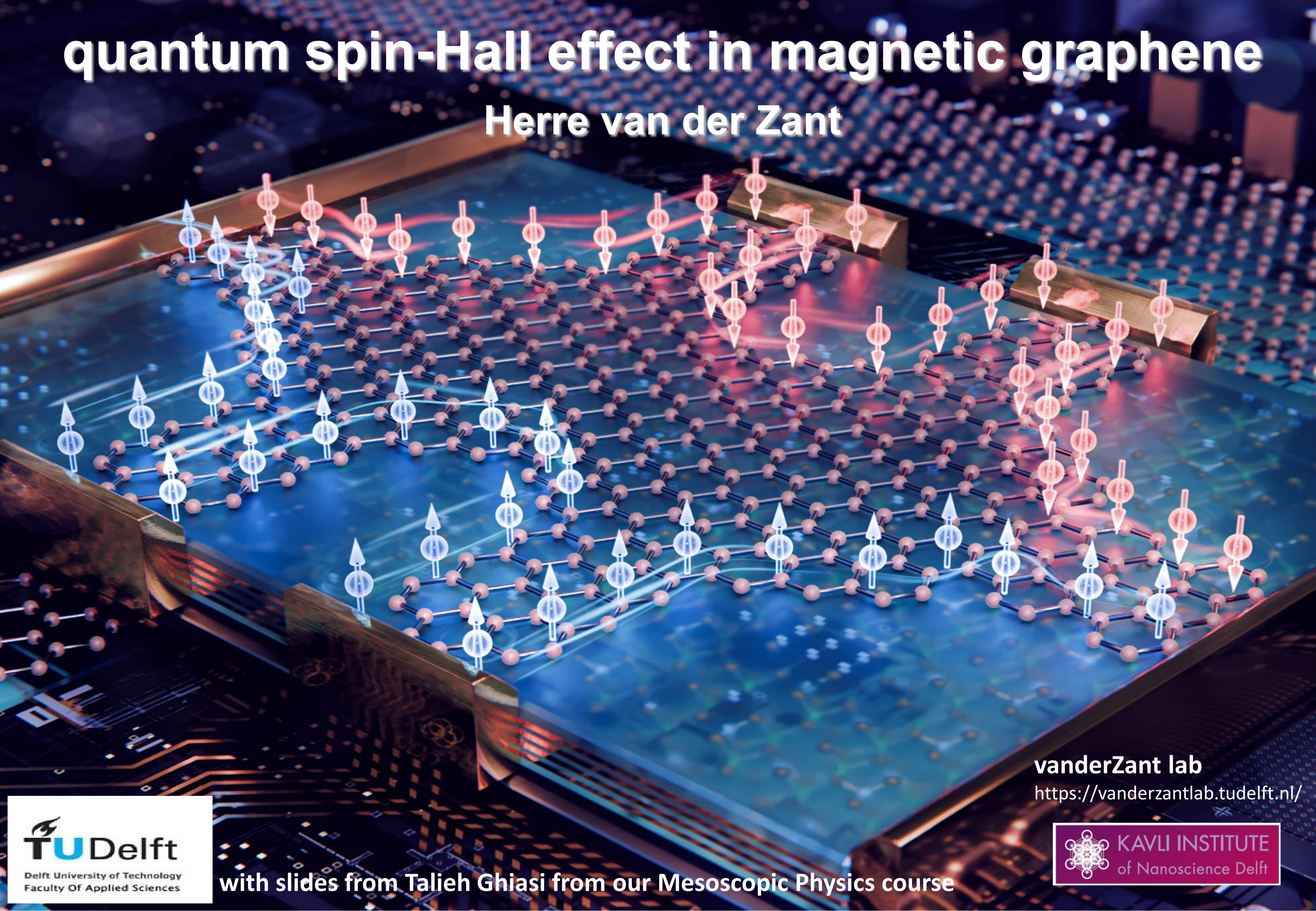
quantum spin-Hall effect in magnetic graphene

Herre van der Zant



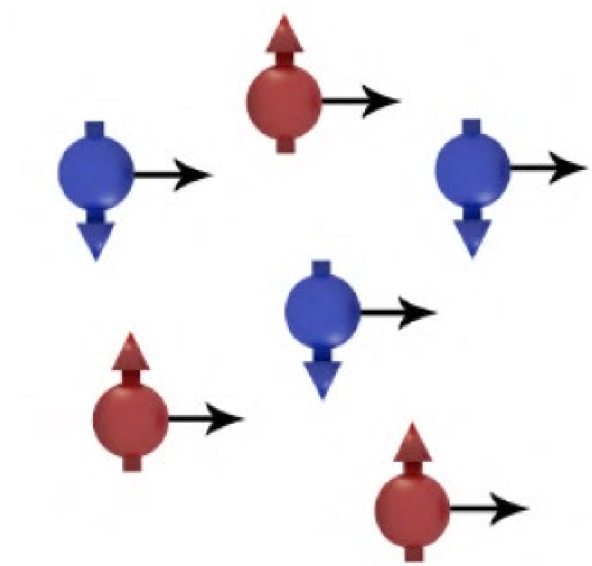
vanderZant lab
https://vanderzantlab.tudelft.nl/

TU Delft
Delft University of Technology
Faculty Of Applied Sciences

KAVLI INSTITUTE
of Nanoscience Delft

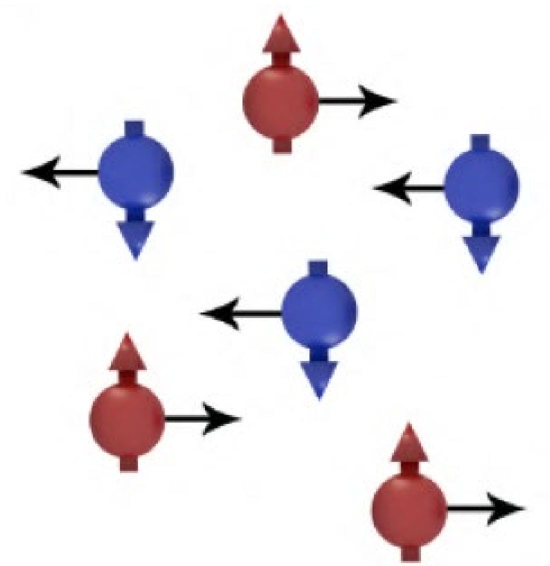
with slides from Talieh Ghiasi from our Mesoscopic Physics course

electrons carry charge and spin



$$I = I_\uparrow + I_\downarrow$$

$$I_s = I_\uparrow - I_\downarrow$$



pure charge current

$$I \neq 0$$

$$I_s = 0$$

pure spin current

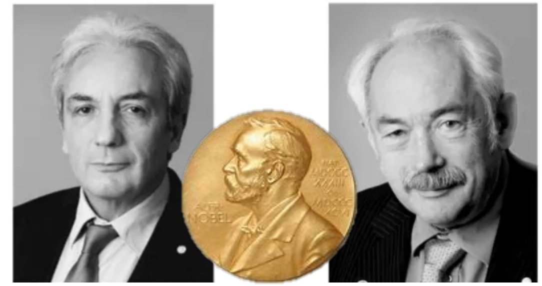
$$I = 0$$

$$I_s \neq 0$$

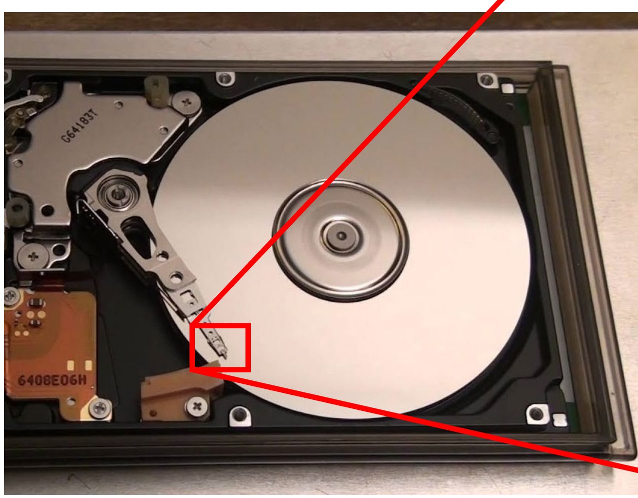
spintronics = electronic + spin

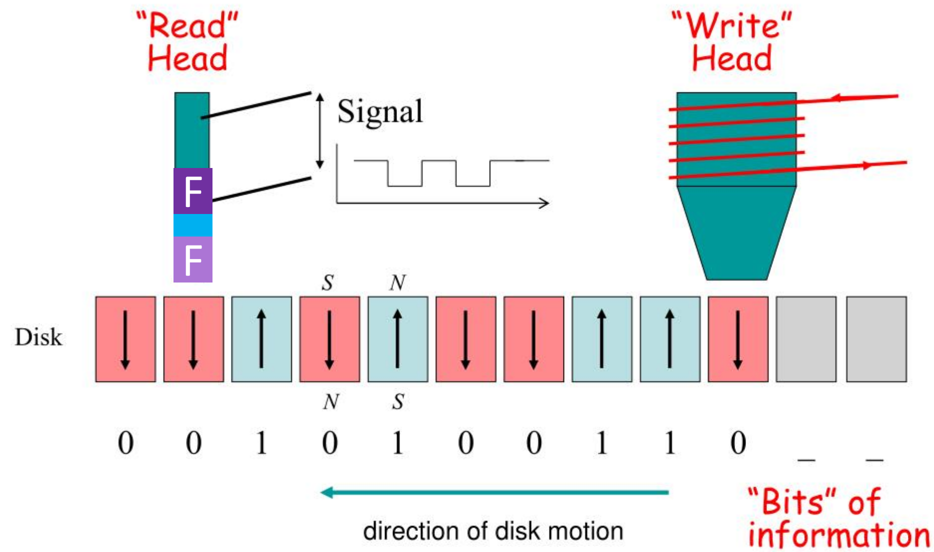
massive information storage

magnetic hard drives



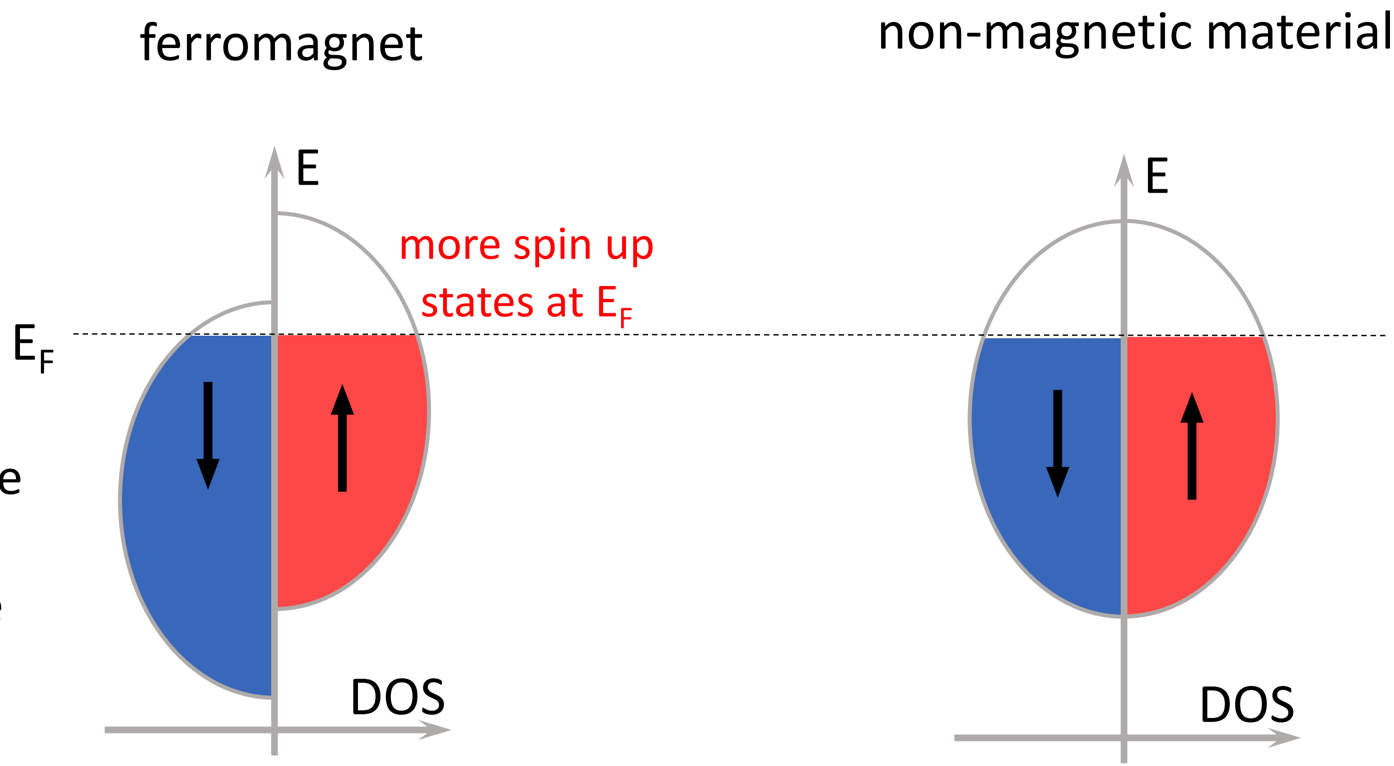
Nobel prize 2007





F = ferromagnetic material

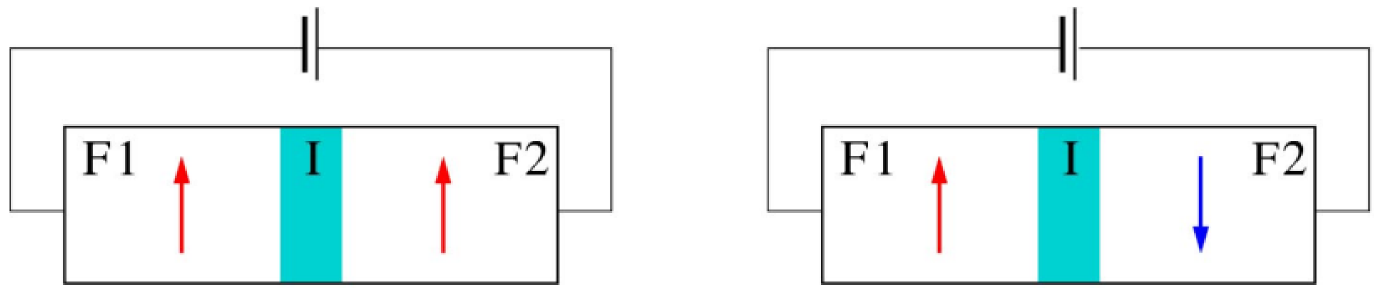
ferromagnetic versus non-magnetic material



