Axis 3 : Optical, Excitonic and photonic properties

GDR *HOWDI* : Kick-Off Meeting, March 2021

Proximity effects in Ferromagnetic/Semiconducting heterostructures with 2D materials

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Proximity effects in Ferromagnetic/Semiconducting heterostructures with 2D materials

Outline:

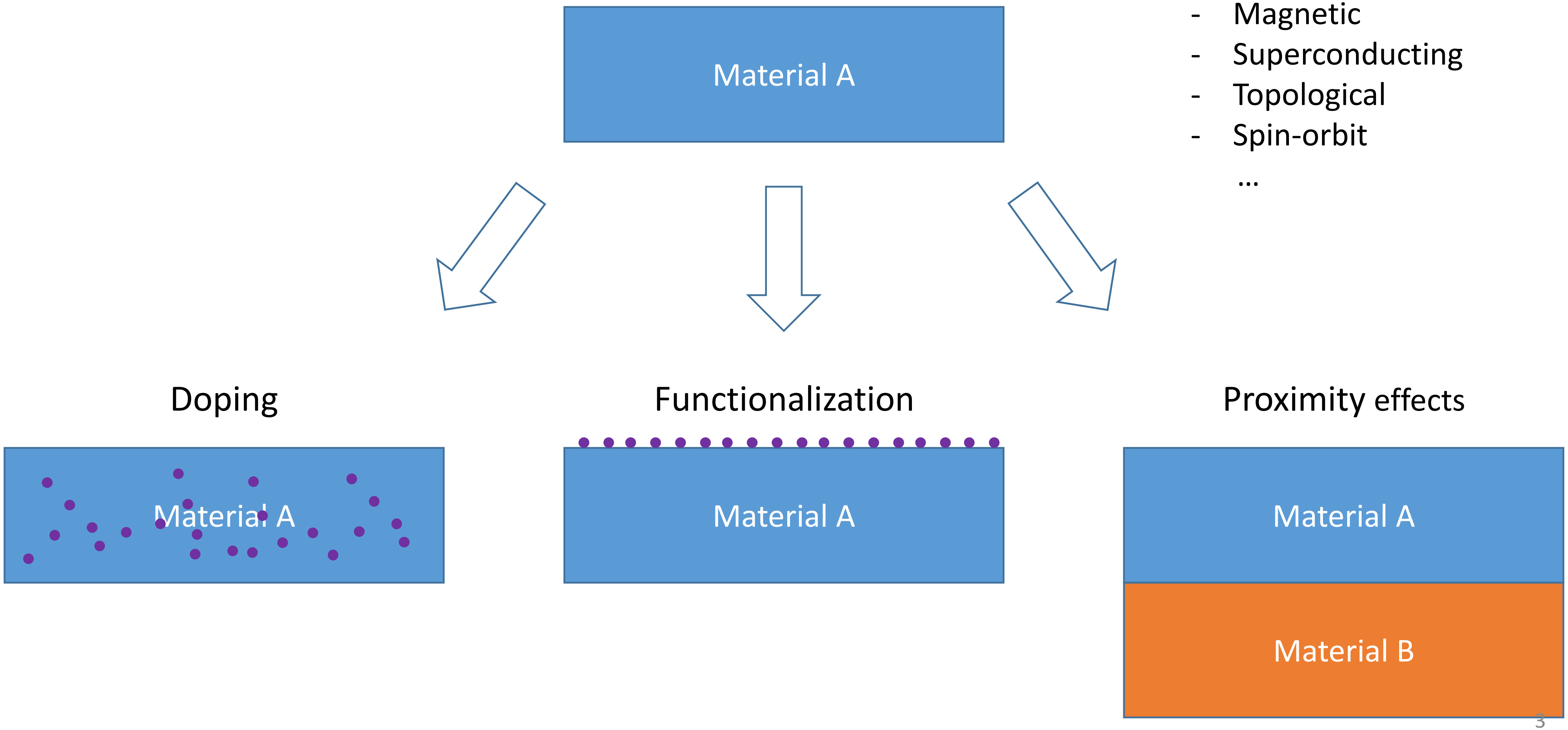
- What do we mean by proximity effects?
- Why 2D materials?
- State-of-the-art of TMD/ferromagnetic heterostructures

General context

Goal: - tune the properties of a material
- upgrade a material with a new property

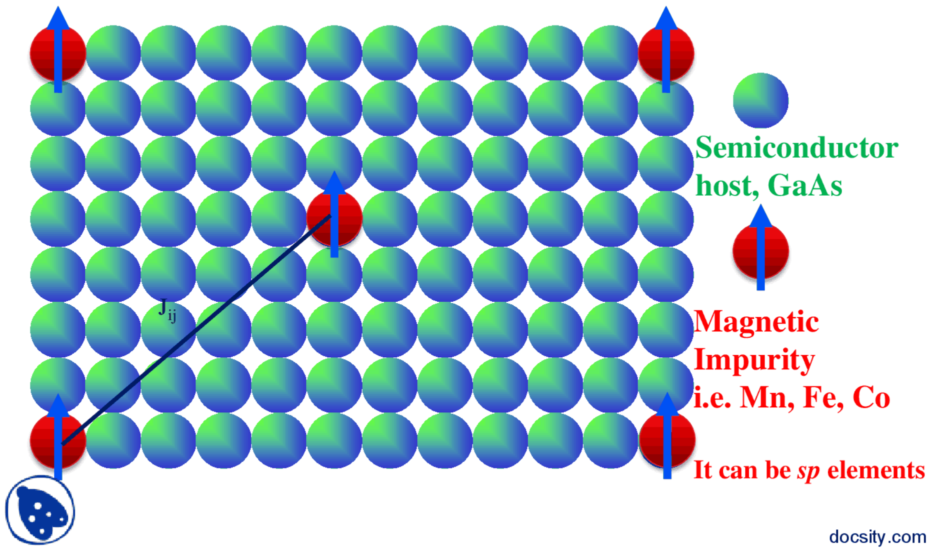
- Magnetic
- Superconducting
- Topological
- Spin-orbit

