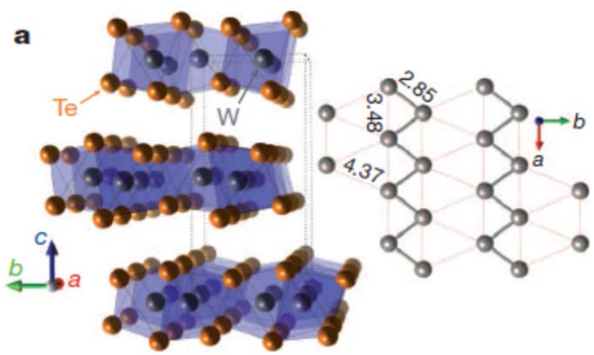
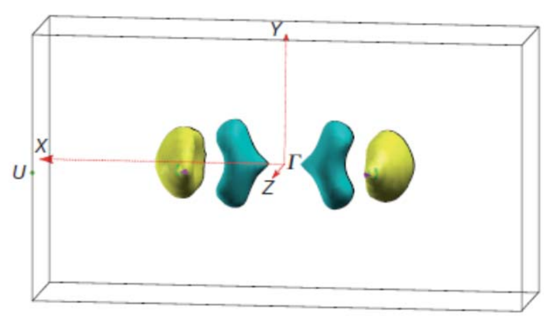
Large, non-saturating magnetoresistance in WTe_2

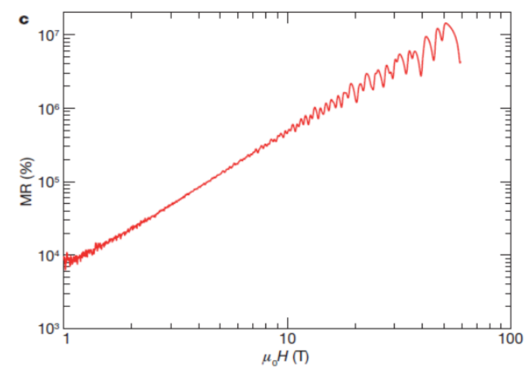
M. N. Ali et al., *Nature* 514, 205-208 (2014)

Team 5 – Alina Kononov, Sangjun Lee, Mao Lin

November 21, 2014





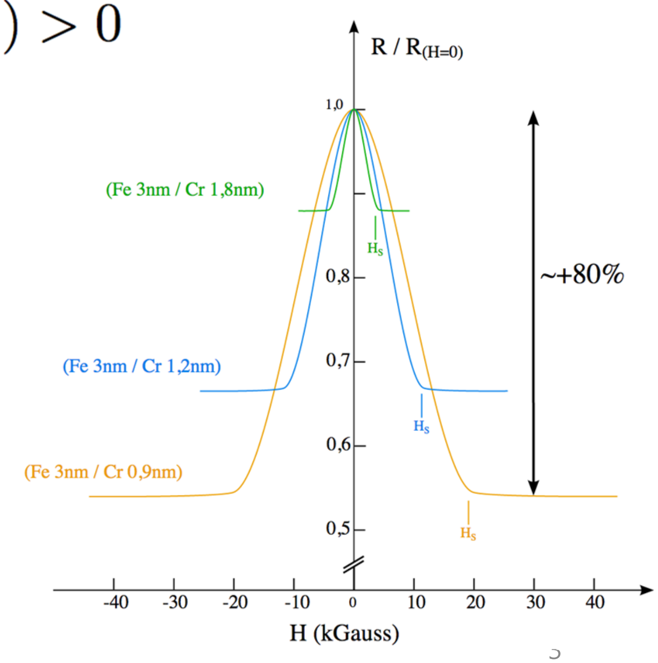


Outline

- Introduction
- Summary of the paper
- Comparison with previous work
- Critiques of the work
- Potential impact
- Citation analysis
- Conclusion

What is magnetoresistance (MR)?

- Change of the resistivity of a material due to magnetic field. *
- $\mathrm{MR}(\%) = (\rho[H] - \rho[0])/\rho(0)$
- Metal, semimetal, semiconductor: $\mathrm{MR}(\%) > 0$
- Magnetic material: $\mathrm{MR}(\%) < 0$



* http://en.wikipedia.org/wiki/Magnetoresistance

Baibich M. N et al. (1988). "Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices". Physical Review Letters 61 (21): 2472–2475

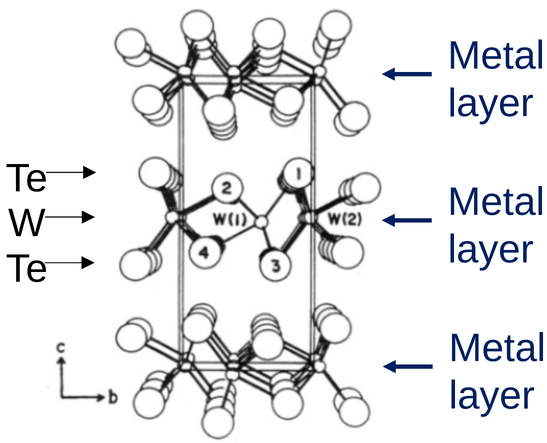
Magnetoresistance has important applications

- Giant MR is the standard technology in data-reading since 1997. *
  - Information is encoded magnetically.
  - Change of magnetic field induces change of resistivity, as well as the current in the GMR system.
  - Detection of current enable one to decode the information
- Enable one to probe the density and mobility of electrons in the materials.