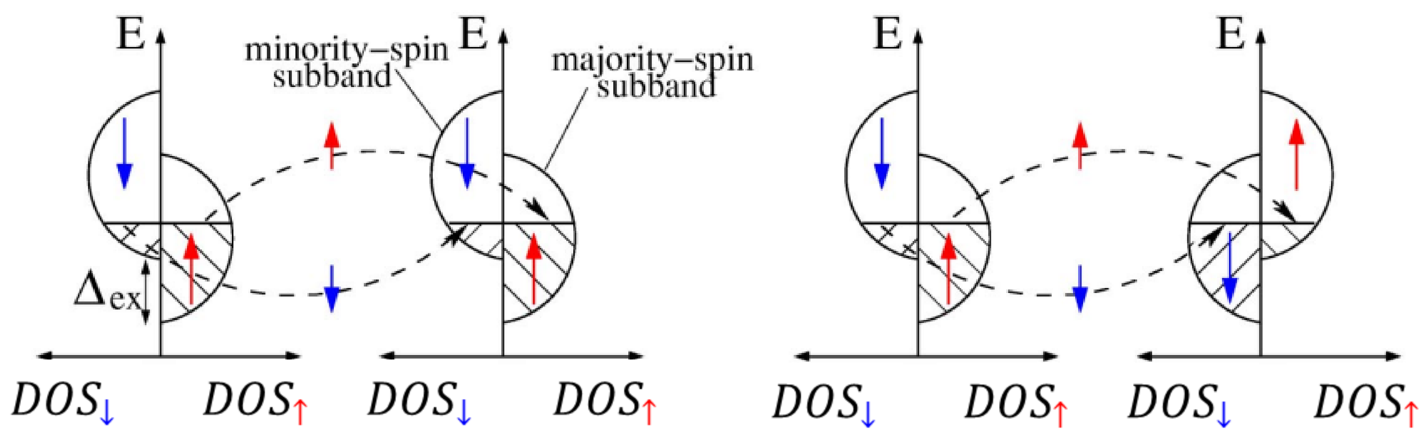
for charge transport, only the states near the Fermi energy are important

difference in the density of states (DOS)

magnetic tunnel junctions: tunneling magnetoresistance

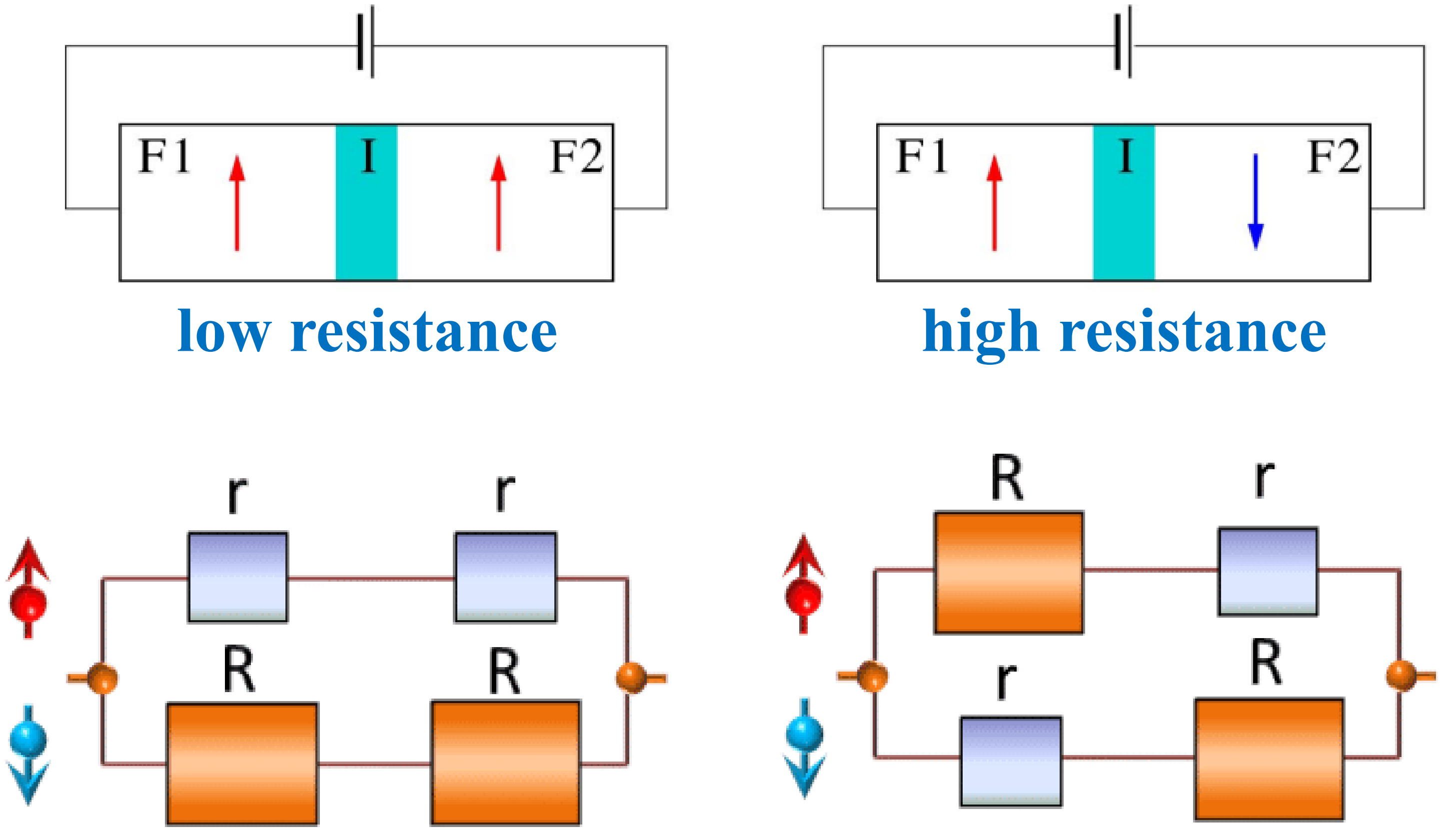


low resistance high resistance



Zutic *et al.*, Reviews of Modern Physics **76**, 323 (2004)

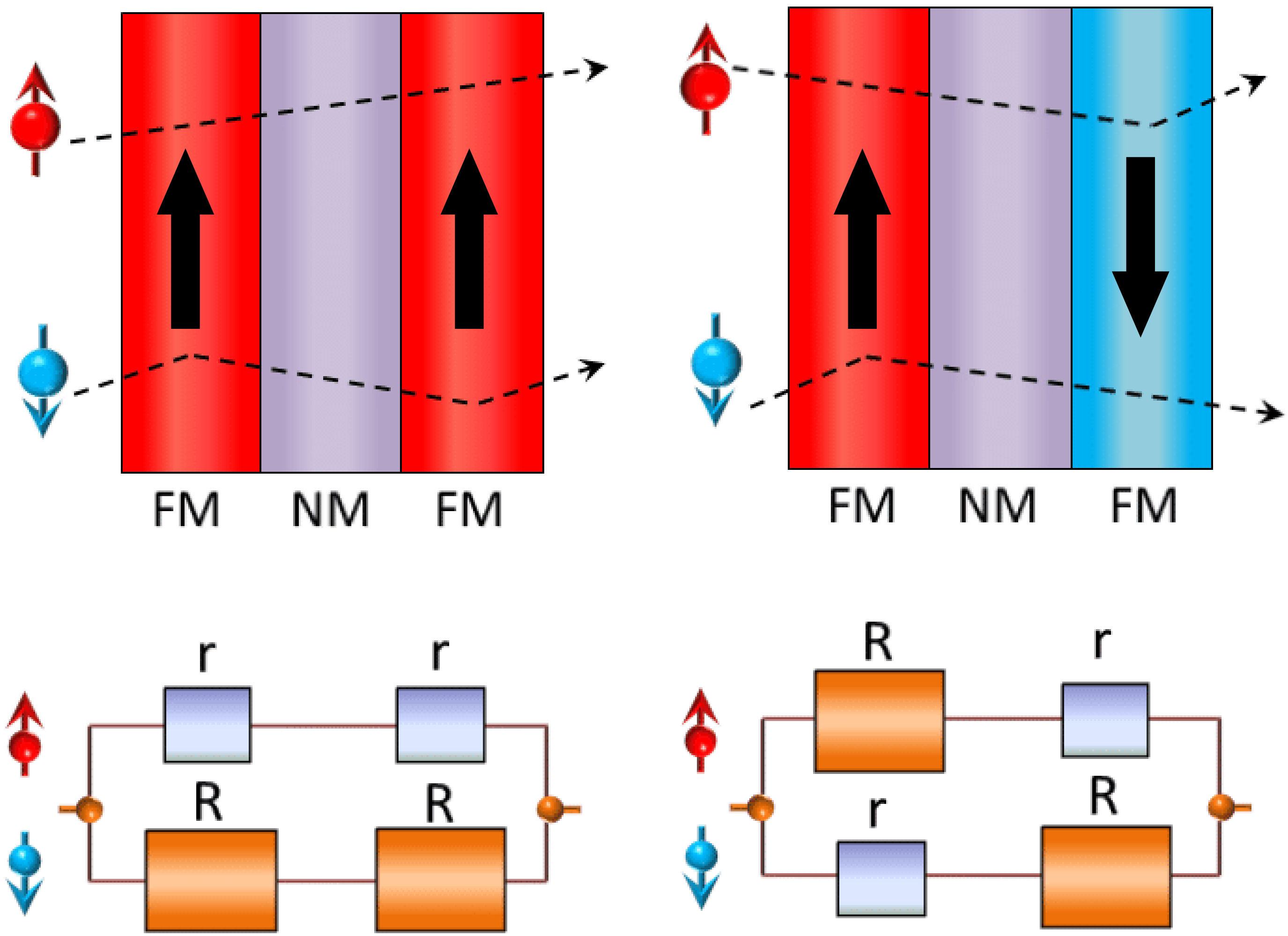
magnetic tunnel junctions: corresponding electrical circuit



Zutic *et al.*, Reviews of Modern Physics **76**, 323 (2004)

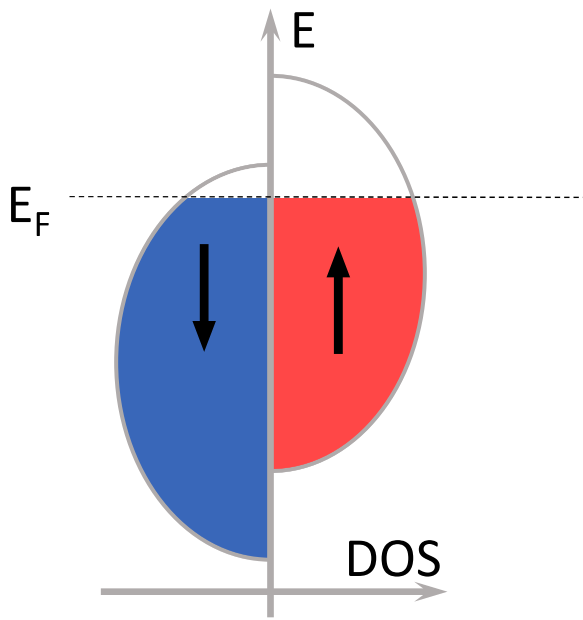
giant magnetoresistance

replacing the insulator with a conducting material… (almost the) same story

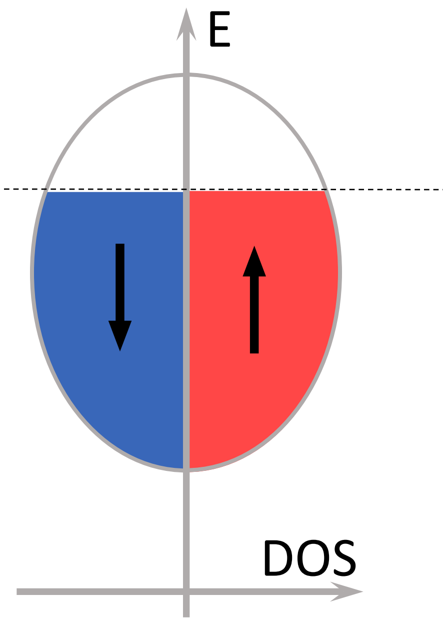


ferromagnetic versus non-magnetic material

Ferromagnet (FM)

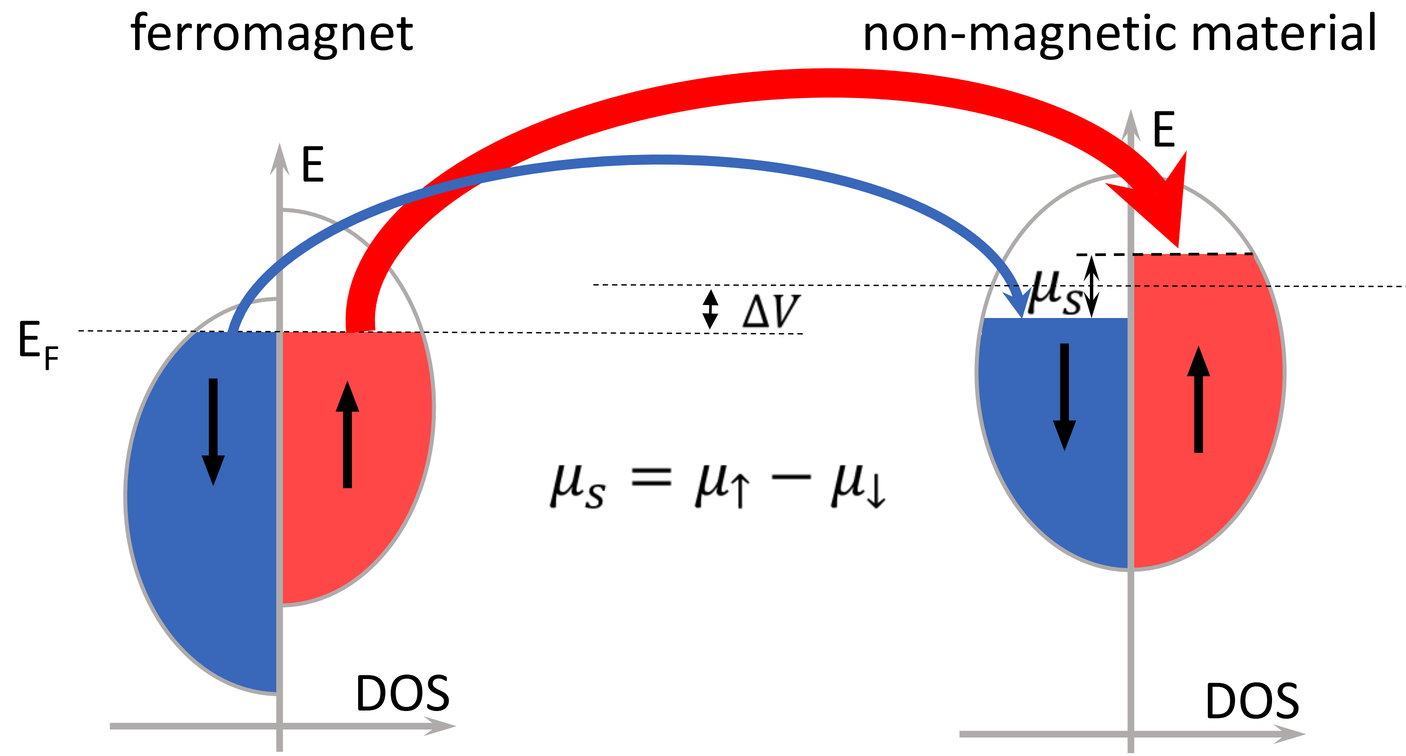


Non-magnetic material (NM)



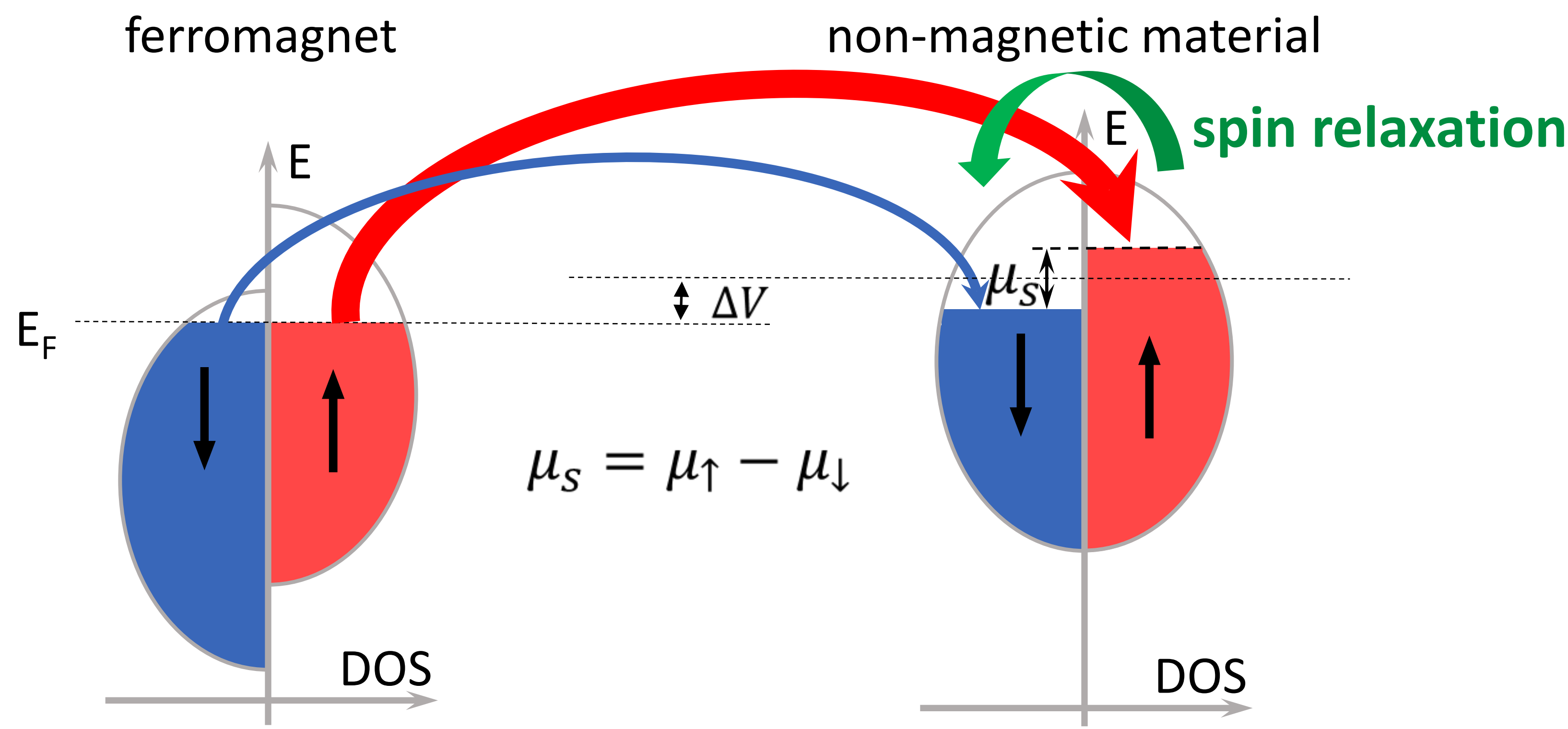
What happens if we pass a current between them?

