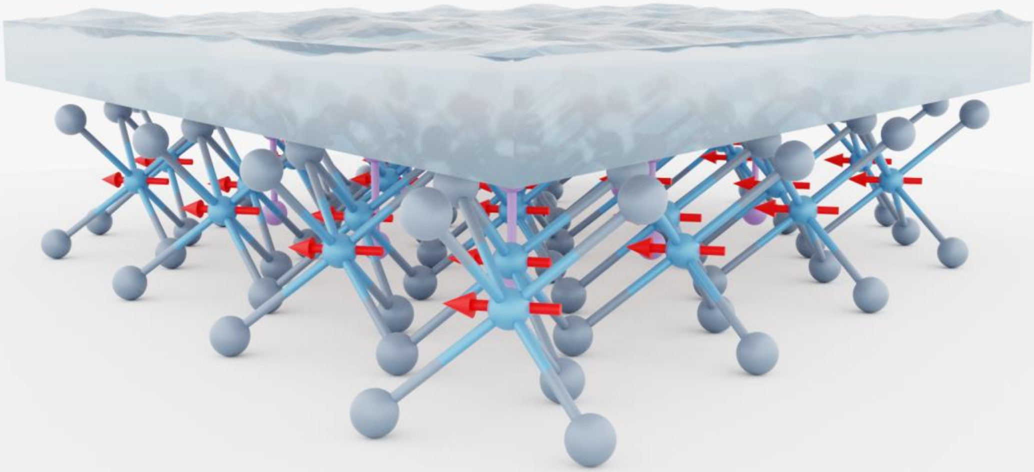
Electrostatic Control of Magnetism in Van Der Waals Ferromagnets

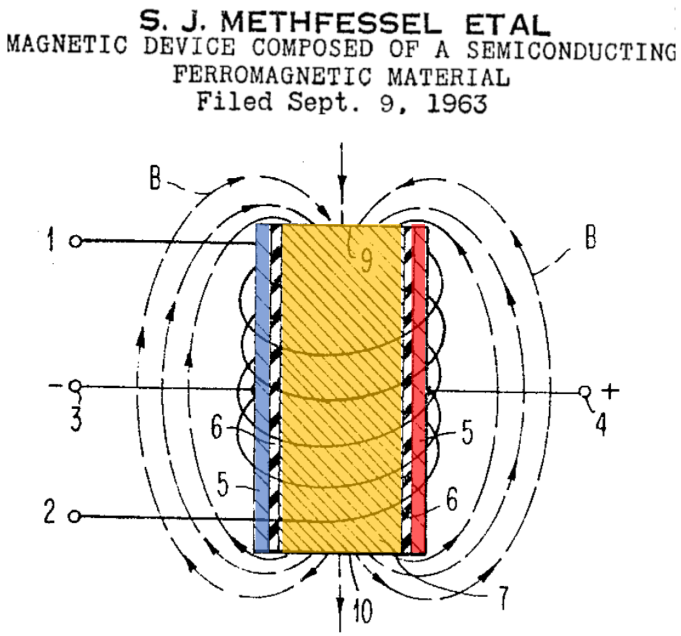
Ivan Verzhbitskiy

Department of Physics
National University of Singapore

ivan@nus.edu.sg
http://www.physics.nus.edu.sg/~phyeda/



Voltage Control Over Magnetism



Siegfried J Methfessel & Holtzberg Frederic (1963)
Magnetic device composed of a semiconducting ferromagnetic material
US Patent #3271709A

Theory of carrier-controlled magnetism

$$T_c = S(S+1)\sum_j J_{ij}/3k_B$$

$$J_{ij} \sim \rho(E_F)$$

M. A. Ruderman and C. Kittel (1954) Phys. Rev. 96, 99

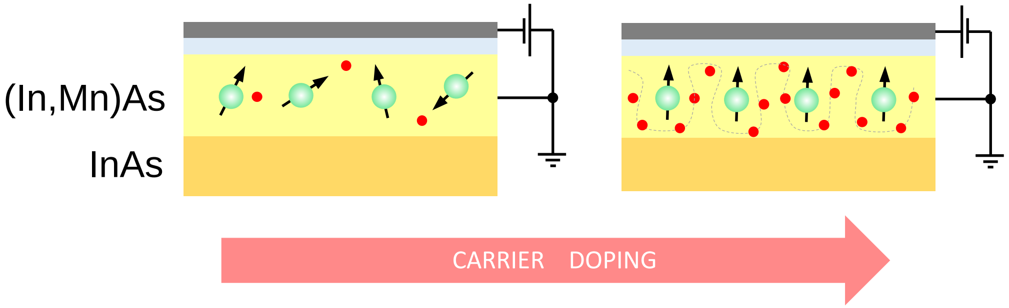
T. Kasuya (1956) Progr. Theoret. Phys. (Kyoto) 16,45

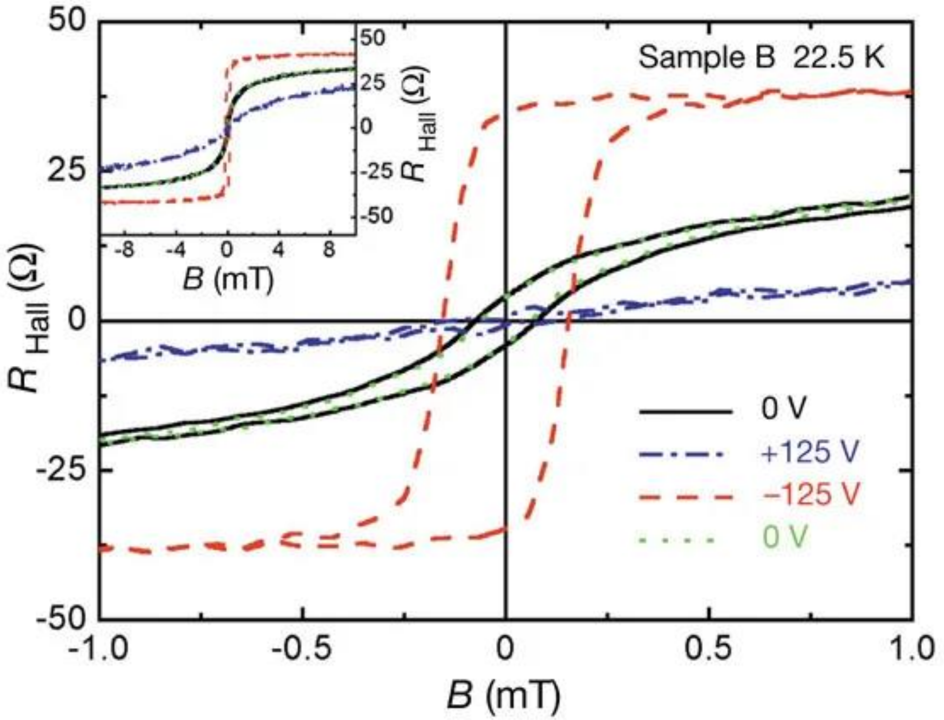
K. Yosida (1957) Phys. Rev. 106, 893

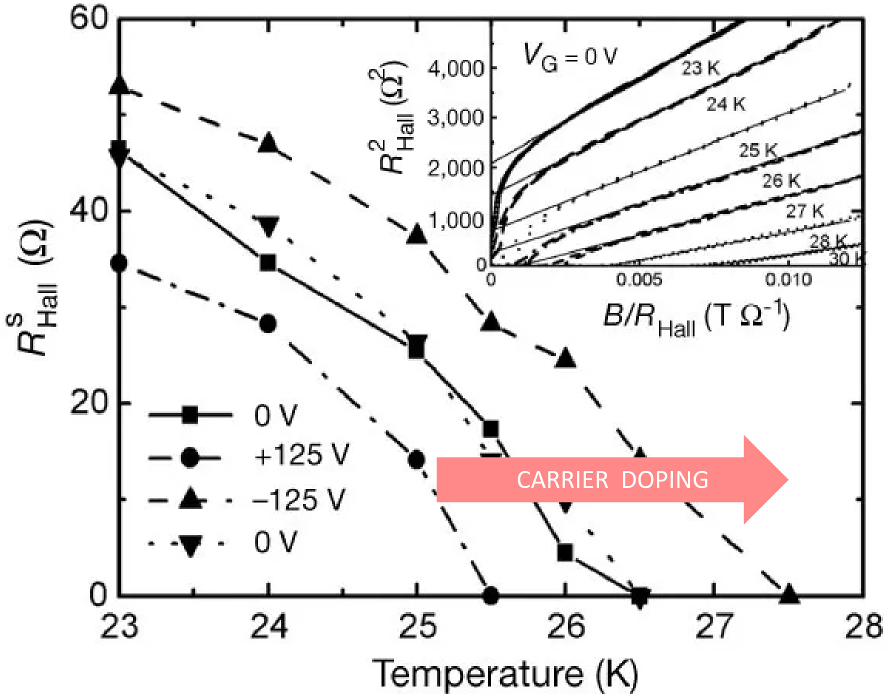
James C. Maxwell (1865)
A dynamical theory of the electromagnetic field
Phil. Trans. R. Soc.155, pp. 459–512

Voltage Control Over Magnetism

Hideo Ohno et al. (2000), Nature 408, 944

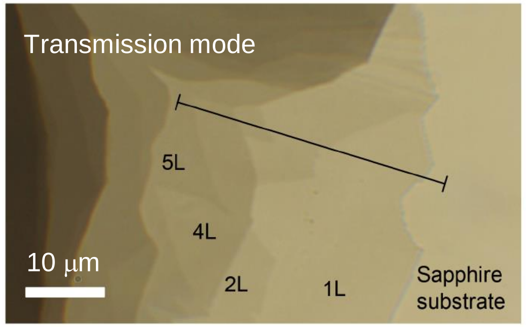


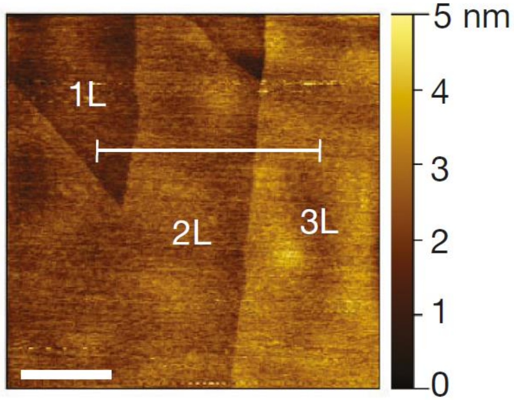


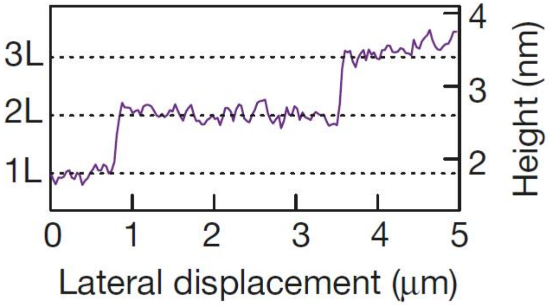


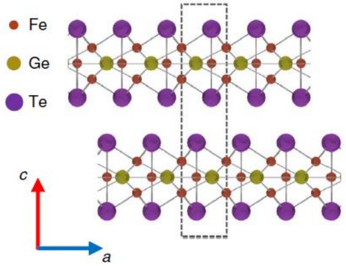
Van Der Waals Ferromagnetic Metal: Fe_3GeTe_2

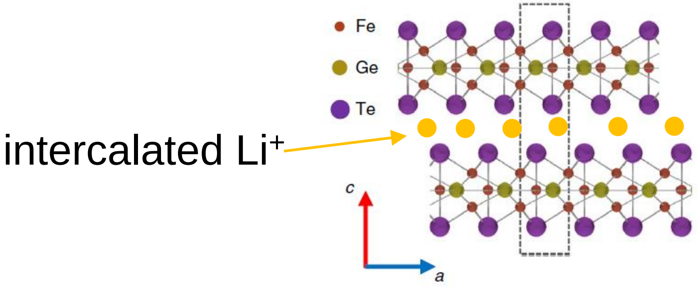
Yujun Deng et al. (2018), Nature 563, 94

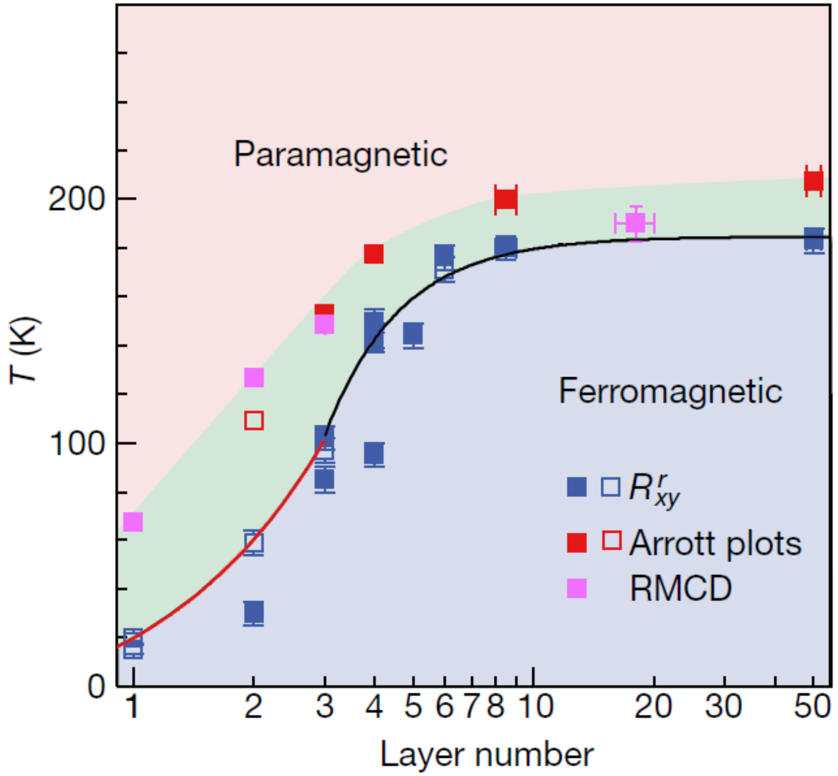


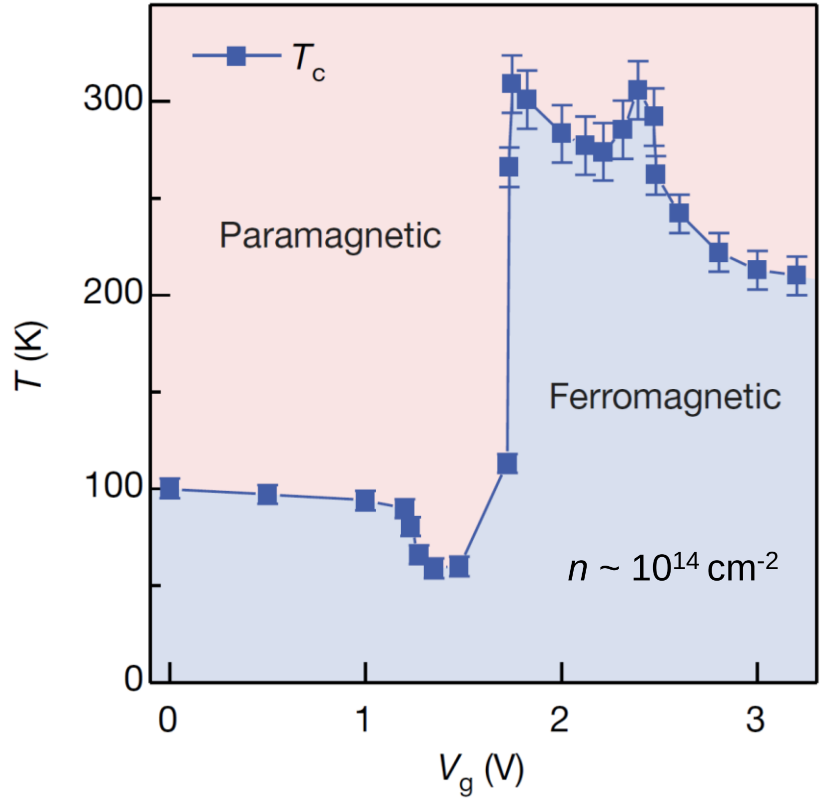










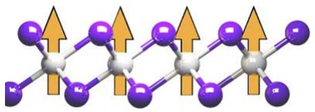


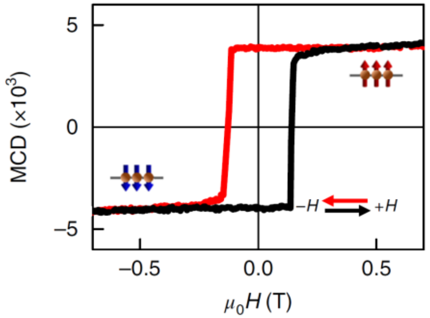
Van Der Waals Ferromagnetic Semiconductors

