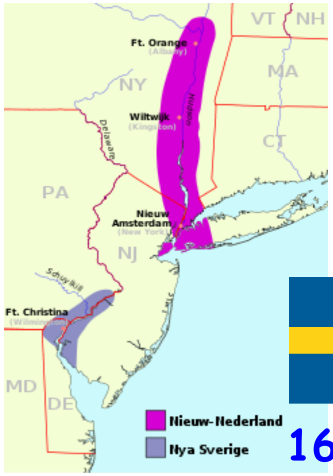
Origins of Nonlocal Resistance in Multiterminal Graphene: Spin Hall and Valley Hall vs. Other Competing Mechanisms

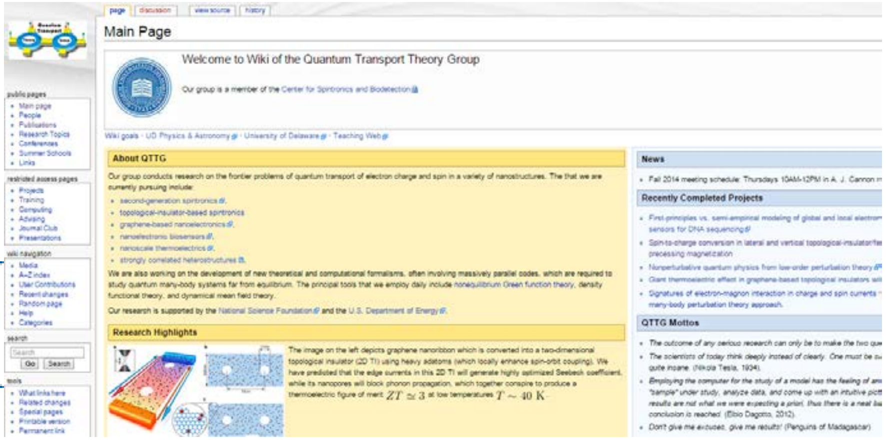
Branislav K. Nikolić

Department of Physics & Astronomy, University of Delaware, Newark, DE 19716, U.S.A.



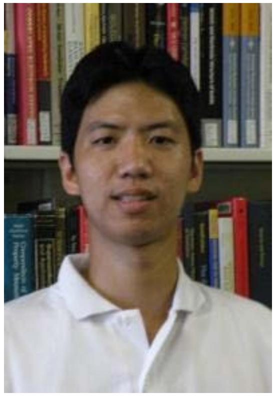
1638–1655

https://wiki.physics.udel.edu/qttg



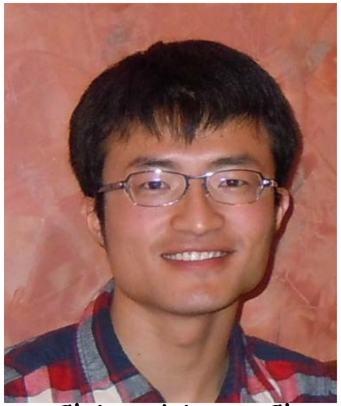
Collaborators

Juan M. Marmolejo-Tejada

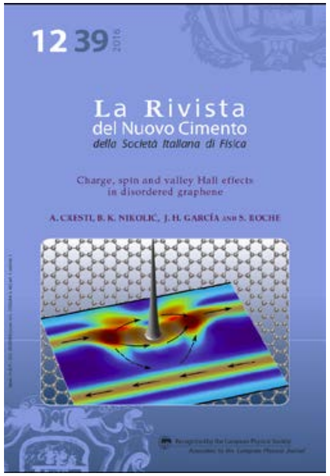


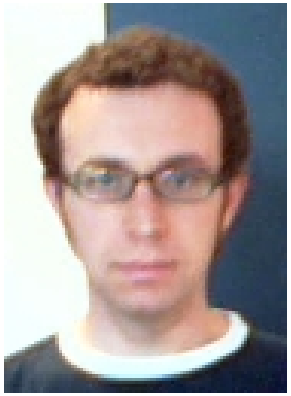
Dr. Po-Hao Chang

Dr. Xian-Lei Sheng



Dr. Chien-Liang Chen





Dr. Alessandro Cresti

Dr. Jose H. García

Prof. Stephan Roche

Dr. Xavier Waintal

Prof. Ching-Ray Chang

"Ancient" History: Nonlocal Resistance in Quantum Hall Systems

VOLUME 64, NUMBER 17 PHYSICAL REVIEW LETTERS 23 APRIL 1990

New Resistivity for High-Mobility Quantum Hall Conductors

P. L. McEuen, A. Szafer, C. A. Richter, B. W. Alphenaar, J. K. Jain,[a] A. D. Stone, and R. G. Wheeler
Department of Applied Physics, Yale University, New Haven, Connecticut 06520-2157

R. N. Sacks
United Technologies Research Center, East Hartford, Connecticut 06108
(Received 15 February 1990)

Landauer-Büttiker formula for quantum transport gains traction

PHYSICAL REVIEW B VOLUME 38, NUMBER 14 15 NOVEMBER 1988-I

Absence of backscattering in the quantum Hall effect in multiprobe conductors

M. Büttiker
IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
(Received 21 March 1988)

VOLUME 59, NUMBER 17 PHYSICAL REVIEW LETTERS 26 OCTOBER 1987

Edge States, Transmission Matrices, and the Hall Resistance

P. Streda and J. Kucera
Institute of Physics, Czechoslovakian Academy of Sciences, 18040 Praha, Czechoslovakia

and

A. H. MacDonald[a]
National Research Council of Canada, Ottawa, Canada K1A 0R6
(Received 6 July 1987)

RAPID COMMUNICATIONS

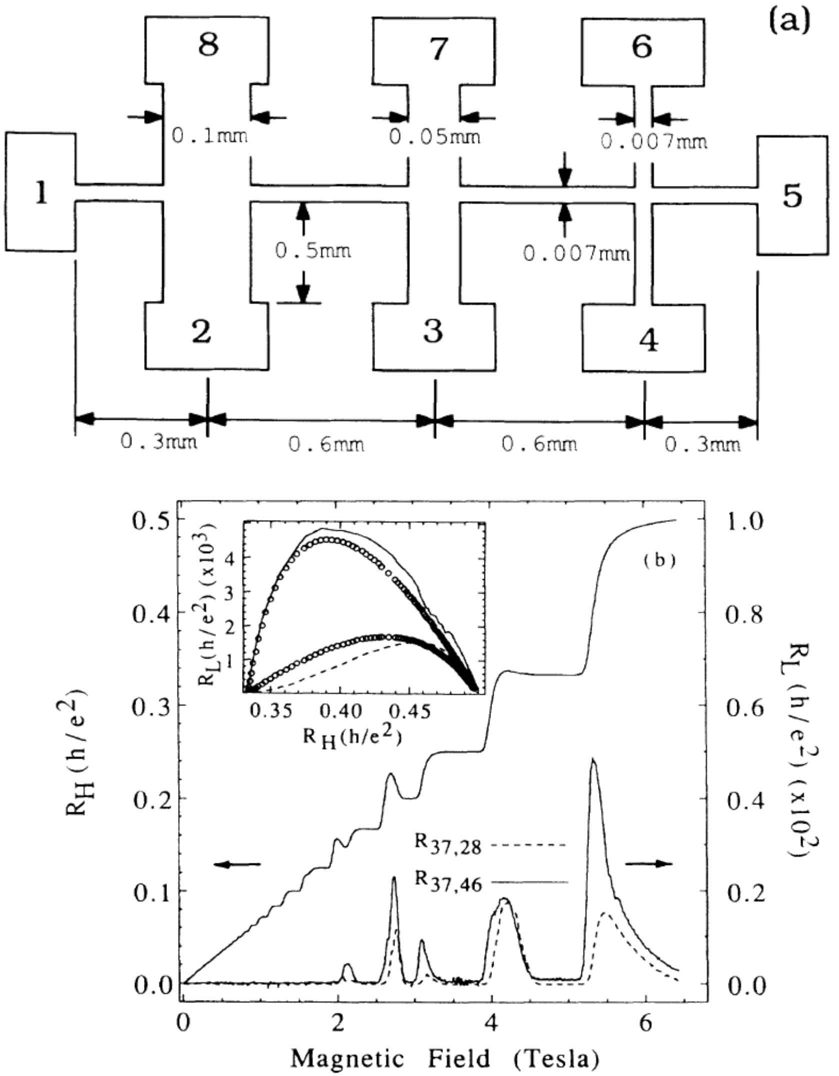
PHYSICAL REVIEW B VOLUME 37, NUMBER 8 15 MARCH 1988-I

