$CrPS_4$ field-effect transistors

Alberto Morpurgo

UNIVERSITÉ DE GENÈVE

Transport experiments: F. Yao, M. Liao, F. Wu, X. Lin, C.-Y. Yeon, N. Ubrig, I. Gutierrez (Geneva)

Theory: M. Gibertini (Modena)

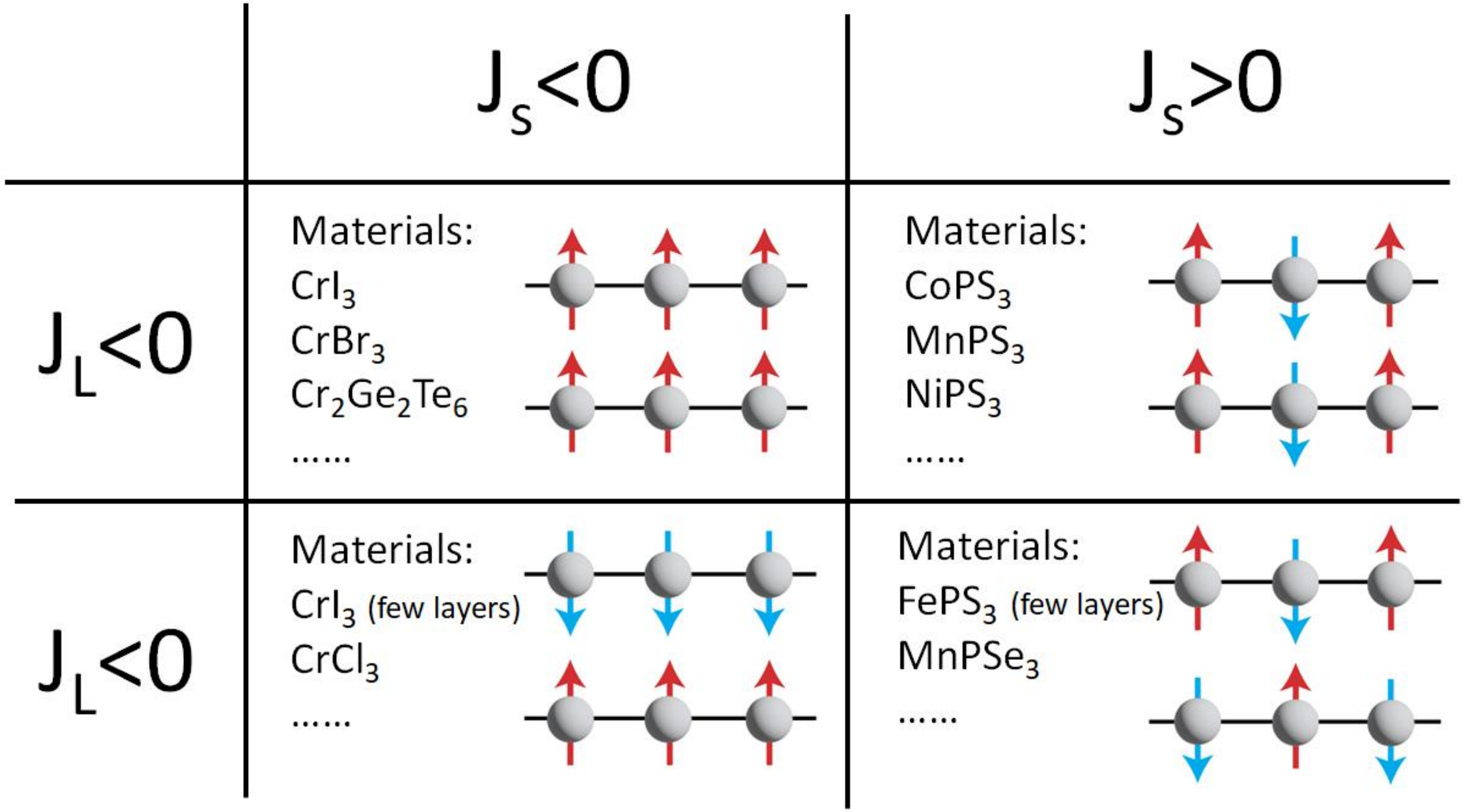
Materials: T. Taniguchi, K. Watanabe (NIMS)

FNSNF
SWISS NATIONAL SCIENCE FOUNDATION

GRAPHENE FLAGSHIP

Interplay between semiconducting properties and magnetism

Broad variety of magnetic states



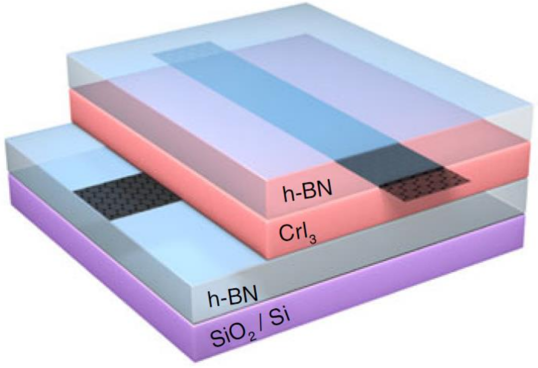
How do we probe magnetism in atomically thin layers?

Can we control the magnetic state?

What new functionalities can emerge?

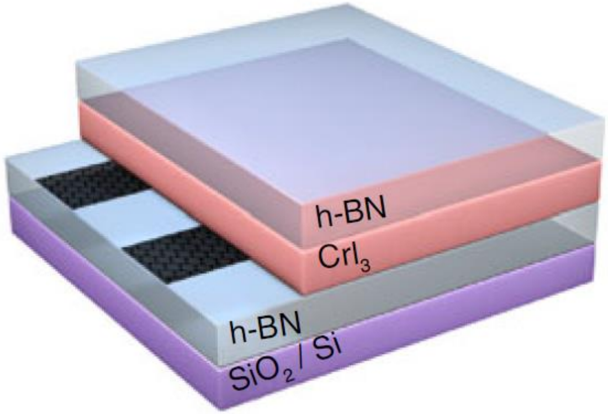
Vertical and in-plane transport

Vertical transport:
Tunnel barrier configuration



- *Easier to make*
- *"Always work"*
- *Less flexibility and no gate control*

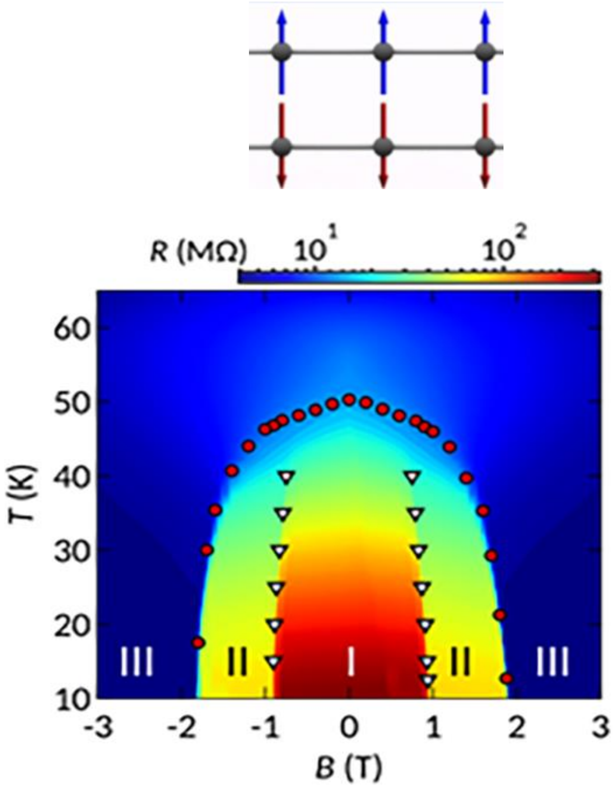
In-plane transport:
Field effect transistor configuration



- *More complex fabrication (especially 4 terminal)*
- *Only works for sufficiently large bandwidth (localization effects)*
- *More flexibility and gate control*

Magnetic phase diagram from tunnelling magnetoconductance

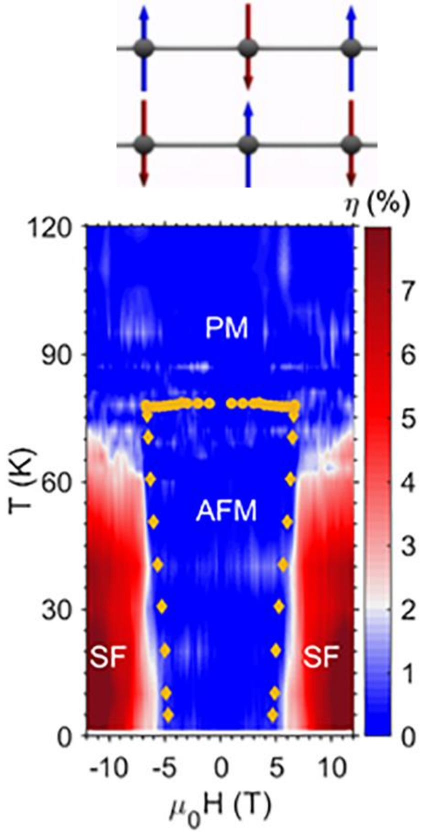
CrI_3: Anisotropic layered antiferromagnet



Spin-flip transitions

Nat Comms **9**, 2516 (2018)