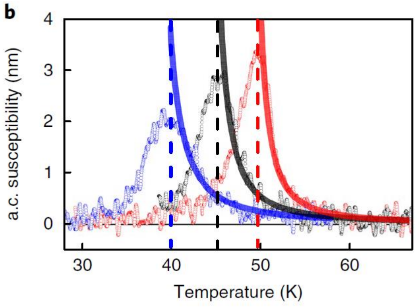
Shengwei Jiang et al. (2018), Nature Nano 13, 549

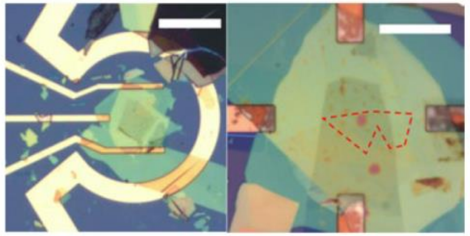
Zhi Wang et al. (2018), Nature Nano 13, 554

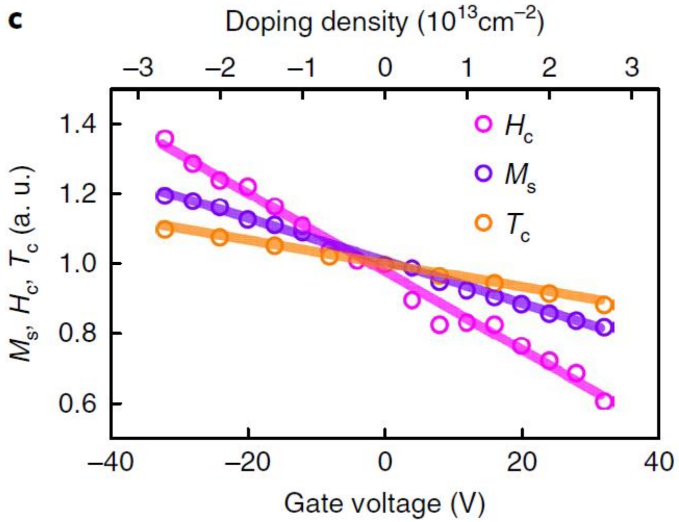
CrI_3



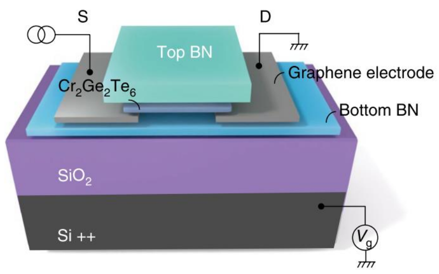


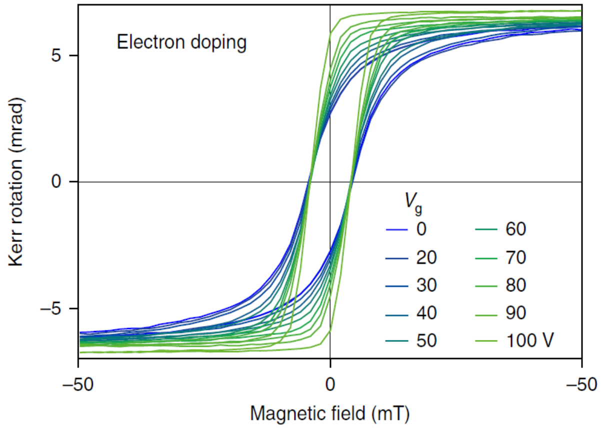


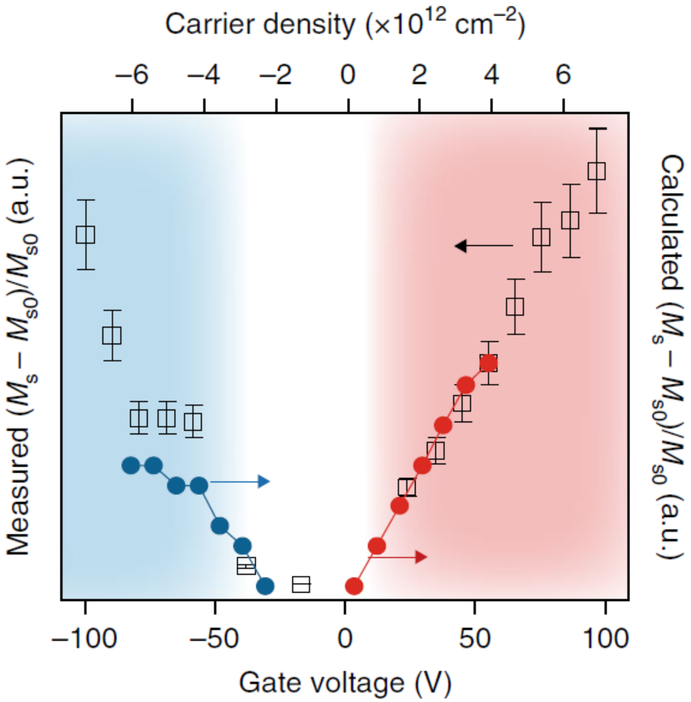


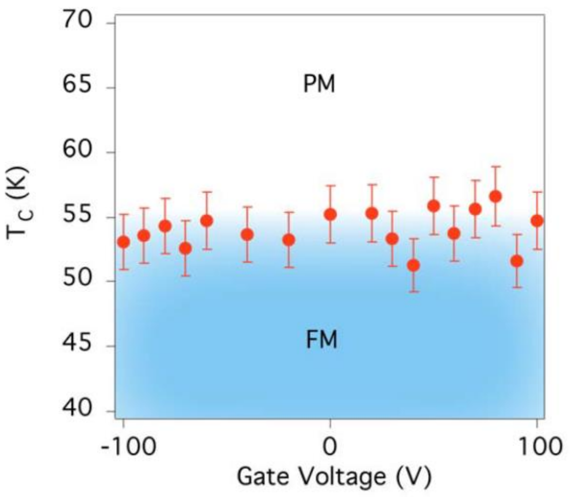


$Cr_2Ge_2Te_6$

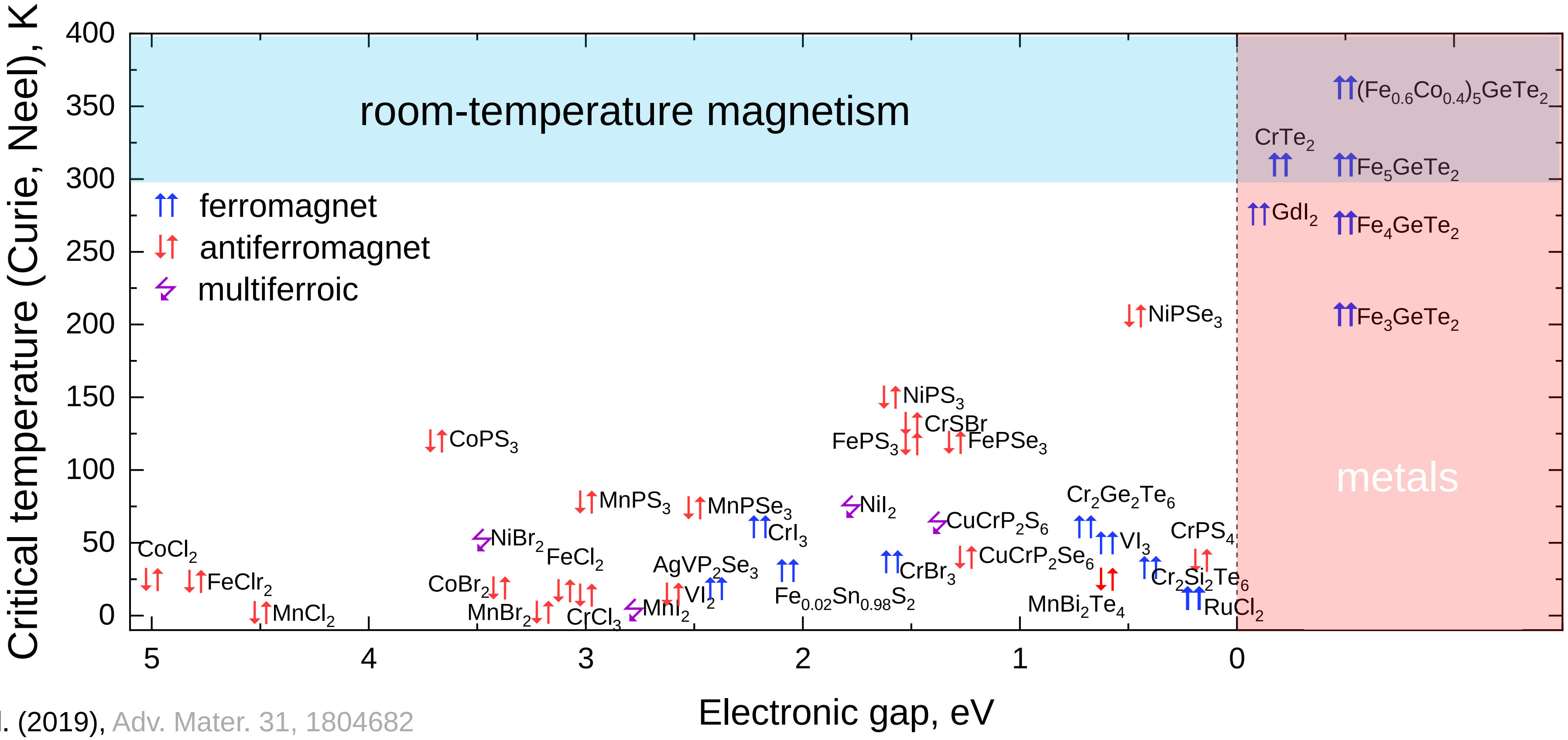






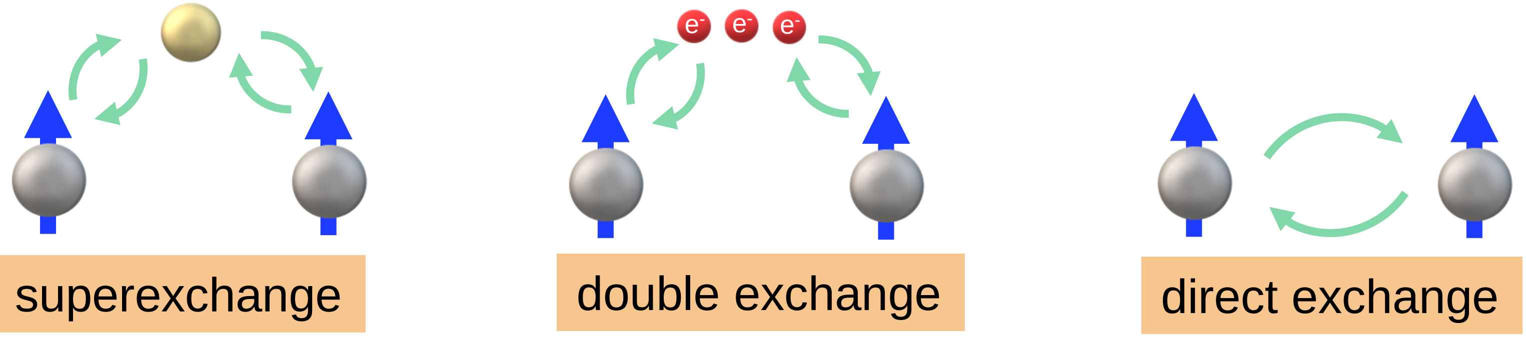


Van der Waals magnets



Xinsheng Wang et al. (2019), Adv. Mater. 31, 1804682

Michael A. McGuire (2017), Crystal 7, 121

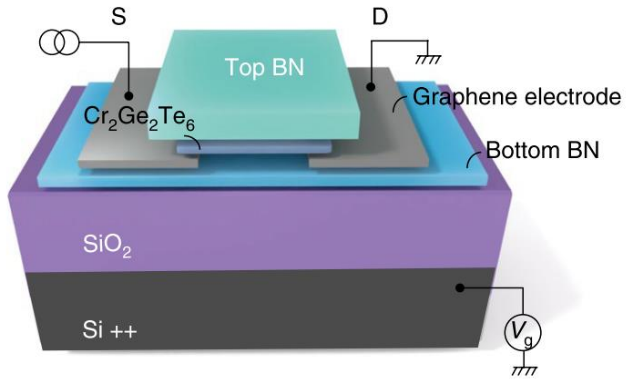


Boosting carrier density in $Cr_2Ge_2Te_6$

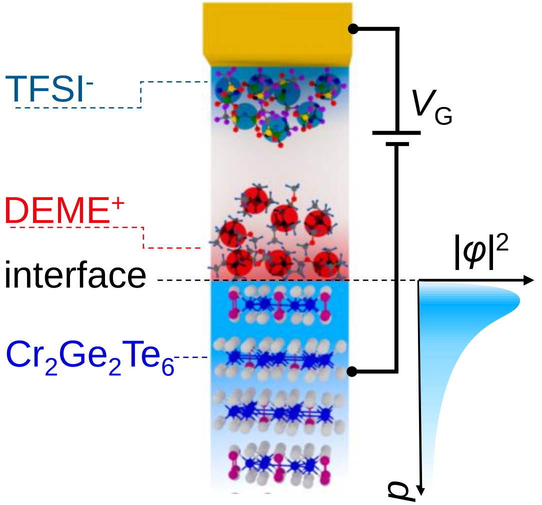
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

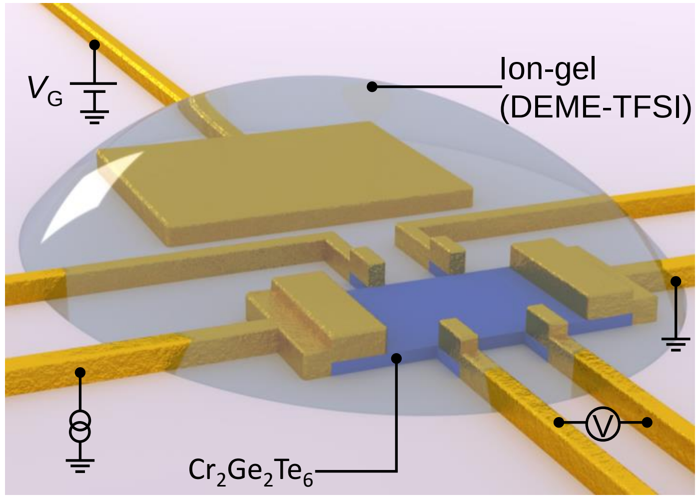
solid-gate through oxide (SiO_2)

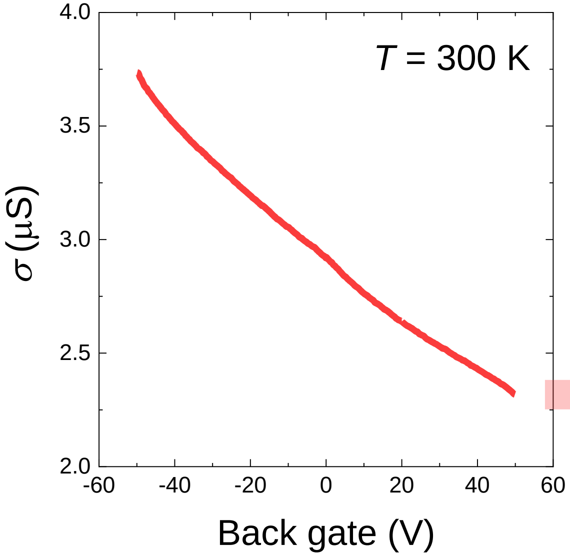
ionic electrolyte (DEME-TFSI)



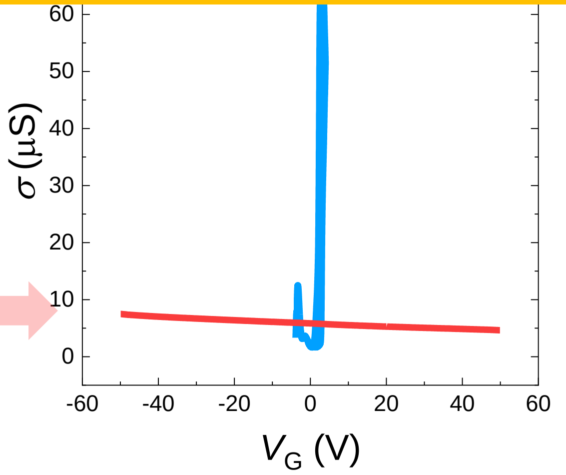
Schematic adopted from Nature Nano 13, 554 (2018)