Landauer-type formulation of quantum-Hall transport: Critical currents and narrow channels

J. K. Jain
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

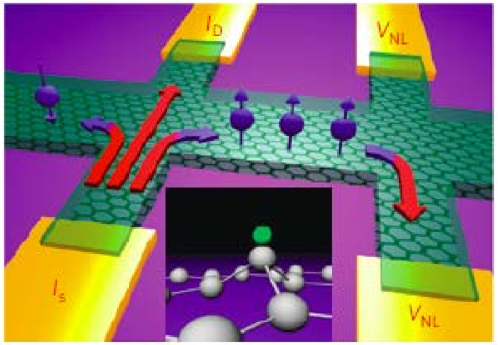
S. A. Kivelson
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 27 October 1987)

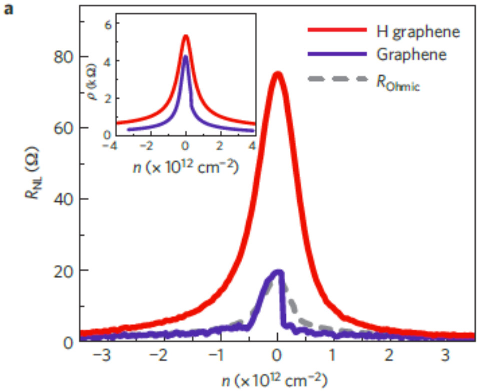
$n_s = 3.5\times10^{11}/\mathrm{cm}^2$ and $\mu = 1\,200\,000\ \mathrm{cm}^2/\mathrm{V\,s}$.

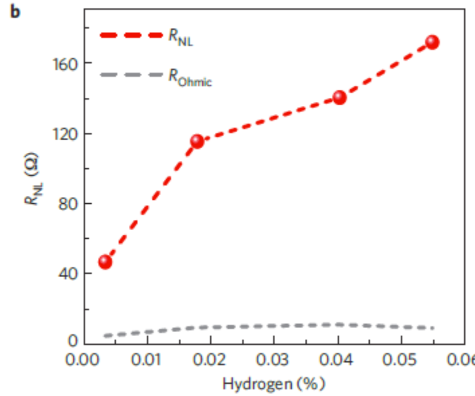


Nonlocal Resistance in Graphene with Adatoms due to Direct and Inverse Spin Hall Effect (SHE)

Nature Phys. **9**, 284 (2013) and Nat. Commun. **5**, 4748 (2015)







LB quantum transport theory removed in favor of semiclassical theory connecting R_{NL} to bulk conductivities based on PRB **79**, 035304 (2009)

Table 1 | Graphene decorated with metallic adatoms.

Adatom	Mobility (cm^{2}V^{-1}s^{-1})	λ_s (μm)	γ	Δ (meV)
Cu-CVD	11,000	1.9	0.17	14.4
Cu-EPG	9,000	1.1	0.27	17.4
Au-EPG	15,000	2.0	0.15	18.0

CVD, chemical vapour deposition; EPG, exfoliated pristine graphene.
The extracted values for Δ assume predominant intrinsic SOC (see main text).

Nature **511**, 449 (2014)

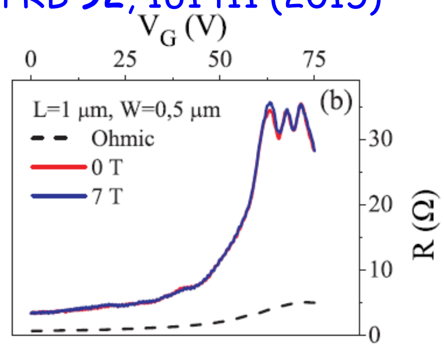
Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for Bi_2Se_3 with other materials

Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
$\theta_\parallel$	2.0–3.5	0.08	0.15	0.24	0.3
$\sigma_{S,\parallel}$	1.1–2.0	3.4	0.8	—	1.8

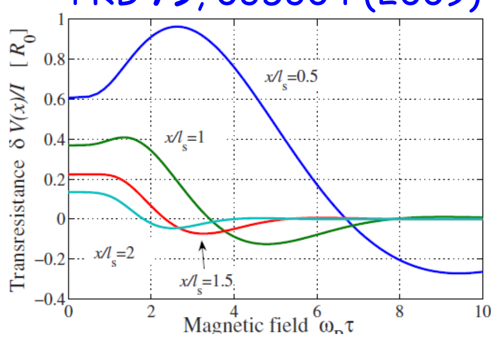
$\theta_\parallel$ is dimensionless and the units for $\sigma_{S,\parallel}$ are $10^5\hbar/2e\ \Omega^{-1}\ m^{-1}$.

CONTROVERSY

PRB **91**, 165412 (2015)
PRB **92**, 161411 (2015)



PRB **79**, 035304 (2009)



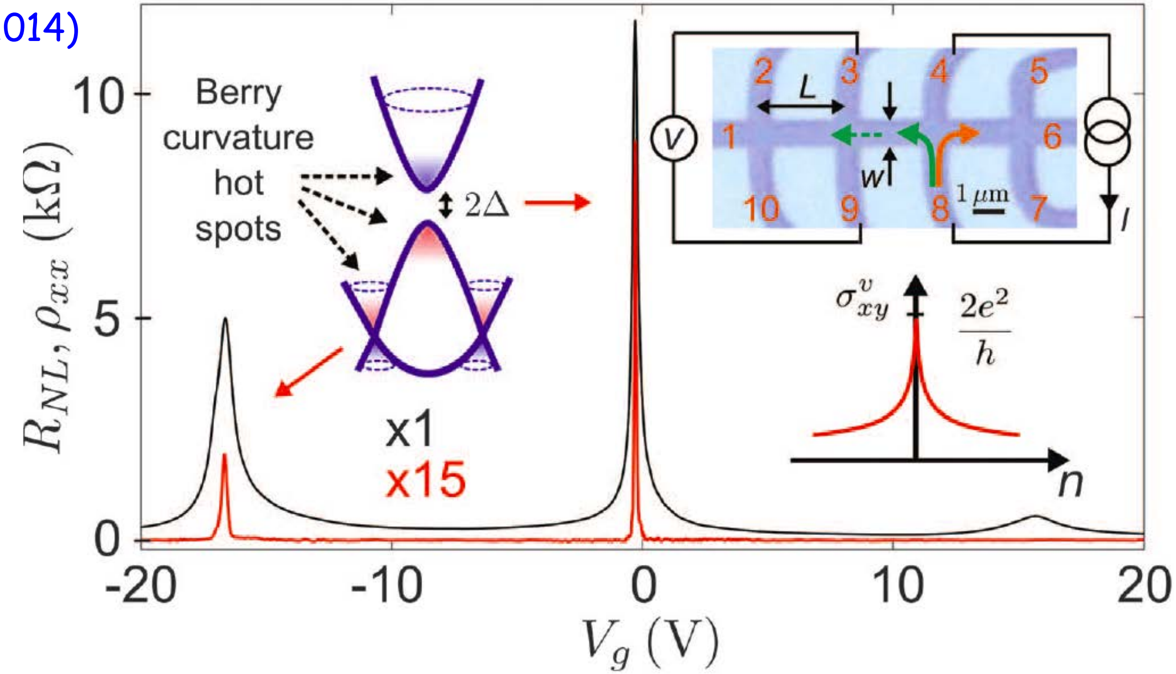
PRL **103**, 166601 (2009) PHYSICAL REVIEW LETTERS 16 OCTOBER 2009

Negative Nonlocal Resistance in Mesoscopic Gold Hall Bars: Absence of the Giant Spin Hall Effect

G. Mihajlović,[1,*] J. E. Pearson,[1] M. A. Garcia,[2] S. D. Bader,[1,3] and A. Hoffmann[1,3]
[1]*Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Dpto. Física de Materiales, Universidad Complutense de Madrid, 28040 Madrid, Spain*
[3]*Center for Nanoscale Materials, Argonne National Laboratory, Argonne, Illinois 60439, USA*
(Received 11 February 2009; published 14 October 2009)

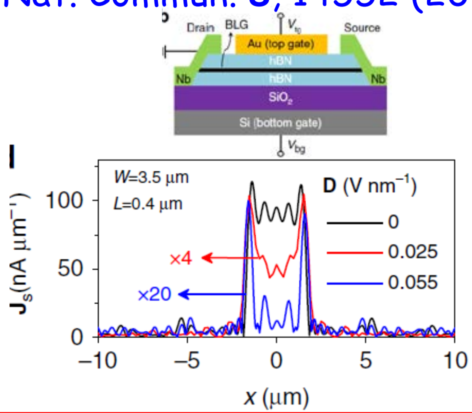
Nonlocal Resistance in Graphene due to (?) Direct and Inverse Valley Hall Effect