…



Semiconductor and magnetic properties

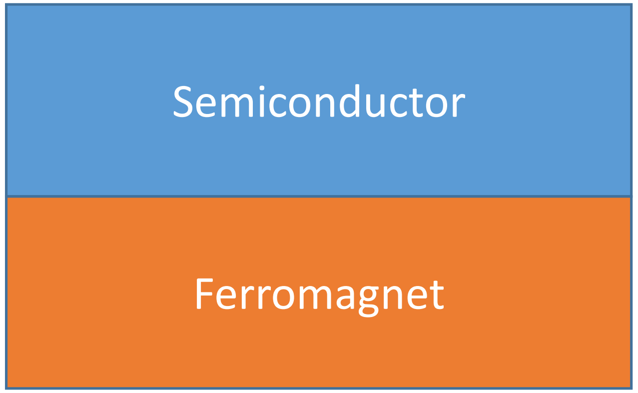
- Doping: dilute magnetic semiconductor



Drawbacks:
- low Curie temperature
- degradation of material properties

T. Dietl, Nature Materials **9**, 965 (2010).

- Proximity effects



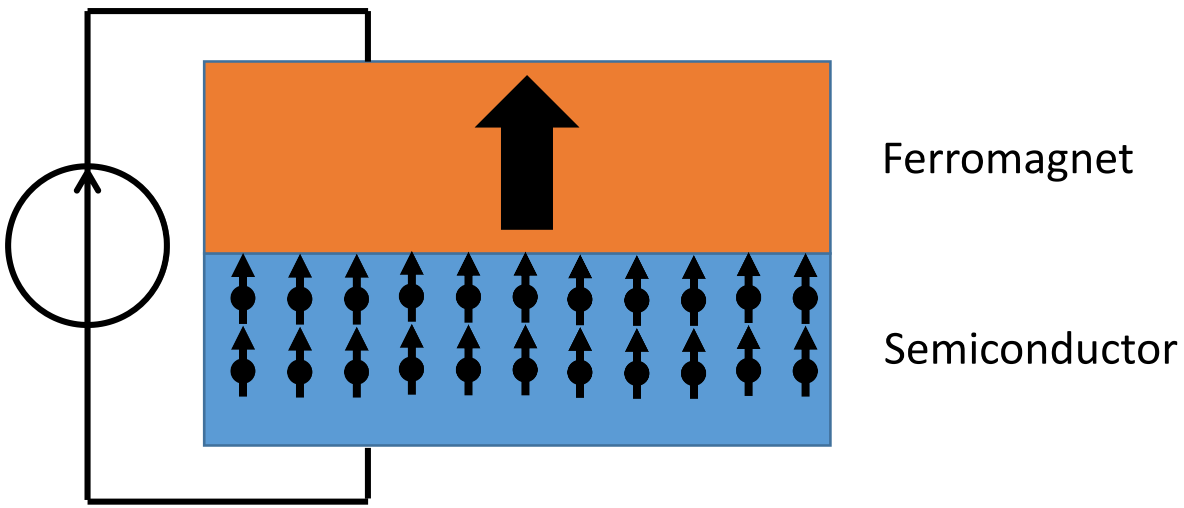
Hybrid structure

Pros:
- Preserves the individual properties of each material
- Mutual control of their properties

G.A. Prinz, Science **250**, 1092 (1990).

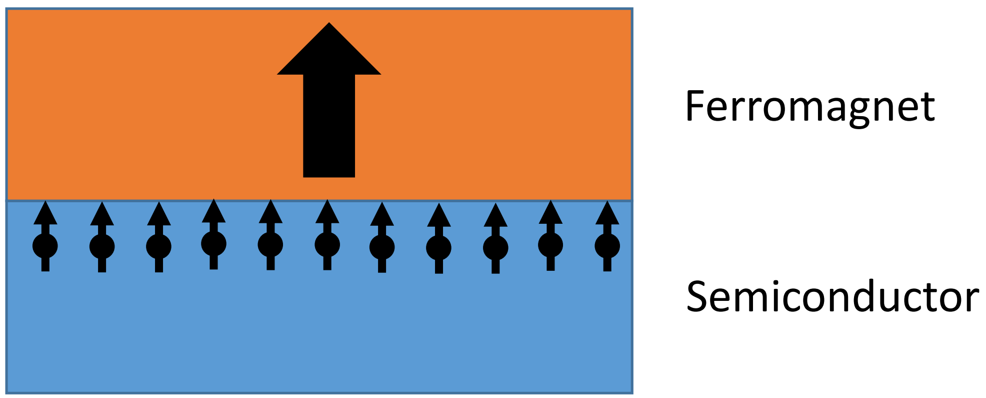
Ferromagnetic/Semiconductor Hybrid structure

- Spin injection or spin-dependent charge transfer



Length scale: spin diffusion length in the non magnetic material
~100's of nm to several µm

