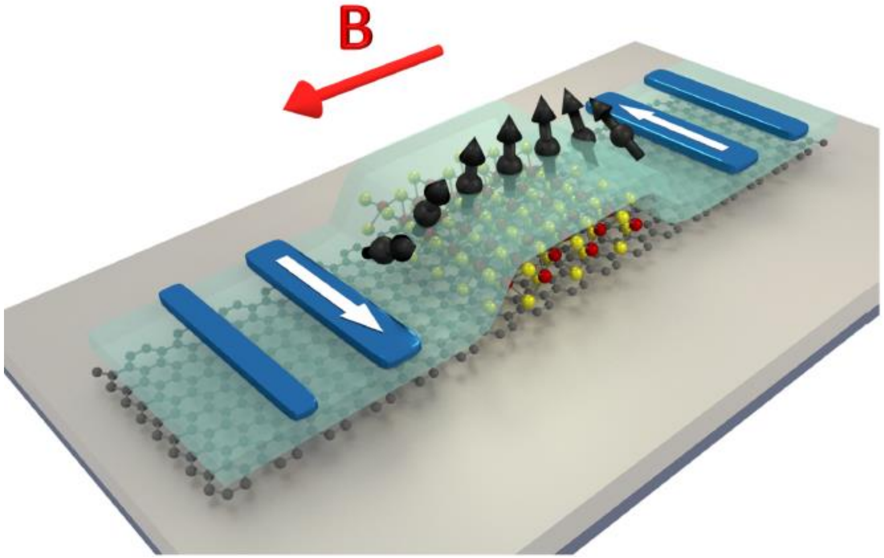
2018 IMAGINENANO
Bringing together Nanoscience & Nanotechnology
SCIENCE • INDUSTRY • SOCIETY
The largest European event in Nanotechnology
MARCH 13-15, BILBAO (SPAIN)

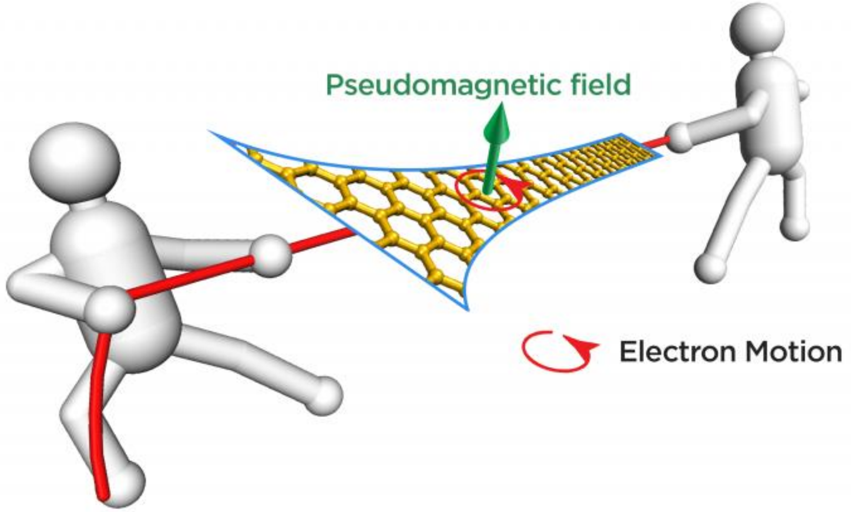
ICN2
Institut Català de Nanociència i Nanotecnologia

BIST
Barcelona Institute of Science and Technology

2D materials for Spin/Valleytronics
Theoretical Perspective

Stephan Roche ICREA

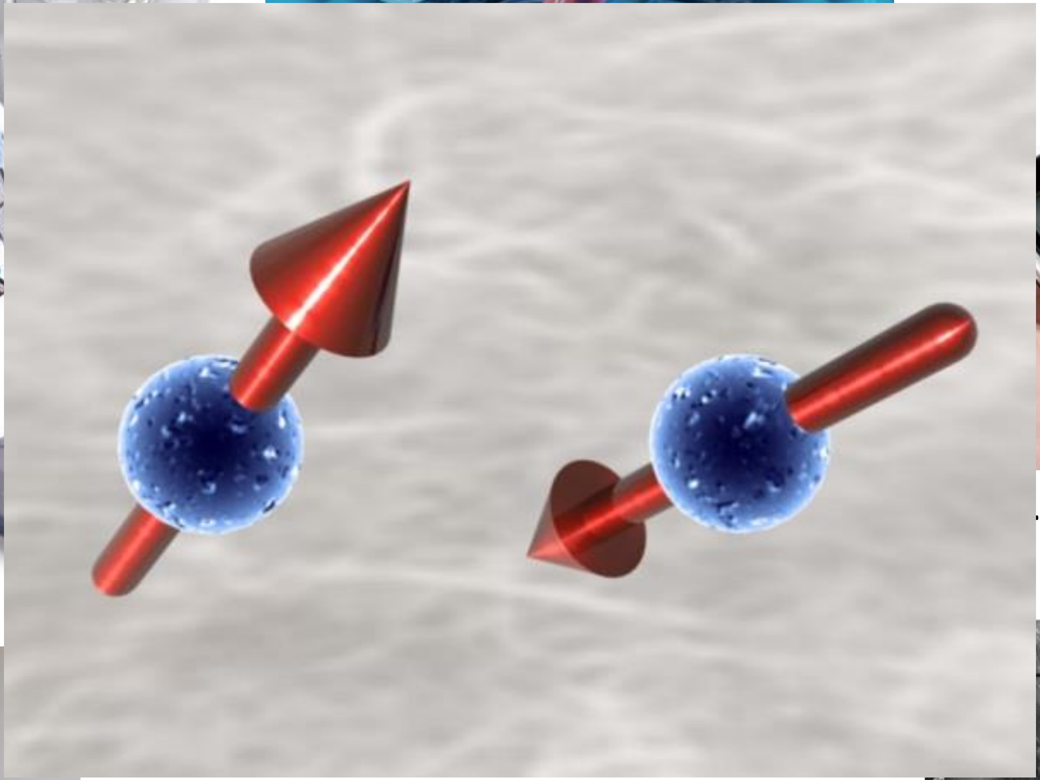




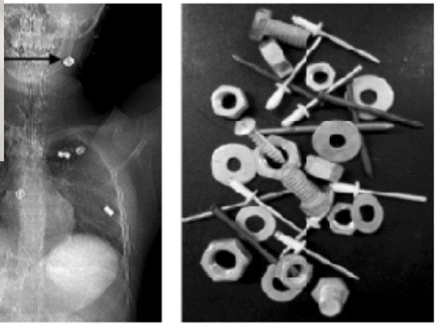
Institució CERCA Centres de Recerca de Catalunya
Generalitat de Catalunya
CSIC Consejo Superior de Investigaciones Científicas
UAB Universitat Autònoma de Barcelona

Spintronics inside !

ROBOTICS/SURGERY



-OF-CARE DIAGNOSTICS



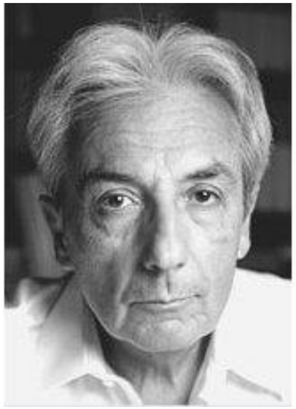
WELDING

COMPASS

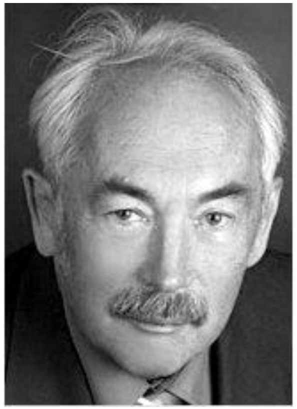
LOCATION OF SHRAPNEL

Spintronics and its industrial/Societal impact

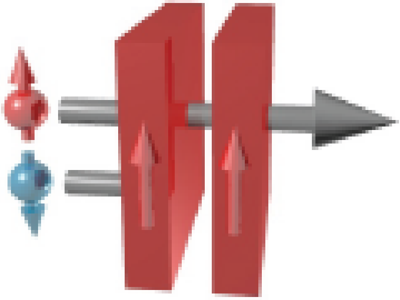
Albert Fert



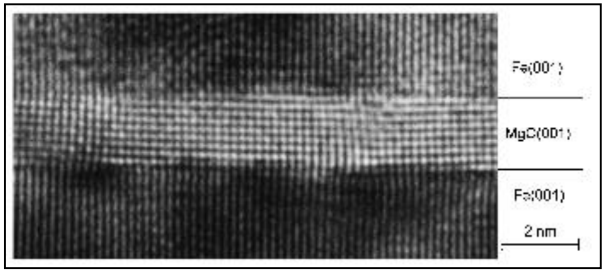
Peter Grünberg

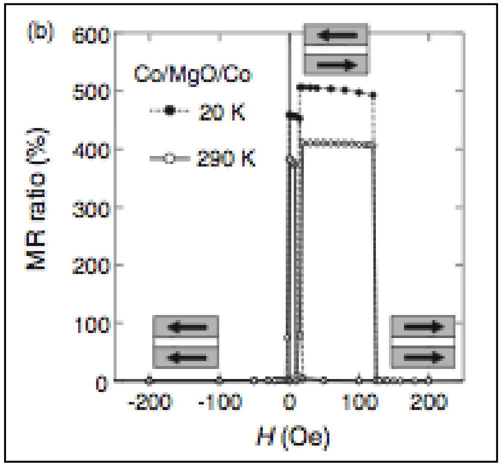


2007 Physics Nobel Laureates



$$MR = \frac{R_{AP}-R_P}{R_P}$$





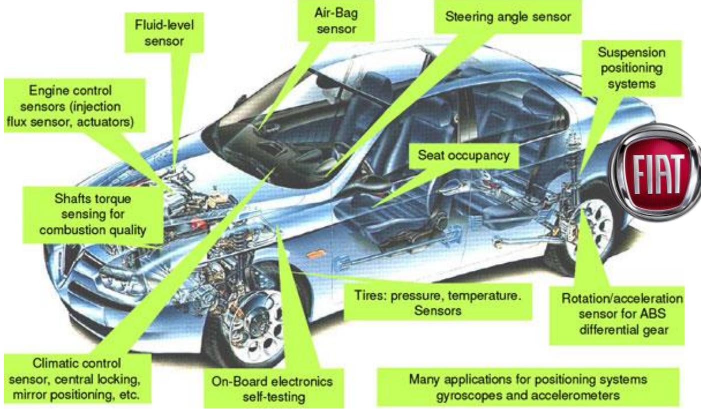
Magnetic field sensors used to read data in hard disk drives,

Microelectromechanical systems

Minimally invasive surgery

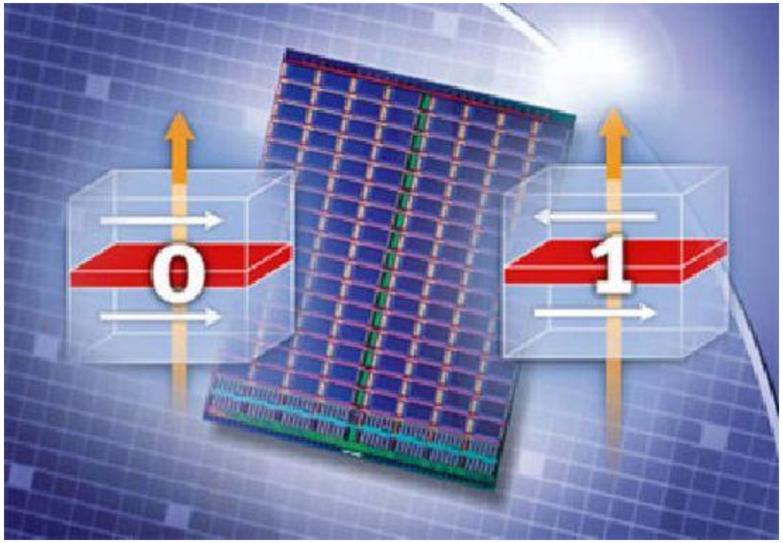
Automotive sensors for fuel handling system,

Anti-skid system, speed control & navigation



Data Storage & TMR

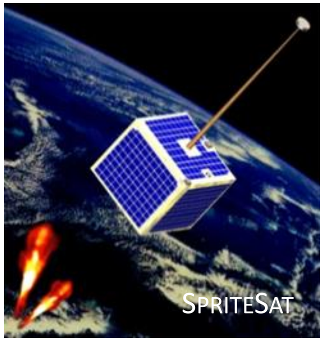
Magnetic junctions and MRAM



DELL Schneider Electric

SIEMENS Honeywell

Memory Buffer SSD



Aerospace

Aeronautics

Automotive

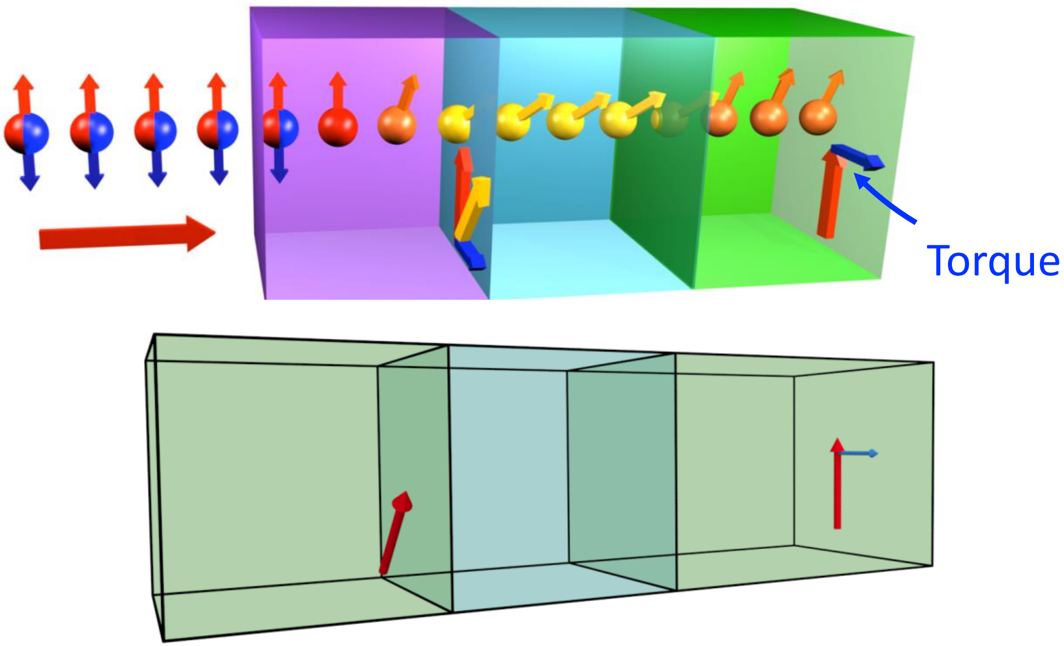
RAID Servers

Factory Automatization

Advanced generation of Spin Transfert Torque MRAM

(proposed by Slonczewski, Berger 1996)

Spin Transfer Torque



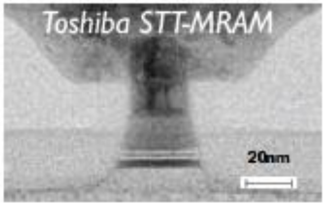
256Mb in production 2018

EVERSPIN®
TECHNOLOGIES
The MRAM Company™

GLOBALFOUNDRIES®

300mm Manufacturing

2016



SAMSUNG

In production
for 2019

OUTLINE

Why Spintronics using 2D Materials ?

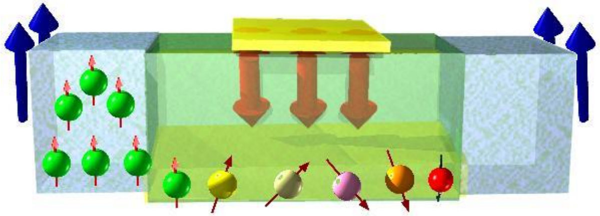
Proximity effects in 2D Materials-based heterostructures (spin dynamics & relaxation, SHE, weak antilocalization, QSHE)

Generating valley polarized quantum transport (valleytronics)

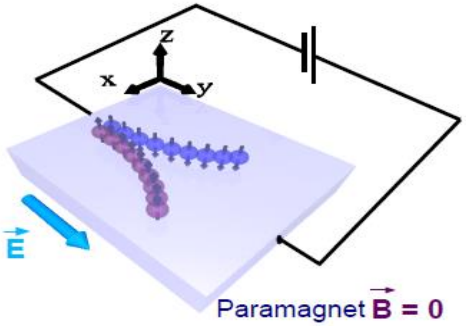
Spin-based information processing ?

Active devices based on **Spin manipulation** ?

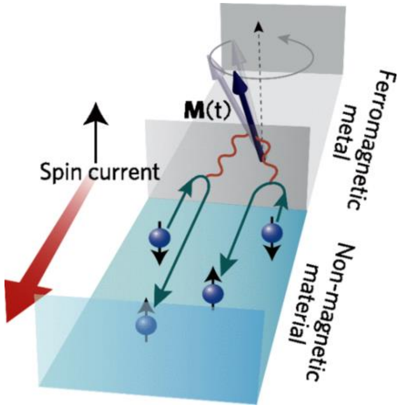
Datta-Das spin transistor



Spin Hall Effect/QSHE



Spin torques/pumping



Need for spin information transport on long distance (room T)
Spin injection and detection (ferromagnets/non magnetic materials)

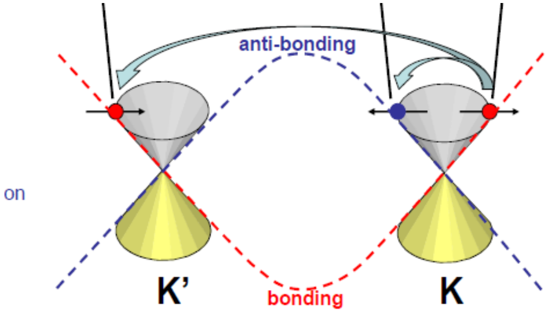
Metals/semiconductors… short spin diffusion length (spin lifetime 0.1-1ns), 1% (or below) of MR signal

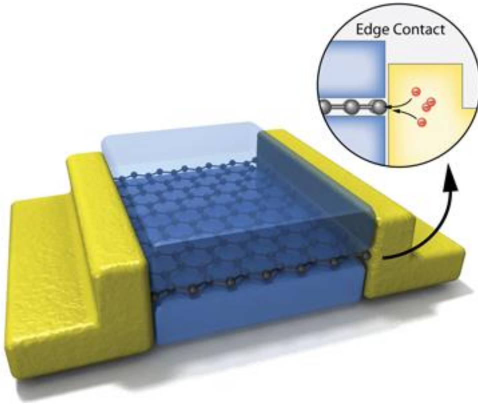
What makes graphene attractive

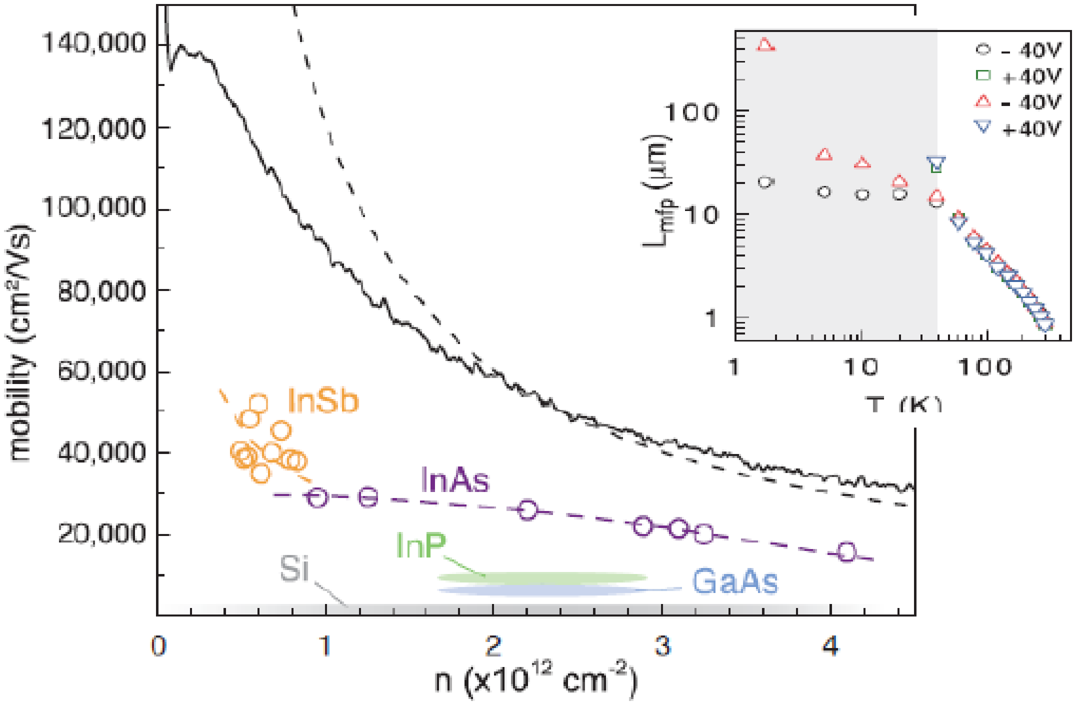
- Ambipolar/tuneable transport
- **Linear energy dispersion &Large mobilities**

(> 100k cm²/V.s at RT, 1M cm²/V.s at 4K)

- **Low spin-orbit interaction**
- Graphene properties can **be tailored by proximity effects**







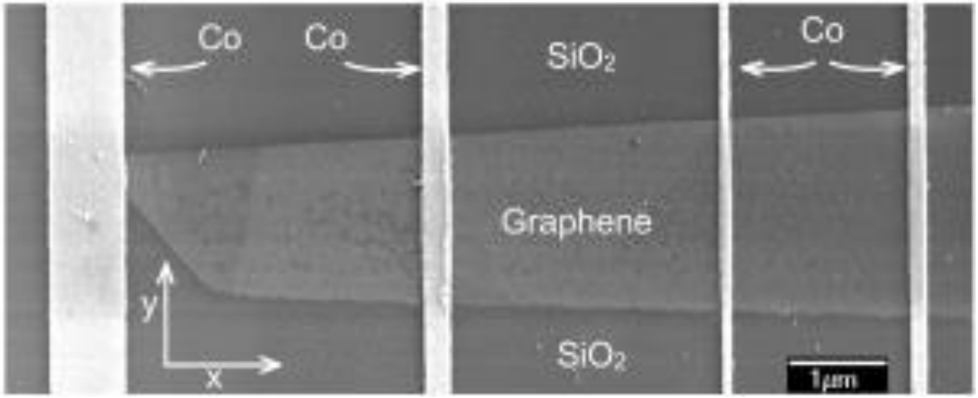
Wang et al., Science (2013)

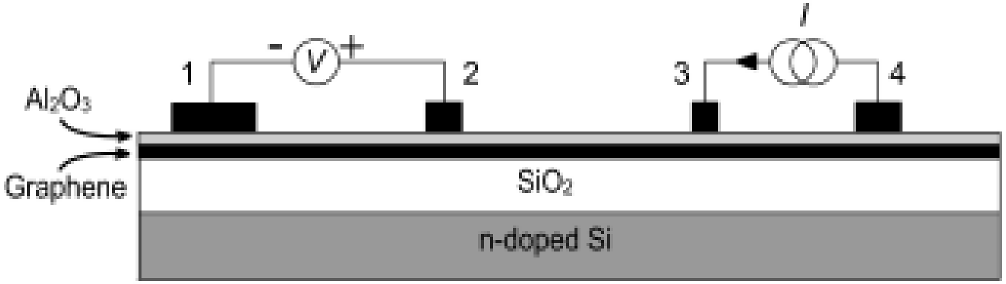
nature

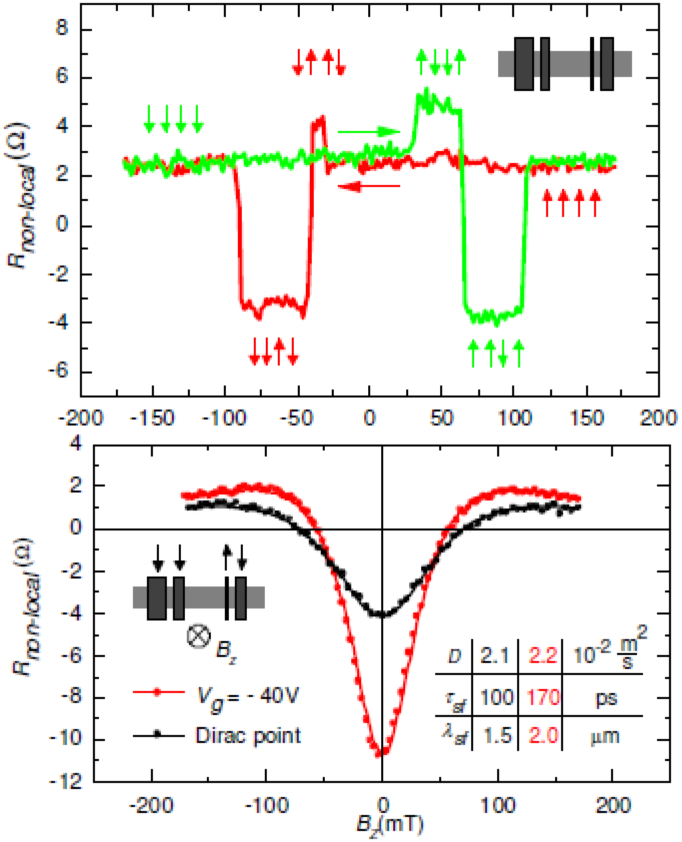
10 years ago !