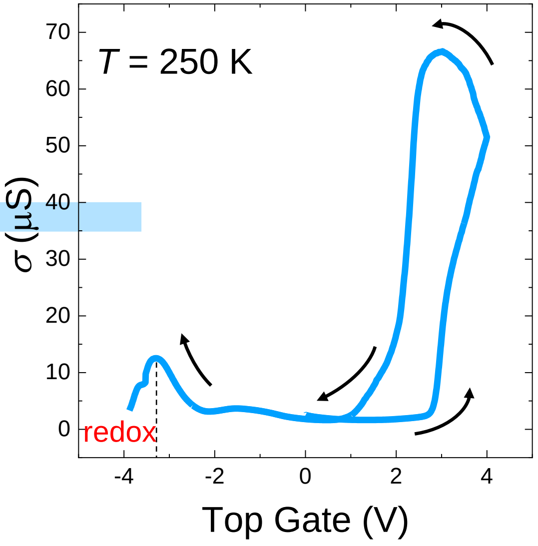






❑ Ionic gating induce strong surface doping

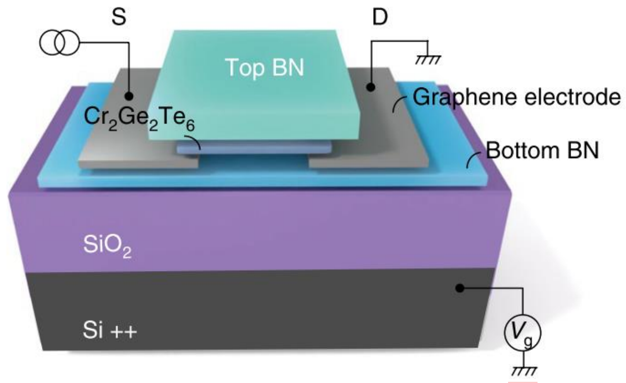




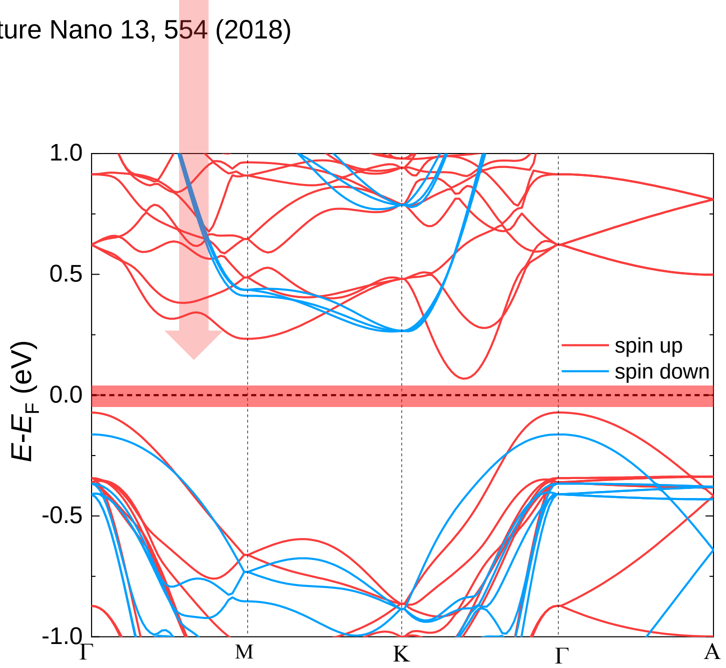
Boosting carrier density in $Cr_2Ge_2Te_6$

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

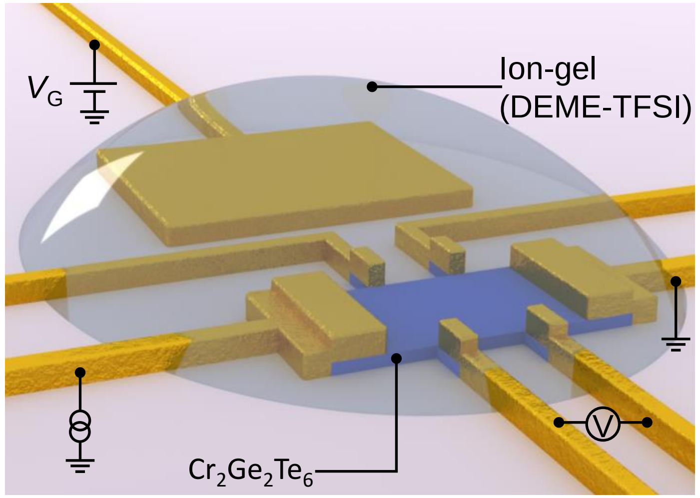
solid-gate through oxide (SiO_2)



Schematic adopted from Nature Nano 13, 554 (2018)



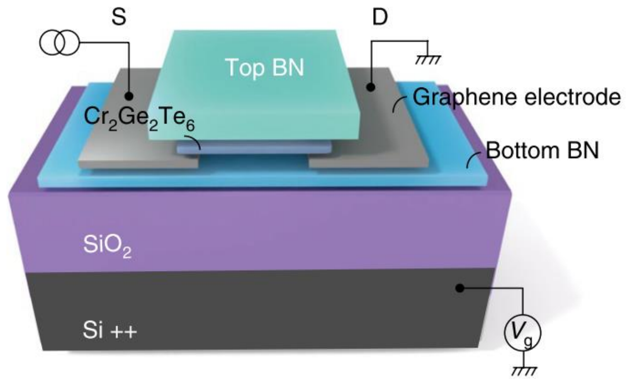
ionic electrolyte (DEME-TFSI)



Boosting carrier density in $Cr_2Ge_2Te_6$

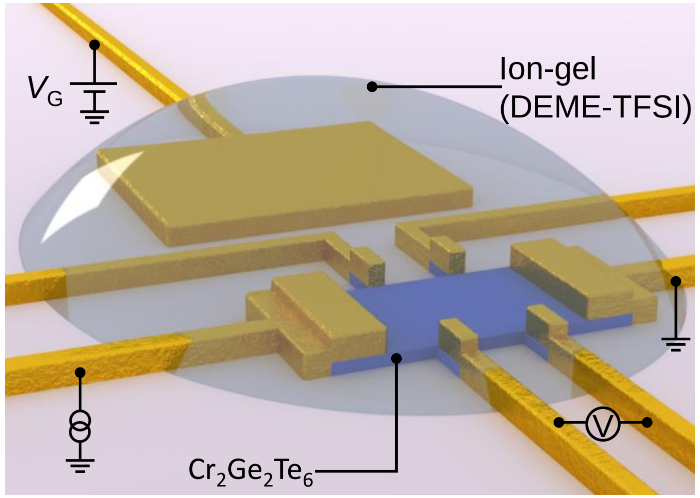
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

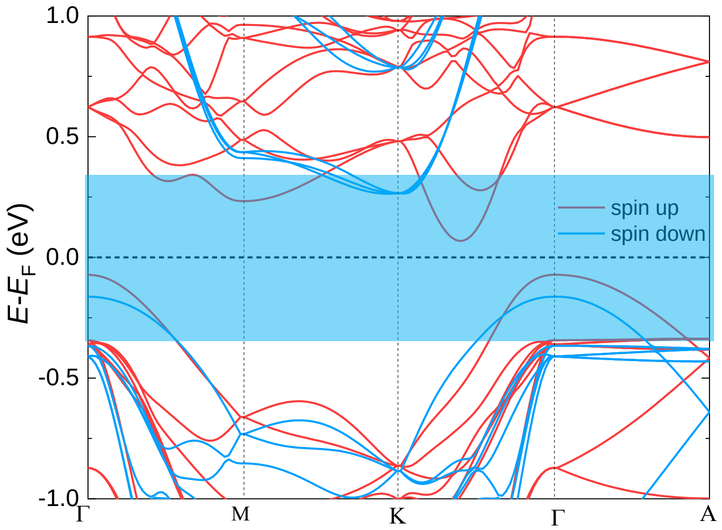
solid-gate through oxide (SiO_2)



Schematic adopted from Nature Nano 13, 554 (2018)

ionic electrolyte (DEME-TFSI)

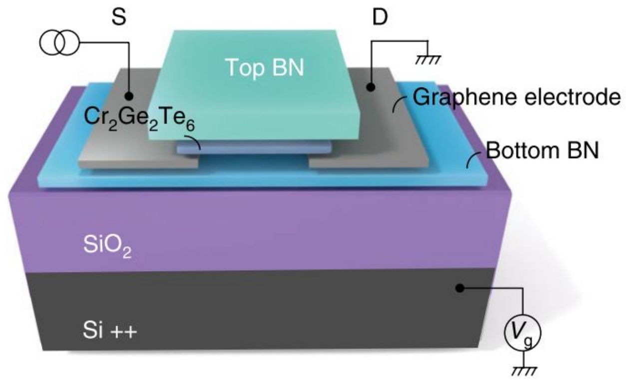




Boosting carrier density in $Cr_2Ge_2Te_6$

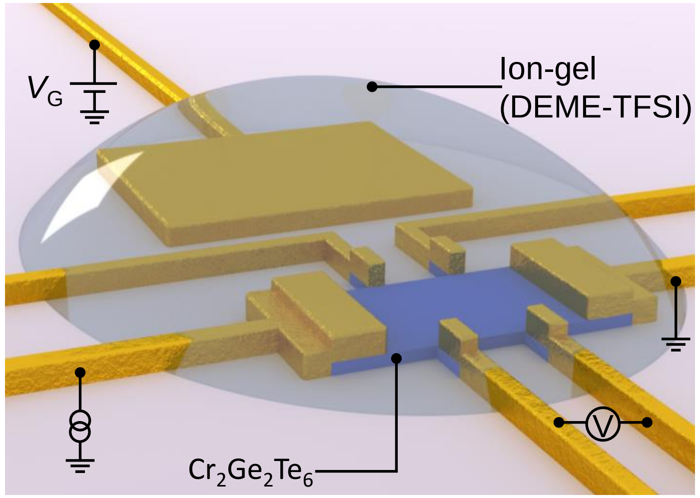
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

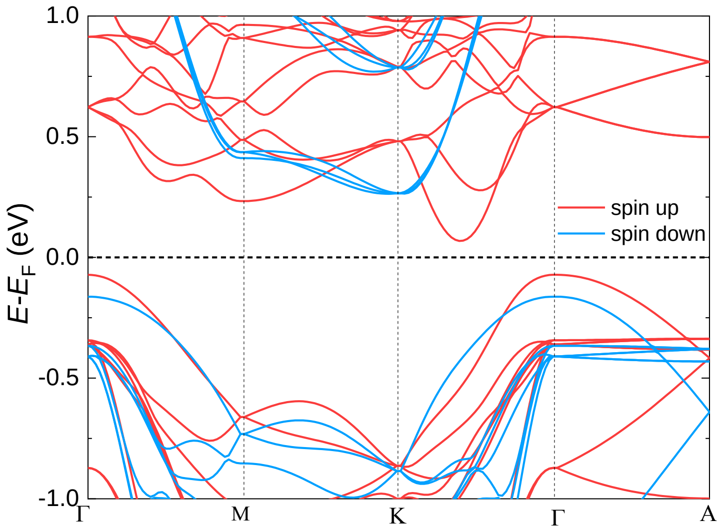
solid-gate through oxide (SiO_2)



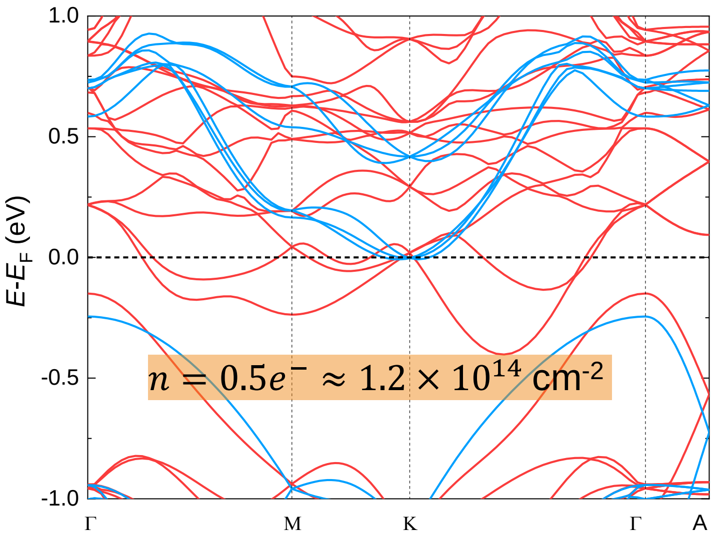
Schematic adopted from Nature Nano 13, 554 (2018)

ionic electrolyte (DEME-TFSI)