- Magnetic proximity effect

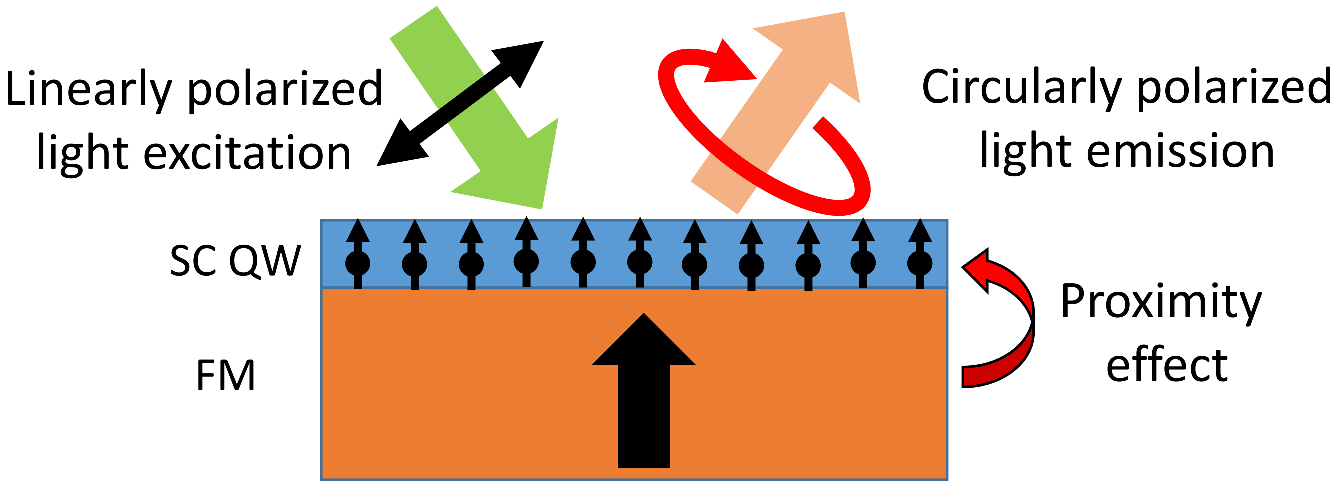


Mechanism: exchange interaction and/or hybridization of orbitals
Length scale: very short range ~1nm

Negligible except for very thin films

Proximity effects with thin films

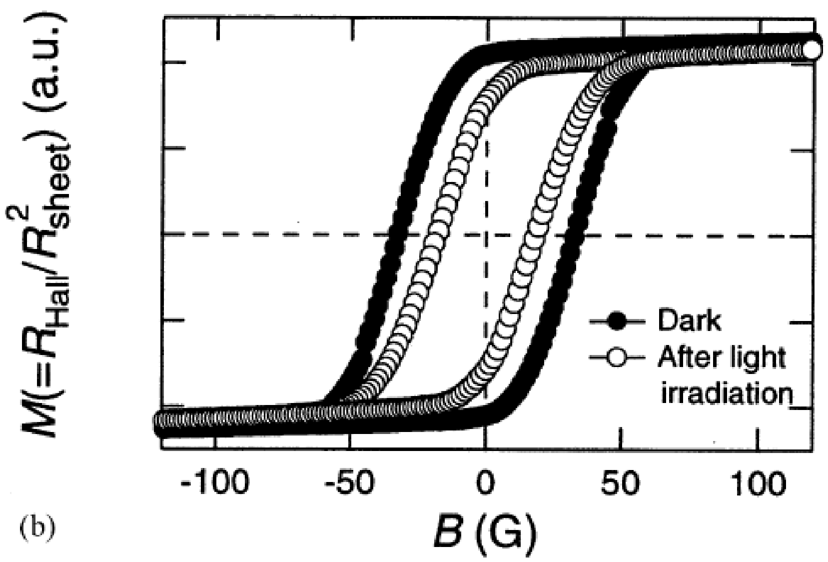
- Direct proximity effect



CdTe QW / Co Nat. Phys. **12**, 85 (2016).
(In)GaAs QW / MnAs Nat. Comm. **3**, 959 (2012)
PRB **69**, 161305 (2004)

Induced spin polarization: a few %

- "Indirect" proximity effect
  Control of magnetism with the semiconductor
  Optical or electrical



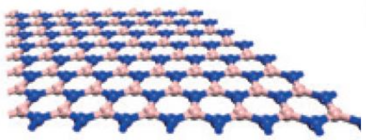
GaSb / InMnAs Phys. E **13**, 516 (2002)

Change of hysteresis loop, coercitive field …

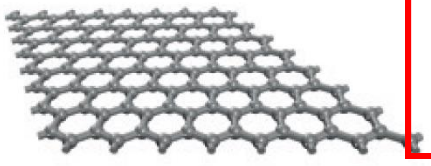
Weak effects → poor interfacial quality

Advantages of 2D materials

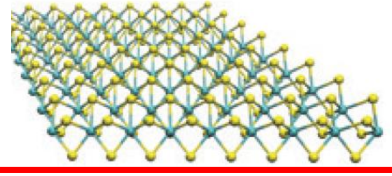
Insulator
(hBN)



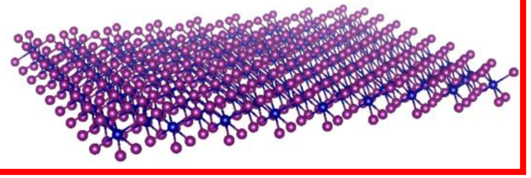
Semimetal
(Graphene)



Semiconductor
(TMD (MoS_2 ...))