N. Tombros, … **Bart J. van Wees**

Nature 448, 571-574 (2 August 2007)







"non-local" spin valve geometry
+ Hanle spin precession measurements

Spin diffusion length *2µm (RT)*

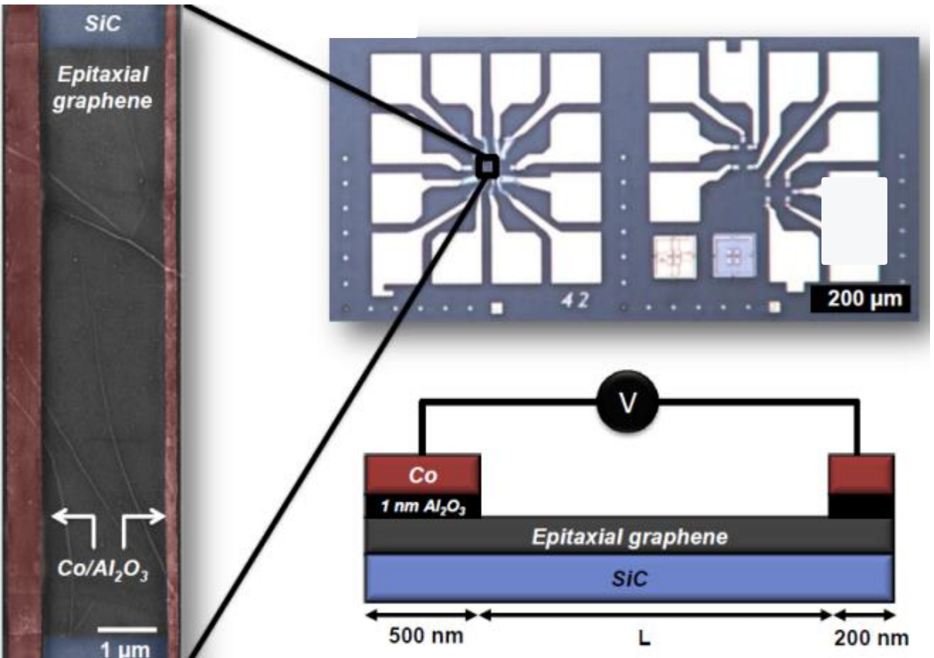
Spin diffusion length in epitaxial graphene

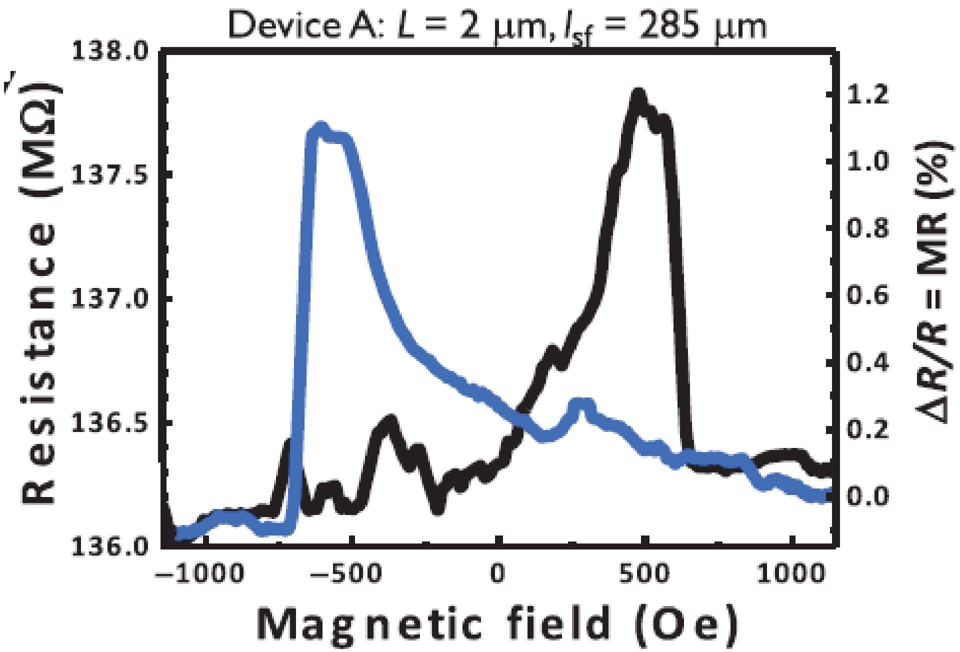
B. Dluback et al, A. Fert

Nature Phys. 8,557 (2012)

2-T magnetoresistance

Spin diffusion length up to ***100 μm(RT)***




Device A: L = 2 μm, l_{sf} = 285 μm

Graphene Flagship

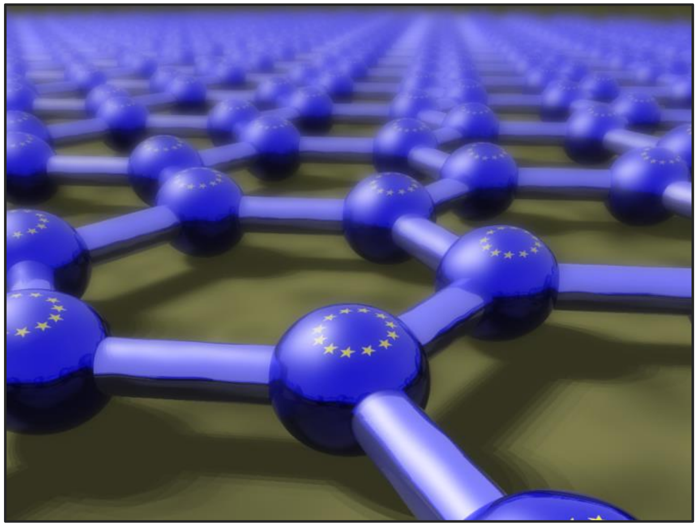
GRAPHENE FLAGSHIP

Europe has chosen Graphene Flagship as one of only two FET projects, with

1,000 million € over 10 years…

Launch in 2013

"to take graphene and related layered materials from academic laboratories to society, revolutionize multiple industries and create economic growth and new jobs in Europe."



- 154 partners with in 17 EU countries with an
- Potential applications include:
  - flexible consumer electronics
  - lighter and more energy efficient airplanes
  - optical devices and artificial retinas
  - functional lightweight components
  - advanced batteries
  - **-spintronics**

GRAPHENE FLAGSHIP

Spintronics consortium/WP

Experimental partners

Univ. of Groningen [*RUG*] : **Bart van Wees**

Univ. of Manchester [*UNIMAN*] : **Irina Grigorieva**

Univ. of Aachen [*RWTH*] : **Christoph Stampfer, Bernd Beschoten**

Univ. of Basel [*UNIBAS*]: **Christian Schönenberger**

CNRS/Thales [CNRS]: **Pierre Seneor and Albert Fert**

Chalmers University Technology [CUT]: **Saroj Dash**

Catalan Inst. Nanoscience & Nanotech [ICN2]: **Sergio Valenzuela**

NanOSC AB : **Johan Åkerman**

Theoretical partners:

Catalan Inst. Nanoscience & Nanotech [ICN2]: **Stephan Roche**

Université Catholique de Louvain [*UCL*]: **Jean Christophe Charlier**

University of Regensburg [*UREG*] : **Jaroslav Fabian**

Commissariat à l´Energie Atomique [*CEA*]: **Mairbek Chshiev, Xavier Waintal**

IMDEA : **Paco Guinea**

“The global objective of the Graphene Spintronics task force is to establish the ***ultimate scientific and technological potential of graphene and graphene related materials for spintronics****, targeting efficient spin injection, transport and detection but also demonstrating spin gating and spin manipulation in graphene spintronic devices and realizing operational devices for information storage and information processing, by engineering device architecture and material transformations”*

GRAPHENE FLAGSHIP

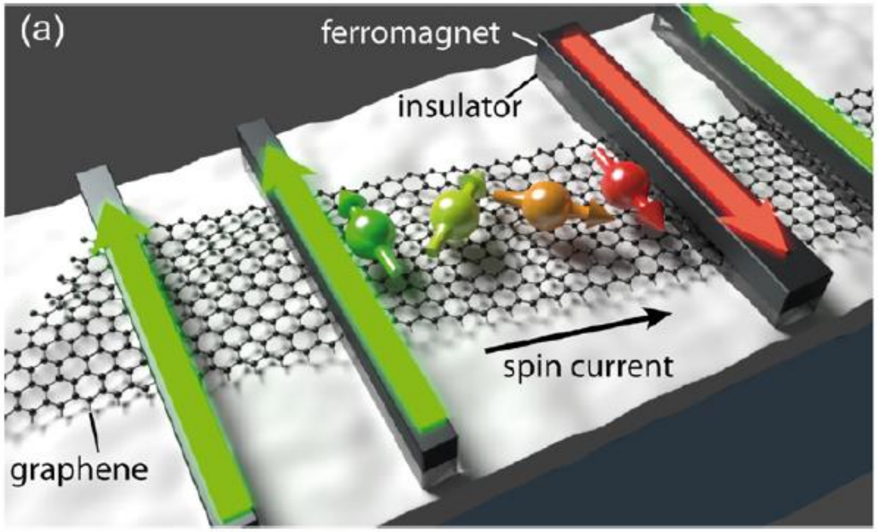

2D Materials

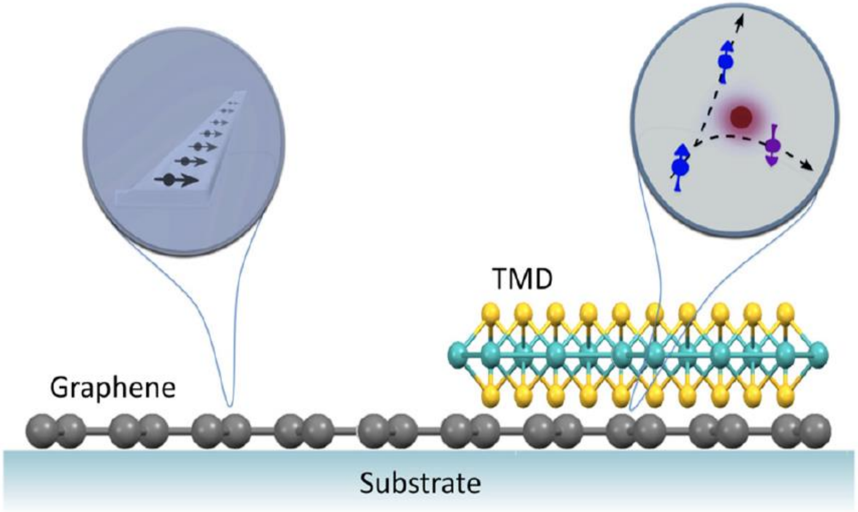
EDITORIAL

Graphene spintronics: the European Flagship perspective

Stephan Roche[1,2], Johan Åkerman[3,4,5], Bernd Beschoten[6], Jean-Christophe Charlier[7], Mairbek Chshiev[8,9], Saroj Prasad Dash[10], Bruno Dlubak[12], Jaroslav Fabian[11], Albert Fert[12], Marcos Guimarães[13,19], Francisco Guinea[14,15], Irina Grigorieva[14], Christian Schönenberger[16], Pierre Seneor[12], Christoph Stampfer[17], Sergio O Valenzuela[1,2], Xavier Waintal[9,18] and Bart van Wees[19]

2D Mater. 2 (2015) 030202

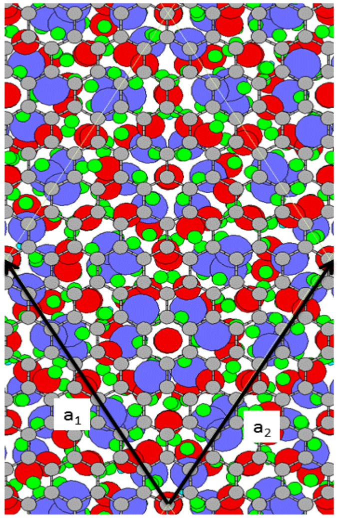


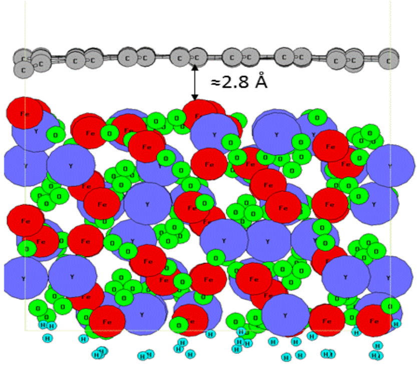


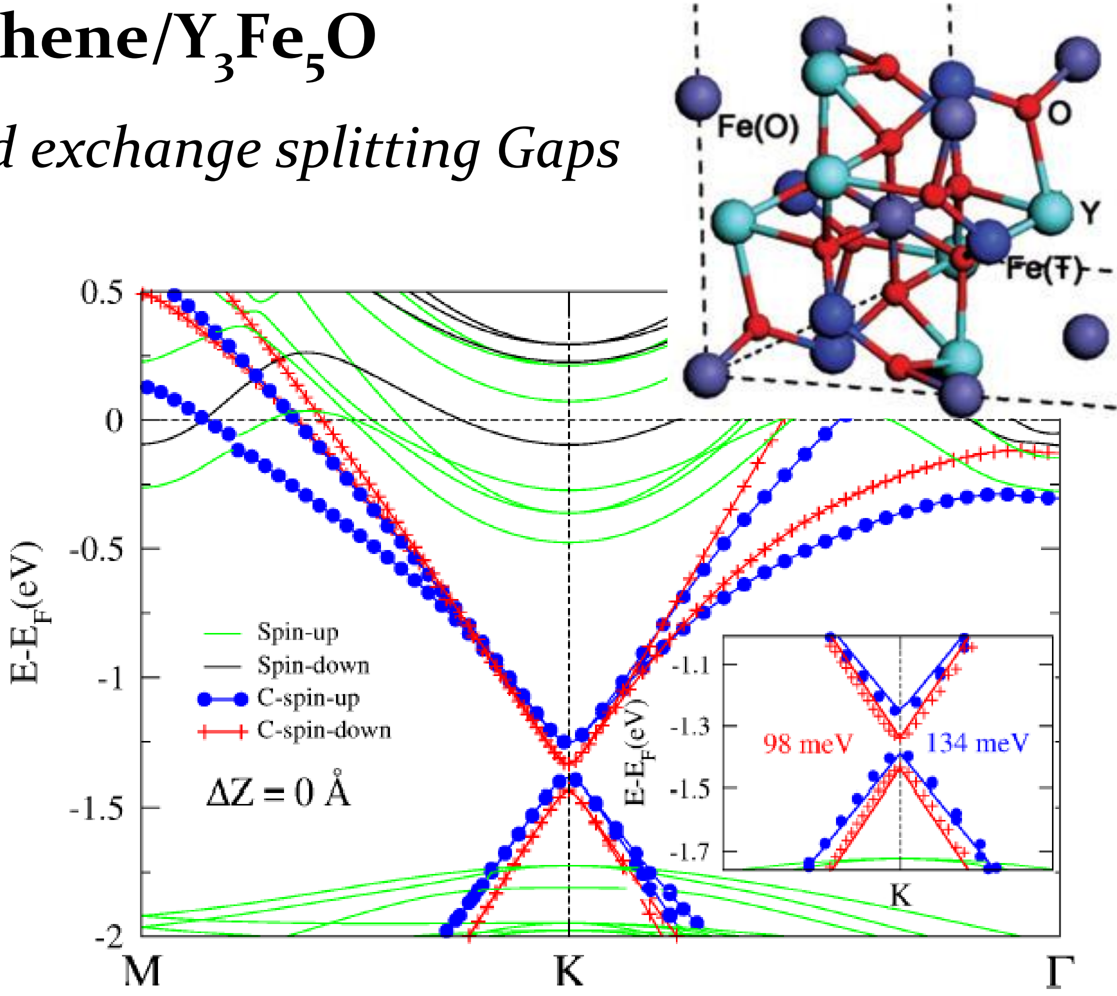
Graphene/Magnetic insulators

Graphene/EuO and Graphene/Y_3Fe_5O

Spin filtering and exchange splitting Gaps







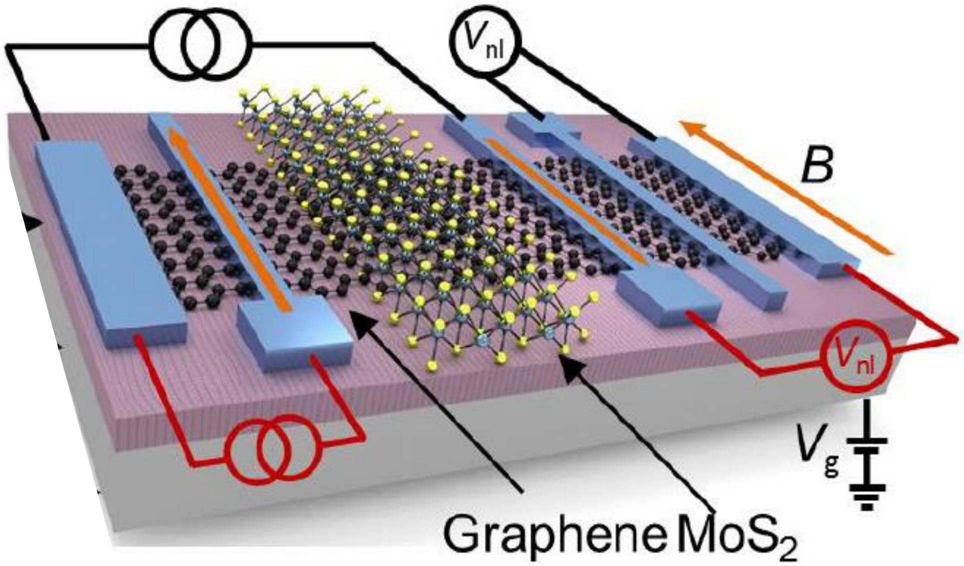
Exchange splitting (G/YIG) = 40 meV

Yang, Hallal, Waintal, Roche, Chshiev, **PRL 110, 046603 (2013)**
Hallal et al. **2D materials 4 , 025074 (2017)**

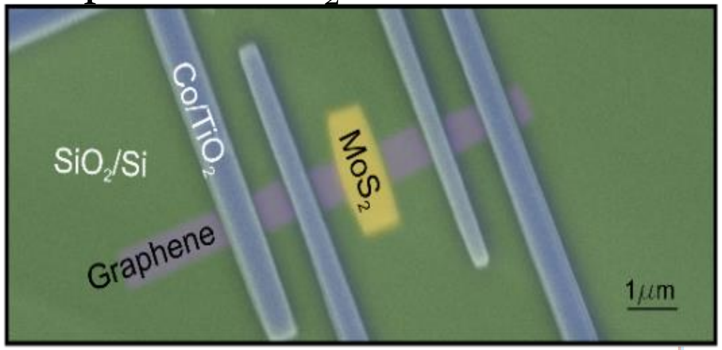
All-Electrical Spin-FET

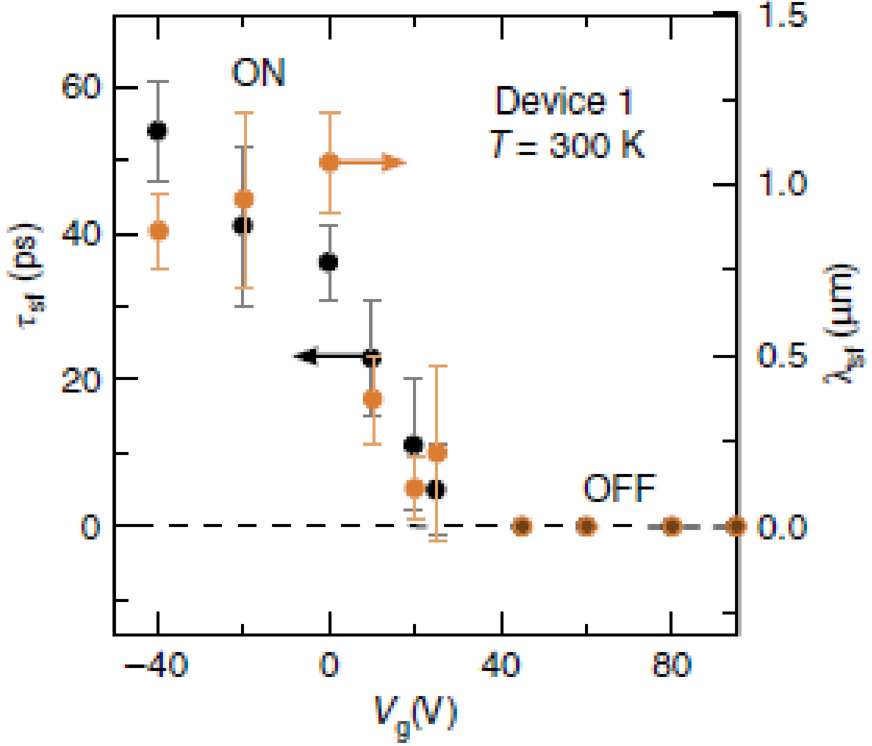
Gate control of spin information (switch ON/OFF)

W. Yan, O. Txoperena, R. Llopis, H. Dery, **L. E. Hueso & F. Casanova**,
Nature Comm. 7, 13372 (2016)



Graphene/MoS_2 heterostructures

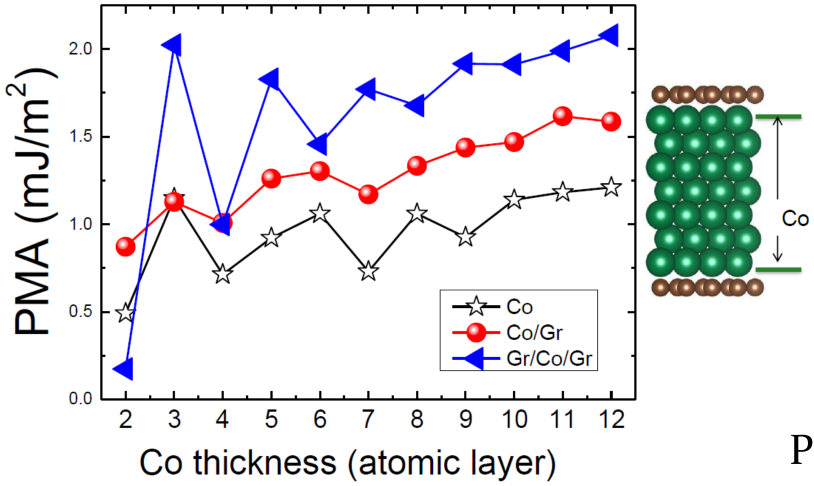


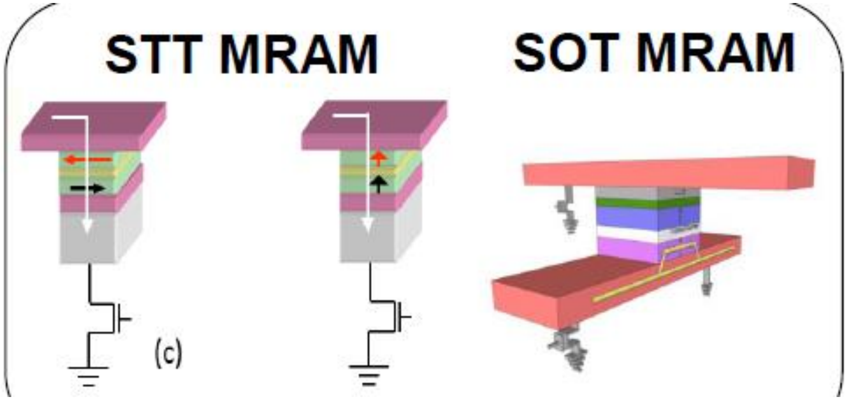


Room Temperature

A. Dankert & S. P. Dash,
Nature Comm. 8, 16093 (2017)

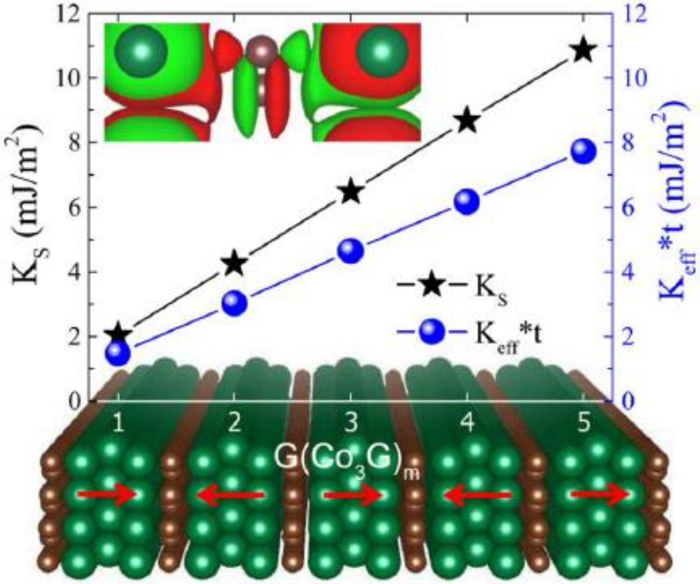
2D Materials for STT-MRAM technologies





Perpendicular Magnetic Anisotropy in FM/Ox and FM/Graphene interfaces :
Strongly enhanced PMA of Co realized by graphene coating

Layer and orbital resolved contributions unveil the PMA mechanisms
Superlattice structures to obtain Giant PMA



$$K_{eff} = \frac{K_s}{t_{Co}} - E_{demag}$$

Yang, Coraux/Chshiev et al,
Nano Letters 16, 145 (2015)

Opportunities “in the valley”

PRL 99, 236809 (2007)

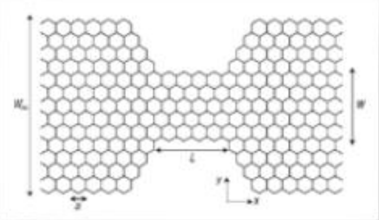
PHYSICAL REVIEW LETTERS

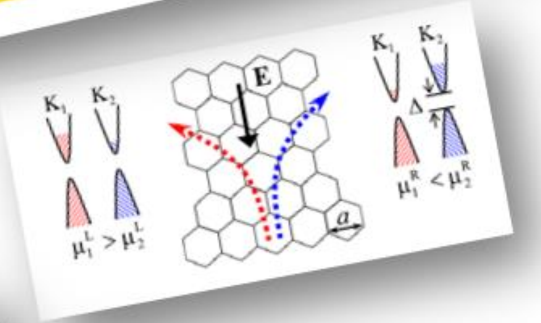
Valley-Contrasting Physics in Graphene: Magnetic Moment and Topological Transport

Di Xiao,* Wang Yao,* and Qian Niu
Department of Physics, The University of Texas, Austin, Texas 78712-0264, USA

(Received 11 September 2007; published 7 December 2007)

We investigate physical properties that can be used to distinguish the valley degree of freedom in systems where inversion symmetry is broken, using graphene systems as examples. We show that the pseudospin associated with the valley index of carriers has an intrinsic magnetic moment, in close analogy with the Bohr magneton for the electron spin. There is also a valley dependent Berry phase effect that can result in a valley contrasting Hall transport, with carriers in different valleys turning into opposite directions transverse to an in-plane electric field. These effects can be used to generate and detect valley polarization by magnetic and electric means, forming the basis for the valley-based electronics applications.