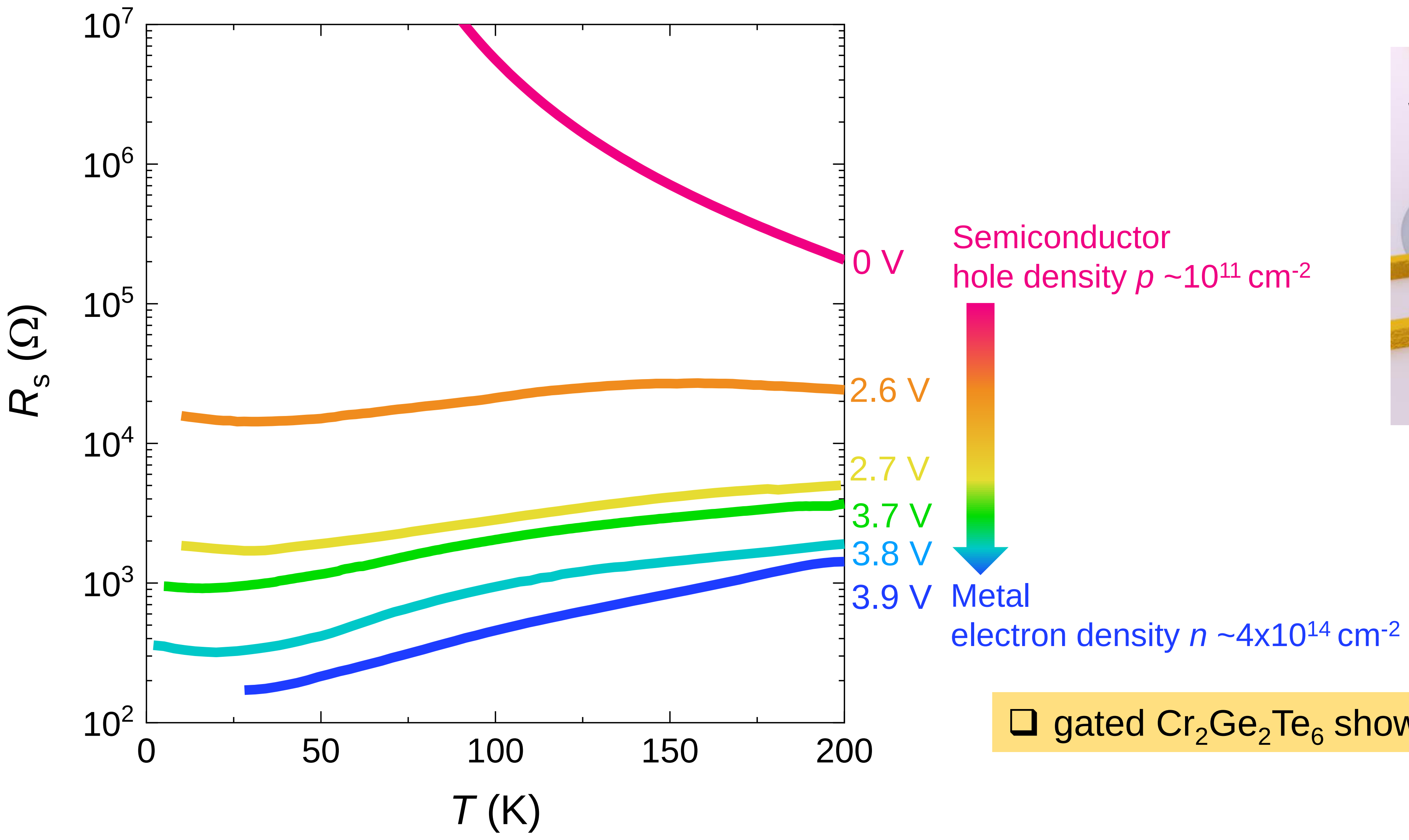


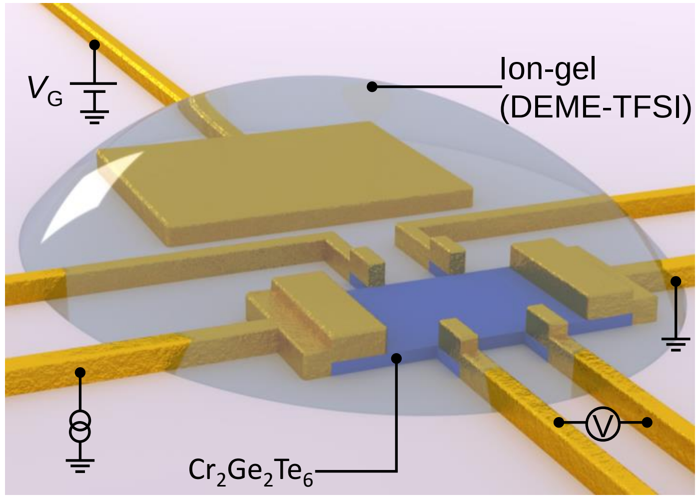
ELECTROSTATIC GATING



Boosting carrier density in $Cr_2Ge_2Te_6$

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

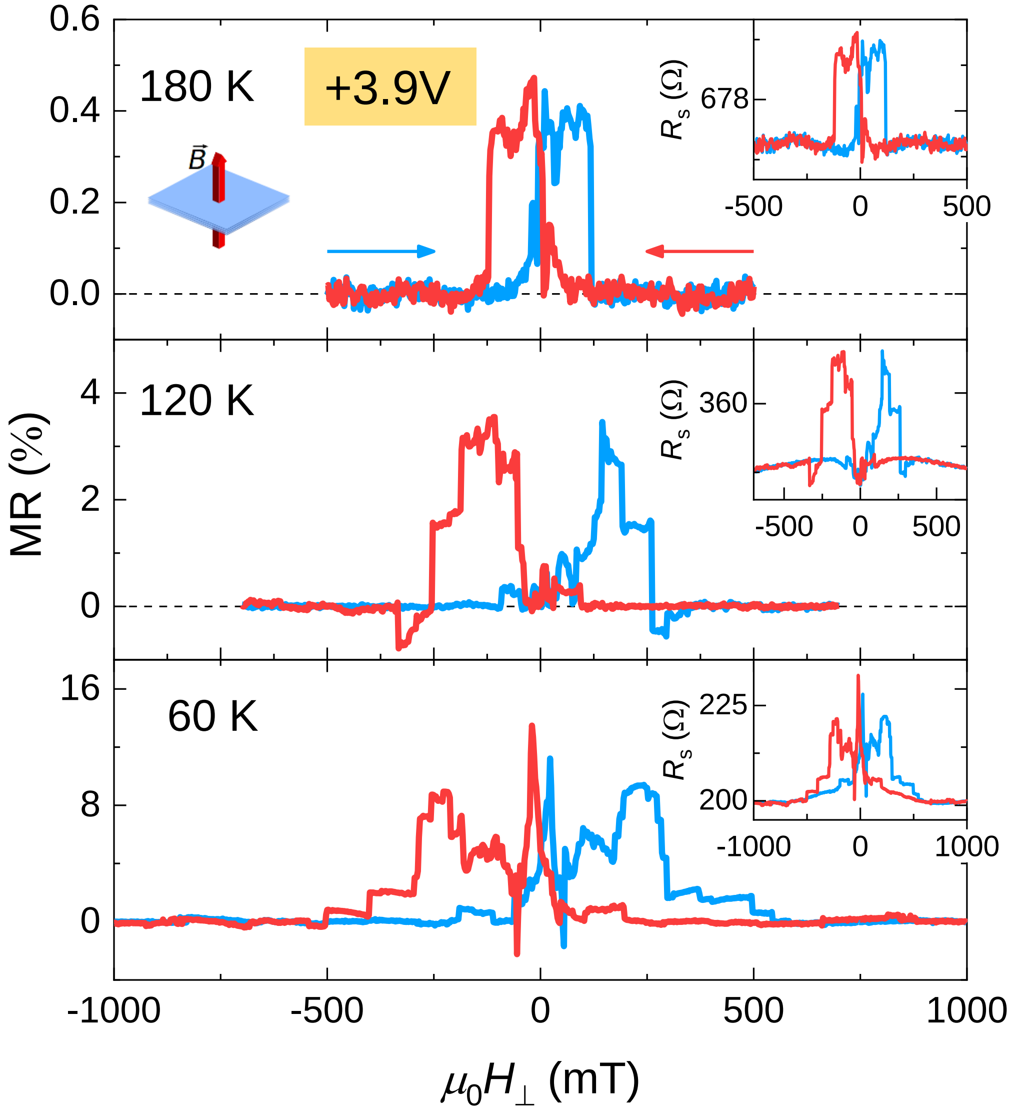


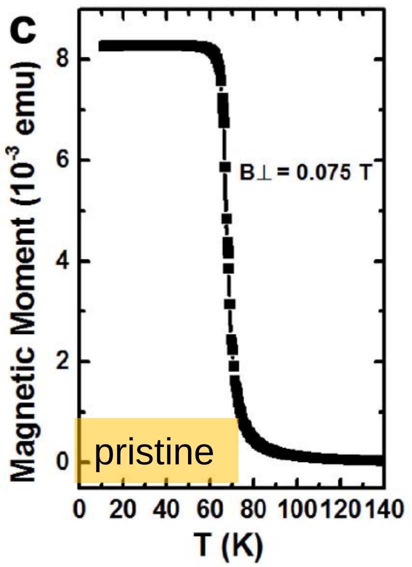


- ❑ gated $Cr_2Ge_2Te_6$ shows metal-like behaviour

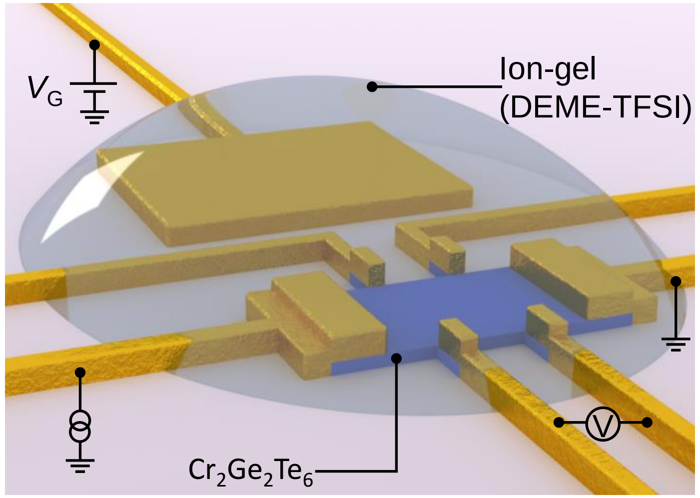
Magnetoresistance in gated $Cr_2Ge_2Te_6$

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460





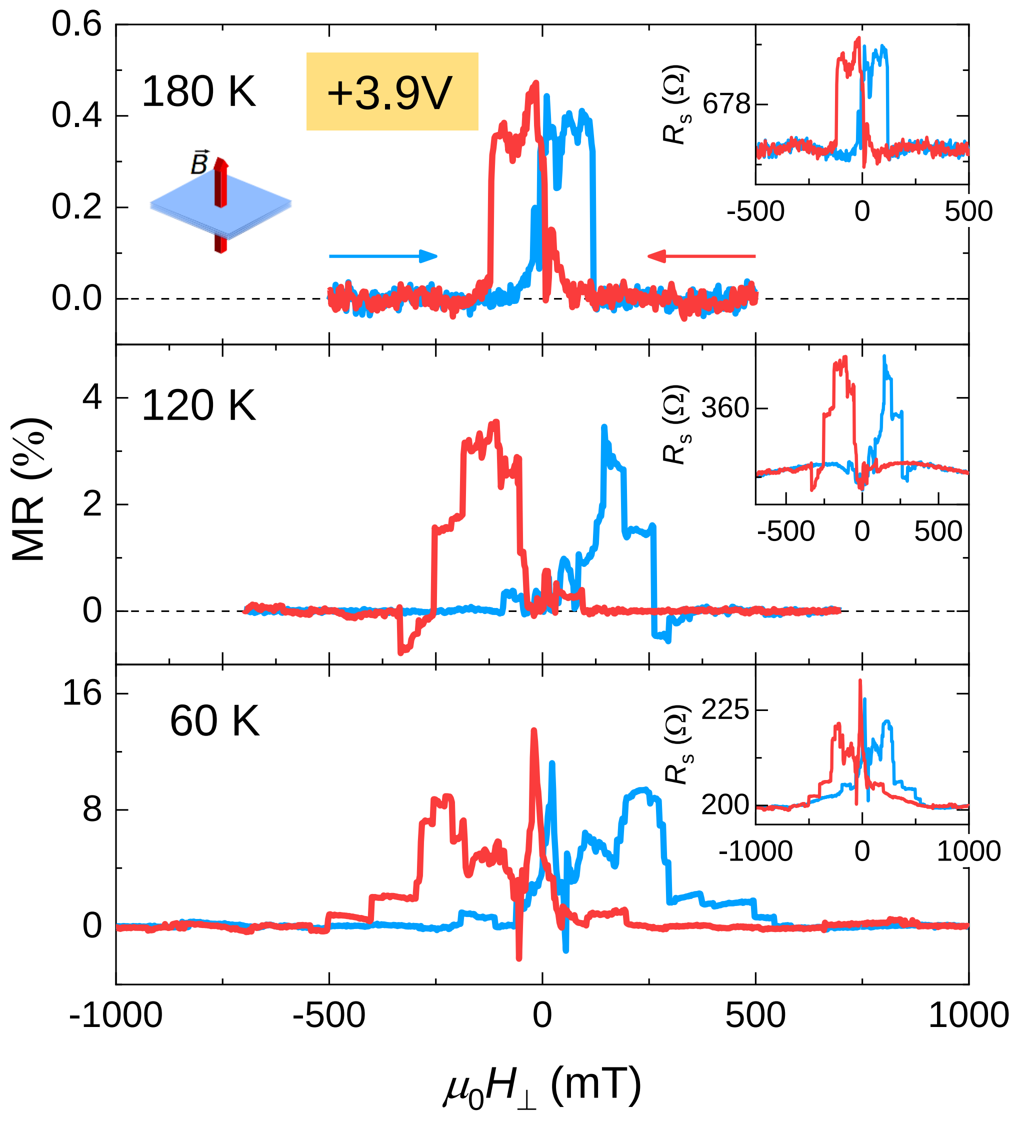
Cheng Gong, et al. (2017), Nature 546, 265

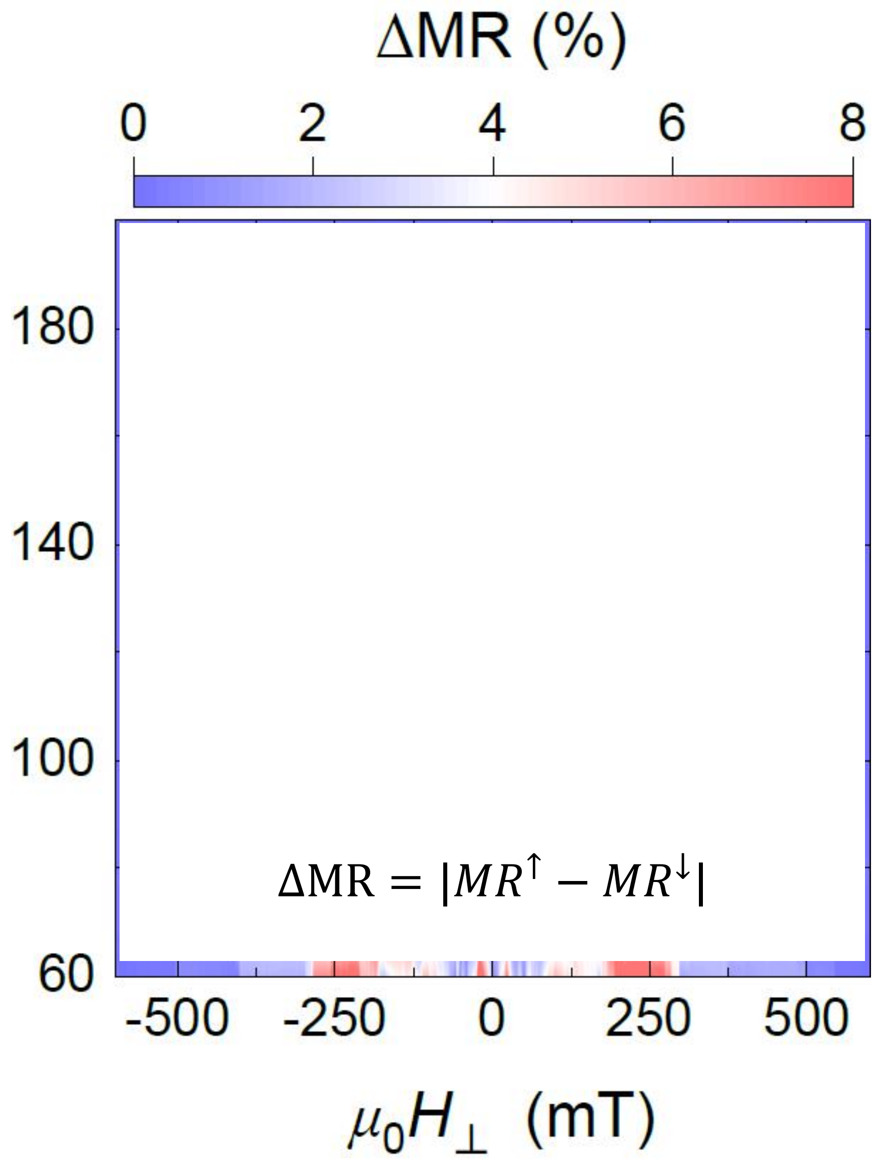


- ❑ Hysteresis observed at temperatures <u>higher</u> than T_C of undoped bulk $Cr_2Ge_2Te_6$ (~66 K)

Magnetoresistance in gated $Cr_2Ge_2Te_6$

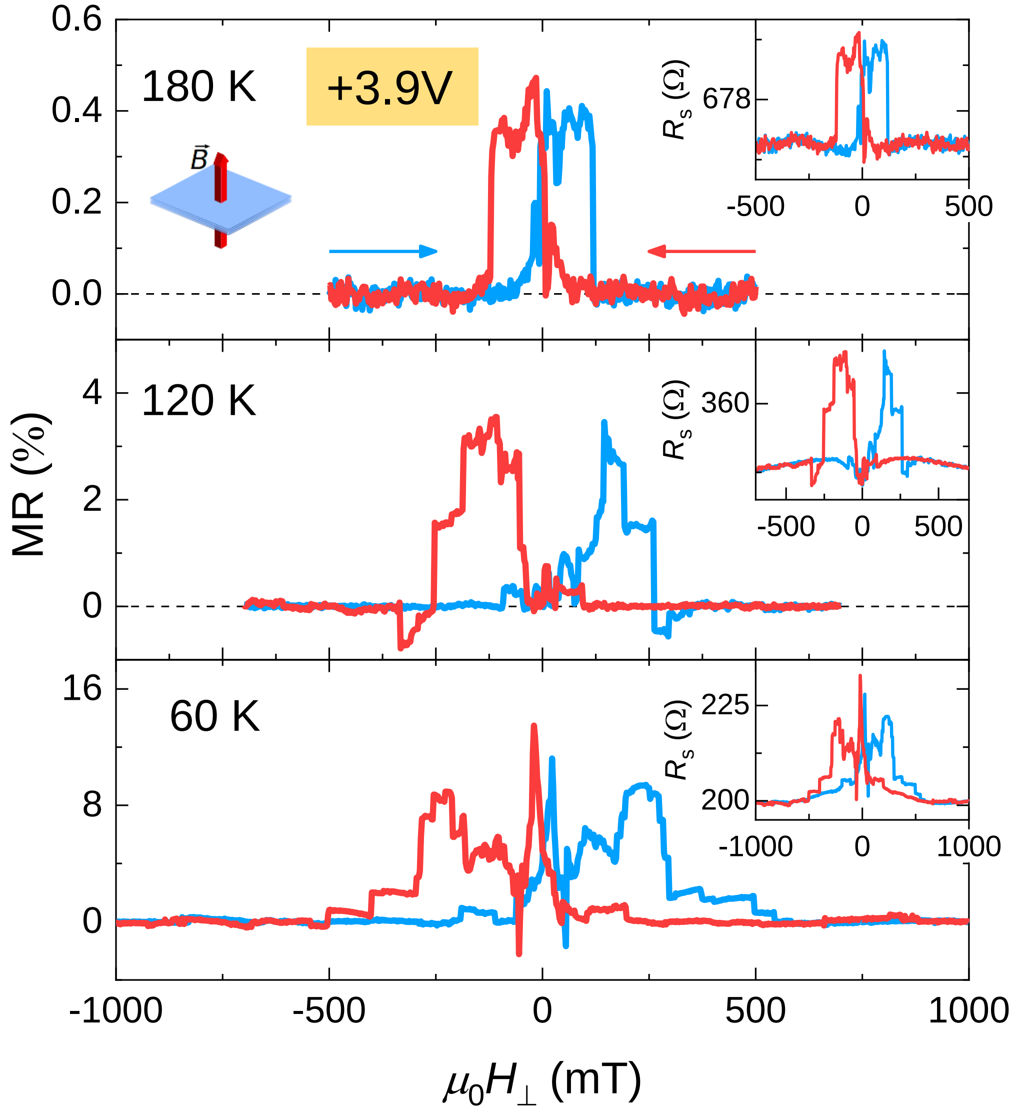
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

