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Proximity induced spin-orbit coupling and magnetism in graphene

Alexey Kaverzin, Talieh Ghiasi, Dennis de Wal, Bart van Wees

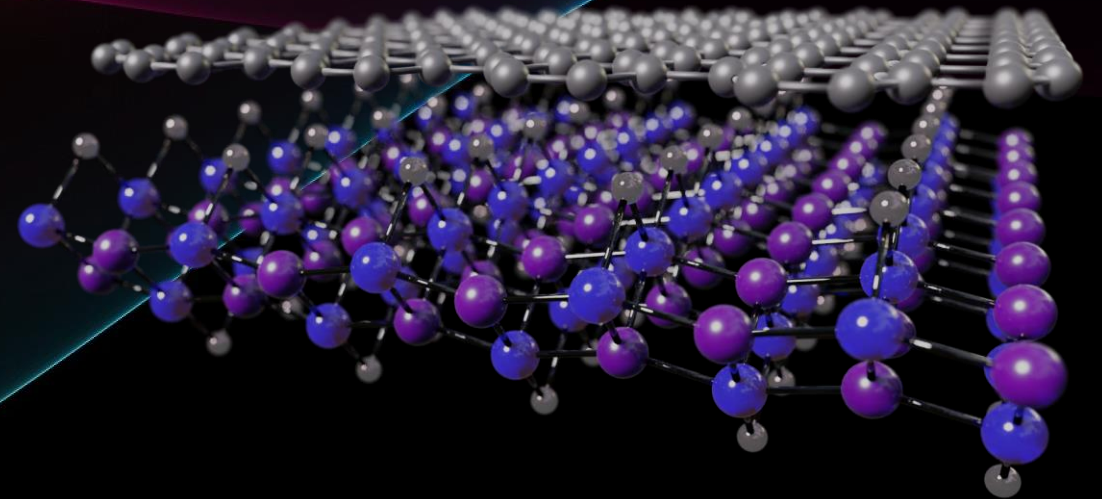


Physics of
 Nanodevices

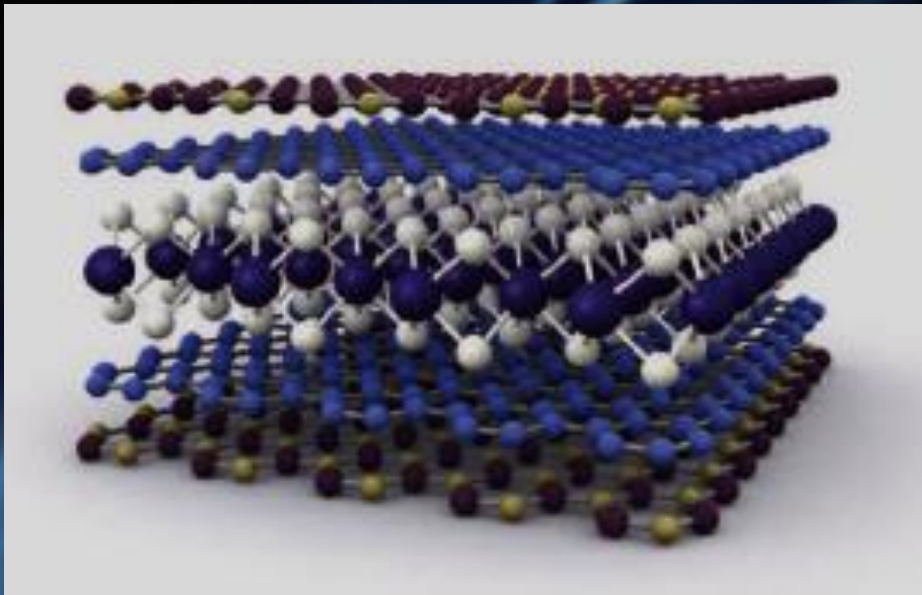
Avalon H. Dismukes, Xavier Roy

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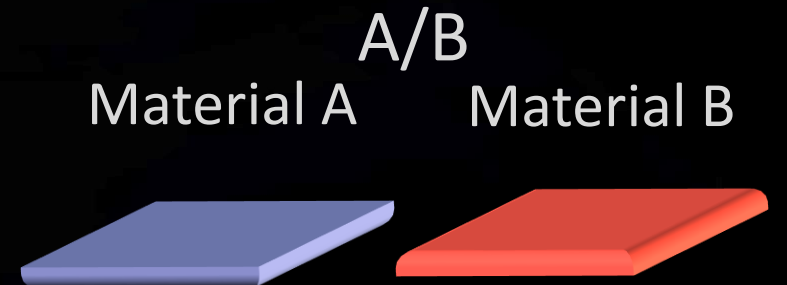
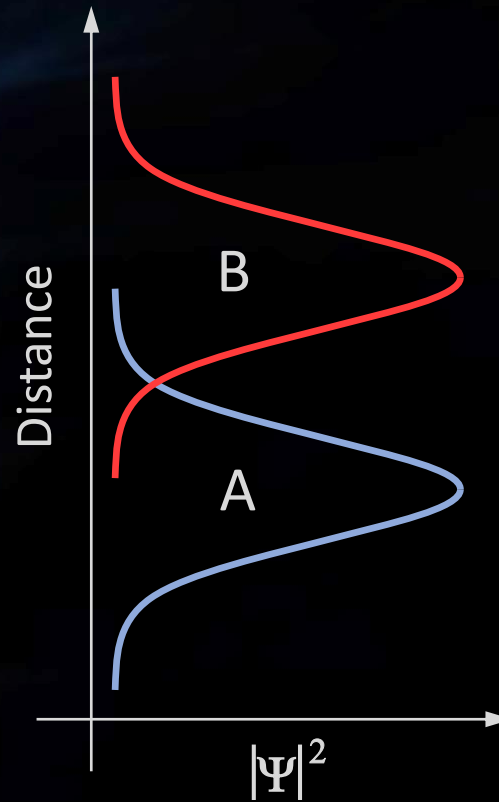
arXiv:2007.15597