Science **346**, 448 (2014)

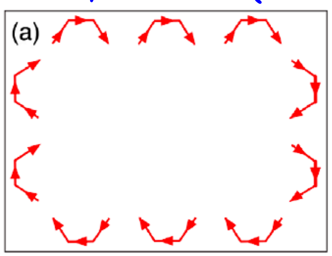


CONTROVERSY

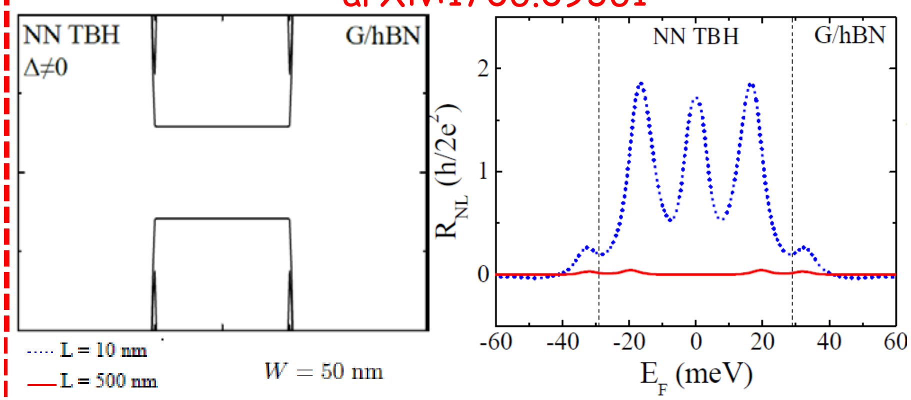
Nat. Commun. **8**, 14552 (2017)



PRL **114**, 256601 (2015)

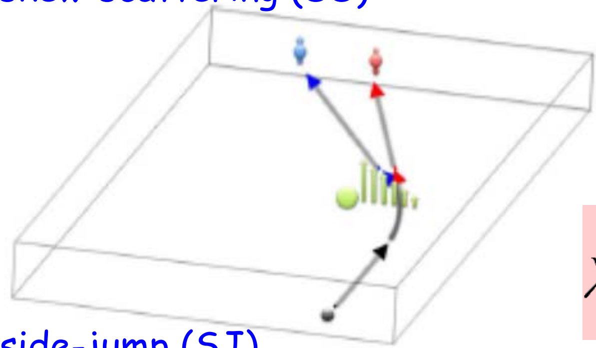


arXiv:1706.09361



Physical Mechanisms of SHE: Extrinsic vs. Intrinsic

skew-scattering (SS)

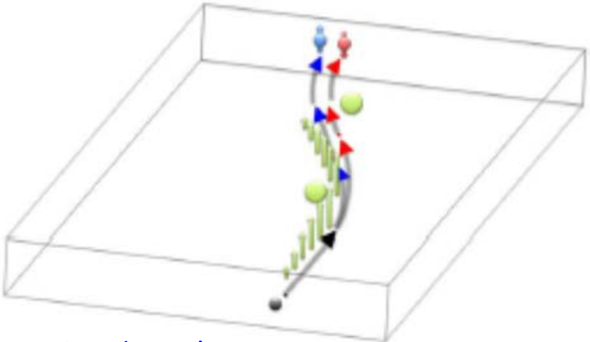


$$\hat{H}_{\rm SO} = -\frac{\lambda^2}{4\hbar}[\hat{\mathbf{p}} \times \nabla V(\mathbf{r})] \cdot \hat{\boldsymbol{\sigma}} \mapsto \lambda_c^2[\hat{\mathbf{k}} \times \nabla V(\mathbf{r})] \cdot \hat{\boldsymbol{\sigma}}$$

$$\lambda^2 = \frac{\hbar^2}{m^2c^2} \simeq 1.5 \times 10^{-6}\text{Å}^2 \mapsto \lambda_c^2 \simeq 5\text{Å}^2$$

strong SOC with the nuclei of the periodically arranged atoms is hidden behind the vacuum-like form

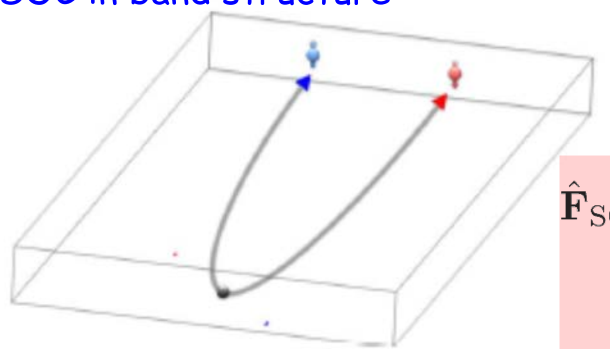
side-jump (SJ)



$$\hat{\mathbf{r}}_{\rm phys} = \hat{\mathbf{r}} + \lambda_c^2 \hat{\mathbf{p}} \times \hat{\boldsymbol{\sigma}} \quad \Rightarrow \quad \hat{\mathbf{v}} = \frac{\hbar\hat{\mathbf{k}}}{m^*} + \frac{2\lambda_c^2}{\hbar}\nabla V_{\rm imp}(\mathbf{r}) \times \hat{\boldsymbol{\sigma}}$$

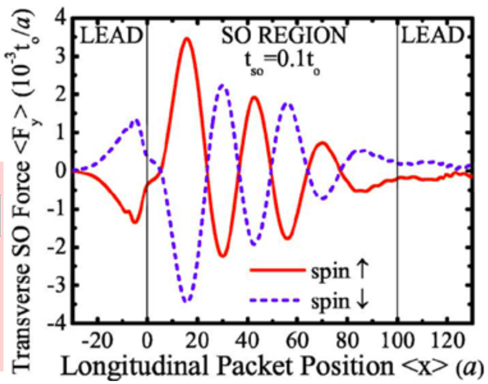
$$\Delta\mathbf{r}_{\rm phys} = \int dt\, \mathbf{v}(t) = -2\lambda_c^2 \Delta\mathbf{k} \times \hat{\boldsymbol{\sigma}}$$

SOC in band structure

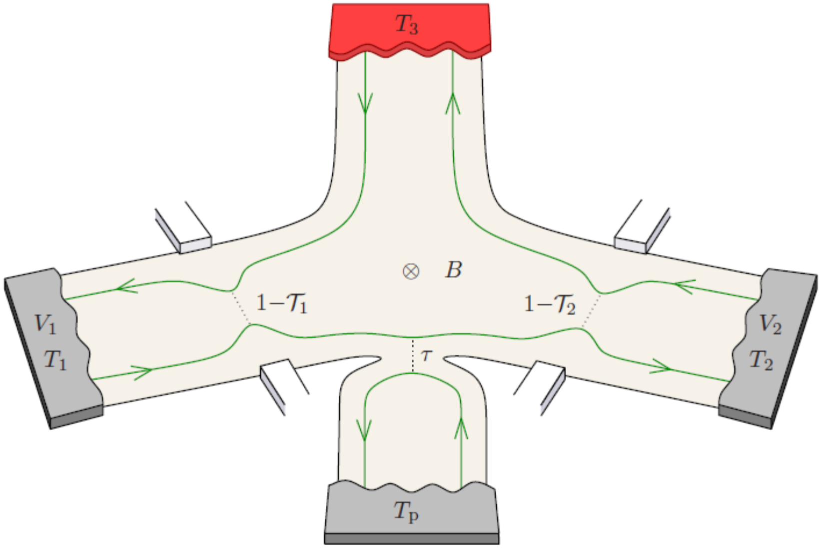


PRB **72**, 075335 (2005)

$$\hat{\mathbf{F}}_{\rm SO} = m^* \frac{d^2\mathbf{r}_H}{dt^2} = \frac{m^*}{\hbar^2}[\hat{H}_{\rm Rashba}, [\hat{\mathbf{r}}_H, \hat{H}_{\rm Rashba}]] = \frac{2\alpha^2 m^*}{\hbar^3}(\hat{\mathbf{p}}_H \times \mathbf{z}) \otimes \hat{\sigma}_H^z$$



Landauer-Büttiker (LB) Quantum Transport Theory for Charge and Spin Currents in Mulititerminal Circuits



PRL **57**, 1761 (1986)

$$I_p = \sum_q G_{pq}(V_p - V_q)$$

$$G_{pq} = \int dE \left(-\frac{\partial f}{\partial E}\right) \mathrm{Tr}\left[\mathbf{t}(E)\mathbf{t}^\dagger(E)\right]$$