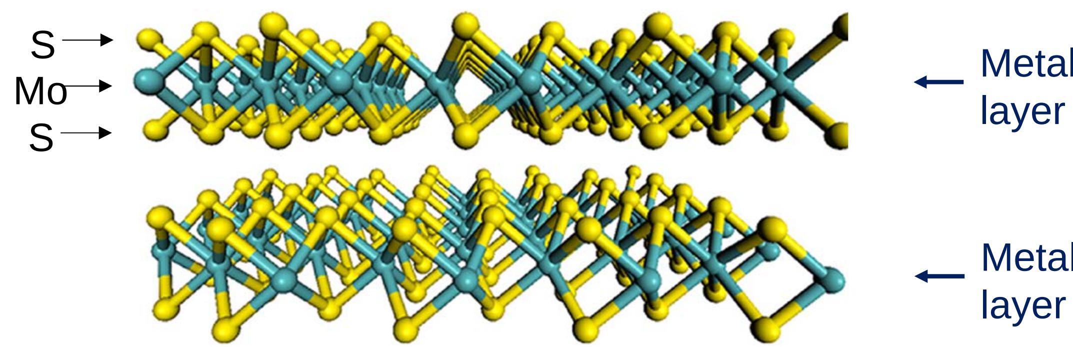
* http://www.nobelprize.org/nobel_prizes/physics/laureates/2007/press.html

Structure of WTe_2

- Layered transition-metal dichalcogenide (TMD) crystal
- A distorted version of the common MoS_2 structure (hexagonal structure)



WTe_2 *



MoS_2

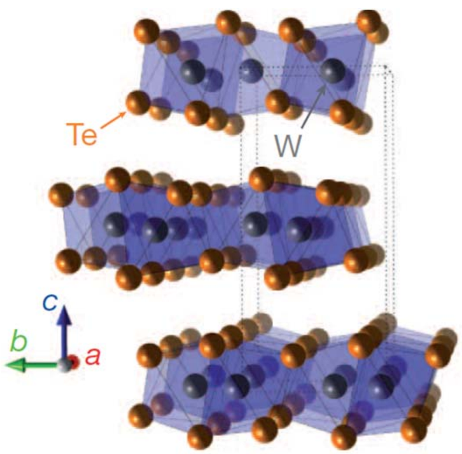
* Image courtesy of Wang et al., MIT

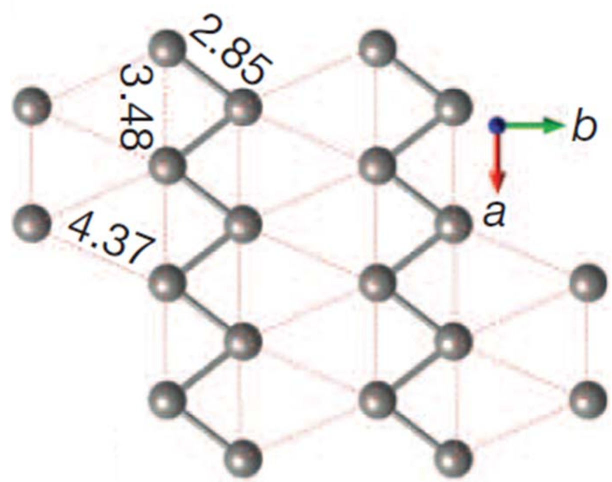
Layered TMDs are typically electronically two-dimensional

* A. Mar, J. Am. Chem. Soc. (1992)

