Spin Hall Effect and Origins of Nonlocal Resistance in Adatom-Decorated Graphene

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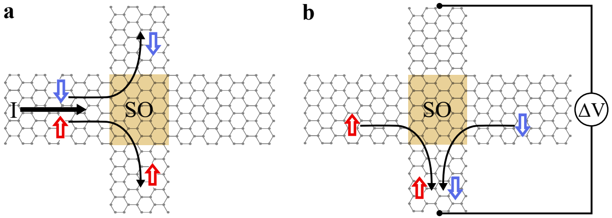
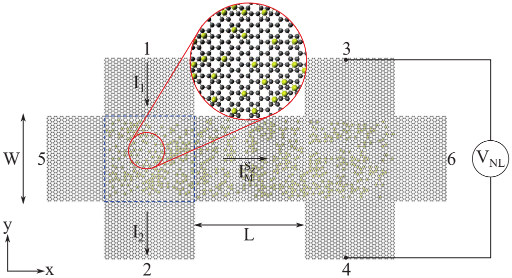
Outline

Motivation



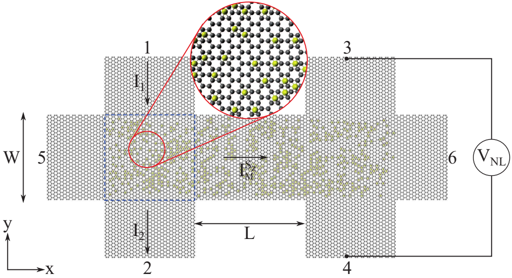
Over the past decade, the spin Hall effect (SHE) has become the standard pure spin-current generator (a) and detector (b).

Six-terminal graphene device



$$\mathscr{H} = -\gamma_0 \sum_{\langle ij \rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_I \sum_{\langle\langle ij \rangle\rangle \in \mathscr{R}} c_i^\dagger \vec{s} \cdot (\vec{d}_{kj} \times \vec{d}_{ik}) c_j$$
$$+ iV_R \sum_{\langle ij \rangle \in \mathscr{R}} c_i^\dagger \vec{z} \cdot (\vec{s} \times \vec{d}_{ij}) c_j - \mu \sum_{i \in \mathscr{R}} c_i^\dagger c_i .$$

Definition of Spin Hall angle and Nonlocal resistance



Spin Hall angle

$\theta_{\mathrm{sH}} = I_5^{S_z}/I_1$

Nonlocal resistance

$R_{\mathrm{NL}} = V_{\mathrm{NL}}/I_1 = (V_3 - V_4)/I_1$

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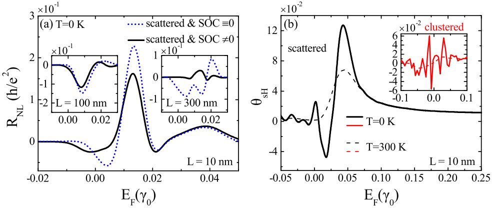
Nonlocal resistance and spin Hall angle in multiterminal graphene



We calculate the total charge I_p and spin $I_p^{S_z}$ currents and voltages V_p in leads p =2–6 in response to injected charge current I_1 using the multiterminal Landauer-Büttiker formula, as implemented in KWANT (http://kwant-project.org/).

Nonlocal resistance and spin Hall angle in multiterminal graphene

Nonzero R_{NL} *even when all SOC terms are switched off* ($V_R = V_I = 0$), while keeping random on-site potential $\mu \neq 0$ due to Au adatoms.

Complex sign change of R_{NL}.

$R_{\mathrm{NL}} = R_{\mathrm{NL}}^{\mathrm{SHE}} + R_{\mathrm{NL}}^{\mathrm{Ohm}} + R_{\mathrm{NL}}^{\mathrm{qb}} + R_{\mathrm{NL}}^{\mathrm{pd}}$

Additive contributions to Nonlocal resistance

$R_{\mathrm{NL}}^{\mathrm{SHE}}$	positive	combined direct and inverse SHE.
$R_{\mathrm{NL}}^{\mathrm{Ohm}}$	positive	classical diffusive charge transport
$R_{\mathrm{NL}}^{\mathrm{qb}}$	negative	quasiballistic contribution due to $T_{32} \neq 0$
$R_{\mathrm{NL}}^{\mathrm{pd}}$	positive	pseudodiffusive transport in Dirac materials

For devices with $W > L$, the positive sign of R_{NL} is dominated by $R_{\mathrm{NL}}^{\mathrm{pd}}$.