PRB **72**, 075361 (2005); PRB **89**, 195418 (2014)

$$I_p^{S_\alpha} = \sum_q G_{pq}^{S_\alpha}\left[(V_p - V_q) - \frac{E - E_F}{eT}(T_p - T_q)\right]$$

$$G_{pq}^{S_\alpha} = \int dE \left(-\frac{\partial f}{\partial E}\right) \mathrm{Tr}\left[\hat{\sigma}_\alpha \mathbf{t}(E)\mathbf{t}^\dagger(E)\right]$$

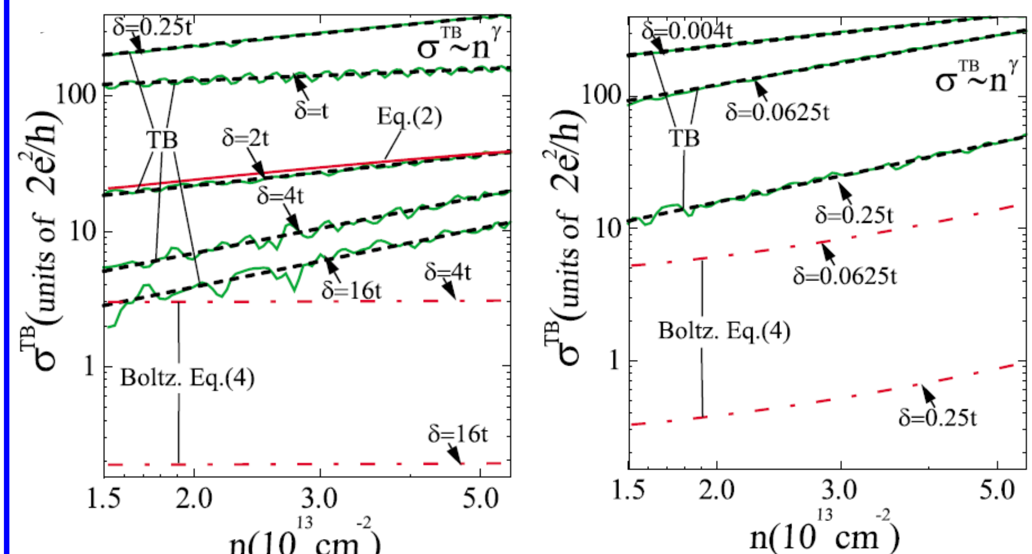
PRL **117**, 176602 (2016)

$$\theta_{\mathrm{SH}} = \frac{I_3^{S_z}}{I_1}$$

kwant

https://kwant-project.org

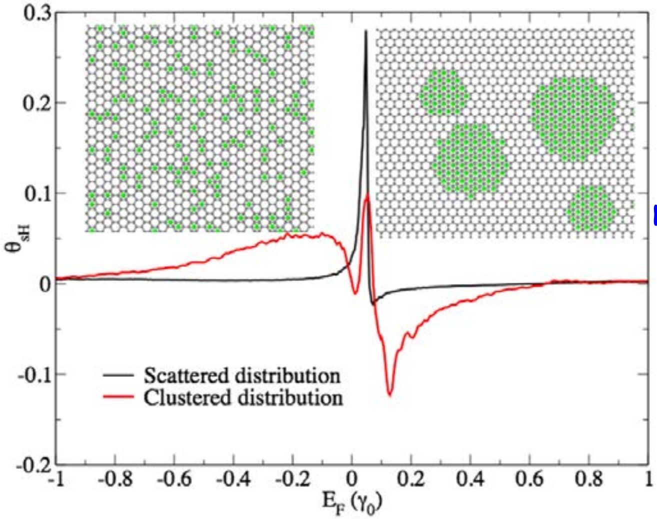
LB theory puts limits on the usage of Boltzmann equation for graphene

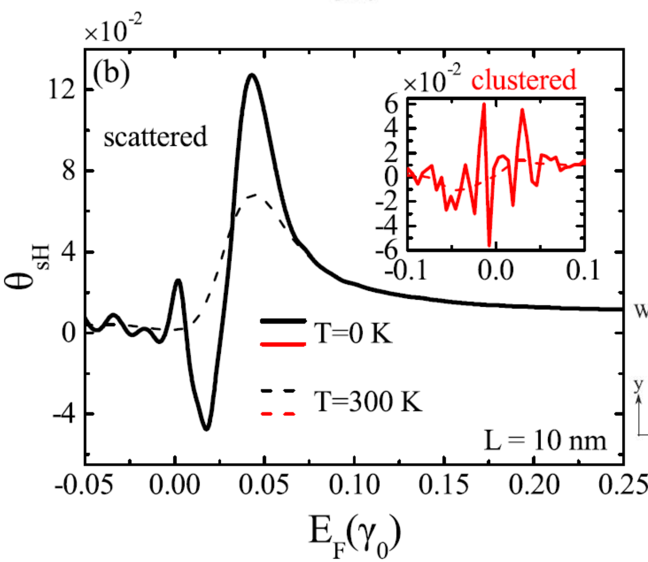


PRB **82**, 081414(R) (2010)

Kubo vs. LB Computed SH Angle of Graphene with SOC due to Adatoms

PRL **117**, 176602 (2016)



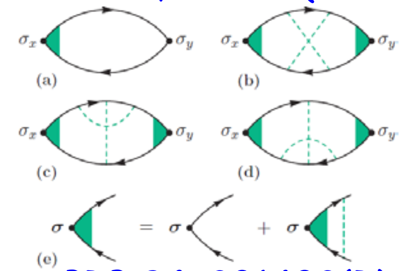


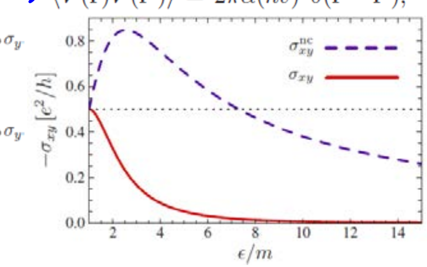
Real-space Kubo formula via kernel polynomial method makes possible numerically exact calculations on ~500 nm x 500 nm square containing ≤ 10 million atoms

Paper-pencil calculations: Which diagrams to consider?

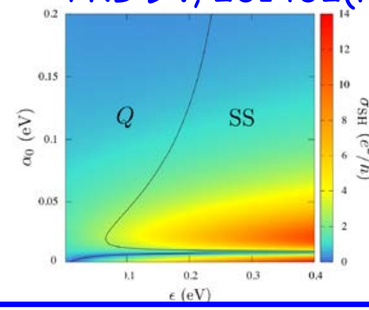
EPL **111**, 37004 (2015)

$$H = v\,\sigma\mathbf{p} + m\sigma_z + V(\mathbf{r}),$$
$$\langle V(\mathbf{r})V(\mathbf{r}')\rangle = 2\pi\alpha(\hbar v)^2\delta(\mathbf{r}-\mathbf{r}'),$$





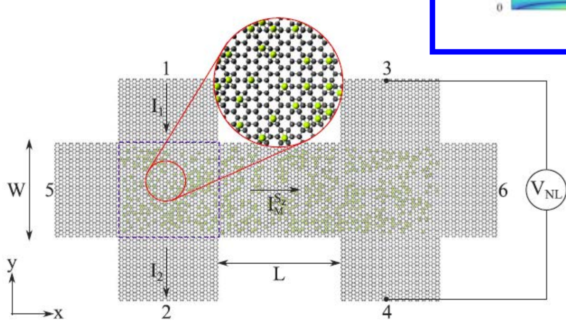
PRB **94**, 201402(R) (2016)