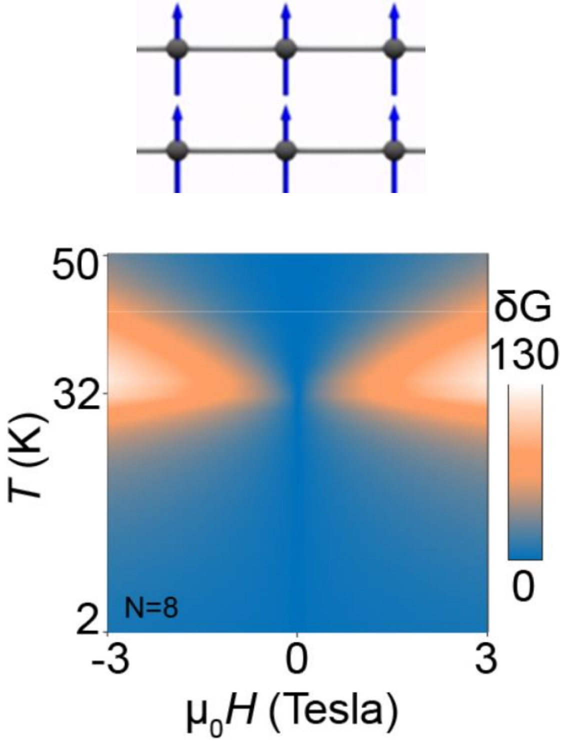
$MnPS_3$: Intralayer antiferromagnet



Spin-flop transitions

Nano Lett. **20**, 2452 (2020)

$CrBr_3$: Ferromagnet



Critical fluctuations

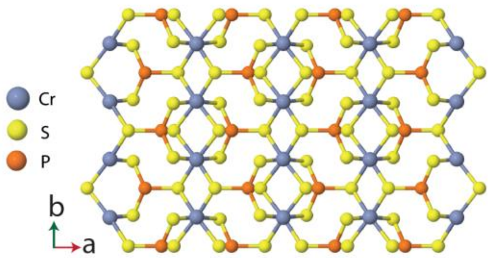
Nat Comms **12**, 6659 (2021)

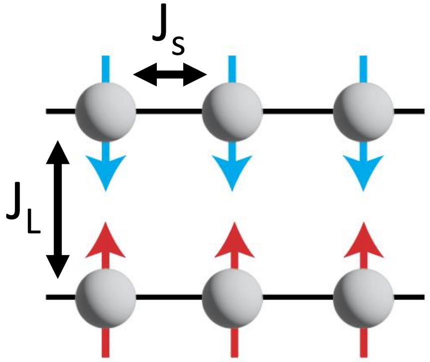
CrPS$_4$: a relative large bandwidth 2D magnetic semiconductor

Ab-initio calculations:

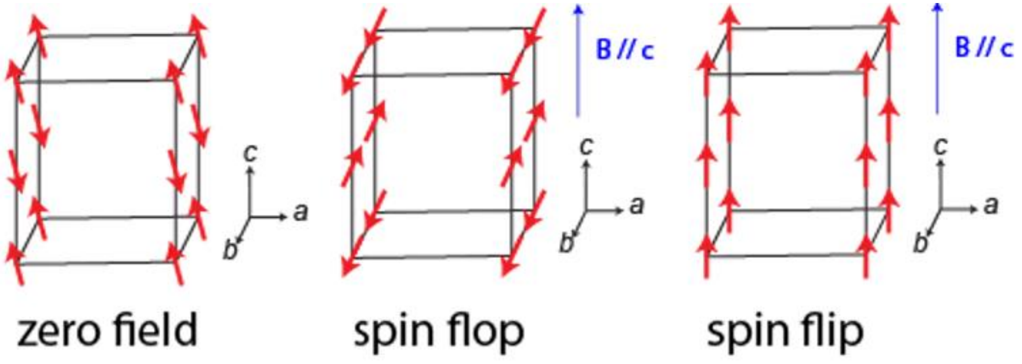
Marco Gibertini

CrPS$_4$ = Weakly anisotropic layered antiferromagnet



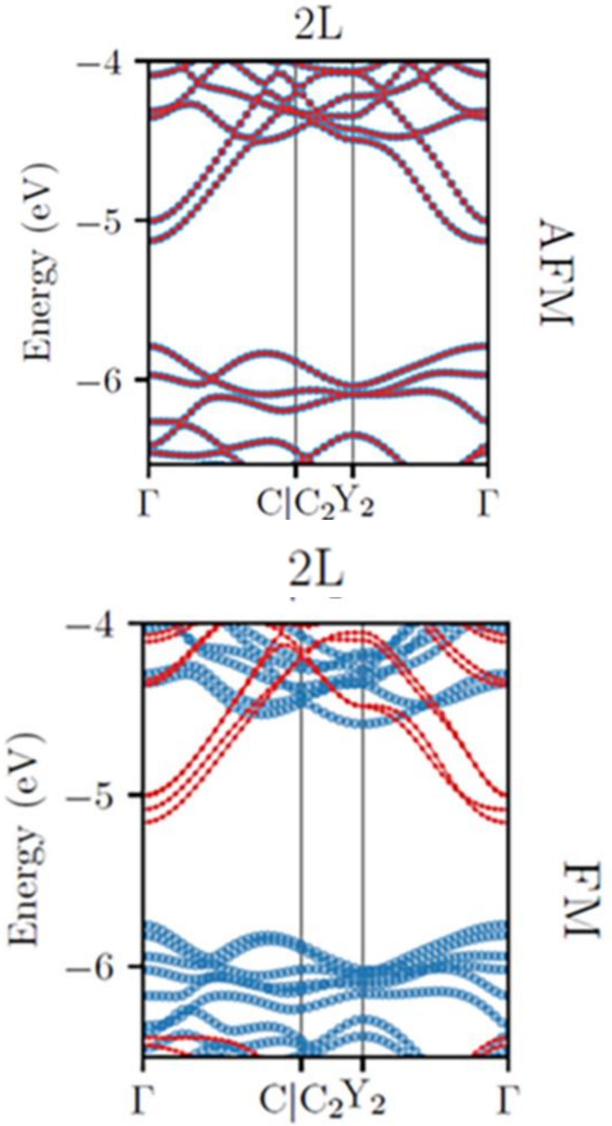


Increasing perpendicular magnetic field

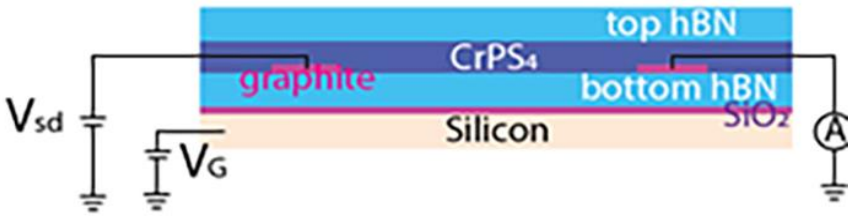


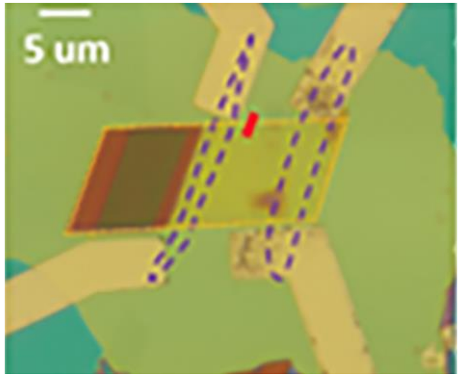
T$_N$ = 38 K; Spin-flip ~ 8 T; Spin-flop ~ 0.8 T