Structure of WTe_2

- W atoms form a chain along the a axis

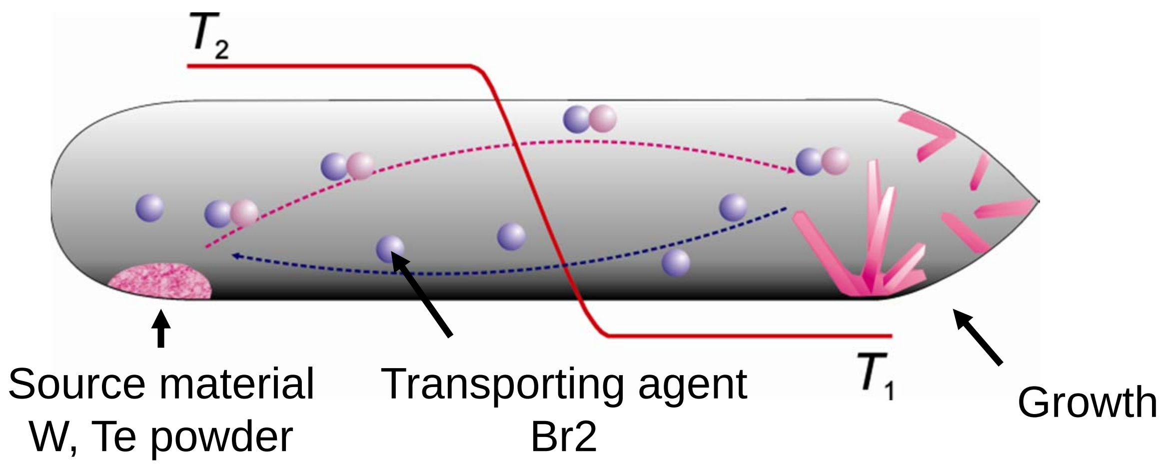




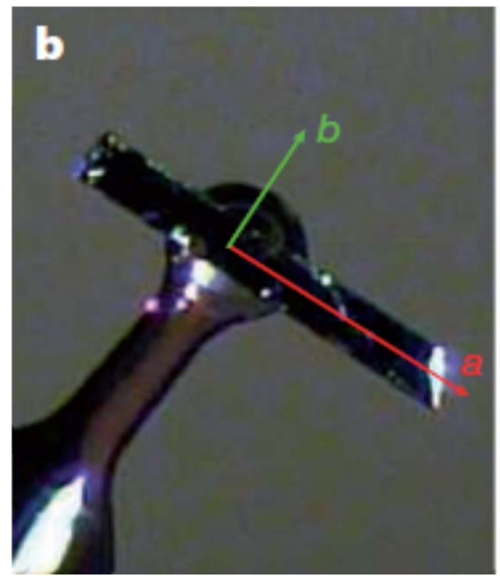
WTe_2 is electronically one-dimensional and shows anisotropy

Methods: Vapor transport crystal growth

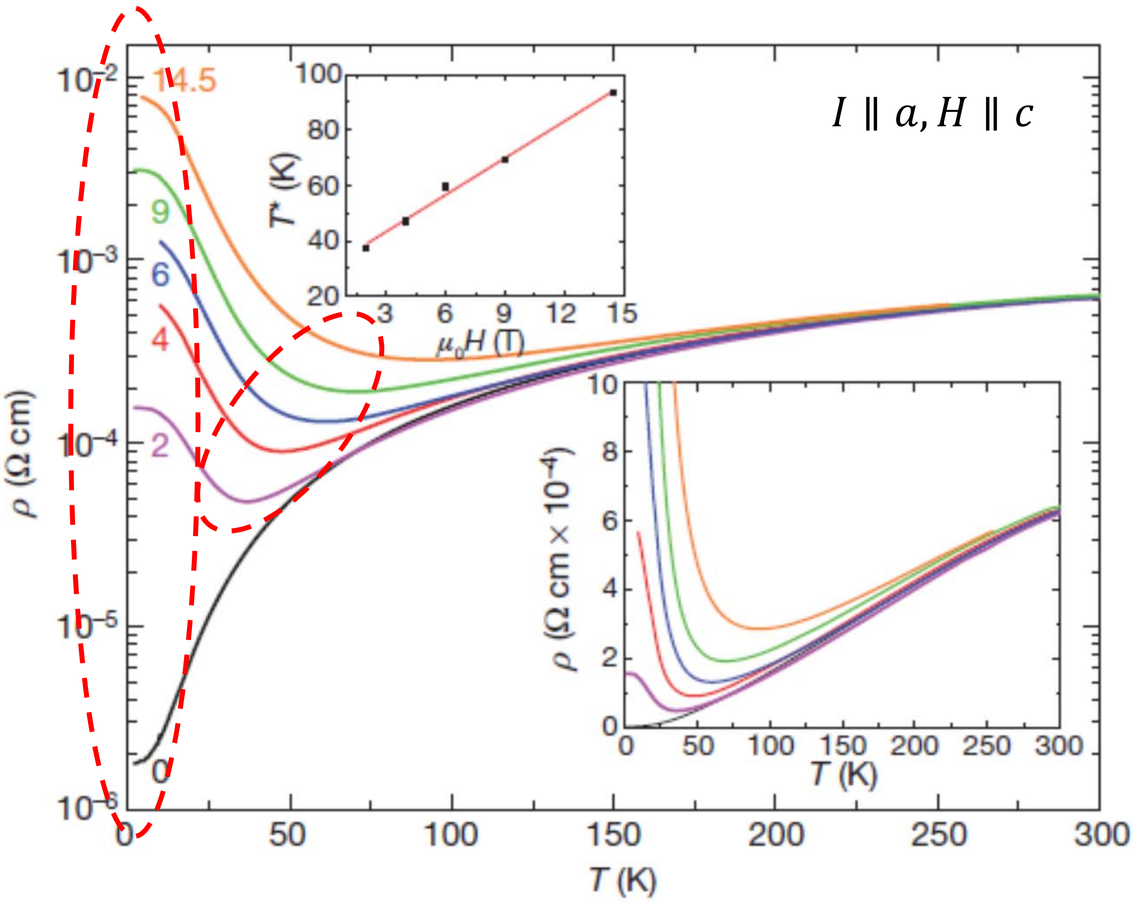
- The crystal grew as thin ribbons along W chain direction