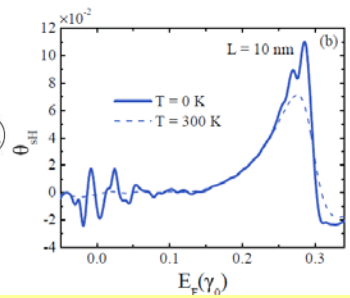


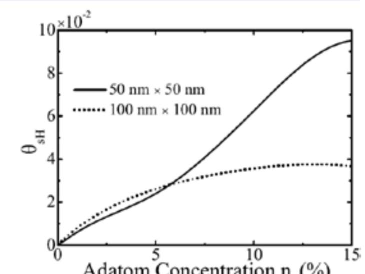
$\sigma_{\rm sH} \propto 1/n_i$ SS

$\sigma_{\rm sH} \propto n_i^0$ SJ

$\sigma_{\rm sH} \propto n_i^{-\alpha}$ Q



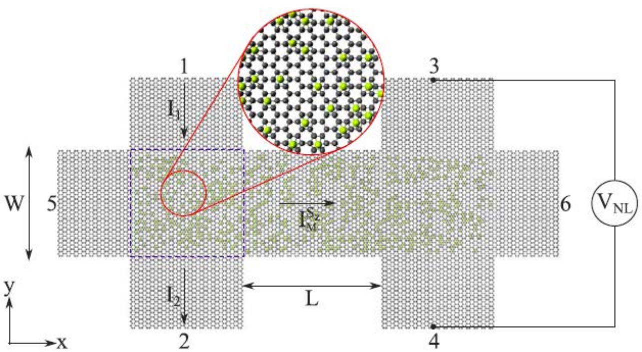


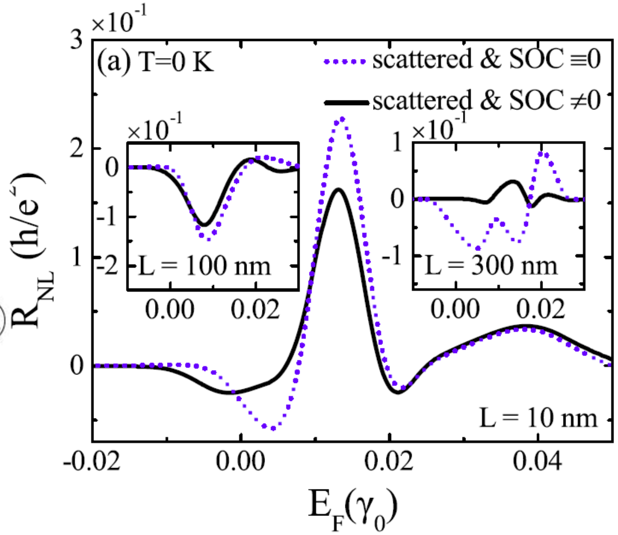


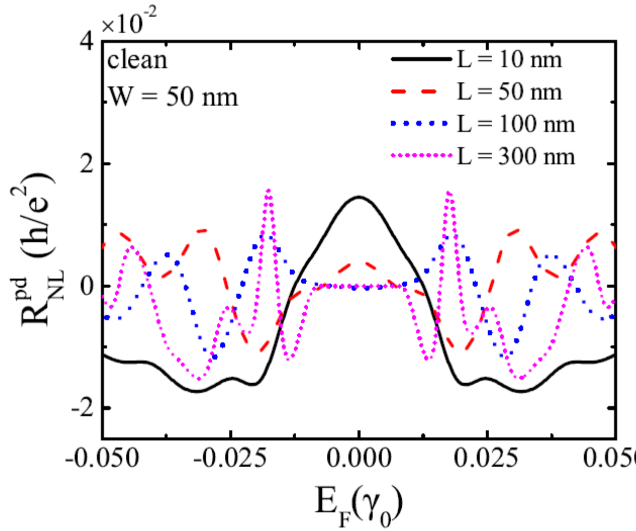
$$\hat{H} = -\gamma_0 \sum_{\langle ij\rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{\rm I} \sum_{\langle\langle ij\rangle\rangle \in \mathcal{R}} c_i^\dagger \mathbf{s}\cdot(\mathbf{d}_{kj}\times\mathbf{d}_{ik})c_j + iV_{\rm R}\sum_{\langle ij\rangle\in\mathcal{R}} c_i^\dagger \hat{z}\cdot(\mathbf{s}\times\mathbf{d}_{ij})c_j - \mu\sum_{i\in\mathcal{R}} c_i^\dagger c_i$$

LB Theory of Nonlocal Resistance in Multiterminal Graphene with Adatoms

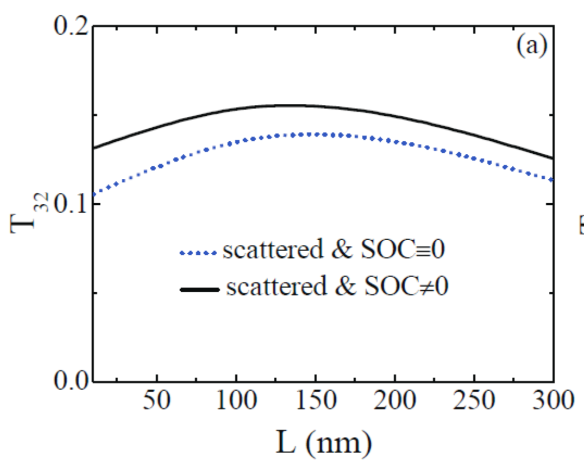
PRL **117**, 176602 (2016)

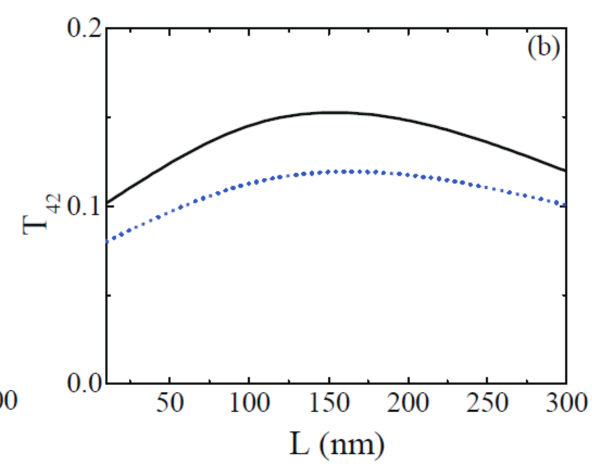


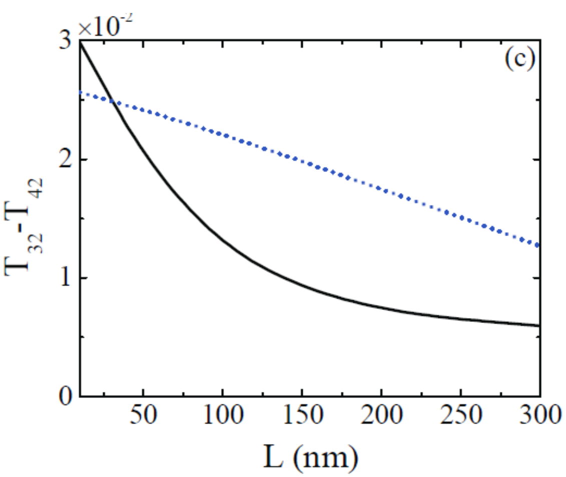




$$R_{\rm NL} = R_{\rm NL}^{\rm SHE} + R_{\rm NL}^{\rm Ohm} + R_{\rm NL}^{\rm pseudodiffusive} + R_{\rm NL}^{\rm quasiballistic}$$