Bandwidth: ~ 1 eV

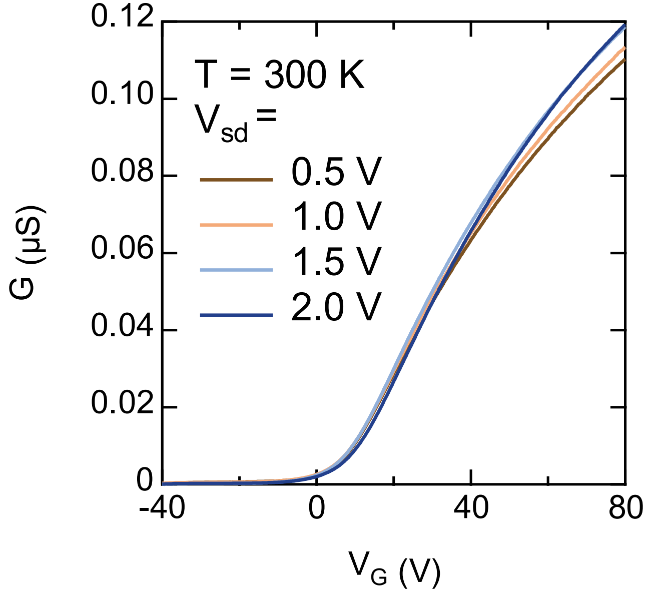


Field-effect transistors on $CrPS_4$

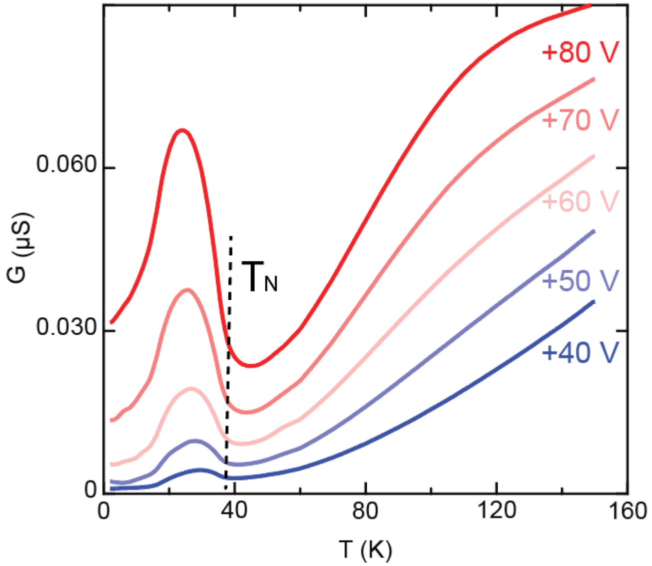




Room-Temperature



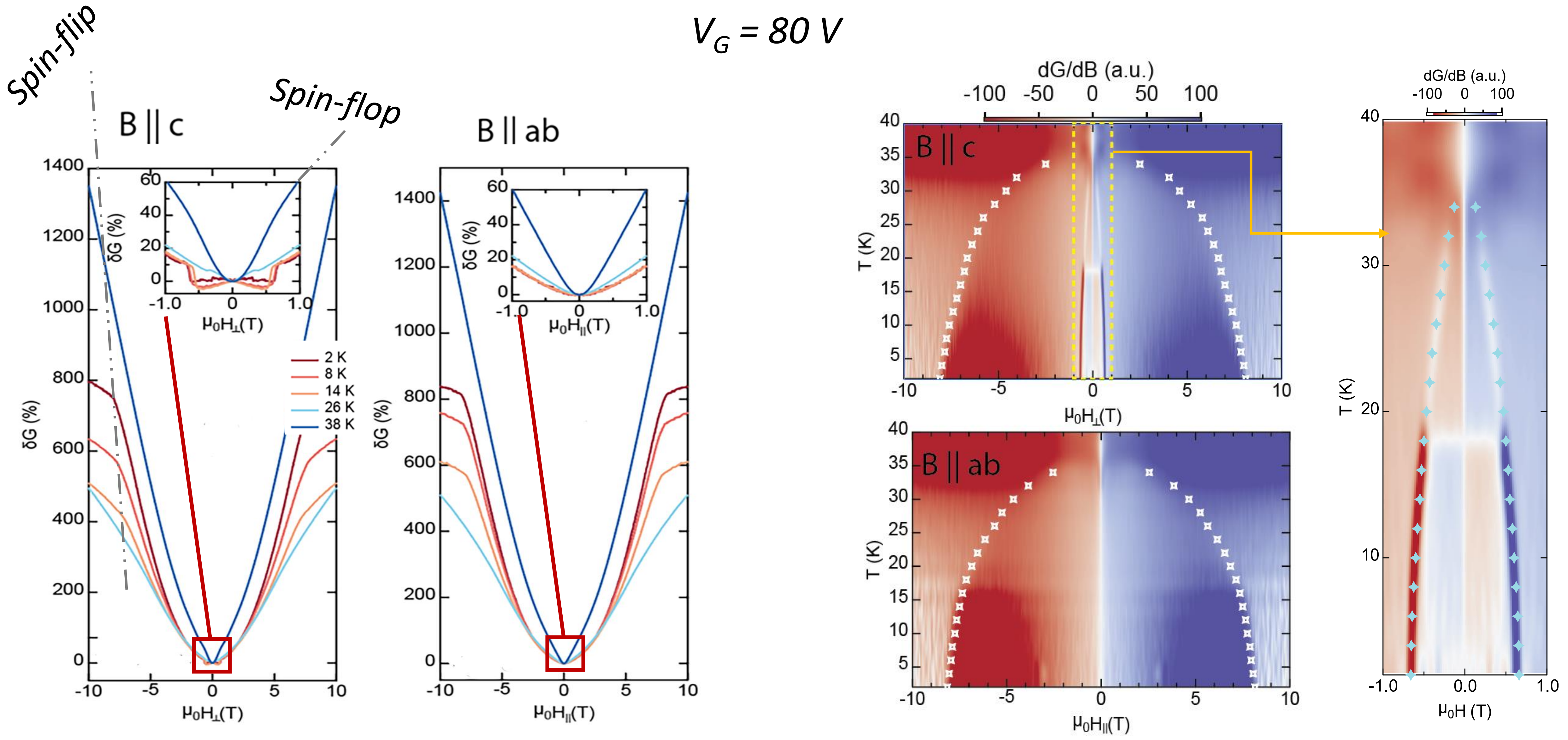
Low-Temperature



CPS_4 FETs function properly at low-temperature and conductance affected by magnetism!

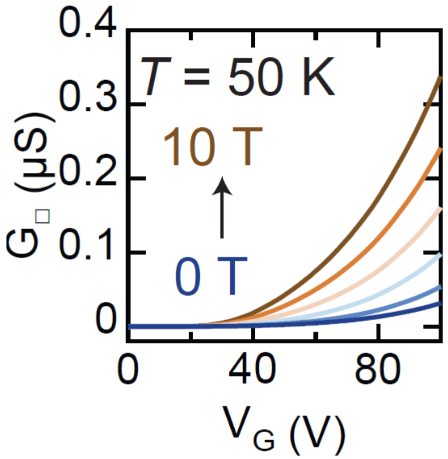
Magnetoconductance & magnetic phase diagram

$V_G = 80$ V



Phase diagram determined from in-plane transport

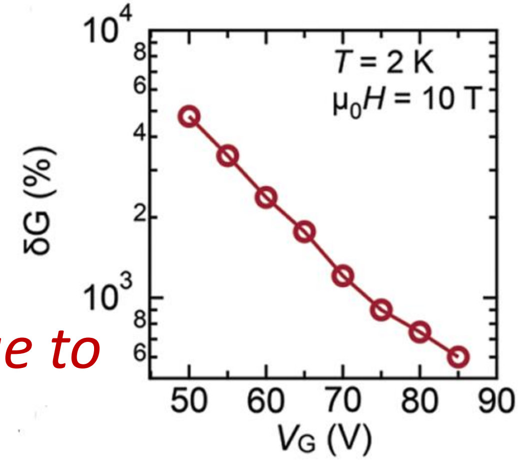
Origin of magnetoconductancee



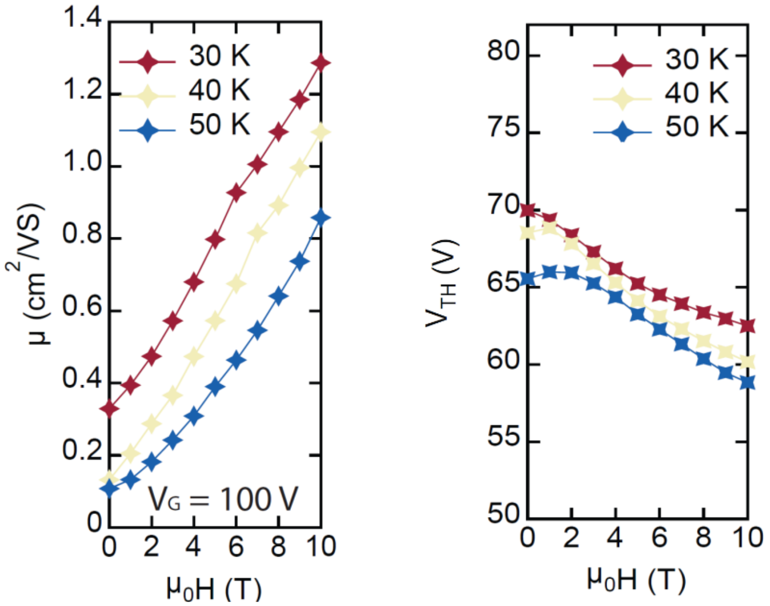
$$G_{\square} = \mu \cdot C \cdot (V_{\mathrm{G}} - V_{\mathrm{TH}})$$

Low T, $T << T_N$: mobility independent of field

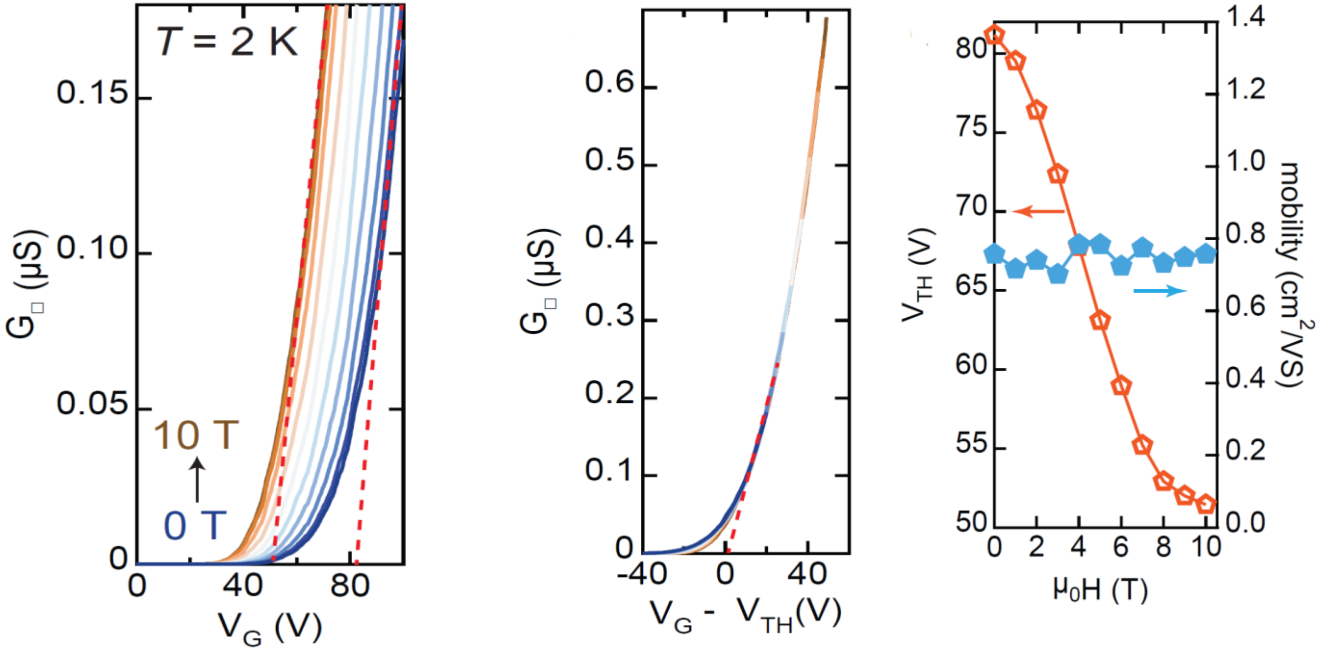
Magnetoconductance due to threshold voltage shift