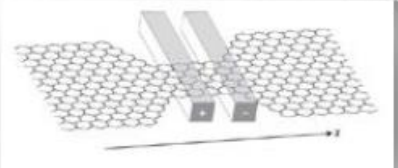


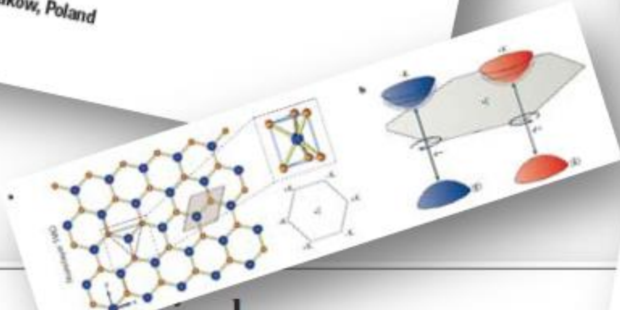


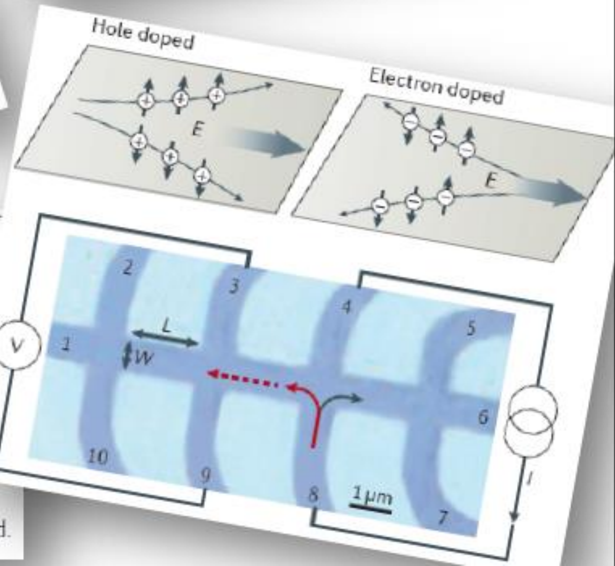
LETTERS

Valley filter and valley valve in graphene

A. RYCERZ[1,2], J. TWORZYDŁO[3] AND C. W. J. BEENAKKER[1]*
[1]Instituut-Lorentz, Universiteit Leiden, PO Box 9506, 2300 RA Leiden, The Netherlands
[2]Marian Smoluchowski Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Kraków, Poland
[3]Institute of Theoretical Physics, Warsaw University, Hoża 69, 00-681 Warsaw, Poland
*e-mail: beenakker@lorentz.leidenuniv.nl



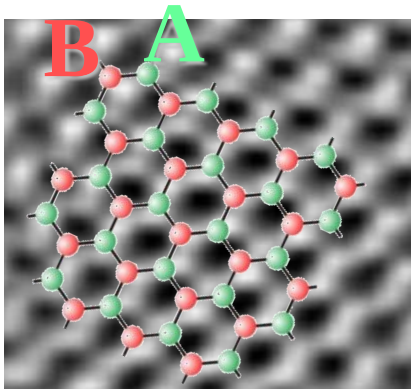




Valleytronics in 2D materials

John R. Schaibley[1], Hongyi Yu[2], Genevieve Clark[3], Pasqual Rivera[1], Jason S. Ross[3], Kyle L. Seyler[1], Wang Yao[2] and Xiaodong Xu[1,3]

NATURE REVIEWS | MATERIALS



« Low » Energy Excitations in clean Graphene

*No intervalley/spin mixing - **(low disorder & SOC)***

8-components Matrix

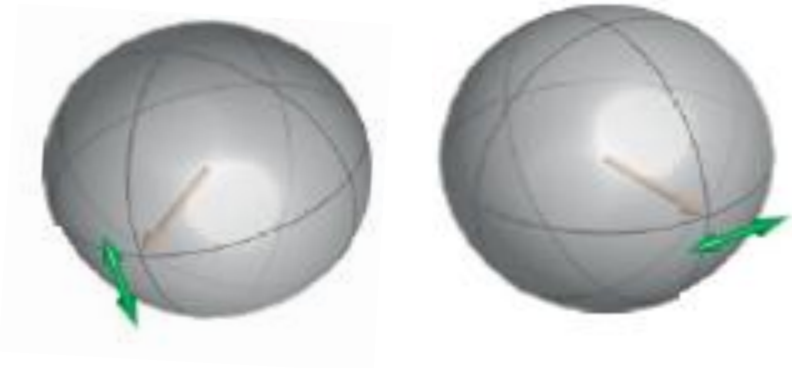
$$\begin{pmatrix} 0 & p_x - ip_y & 0 & 0 & 0 & 0 & 0 & 0 \\ p_x - ip_y & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -p_x + ip_y & 0 & 0 & 0 & \\ 0 & 0 & -p_x + ip_y & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & p_x - ip_y & 0 & 0 \\ 0 & 0 & 0 & 0 & p_x - ip_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -p_x + ip_y \\ 0 & 0 & 0 & 0 & 0 & 0 & -p_x + ip_y & 0 \end{pmatrix} \begin{pmatrix} \Psi^{\Uparrow}_{A,+} \\ \Psi^{\Uparrow}_{B,+} \\ \Psi^{\Uparrow}_{A,-} \\ \Psi^{\Uparrow}_{B,-} \\ \Psi^{\Downarrow}_{A,+} \\ \Psi^{\Downarrow}_{B,+} \\ \Psi^{\Downarrow}_{A,-} \\ \Psi^{\Downarrow}_{B,-} \end{pmatrix}$$

Three internal degrees of freedom

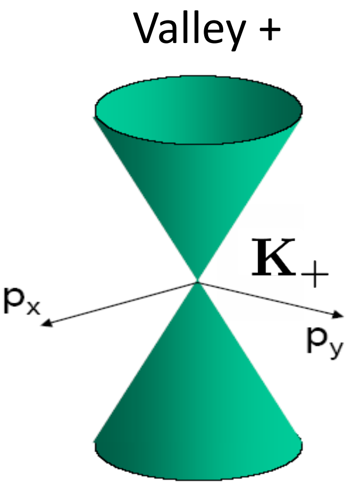
Spin

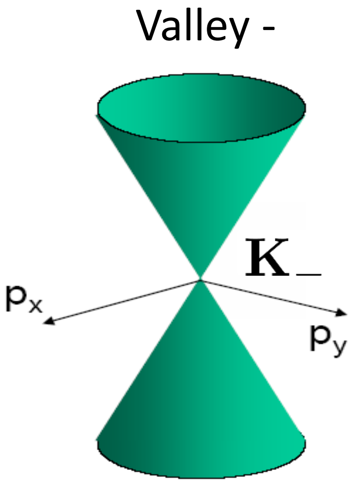
Valley index

Sublattice pseudospin



Massless Dirac Fermions in 2D graphene





$$\vec{Q} = K_+ + \vec{p}/\hbar$$

linearization close to Fermi level

Two valleys -> Dirac cones

$$E(\vec{p}) = v_F|\vec{p}|$$

$$\boxed{\mathcal{H}_{K_+} = v_F \vec{\sigma}.\vec{p} = v_F(p_x\sigma_x + p_y\sigma_y)}$$

Pseudo-spinors are eigenstate of the **helicity operator**

$$\hat{h} = \frac{1}{2}\vec{\sigma}.\frac{\vec{p}}{|\vec{p}|}$$

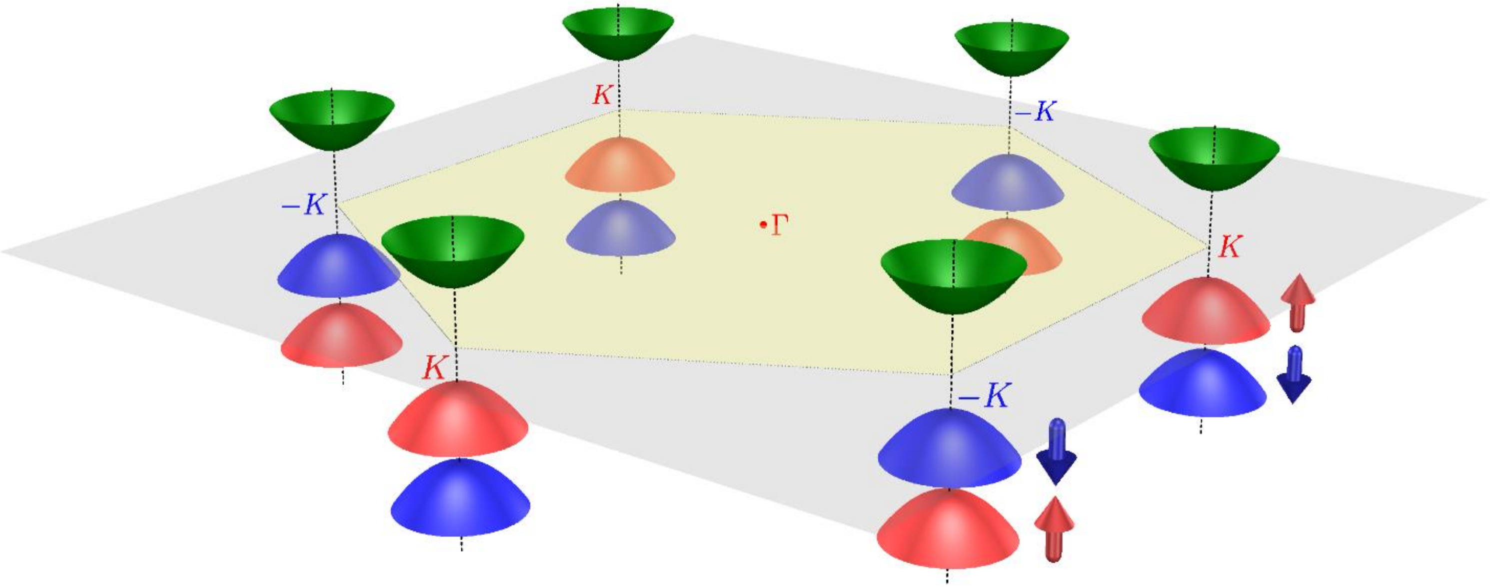
$$\Psi_{\vec{p}} = \frac{1}{\sqrt{2}}\left(\Psi_{\vec{p}}(A)\begin{pmatrix}1\\0\end{pmatrix} + \Psi_{\vec{p}}(B)\begin{pmatrix}0\\1\end{pmatrix}\right) = \frac{1}{\sqrt{2}}\begin{pmatrix} se^{i\theta_p/2} \\ e^{-i\theta_p/2}\end{pmatrix}$$

"**pseudospin**"= sublattice index : **up (on A) / down (on B)**

$$\tan\theta_p = \frac{p_y}{p_x}$$

Transition Metal dichalcogenides (monolayer)

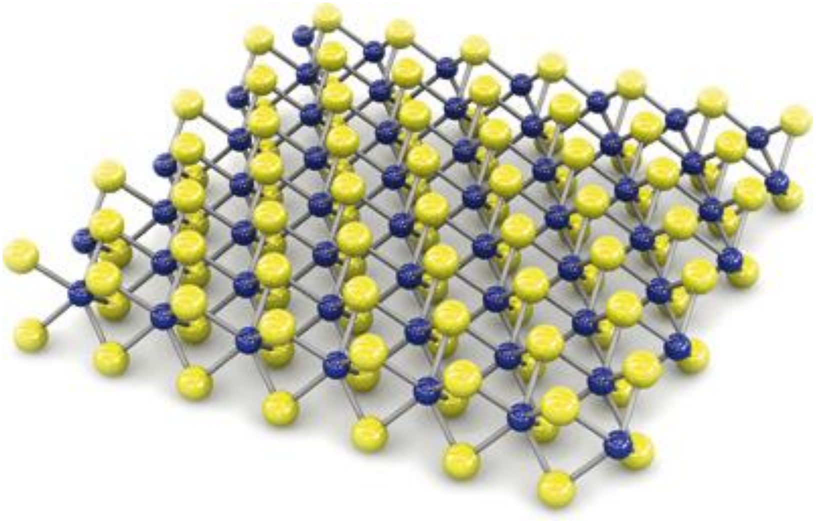
Broken inversion symmetry



D. Xiao et al.

PRL 108, 196802 (2012)

$$\mathcal{H} = at(\tau_z k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + \frac{\Delta}{2}\sigma_z + \lambda_{SO}\tau_z \hat{s}_z$$



Massive Dirac Fermion model

Partially filled d-orbitals (metal)

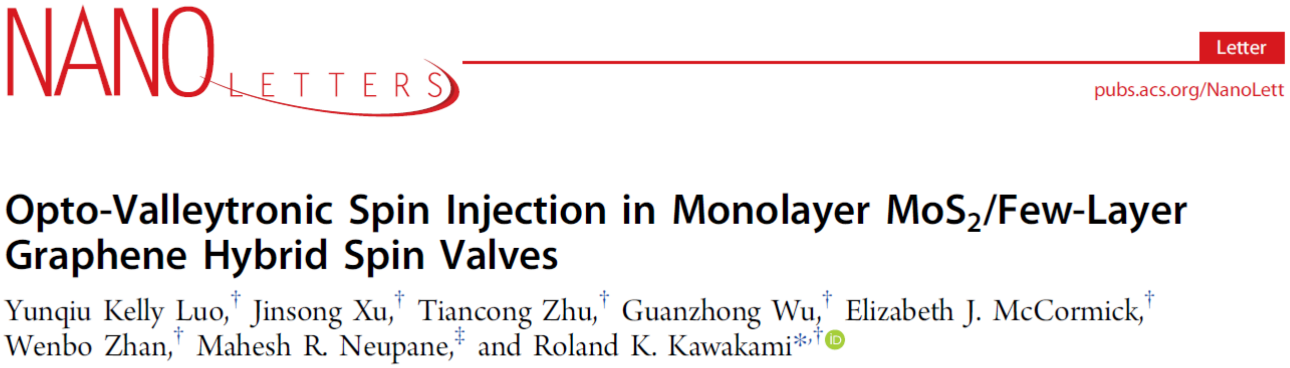
Gap ~ 2 eV

Spin-Split vbands $\sim 150-400$ meV

Valley pseudospin $\pm K(\tau = \pm 1)$

Spin-valley locking

Interlinking optics with Valleytronics & Spintronics



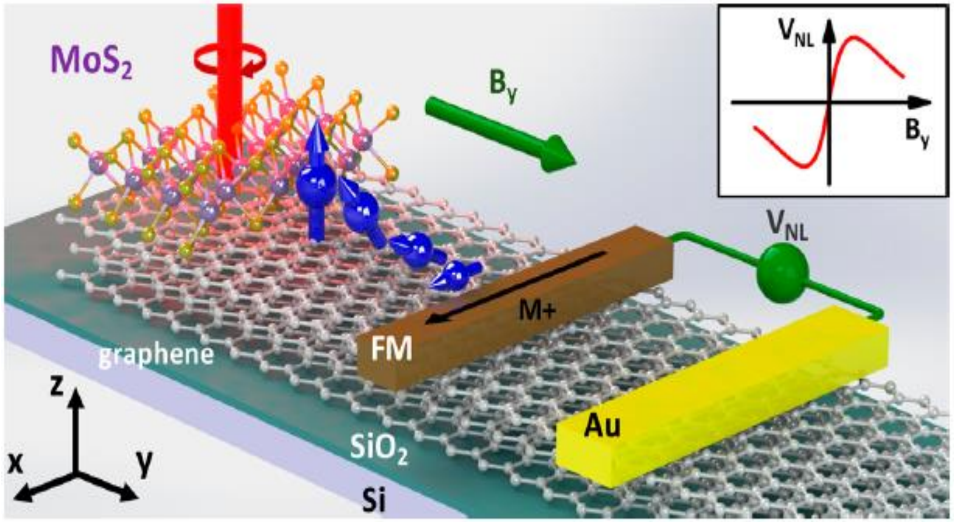
NANO LETTERS

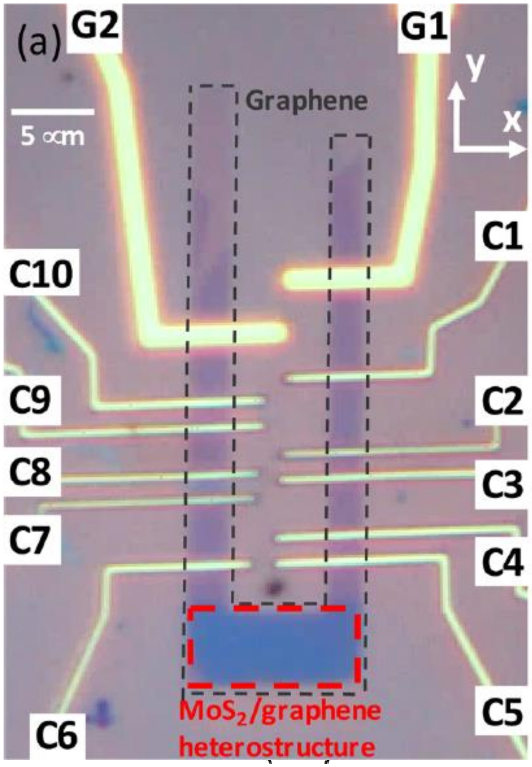
Letter

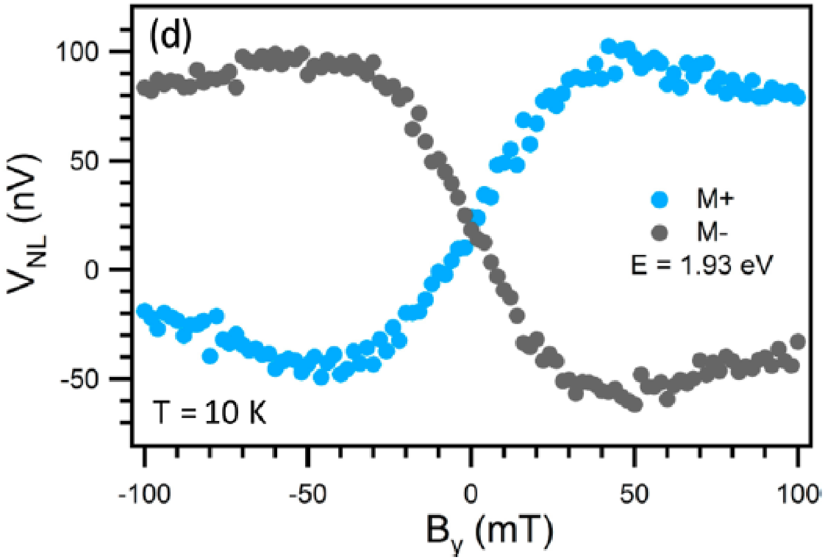
pubs.acs.org/NanoLett

Opto-Valleytronic Spin Injection in Monolayer MoS_2/Few-Layer Graphene Hybrid Spin Valves

Yunqiu Kelly Luo,[†] Jinsong Xu,[†] Tiancong Zhu,[†] Guanzhong Wu,[†] Elizabeth J. McCormick,[†] Wenbo Zhan,[†] Mahesh R. Neupane,[‡] and Roland K. Kawakami*[,†]







Multifunctional 2D spintronic/valleytronic devices

OUTLINE

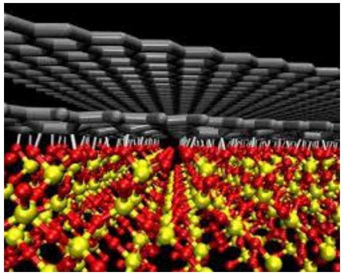
Why Spintronics using 2D Materials ?

Proximity effects in 2D Materials-based heterostructures (spin dynamics & relaxation, SHE, weak antilocalization, QSHE)

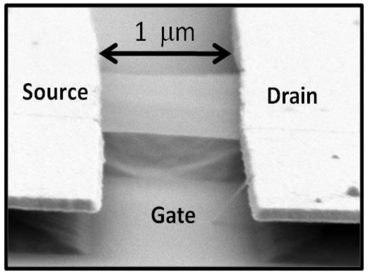
Generating valley polarized quantum transport (valleytronics)

Experimental spin lifetime features

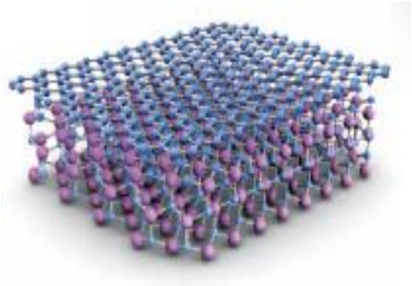
Graphene on SiO2



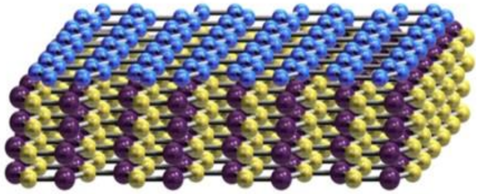
Suspended Graphene



Epitaxial graphene on SiC



Graphene on BN

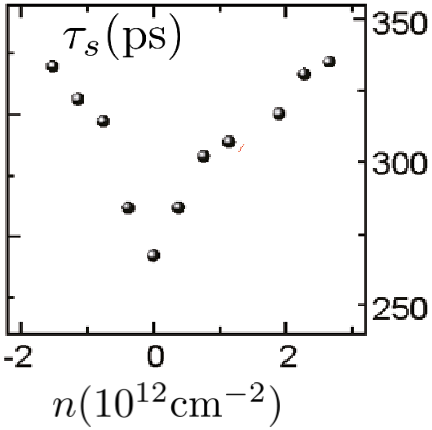


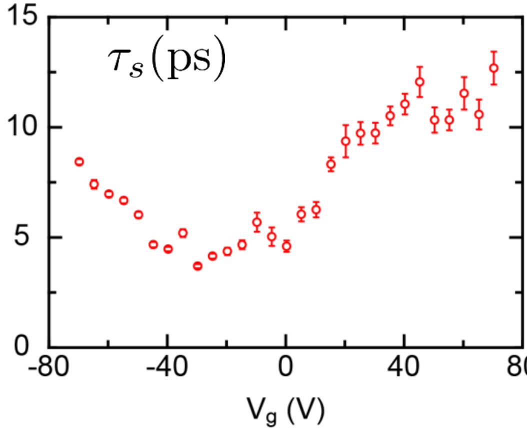
charge mobility $\mu \sim 100 - 100.000 \mathrm{cm}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$

Room temperature

$$\boxed{\tau_s \sim 0.1 - 10 \text{ ns}}$$

Avsar et al, Nano Lett. 11, 2363 (2011)
Drögeler et al. Nano Lett. 14, 6050 (2014)
Guimarães et al Phys Rev Lett 113, 086602 (2014)
Drögeler et al. Nano Lett. 16 (6), 3533 (2016)





Tight-binding Modelling

$$\mathcal{H} = -\gamma_0 \sum_{\langle ij \rangle} c_i^+ c_j + \sum_{\langle i \rangle} V_i c_i^+ c_i + i V_R \sum_{\langle ij \rangle} c_i^+ \vec{z} \cdot (\vec{s} \times \vec{d}_{ij}) c_j$$