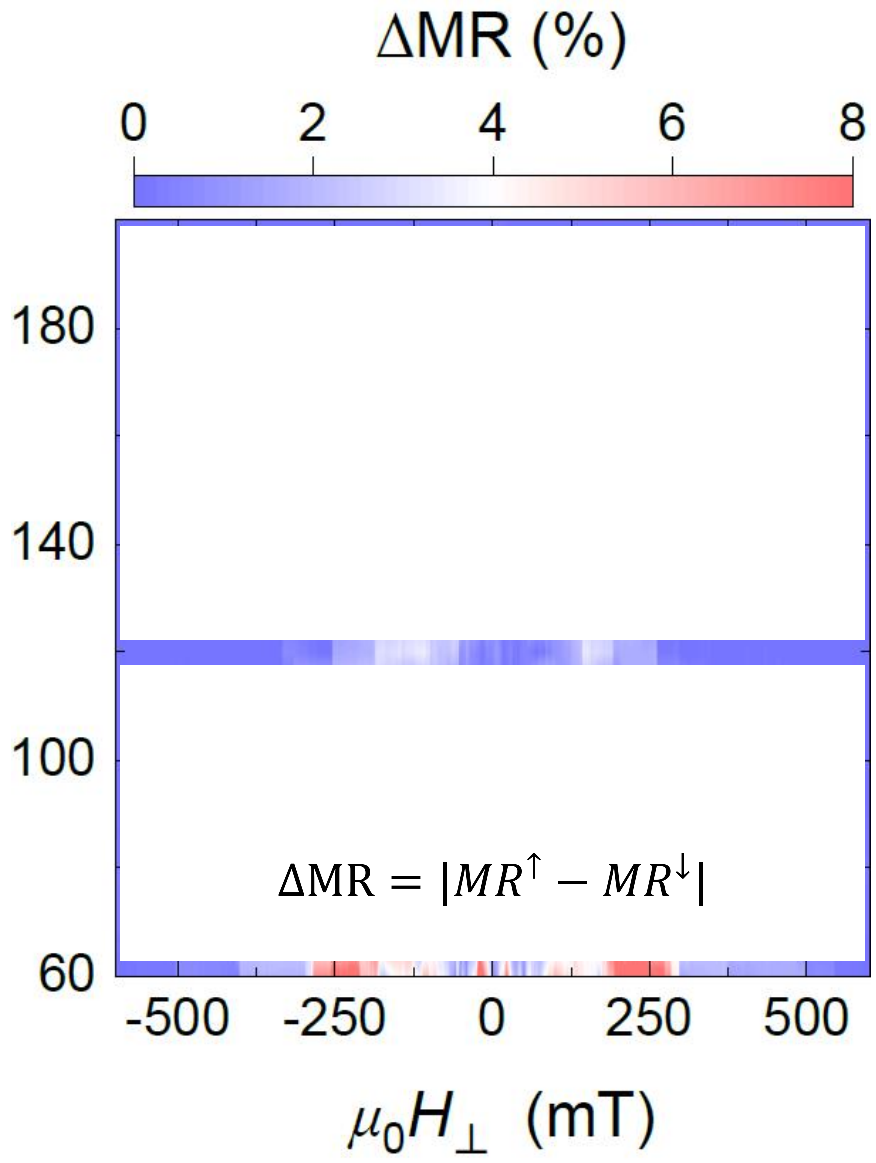




Magnetoresistance in gated $Cr_2Ge_2Te_6$

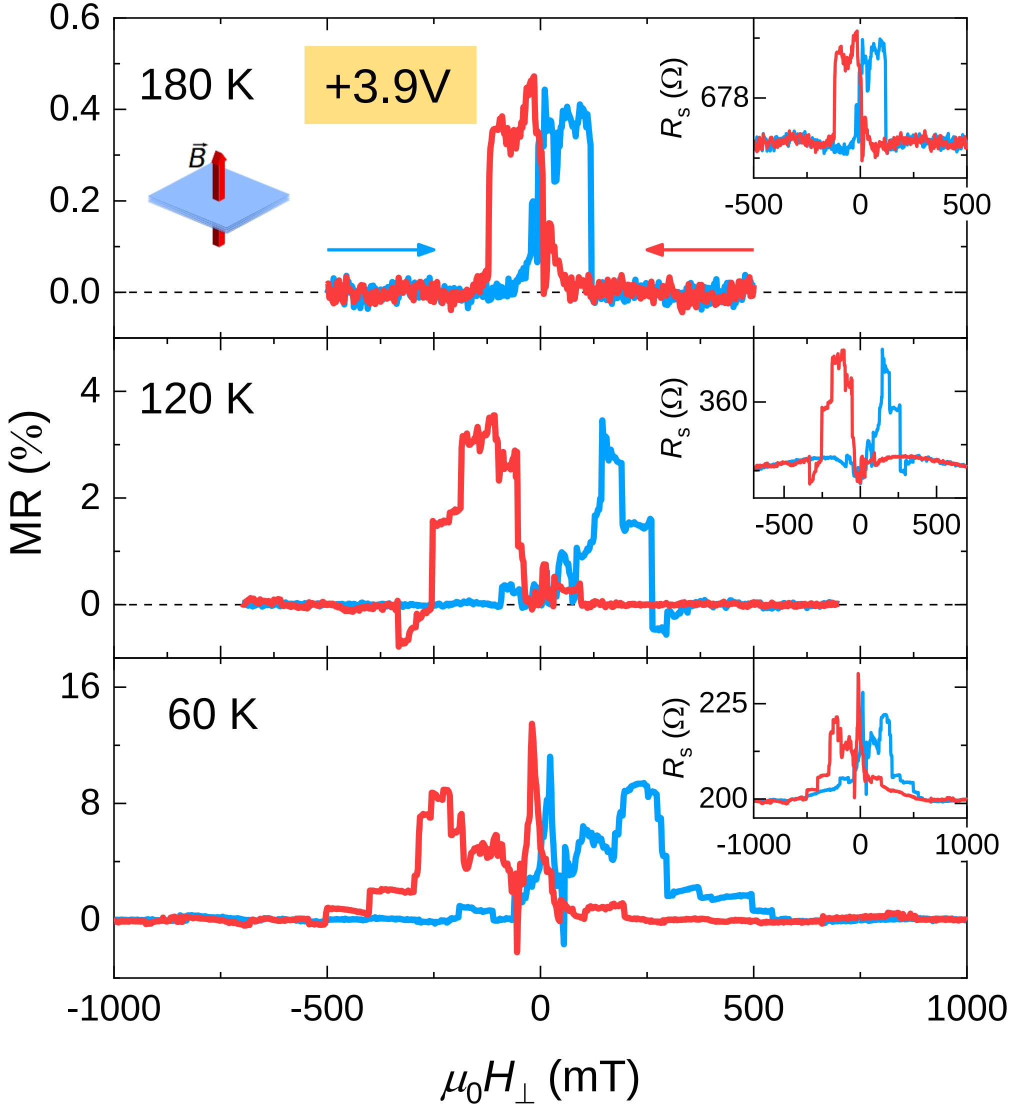
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

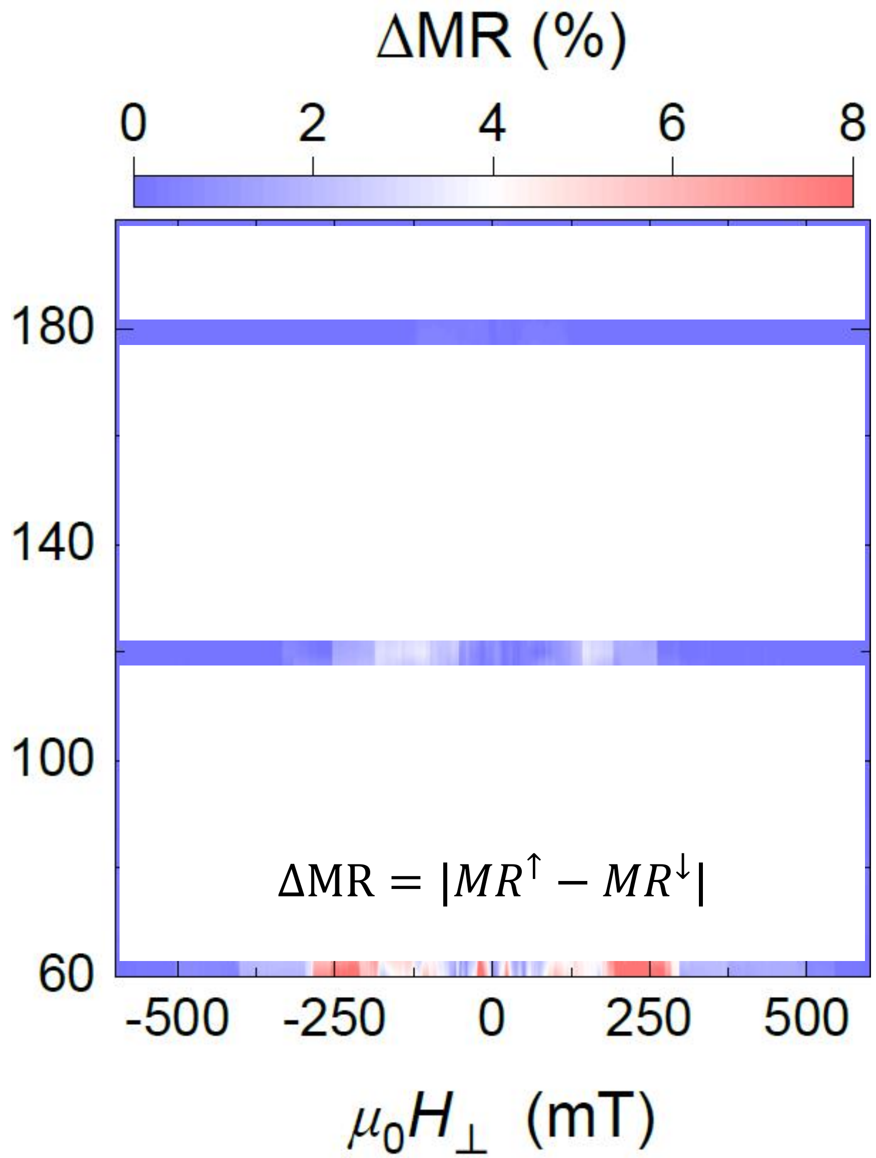




Magnetoresistance in gated $Cr_2Ge_2Te_6$

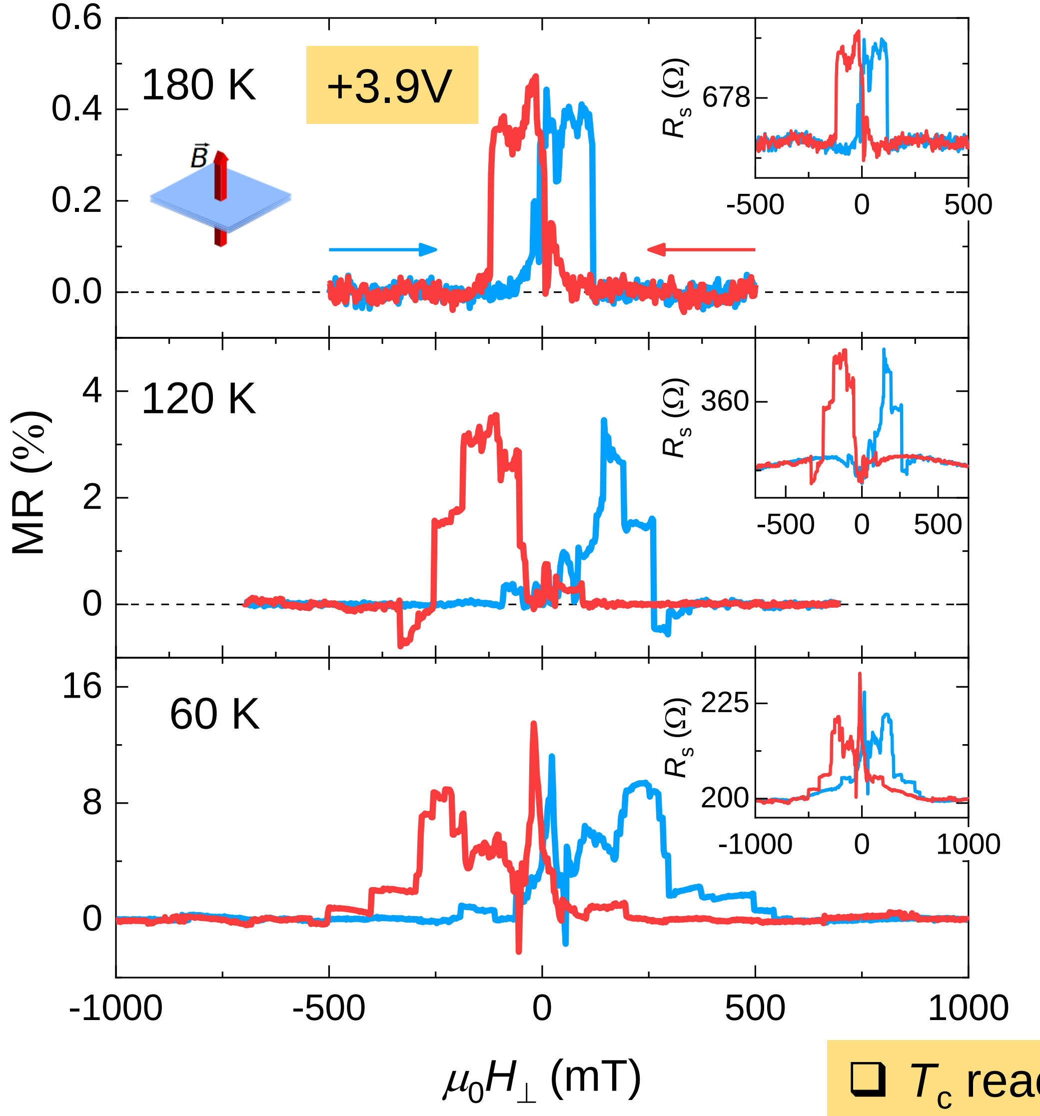
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

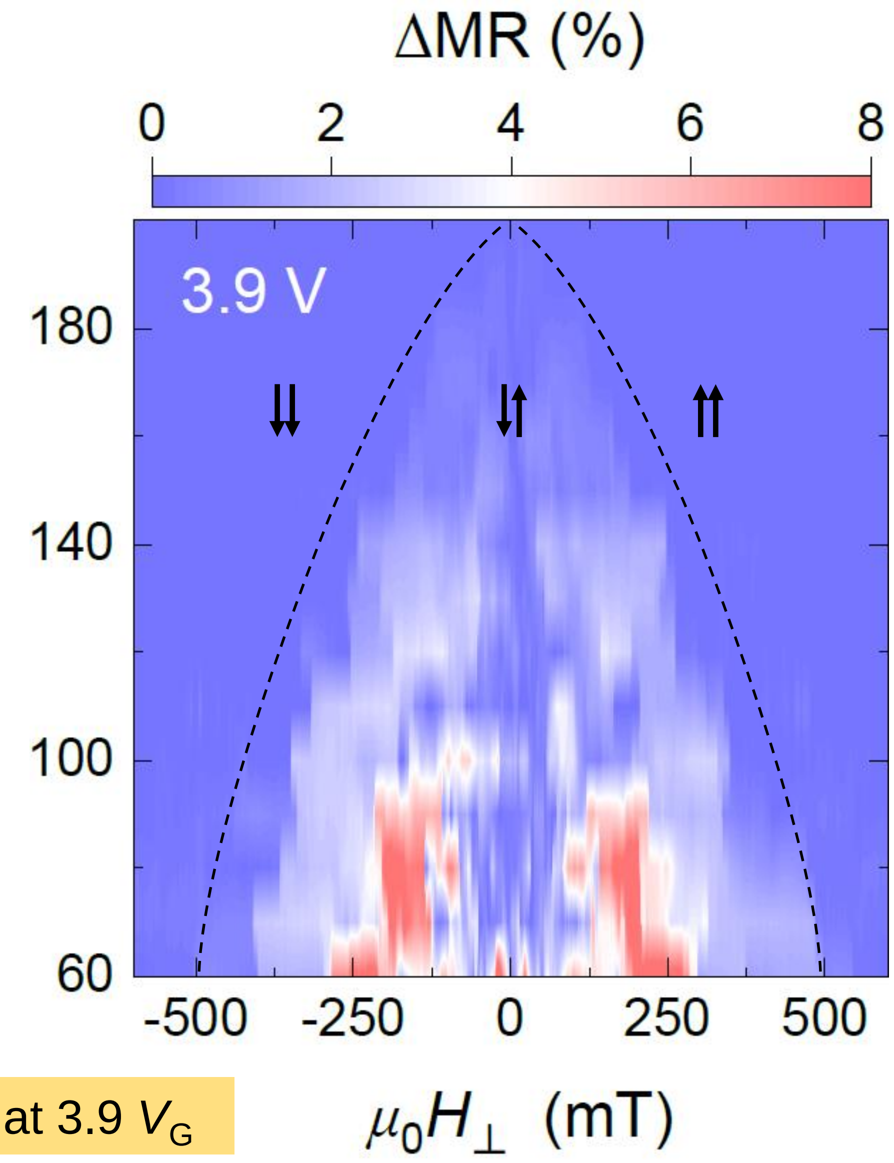




Magnetoresistance in gated $Cr_2Ge_2Te_6$

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460





❑ T_c reaches ~200 K at 3.9 V_G

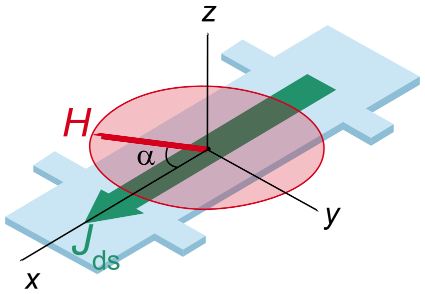
Magnetoresistance symmetry

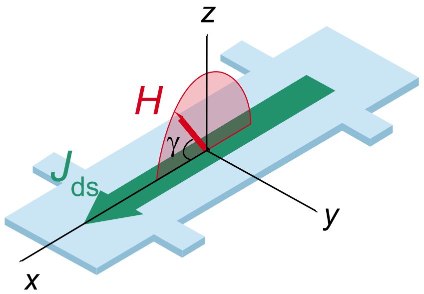
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