Proximity effects in van der Waals heterostructures

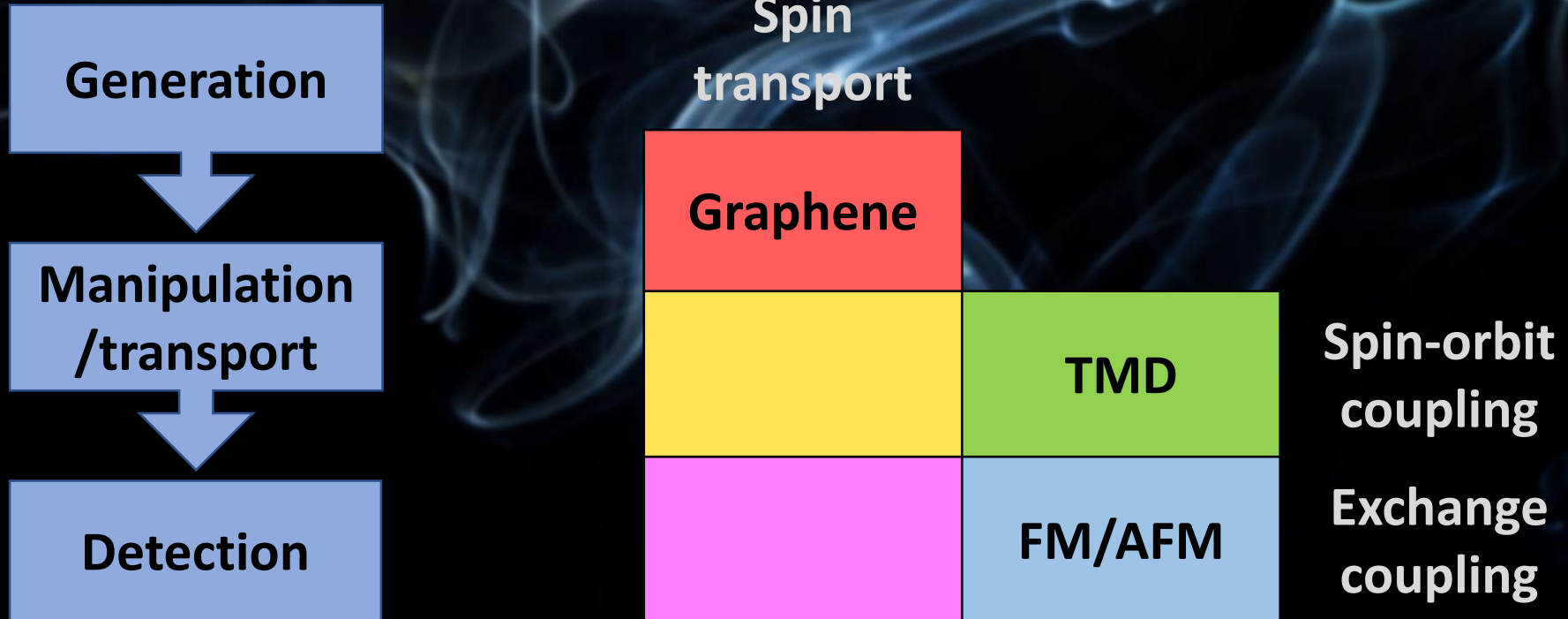


K. S. Novoselov *et al.*, Science 353, 9439 (2016)



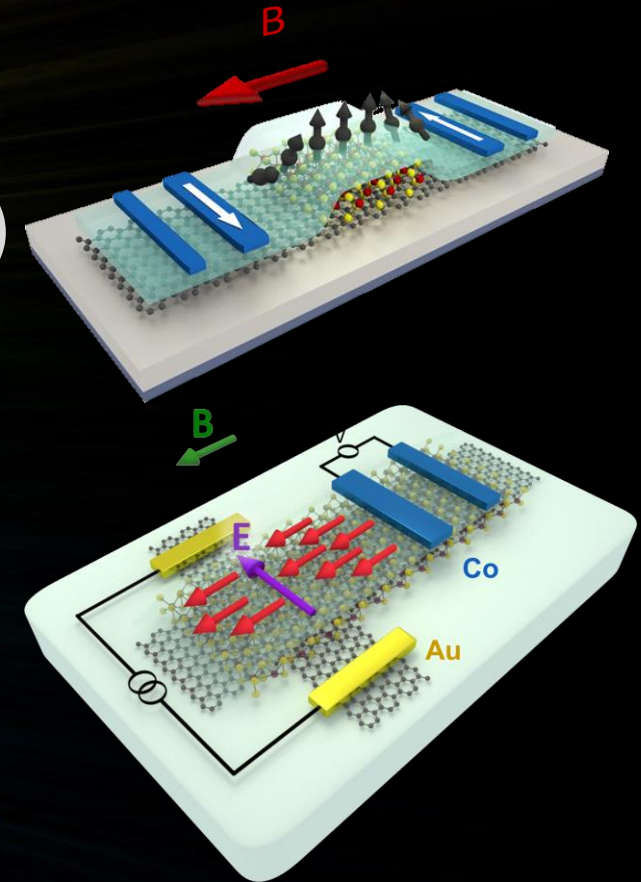
- No lattice matching required
- Atomically flat
- Easy transfer methods
- Short-range effect

Necessary components of spin-based devices



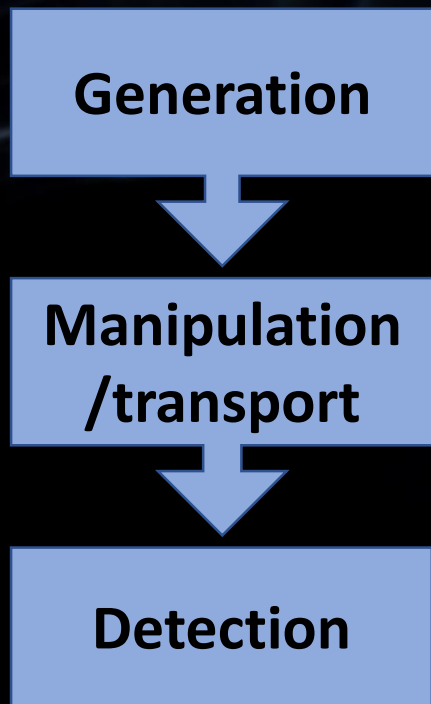
Induced spin-orbit interaction in graphene

- Z. Wang et al., Nat. Commun. 6, 8339 (2015)
- T.S. Ghiasi et al., Nano letters 17, 7528–7532 (2017)
- L. A. Benítez et al., Nature Physics 14, 303 (2018)
- C. Safeer et al., Nano Lett. 19, 1074–1082 (2019)
- T.S. Ghiasi et al., Nano Lett. 19, 5959–5966 (2019)
- L. A. Benítez et al., Nat. Mater. 19, 170–175 (2020)



Weak localisation, spin relaxation time anisotropy,
spin Hall effect, Rashba-Edelstein effect

Necessary components of spin-based devices



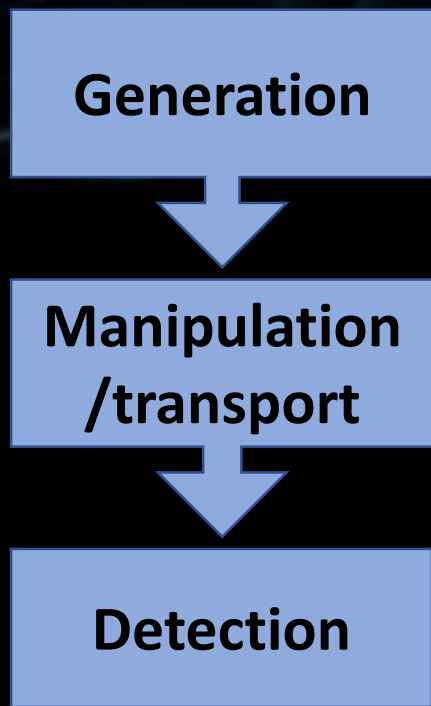
| Spin transport | | |
|----------------|--------|---------------------|
| Graphene | | |
| ✓ | TMD | Spin-orbit coupling |
| | FM/AFM | Exchange coupling |

A table with three rows and three columns. The first row is a header for "Spin transport" and is empty in the second column. The second row has "Graphene" in the first column and is empty in the second and third columns. The third row has a checkmark "✓" in the first column, "TMD" in the second column, and "Spin-orbit coupling" in the third column. The fourth row has an empty first column, "FM/AFM" in the second column, and "Exchange coupling" in the third column.

Induced exchange interaction in graphene

- P. Wei et al. Nat Mat 15, 711-716 (2016): EuS
 - Y.-F. Wu et al. PRB 95, 195426 (2017): BFO₃
 - C. Tang et al. Adv Mat, 1908498 (2020): CrBr₃
 - Z. Wang et al. PRL 114, 016603 (2015): YIG
 - C. Tang et al. APL Materials 6, 026401 (2018): YIG
 - J. Mendes et al. PRL 115, 226601 (2015): YIG
 - J. C. Leutenantsmeyer et al. 2D Mat 4, 014001 (2016): YIG
 - S. Singh et al. PRL 118, 187201 (2017): YIG
 - B. Karpiak et al. 2D Mat 7, 015026 (2019): Cr₂Ge₂Te₆
- Zeeman spin
Hall effect
- Anomalous
Hall effect
- magnetoresistance
- non-local
spin transport