Screened Coulomb potential

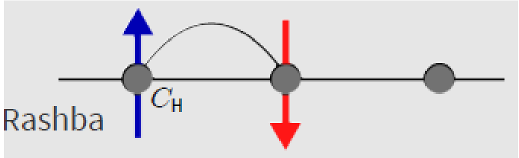
Long range (Gaussian) potential

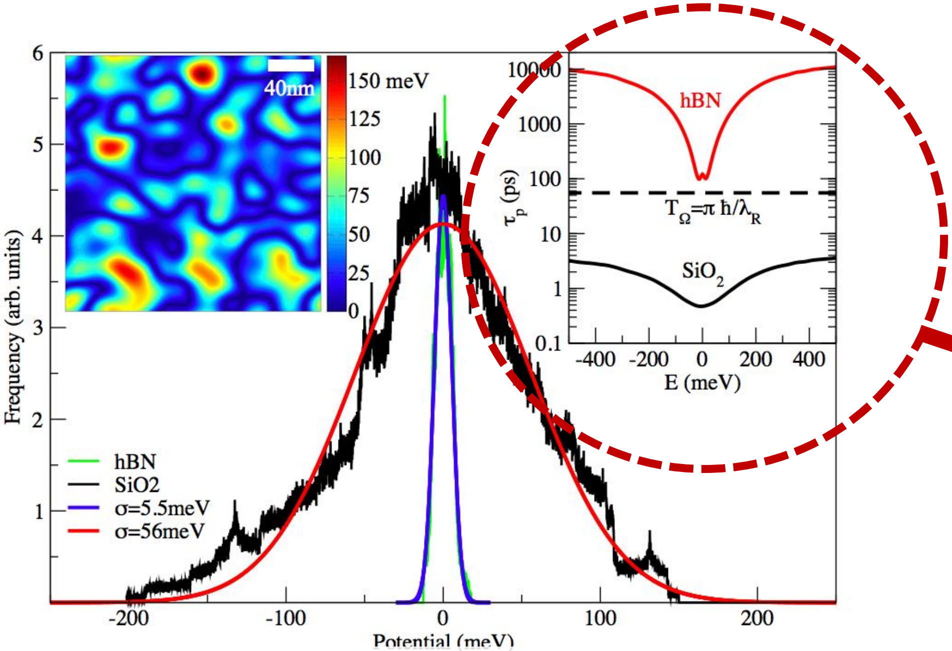
$$V_i = \sum_{\alpha=1}^{N_\alpha} \varepsilon_\alpha \exp(-|\mathbf{r}_\alpha - \mathbf{r}_i|^2/(2\xi^2))$$

Shaffique Adam et al **Phys. Rev. B 84, 235421 (2011)**

Rashba SOC

$$V_R \sim 20\mu\text{eV}$$



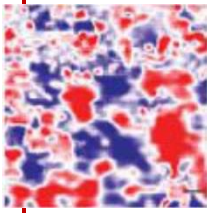


Onsite energy distribution of the π –orbitals with

standard deviation for hBN (5meV) & SiO2 (56meV)

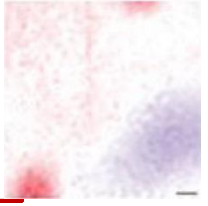
Graphene on SiO2

$$\tau_p^{\mathrm{SiO_2}}/T_\Omega \ll 1$$



Graphene on hBN

$$\tau_p^{\mathrm{hBN}}/T_\Omega \geq 1$$



Spin dynamics of propagating wavepacket

$$|\Psi_\perp(0)\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} |\varphi_{RP}\rangle$$

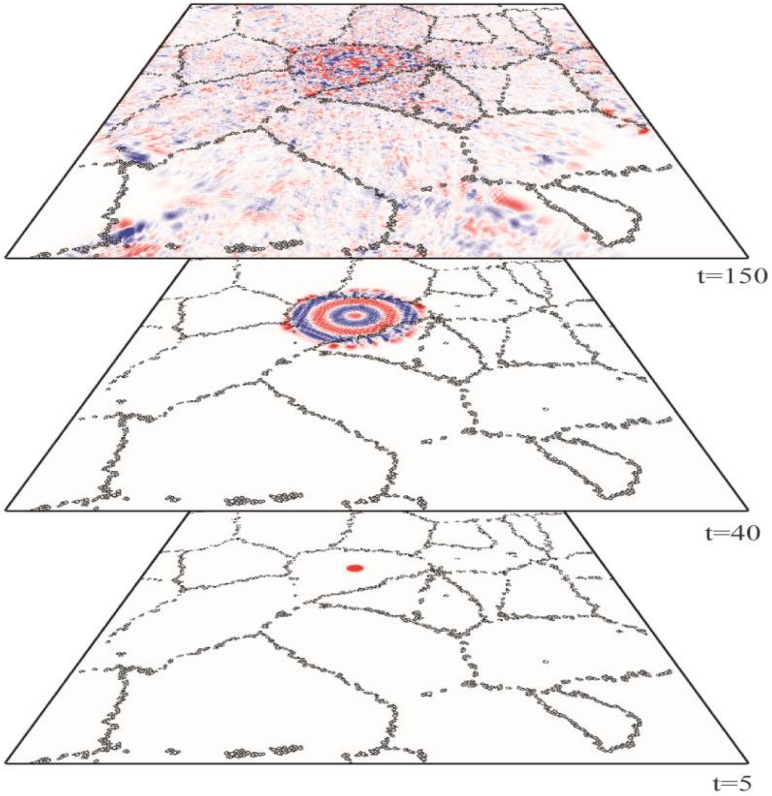
$$|\Psi(t)\rangle = e^{-i\hat{\mathcal{H}}t/\hbar}|\Psi(0)\rangle$$

$$s_i(t) = |\Psi_i^\uparrow(t)|^2 - |\Psi_i^\downarrow(t)|^2$$

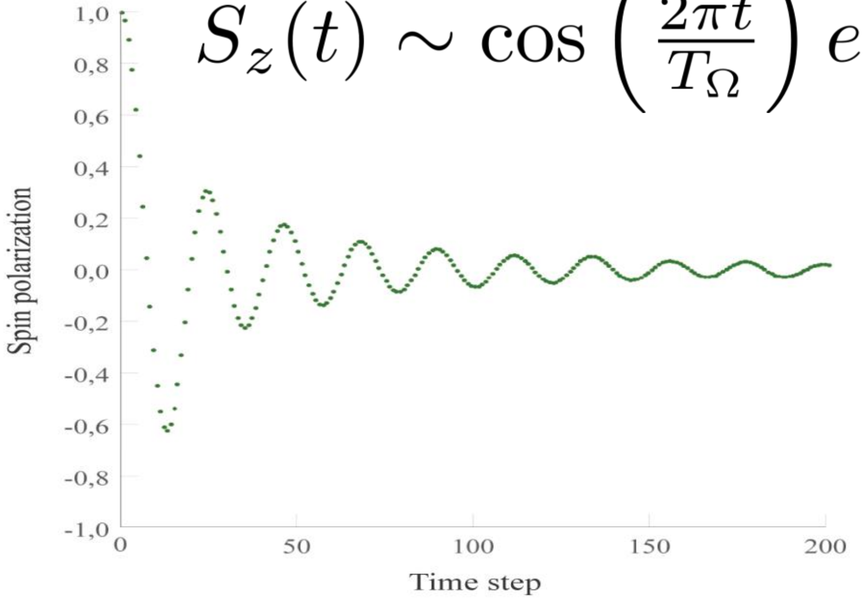
(time-dependent)

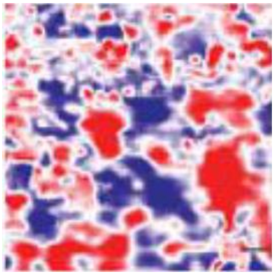
Local spin density in real space

$$\frac{\langle\Psi(t)|\sigma_z\delta(E-\hat{\mathcal{H}})+\delta(E-\hat{\mathcal{H}})\sigma_z|\Psi(t)\rangle}{2\langle\Psi(t)|\delta(E-\hat{\mathcal{H}})|\Psi(t)\rangle}$$



$$S_z(t) \sim \cos\left(\frac{2\pi t}{T_\Omega}\right) e^{-t/\tau_s}$$

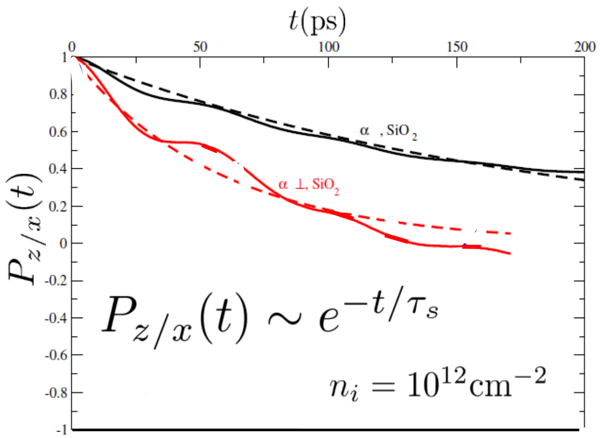




Graphene on SiO2

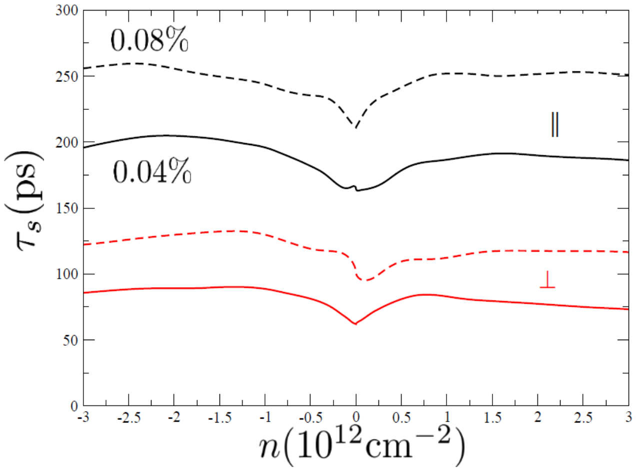
electron-hole puddles drive the relaxation

$$\tau_p^{\mathrm{SiO_2}}/T_\Omega \ll 1$$



$$P_{z/x}(t) \sim e^{-t/\tau_s}$$

$$n_i = 10^{12}\mathrm{cm}^{-2}$$

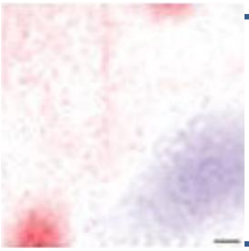


$$\tau_s \sim \frac{1}{n_i}$$

$$\tau_s^{\perp}/\tau_s^{\parallel} \to 0.5$$

Dyakonov-Perel

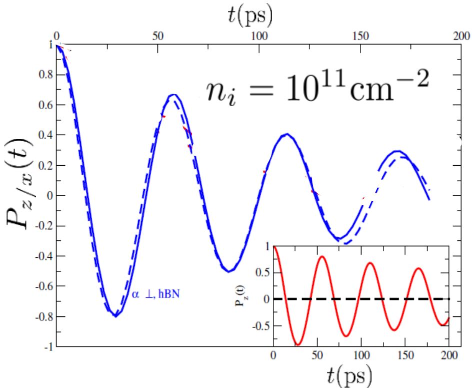
relaxation mechanism



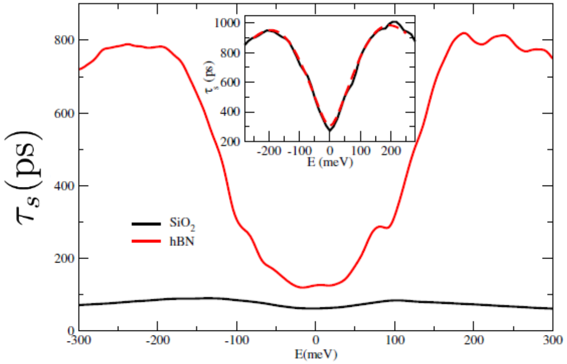
Graphene on hBN

electron-hole puddles drive the relaxation

$$\tau_p^{\mathrm{hBN}}/T_\Omega \geq 1$$



$$n_i = 10^{11}\mathrm{cm}^{-2}$$



$$\tau_s(E) \approx 4T_\Omega \approx 4\frac{\pi\hbar}{\lambda_R}$$

$$\boxed{\tau_s \simeq 1-10\ \mathrm{ns}}$$

$$(\text{for } \lambda_R \to 5\mu\mathrm{eV})$$

Dephasing

relaxation mechanism

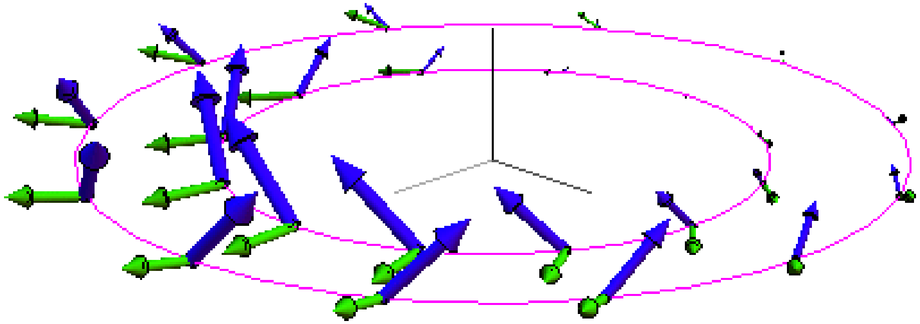
nature
physics

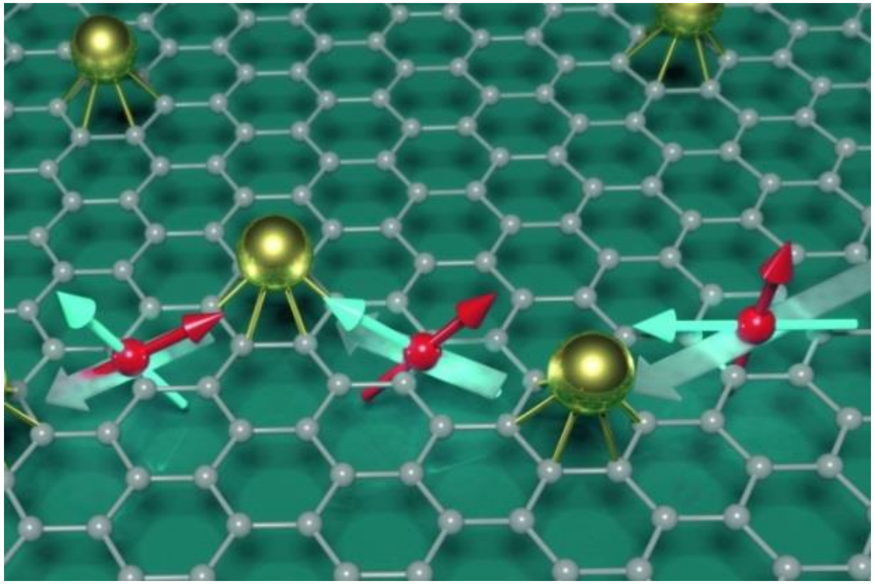
ARTICLES

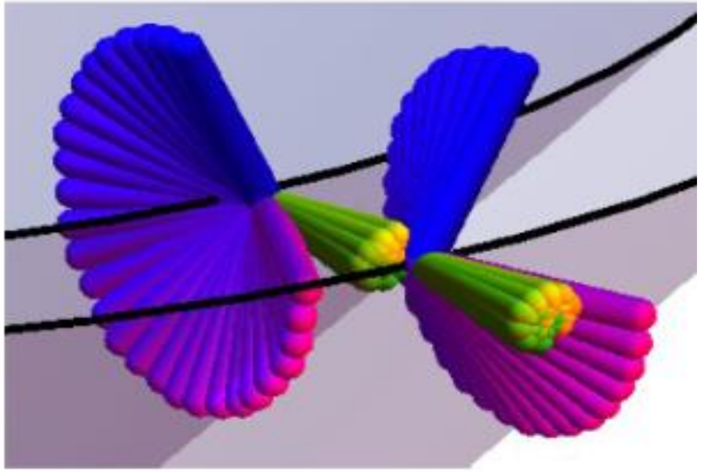
PUBLISHED ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NPHYS3083

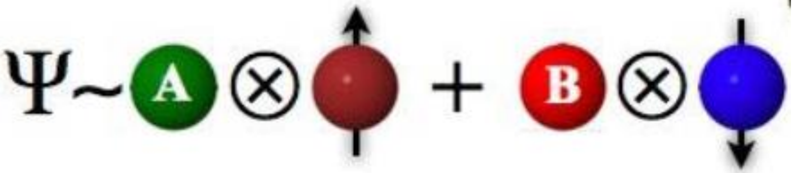
Pseudospin-driven spin relaxation mechanism in graphene

Dinh Van Tuan[1,2], Frank Ortmann[1,3,4], David Soriano[1], Sergio O. Valenzuela[1,5] and Stephan Roche[1,5]*

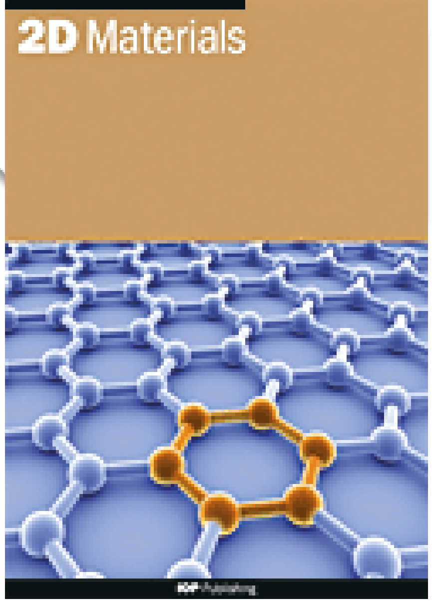


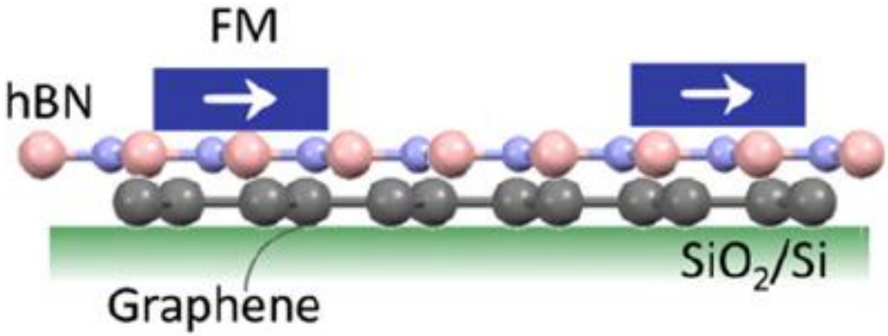


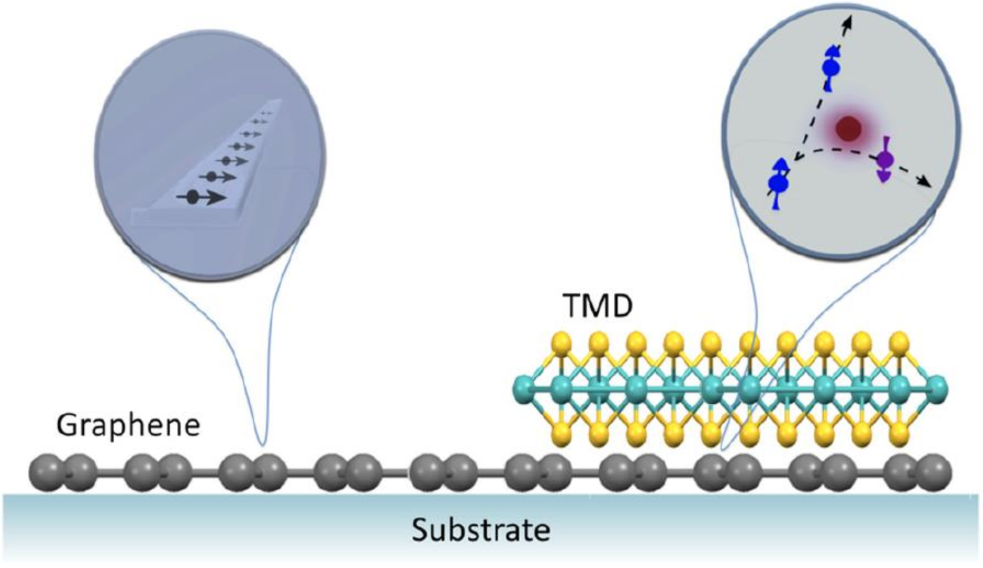




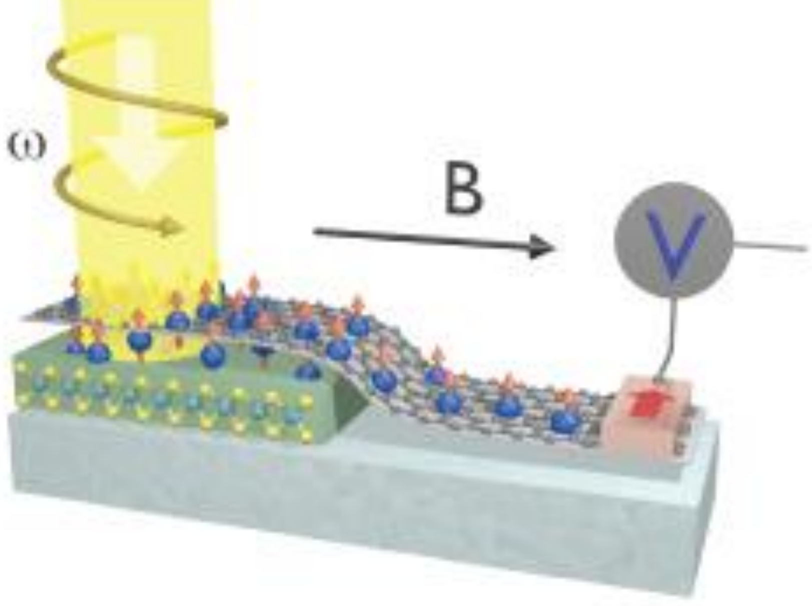
Hybrid devices of graphene and other 2D materials





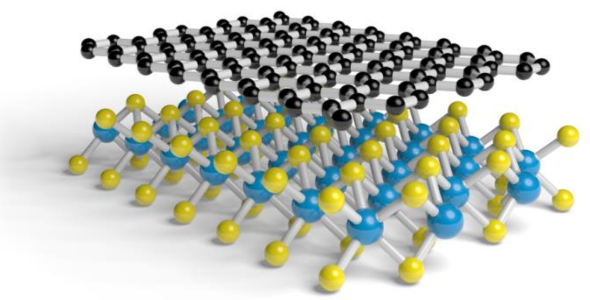


2D Mater. 2 (2015) 030202



Martin Gmitra and Jaroslav Fabian
Phys. Rev. B **92**, 155403 (2015)

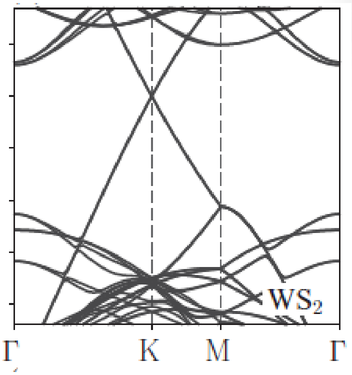
Realistic Model of Graphene/TMDC
with interface disorder



DFT-TB model from

M. Gmitra , D. Kochan, P. Högl, & J.Fabian

PRB 93, 155104 (2016)

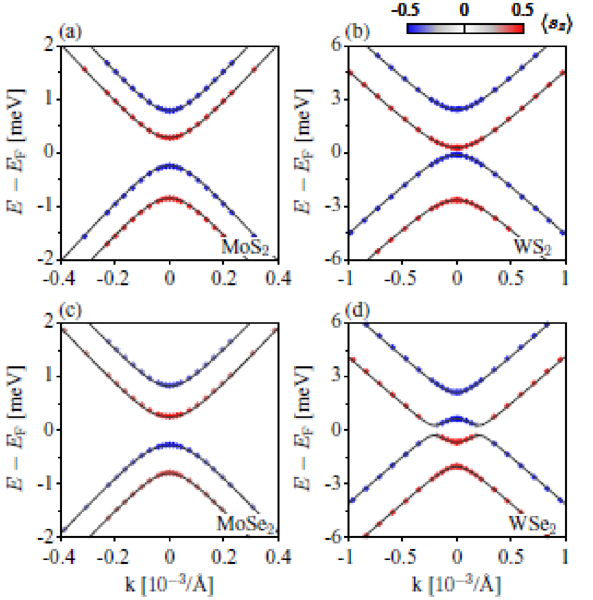


$$H_0 = -t \sum_{\langle i,j \rangle} \left(a_i^\dagger b_j + b_i^\dagger a_i \right) + \frac{\Delta}{2} \sum_i (a_i^\dagger a_i - b_i^\dagger b_i)$$

$$H_{\mathrm{so}} = \frac{2i}{3} \sum_{\langle i,j \rangle,\sigma} (\hat{\boldsymbol{s}} \times \boldsymbol{d}_{i,j})_{z,\sigma,\bar{\sigma}} \; \lambda_{\mathrm{R}} \, a_{i,\sigma}^\dagger \, b_{j,\bar{\sigma}} + h.c$$

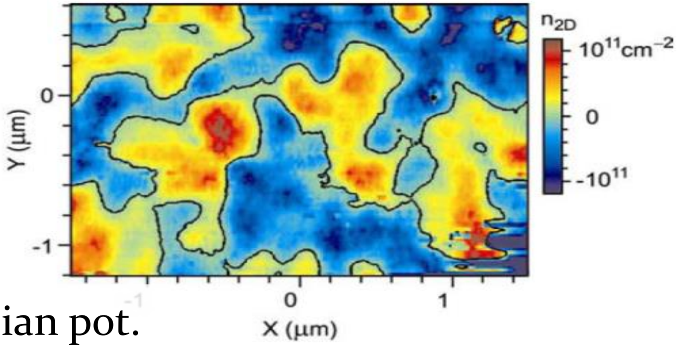
$$+ \frac{2i}{3} \sum_{\langle\langle i,j \rangle\rangle,\sigma} (\hat{\boldsymbol{s}} \times \boldsymbol{D}_{i,j})_{z,\sigma,\bar{\sigma}} \left(\lambda_{\mathrm{PIA}}^{(A)} \, a_{i,\sigma}^\dagger a_{j,\bar{\sigma}} + \lambda_{\mathrm{PIA}}^{(B)} \, b_{i,\sigma}^\dagger b_{j,\bar{\sigma}} \right)$$

$$+ \frac{i}{3\sqrt{3}} \sum_{\langle\langle i,j \rangle\rangle,\sigma} \nu_{i,j} (\hat{s}_z)_{\sigma,\sigma} \, (\lambda_I^{(A)} a_{i,\sigma}^\dagger a_{j,\sigma} - \lambda_I^{(B)} b_{i,\sigma}^\dagger b_{j,\sigma}),$$



Random distribution of n_p electron-hole puddles

S. Adam et al. PRB 84, 235421 (2011)

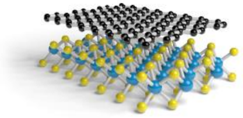


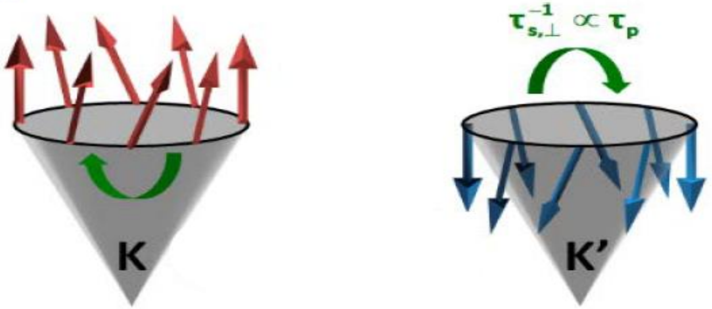
$$U_n(\boldsymbol{r}) = u_n \exp\left(-\frac{(\boldsymbol{r} - \boldsymbol{R}_n)^2}{2\xi_{\mathrm{p}}^2} \right)$$

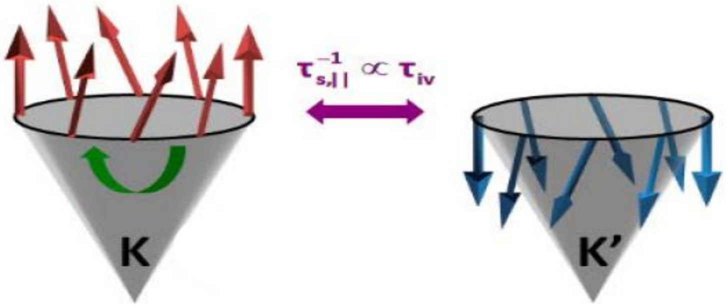
$\xi_{\mathrm{p}} = \sqrt{3}a$ Puddle range

$u_n \in [-U_{\mathrm{p}}, U_{\mathrm{p}}]$ $\boldsymbol{R}_n$ is the position of the center of the Gaussian pot.