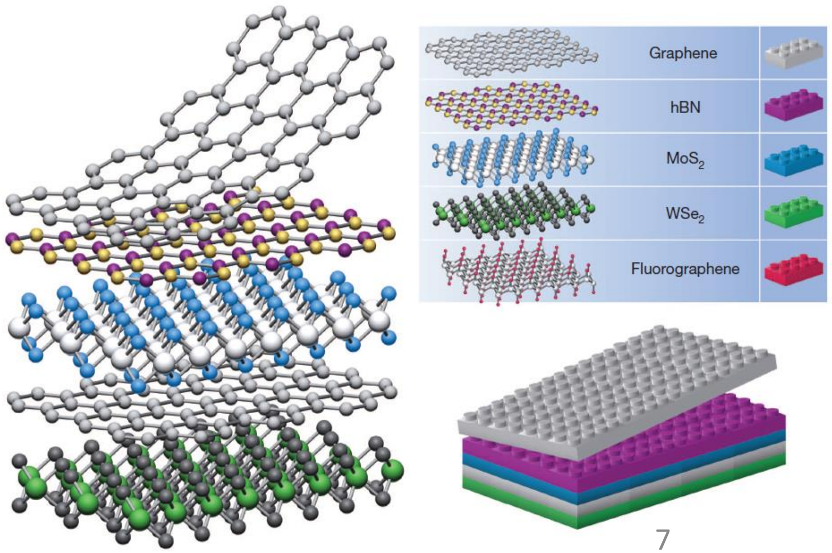
Magnetic
(CrX_3, FGT, CGT, $CrTe_2$...)



And many more: superconductors, topological insulator...

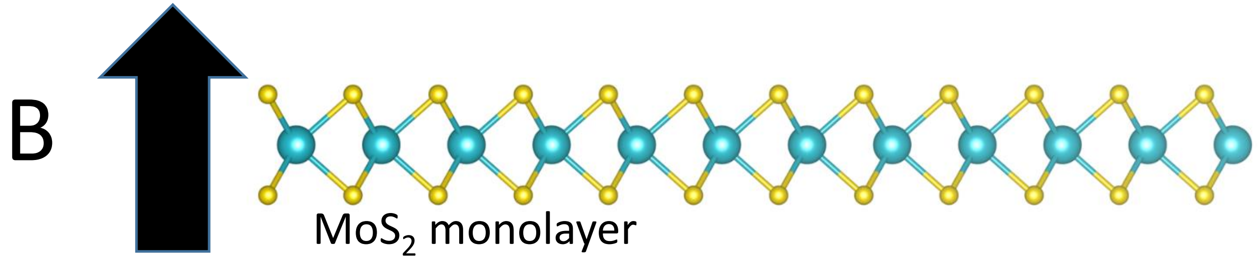
Nature Photon. **8**, 899 (2014)

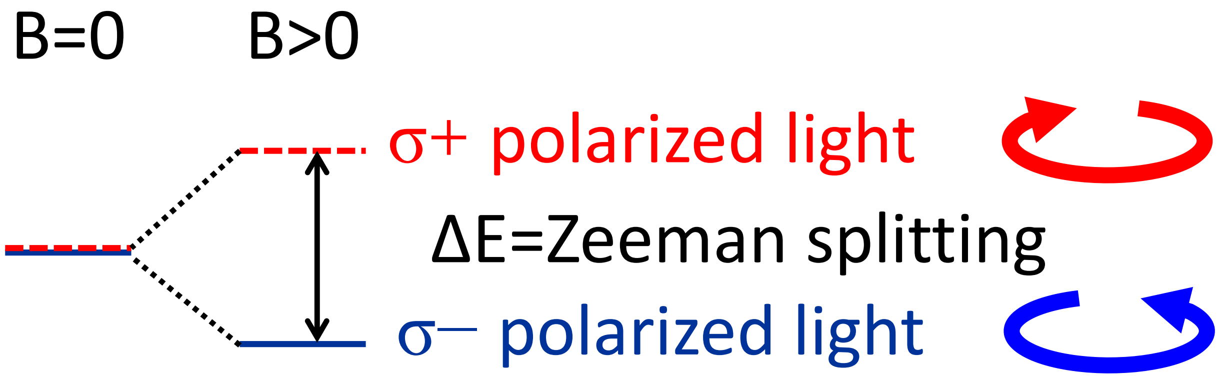
- Ultimately thin (ideal for proximity effects)
- Expected high quality interface (no dangling bonds)
- Large choice of heterostructure (no need to satisfy lattice matching conditions)
- Hybridization controled by the van der Waals gap