* Image courtesy of INTECH



Result: MR in WTe_2 is very large at low temperatures



- 452,700% at 4.5K in 14.7T

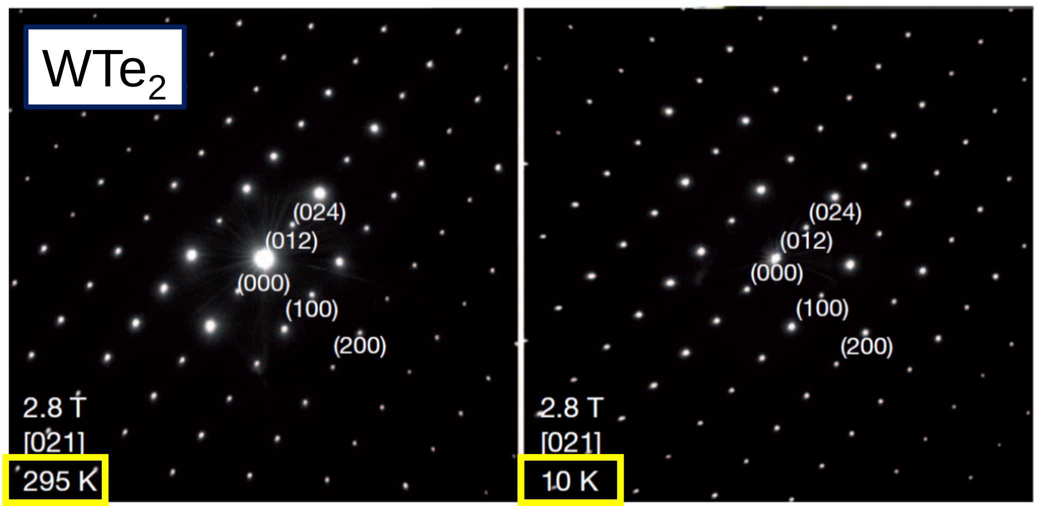
$$\mathrm{MR}(\%) = (\rho[H] - \rho[0])/\rho(0)$$

- “Turn on” temperature T*: below which the resistivity begins to increase markedly

Is there any phase transition that changes scattering mechanism?

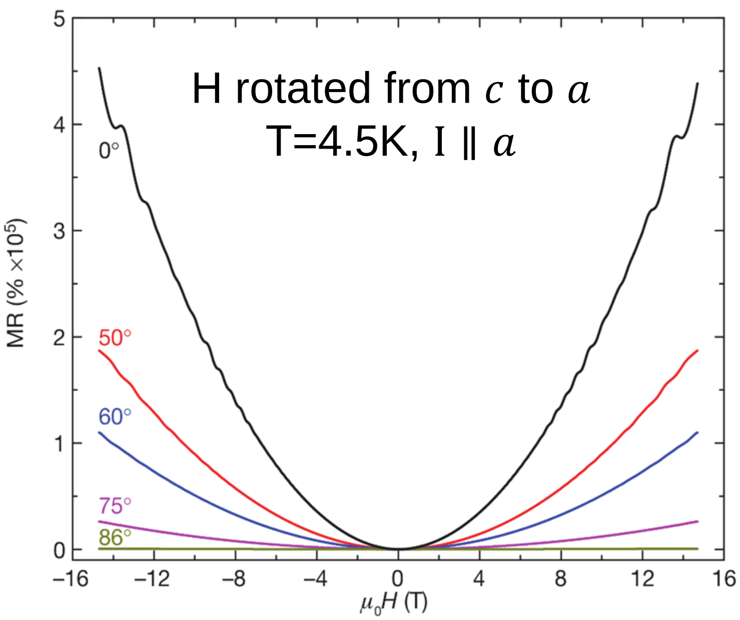
Result: Electron diffraction pattern shows no structural changes

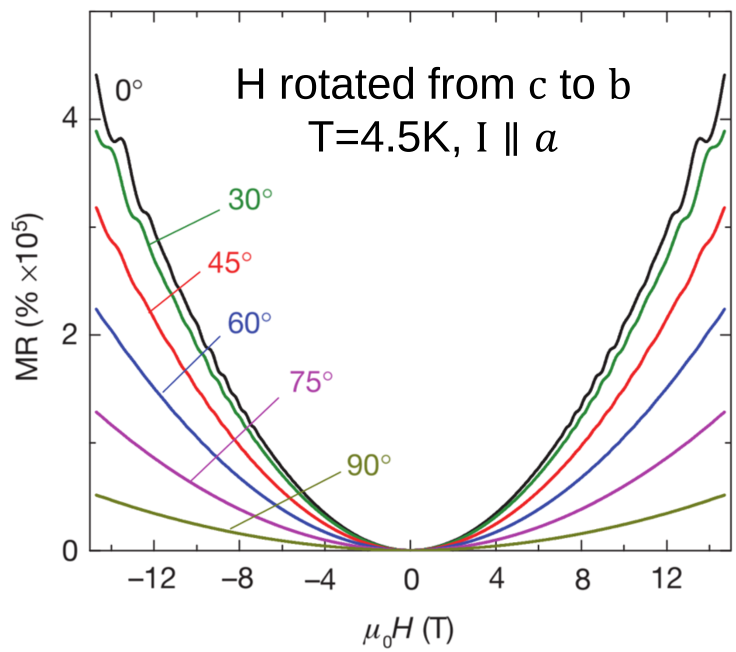
- WTe_2 shows no structural phase transition in MR regime