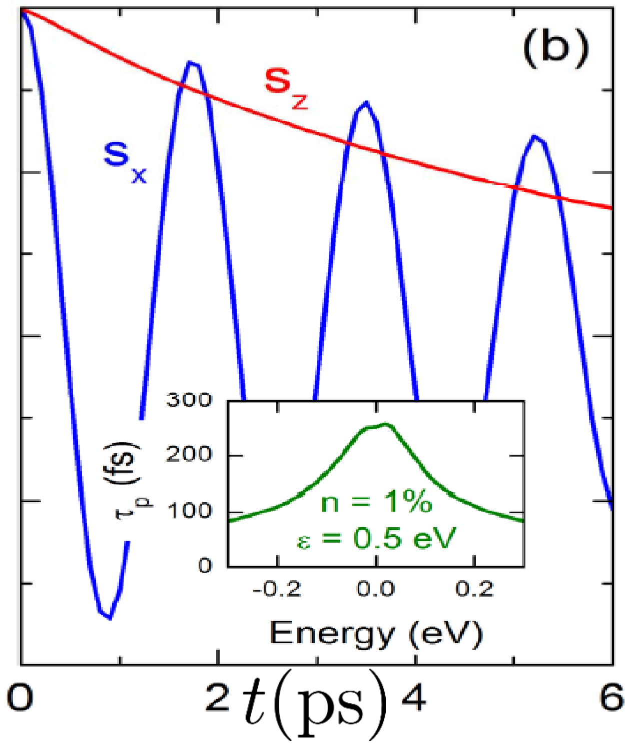
Spin dynamics (Graphene/TMDC+ el-h puddles)



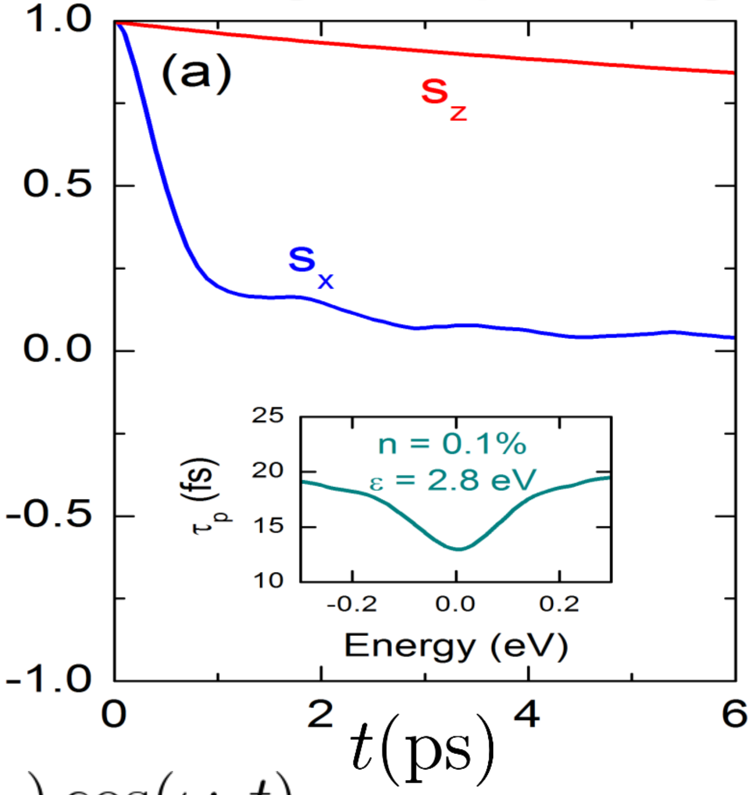




Intravalley scattering



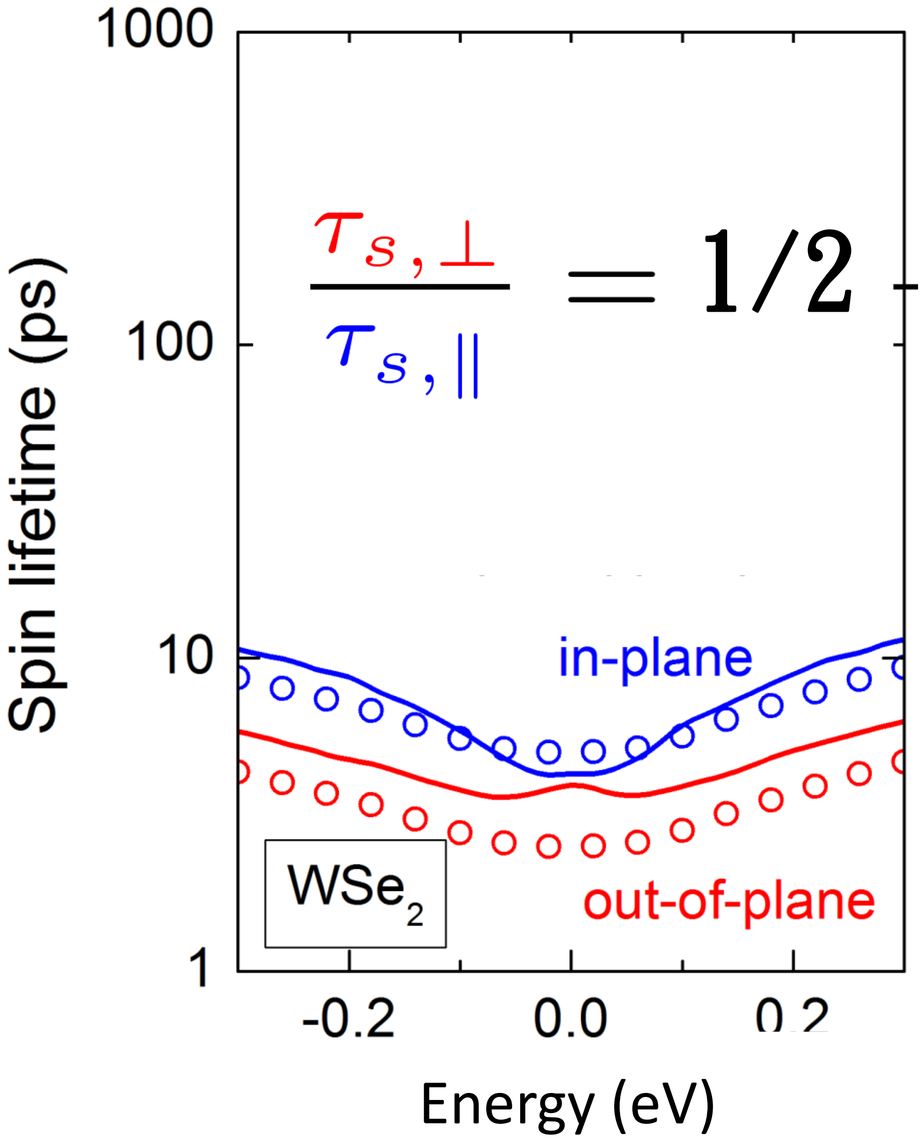
Strong valley mixing



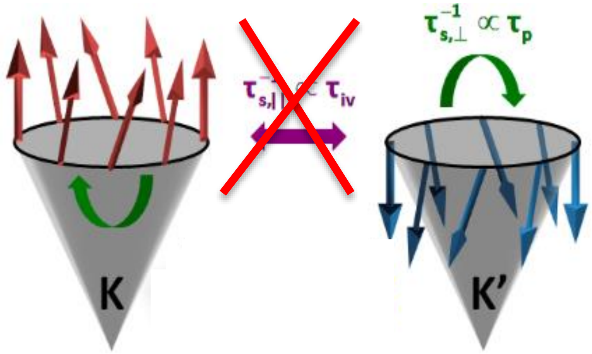
$$S_\alpha \simeq \exp(-t/\tau_{s,\alpha})\cos(\omega_z t)$$

High-quality Graphene/TMDC

Absence of valley mixing (Dyakonov-Perel)



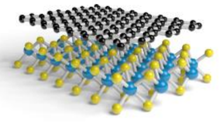
$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 1/2$$



Weak anisotropy as in conventional ***Rashba disordered systems***

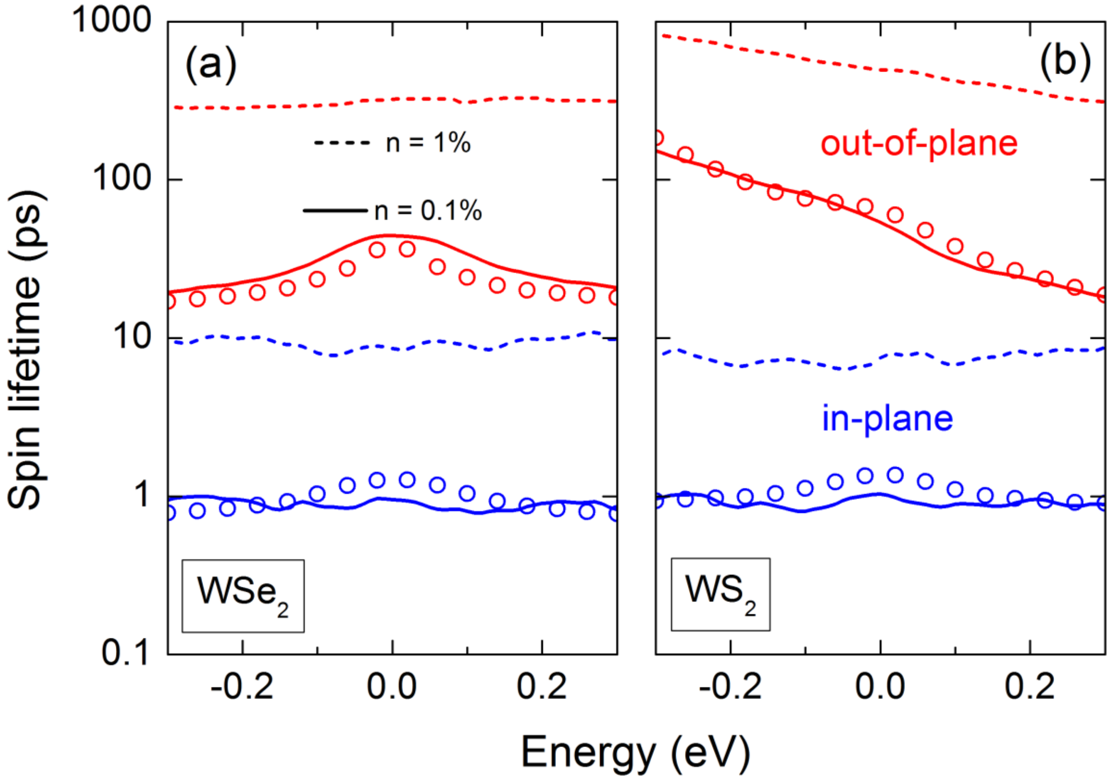
Dyakonov-Perel regime

(single valley approximation)



Giant spin lifetimes anisotropy

in low quality Graphene/TMDC*(strong valley mixing)*



$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 10 - 100$$

Lifetime values

$$\tau_{s,\perp} \in [10, 1000]\mathrm{ps}$$

$$\tau_{s,\parallel} \in [1, 10]\mathrm{ps}$$

Dyakonov-Perel mechanism

$$\tau_{s,\perp} \& \ \tau_{s,\parallel} \sim 1/n_p$$

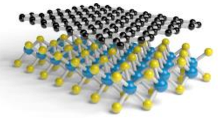
Symbols:
Effective spin-orbit fields arising from the SOC terms + equation of motion of density matrix

$$H = H_0 + \tfrac{1}{2}\hbar\vec{\omega}(t)\cdot\vec{s} \qquad \overline{\omega_\alpha(t)\omega_\beta(t')} = \delta_{\alpha\beta}\overline{\omega_\alpha^2}\mathrm{e}^{-|t-t'|/\tau_{c,\alpha}},$$

$$\frac{\mathrm{d}\overline{\rho_I(t)}}{\mathrm{d}t} = \left(\frac{1}{i\hbar}\right)^2 \int_0^{t\gg\tau_c} \overline{[V_I(t),[V_I(t'),\overline{\rho_I(t)}]]}\,\mathrm{d}t',$$

$$V_I(t) = \tfrac{1}{2}\hbar\vec{\omega}(t)\cdot\vec{s}_I(t) \text{ and } \vec{s}_I(t) = \mathrm{e}^{iH_0t/\hbar}\vec{s}\mathrm{e}^{-iH_0t/\hbar}$$

Theoretical prediction confirmed !!!

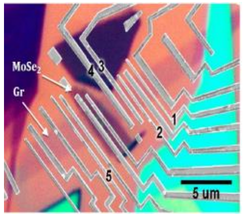


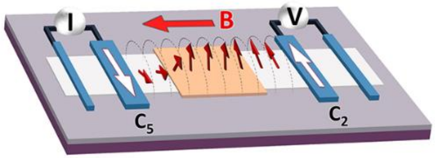
AW. Cummings, J.H. García, J. Fabian, S. Roche,

Phys. Rev. Lett 119, 206601 (2017)

NANO LETTERS

Cite This: *Nano Lett.* XXXX, XXX, XXX−XXX

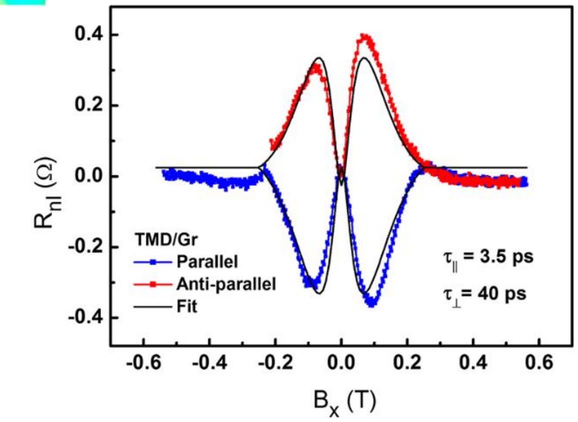




Large Proximity-Induced Spin Lifetime Anisotropy in Transition-Metal Dichalcogenide/Graphene Heterostructures

Talieh S. Ghiasi,* Josep Ingla-Aynés, Alexey A. Kaverzin, and Bart J. van Wees

Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, Groningen, 9747 AG, The Netherlands



nature physics

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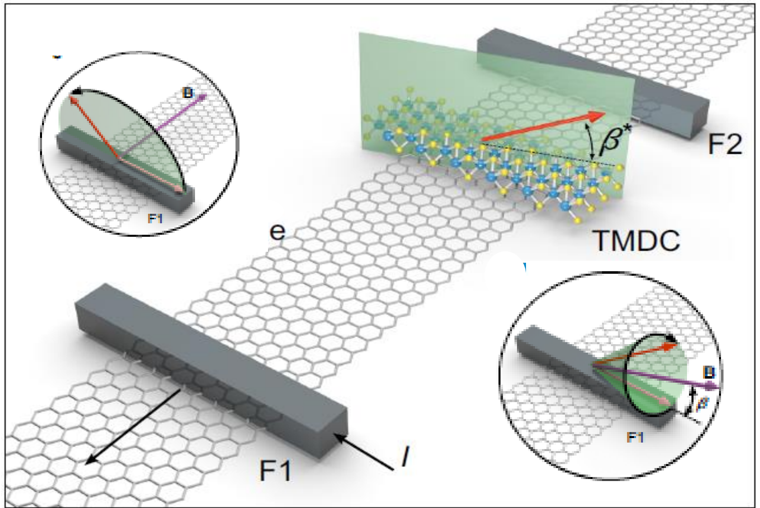
https://doi.org/10.1038/s41567-017-0019-2

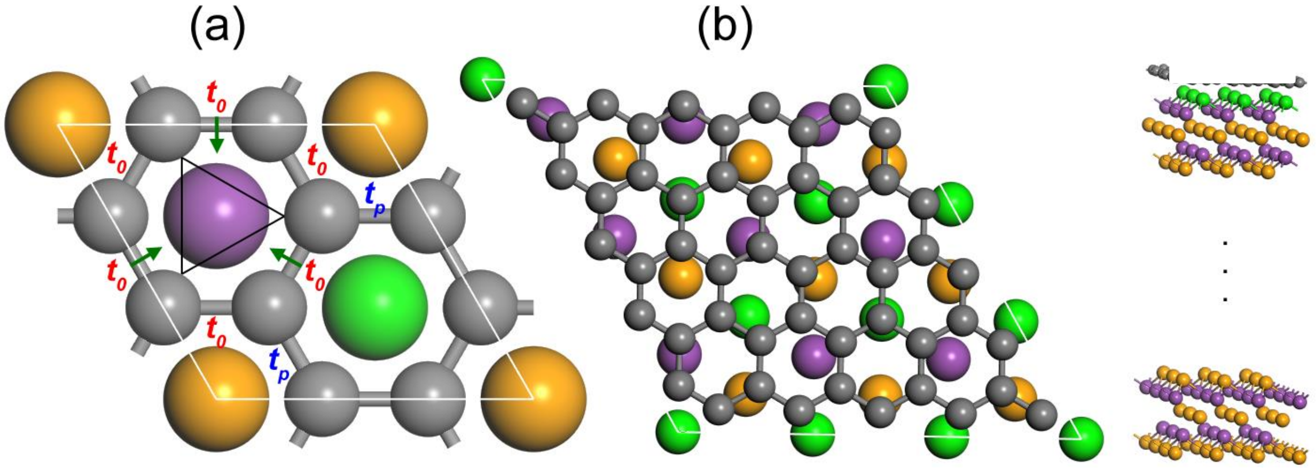
Strongly anisotropic spin relaxation in graphene–transition metal dichalcogenide heterostructures at room temperature

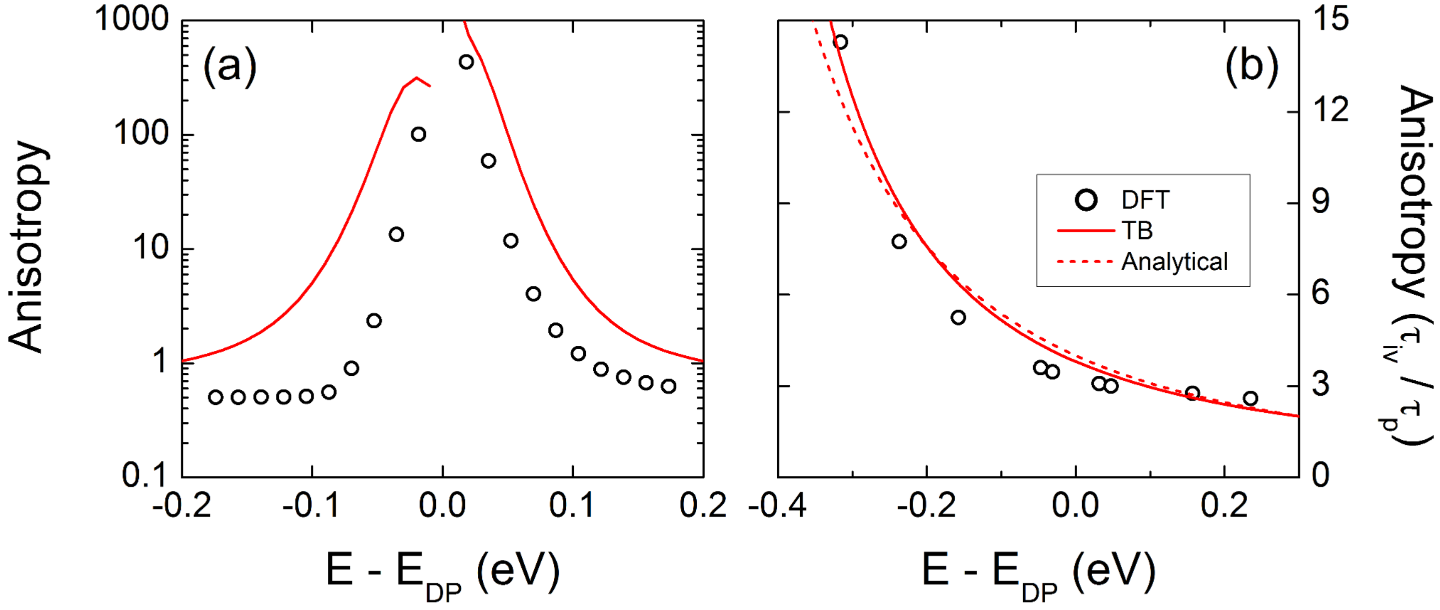
L. Antonio Benítez[1,2]*, Juan F. Sierra[1], Williams Savero Torres[1], Aloïs Arrighi[1,2], Frédéric Bonell[1], Marius V. Costache[1] and Sergio O. Valenzuela[1,3]*