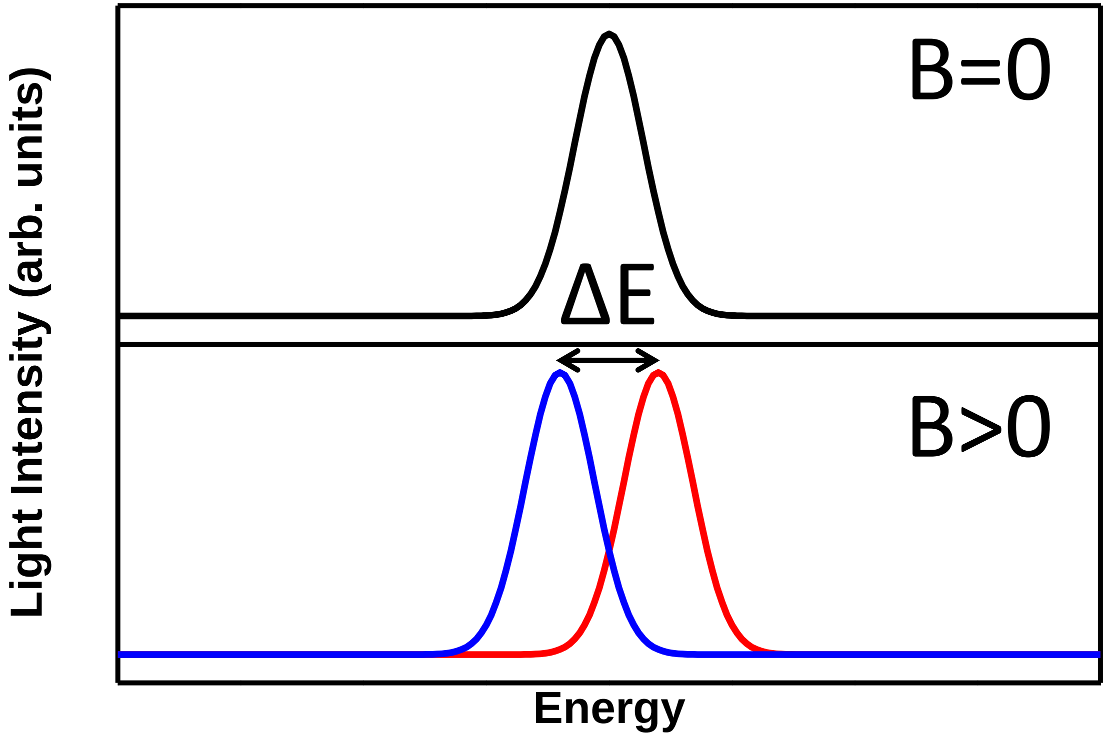


TMD in an external magnetic field

Optical probing of magnetization of the semiconductor





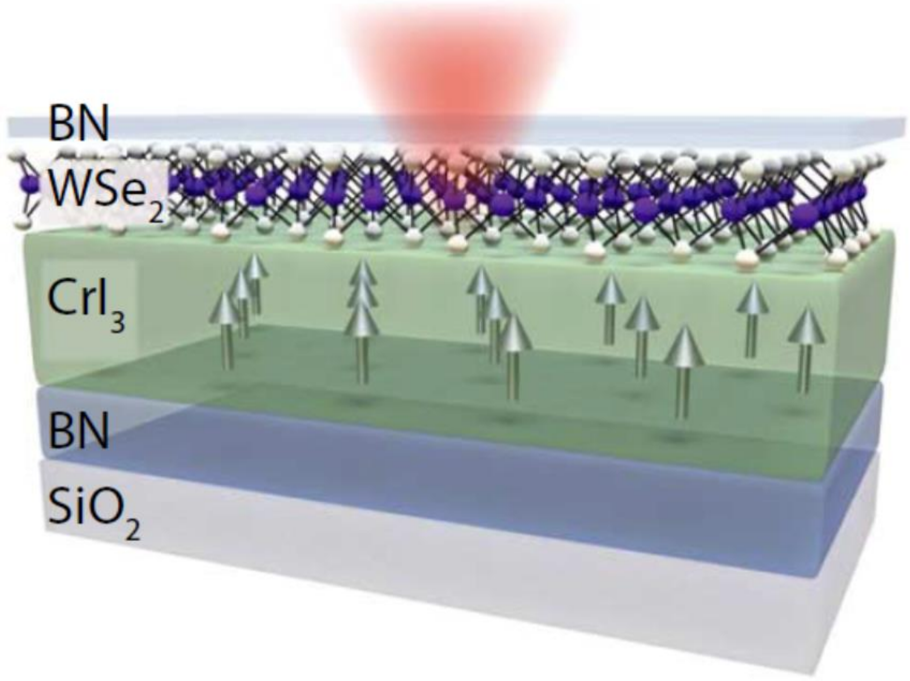


$\Delta E \propto B$ ($0.2\ meV.T^{-1}$) for MoS_2

TMD/Ferro heterostructure