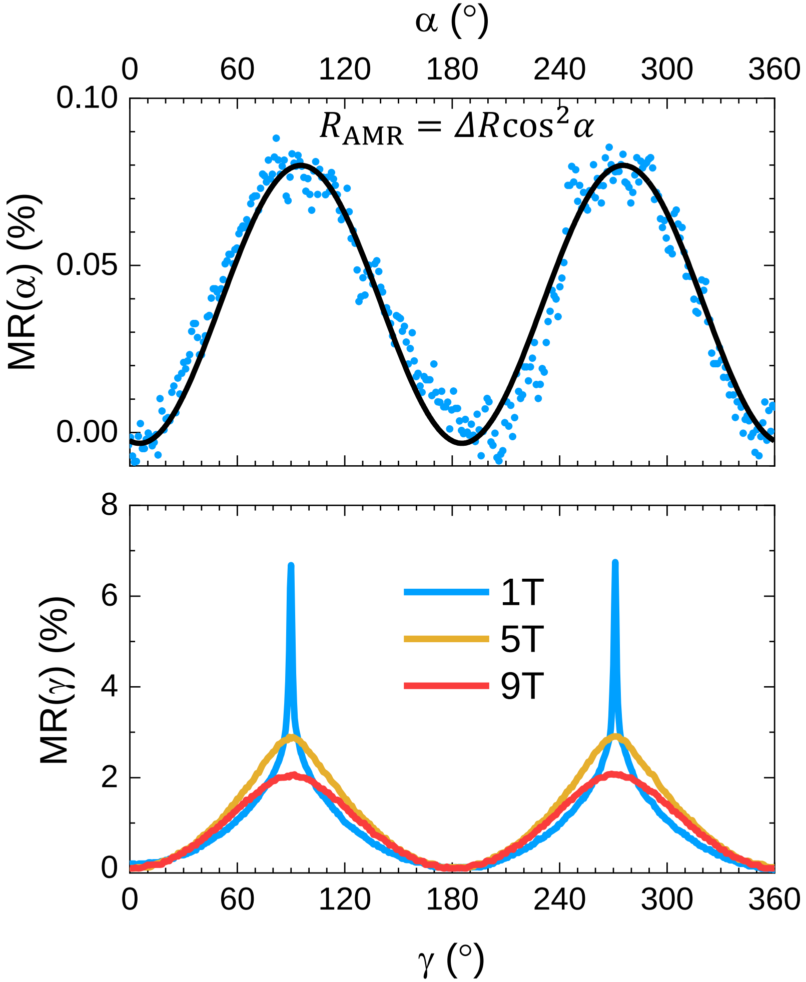
$$\mathrm{MR} = \frac{R_{\mathrm{xx}}(\alpha,\gamma) - R(0)}{R(0)}$$

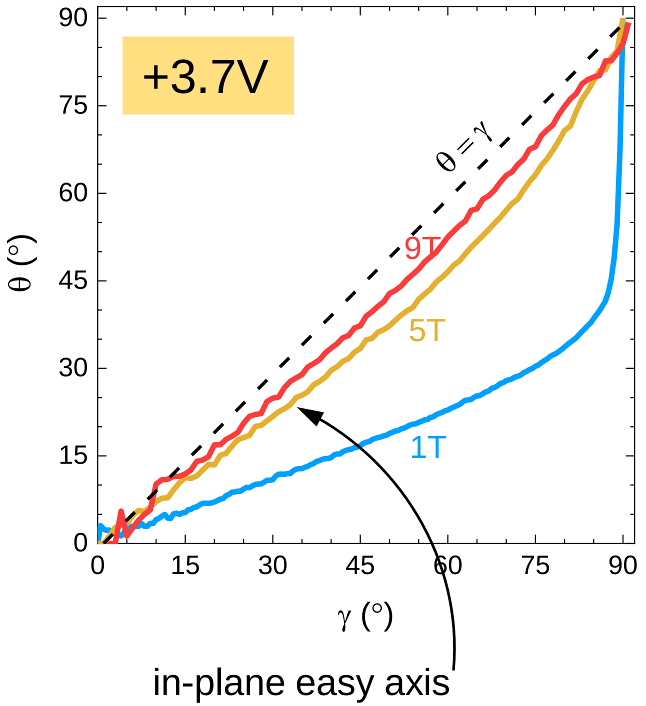
$$R_{\mathrm{xx}}(\gamma) = R(90) + [(R(0) - R(90)]\cos^2\theta$$

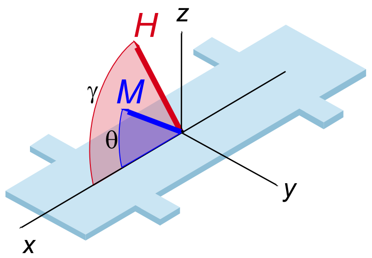
$$\Longrightarrow \theta(\gamma) = \mathrm{acos}\left(\sqrt{\frac{R_{\mathrm{xx}}(\gamma) - R(90)}{(R(0) - R(90))}}\right)$$







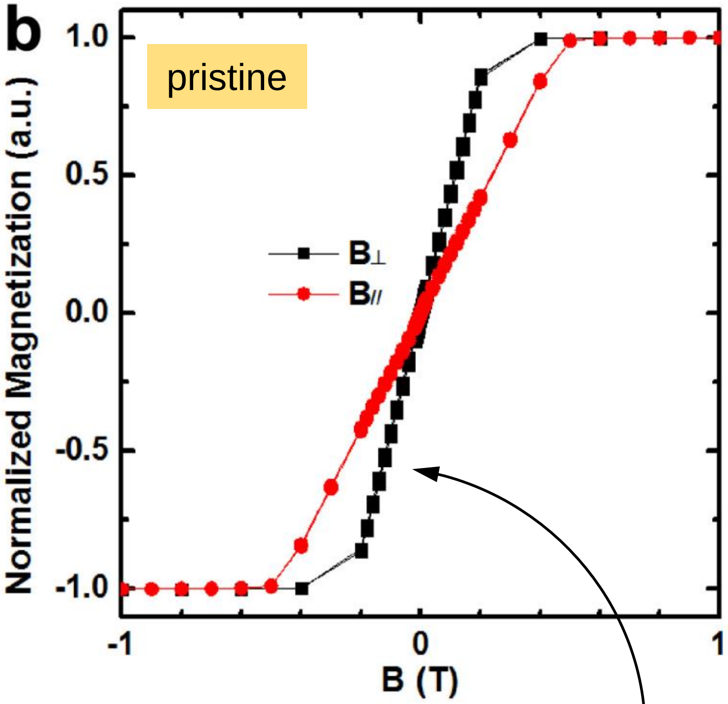




Easy axis rotation

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

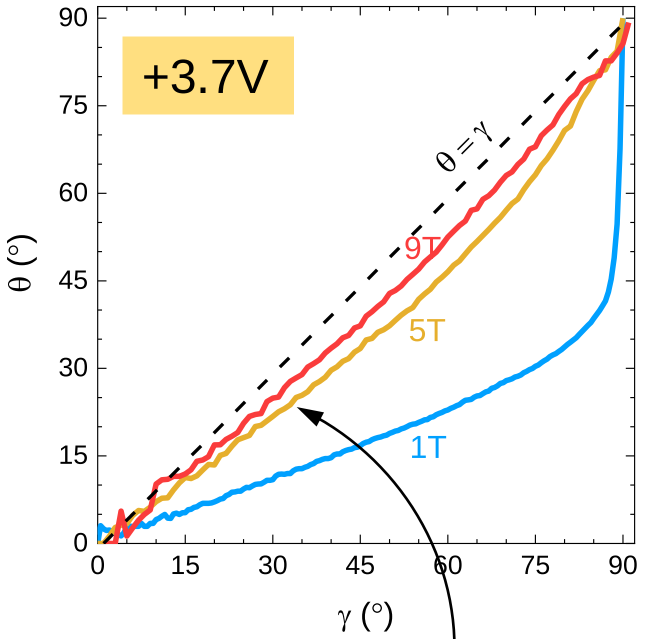
Cheng Gong, et al. (2017), Nature 546, 265

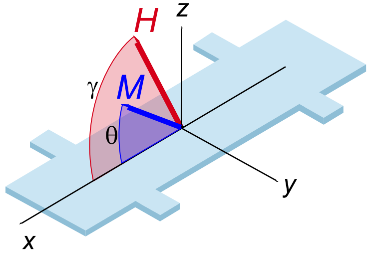


out-of-plane easy axis

$$R_{xx}(\gamma) = R(90) + [(R(0) - R(90)]\cos^2\theta$$

$$\Longrightarrow \theta(\gamma) = \mathrm{acos}\left(\sqrt{\frac{R_{xx}(\gamma) - R(90)}{(R(0) - R(90))}}\right)$$



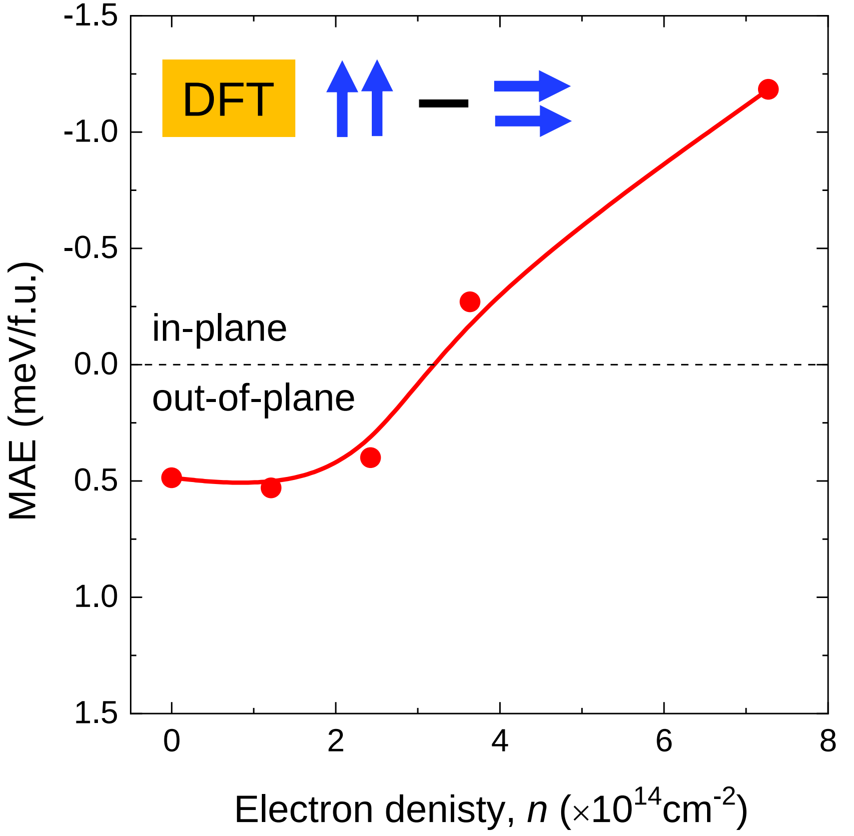


in-plane easy axis

❑ Easy axis is rotated by 90°

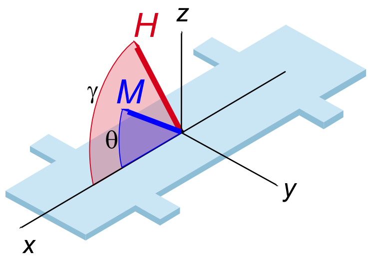
Easy axis rotation

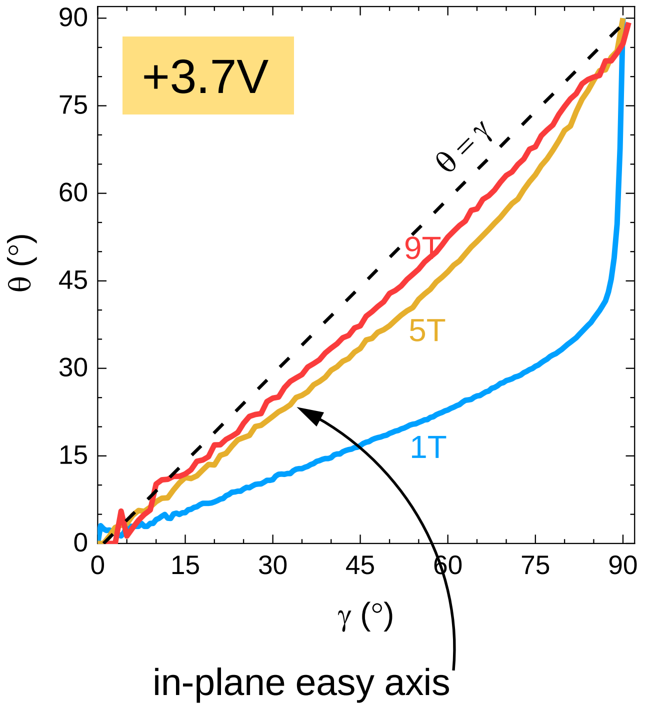
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460



$$R_{xx}(\gamma) = R(90) + [(R(0) - R(90)]\cos^2\theta$$

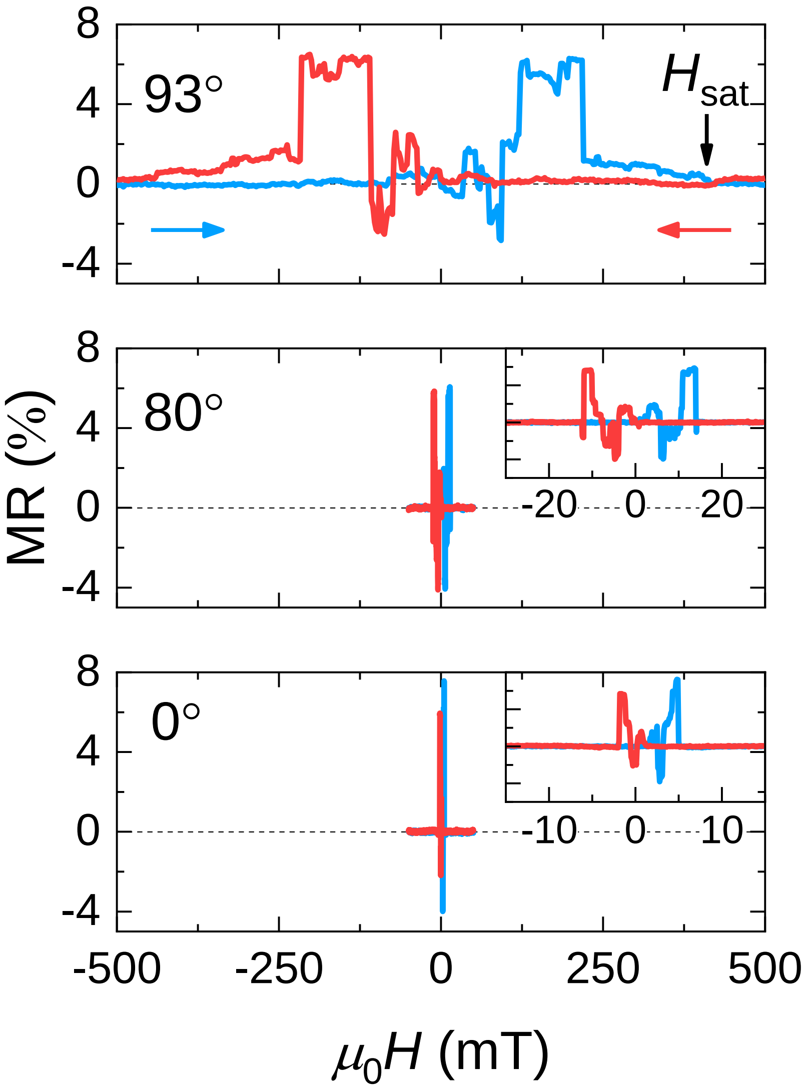
$$\Rightarrow \theta(\gamma) = \operatorname{acos}\left(\sqrt{\frac{R_{xx}(\gamma) - R(90)}{(R(0) - R(90)}}\right)$$