ferromagnetic versus non-magnetic material



Which factors determine μ_s?

ferromagnetic versus non-magnetic material



Which factors determine μ_s?

spin polarization in FM and spin relaxation in non magnet

spin relaxation

spin relaxation length (λ_s)

$$\lambda_s = \sqrt{\tau_s D}$$

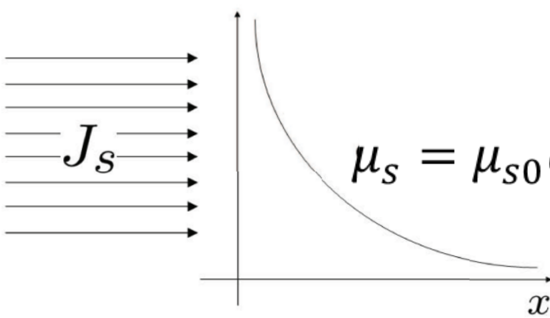
D: diffusion coefficient $\left(D = \frac{1}{2} v_F^2 \tau\right)$

spin diffusion equation

$$\frac{d\mu_s}{dt} = D\frac{d^2\mu_s}{dx^2} - \frac{\mu_s}{\tau_s}$$

μ_s: spin accumulation
τ_s: spin lifetime

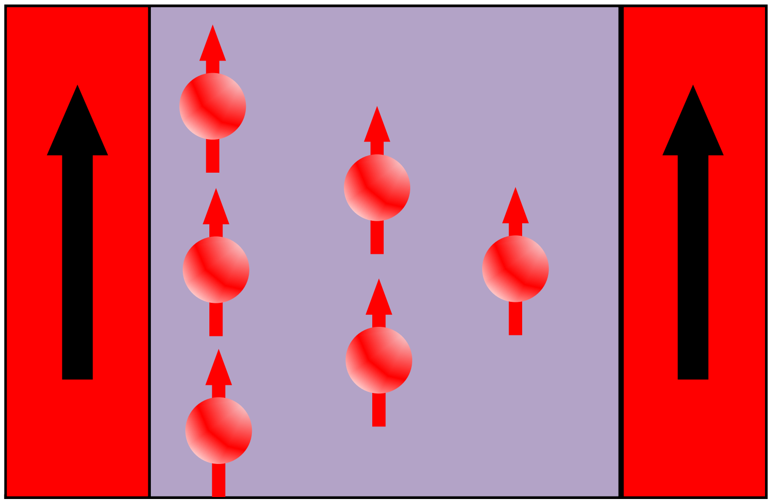
$$\mu_{s0} \sim J_s \lambda_s$$

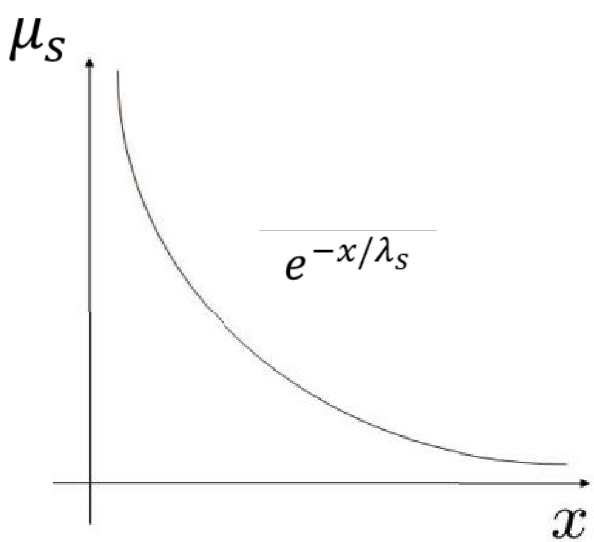


$$\mu_s = \mu_{s0} e^{-x/\lambda_s}$$

steady state solution $\frac{d\mu_s}{dt} = 0$

thickness dependence of giant magnetoresistance





	λ_s
Pt	10 nm
Al/Cu	0.1-1 µm
graphene	1-30 µm

very long spin relaxation lengths for graphene makes it an interesting material for spintronics

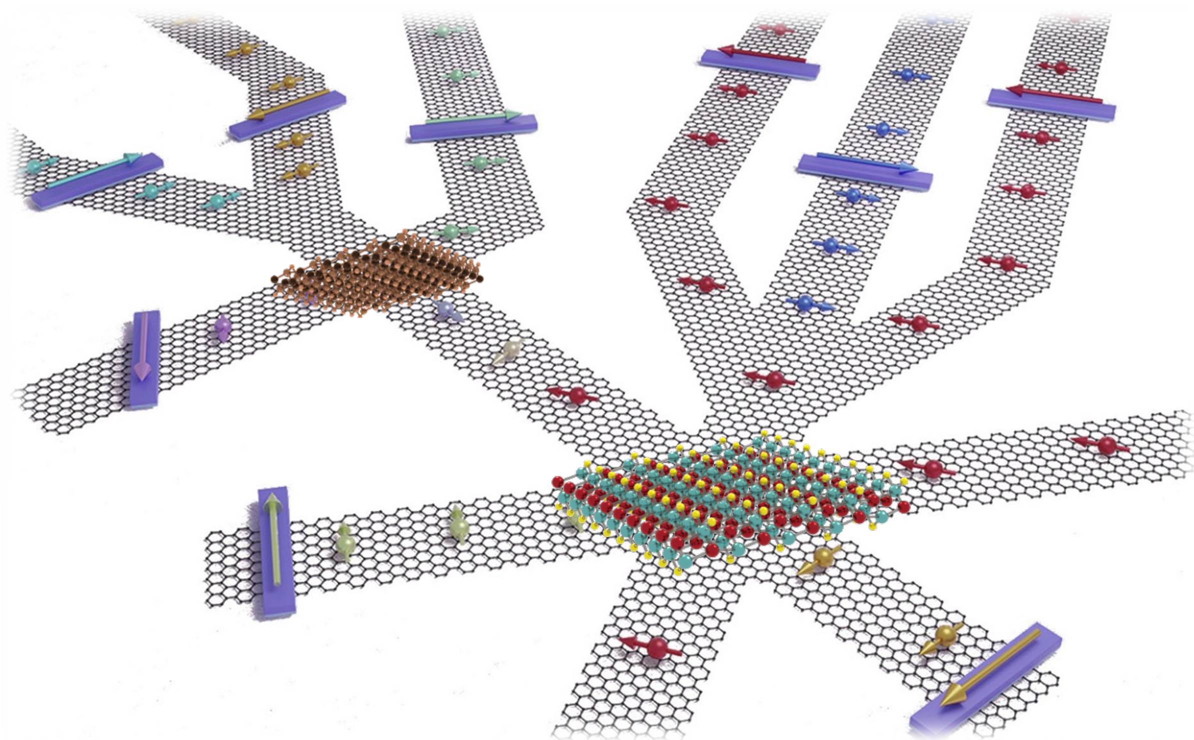
diffusive planar spintronic circuits
spin valve and spin-Hall effect

graphene-based spintronic circuits

How to do computations with spin, how to make spintronic logic circuits?

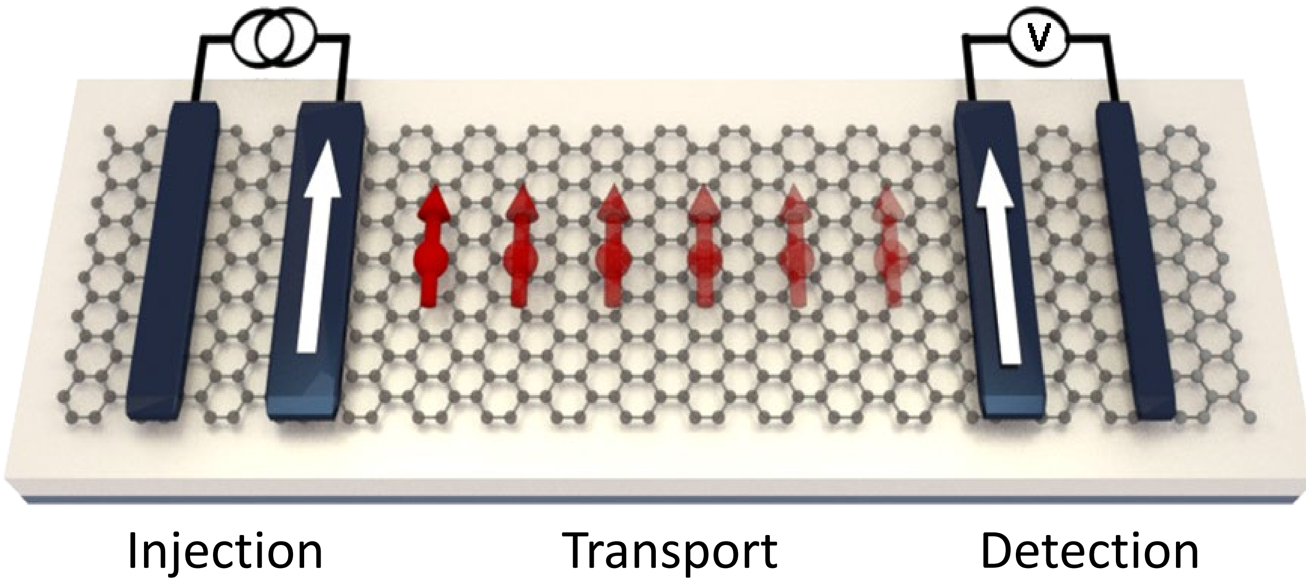
(1) one needs to be able to manipulate the spin .....

(2) while minimizing spin dephasing by spin diffusion



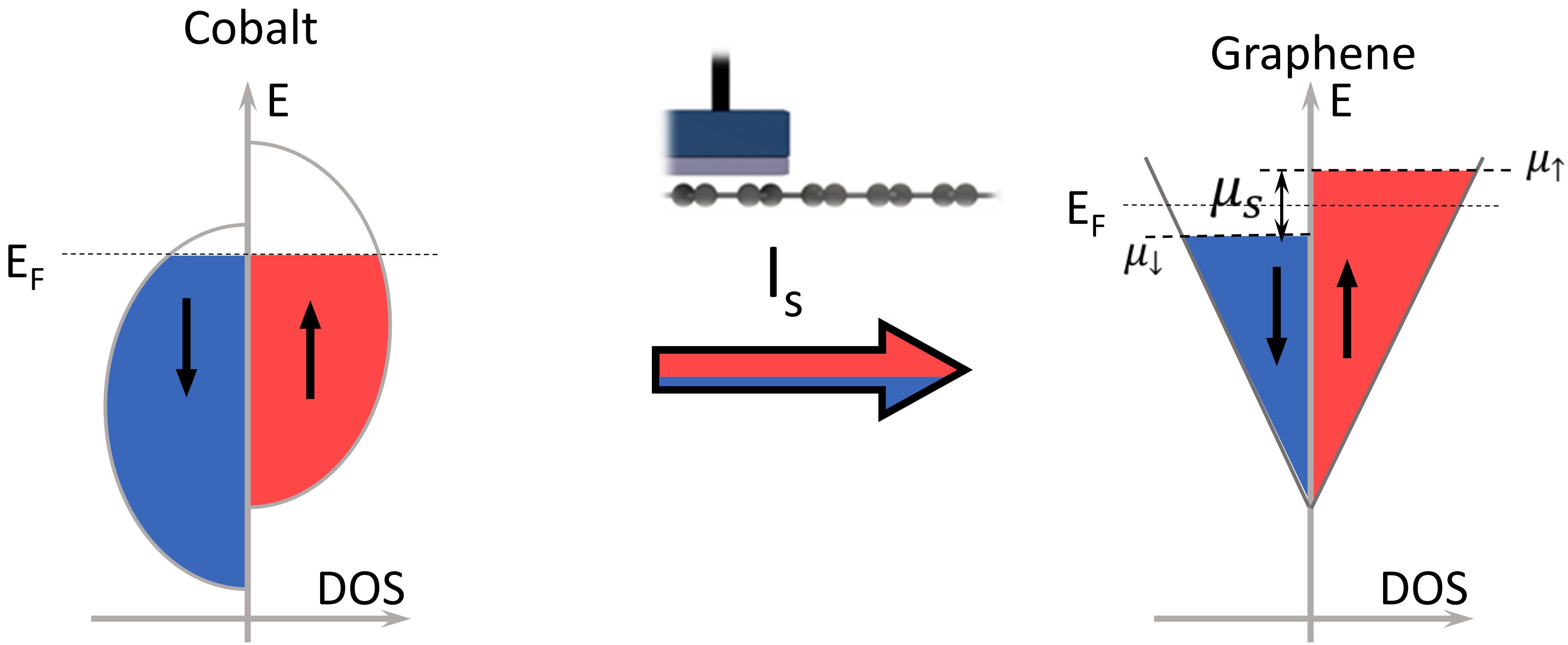
D. Khokhriakov *et al.*, Carbon **161**, 892 (2020)