Necessary components of spin-based devices

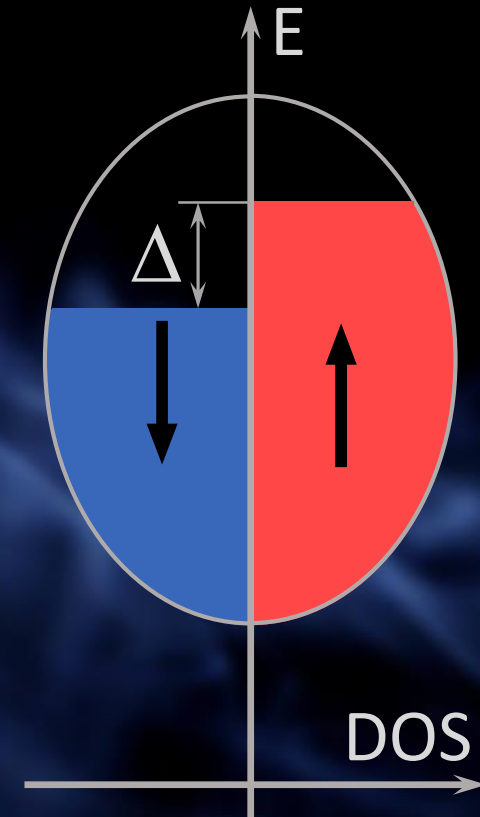
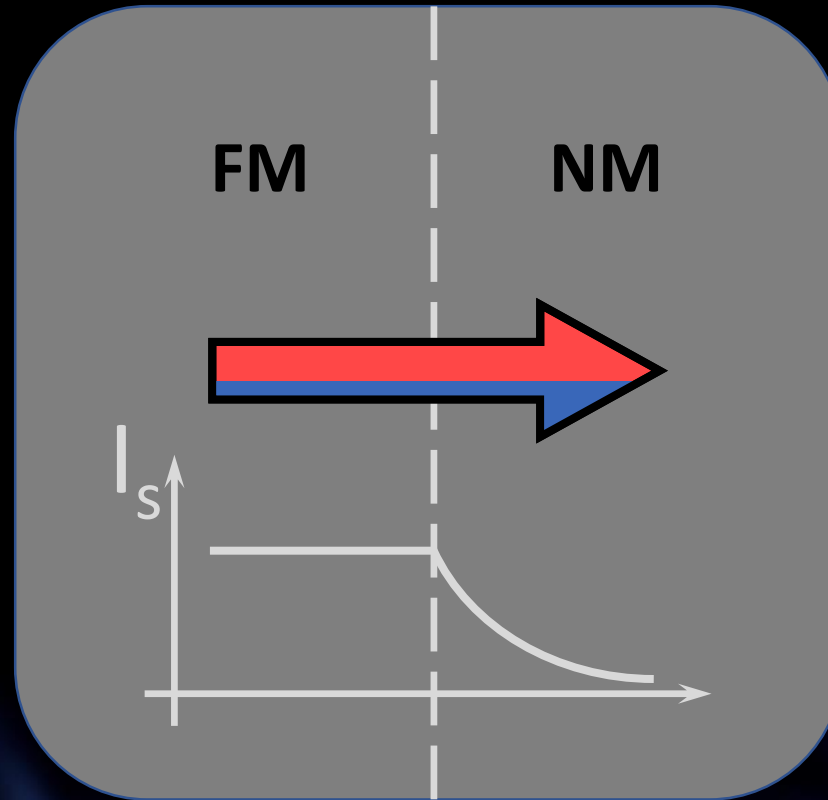
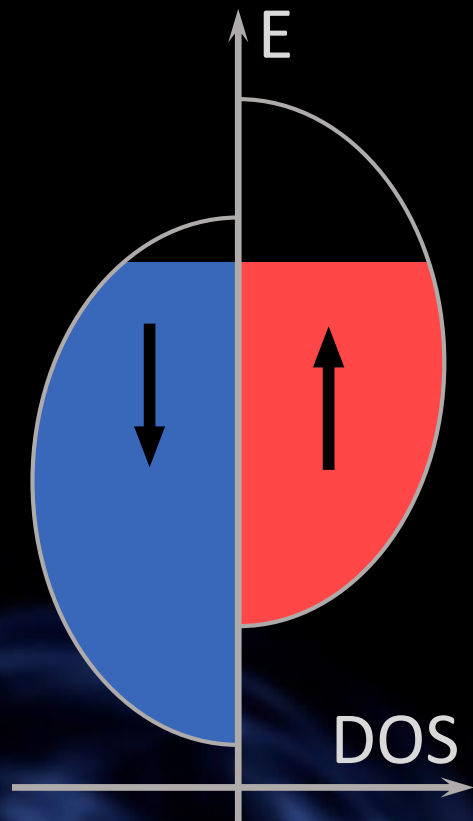


| Spin transport | |
|----------------|--------|
| Graphene | |
| ✓ | TMD |
| ✓ | FM/AFM |

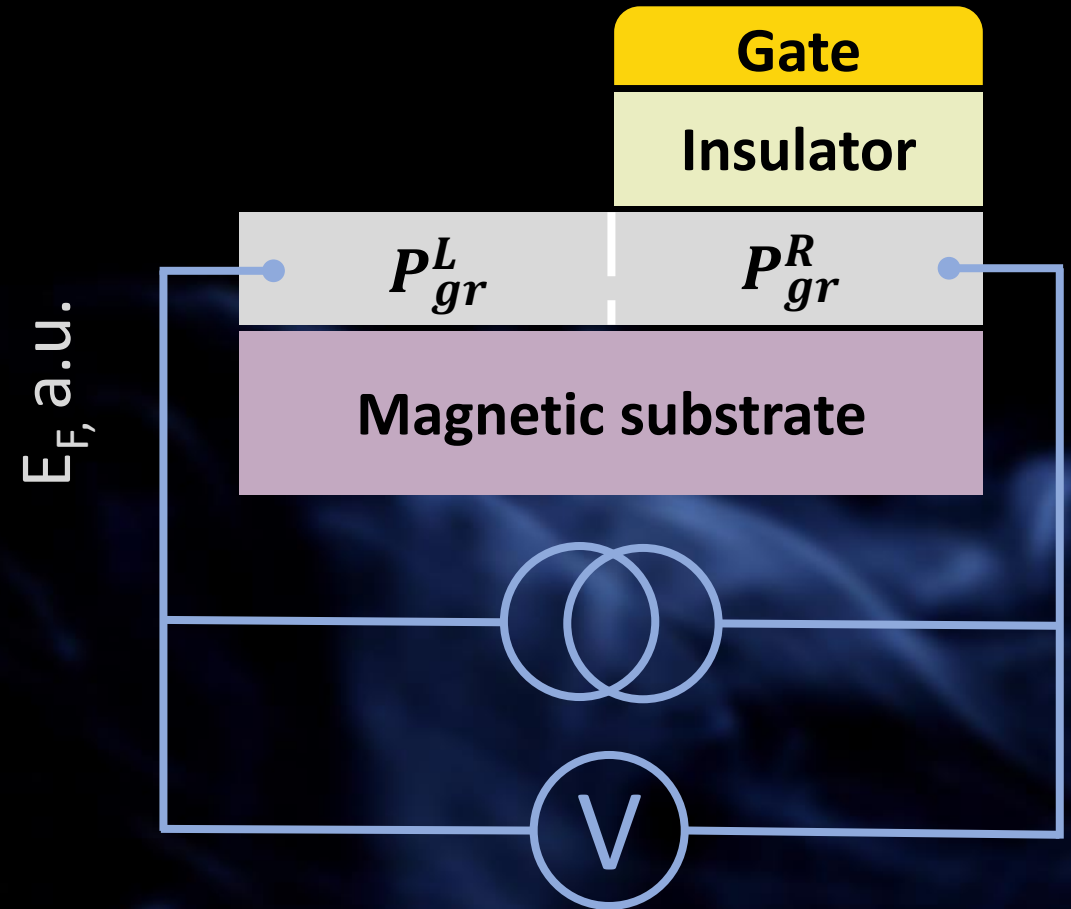
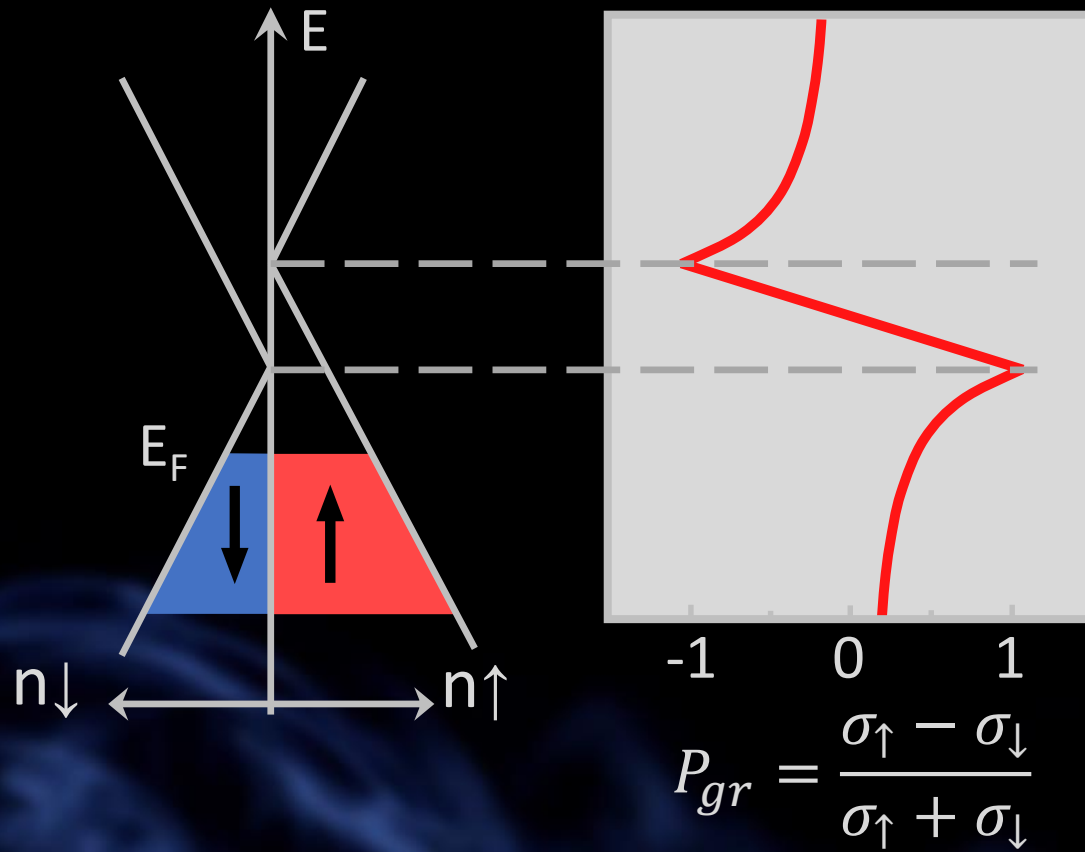
Spin-orbit coupling