Near T_N: field causes
10 x increase in mobility

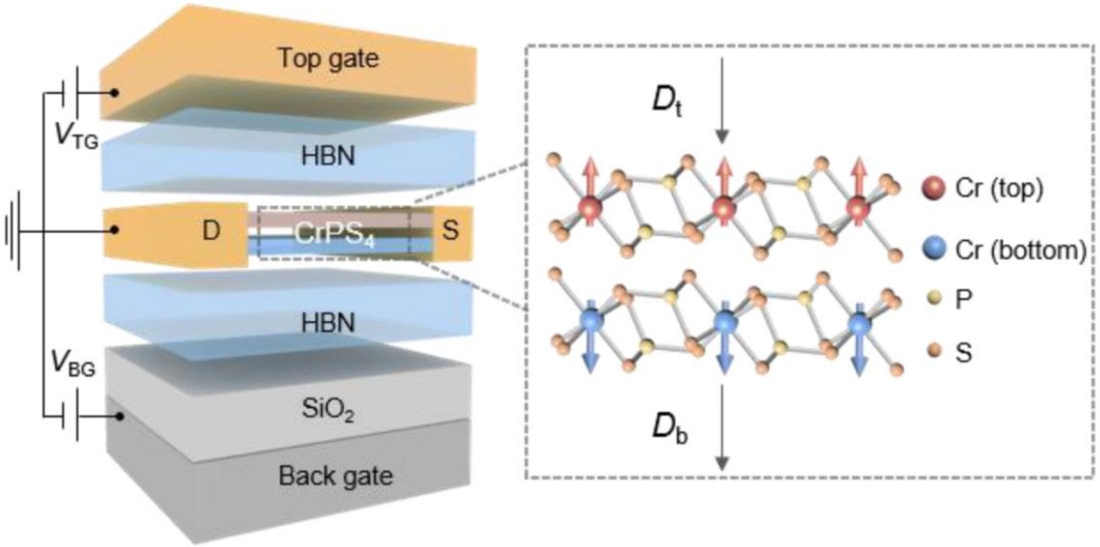


Magnetoconductance from reduced spin disorder



Change in magnetic state causes downshift of conduction band edge

Double-gated bilayer $CrPS_4$ transistors

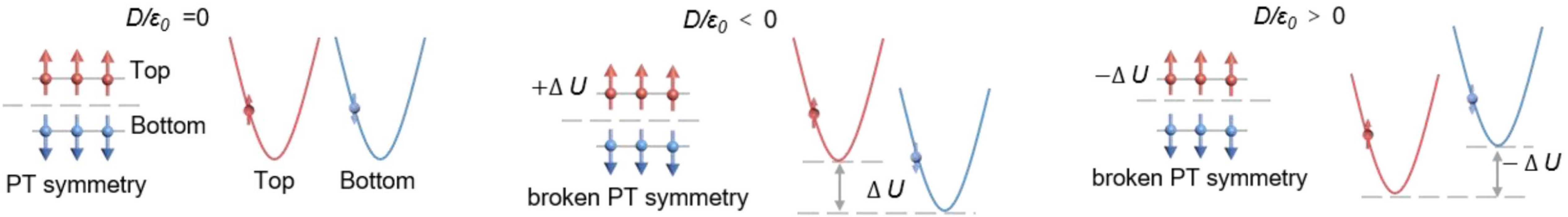


Double Gated $CrPS_4$ Bilayers

- Independent control of
  - *electron density n*
  - *perpendicular electric field (D/ε_0)*

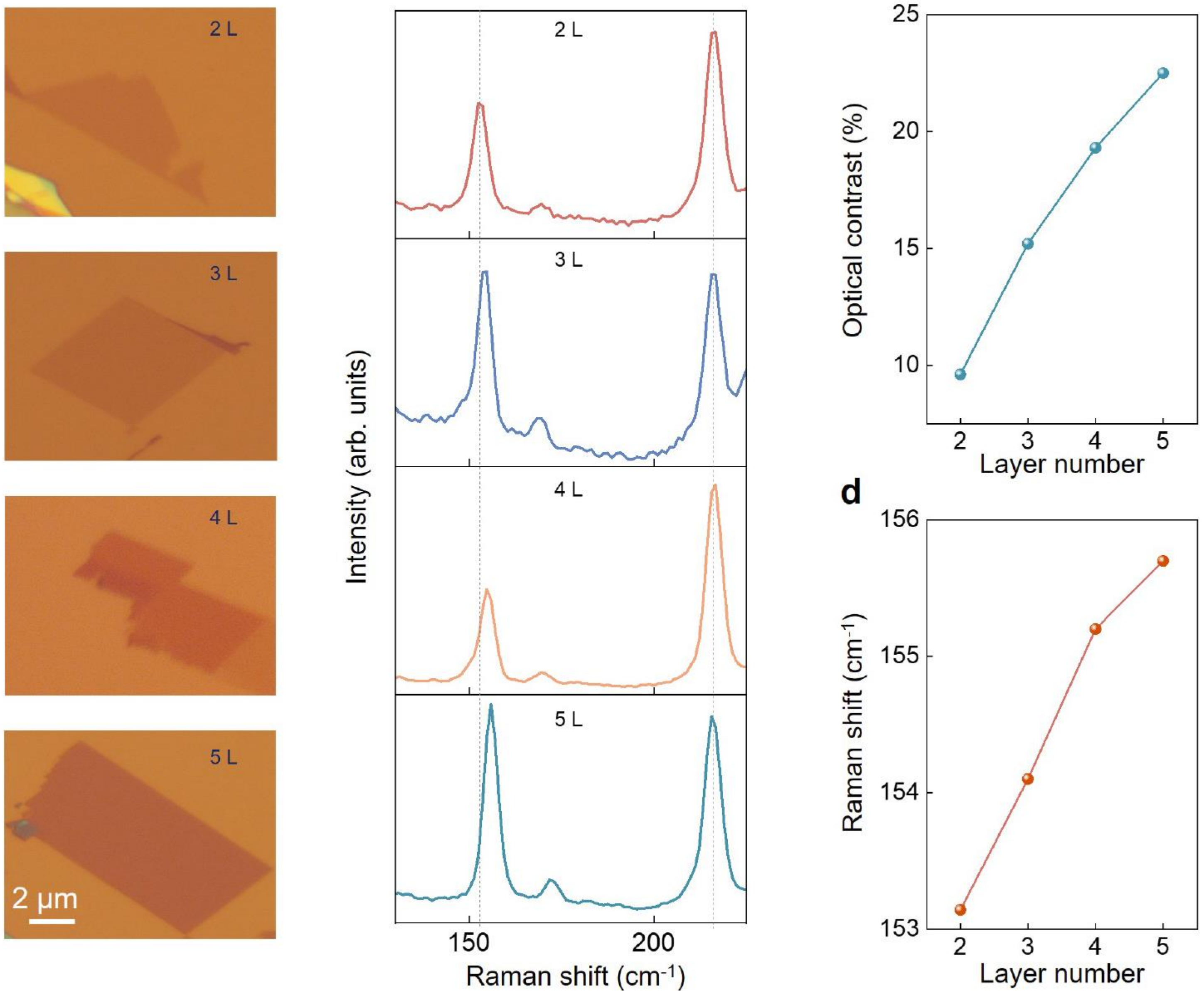
- Finite electric field breaks:
  - *inversion symmetry (P)*
  - *Time space inversion (PT)*

Perpendicular electric field = gate-switchable spin polarization in conduction band

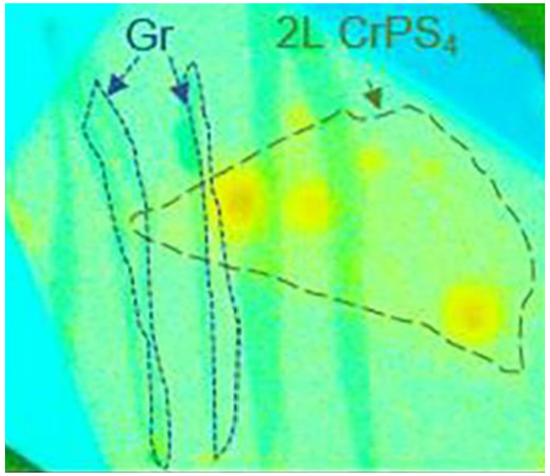


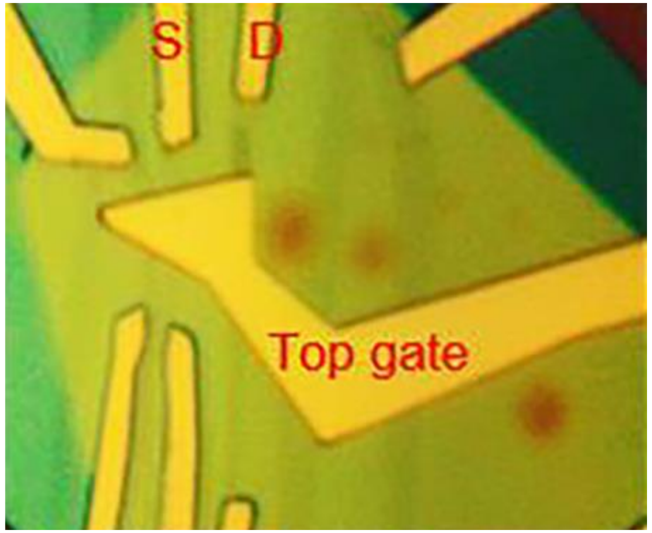
Switching on & off the physics of anomalous Hall effect antiferromagnets

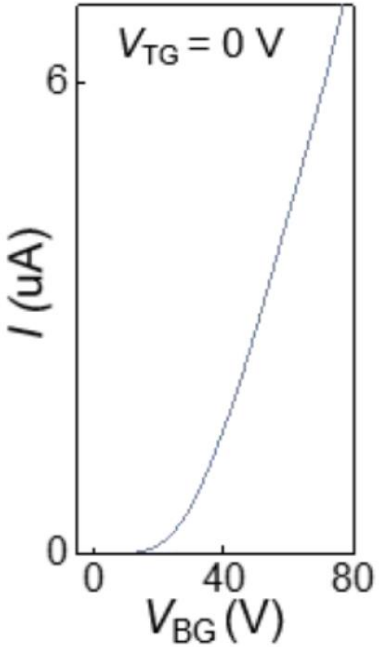
Thickness identification: Optical contrast & Raman shift