graphene-based spintronic circuits: *planar* spin valve device



- High charge carrier mobility
- Low spin-orbit coupling

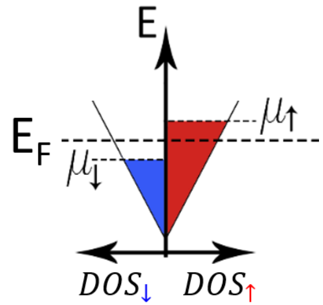
spin injection from cobalt to graphene

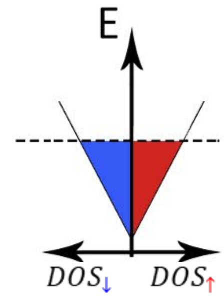


$$\mu_s = \mu_\uparrow - \mu_\downarrow$$

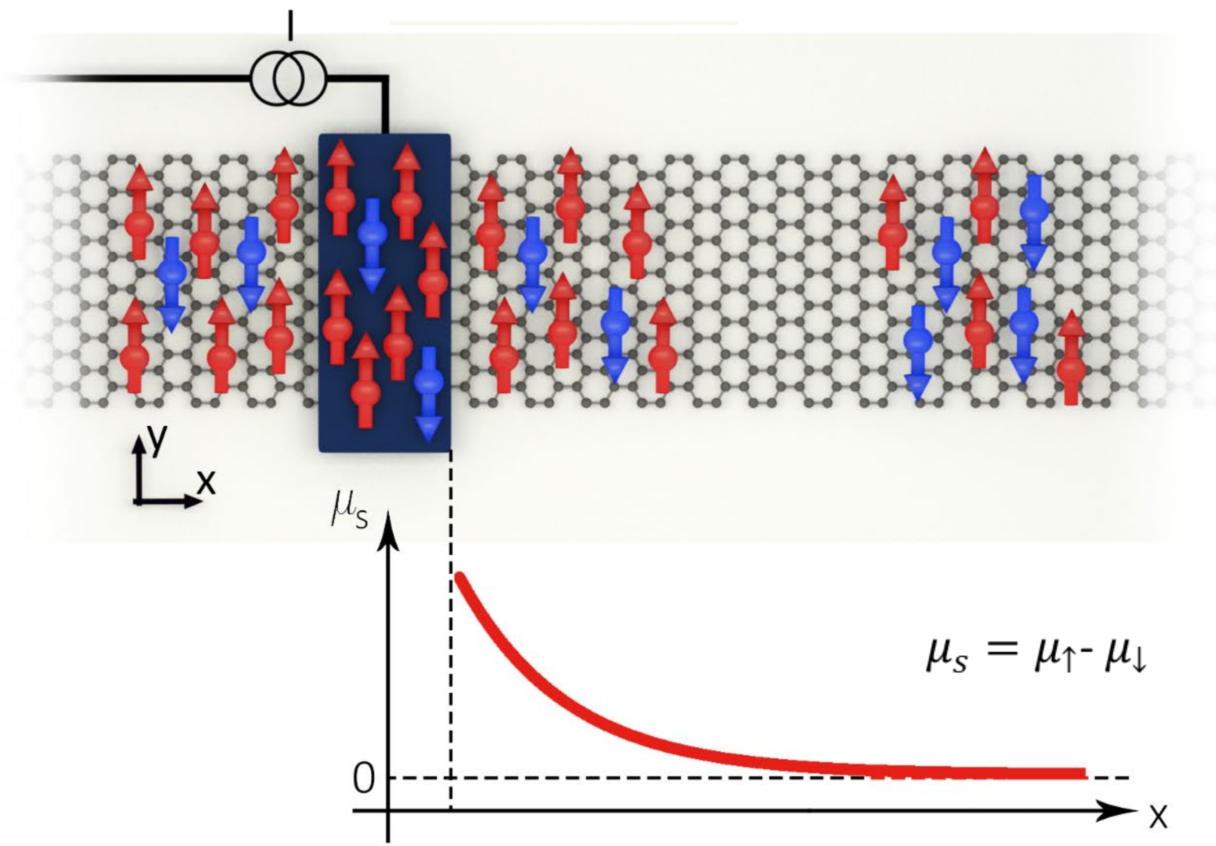
Spin accumulation

spin injection from cobalt to graphene and spin diffusion



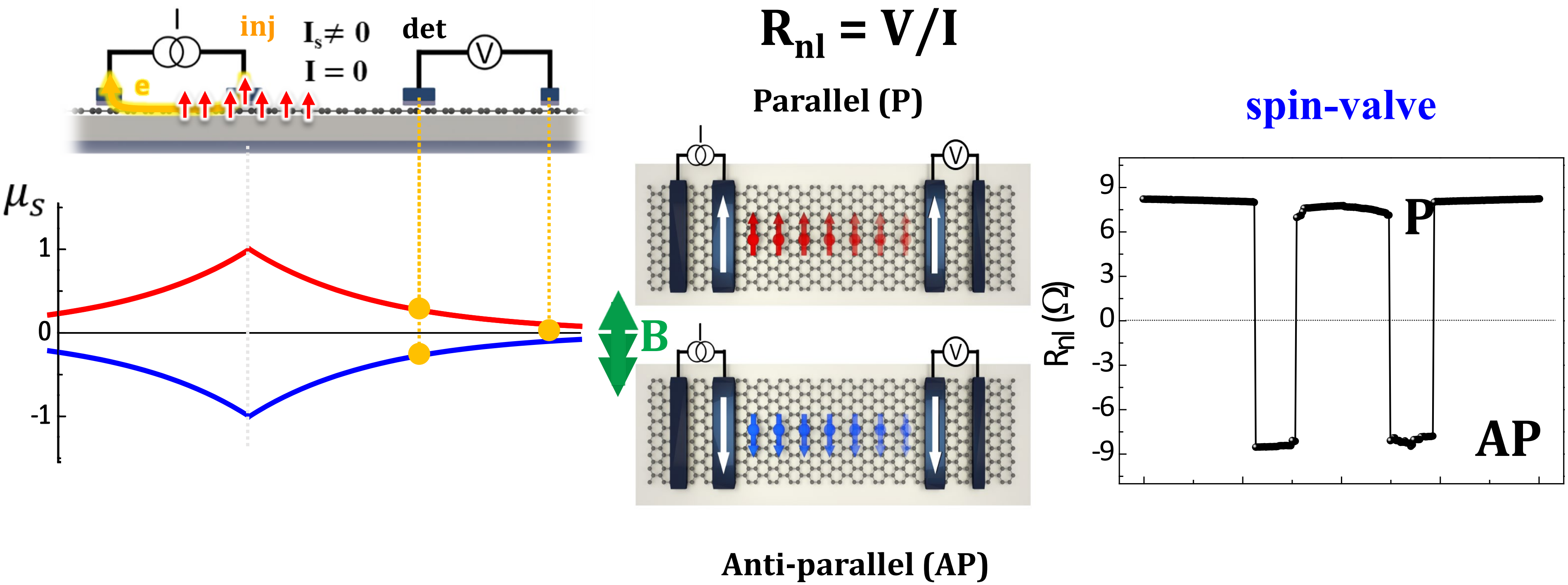


Nano letters **16**, 3533 (2016)



$\lambda_s = 30\ \mu m$

‘non-local’ measurement of spin signal: spin valve

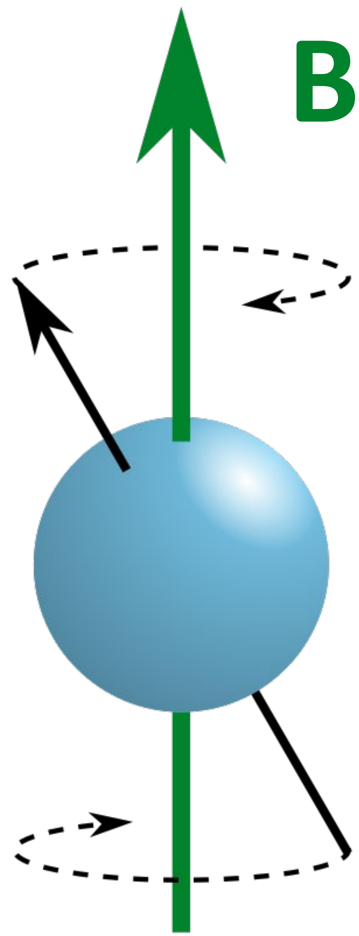


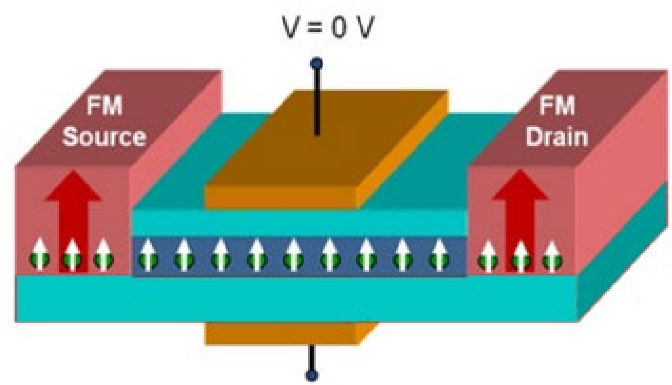
What do we need for spin logic operations?

Manipulation of the spin signal… but how?

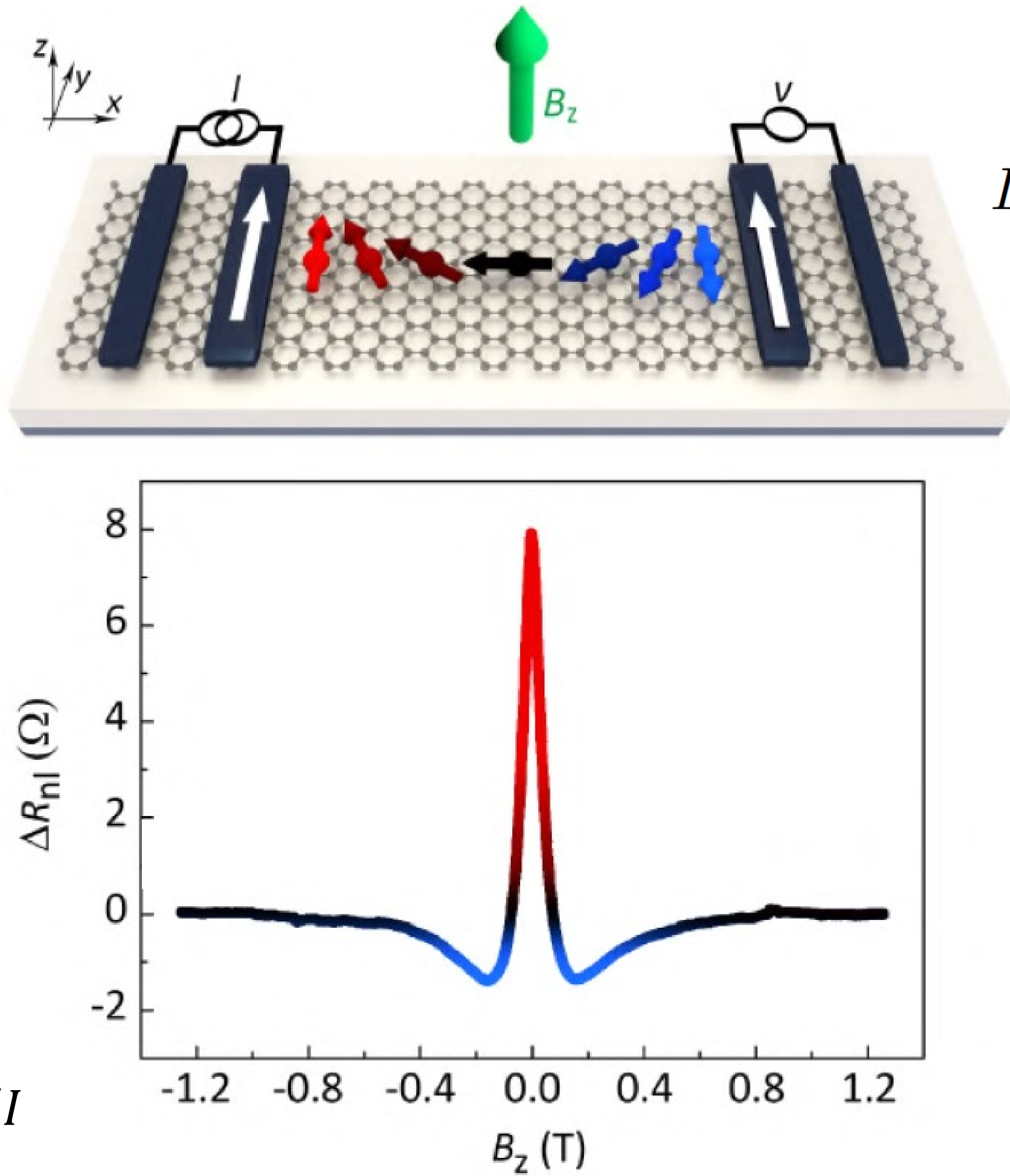
1. By magnetic field:

$$\vec{\omega} = \frac{g\mu_B \vec{B}}{\hbar}$$





Larmor precession



$$D_s \nabla^2 \vec{\mu}_s - \vec{\mu}_s/\tau_s + \vec{\omega} \times \vec{\mu}_s = 0$$

$R_{nl} = V/I$

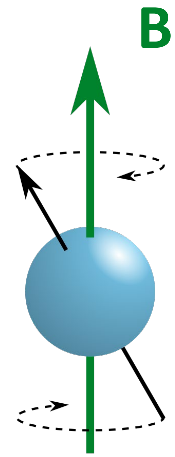
Application in integrated circuits?!

What do we need for spin logic operations?

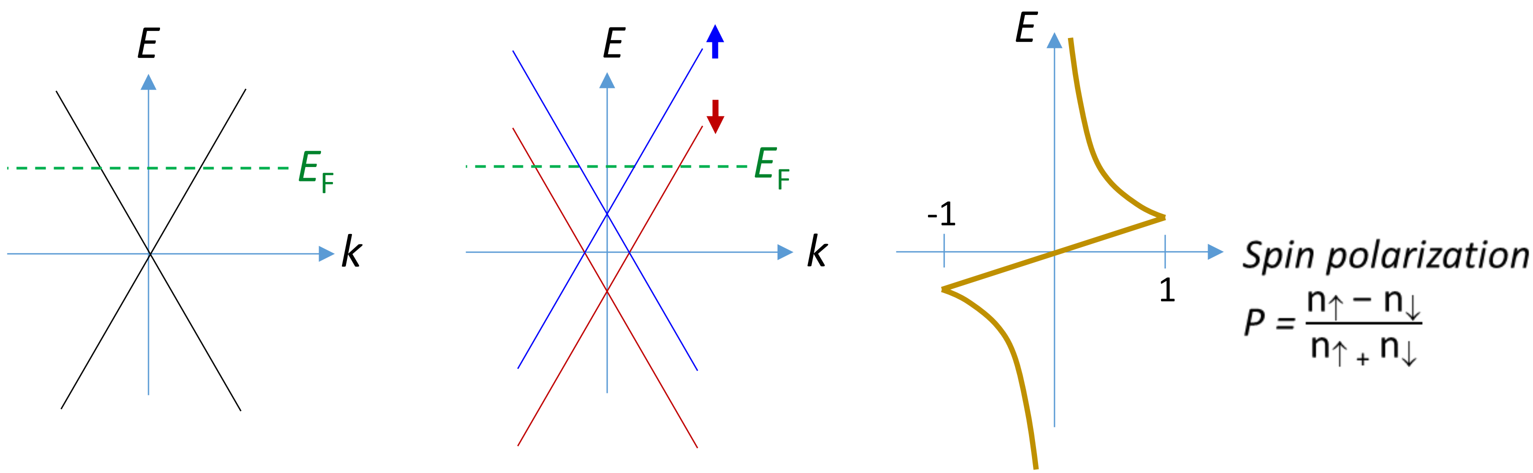
Manipulation of the spin signal… but how?

1. By magnetic field: through Larmor precession

$$\vec{\omega} = \frac{g\mu_B \vec{B}}{\hbar}$$



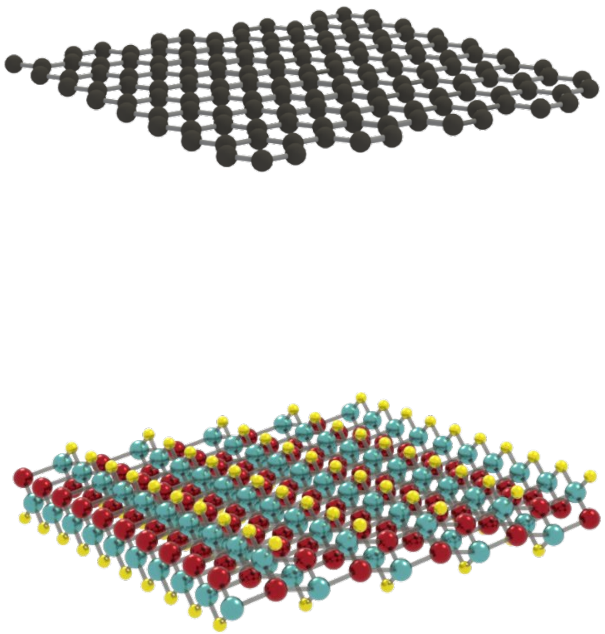
2. By electric field: through introducing spin-splitting in graphene band structure

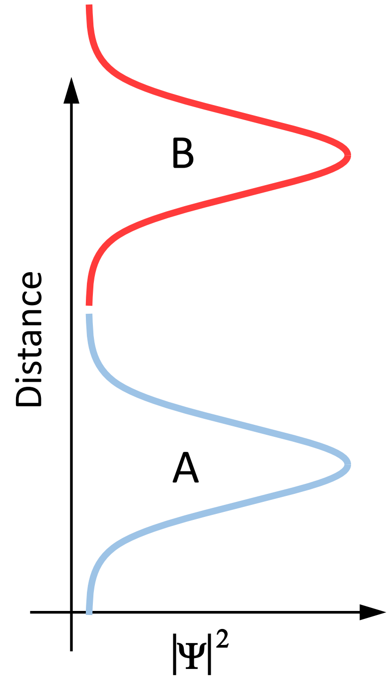


How to change graphene band structure? proximity effect

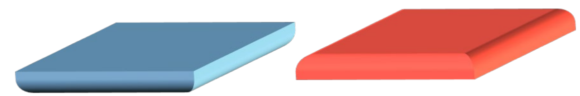
graphene on graphene:
twistronics and bi-layer
graphene with a gap