Exchange coupling

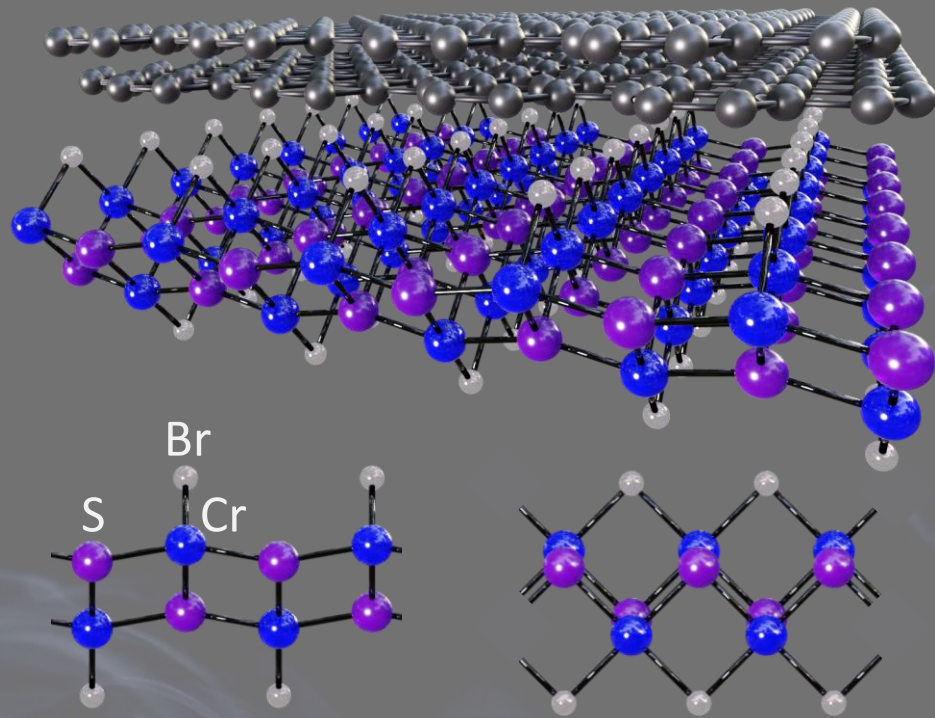
Spin injection from FM to NM



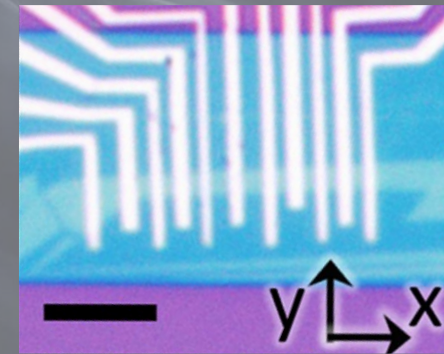
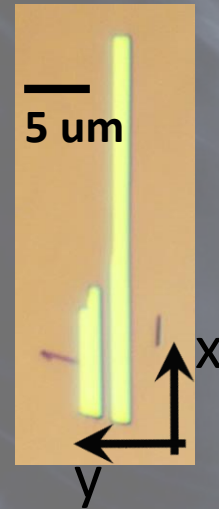
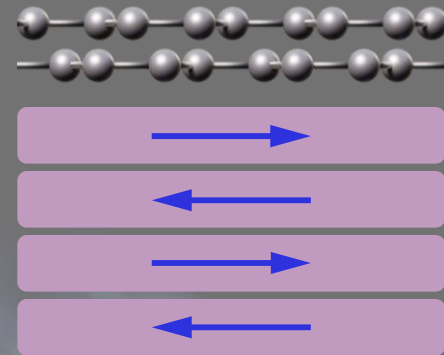
Magnetic graphene



Graphene on CrSBr



Graphene
CrSBr

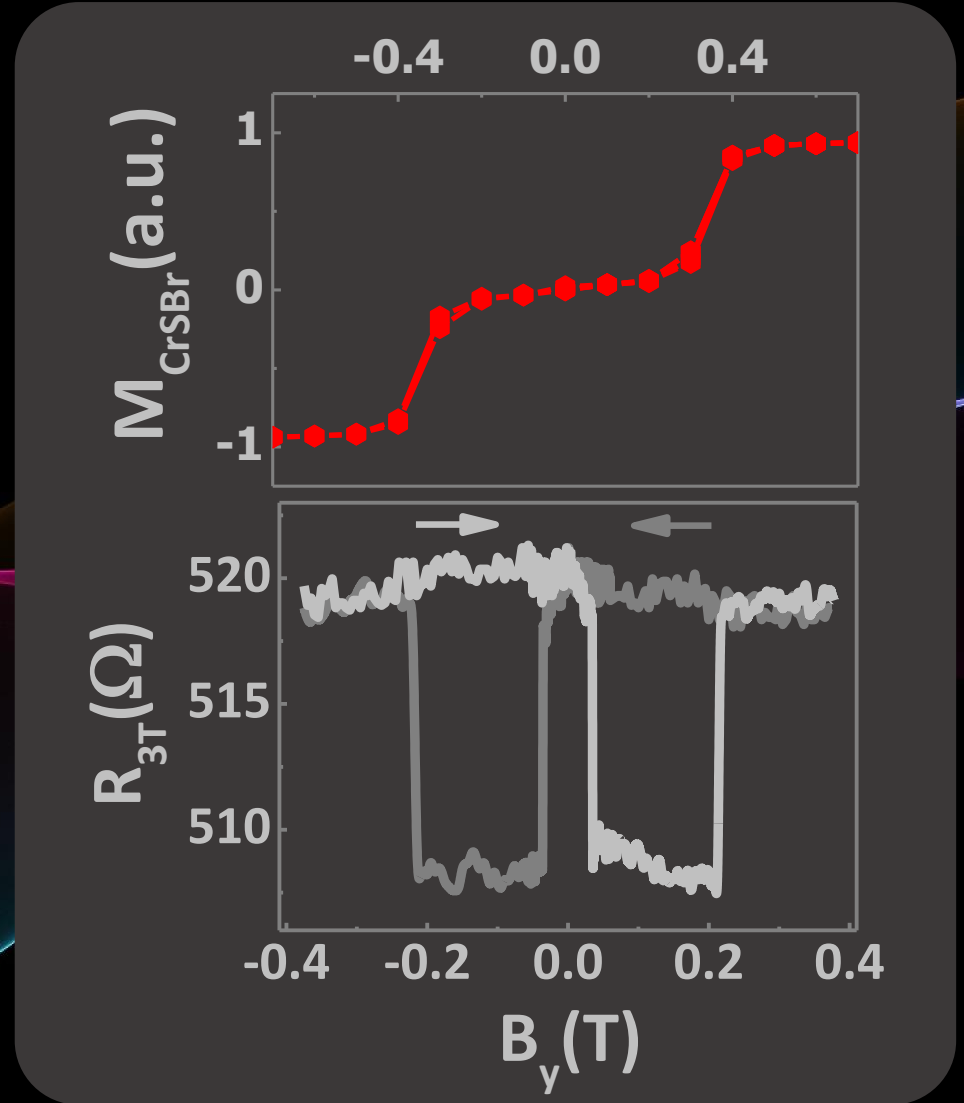
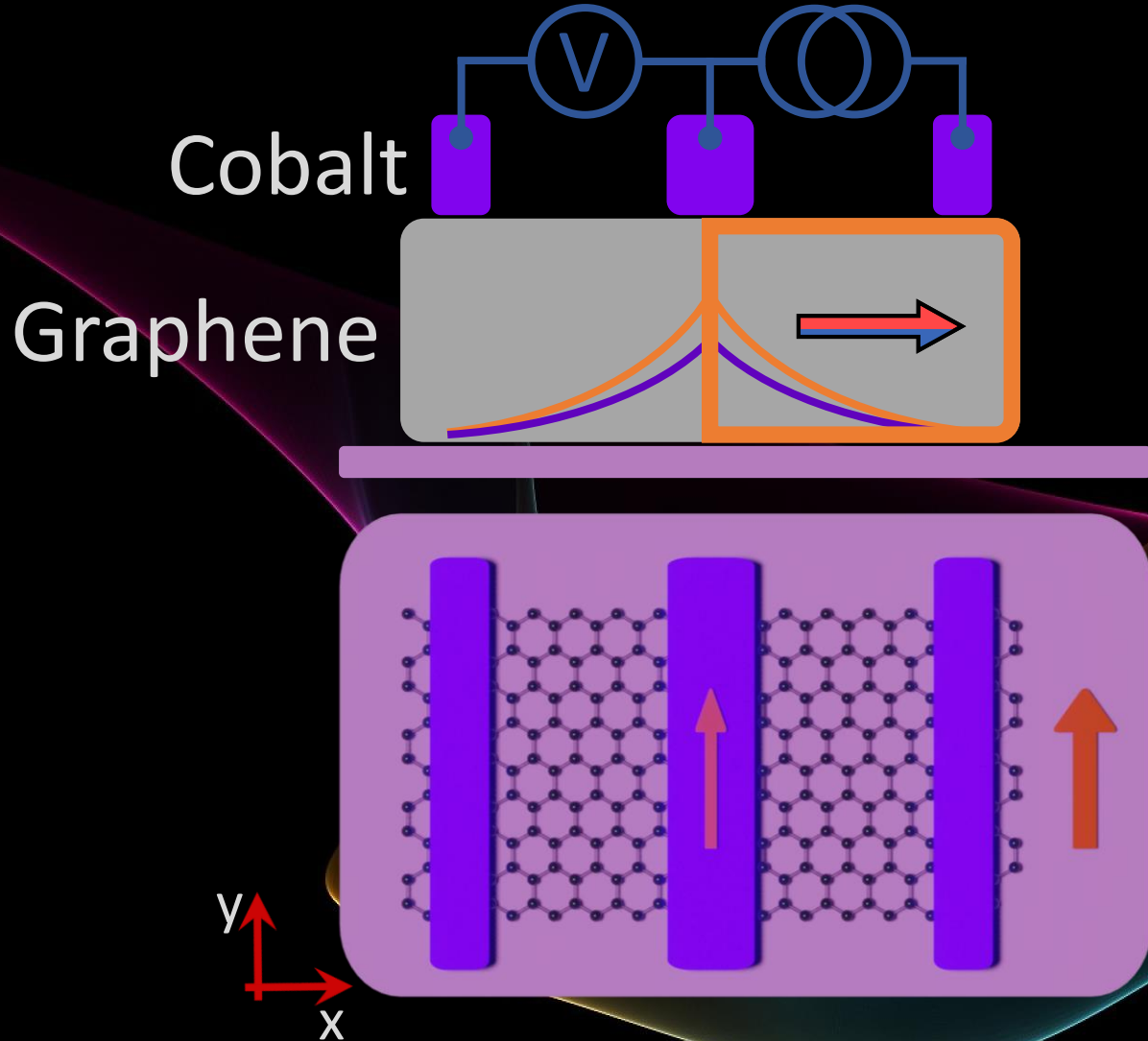