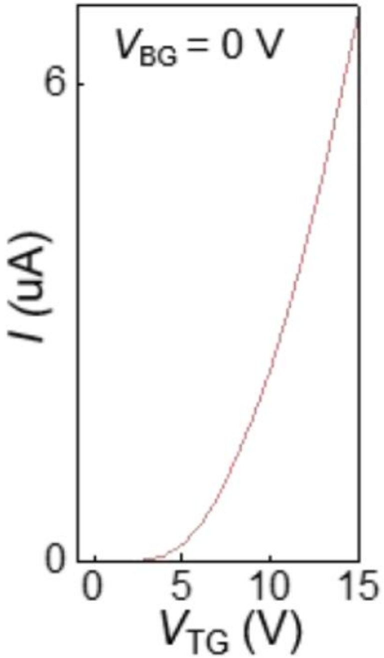


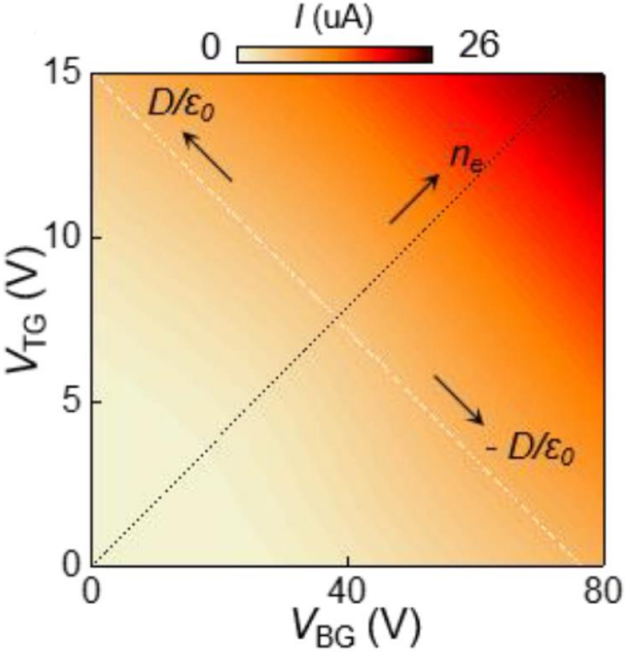
Double Gated $CrPS_4$ Bilayer Transistors: Electrical characterization (2 K)







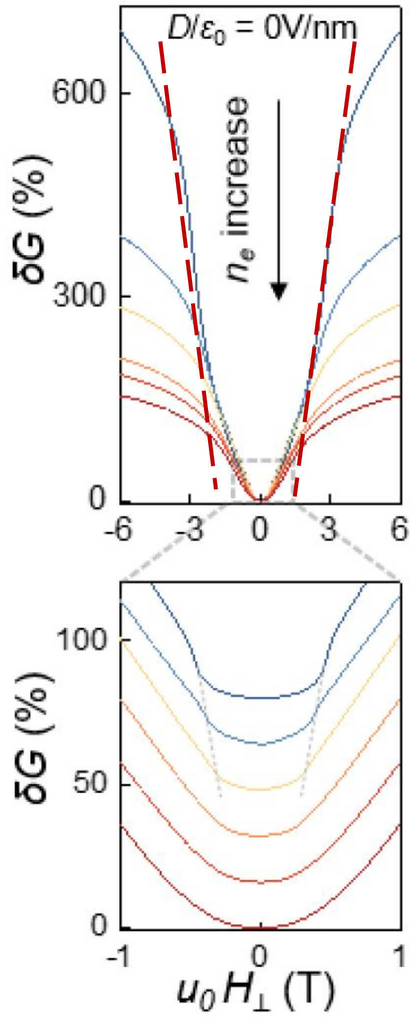




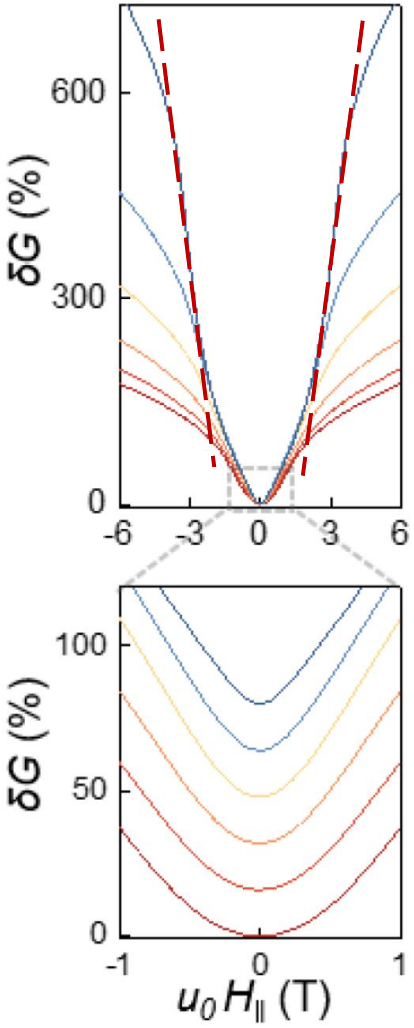
Magnetic state characterization

Magnetotransport at zero perpendicular electric field

Out-of-plane



In-plane

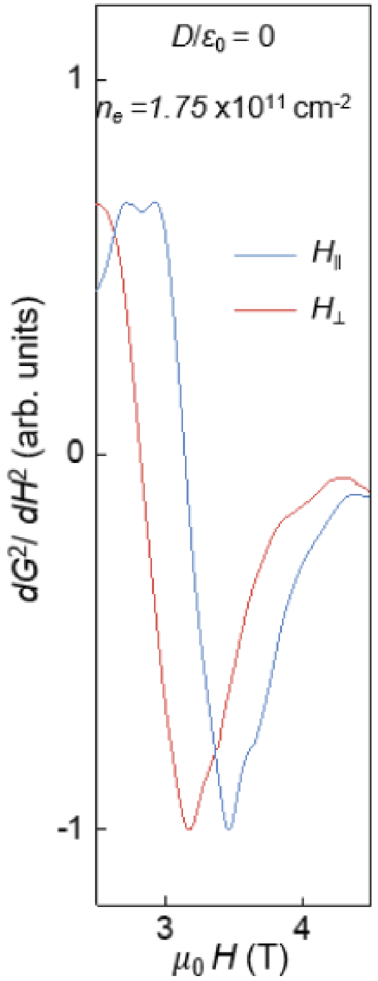


Spin-flip

Spin-flop

Increasing electron density

Determination of spin-flip field



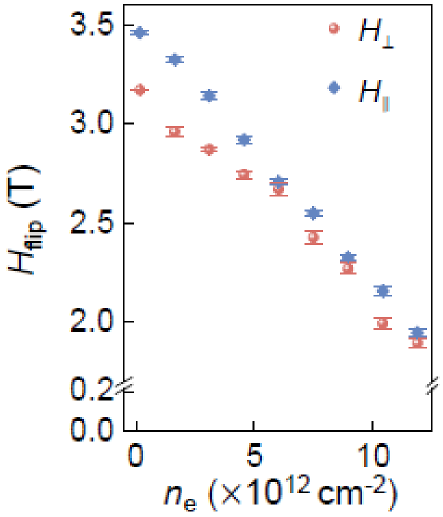
Minimum of d^2G/dH^2

Extracting interlayer exchange and magnetic anisoropy

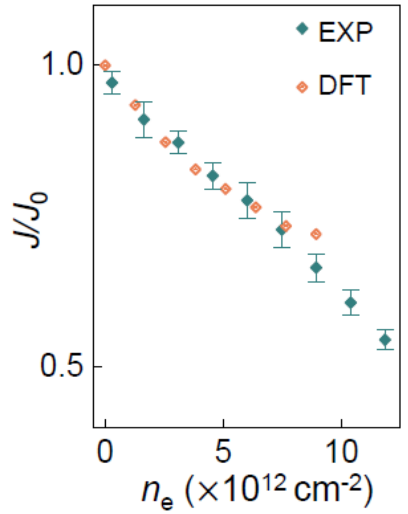
$$E = J\boldsymbol{M}_1\cdot\boldsymbol{M}_2\,/M_s^2 -$$

$$- \; K/2\,(M_{1z}/M_s)^2 - K/2\,(M_{2z}/M_s)^2 - \mu_0\,\boldsymbol{H}\cdot(\boldsymbol{M}_1+\boldsymbol{M}_2)$$