Van der Waals heterostructures





Material A Material B

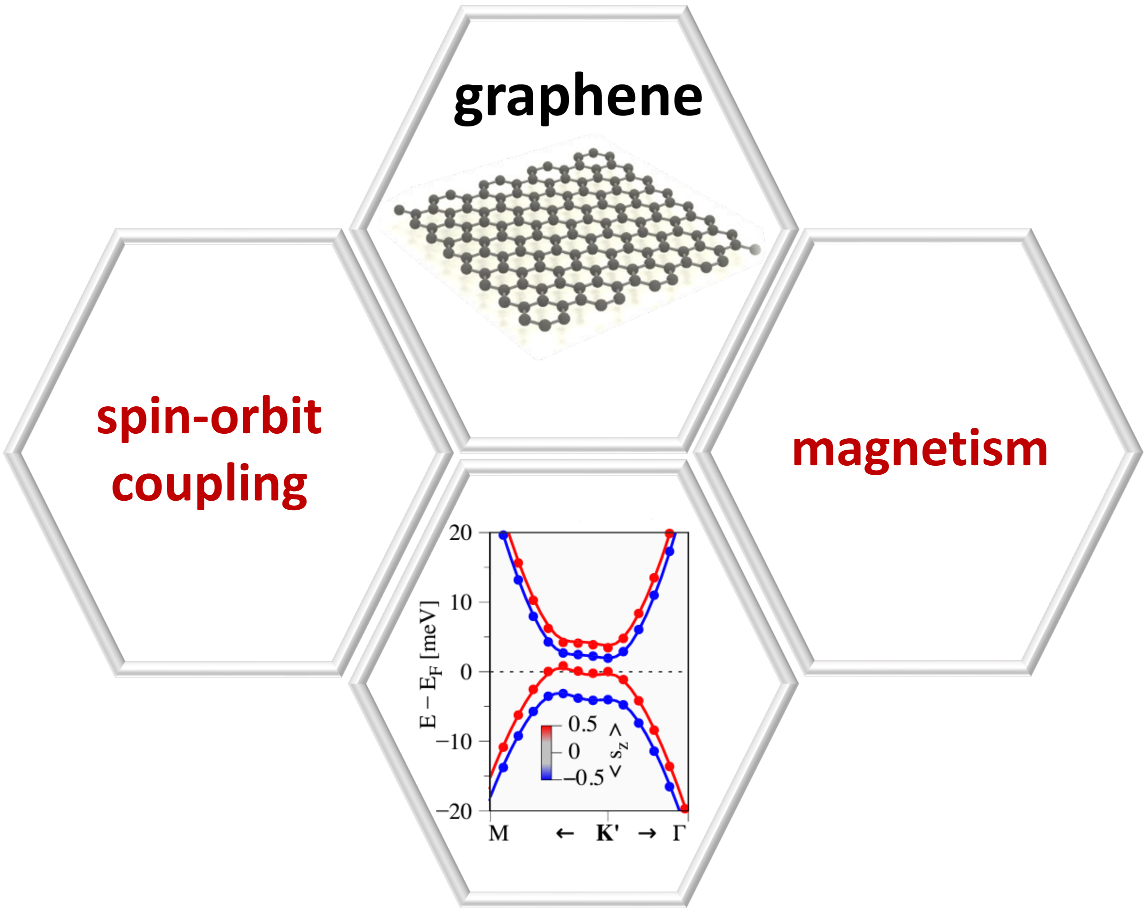


KS Novoselov et al., Science **353**, 9439 (2016)

JF Sierra, et al. Nat. Nano. **16**, 856 (2021)

in this way, materials with new properties can be created …

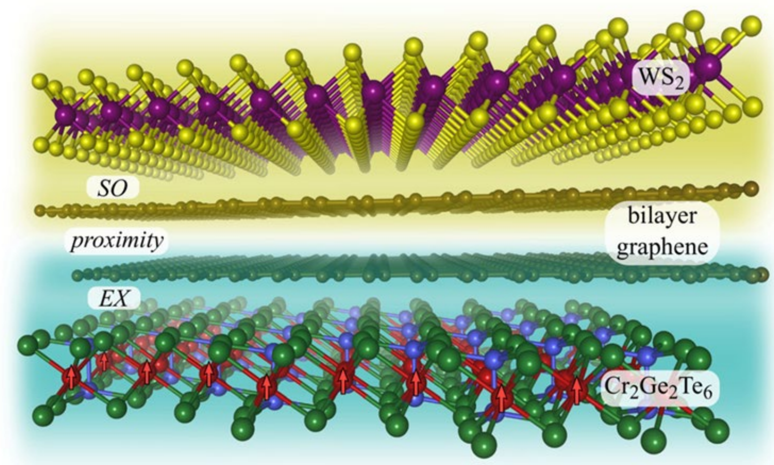
tailoring graphene band structure



- exchange, spin-orbit and charge transfer may all be present at the same time: difficult to predict the behavior of heterostructures

- angle between the atomic lattices, and interface are other important considerations

transition metal dichalcogenides (MX_2)



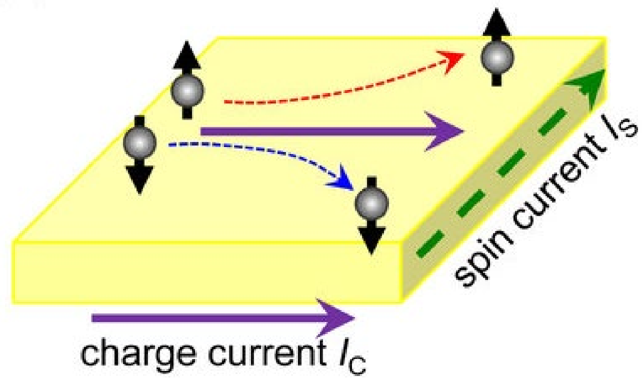
magnetic material

K Zollner et al., PRL **125**, 196402 (2020)

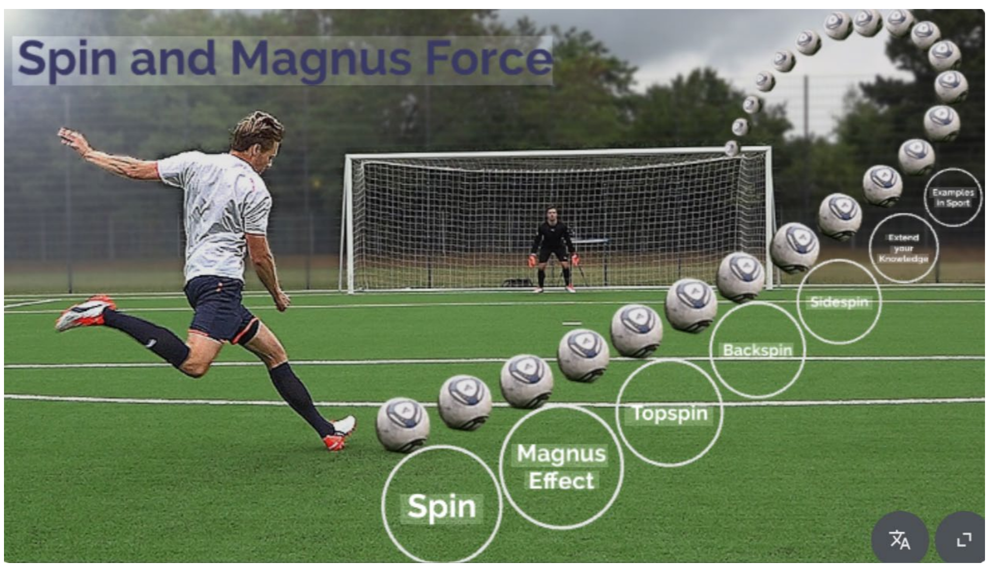
spin Hall effect due to the spin-orbit coupling in the TMDC

- coupling of spin and orbital motion of electrons results in deviation of the spin-up and spin-down electrons towards opposite directions

- spin-to-charge conversion of information

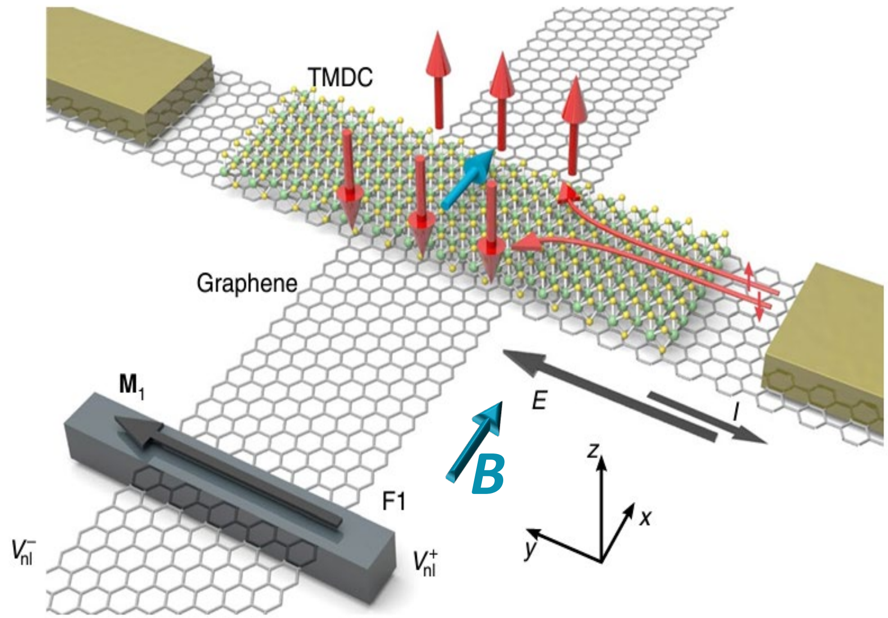


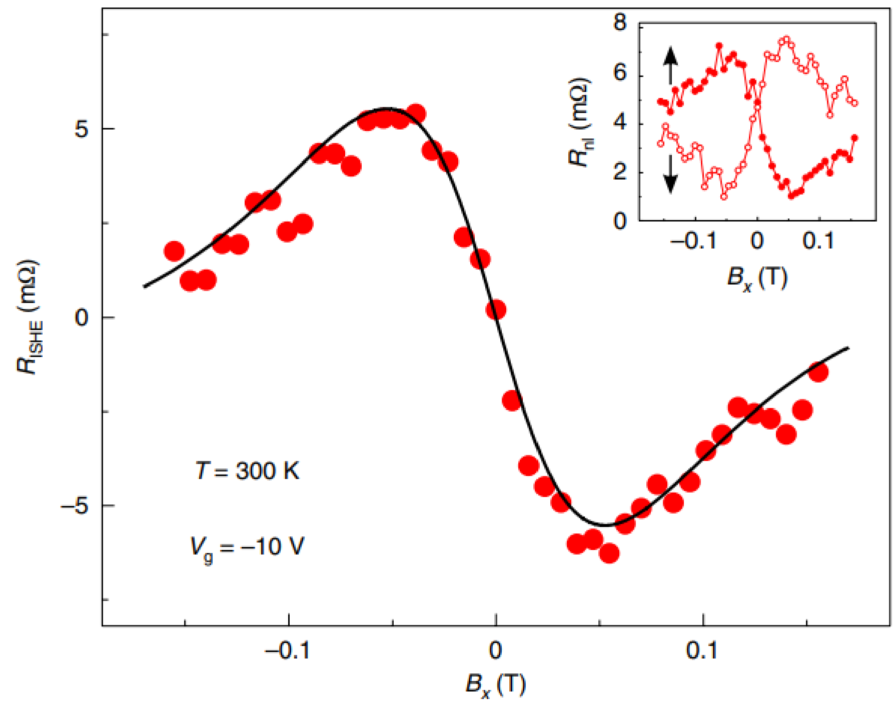
analogous to Magnus effect



spin Hall effect in a graphene-TMDC heterostructure

TMDC = WS_2





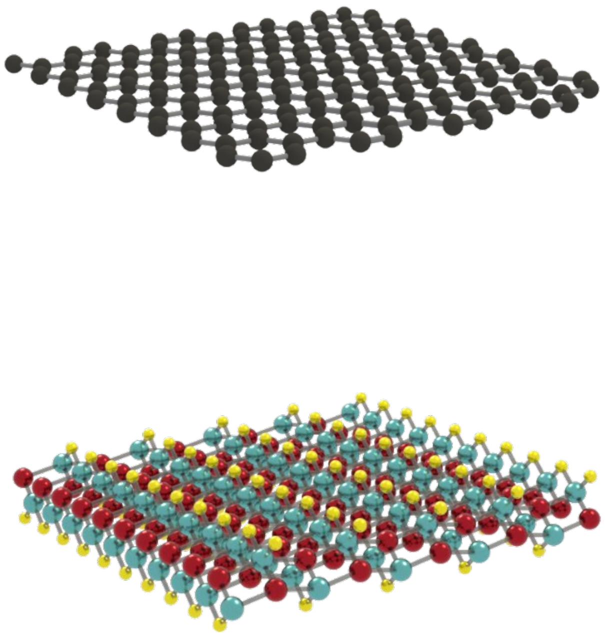
a charge current generates a diffusive, transverse spin current and a non-equilibrium spin density leading to a non-local resistance at position F1 (not an easy measurement to understand in one slide)

L Benitez et al., Nat. Mat. **19** (2020) 170 - 175

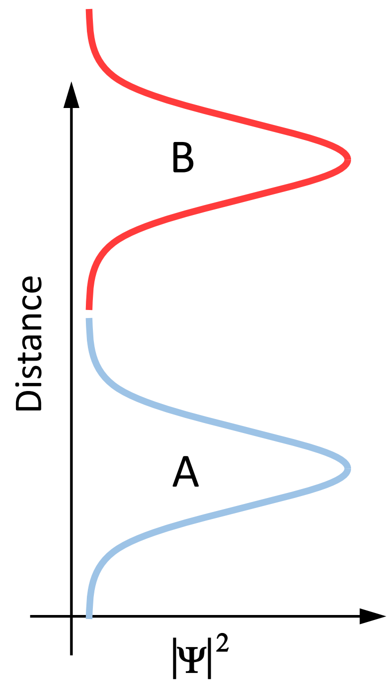
magnetic graphene and the quantum spin Hall effect

inducing magnetism in graphene

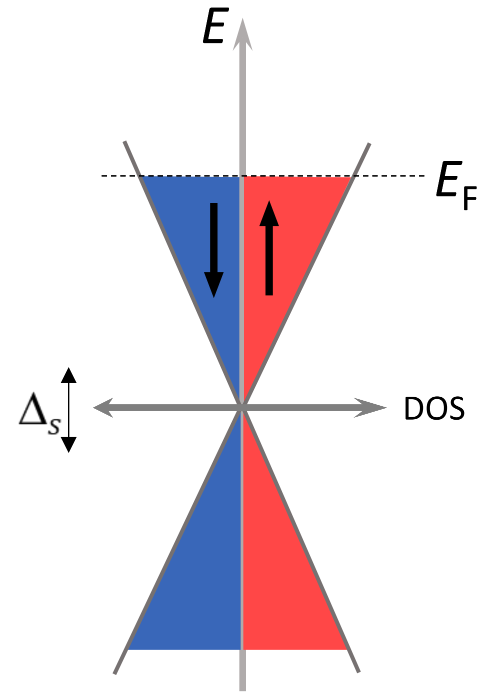
van der Waals heterostructures



2D magnet



graphene

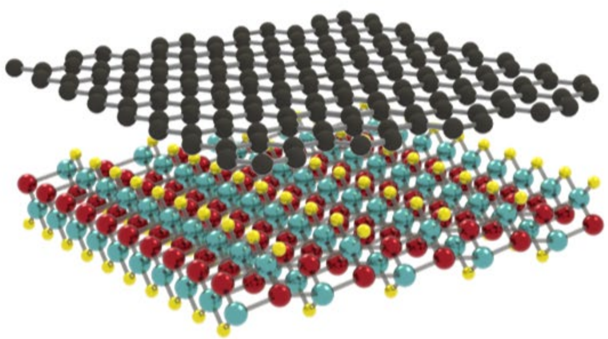


KS Novoselov et al., Science **353**, 9439 (2016)

