Competing Channels for Hot-Electron Cooling in Graphene

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**Photo-Thermoelectric Effect**

Graphene

Slow electron-lattice thermalization*
long-lived hot carriers at room T

For high T:
Assisted by Disorder Scattering**

Super Collisions...

For low T:
Acoustic phonon emission

Normal Collisions..

\[ V_{PH} = (S_1 - S_2) \Delta T_{pn} \]

*R.Bistrizer et al. PRL 102, 206410 (2009)

**J.C.W. Song et al. PRL 109, 106602 (2012)
- Mechanical exfoliation of Graphene on SiO$_2$
- Cr/Au (0.3/60nm) contacts
- 10-20 nm thick hBN top layer
- Cr/Au (0.3/100nm) local top gate
- 8 devices with $\sim$10 000 cm$^2$/Vs

Photovoltage measurements:
- Focused laser with 1µm diameter
- $\lambda = 850$ nm
$V_{PH}$ at p-n Junction

Photovoltage wrt $V_{TG}$ and $V_{BG}$

$\mu_1 = -\mu_2$

Similar response from 4K to 300K

Photovoltage wrt $V_{TG}$ along $\mu_1 = -\mu_2$

$T^* = 60K$

Photovoltage wrt $T$

$V_{PH} / V_{max}$ vs Temperature (K)
Results:
- Qualitatively similar dependence on charge density
- Nonmonotonic dependence on $T$
  Greatest magnitude at an intermediate temperature ($T^*$)
- $R$ stays fairly constant over $T$ range
- Shift of $T^*$ for higher density
Hot Electron Dynamics

PTE Voltage:

\[ V_{PH} = (S_1 - S_2) \Delta T_{pn} \]

\[ \Delta T_{pn} = \Delta T_{y=0}. \quad \Delta T(y) = T_e(y) - T_0 \]

Characteristic cooling length*:

\[ \xi = \frac{\kappa}{\gamma C_e} \]

Both \( \kappa \) and \( C_e \) are linear in \( T \)

\( \gamma \) : el-latt cooling rate

Solution to heat equation:

\[ T_e(y) - T_0 = \left[ \xi \sinh \left( \left( \frac{1}{2} L - |y| \right)/\xi \right)/2 \cosh(L/2\xi) \right] \left( \dot{Q}/\kappa \right) \]

\[ V_{PH} = (S_1 - S_2) \frac{\dot{Q} L}{\kappa} \frac{\xi \sinh(L/2\xi)}{2L \cosh(L/2\xi)} \]

\( T \) dependence of \( S \) and \( \kappa \) cancels out

Spatial profile of \( T_e - T_0 \)

Linear from laser spot

\( T \) dependence of \( V_{PH} \)
is due to \( \gamma \)

*J.C.W. Song et al. Nano Lett. 10, 562 (2011)
Temperature dependence of $\gamma$

Electron-Lattice Cooling in Graphene

$$\gamma = \gamma_{NC} + \gamma_{SC} = \frac{A}{T} + BT$$

$$A = \frac{3\hbar g^2 k_F^2 s^2 \nu(\mu)}{\pi k_B} \quad B = 2.2 \frac{g^2 \nu(\mu) k_B}{\hbar k_F \ell}$$

$g$ : electron-phonon coupling
$\nu(\mu)$ : density of states per spin/valley
$l$ : disorder dependent mean free path

Result:
- NC cooling dominates at low T
- SC cooling dominates at high T
- Crossover temperature $T^*$
  - $T^*$: optimal temperature for photodetection
- Control $T^*$ by tuning charge carrier density and disorder concentration

J.C.W. Song et al. PRL 109, 106602 (2012)
$V_{PH}$ at G/M interface

$V_{TG}$ (V)

$V_{BG}$ (V)

$V_{PH}$ (µV)

$V_{BG}$ (V)

$V_{PH}$ (µV)

Temperature (K)

@250K

25 K

60 K

100 K

150 K

200 K

300 K
Due to scattering mechanisms (NC or SC),
Electrons strongly thermalize with lattice before they
reach top gated region
- Shorter $\xi$

At $T^*$, el-lat coupling is low
- Longer $\xi$
Remarks

All the arguments based on linear response regime*: \( T_e \gtrsim T_0 \)

Otherwise one needs more elaborate calculations
And if \( T_e \gg T_0 \), then SC will also dominate even at low temperatures.

It should also be noted that, substrate surface phonons can also contribute to electron cooling, especially at higher temperatures. This would be the reason for the discrepancy between the experimental data and the model.

Dashed black line is the model for the low density
Dashed green line is the model for the high density

This signal decays with distance away from the p-n edge at different rates depending on temperature.

The lowest decay rate is observed at the peak temperature \( T = 60 \) K, corresponding to the longest cooling length.

J.C.W. Song et al. PRL 109, 106602 (2012)
Conclusion

Strong nonmonotonic temperature dependence of PTE on graphene p-n junction

Competing energy loss mechanisms:
Normal collisions for low T
Super collisions at high T

At peak temperature (T*) electrons cool slowest

T* can be controlled with charge density and disorder concentration

Thank you
\[ V_{PH} = (S_1 - S_2) \frac{\dot{Q}_L}{\kappa} \xi \text{sinh}(L/2\xi)/2L \text{cosh}(L/2\xi) \]

**PTE Voltage:**

\[ V_{PH} = (S_1 - S_2) \Delta T_{pn} \]

\[ \Delta T_{pn} = \Delta T_{y=0}, \quad \Delta T(y) = T_{e}(y) - T_0 \]

electron-phonon coupling \( g = D/\sqrt{2\rho s^2} \),

\[ k_B \tilde{T}_{BG} = \hbar s \kappa_F \]