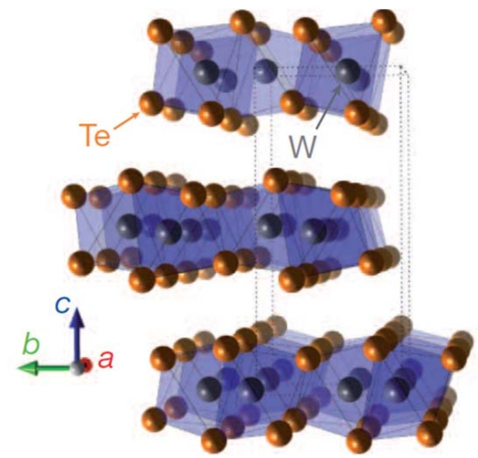


Electron diffraction pattern shows no change in structure of WTe_2 on cooling

Result: MR in WTe_2 is anisotropic

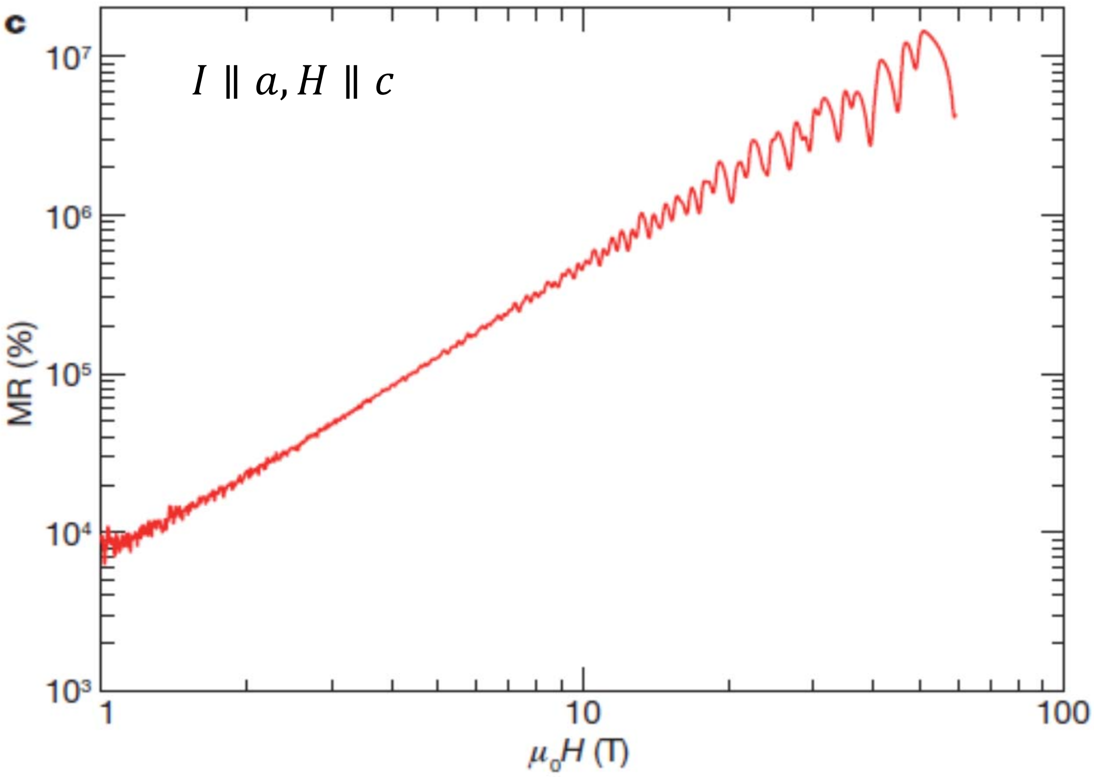






- MR is maximized when the magnetic field is parallel to the c axis
- Probably due to the very anisotropic Fermi surface of WTe_2