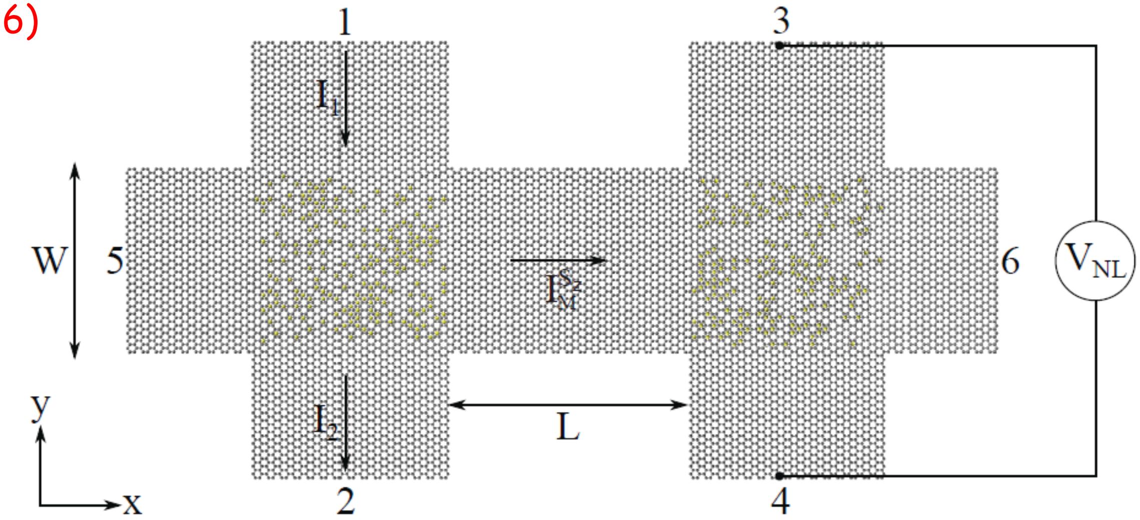


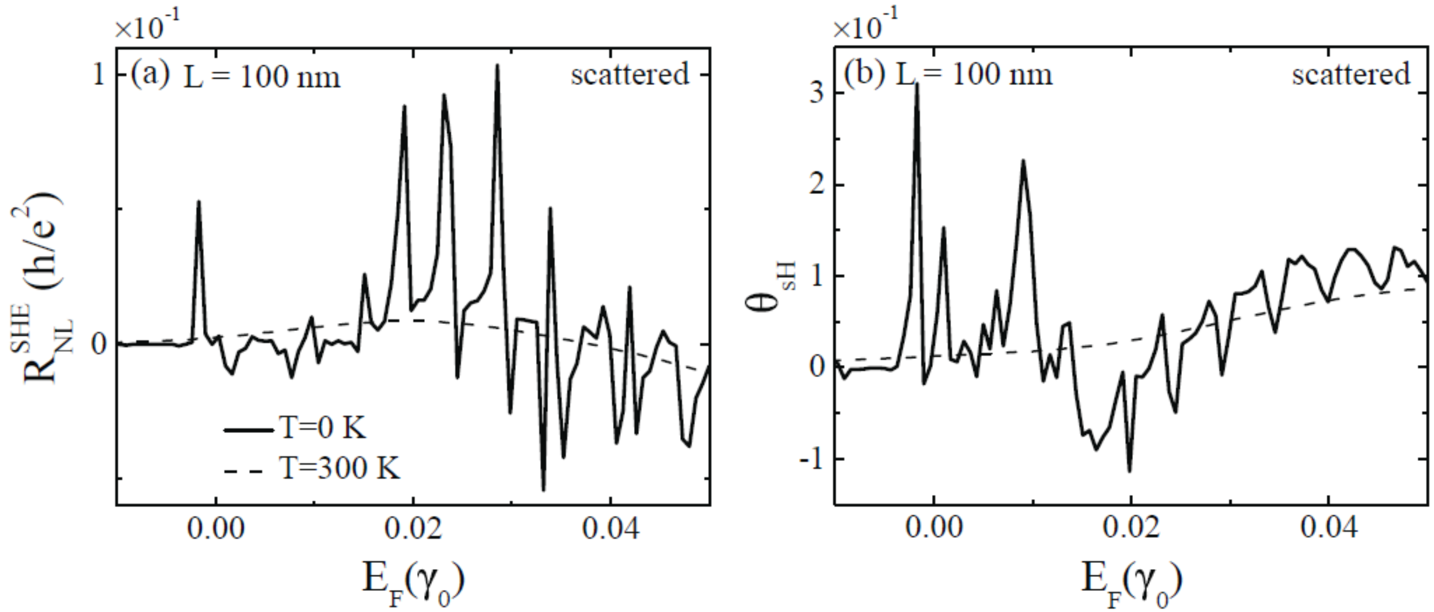




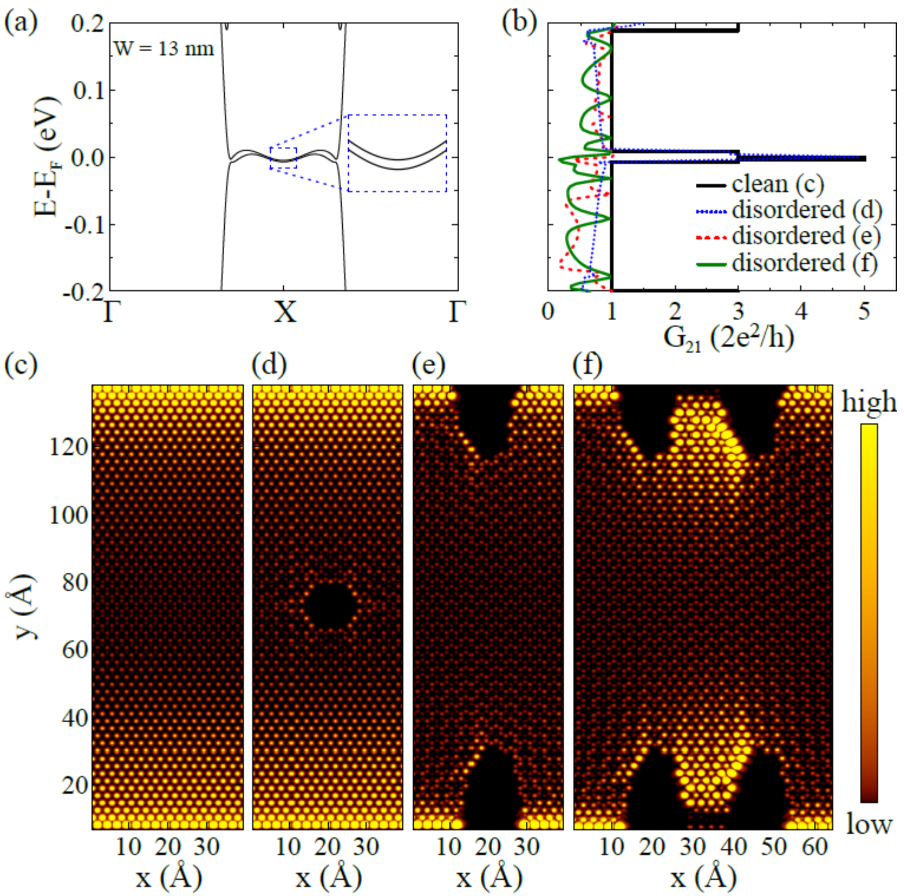
How to Get Nonlocal Resistance Due to Purely Direct and Inverse SHE in Graphene with Adatoms

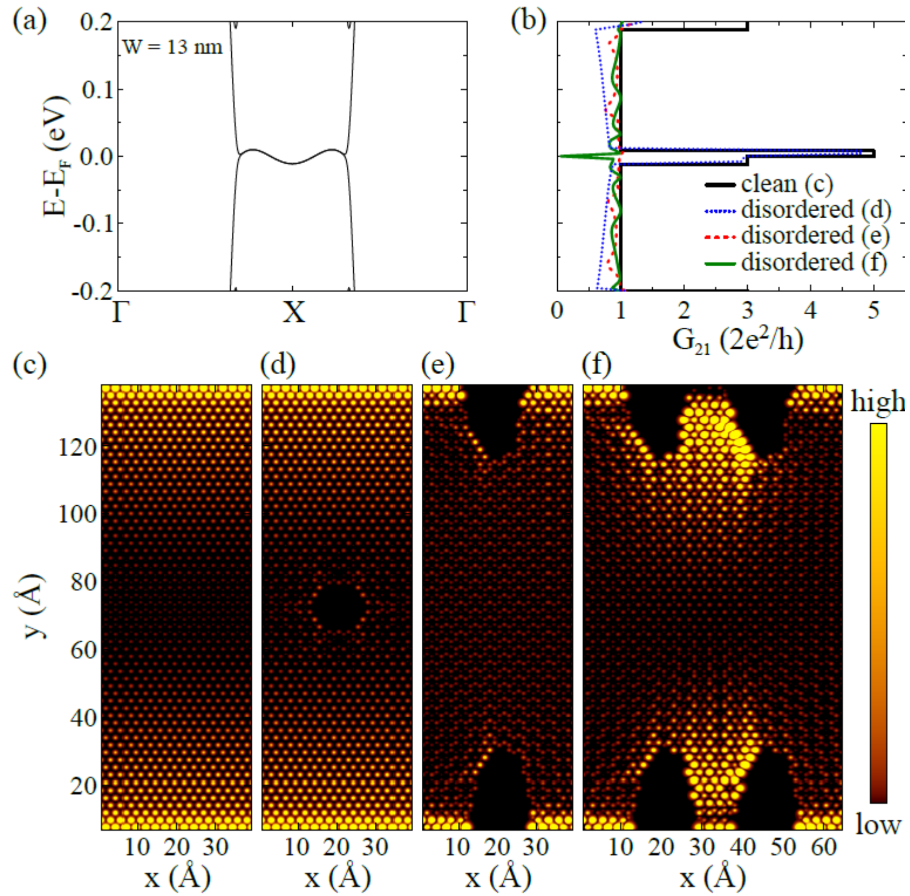
PRL **117**, 176602 (2016)





First-Principles Bandstructure and Quantum Transport in Zigzag Nanowires of G/hBN vs. G