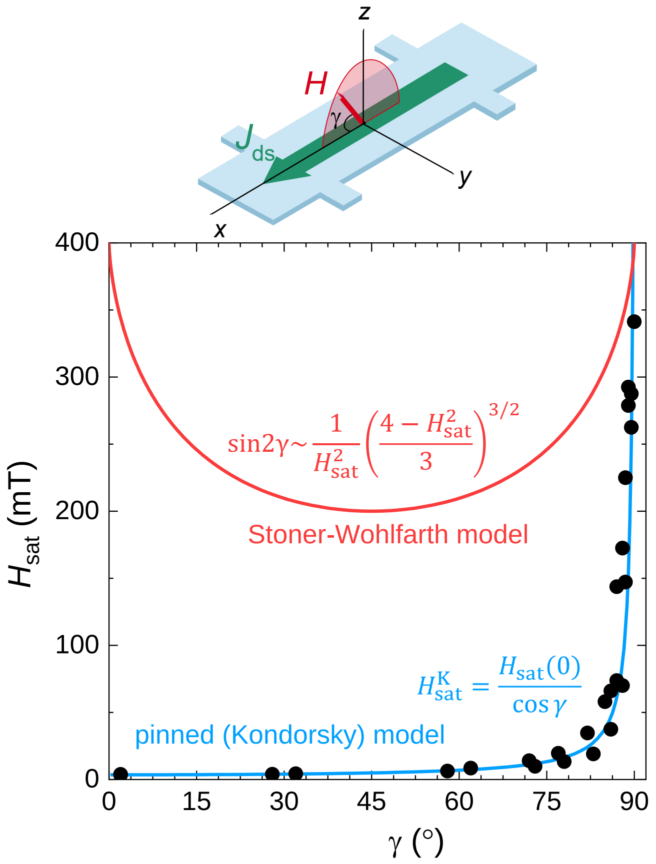




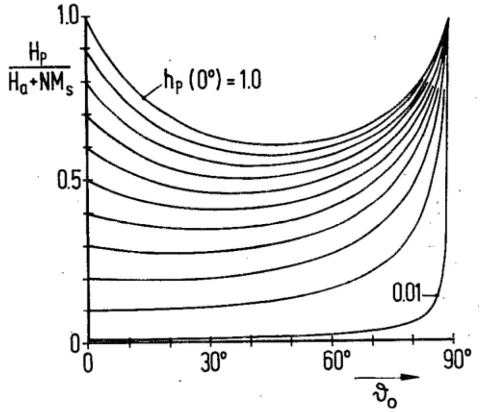
Magnetic domain wall motion

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460





$$H_{sat} = \frac{H(0)}{\cos\gamma}\left(\frac{\Theta(\gamma)}{\Theta(0)}\right)$$

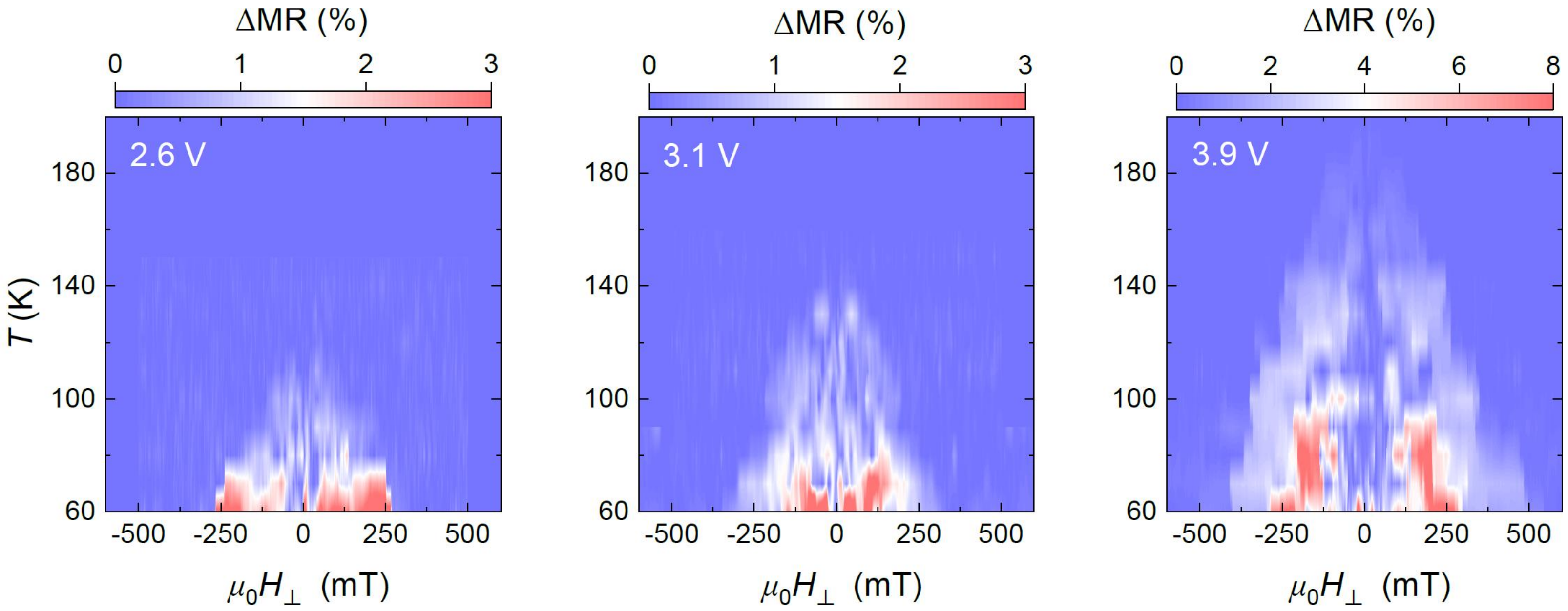


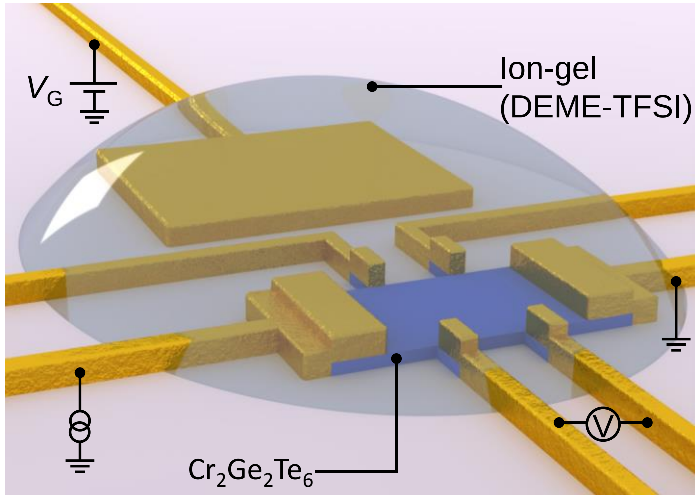
F. Schumacher (1991), J. Appl. Phys. 70, 3184

- ❑ H_{sat} fits the domain-wall model

Tuning phase transition

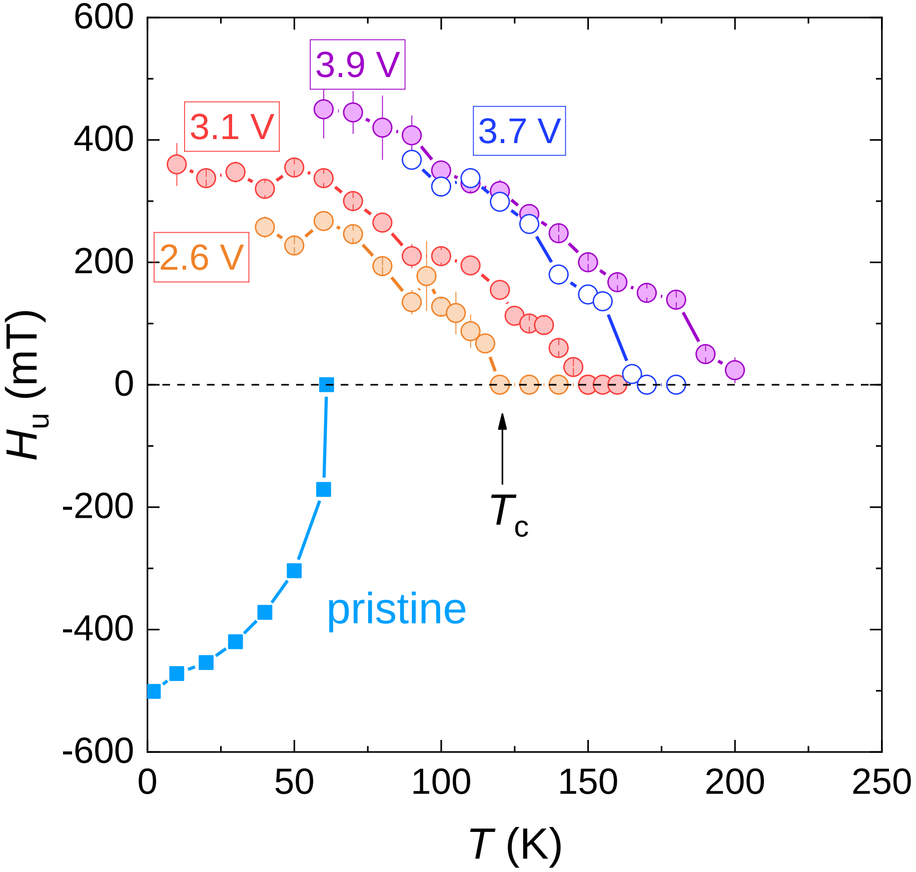
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460

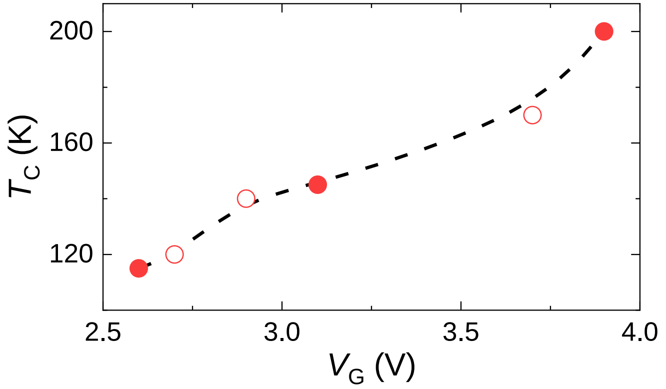


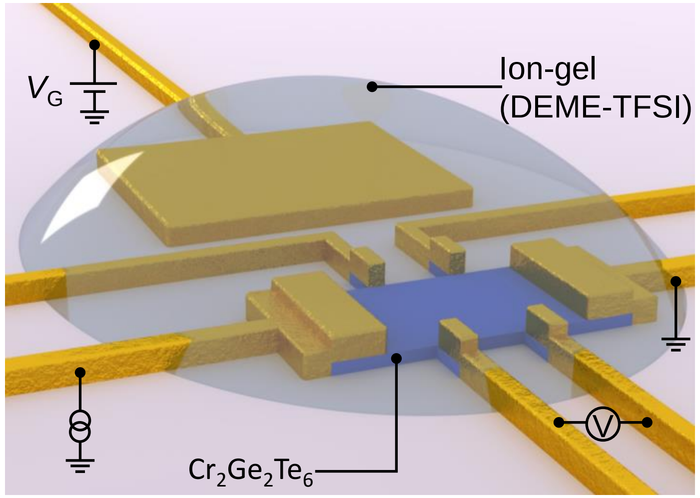


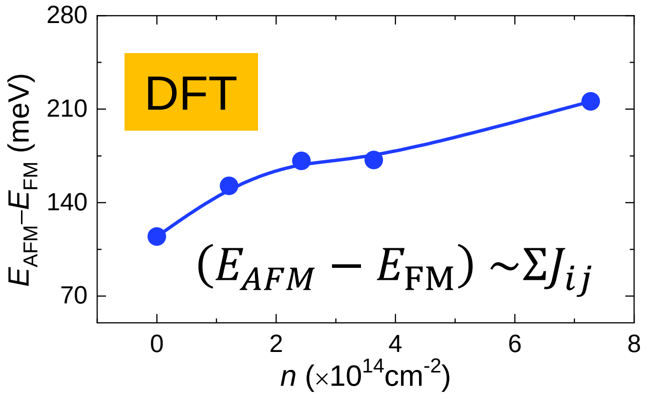
Tuning phase transition

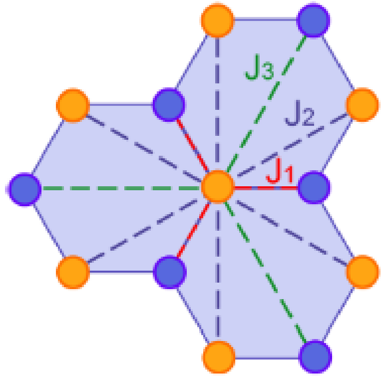
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460







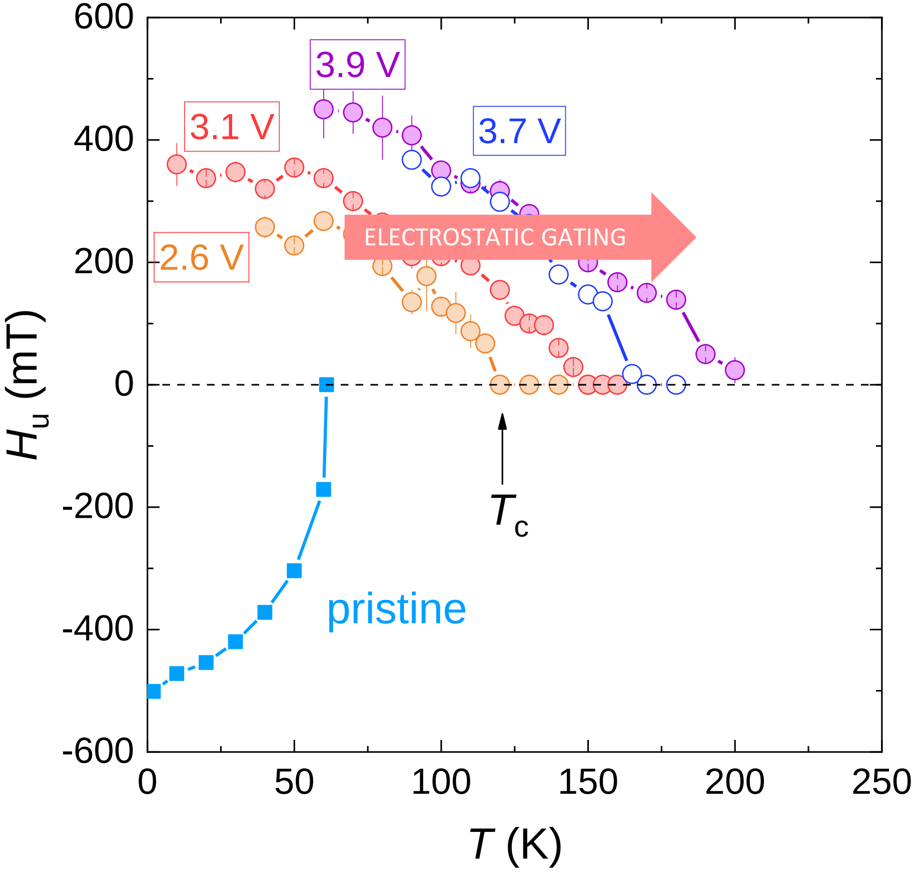


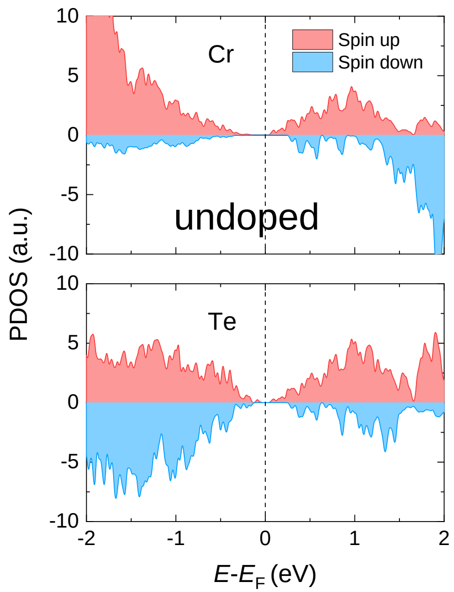


❑ T_c can be continuously and reversibly tuned over $\Delta T \approx 140$K

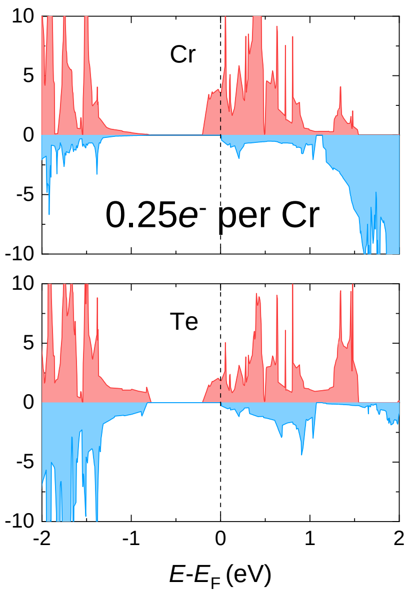
Tuning phase transition

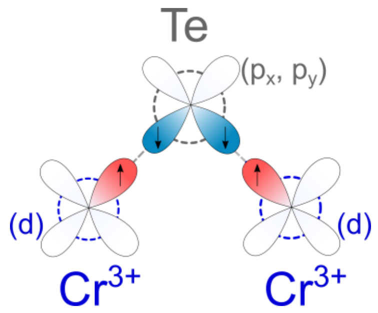
Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460