GRAPHENE FLAGSHIP

Tunable spin lifetimes in Graphene/Bi2Se3



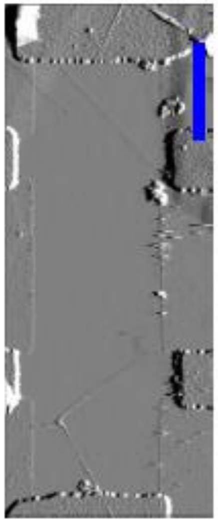


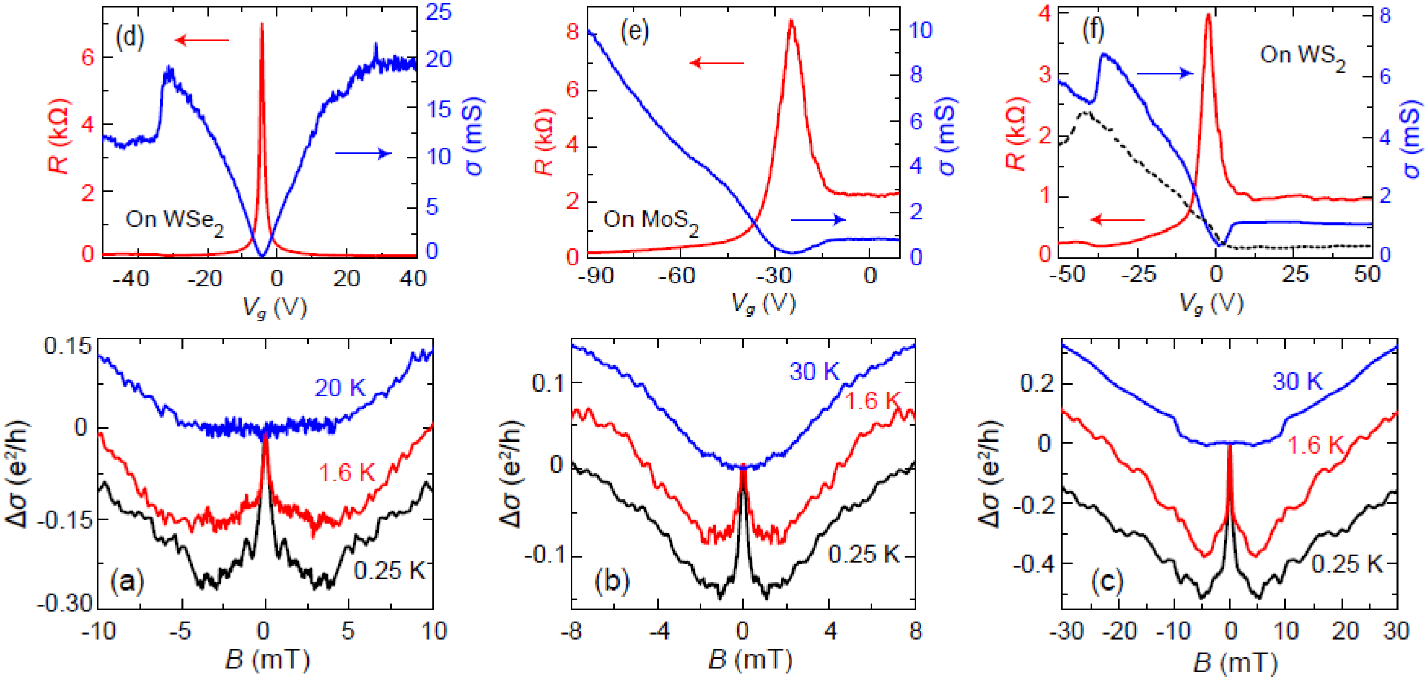
K. Song D. Soriano, A. W. Cummings, R. Robles, P. Ordejón, and S. Roche

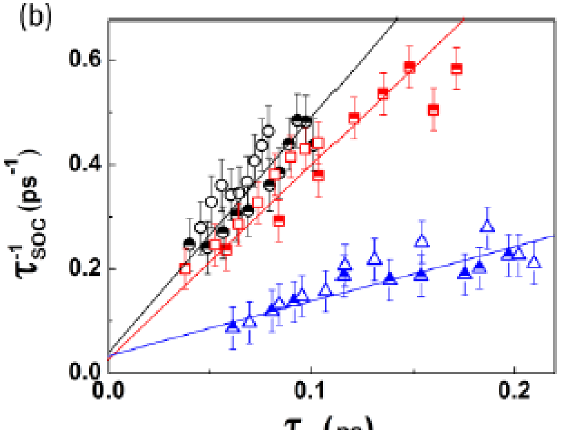
Nano Lett. Article ASAP- DOI: 10.1021/acs.nanolett.7b05482

SOC-proximity effect &Weak antilocalization

Wang et al, **Phys. Rev. X 6, 041020 (2016)**





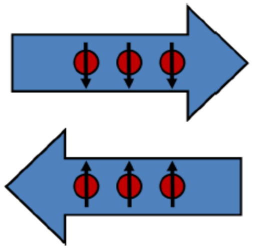


From the fits the scaling of spin scattering times versus Momentum scattering time yields

DYAKONOV PEREL mechanism

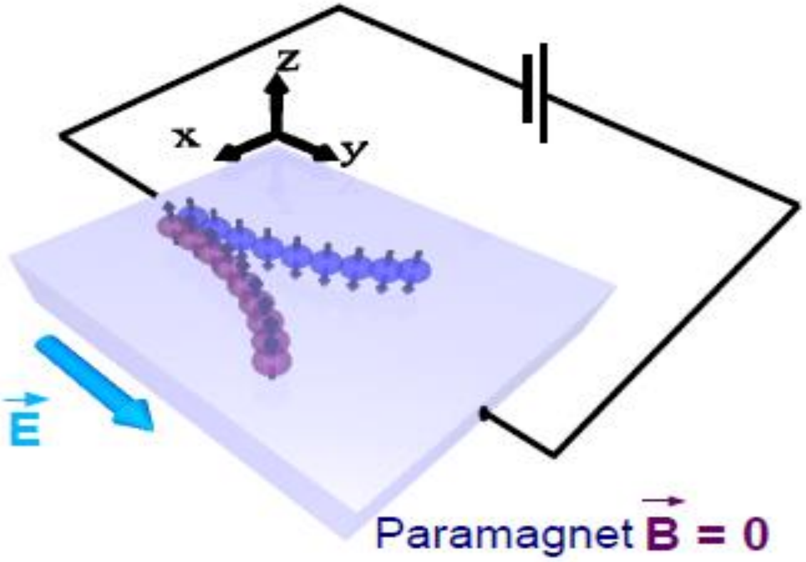
B. Yang et al. **Phys. Rev. B 96, 041409(RC) (2017)**

Spin Hall Effect



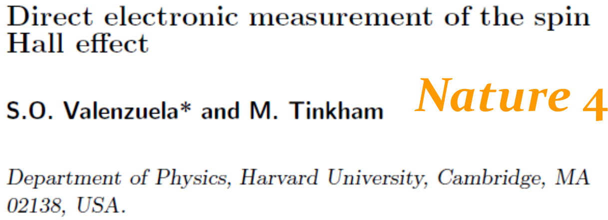
M.I. Dyakonov and V.I. Perel (1971)

Appearance of **spin accumulation** on the lateral surfaces
of an electric current-carrying sample
(*signs of the spin directions being opposite on the opposing boundaries*)



Strong spin-orbit coupling materials
(“effective magnetic field)

Interest !
Manipulate Spin
by electrical means
Without the use of
ferromagnetic
materials or real
magnetic fields



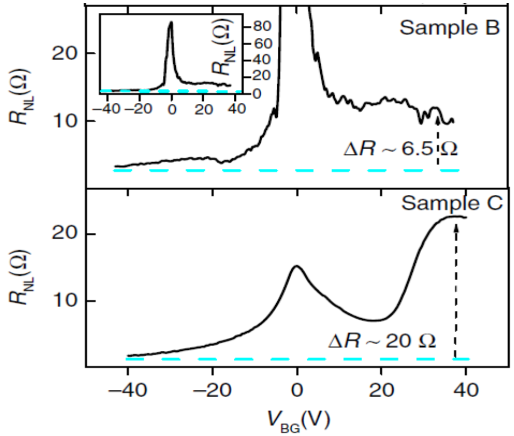
Direct electronic measurement of the spin
Hall effect

S.O. Valenzuela* and M. Tinkham

Department of Physics, Harvard University, Cambridge, MA
02138, USA.

Nature 442, 176-179 (2006)

nature
COMMUNICATIONS



ARTICLE

Received 10 Mar 2014 | Accepted 31 Jul 2014 | Published 26 Sep 2014

Spin-orbit proximity effect in graphene

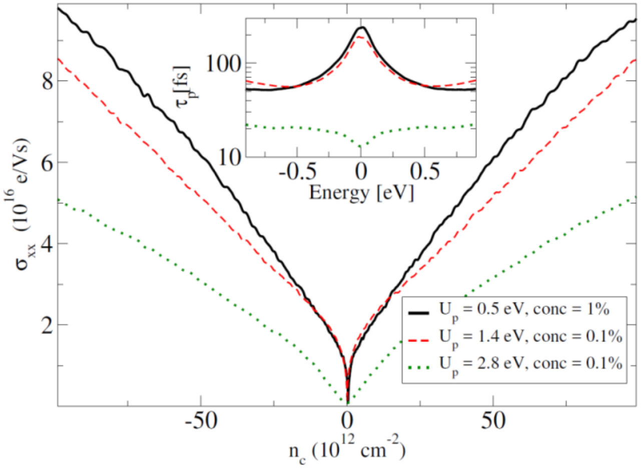
A. Avsar[1,2], J.Y. Tan[1,2], T. Taychatanapat[1,2], J. Balakrishnan[1,2], G.K.W. Koon[1,2,3], Y. Yeo[1,2], J. Lahiri[1,2], A. Carval
A.S. Rodin[4], E.C.T. O'Farrell[1,2], G. Eda[1,2], A.H. Castro Neto[1,2] & B. Özyilmaz[1,2,3]

$$\tau_s \simeq 5 - 10\text{ps}$$

"Graphene acquires spin–orbit coupling up to ***17 meV,*** *three orders of magnitude higher than its intrinsic value, without modifying the structure of the graphene.*

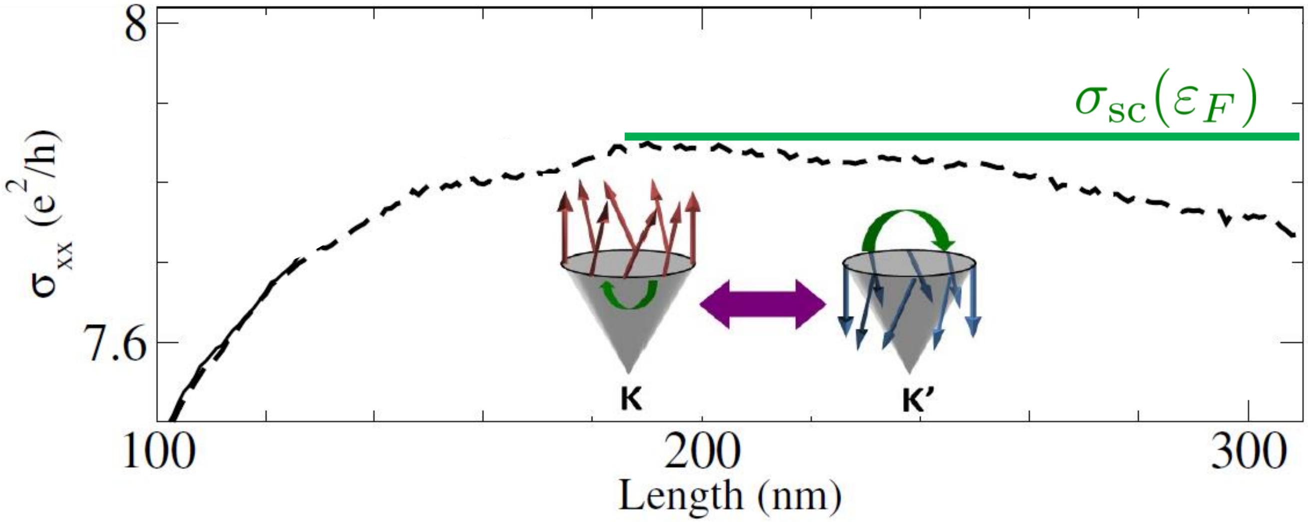
The proximity SOC leads to the spin Hall effect even at room temperature, *and opens the door to spin field effect transistors"*

Localization effects for *graphene/WS2 + el-h puddles*



Scaling theory of localization

$$\sigma_{\mathrm{xx}}(\varepsilon_F) = \sigma_{\mathrm{sc}}(\varepsilon_F) + \delta\sigma(\varepsilon_F)$$



$$\tau_{\mathrm{p}} = \frac{\sigma_{\mathrm{sc}}(\varepsilon_F)}{v_F^2\rho(\varepsilon_F)}$$

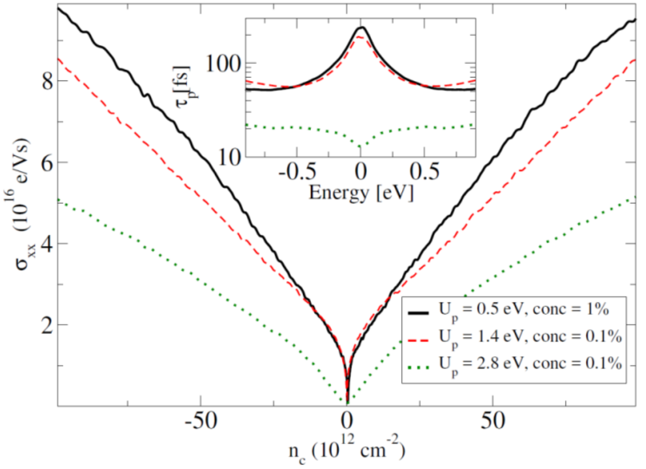
Case of strong scatterers (puddles) and large **intervalley scattering**

SOC switch OFF

$$\delta\sigma = -\frac{2e^2}{\pi h}\log(L/\ell_e)$$

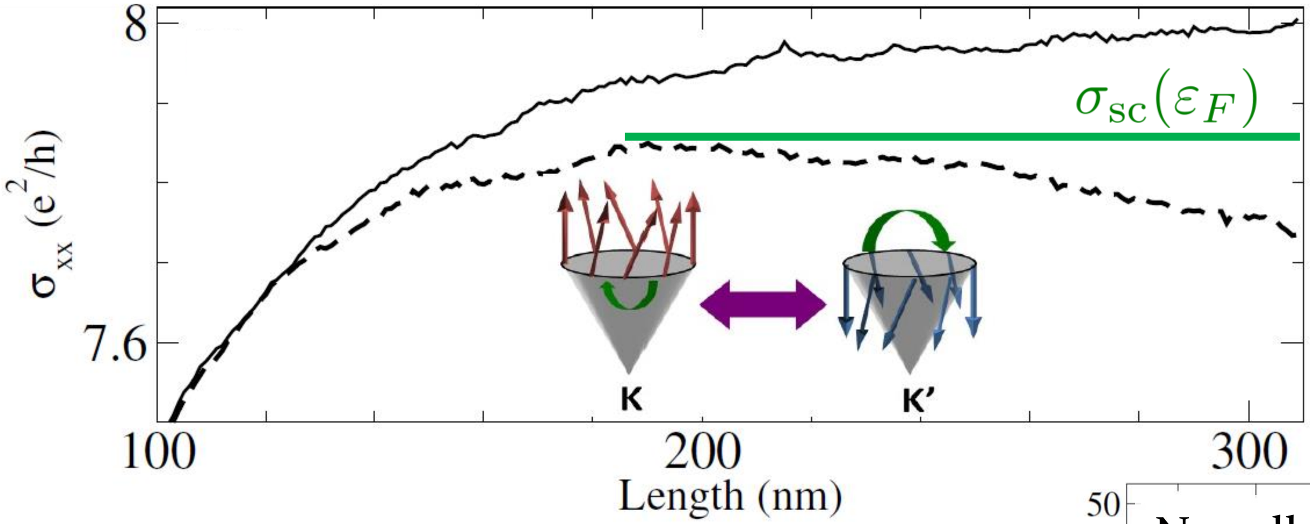
Weak localization

Localization effects for *graphene/WS2 + el-h puddles*



Scaling theory of localization

$$\sigma_{\rm xx}(\varepsilon_F) = \sigma_{\rm sc}(\varepsilon_F) + \delta\sigma(\varepsilon_F)$$

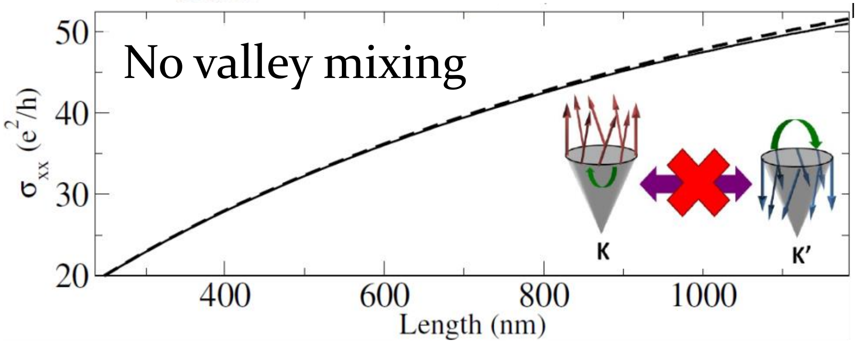


Case of strong scatterers (puddles) and large **intervalley scattering**

SOC switch ON

$$\delta\sigma = +\frac{2e^2}{\pi h}\log(L/\ell_e)$$

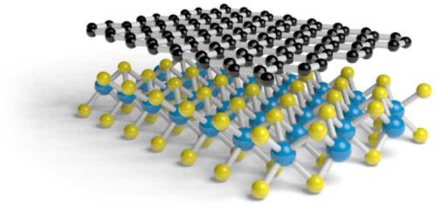
Weak Antilocalization



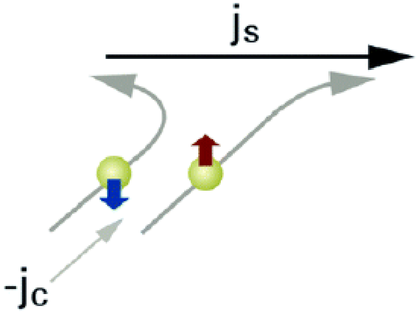
J.H. García, A. W. Cummings, S. Roche **Nano Lett. 17 5078 (2017)**

Spin Hall Effect for Graphene /TMDC heterostructures

Intrinsic mechanism



Driven by the translational invariant spin-orbit coupling fields (effective B fields)
Rashba+ intrinsic + Pseudospin Inversion Asymmetry terms…



Extrinsic mechanism

If impurities introduce local changes of SOC here **electron-hole puddles** (disorder)

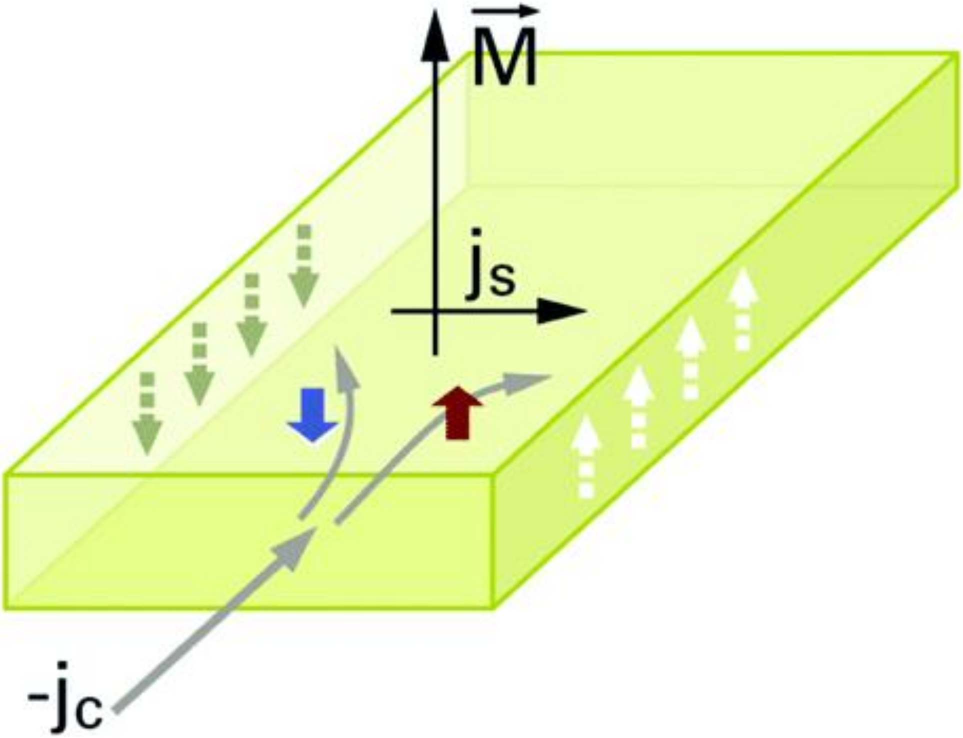
Spin Hall Kubo conductivity

in clean graphene/TMDC interfaces

θ_{sH}

Spin Hall angle

measures the efficiency of ***converting charge current to spin current***



$$\theta_{sH} = \frac{|J_s^z|}{|J_c|}$$

Dissipative SHE

$$\theta_{sH} = \frac{\sigma_{xy}^z}{\sigma_{xx}}$$

Spin Hall Kubo conductivity

in large scale disordered graphene models

$$\boxed{\sigma_{\mathrm{sH}} = \frac{e\hbar}{\Omega}\sum_{m,n}\frac{f(E_m)-f(E_n)}{E_m-E_n}\frac{\mathcal{I}m[\langle m\,|J_x^z|\,n\rangle\,\langle n\,|v_y|\,m\rangle]}{E_m-E_n+i\eta},}$$

$J_x^z = \frac{\hbar}{4}\{\sigma_z, v_x\}$ is the spin current operator

real-space formalism

$$\sigma_{\mathrm{sH}} = \frac{e\hbar}{\Omega}\int dudv\,\frac{f(u)-f(v)}{(u-v)^2+\eta^2}\,j(u,v),$$

$$j(u,v) = \textstyle\sum_{m,n}\mathcal{I}m[\langle m\,|J_x^z|\,n\rangle\,\langle n\,|v_y|\,m\rangle]\delta(u-E_m)\delta(v-E_n)$$

$$= \textstyle\sum_{m,n}^{M}(4\mu_{mn}g_m g_n T_m(\hat{u})T_n(\hat{v}))/((1+\delta_{m,0})(1+\delta_{n,0})\pi^2\sqrt{(1-\hat{u}^2)(1-\hat{v}^2)}),$$

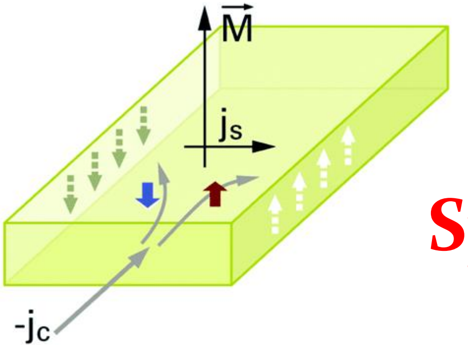
$$\mu_{mn} = \tfrac{4}{\Delta E^2}\mathcal{I}m[Tr[J_x^z T_n(\hat{H})v_y T_m(\hat{H})]]$$

The trace in μ_{mn} is computed by the average on a small number $R \ll N$ of random phase vectors $|\varphi\rangle$

$$\boxed{\sigma_{xx} = \frac{2\hbar e^2}{\pi\Omega}\sum_{m,n=0}^{M}\mathcal{I}m[g_m(\epsilon+i\eta)]\mathcal{I}m[g_n(\epsilon+i\eta)]\mu_{mn}}$$

dc-Kubo conductivity

Spin Hall Kubo conductivity
in clean graphene/TMDC interfaces

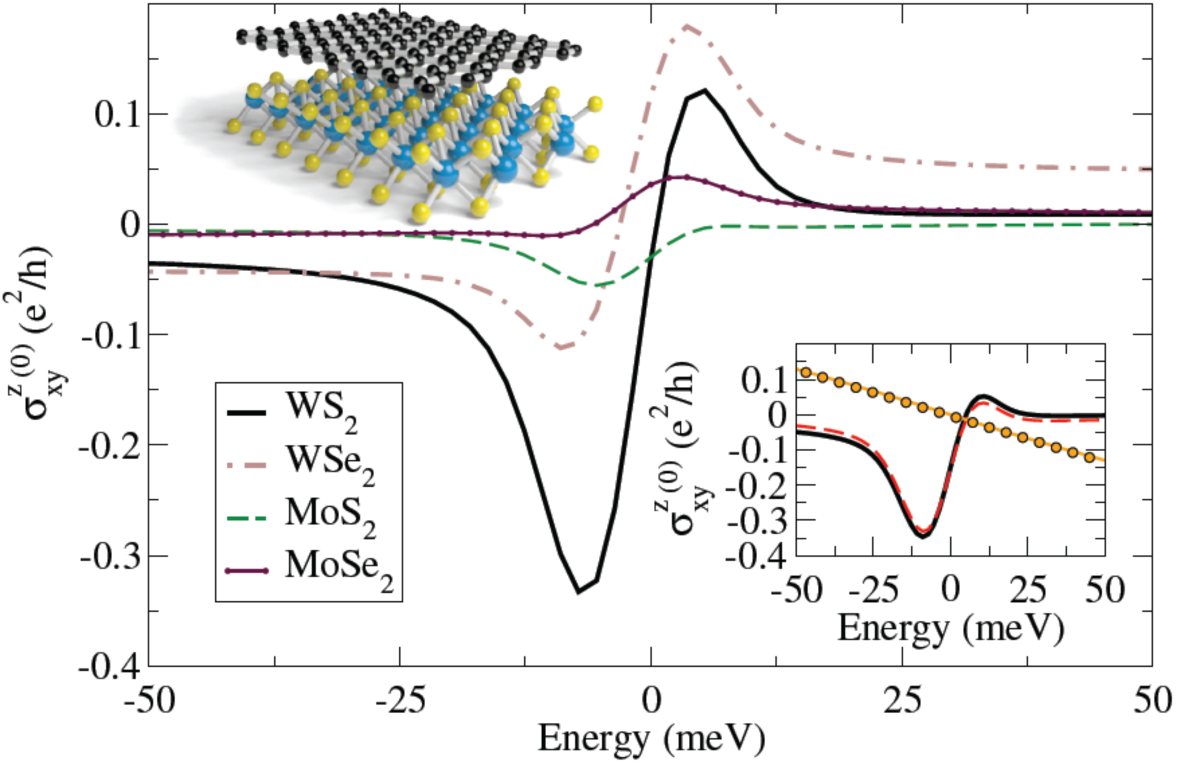


$$\theta_{sH}$$

Spin Hall angle

measures the efficiency of ***converting charge current to spin current***

$$\theta_{sH} = \frac{|J_s^z|}{|J_c|}$$



Dissipative SHE

$$\theta_{sH} = \frac{\sigma_{xy}^z}{\sigma_{xx}}$$

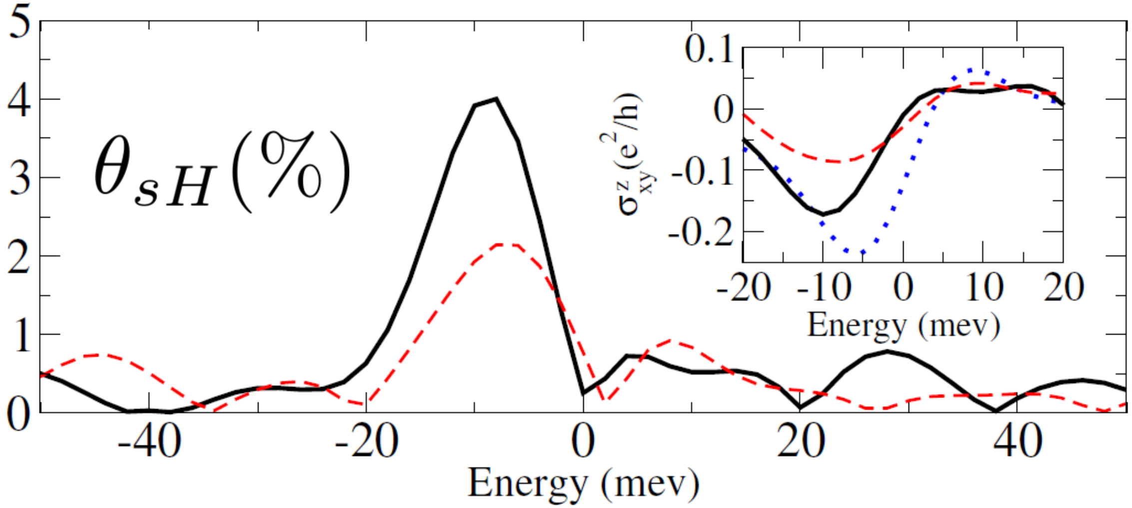
Clean case :