Result: MR in WTe_2 doesn't saturate up to 60T



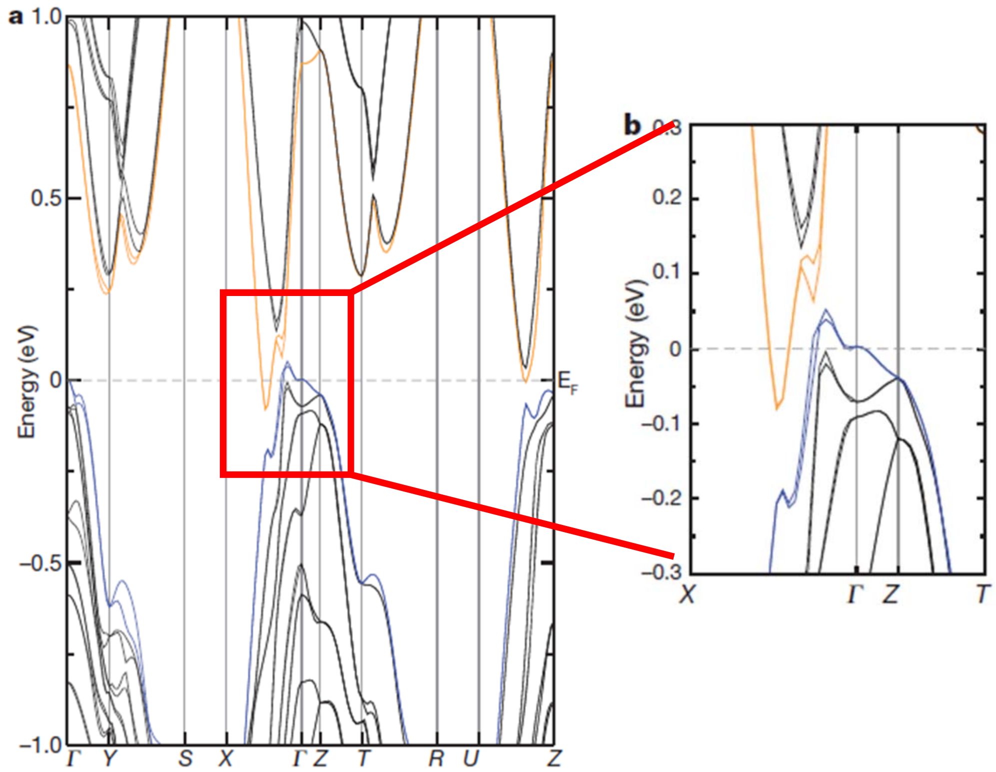
- MR does not saturate up to 60T (13,000,000% at 0.53K in 60T)

- The dependence of the MR on magnetic field is quadratic: $\rho(H)/\rho(0) \propto H^m \ (m = 2)$

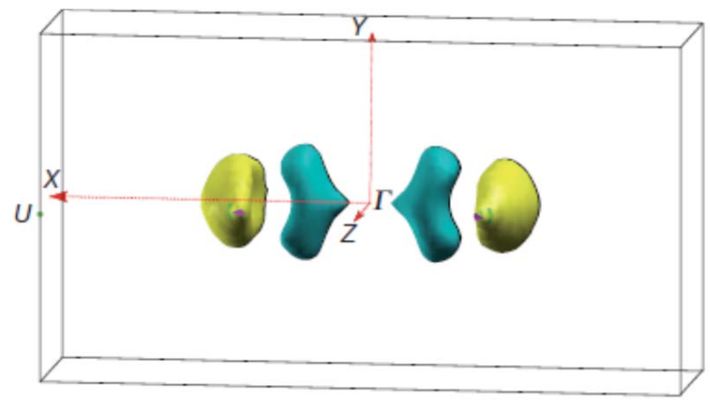
How can we explain this non-saturating behavior?

Explanation for Non-saturating MR

- Electronic structure calculation shows that valence and conduction bands cross the Fermi level at different places.



- The small electron and hole pockets makes WTe_2 a semimetal



Explanation for Non-saturating MR

- Two-band model for charge transport in semimetal in Strong B field

$$\rho_{xx} = \frac{(n^2\rho_e + p^2\rho_h)}{(n^2\rho_e + p^2\rho_h)^2\frac{(ec)^2}{B^2} + (n-p)^2}$$

* For the derivation, refer to "Introduction to Solid State Physics", Kittel, p. 219

Resistivity predicted by Drude theory

Electron concentration

Hole concentration

In strong B field,

if $n \neq p$, $\rho_{xx} \rightarrow \frac{n^2\rho_e + p^2\rho_h}{(n-p)^2}$ MR saturates to a field-independent value

if $n = p$, $\rho_{xx} \propto B^2$ MR increases as B^2 without saturation : WTe2

WTe2 displays nearly perfect n-p compensation

Author's conclusions

- Extremely large magnetoresistance is measured in WTe_2 (452,700% at T=4.5K, μ_0H=14.7T, 13,000,000% at T=0.53K, μ_0H=60T)
- This effect has anisotropy: MR is maximized when the applied magnetic field is parallel to c axis
- WTe_2 displays a non-saturating MR.
- WTe_2 seems to be the first known material that shows nearly perfect n-p compensation.

Comparison with previous work

- Do other materials exhibit such large MR?
  - $PtSn_4$ is reported to exhibit MR $\sim 5 \times 10^5\%$ at 1.8K and 10T.