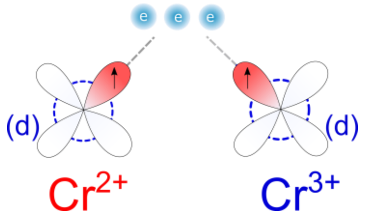


ELECTROSTATIC GATING



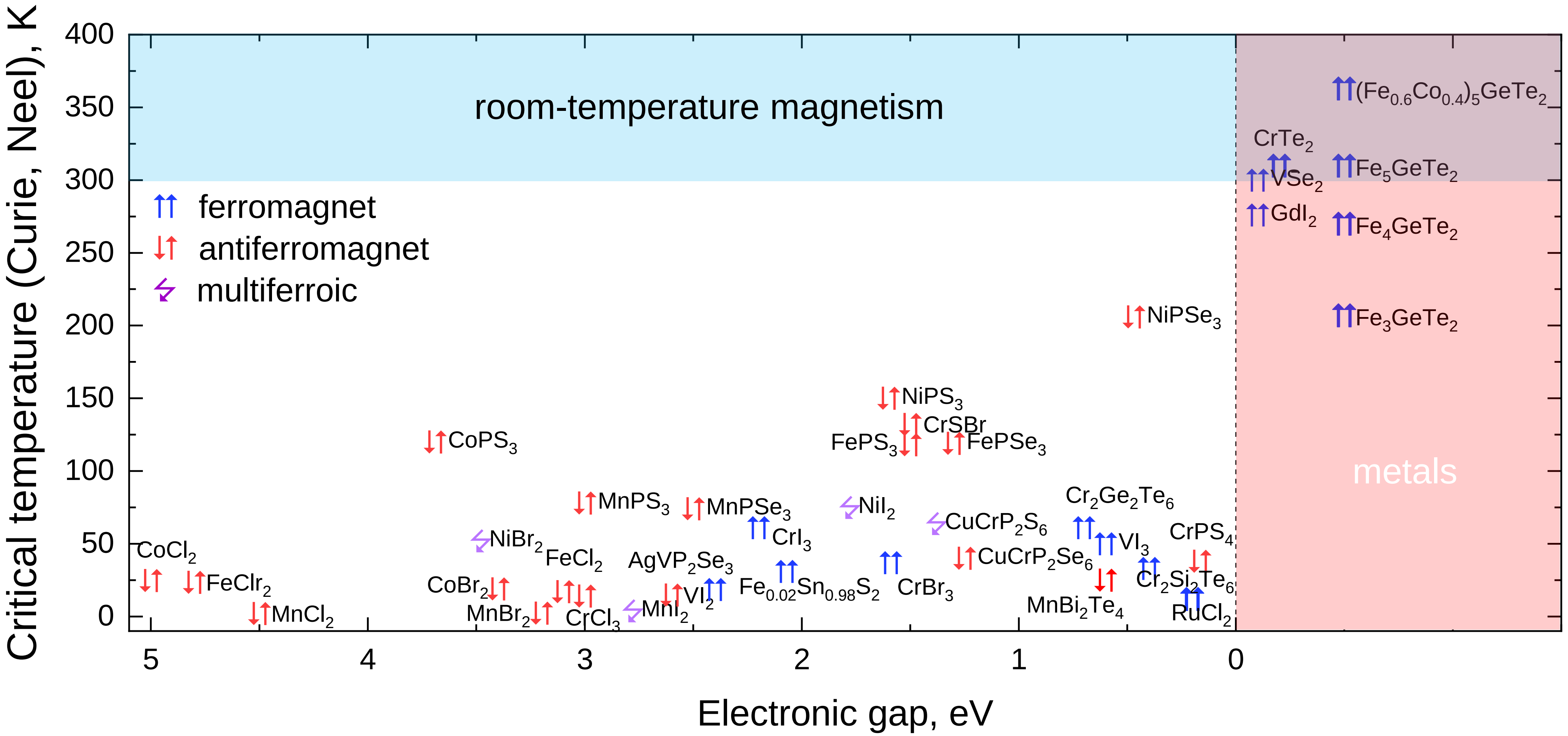


superexchange

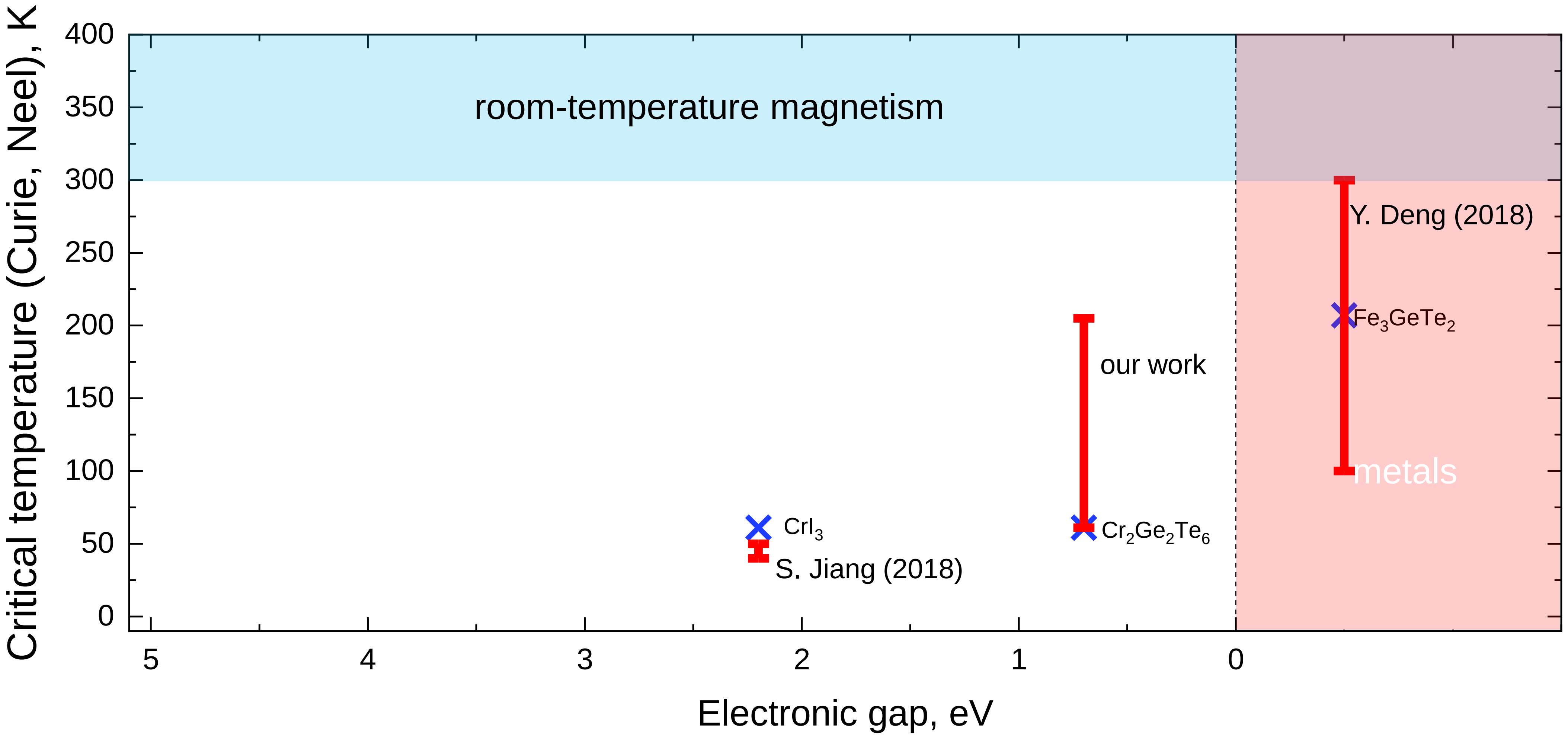


double exchange

Tuning phase transition



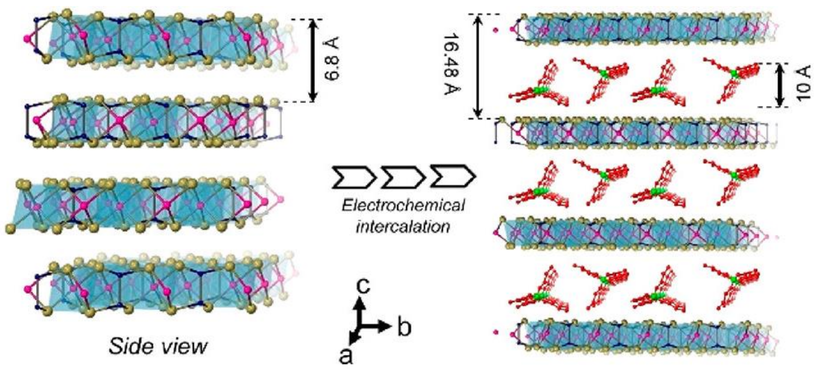
Tuning phase transition

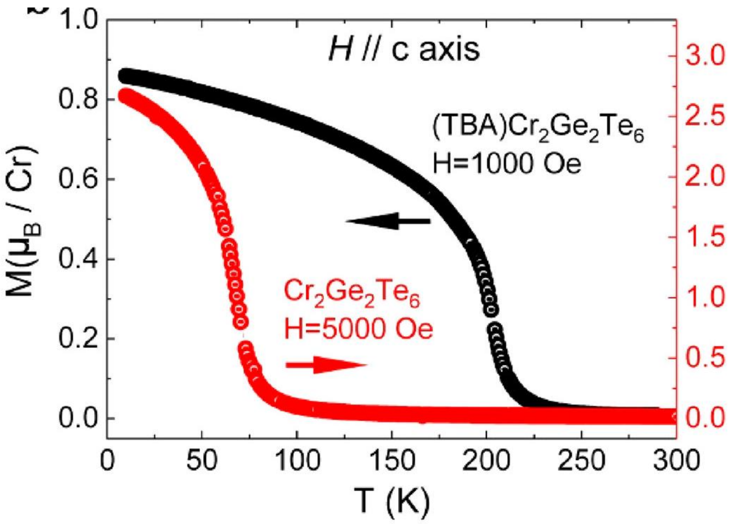


Intercalation compounds of $Cr_2Ge_2Te_6$

$Cr_2Ge_2Te_6$ intercalated with TBA^+
(tetrabutyl ammonium)

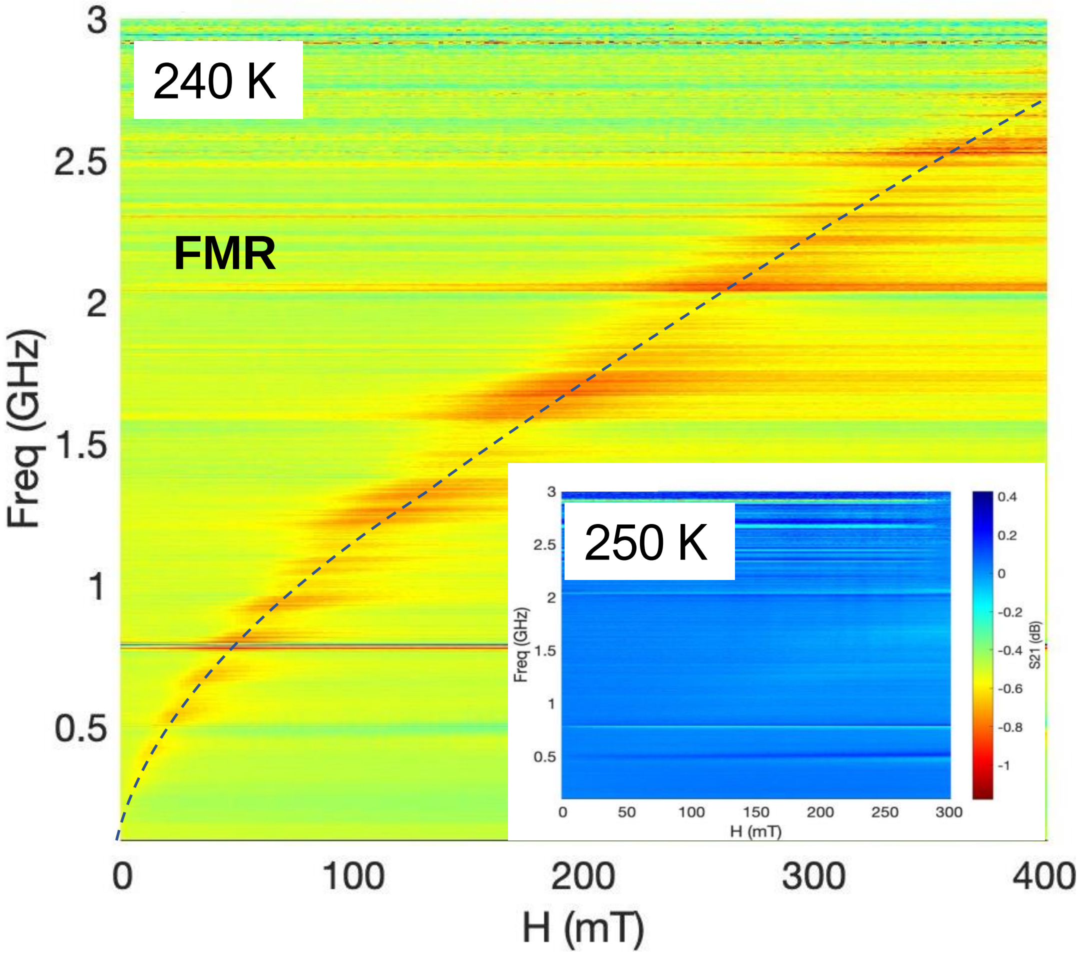
Naizhou Wang et al. (2019),
J. Am. Chem. Soc. 141, 43, 17166





$Cr_2Ge_2Te_6$ intercalated with Na^+

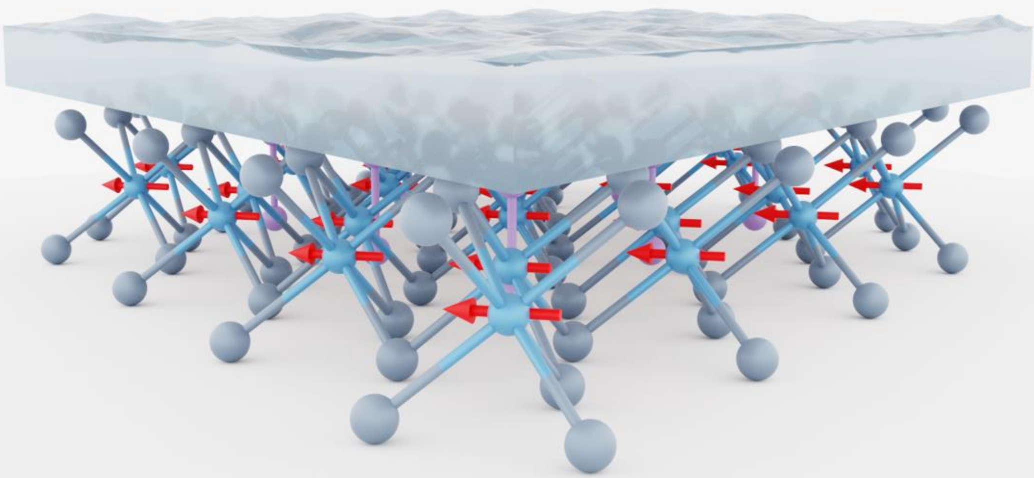
Safe Khan et al., unpublished



Summary

- Electrostatic doping in $Cr_2Ge_2Te_6$ switches the leading magnetic exchange mechanism from superexchange to double exchange
- Strongly doped $Cr_2Ge_2Te_6$ posses higher Curie temperature and in-plane easy axis
- This method can in principle be applied to other 2D magnetic systems

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460
https://doi.org/10.1038/s41928-020-0427-7



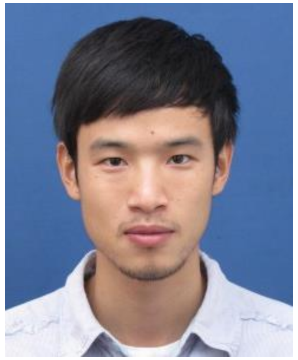
Acknowledgements

Prof. Dr. Goki Eda
NUS, Singapore

Prof. Dr. Hidekazu Kurebayashi
UCL, London

Dr. Safe-Ur-Raman Khan
UCL, London

Prof. Dr. Feng Yuan Ping
NUS, Singapore



Dr. Zhou Jun
NUS, Singapore

Ivan Verzhbitskiy et al. (2020), Nature Electronics 3, 460
https://doi.org/10.1038/s41928-020-0427-7