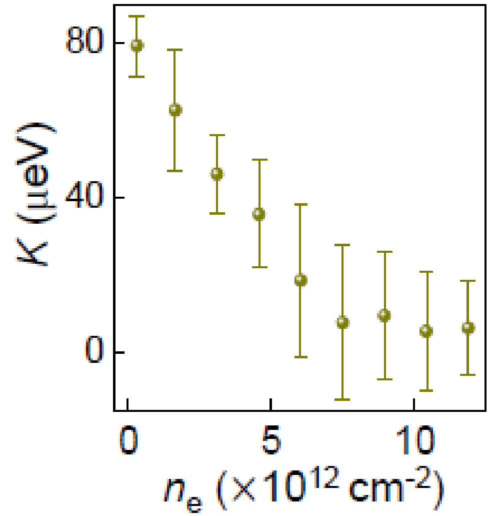
in- vs out-of-plane
Spin-flip field



Interlayer
exchange



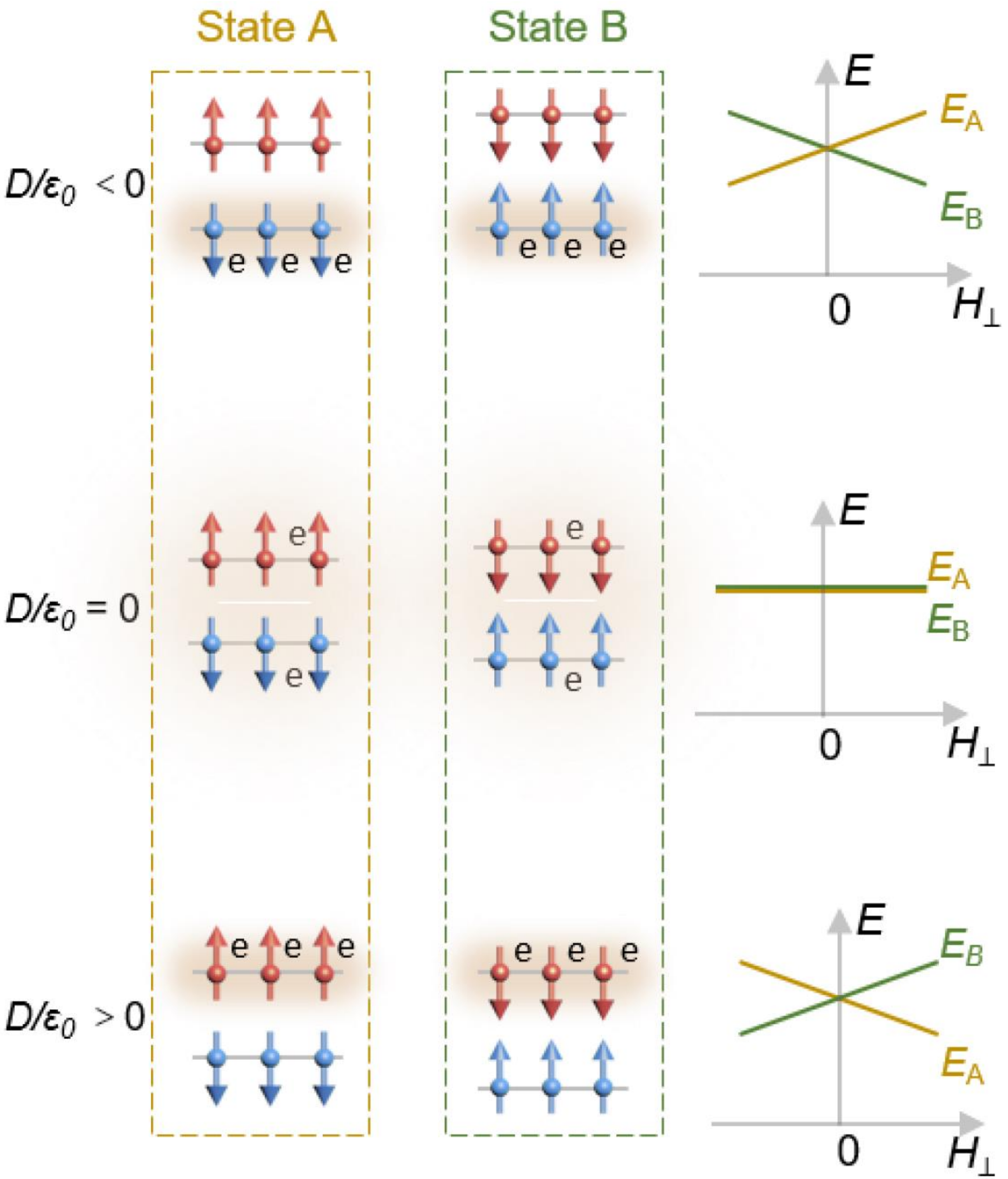
Anisotropy



Magnetic anisotropy: small & changes sign at large n
Easy axis-to-easy plane transition

Finite displacement field: Two states possible

out-of-plane field



*With **out-of-plane** magnetic field*

Ground state depends on:

- *Electric field polarity*
- *Direction of magnetic field*

If the two states have different magnetoconductance

- *Hysteretic magnetoconductance*

With in-plane magnetic magnetic field

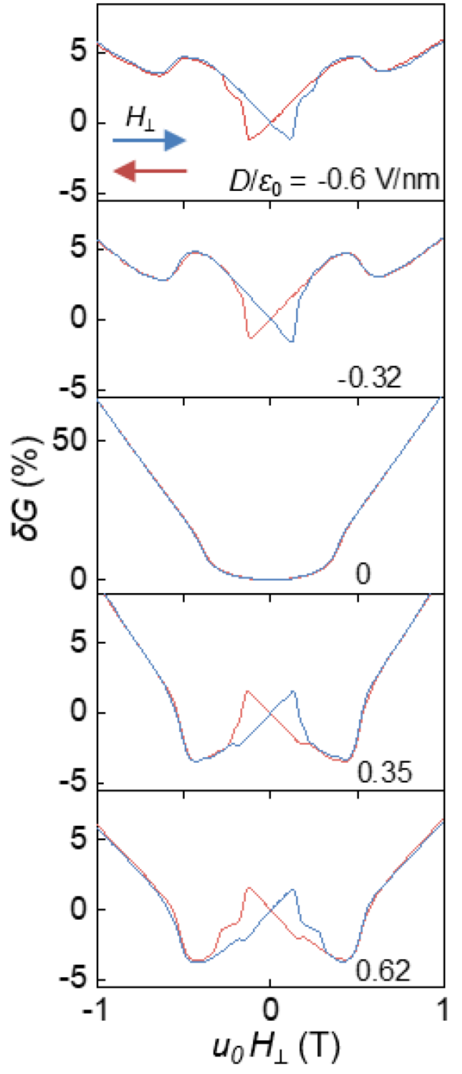
State A & B always degenerate

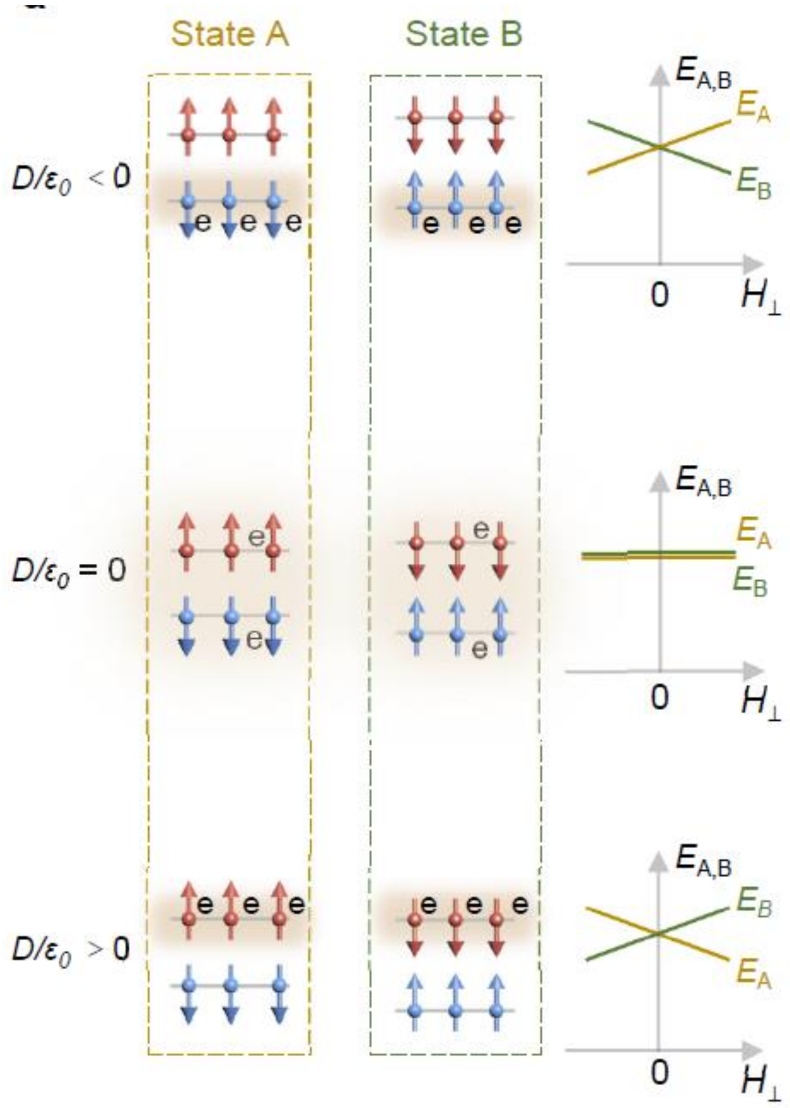
- *No hysteretic magnetoconductance*

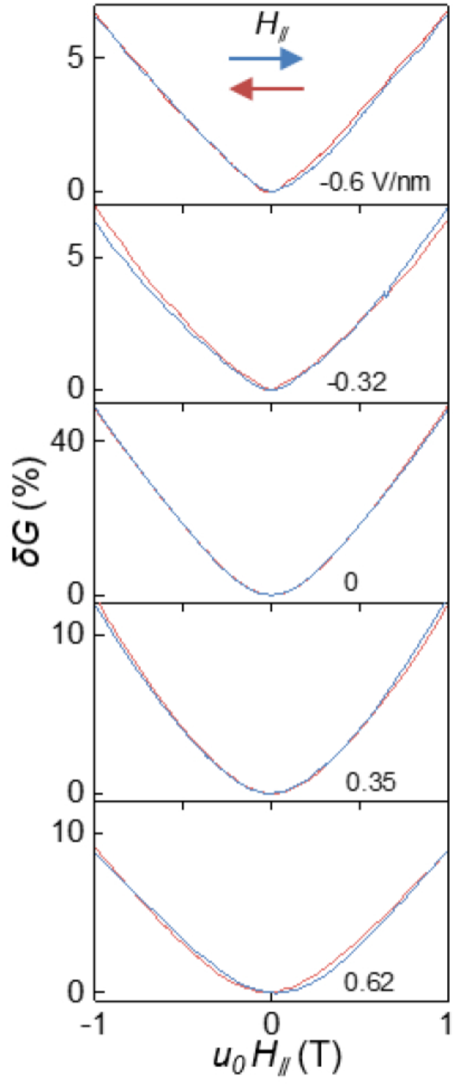
Magnetoconductance at finite perpendicular electric field