- Interlayer antiferromagnet

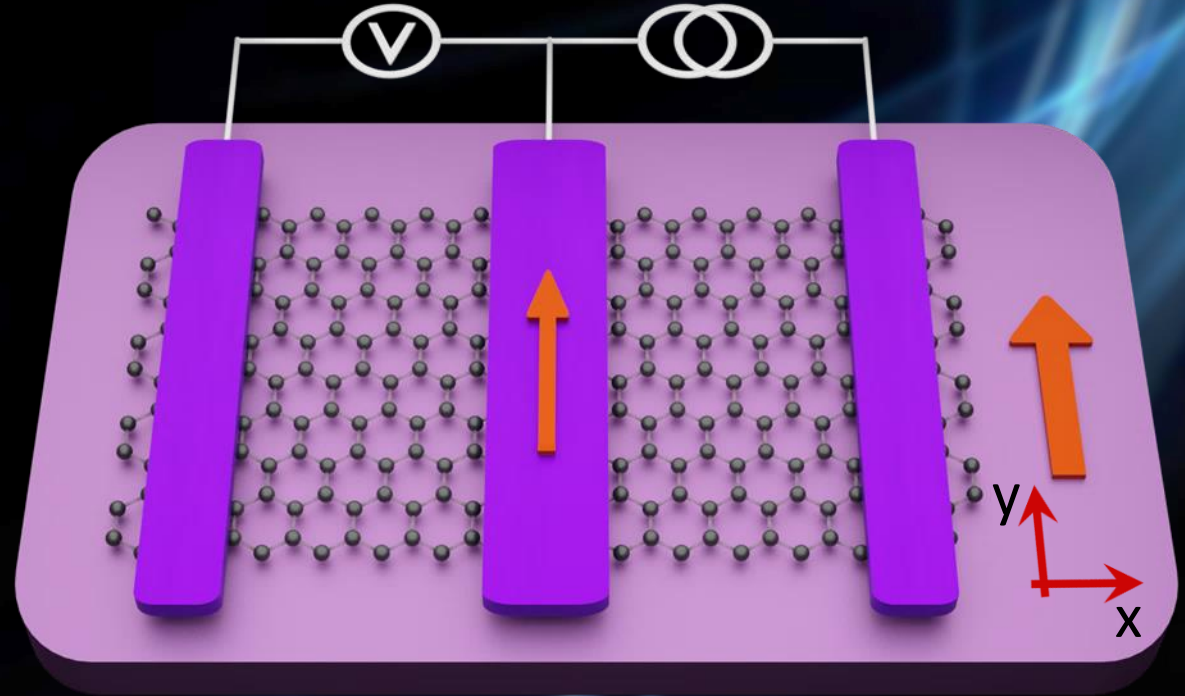
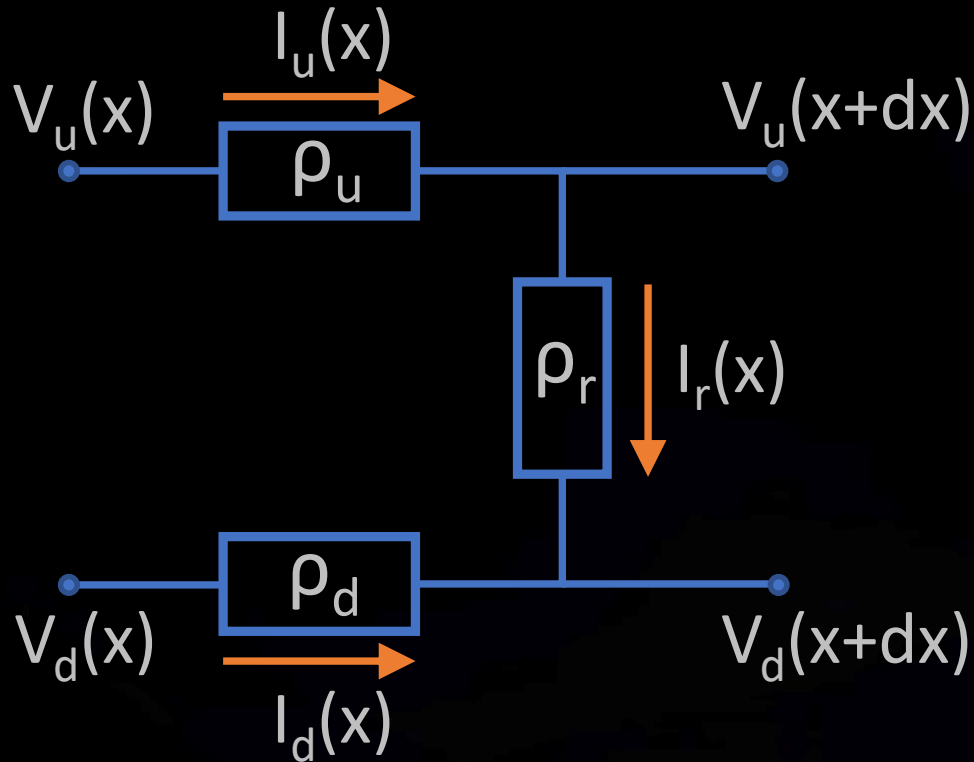
O. Goser et al., Journal of magnetism and magnetic materials 92, 129-136 (1990)