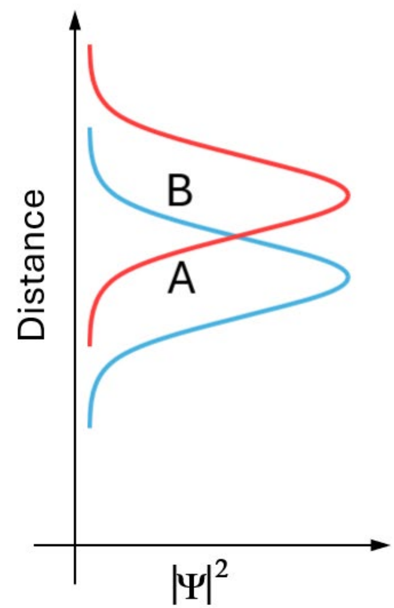
JF Sierra, et al. Nat. Nano. **16**, 856 (2021)

inducing magnetism in graphene

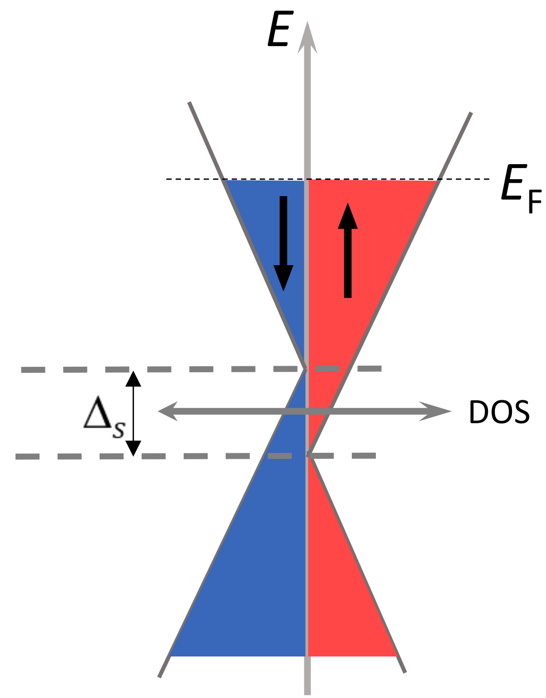
Van der Waals heterostructures



2D magnet



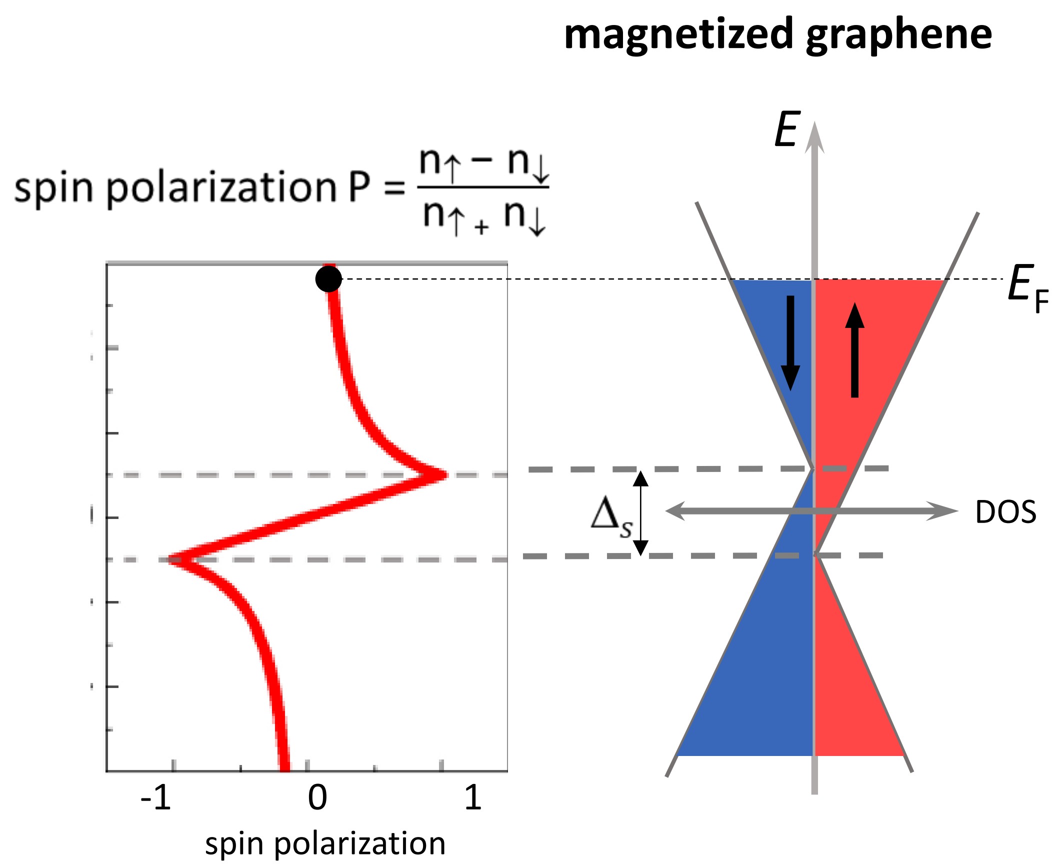
magnetized graphene



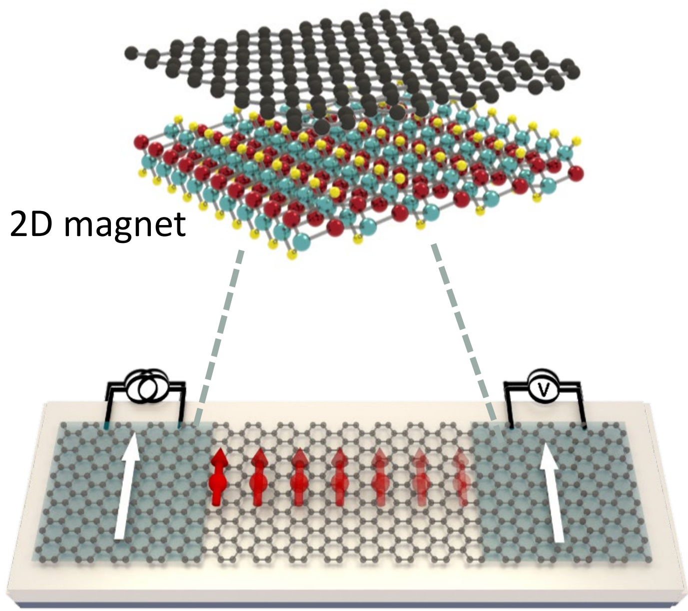
KS Novoselov et al., Science **353**, 9439 (2016)

JF Sierra, et al. Nat. Nano. **16**, 856 (2021)

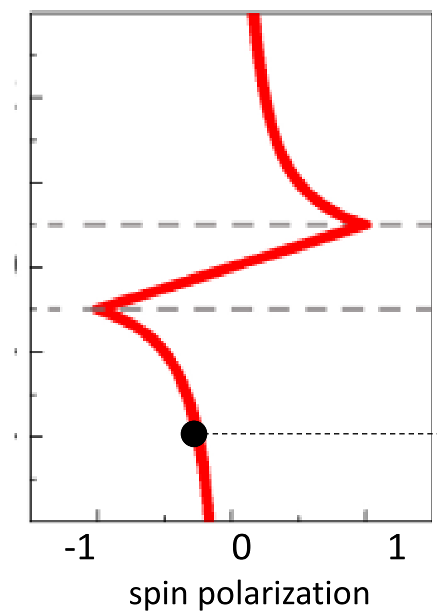
inducing magnetism in graphene



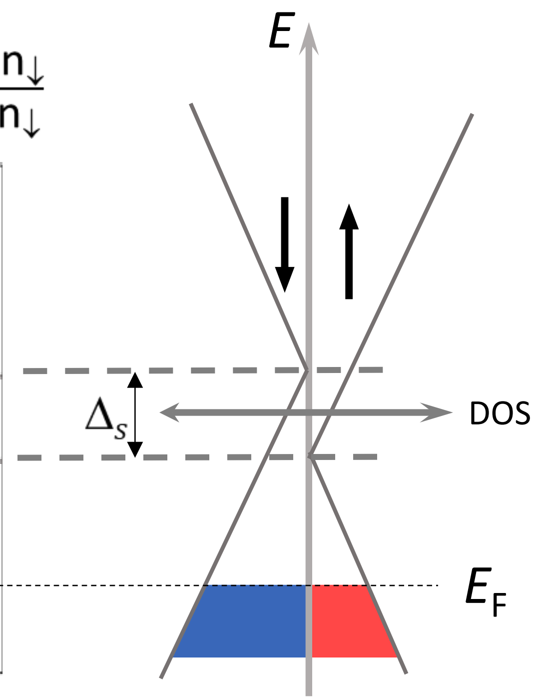
inducing magnetism in graphene



spin polarization $P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$

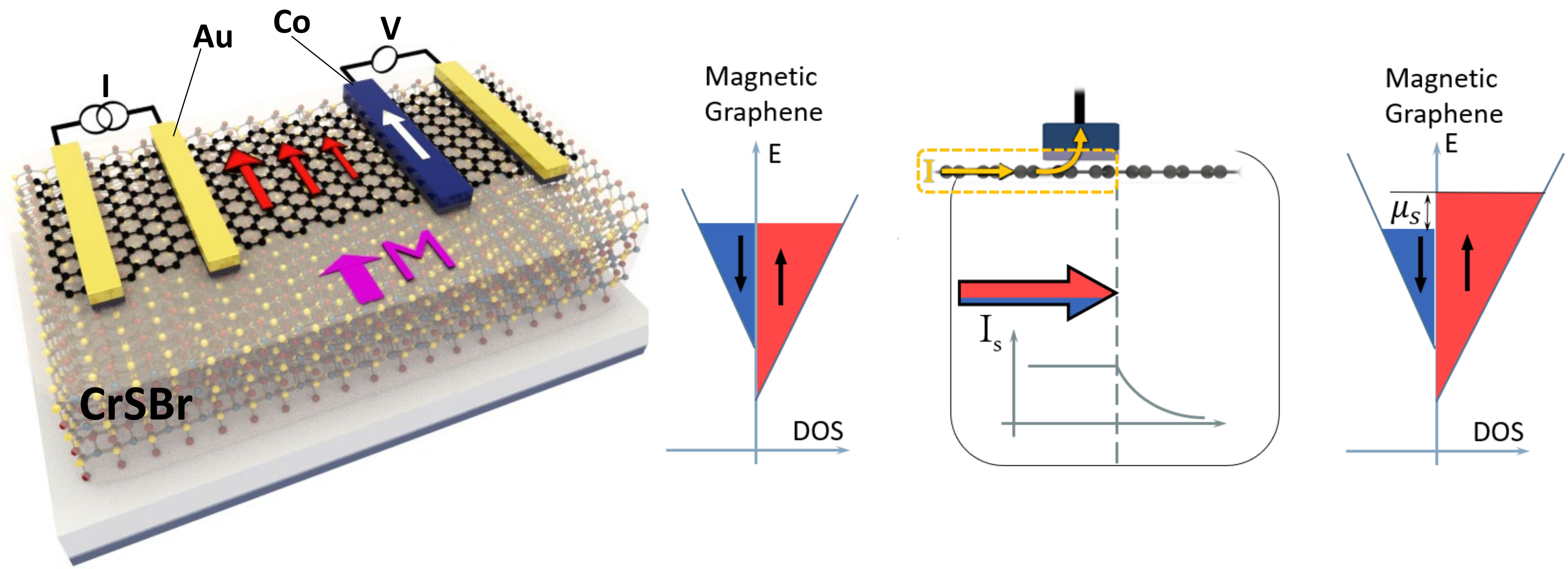


magnetized graphene



TS Ghiasi et al., Nat. Nano. **16**, 788 (2021)
AA Kaverzin et al., 2D Mater. **9**, 045003 (2022)

spin injection by magnetized graphene

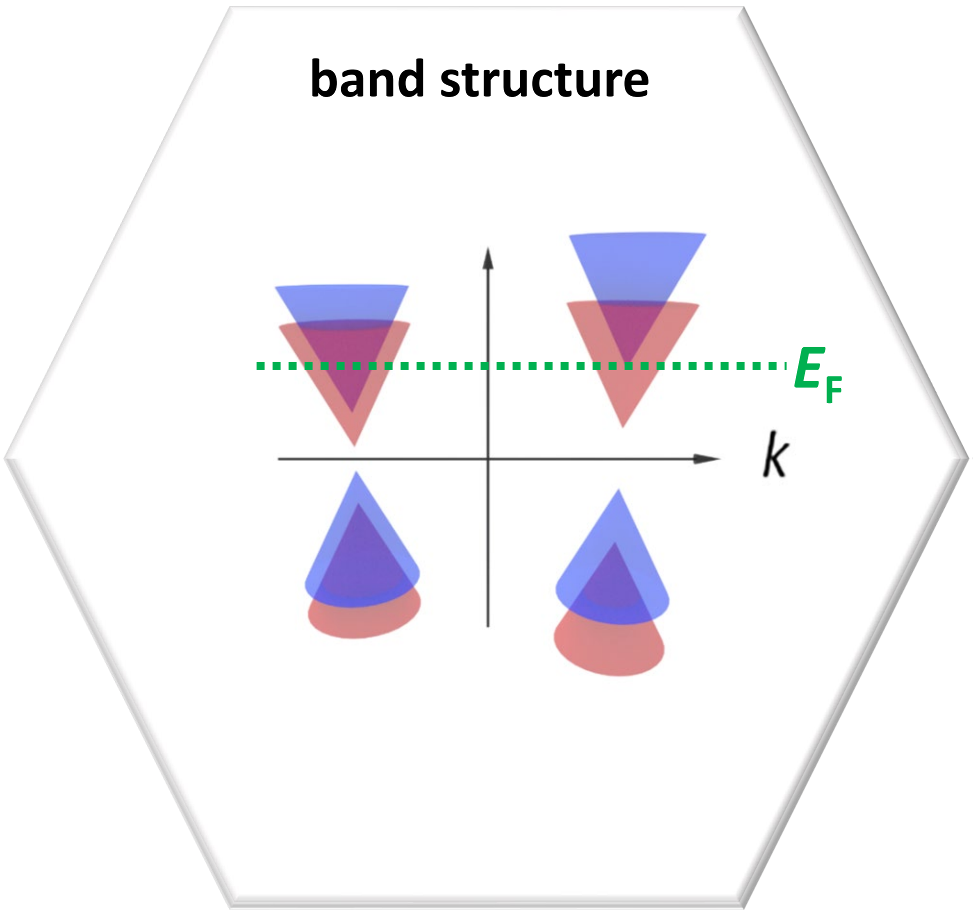


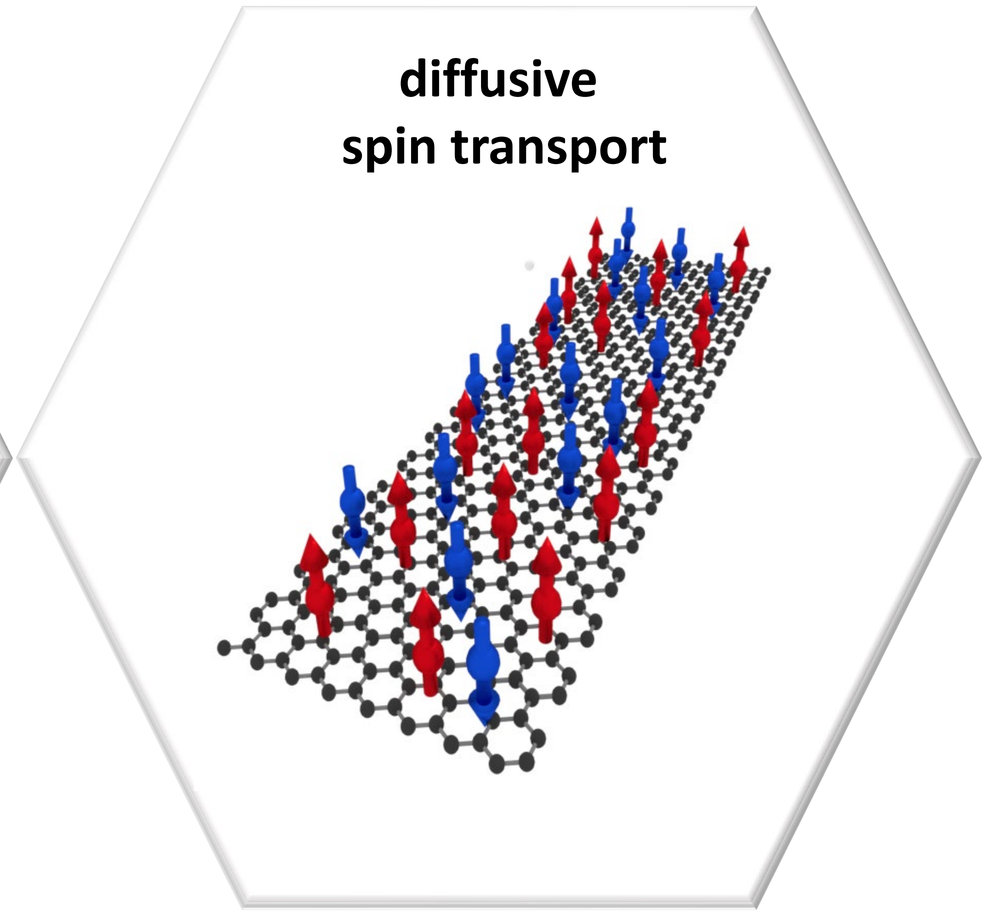
for spin detection one Cobalt electrode is still needed

AA Kaverzin et al., 2D Mater. **9**, 045003 (2022)

diffusive spin transport: spin relaxation

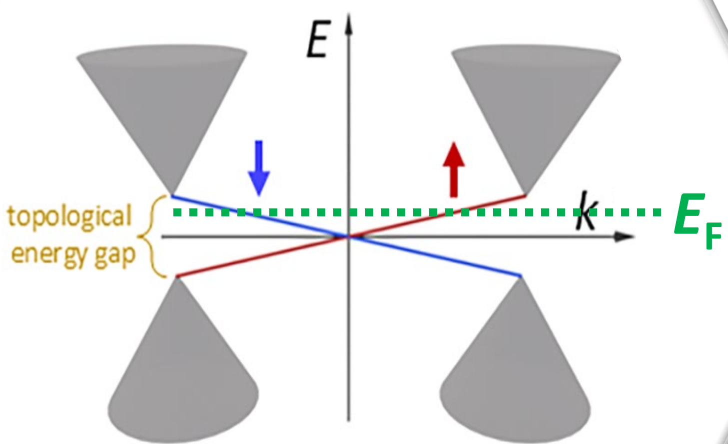
How to do computations with spin, how to make spintronic logic circuits?
(1) one needs to be able to manipulate the spin .....
(2) while minimizing spin dephasing by spin diffusion