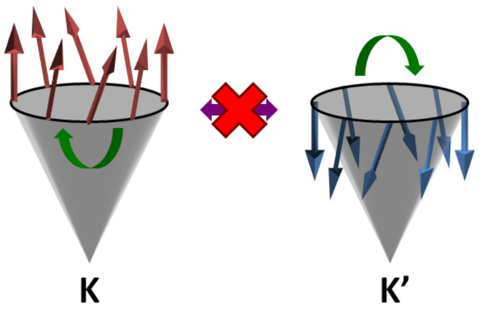
"intrinsic SHE"

WS$_2$ leads to larger
Spin Hall conductivity
(larger SHA)

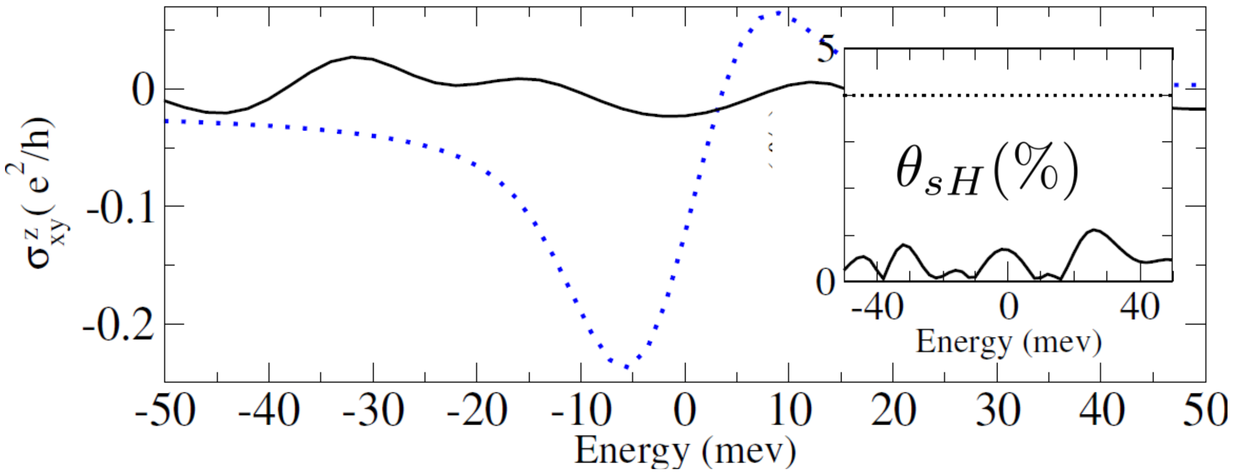
Spin Hall Effect

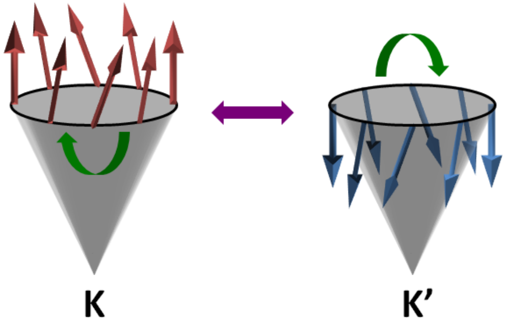
in disordered graphene/TMDC interfaces





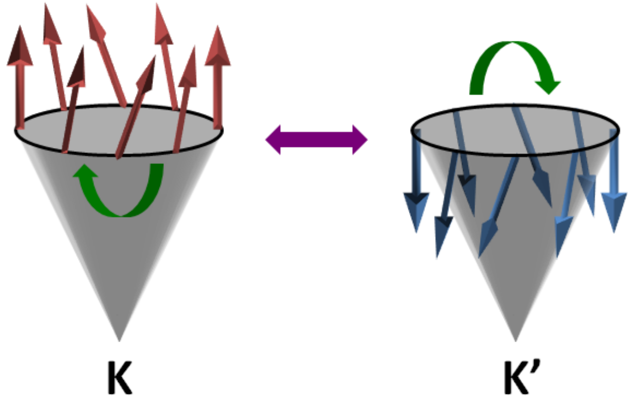
$\theta_{sH}(\%) \simeq 4\%$

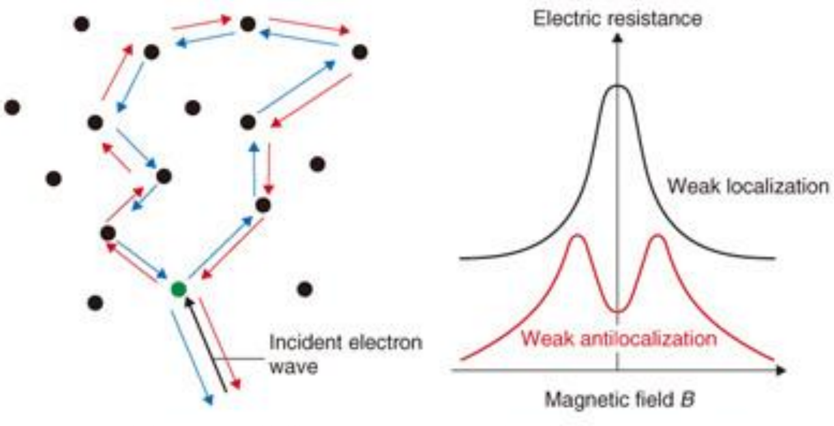




$\theta_{sH}(\%) \ll 1\%$

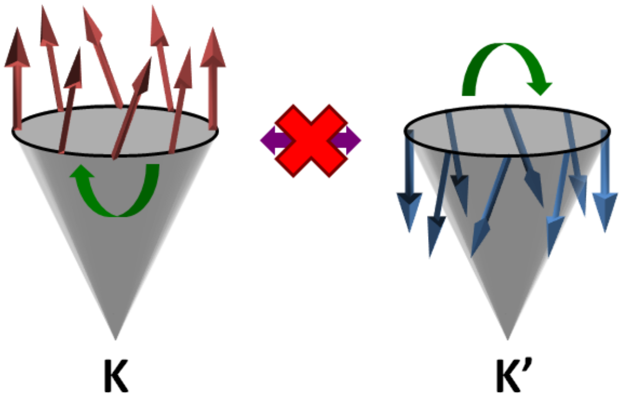
Weak antilocalization vs Spin Hall Effect

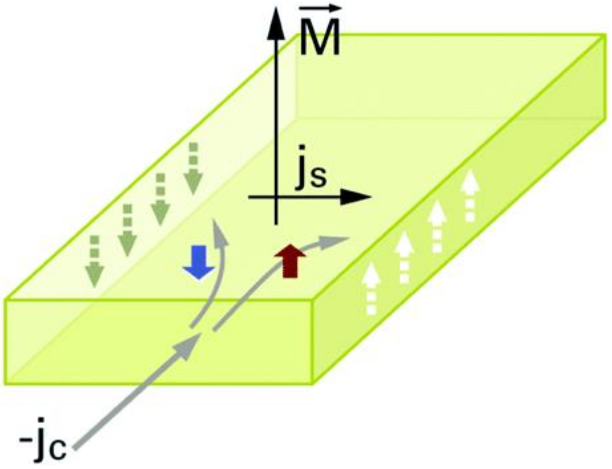




(a) Generation mechanism (b) Magneto-resistance effect

$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 10 - 100$$





$$\frac{\tau_{s,\perp}}{\tau_{s,\parallel}} = 1/2$$

OUTLINE

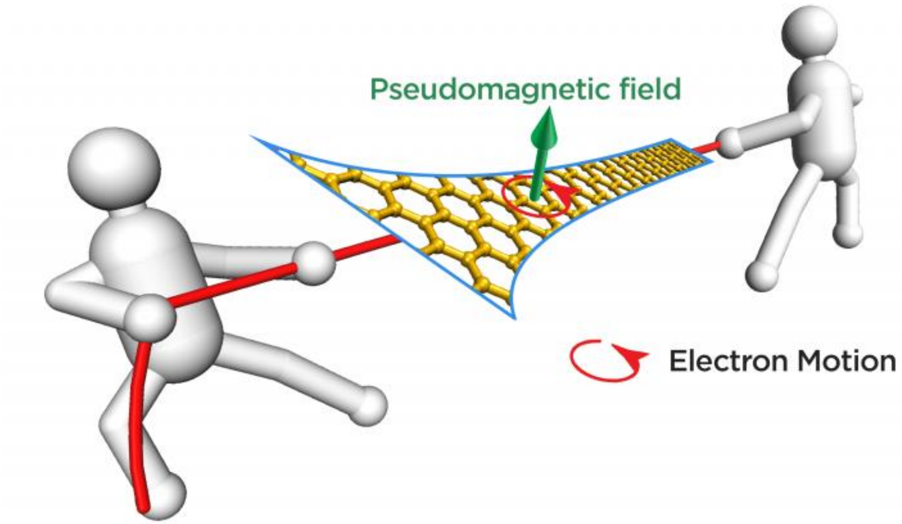
Why Spintronics using 2D Materials ?

Proximity effects in 2D Materials-based heterostructures (spin dynamics & relaxation, SHE, weak antilocalization, QSHE)

Generating valley polarized quantum transport (valleytronics)

Lattice deformation strain & pseudomagnetic fields

F. Guinea, M. I. Katsnelson,
and A. K. Geim
Nat. Phys. 6, 30 (2010)

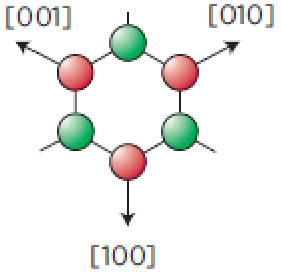


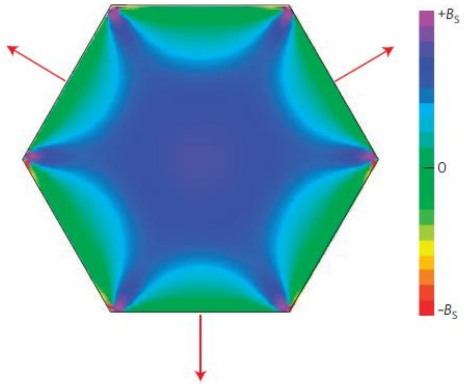
Strained superlattices
Gap opening & QHE

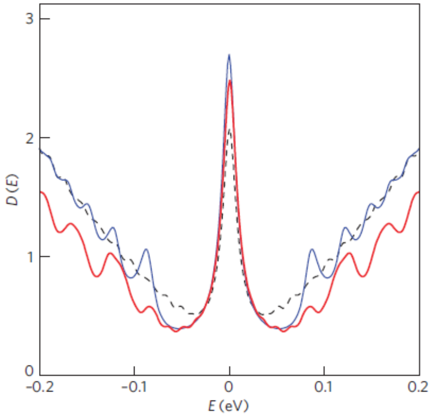
$$\mathbf{B}_{strain} = \nabla \times \mathbf{A}$$

The strain-induced, pseudomagnetic field (idem for gauge-field vector potential) **has opposite signs for graphene's two valleys K and K´** **(no TRS breaking)**

Distribution of strain (triangular symmetry) results in a
strong uniform pseudomagnetic field



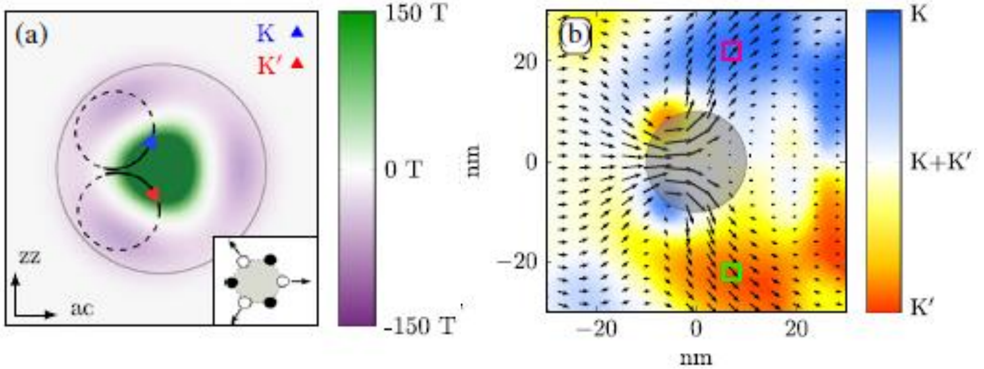




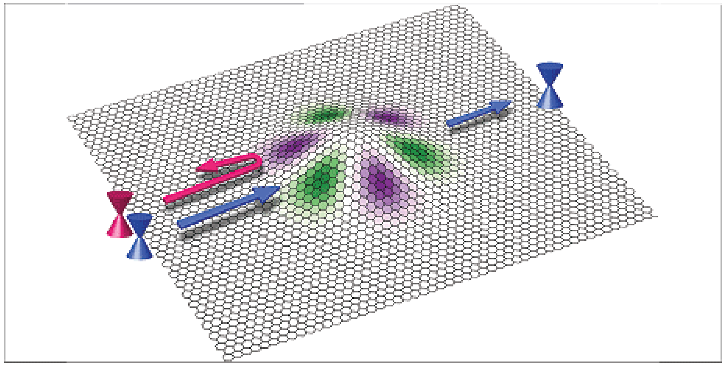
Strain of 10%
B_{field}= 40 Tesla

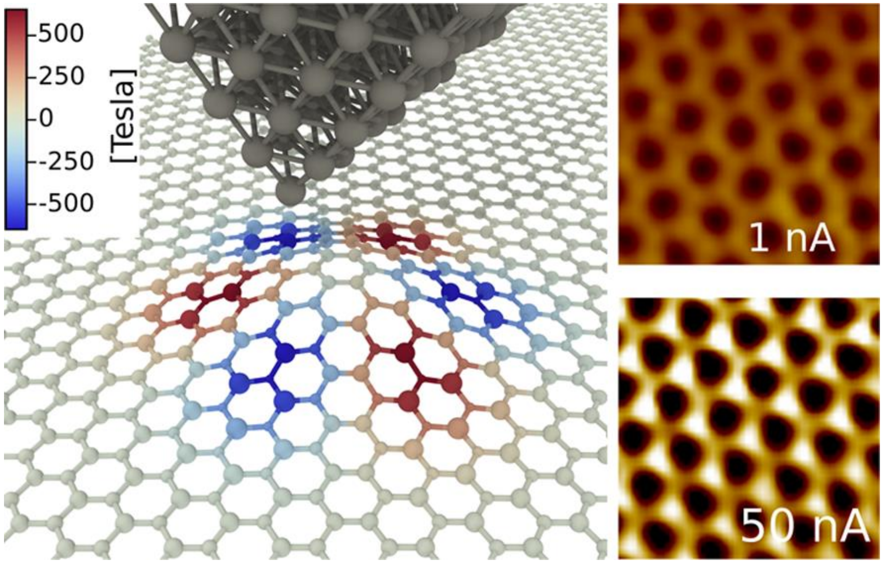
Lattice deformation strain & pseudomagnetic fields

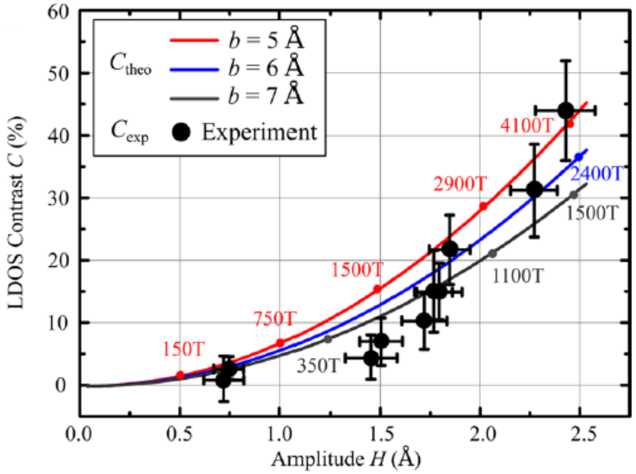
M. Settnes et al. **Phys. Rev. Lett. 117, 276801 (2016)**



Graphene nanobubble







B_{field}= 1000 Tesla

Signature of the pseudomagnetic field is a local sublattice symmetry breaking observable as a redistribution of the local density of states

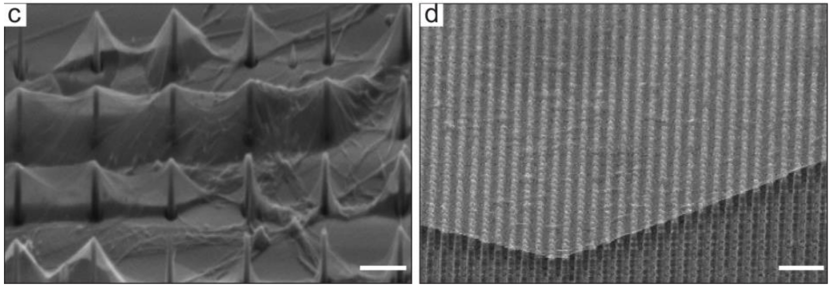
A. Georgi et al **Nano Lett. 17 (4), pp 2240–2245 (2017)**

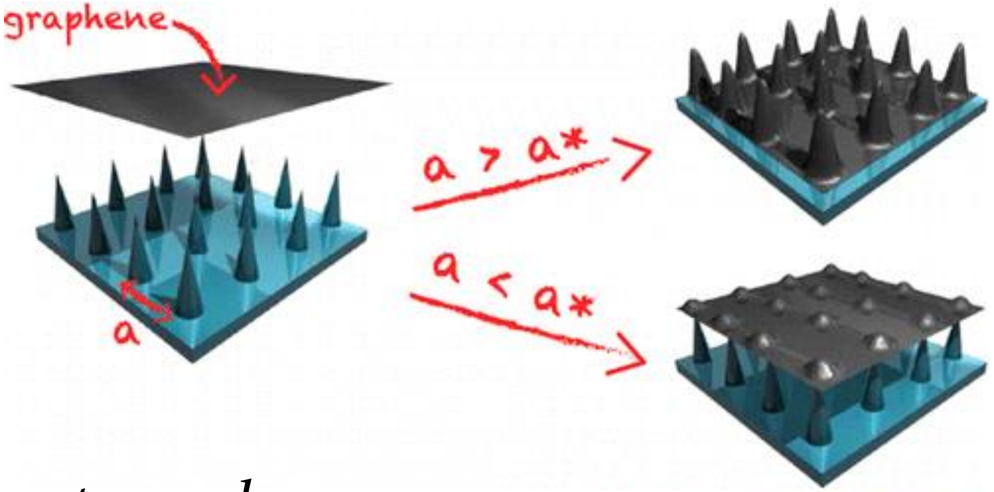
Engineering strain fields in graphene

***Strain Superlattices** in graphene induced by corrugated substrates*

A. Reserbat-Plantey et al,

Nano Lett. 14 (9), 5044 (2014)

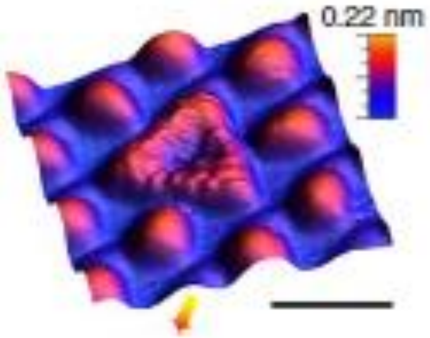


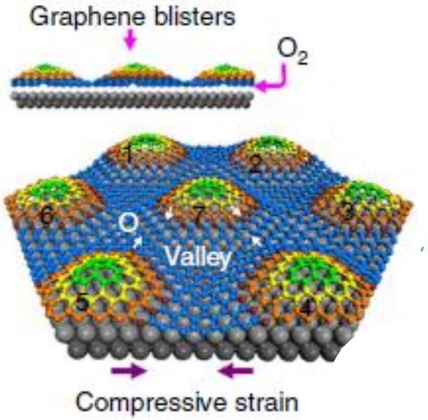


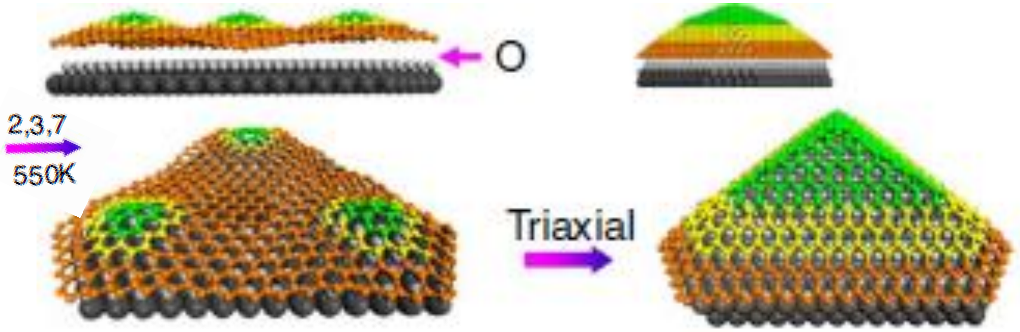
*Evolution of graphene Moiré blisters towards geometrically well-defined **graphene nanobubbles***

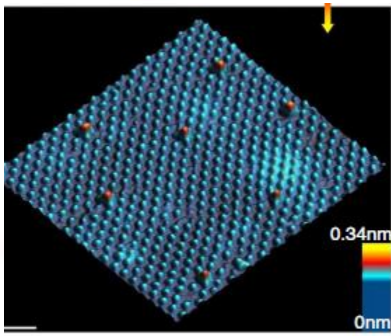
Jiong Lu, A.H. Castro Neto & Kian Ping Loh

Nature Communications 3, 823 (2012)

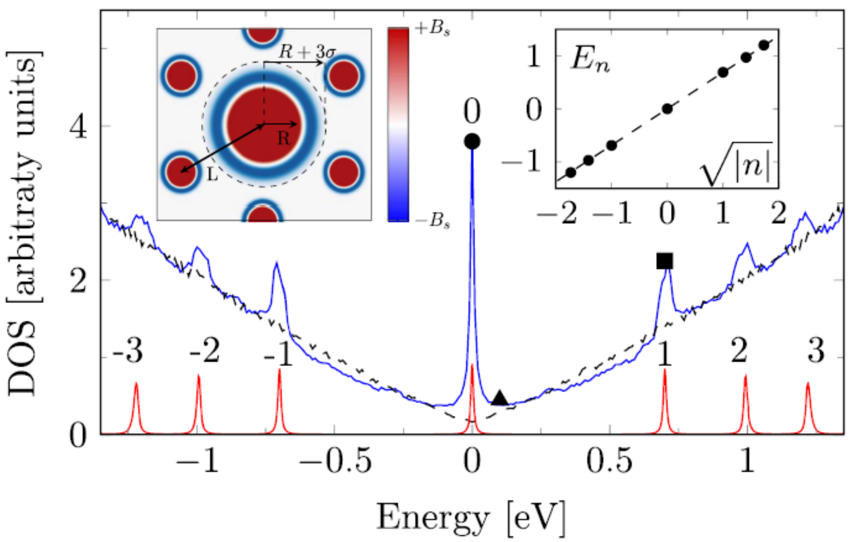








Pseudomagnetic fields for an array of nanobubbles



DoS of a strain array (blue) with local **B_s=450 Tesla**
(dashed : unstrained)
(red: inner part of the strained region)

$$E_n = \hbar\omega^{Dirac}\mathrm{sgn(n)}\sqrt{|n|}$$

$$\omega^{Dirac} = v_F\sqrt{\frac{2eB}{\hbar c}}$$

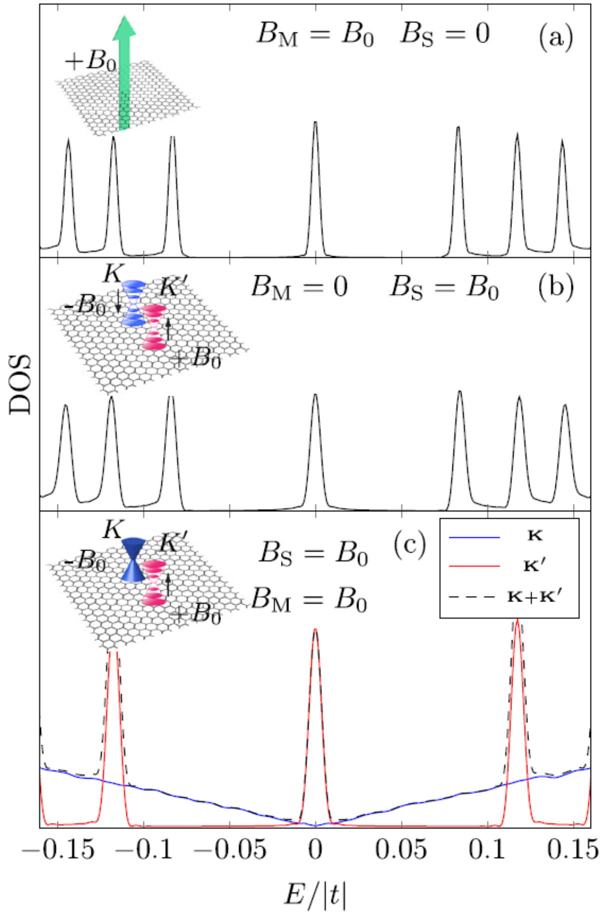
M. Settnes, J.H. Garcia, S. Roche
2D Mater. 4, 031006 (2017)