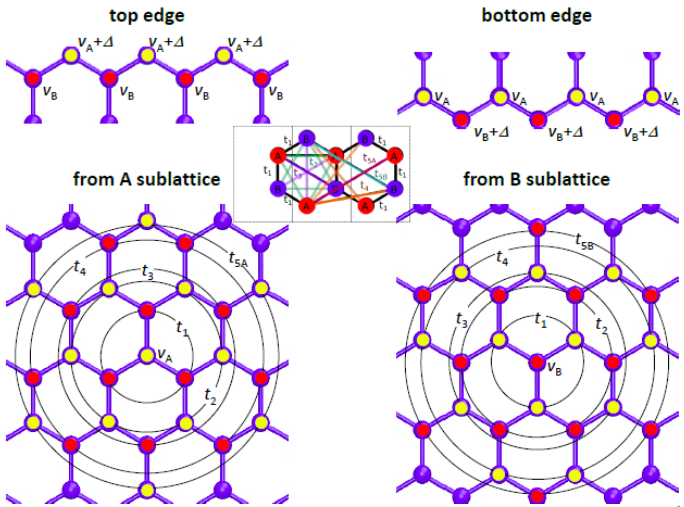




arXiv:1706.09361

Ab Initio Tight-Binding Hamiltonian for Graphene-on-hBN Nanowires with Zigzag Edges

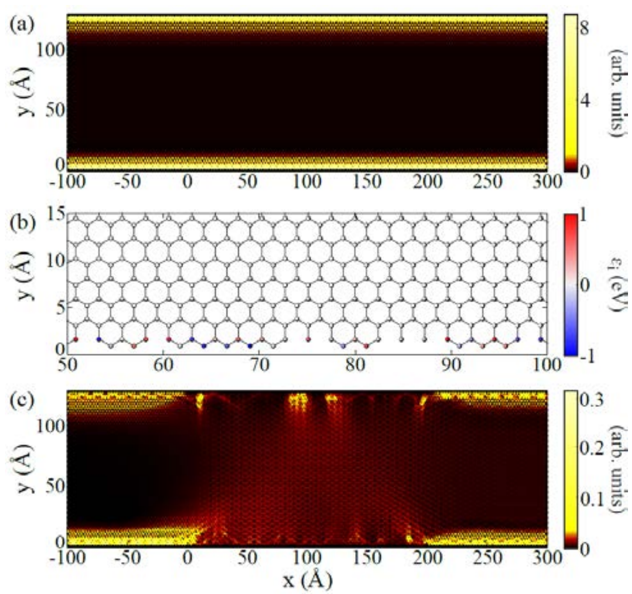
(a) 5NN Tight-binding Hamiltonian: Definition of parameters

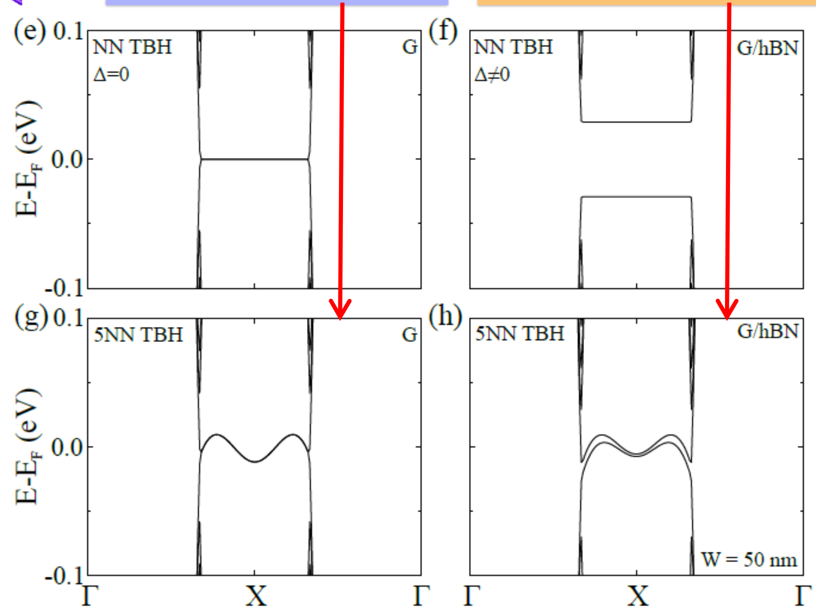


(b) 5NN Tight-binding Hamiltonian: Numerical values of parameters

Isolated graphene wire with zigzag edges	Graphene-on-hBN wire with zigzag edges
v_A = 0.3667 eV	v_A = 0.3495 eV
v_B = 0.3667 eV	v_B = 0.352 eV
Δ = 0.06262 eV	Δ = 0.0855 eV
t_1 = 2.6672 eV	t_1 = 2.6672 eV
t_2 = 0.2083 eV	t_2 = 0.2083 eV
t_3 = 0.2000 eV	t_3 = 0.2000 eV
t_4 = -0.1800 eV	t_4 = -0.1800 eV
t_{5A} = 0.0416 eV	t_{5A} = 0.0416 eV
t_{5B} = 0.0416 eV	t_{5B} = 0.0428 eV

Edge currets for TBH

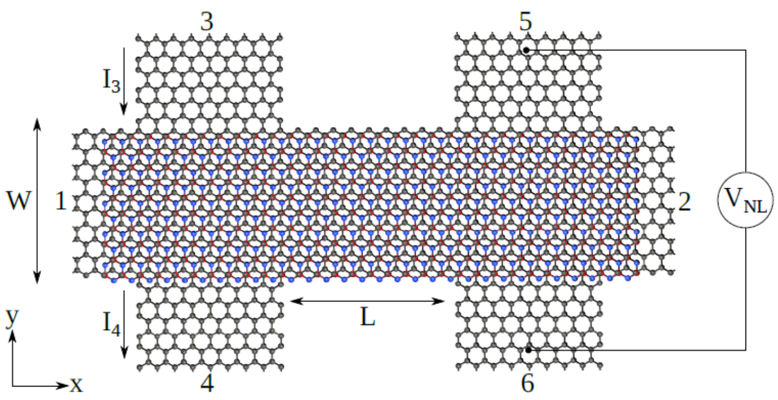


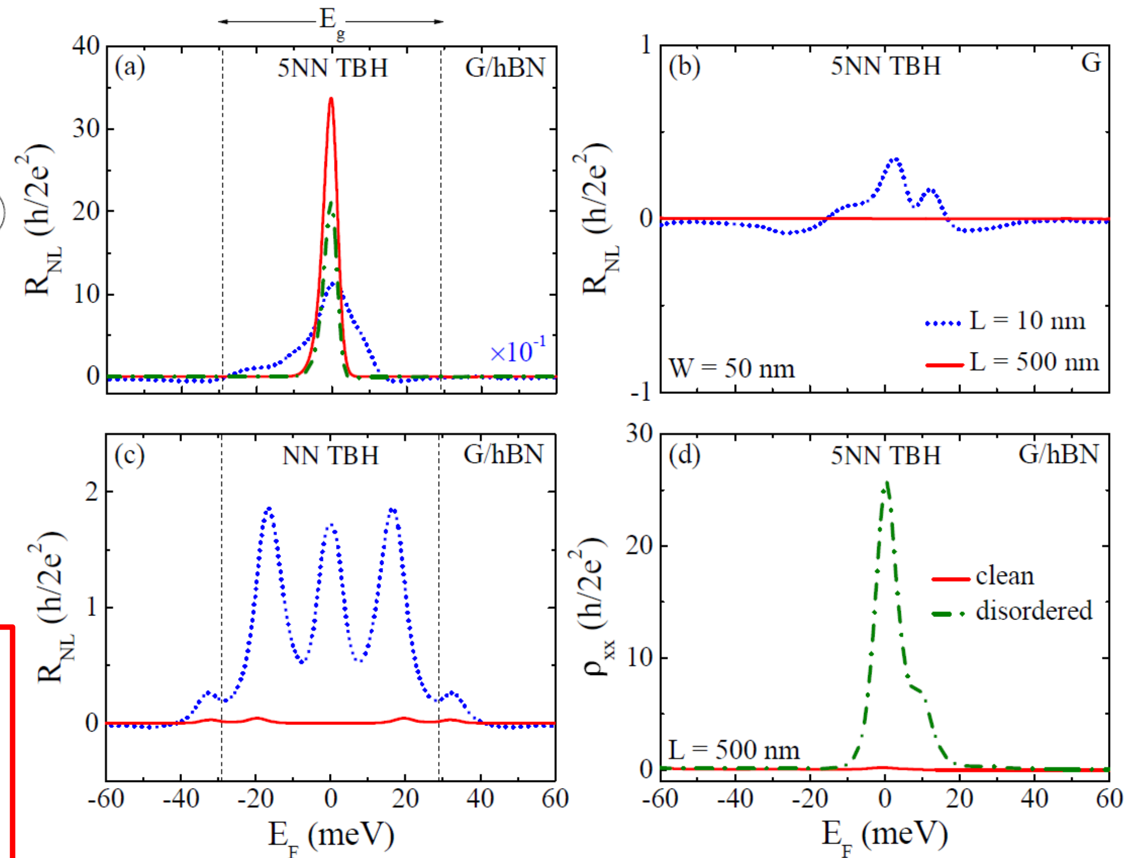


arXiv:1706.09361

Landauer-Büttiker Theory of Nonlocal Resistance and ρ_{xx} in Multiterminal Graphene/hBN