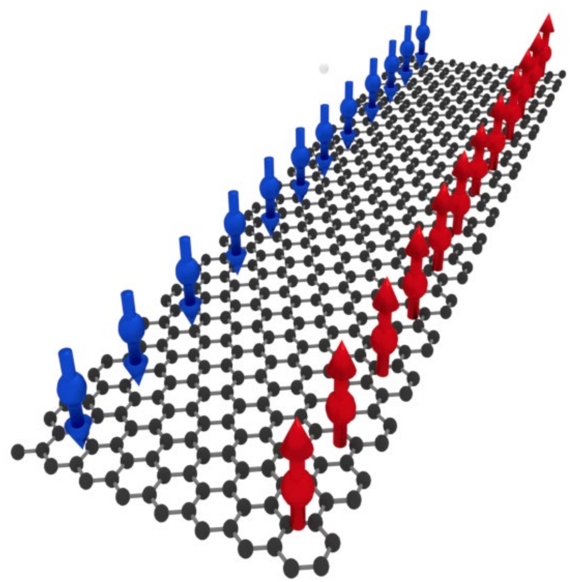


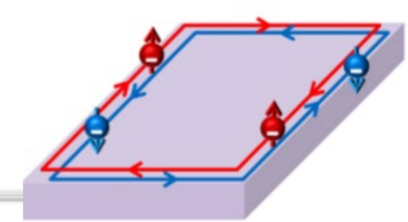
ballistic spin transport: topologically protected spin transport

topological band structure



topological spin transport





helical states
(counter-propagating spin-polarized edge states)

L. Kane and J. Mele. PRL **95**, 226801 (2005)

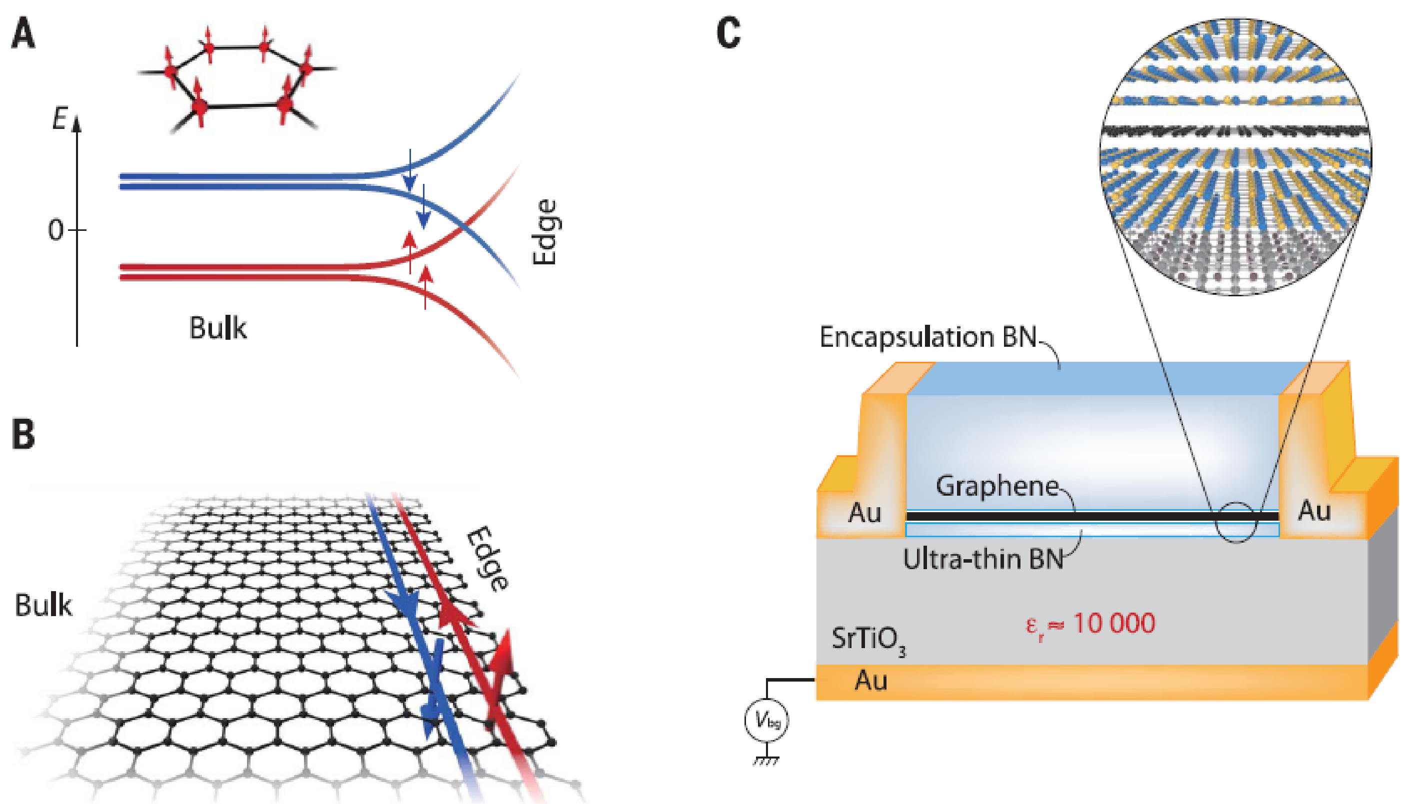
helical edge states at low magnetic field

TOPOLOGICAL MATTER

Veyrat *et al.*, *Science* **367**, 781–786 (2020)

Helical quantum Hall phase in graphene on $SrTiO_3$

Louis Veyrat[1], Corentin Déprez[1], Alexis Coissard[1], Xiaoxi Li[2,3,4], Frédéric Gay[1], Kenji Watanabe[5], Takashi Taniguchi[5], Zheng Han[2,3,4], Benjamin A. Piot[6], Hermann Sellier[1], Benjamin Sacépé[1*]



- quantum Hall topological insulator due to suitable screening of the Coulomb interaction with the high dielectric constant of the substrate
- helical edges states that are spin and valley filtered observed for magnetic fields as low as 1 T

nature communications

Article

https://doi.org/10.1038/s41467-025-60377-1

Quantum spin Hall effect in magnetic graphene

Received: 28 October 2024

Accepted: 12 May 2025

Published online: 24 June 2025

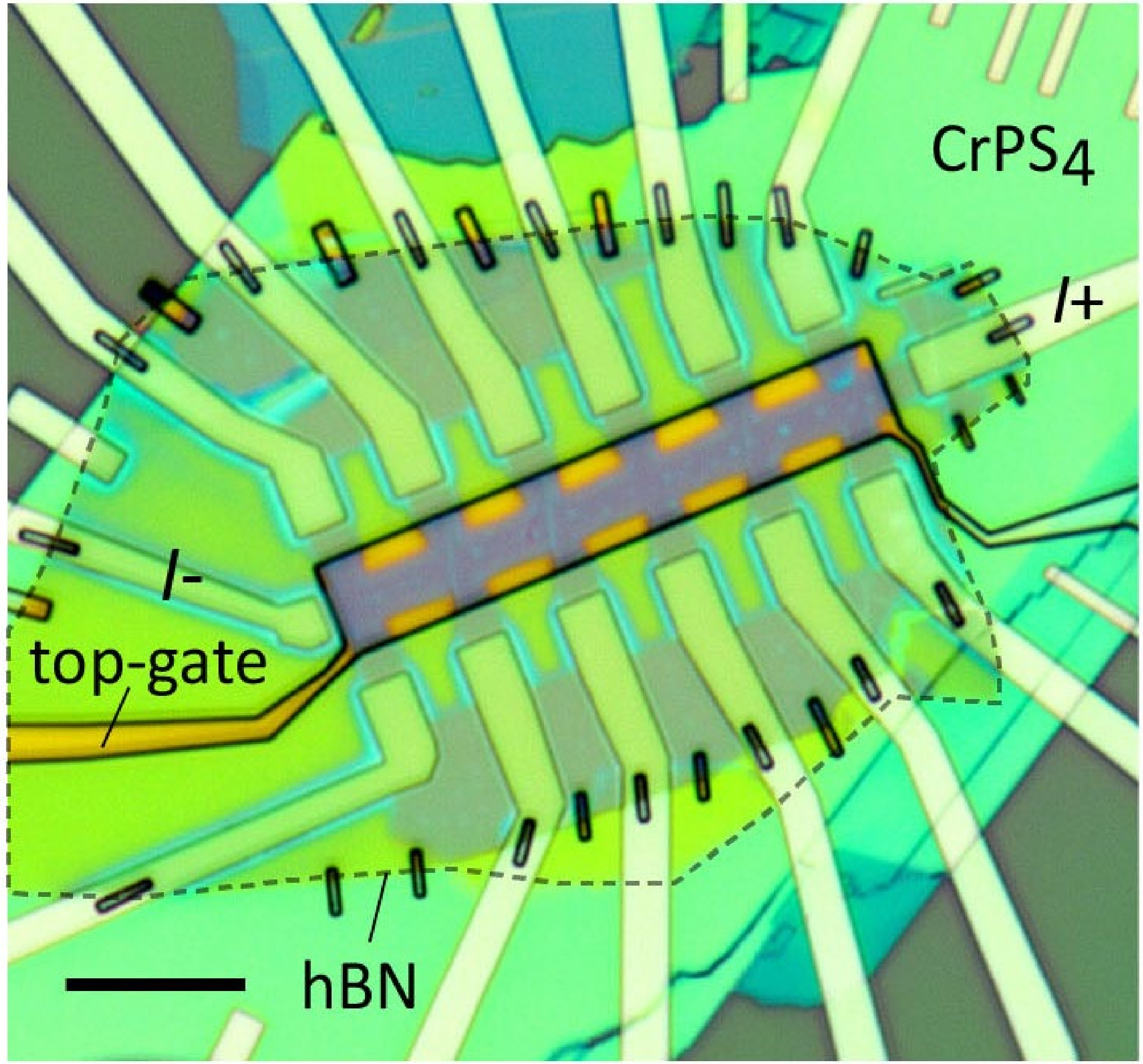
Talieh S. Ghiasi [1,2] ✉, Davit Petrosyan [1], Josep Ingla-Aynés [1], Tristan Bras [1], Kenji Watanabe [3], Takashi Taniguchi [4], Samuel Mañas-Valero [1,5], Eugenio Coronado [5], Klaus Zollner [6], Jaroslav Fabian [6], Philip Kim [2] & Herre S. J. van der Zant [1]

spin-polarized helical edge transport in graphene at zero external magnetic field, allowed by the proximity of an interlayer antiferromagnet, CrPS4.

induce magnetism in graphene Hall bar by the proximity of a 2D magnet

Talieh Giashi

- complex heterostructure fabrication with Au top gate with he transfer of the etched graphene Hall bar
- magnetic $CrPS_4$ (insulating) lies underneath the graphene in direct contact
- $CrPS_4$ obtained from the Coronado group (Valencia)

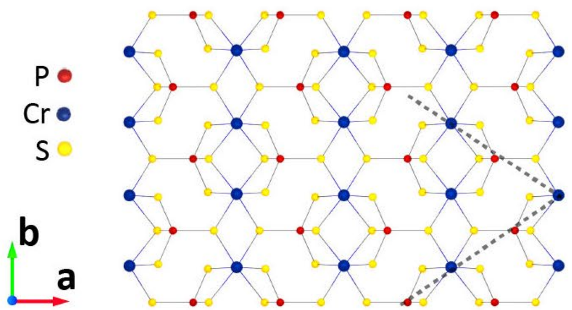


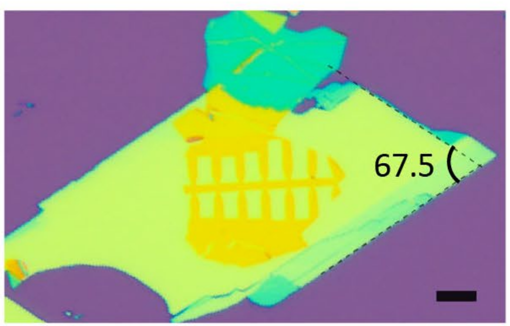
T.S. Ghiasi et al., Nature Communication (2025)

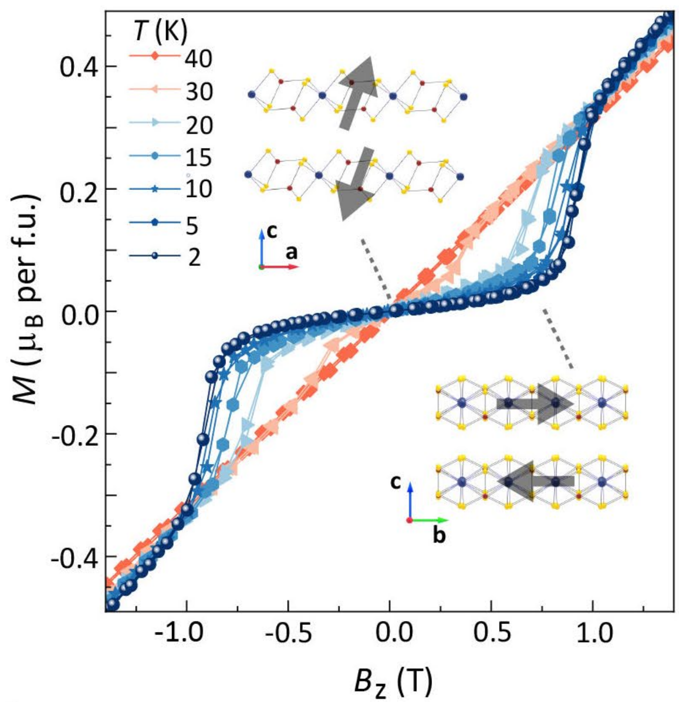
the van der Waals 2D magnet $CrPS_4$

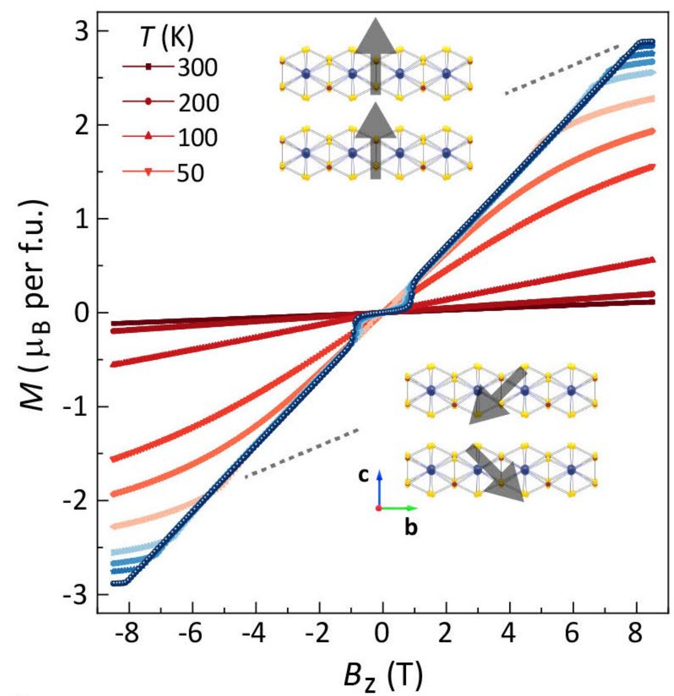
Samuel Mañas Valero

- interlayer antiferromagnet; more or less air-stable semiconductor with a bandgap of ∼1.3 eV and a Néel temperature of 38 K
- increasing B_z above the spin-flop transition field (B_{sf} ∼0.8 T at 2 K) results in canting of the magnetic moments towards the *c*-axis with full saturation at B_z = 8 T