J. Qi et al. arXiv:1811.02674 (2018), E.J. Telford et al. arXiv:2005.06110 (2020)

3-terminal measurement geometry



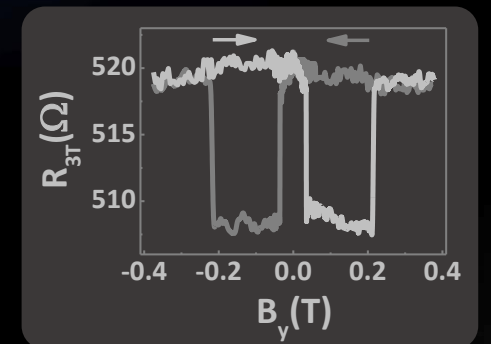
2 channel model



$$R_{3T} = \frac{\lambda R_{sq} (P_c - P_{gr})^2}{2W(1 - P_{gr}^2)}$$



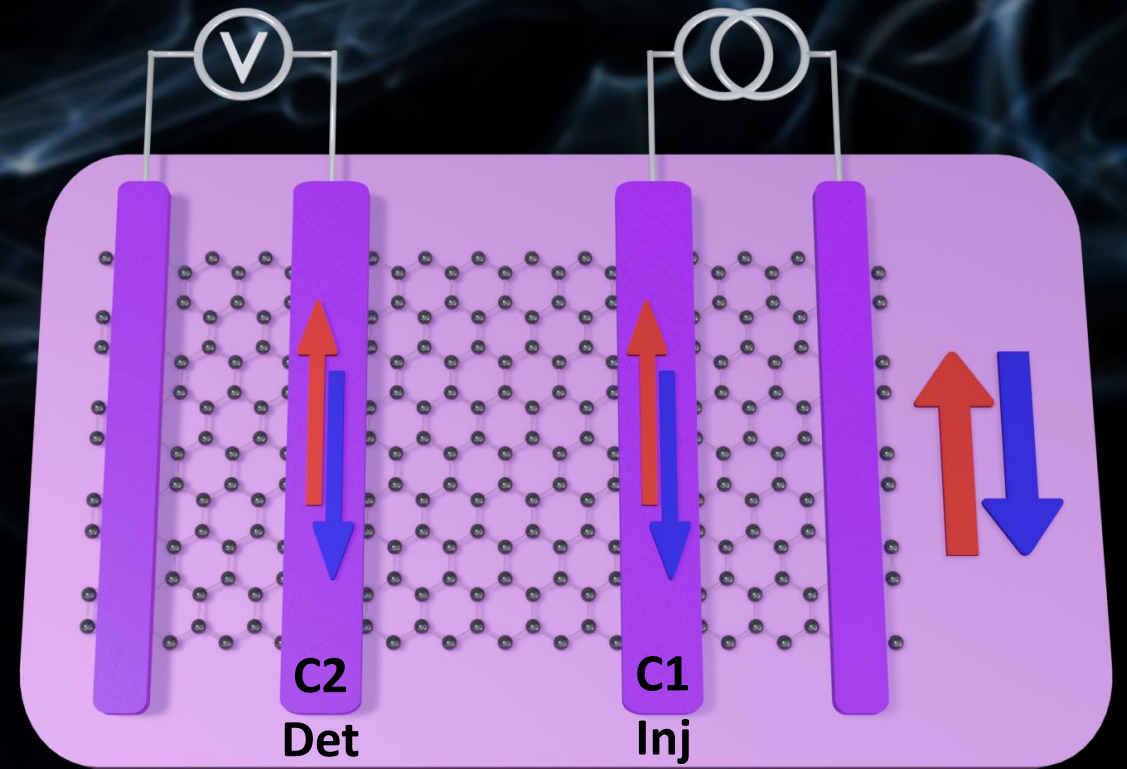
$$\Delta R_{3T} = -\frac{2\lambda R_{sq} P_c P_{gr}}{W(1 - P_{gr}^2)}$$



Non-local spin transport

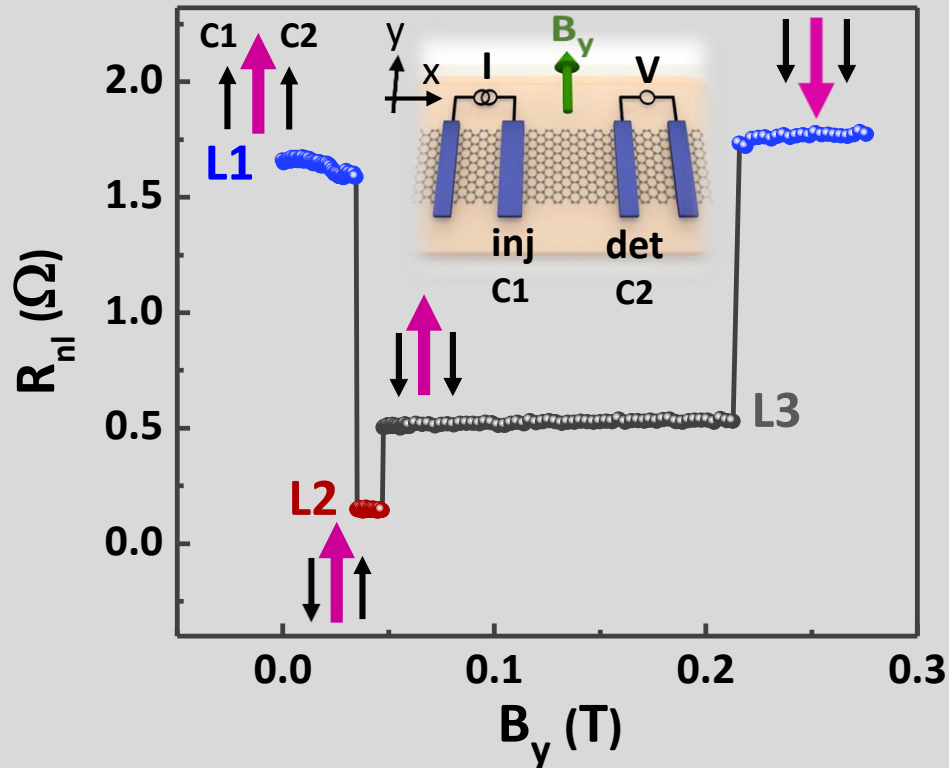
$$R_{nl} = \frac{\lambda R_{sq}}{2W(1 - P_{gr}^2)} e^{-\frac{L}{\lambda}} (P_i - P_{gr})(P_d - P_{gr})$$

| | Injection | Detection |
|-----------------|-----------|-----------|
| $P_i P_d$ | C1 | C2 |
| $P_{gr} P_d$ | graphene | C2 |
| $P_i P_{gr}$ | C1 | graphene |
| $P_{gr} P_{gr}$ | graphene | graphene |