Magnetic field effects on transport properties of $PtSn_4$

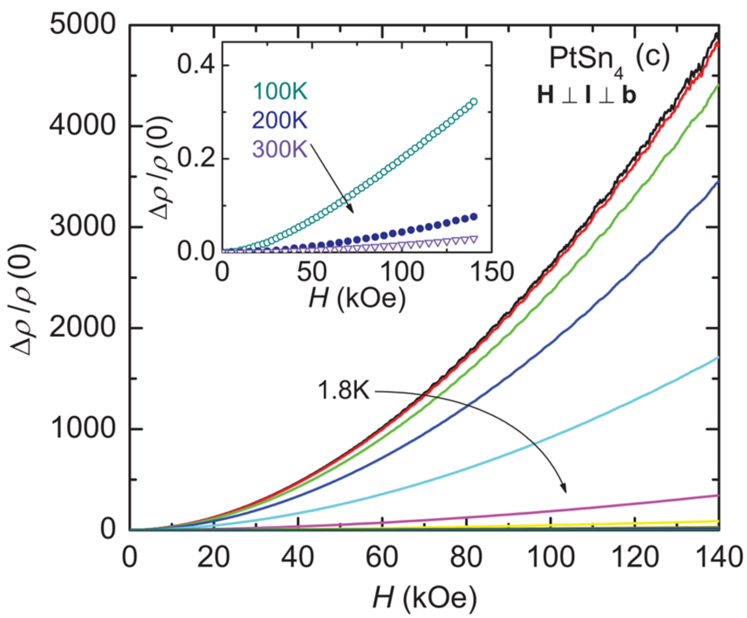
Eundeok Mun,[1] Hyunjin Ko,[2] Gordon J. Miller,[2] German D. Samolyuk,[1,*] Sergey L. Bud'ko,[1] and Paul. C. Canfield[1]
[1]*Ames Laboratory US Department of Energy and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA*
[2]*Ames Laboratory US Department of Energy and Department of Chemistry, Iowa State University, Ames, Iowa 50011, USA*
(Received 6 October 2011; revised manuscript received 17 January 2012; published 31 January 2012)

The anisotropic physical properties of single crystals of orthorhombic $PtSn_4$ are reported for magnetic fields up to 140 kOe, applied parallel and perpendicular to the crystallographic **b** axis. The magnetic susceptibility has an approximately temperature-independent behavior and reveals an anisotropy between the **ac** plane and **b** axis. Clear de Haas-van Alphen oscillations in fields as low as 5 kOe and at temperatures as high as 30 K were detected in magnetization isotherms. The thermoelectric power and resistivity of $PtSn_4$ show the strong temperature and magnetic field dependencies. A change of the thermoelectric power at $H = 140$ kOe is observed as high as $\simeq 50\ \mu V/K$. Single crystals of $PtSn_4$ exhibit very large transverse magnetoresistance of $\simeq 5 \times 10^5\%$ for the **ac** plane and of $\simeq 1.4 \times 10^5\%$ for the **b** axis resistivity at 1.8 K and 140 kOe, as well as pronounced Shubnikov de Haas oscillations. The magnetoresistance of $PtSn_4$ appears to obey Kohler's rule in the temperature and field range measured. The Hall resistivity shows a linear temperature dependence at high temperatures followed by a sign reversal around 25 K which is consistent with thermoelectric power measurements. The observed quantum oscillations and band structure calculations indicate that $PtSn_4$ has three-dimensional Fermi surfaces.

E. Mun, H. Ko, G. J. Miller, G. D. Samolyuk, S. L. Bud'ko,and P. C. Canfield, Phys. Rev. B 85, 035135 (2012)

Comparison with previous work

- What about the non-saturating property?
  - For $PtSn_4$, there will be no saturation below 10T.



As shown in Figs. 6(a) and 6(b), the resistivity has a relatively weak field dependence above 50 K, but depends strongly on magnetic field below this temperature. The size and anisotropy of MR can be seen explicitly in Figs. 6(c) and 6(d). The relative change of the MR as a function of magnetic field is plotted by the typical definition of MR;[8] $\frac{\Delta\rho}{\rho(0)} = [\frac{\rho(H)-\rho(H=0)}{\rho(H=0)}]$, where $\rho(H=0)$ is the zero field resistivity for each given isotherms. Interestingly, there is no evidence of the saturation of MR for either direction in temperature and field range measured. At $T = 1.8$ K and $H = 140$ kOe, a huge MR effect of $\simeq 5 \times 10^5$ % for $\mathbf{H} \perp \mathbf{b}$ and $\simeq 1.4 \times 10^5$ % for $\mathbf{H} \parallel \mathbf{b}$ can be obtained. Note that at 300 K and 140 kOe the observed MR is small; $\Delta\rho/\rho(0) \sim 3\%$ for $\mathbf{H} \perp \mathbf{b}$ and $\Delta\rho/\rho(0) \sim 4\%$ for $\mathbf{H} \parallel \mathbf{b}$. The transverse MR is almost proportional to H^2 over the field range measured. The size of MR in $PtSn_4$ is

E. Mun, H. Ko, G. J. Miller, G. D. Samolyuk, S. L. Bud'ko,and P. C. Canfield, Phys. Rev. B 85, 035135 (2012)

Comparison with previous work

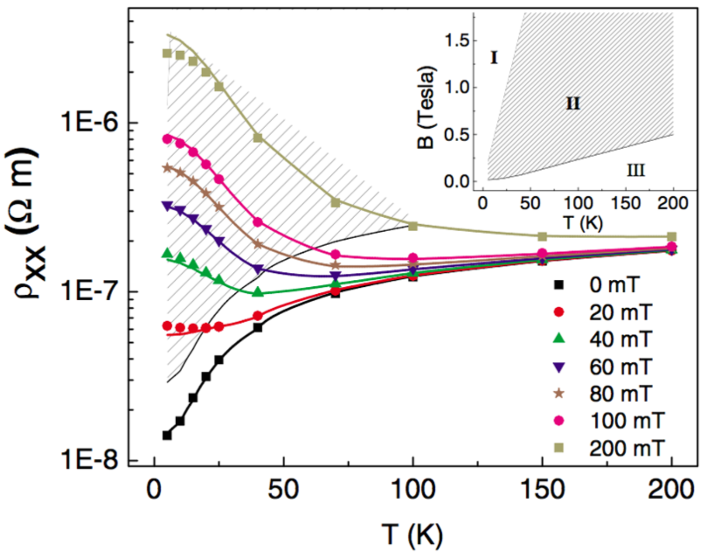
- What about the non-saturating property?
  - For $PtSn_4$, there will be no saturation below 10T.
  - However, for the current paper, the resistivity was measured in a pulsed magnetic field up to 60T.
  - This is the current "world record".
  - The conclusion of non-saturation is more convincing.