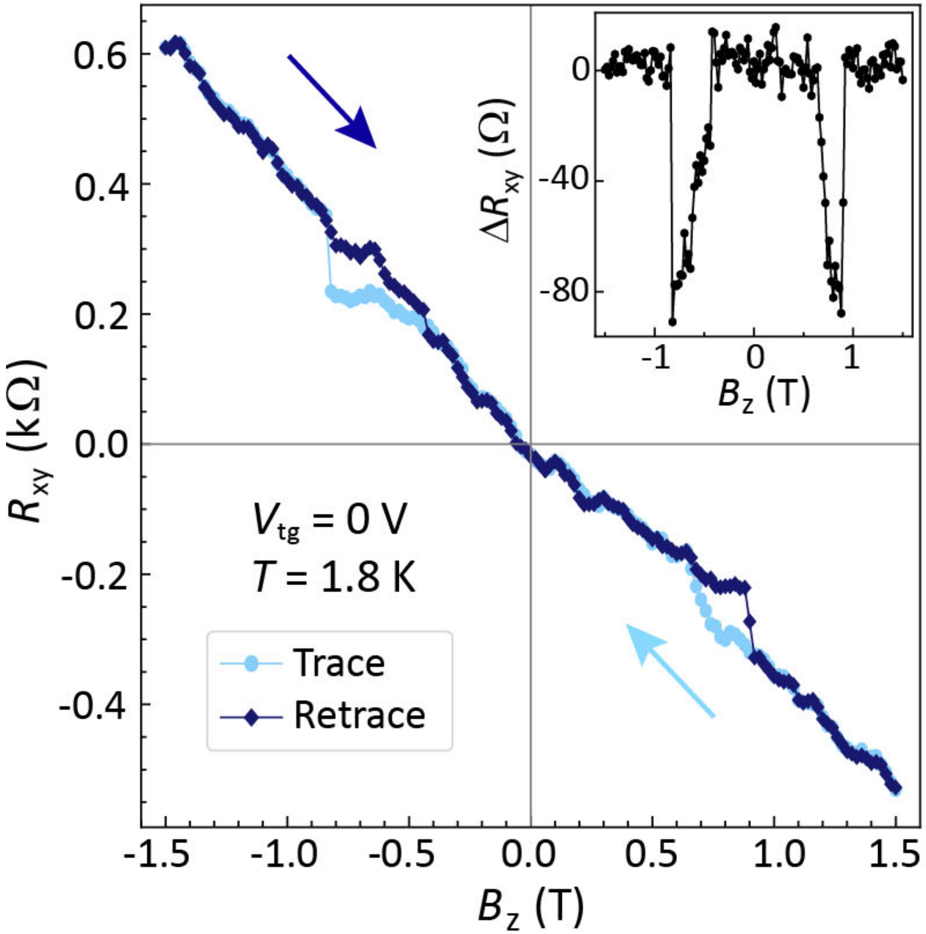




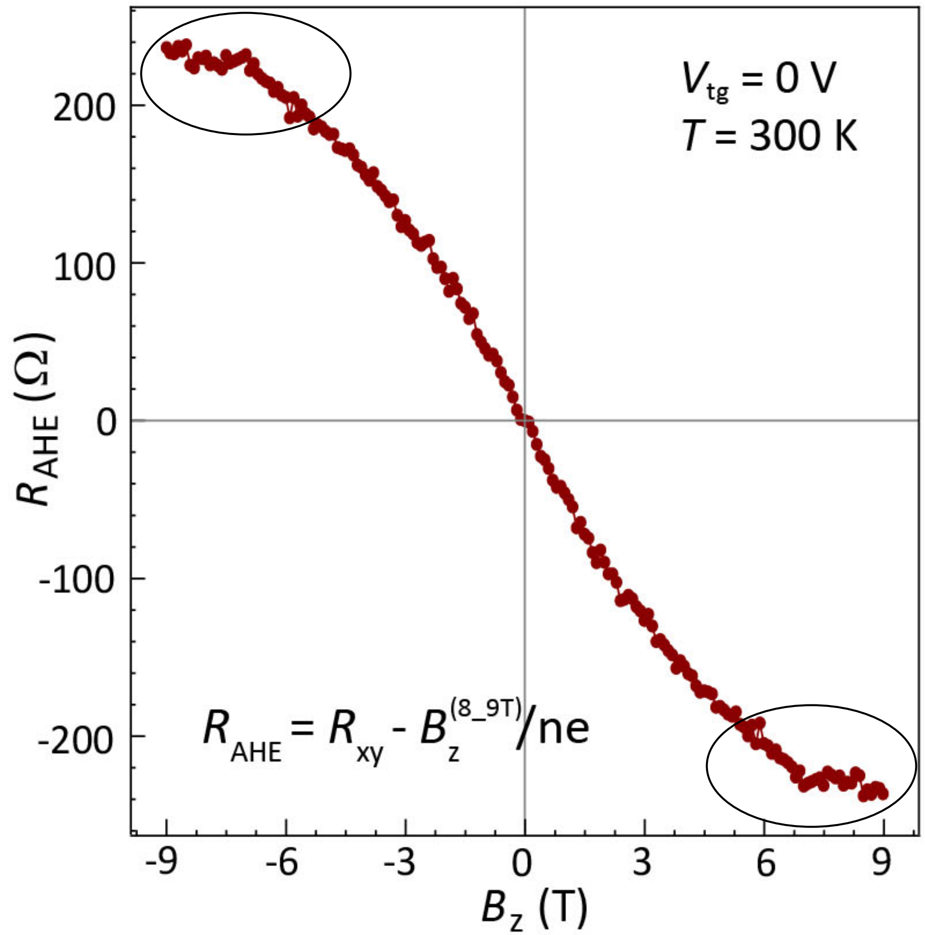


signatures of magnetized graphene

hysteresis near the spin-flop transition

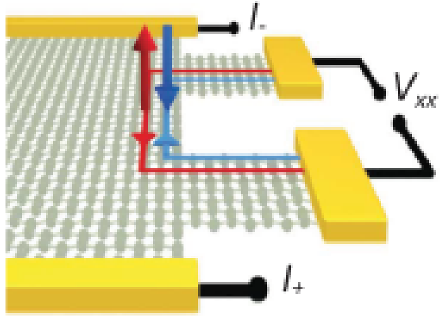


anomalous Hall effect: saturation of the Hall resistance at the saturation field

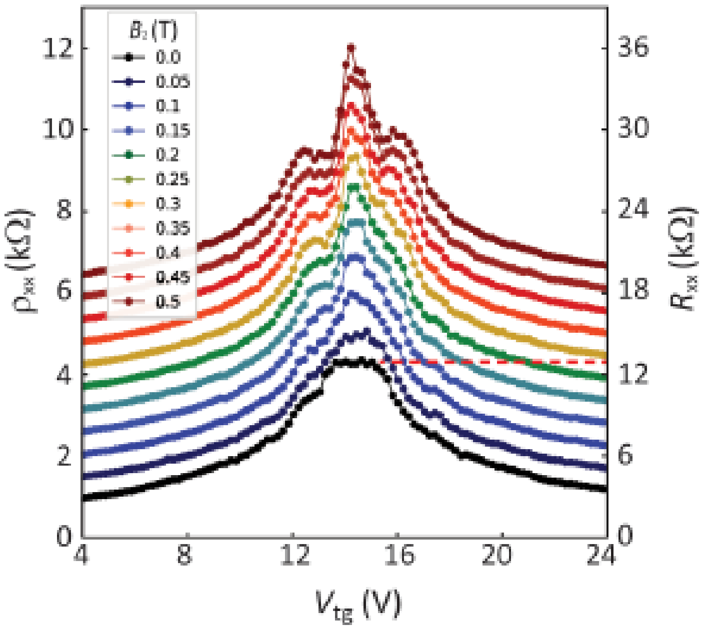


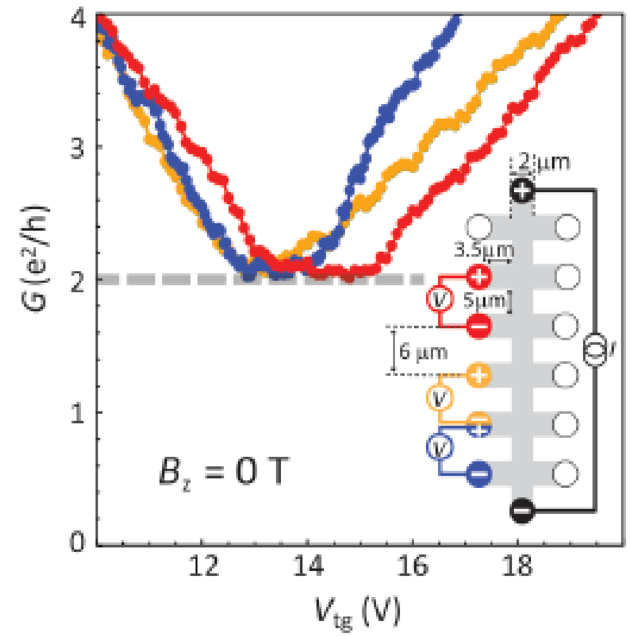
The observation of a sizable signal of 200 Ω is a signature of the co-presence of large induced spin-orbit and exchange interactions in the proximitized graphene up to room temperature

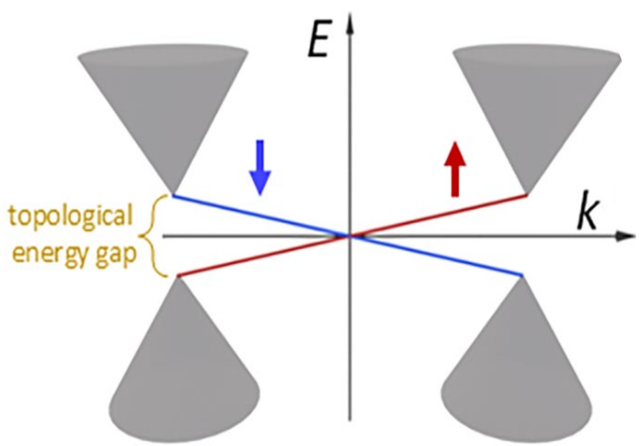
quantum spin Hall states at zero magnetic field



helical states propagate at the edges of the magnetized graphene

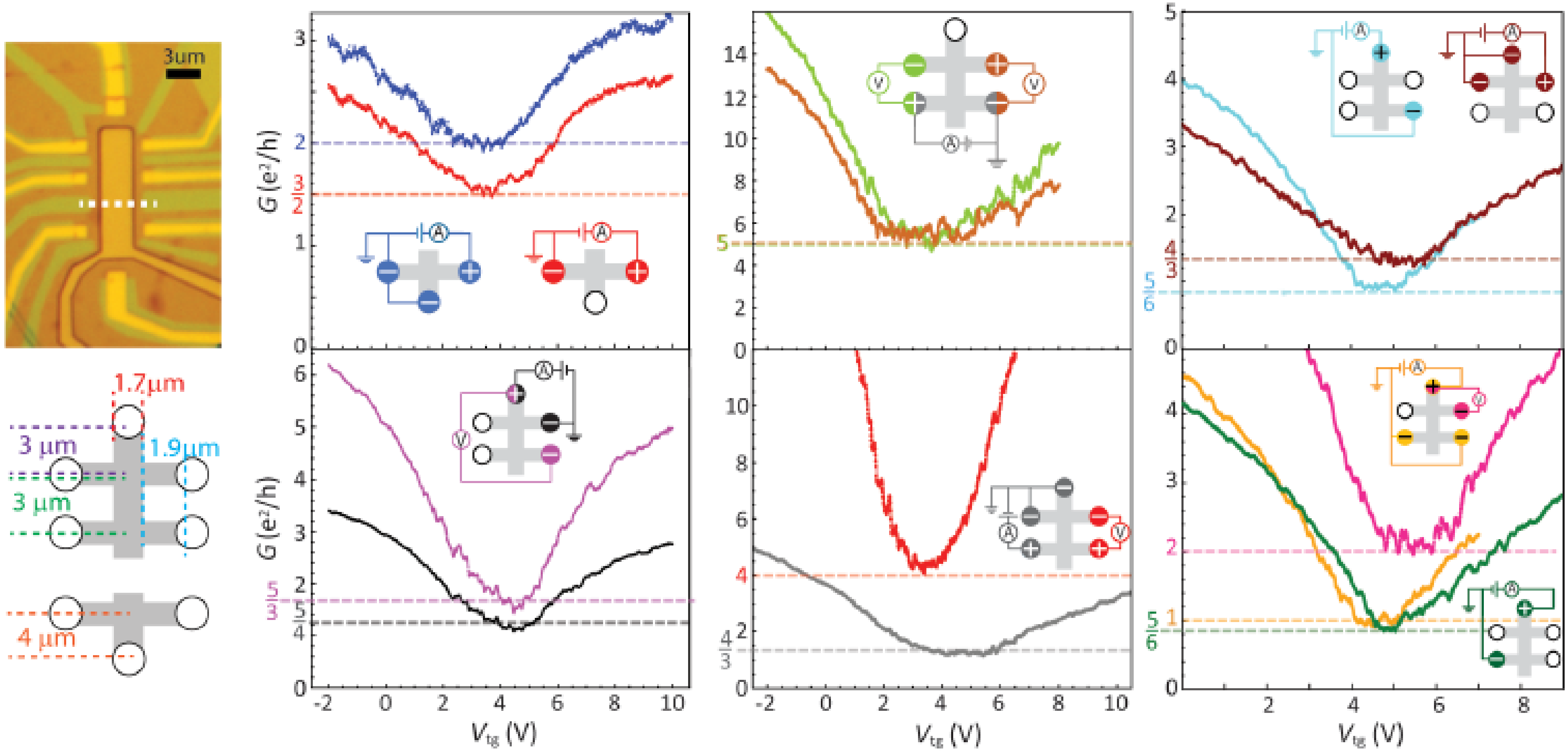






- broadened resistance peak (conductance dip at $2e^2/h$) is a sign for the existence of two edge states measured for different voltage pairs
- (with the top gate voltage the Fermi energy is tuned in the band diagram)

quantum spin Hall states at zero magnetic field



$$G_{2T} = \frac{e^2}{h}\left(\frac{1}{N_L + 1} + \frac{1}{N_R + 1}\right)$$

$N_{L,R}$: number of floating probes along left/right edges

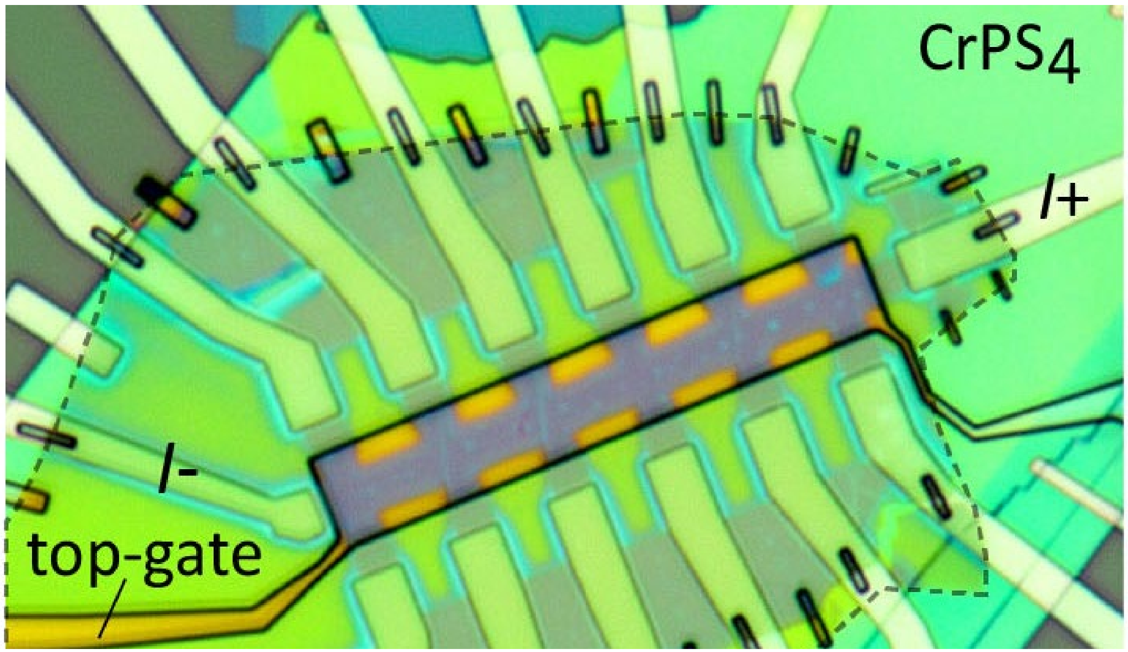
$$G_{4T} = G_{2T}\frac{N_I + 1}{N_V + 1}$$

N_I: number of floating probes along edge where voltage is measured

N_V: number of probes between voltage probes

conclusion

- graphene can be made magnetic by the proximity of a 2D magnet
- a graphene-$CrPS_4$ heterostructure exhibits spin-polariozed helical edge states in the absence of an applied magentic field
- next step in the emerging field of quantum spintronics: combine different components into more complex devices



heterostructures of 2D materials offer many possibilities to fabricate new quantum devices but predictive calculations are difficult: so one sometimes has to be opportunistic and intuitively just try things