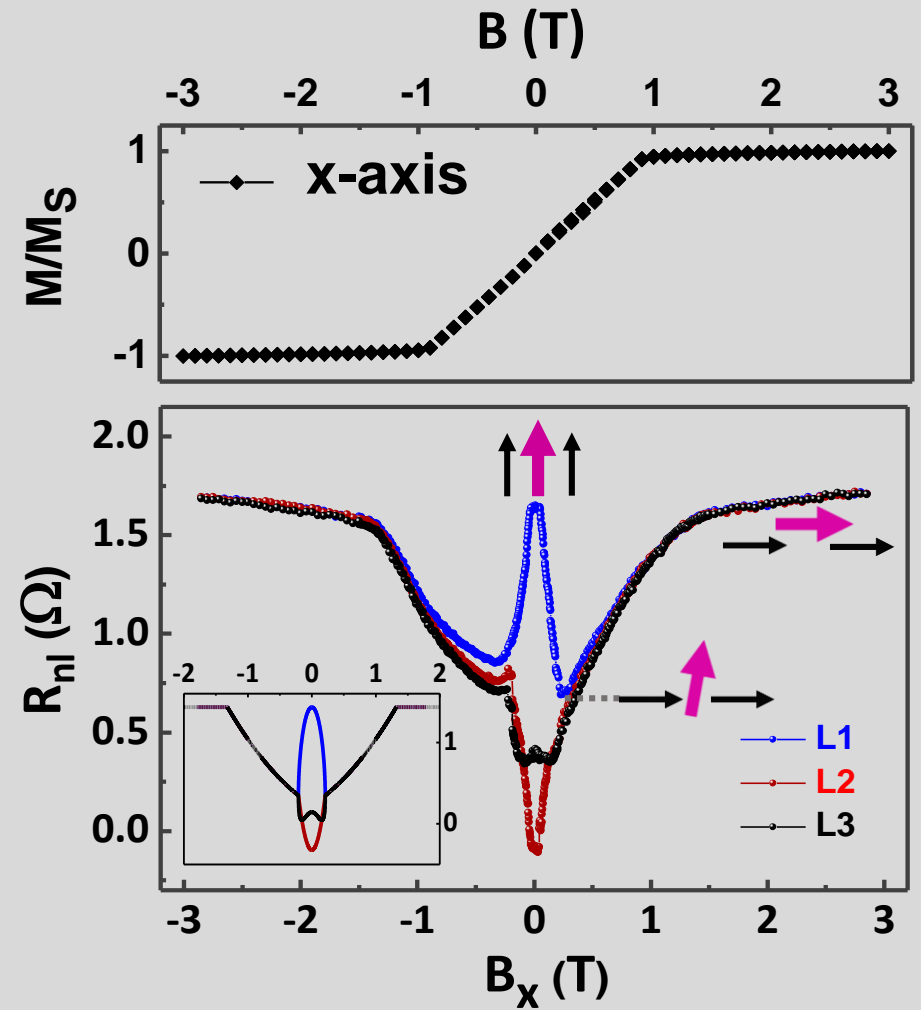


Non-local spin transport

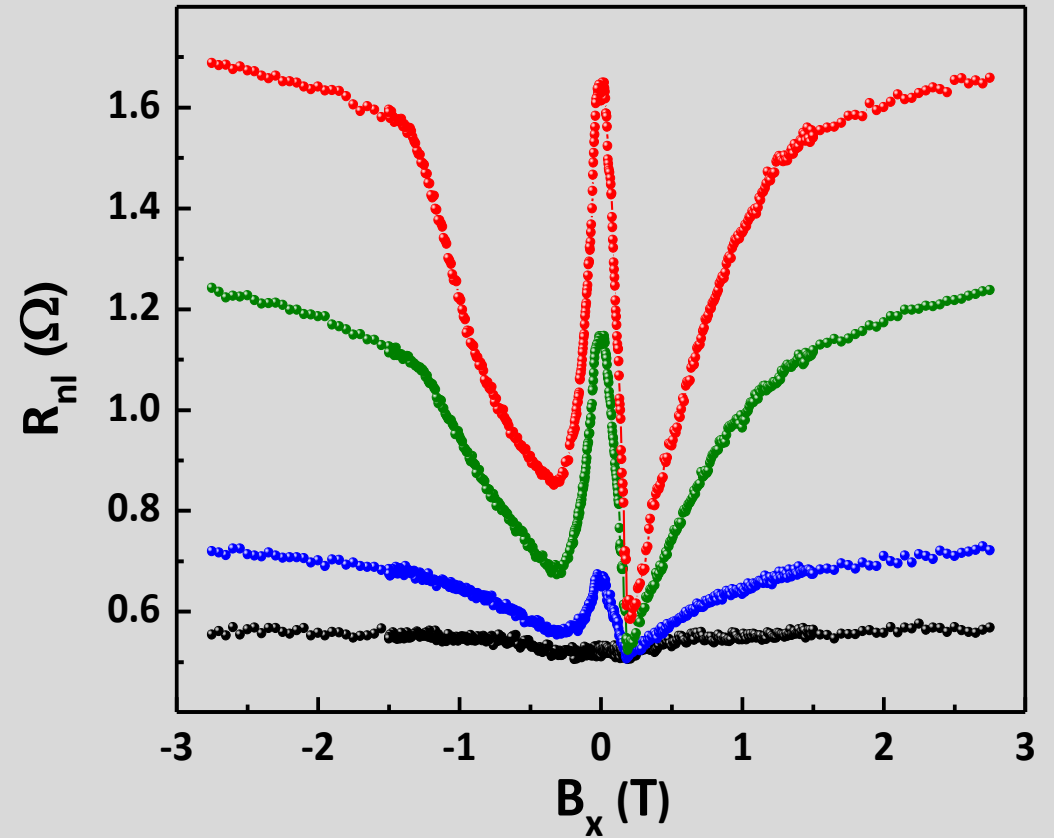
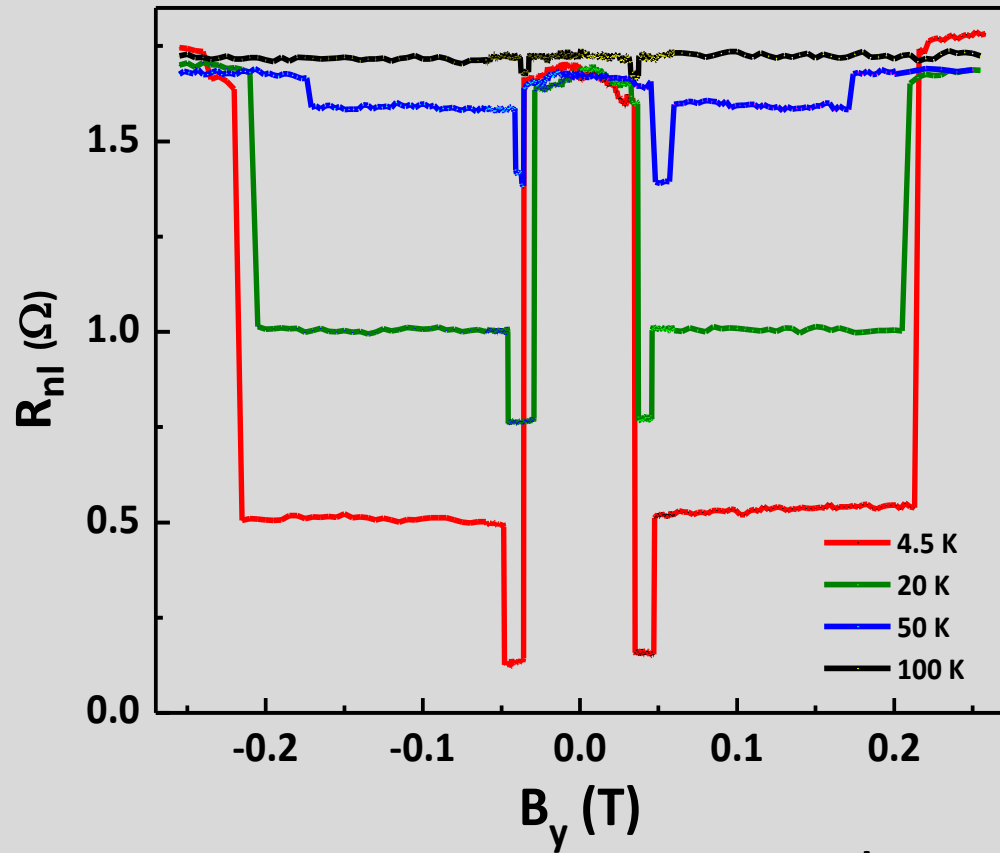
$$R_{nl} = \frac{\lambda R_{sq}}{2W(1 - P_{gr}^2)} e^{-\frac{L}{\lambda}(P_i - P_{gr})(P_d - P_{gr})}$$