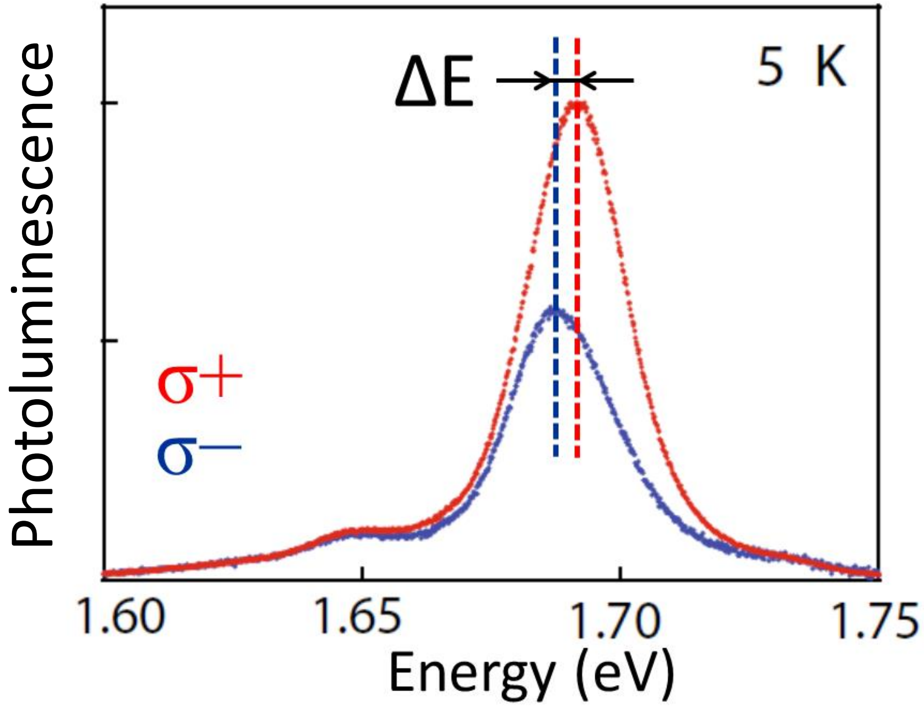
SC

FM



Science Advances **3**, e1603113 (2017) Seattle

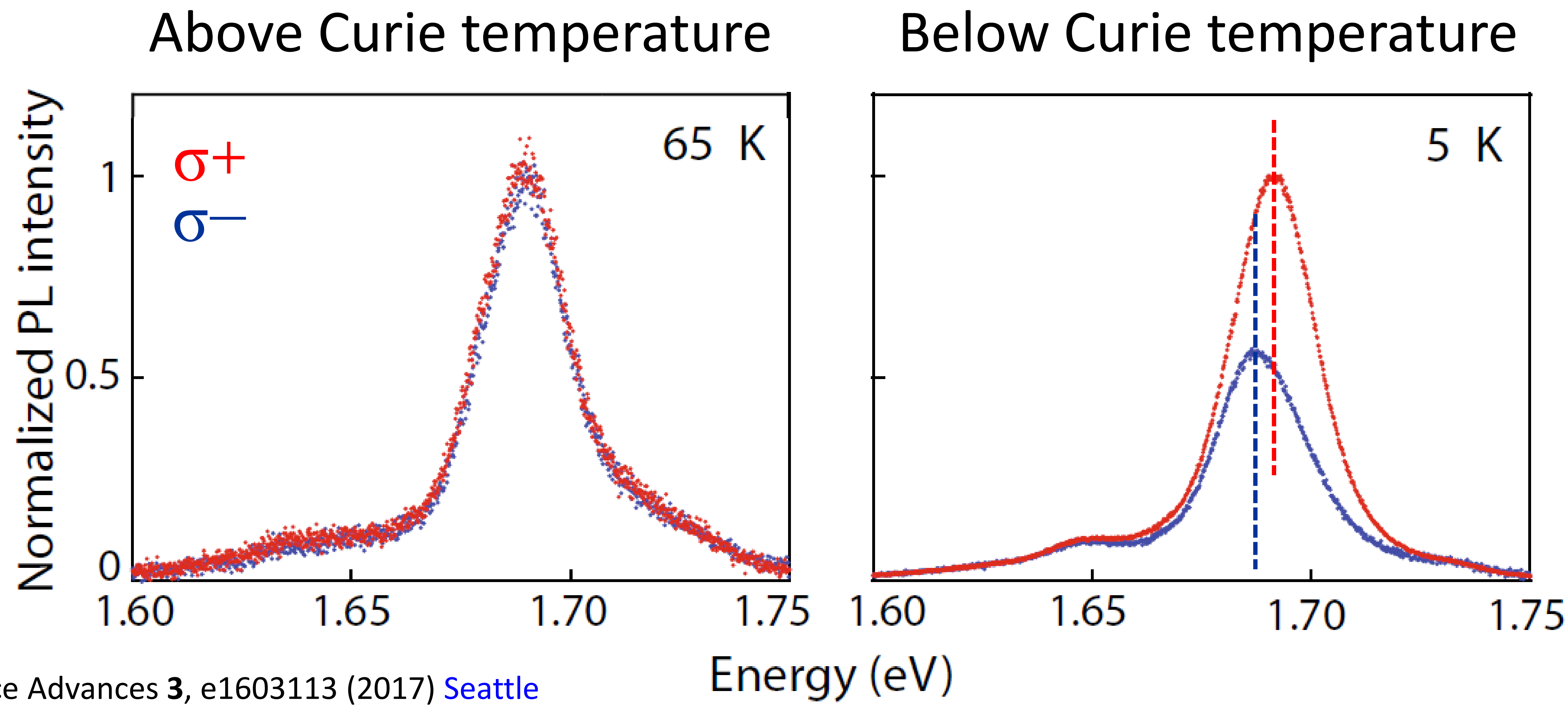
No external magnetic field !



Zeeman splitting ΔE equivalent to an effective magnetic field of 13 T !