For devices with $L > W$, $R_{\mathrm{NL}}^{\mathrm{Ohm}}$ can be neglected; then, the main competition is between $R_{\mathrm{NL}}^{\mathrm{qb}}$ and $R_{\mathrm{NL}}^{\mathrm{SHE}}$.

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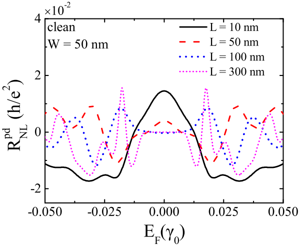
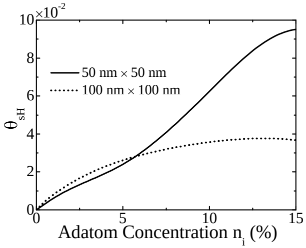
Scaling of the pseudodiffusive contribution to R_{NL}



In pristine graphene, this positive nonlocal signal around the CNP is specific to Dirac electron systems.

This mechanism provides background contribution R^{pd}_{NL} of positive sign to total R_{NL}, as long as $W > L$.

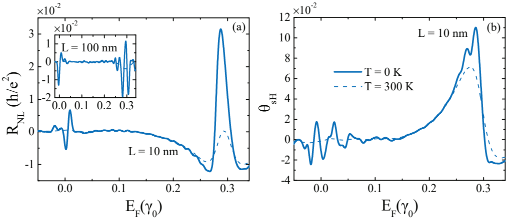
Spin Hall angle as a function of the concentration of randomly scattered Au adatoms



The values of θ_{sH} are averaged over the Fermi energy interval $[-0.01\gamma_0, 0.01\gamma_0]$.

θ_{sH} increases with the adatom concentration in the limit of low n_i.

Nonlocal resistance for a uniform distribution of gold adatoms



The large value of the nonlocal signal and θ_{sH} is away from CNP due to doping of graphene by $\mu = 0.3\gamma_0$, viewing the central region as a single large cluster.

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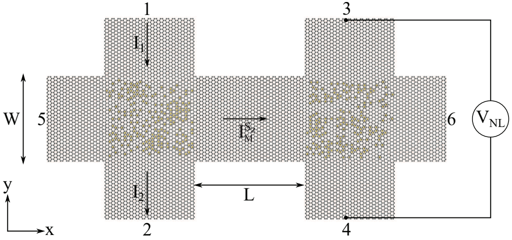
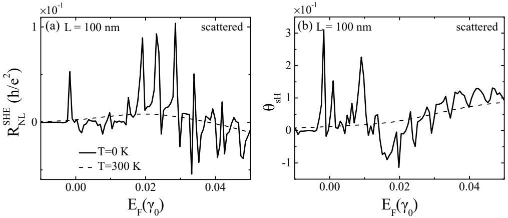
Six-terminal graphene device for isolating the SHE contribution to R_{NL}



We remove adatoms in the channel for isolating $R_{\mathrm{NL}}^{\mathrm{SHE}}$. For a sufficiently long channel, $R_{\mathrm{NL}}^{\mathrm{pd}} = 0$ due to $L > W$ and $R_{\mathrm{NL}}^{\mathrm{qb}}$, $R_{\mathrm{NL}}^{\mathrm{Ohm}} \to 0$ due to the absence of adatom-induced scattering in the channel.

Six-terminal graphene device for isolating the SHE contribution to $R_{\rm NL}$



$R_{\rm NL}$ and $\theta_{\rm sH}$ exhibit a sharp peak at about the same Fermi energy located very close to the CNP, which demonstrates one-to-one correspondence between directly measurable charge transport quantity $R_{\rm NL}$ and indirectly inferred spin transport quantity $\theta_{\rm sH}$.

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Summary

- By using the multiterminal LB formula, we obtained $\theta_{\mathrm{sH}} \sim 0.1$–$0.3$ in Au-decorated graphene with large Au-adatom concentration $n_i = 15\%$.
    - θ_{sH} significantly decreases with temperature and adatom clustering.
- The SHE contribution to R_{NL} was isolated in a special configuration with an impurity-free channel and $L > W$.
    - There is a one-to-one correspondence between directly measurable R_{NL} and indirectly inferred θ_{sH}.