$P_i = -24\%$
 $P_d = -24\%$
 $P_{gr} = 14\%$
 $\lambda = 630$ nm

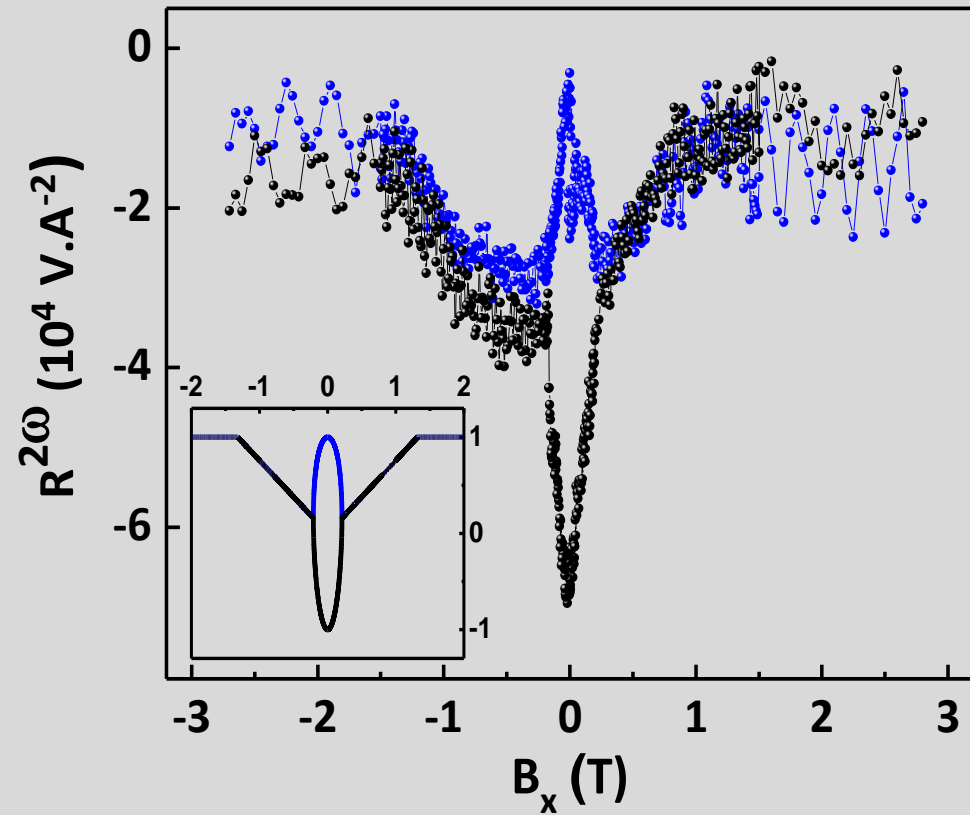
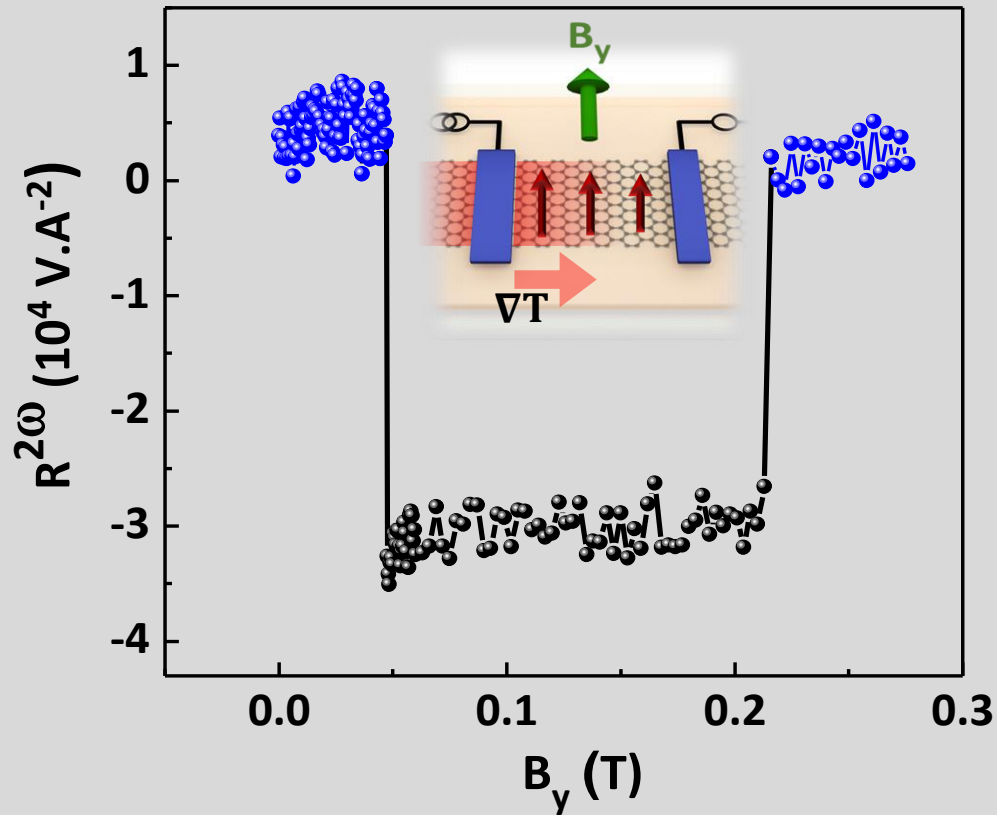


Temperature dependence



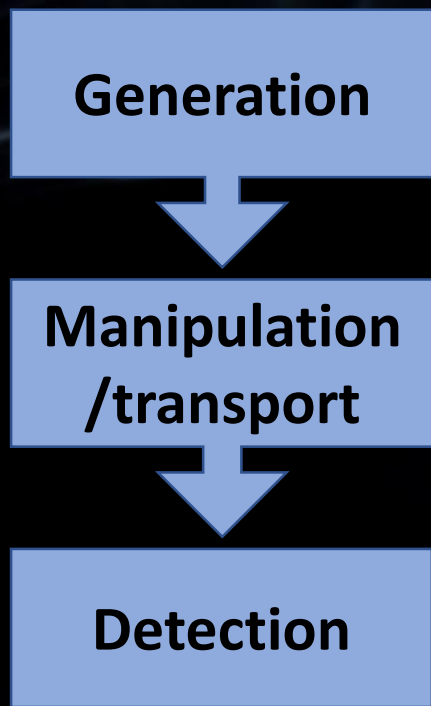
Neel temperature $T_N = 132$ K

Spin dependent Seebeck effect



thermal gradient \rightarrow Seebeck effect \rightarrow spin current

Necessary components of spin-based devices



| Spin transport | |
|----------------|--------|
| Graphene | |
| ✓ | TMD |
| ✓ | FM/AFM |

Spin-orbit coupling

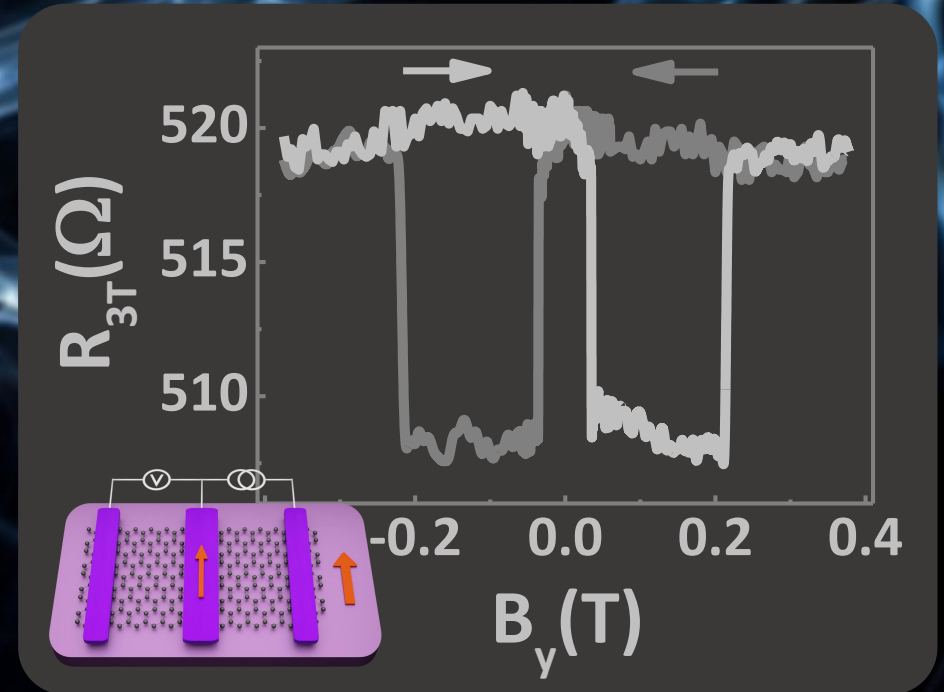
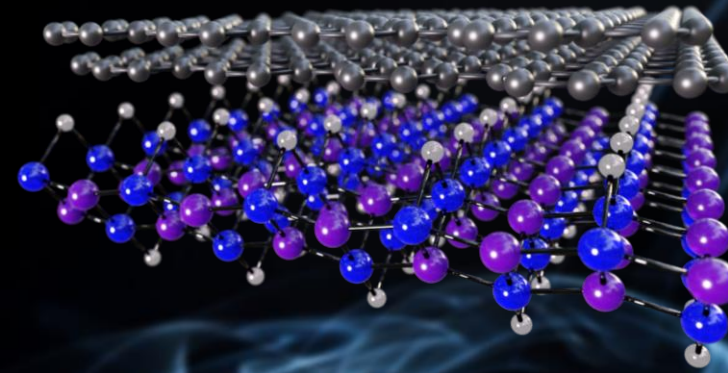
Exchange coupling

Magnetic graphene

- Active generation of spin current
- Spin dependent Seebeck effect
- Anomalous Hall effect

All 2D spin-based devices

arXiv:2007.15597





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Physics of
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Thank you

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