$\pm\vec{A}_\mathrm{S}$ Valley-dependent strain-induced gauge

$$\vec{A}_\mathrm{S} \propto (\epsilon_{xx} - \epsilon_{yy}, -2\epsilon_{xy})$$

strain tensor
- *triaxial deformation-*

M. Settnes et al. 2D Mater. 3, 034005 (2016)



Real magnetic field

$$\mathbf{B}_M = \nabla \times \mathbf{A}$$

Pseudomagnetic field

$$\mathbf{B}_S = \nabla \times \mathbf{A}_S$$

Valley K´
Total effective field
=$2B_o$

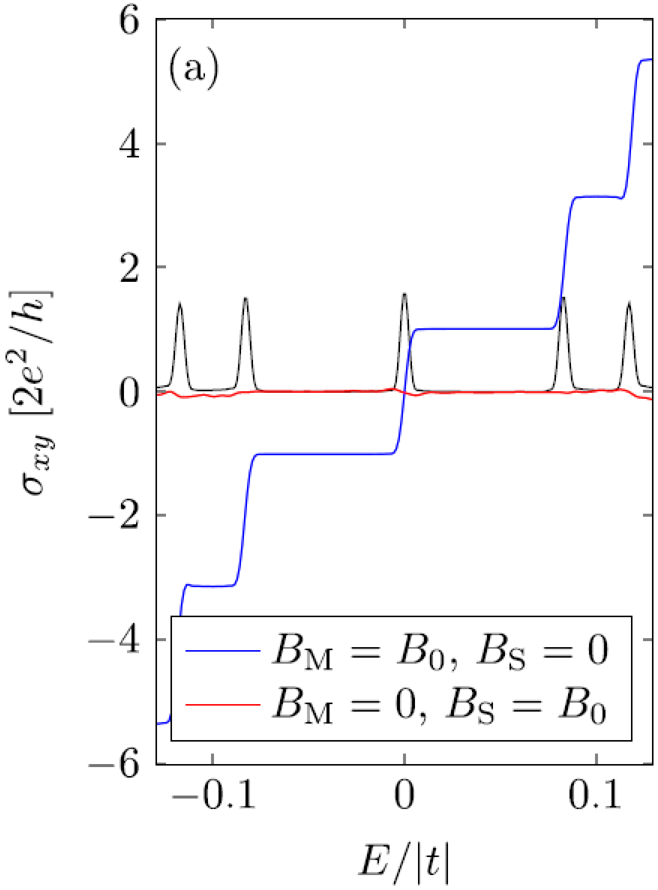
Valley K
Total effective field
=0

Charge and valley Hall Kubo conductivity

$$\sigma_{\alpha\beta} = \frac{\mathrm{i}e^2\hbar}{\Omega}\int_{-\infty}^{\infty} d\epsilon f(\epsilon)\mathrm{Tr}\Big[v_\alpha\delta(\epsilon-H)v_\beta\frac{dG^r(\epsilon)}{d\epsilon} - v_\alpha\frac{dG^a(\epsilon)}{d\epsilon}v_\beta\delta(\epsilon-H)\Big],$$

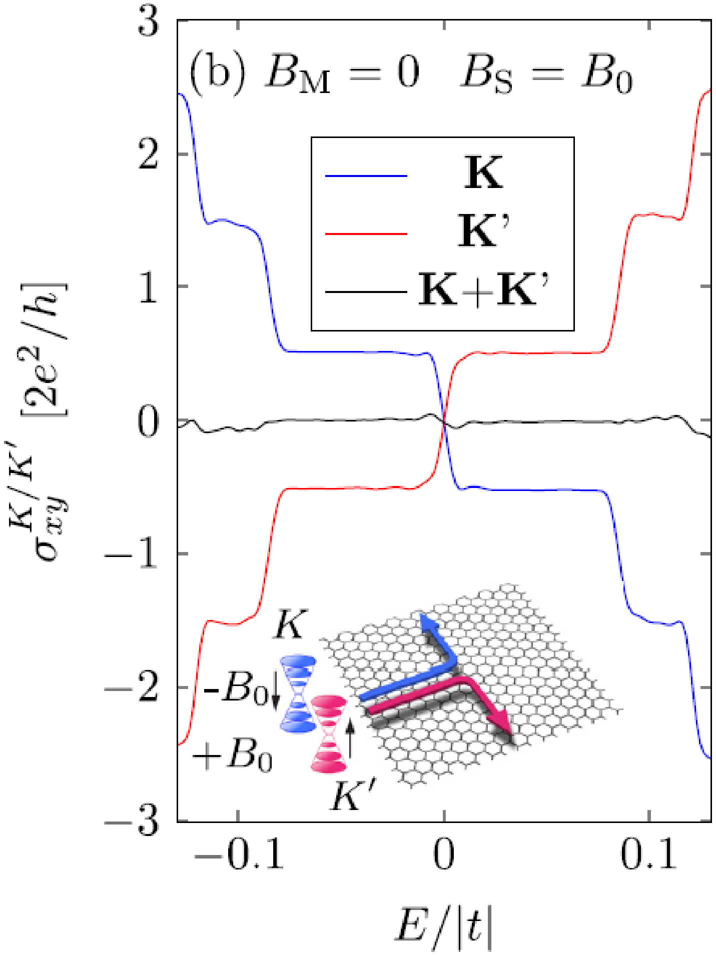
$$v_\beta^v \equiv P_{\vec{K}}v_\beta P_{\vec{K}} - P_{\vec{K}'}v_\beta P_{\vec{K}'}$$

$P_{\vec{K}}(P_{\vec{K}'})$ is the valley projection operator



Total charge Hall current

$$\sigma_{xy} = \sigma_{xy}^{K} + \sigma_{xy}^{K'} = 0$$



K-valley Hall conductivity

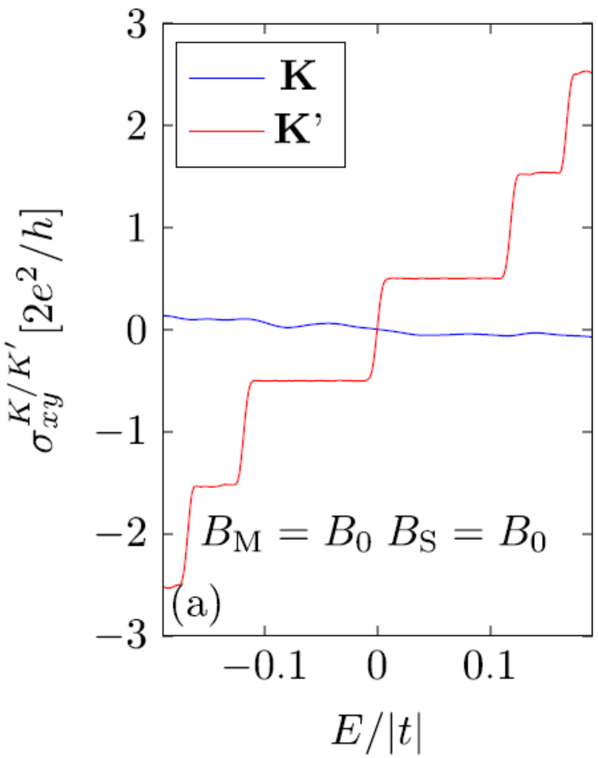
$$\sigma_{xy}^{K}$$

K′-valley Hall conductivity

$$\sigma_{xy}^{K}$$

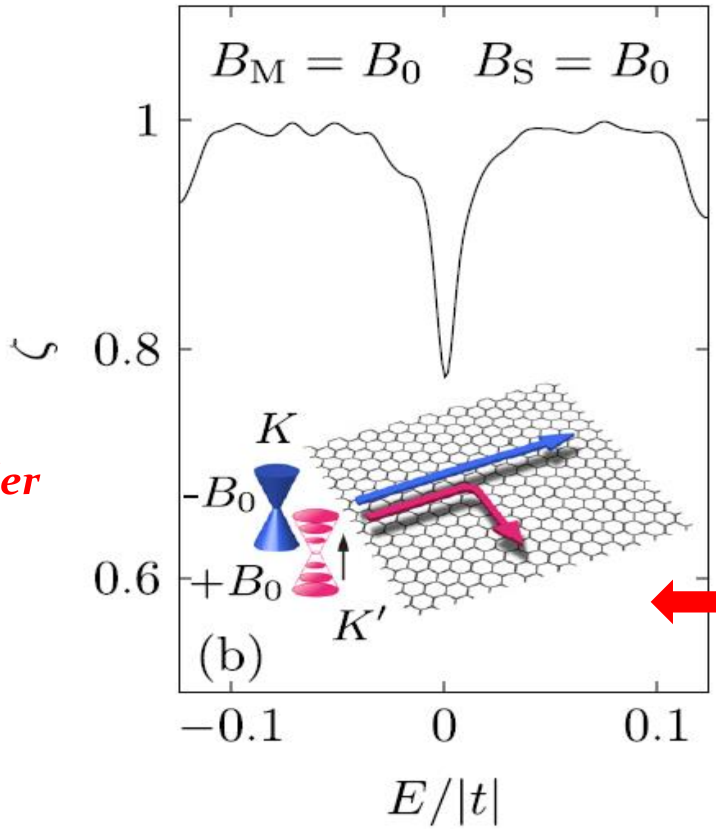
Valley Hall effect
but *valley Hall conductivities*
Are NOT observables

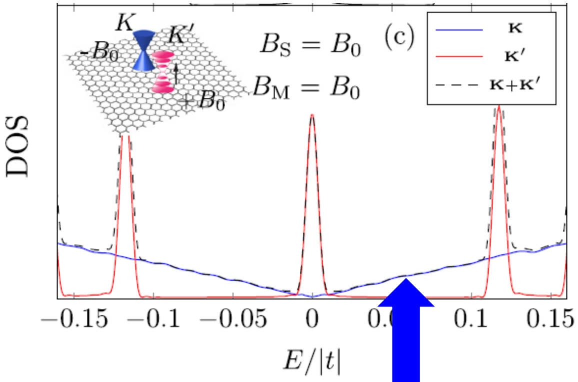
Charge and valley Hall Kubo conductivity



Total charge Hall current $\sigma_{xy} = \sigma_{xy}^{K'} \neq 0$

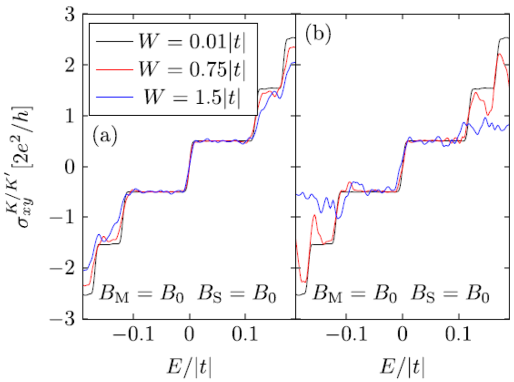
Valley polarization $\zeta = (\sigma_{xx}^{K} - \sigma_{xx}^{K'})/(\sigma_{xx}^{K} + \sigma_{xx}^{K'}) \approx 1$





Robust with respect to disorder

Long range short range



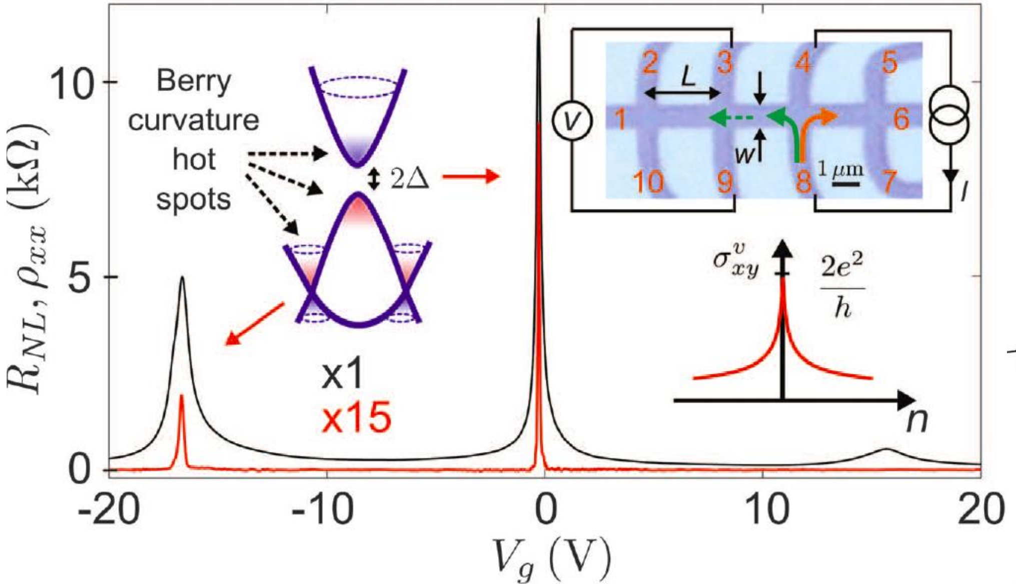
K-Valley polarized
dissipative conductivity

K´-Valley polarized
Hall Conductivity

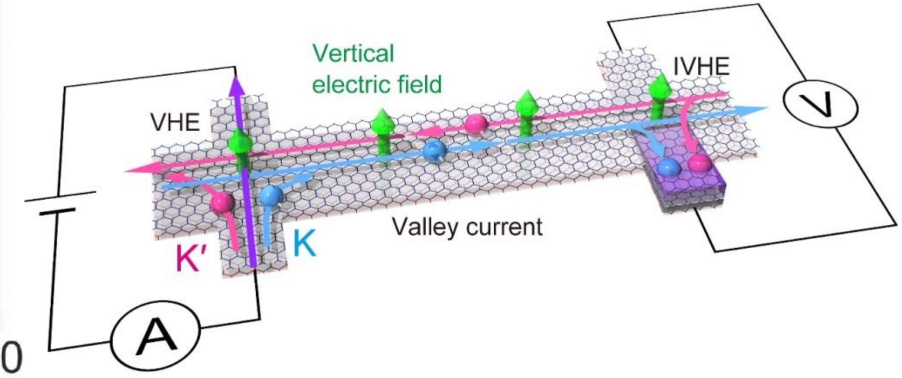
M. Settnes, J.H. Garcia, S. Roche **2D Mater. 4, 031006 (2017)**

Valleytronics and Valley currents

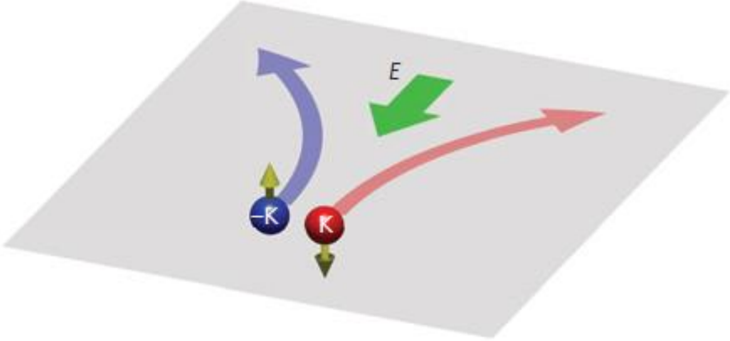
Recent claims of VHE measurements in Graphene/hBN
in **non-local transport geometries**
(***large non-local resistance at the Dirac point***)



Gorbachev et al.
Science 346, 448 (2014)

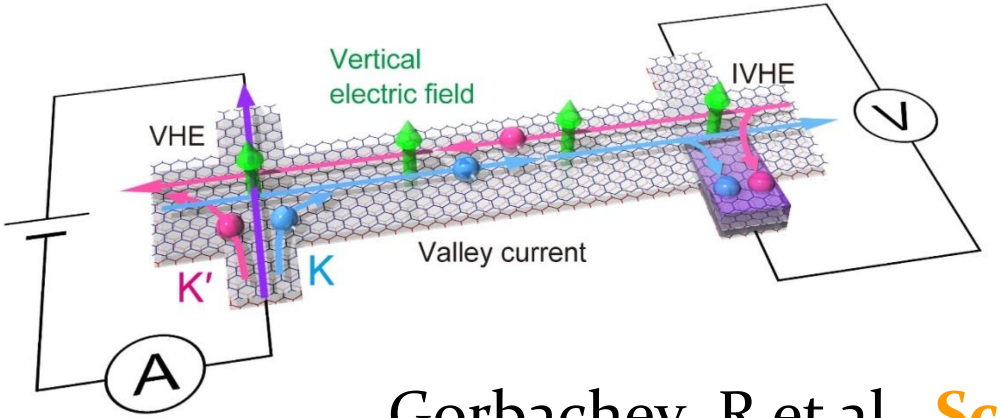


Gapped Dirac fermions+ electric field
An anomalous perpendicular velocity
is generated by the "**Berry curvature**"
Valley Hall effect



$$\mathbf{v} = \frac{1}{\hbar}\frac{\partial \varepsilon_{nk}}{\partial \mathbf{k}} - \partial_t \mathbf{k} \times \mathbf{\Omega}_{nk}$$

Valleytronics and Valley currents ?



Problems !!

Semiclassical argument of gap-induced
Berry´s currvature is not enough
For generating topologiclaly protected
edge states

Gorbachev R et al. Science 346, 448 (2014)
Sui M. et al. Nature Phys. 11, 1027–1031 (2015)
Shimazaki,Y. et al. Nature Phys. 11, 1032–1036 (2015)

Exact calculations
of bulk transport coefficients (Kubo)
of non-local resistance (multiterminal Landauer-Büttiker)

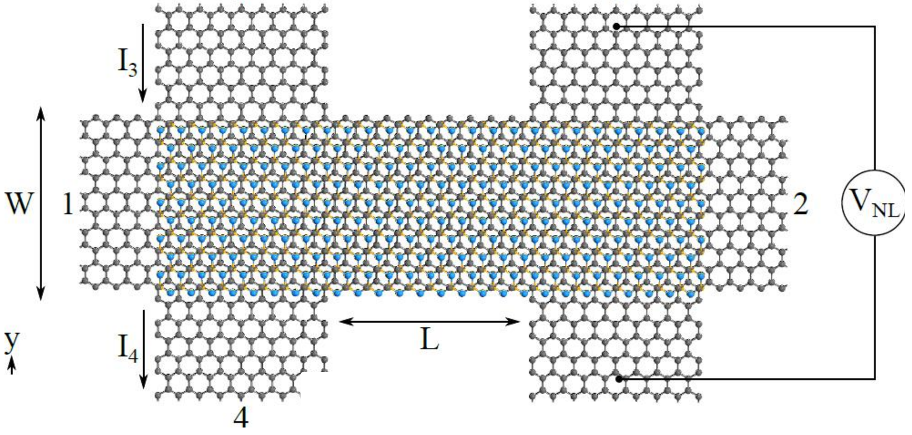
$$R_{\mathrm{NL}} \propto (\sigma^{v}_{xy})^2 \rho^3_{xx}$$

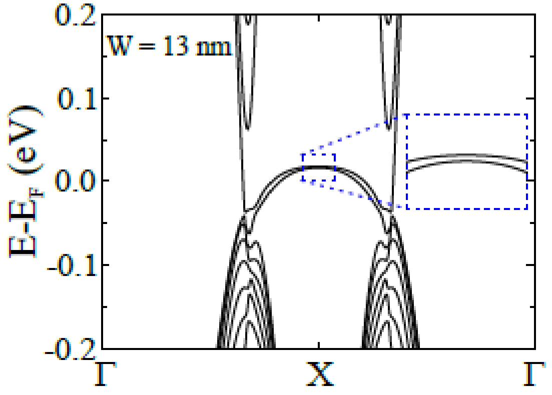
Gapped G/hBN leads to quantized valley Hall conductivity, and zero R_{NL} +disorder broadening invalidates the formula

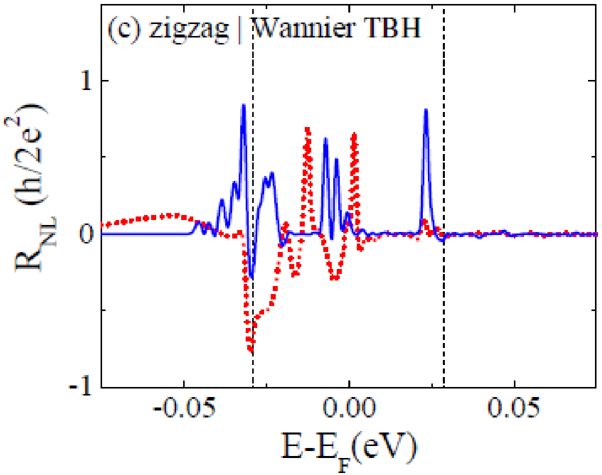
Origin of nonlocal resistance in multiterminal G/hBN heterostructures

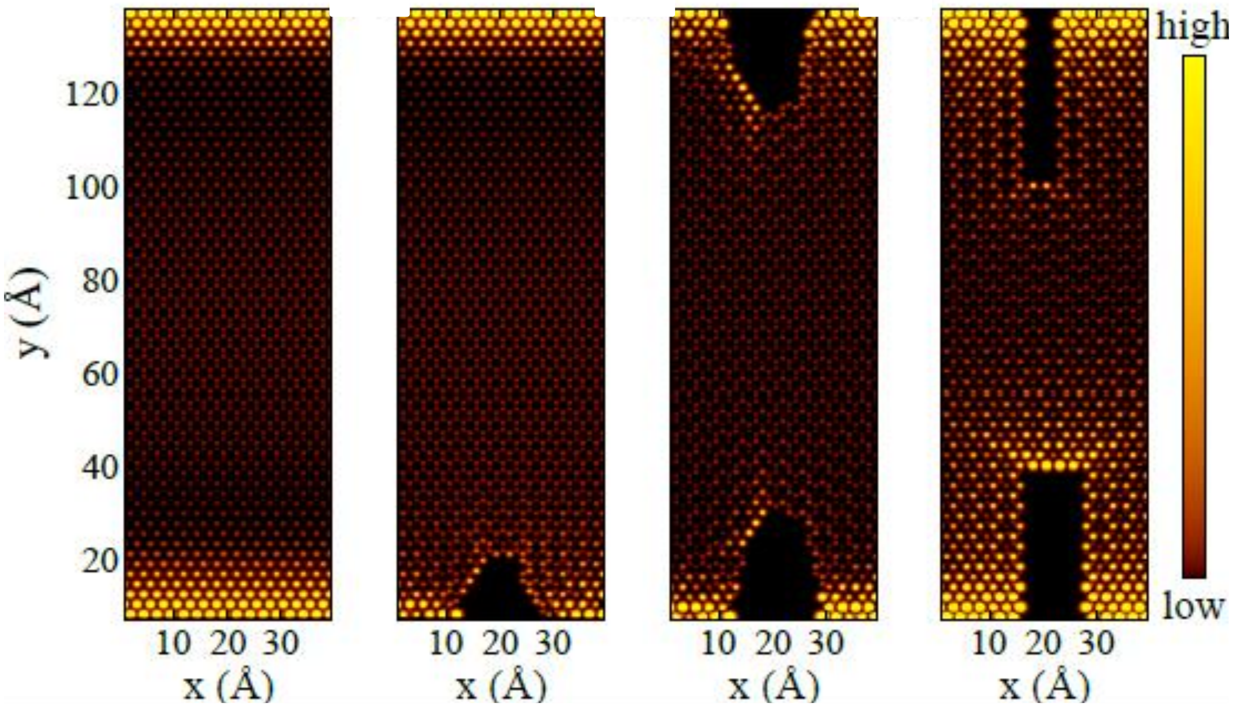
J. M. Marmolejo-Tejada et al

(PRL, arXiv:1706.09361)









ICN2
Institut Català de Nanociència i Nanotecnologia

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GRAPHENE FLAGSHIP

MARIE CURIE ACTIONS

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD

And now dancing with the stars…
In Memoriam