Circular polarization → could be due to spin dependent charge transfer

TMD/Ferro heterostructure

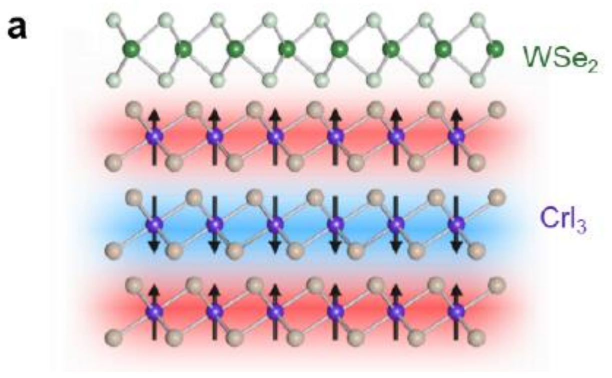


Science Advances **3**, e1603113 (2017) Seattle

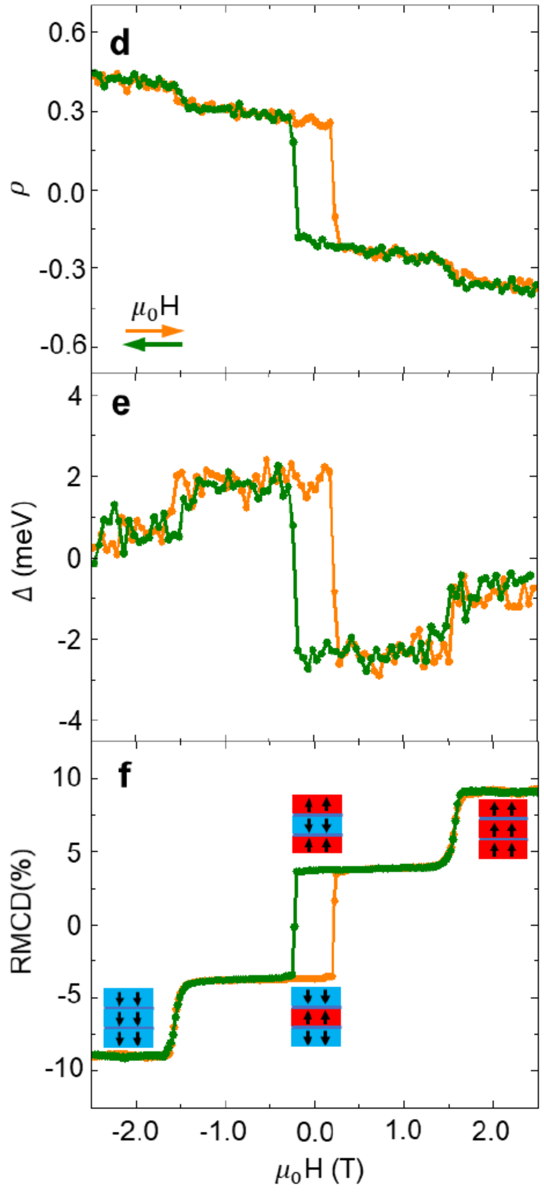
Clear influence of ferromagnetic layer on semiconductor properties

TMD/Ferro heterostructure

Proximity effects vs spin dependent charge transfer



CrI_3 trilayer: antiferro



Polarization → spin-dependent charge transfer → mainly sensitive to the the magnetization of the top CrI_3 layer

Zeeman splitting → proximity effect → sensitive to the whole magnetic structure

TMD monolayer probes the magnetic order of CrI_3

Nat. Nano. 15, 187 (2020) Seattle

TMD/Ferro heterostructure

TMD on 2D magnet

$MoSe_2/CrBr_3$ Phys. Rev. Lett. 124, 197401 (2020) ETH

$MoSe_2/CrBr_3$ Nat. Comm. 11, 6021 (2020) Sheffield

$WSe_2/Cr_2Ge_2Te_6$ Nano Lett. 19, 7301 (2019) New Jersey

$MoSe_2$/Mn Perovskite Adv. Mater. 32, 2003501 (2020) Kyoto

And also TMD on 3D magnet

WSe_2/EuS Nat. Nano. 12, 757 (2017) Buffalo

WS_2/EuS Nat. Comm. 10, 4163 (2019) Buffalo

MoSe2/YIG arXiv 2006.14257 (2020) Tokyo

A few challenges

- Study of magnetic 2D materials: a topic by itself
- Layered magnetic materials: generally air-sensitive materials
- Towards materials with higher Curie temperature
- Optical control of magnetic properties through the semiconductor ("indirect proximity effect")
- Microscopic mechanism → to be demonstrated experimentally
- Challenges for simulation: band offsets …

Thank you

Influence of semiconductor on ferromagnet ?

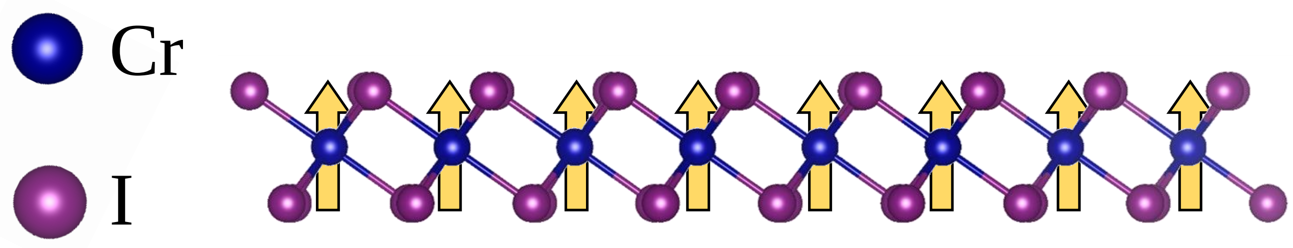
Goal: control of the magnetic properties with the help of the semiconductor

Necessary condition: spin carrier density in the semiconductor is comparable with the density of spins in the ferromagnet.
B.P. Zakharchenya and V.L. Korenev, Phys.-Usp. **48**, 603 (2005).

- Difficult to obtain with ferromagnetic metal
- More efficient for thin ferromagnetic layer