arXiv:1706.09361



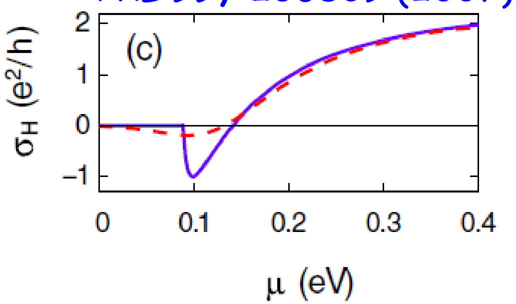


COMPARE TO EXPERIMENT

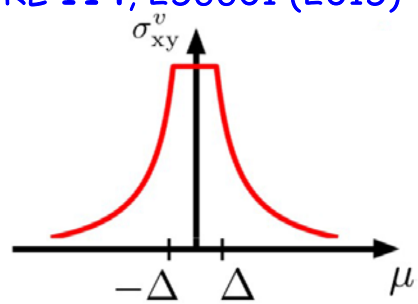
- R_{NL} peak is seen in aligned G/hBN zigzag wires, never in nonaligned ones despite edge states being present
- ρ_{xx} peak value is metallic-like
- ρ_{xx} peak is wider than R_{NL} peak
- R_{NL} peak centroid is slightly shifted to the left of the DP

Kubo Theory of Valley Hall Conductivity in Graphene/hBN

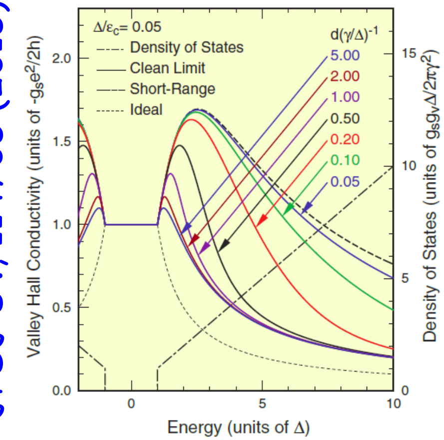
PRL **99**, 236809 (2007)



PRL **114**, 256601 (2015)

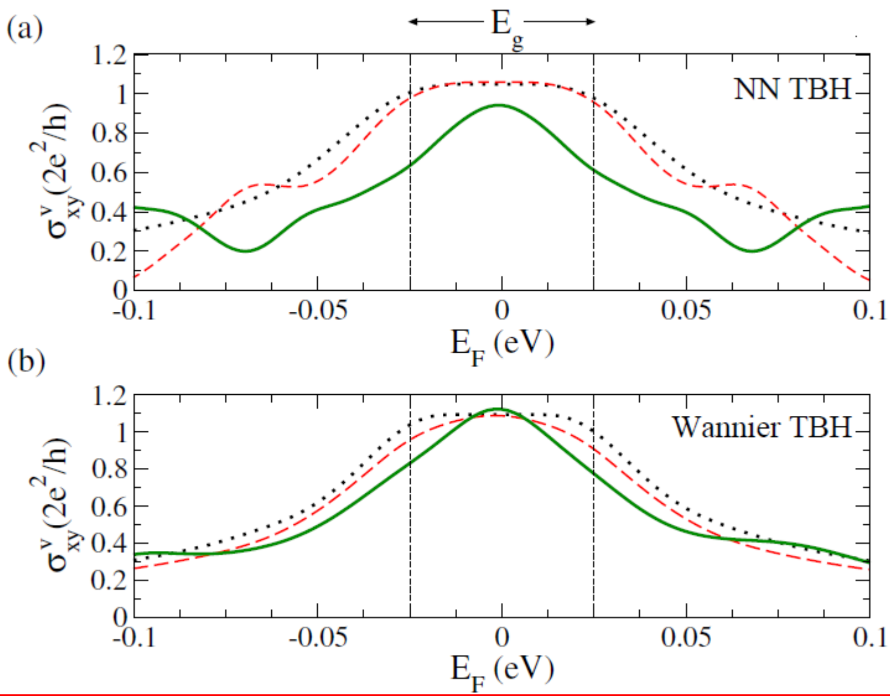


JPSJ **84**, 114705 (2015)



arXiv:1706.09361

real-space numerically exact Kubo formula

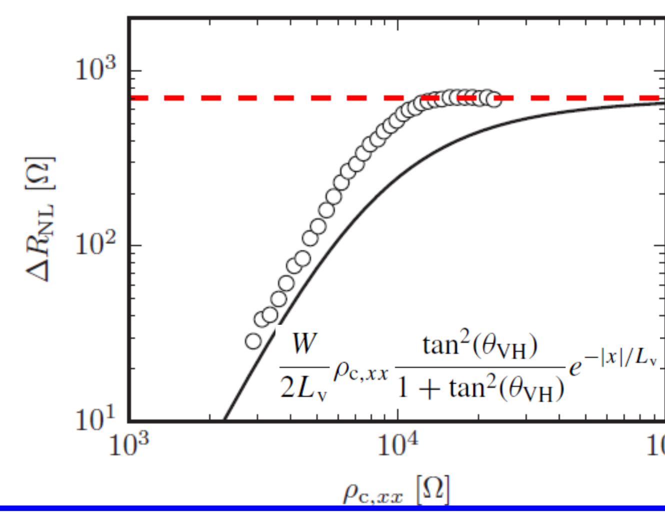


Science **346**, 448 (2014); PNAS **122**, 10879 (2015)

$$R_{\rm NL} \propto (\sigma^v_{xy})^2 \rho^3_{xx}$$

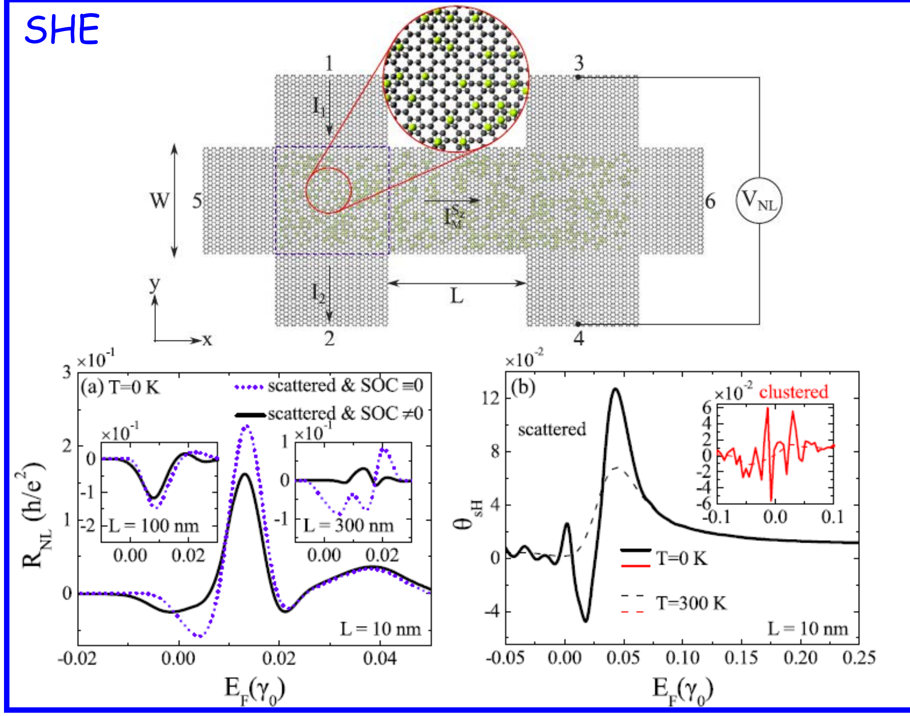
nonlocal resistance obtained indirectly from σ^v_{xy} + semiclassical diffusion

PRB **94**, 121408(R) (2016)



Conclusions in Pictures

SHE



$$R_{NL} = R_{NL}^{SHE} + R_{NL}^{Ohm} + R_{NL}^{pseudodiffusive} + R_{NL}^{quasiballistic}$$

VHE(?)