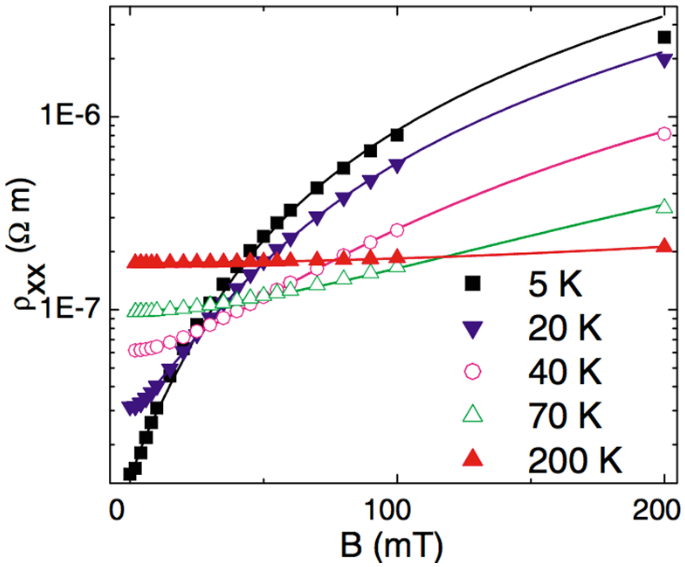
MagLab World Records	
Highest magnetic field for a continuous field magnet (Guinness World Record)	**45 tesla**
Highest non-destructive magnetic field	**100.75 tesla**
Highest field for a long-pulse magnet	**60 tesla**
Highest field for a split magnet	**25 tesla**

http://www.magnet.fsu.edu/mediacenter/factsheets/records.html

Comparison with previous work

- What about the non-saturating property?
  - For other materials, such as semi-metallic bismuth and graphit e, researchers did have found the saturation behavior.





Xu Du, et. al. Phys. Rev. Lett. 94, 166601 (2005)

Comparison with previous work

- What about the non-saturating property?
  - For other materials, such as semi-metallic bismuth and graphite, researchers did have found the saturation behavior.
  - The authors claimed WTe_2 to be the “first know material that p/n resonance is nearly perfect. Comparing with previous work, this claim seems reasonable.

Critiques of the work

- n-p compensation
  - The author didn't provide direct evidence that supports n=p compensation.
  - By doping WTe_2 by electron or hole, and measuring the magnetoresistance, we can find out whether this is correct or not

- Large MR in low temperature and large magnetic field
  - WTe_2 starts to exhibit the MR below 150K and in several Tesla.
  - These constraints make WTe_2 is not suitable for the practical use

Potential Impact to the Field

- Potential applications in other areas
  - Magnetic sensor
  - Electron gate in nano-device fabrication
- Further research directions
  - Searching more materials with similar properties can ease the implementation of the effect.
  - New theoretical model needed if p-n resonance is not perfect.
  - Doping of WTe_2 to reveal more interesting properties
  - …

Citation Evaluation

- Citation
  - Published in September 2014.

[HTML] Large, non-saturating magnetoresistance in WTe2
MN Ali, J Xiong, S Flynn, J Tao, QD Gibson, LM Schoop… - Nature, 2014 - nature.com
Magnetoresistance is the change in a material's electrical resistance in response to an applied magnetic field. Materials with **large magnetoresistance** have found use as magnetic sensors 1, in magnetic memory 2, and in hard drives 3 at room temperature, and their **...**
Cited by 1 Cite Save

  - "Cited" by Wikipedia

Magnetoresistance is the property of a material to change the value of its electrical resistance when an external magnetic field is applied to it. The effect was first discovered by William Thomson (better known as Lord Kelvin) in 1851, but he was unable to lower the electrical resistance of anything by more than 5%. This effect was later called ordinary magnetoresistance (OMR). More recent researchers discovered materials (and multilayer devices) showing giant magnetoresistance (GMR), colossal magnetoresistance (CMR), tunnel magnetoresistance (TMR) and extraordinary magnetoresistance (EMR). Researchers at Princeton University recently discovered a new semimetal, tungsten ditelluride, with no saturation point to the limits of testability and a magnetoresistance of 13,000,000%; they have tentatively chosen the name large magnetoresistance (LMR) for the effect.[1] Generally, resistance can depend either on magnetization (controlled by applied magnetic field) or on magnetic field directly.

Conclusion (made by our team)

- This paper reports a significant discovery in magnetoresistance.
- It represents new direction in the future study
- However, it lacks clear explanations about this phenomenon. Much more study is needed to understand this material.

Thank you!

Q/A