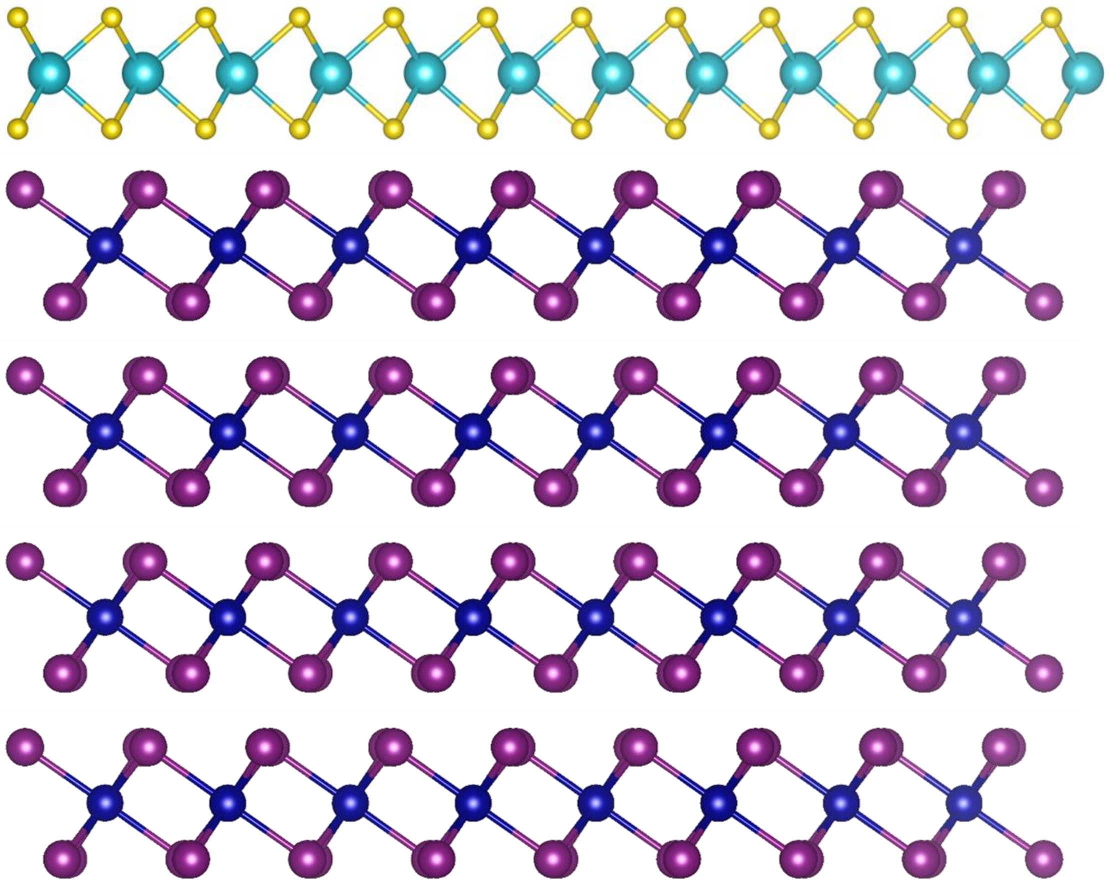
Ideally 2D ferromagnet (insulator or SC)

CrI_3: ferromagnetic layered material
Still ferromagnetic in monolayer form



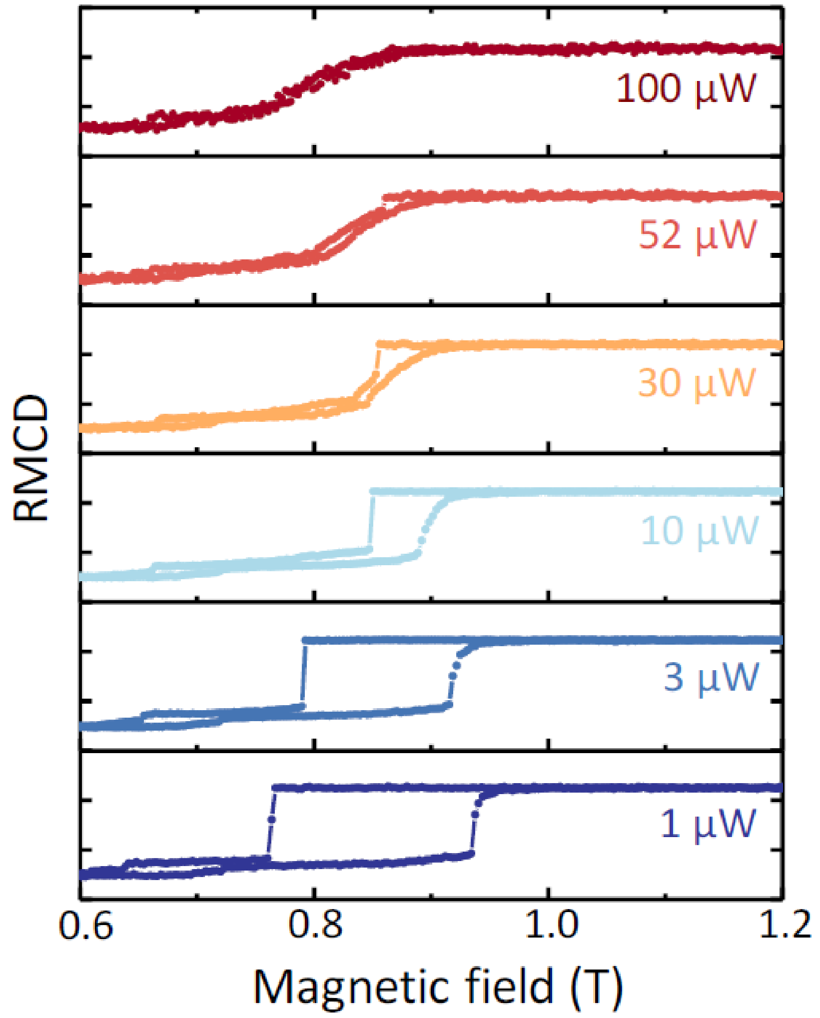
Influence of semiconductor on ferromagnet ?

Nano Lett. **18**, 3823 (2018) Seattle



SC WSe_2

FM CrI_3



Change of hysteresis loop of CrI_3 with light excitation of WSe_2