.46 \times 10^5 \cdot (T[K])^2 / \text{cm}^2 \]

Bilayer

\[ \Delta n_T \approx \frac{2m^* k_B T}{\pi \hbar^2} \]

\[ \approx 2.15 \times 10^9 \cdot T[K] / \text{cm}^2 \]

\[ \sim 10^{12} \text{ cm}^{-2} \text{ at RT} \]

Zuev et al.
PRL 102, 096807 (2009)

Morozov et al.
PRL 100, 0166027 (2008)
Due to the finite DOS in bilayer graphene at the CNP, $T_F$ of the system is almost an order of magnitude smaller than that of the monolayer graphene for a given charge carrier density.
From Graphine to Graphite

Two dimension

Exfoliation

Three dimension

Bilayer

Trilayer


Manchester Univ.
Columbia Univ.