Out-of-plane

In-plane



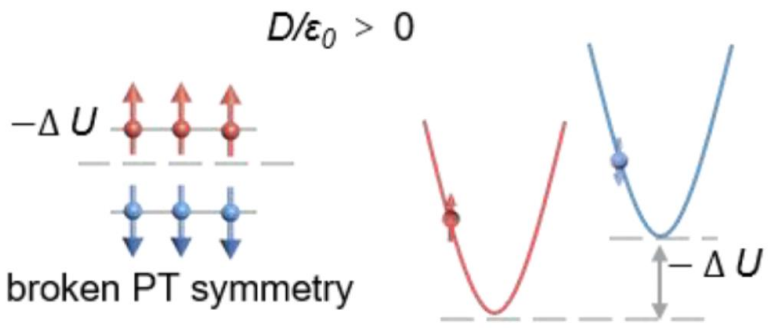




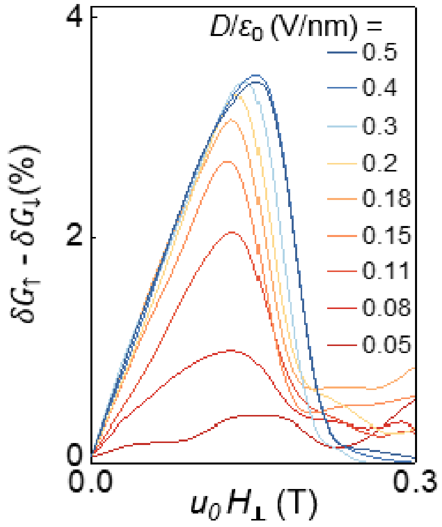
Hysteresis

No hysteresis

Magnetoconductance hysteresis: amplitude evolution

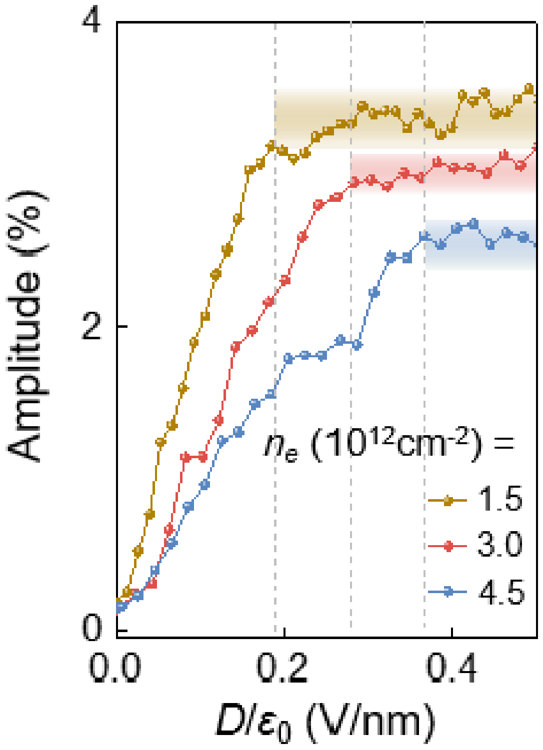


Extract
hysteresis amplitude



Fixed density
Increasing displacement field

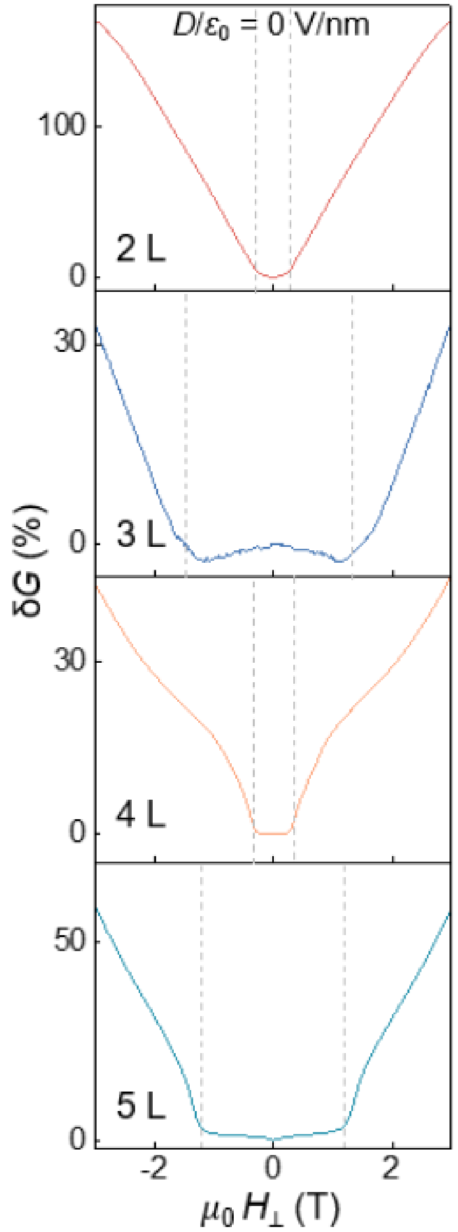
Saturation:
Larger n_e requires larger D/ε_0



Saturation:
spin-splitting larger than
Fermi energy

Spin-flop in weak anisotropy antiferromagnetic multilayers

Even-odd effect

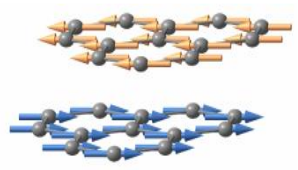


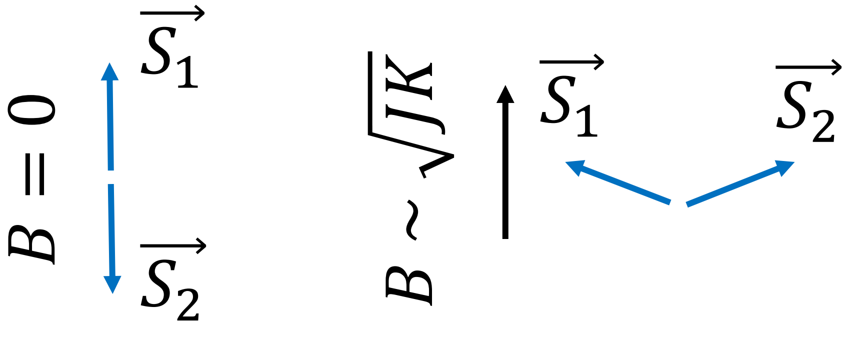
Exchange = J ; $E = J\overrightarrow{S_1} \cdot \overrightarrow{S_1}$

Anisotropy = K ; $E = -K{S_z}^2$ (K small ~ 0)

Zeeman = μB ; $E = -\mu\vec{B} \cdot \vec{S}$

Even-N



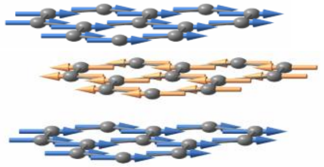


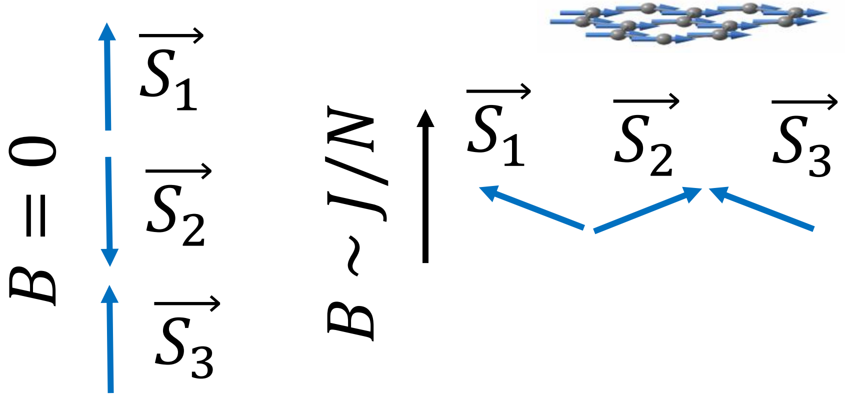
Energy balance:

$$\Delta E \sim -N\frac{\mu B}{J}\mu B$$

Spin-flop transition at B ~ 0

Odd-N



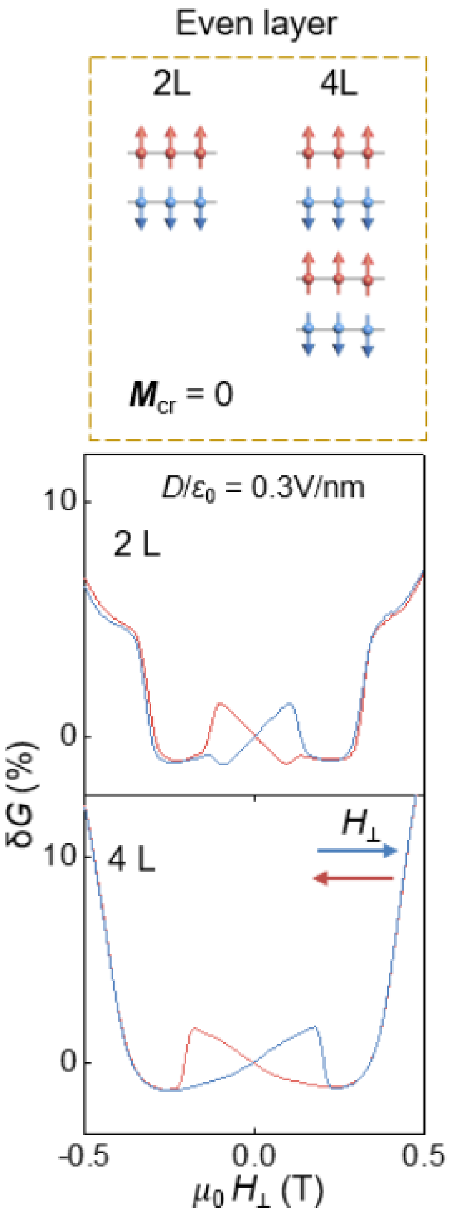


Energy balance:

$$\Delta E \sim -N\frac{\mu B}{J}\mu B + \mu B$$

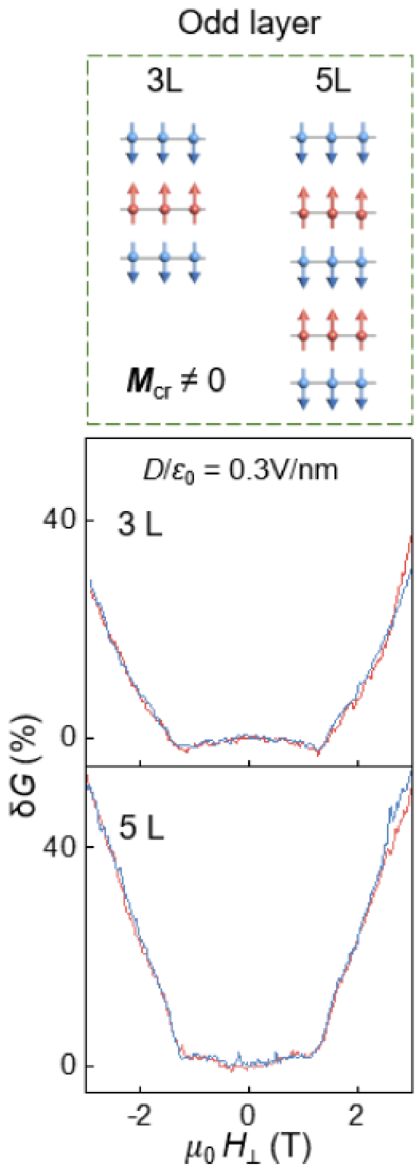
Spin-flop transition at B ~ J/N

Even-odd effect in magnetoconductance hysteresis



- *No net magnetization at n = 0*

- *Opposite magnetization of electrons for opposite displacement fields*



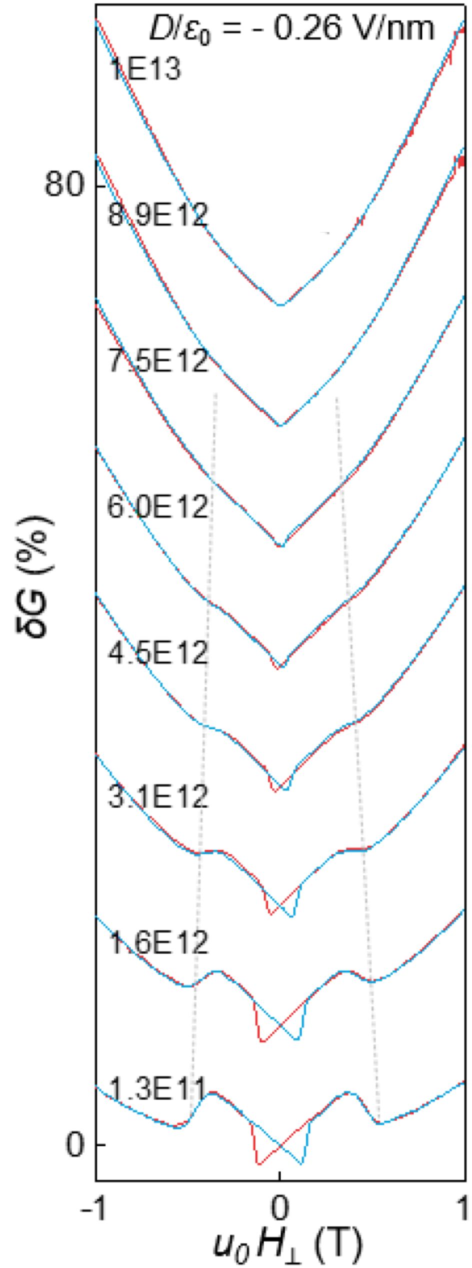
- *Large magnetization already at n = 0*

- *Same magnetization of electrons for opposite displacement fields*

Magnetization DUE to accumulated electrons small & switches at larger field

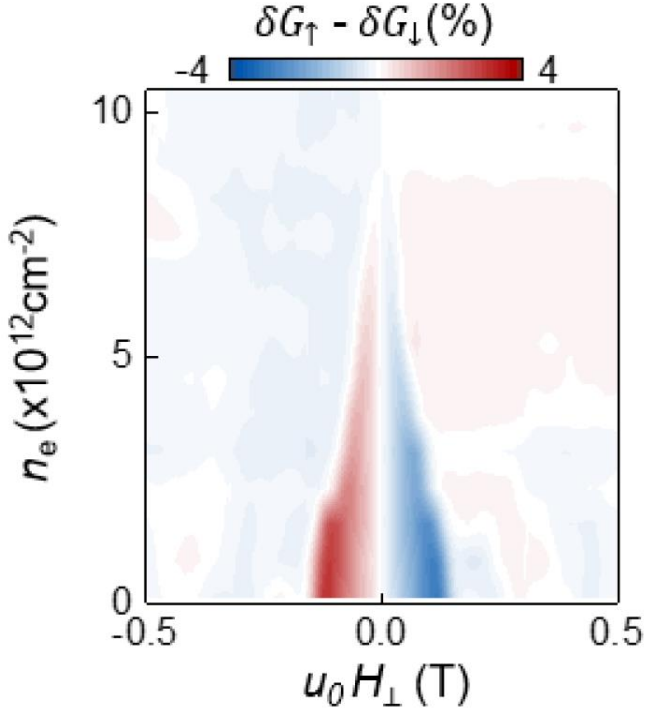
Magnetization switches at very low field independent of n

Behavior at large electron density

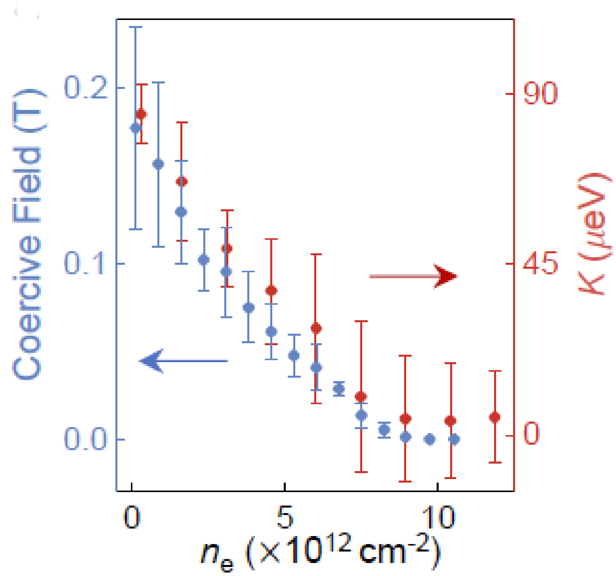


Increasing n
(finite electric field)

Coercive field:
vanishes at 7-8 10^{12} cm^{-2}



Coercive field tracks
magnetic anisotropy constant



All consistent: for n > 7-8 10^{12} cm^{-2} magnetization lies in the plane

Note: magnetic anisotropy K = 0 is a quantum phase transition

Conclusion on double gated bilayes :

- *Perpendicular electric field breaks inversion symmetry and*
  creates spin-polarization in conduction band

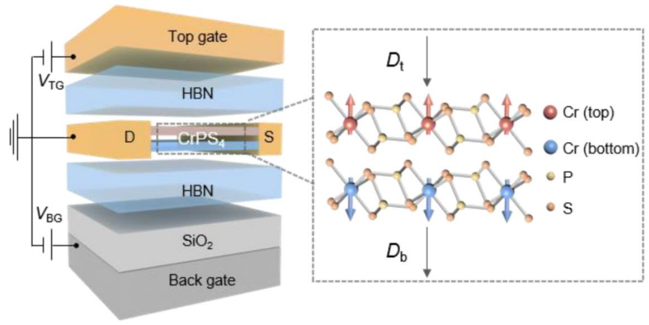
- *Enables gate-switchable antiferromagnetic spintronics*

- *Low-electron density*
  gate-induced half-metallic conductors?

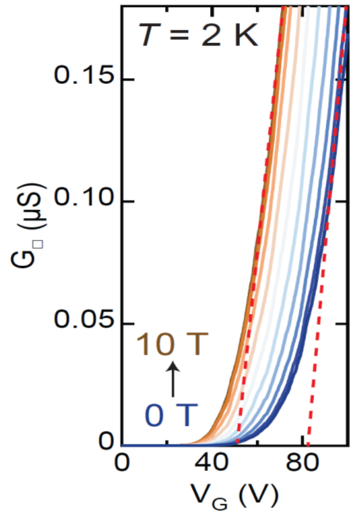
- *High-electron density*
  control of magnetic state: from out-of-plane to in-plane anisotropy

A glimpse on monolayer $CrPS_4$ transistors

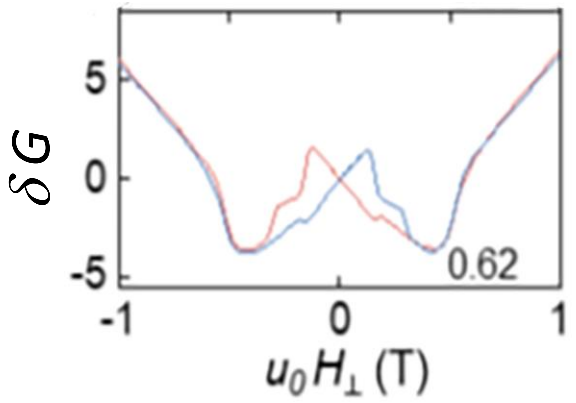
Conclusions



Controllable transistors devices on $CrPS_4$ mono/multilayers



Magnetic state coupled to band structure



Control of symmetries & spin-polarization in double-gated bilayers

Ferromagnetism in monolayer transistors