· 凝聚态物理—北京大学论坛

半导体的几何增强磁电阻

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2007 诺贝尔 物理学奖：巨磁电阻（GMR）效应

Peter Grünberg（Germany）

Albert Fert （France）

- 巨磁阻效应在1988年由德国尤利西研究中心的彼得·格林贝格(Peter Grünberg)和巴黎第十一大学的艾尔伯·费尔(Albert Fert)分别独立发现的，他们因此共同获得2007年诺贝尔物理学奖。

Outlines

1. 背景介绍
   - 1.1 磁电阻和自旋电子学
   - 1.2 各种磁电阻
2. 结果
   - 2.1 **a-C/Si** 异质结构的磁电阻
   - 2.2 硅的低温磁电阻
   - 2.3 硅的室温几何增强磁电阻
     - 对称电极结构的磁电阻
     - 非对称电极结构的磁电阻
3. 半导体几何增强磁电阻的优点和愿景

磁电阻效应

磁电阻（磁阻） magnetoresistance (MR)

MR=[R(H)-R(0)]/R(0) %

任何材料都有磁电阻，这种磁电阻称为**ordinary magnetoresistance (OMR),**

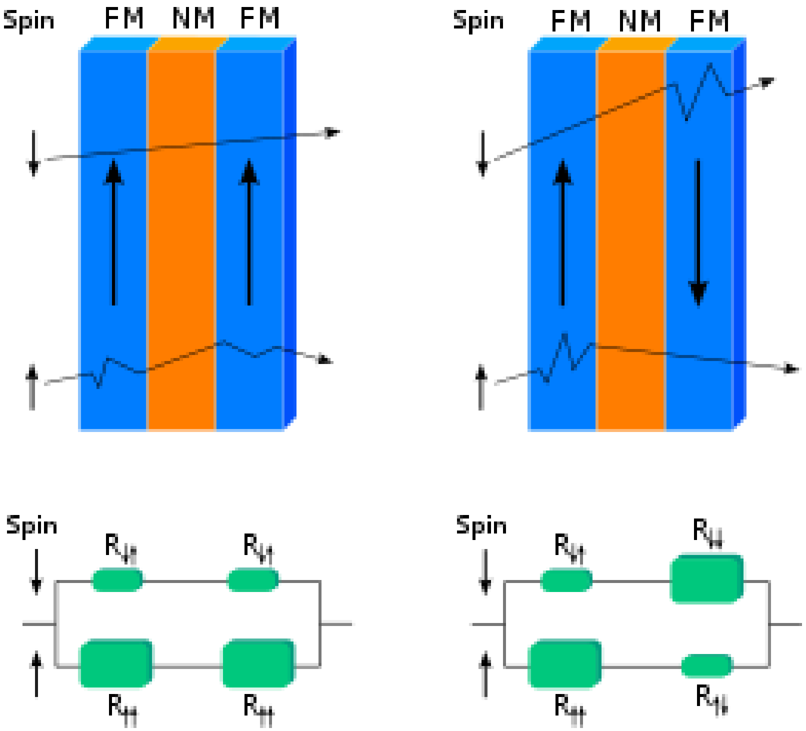
机理是电子在磁场下有洛伦兹偏转，导致电阻增。

OMR很小，通常小于**1－2%**，应用价值不大。

巨磁阻（GMR）效应

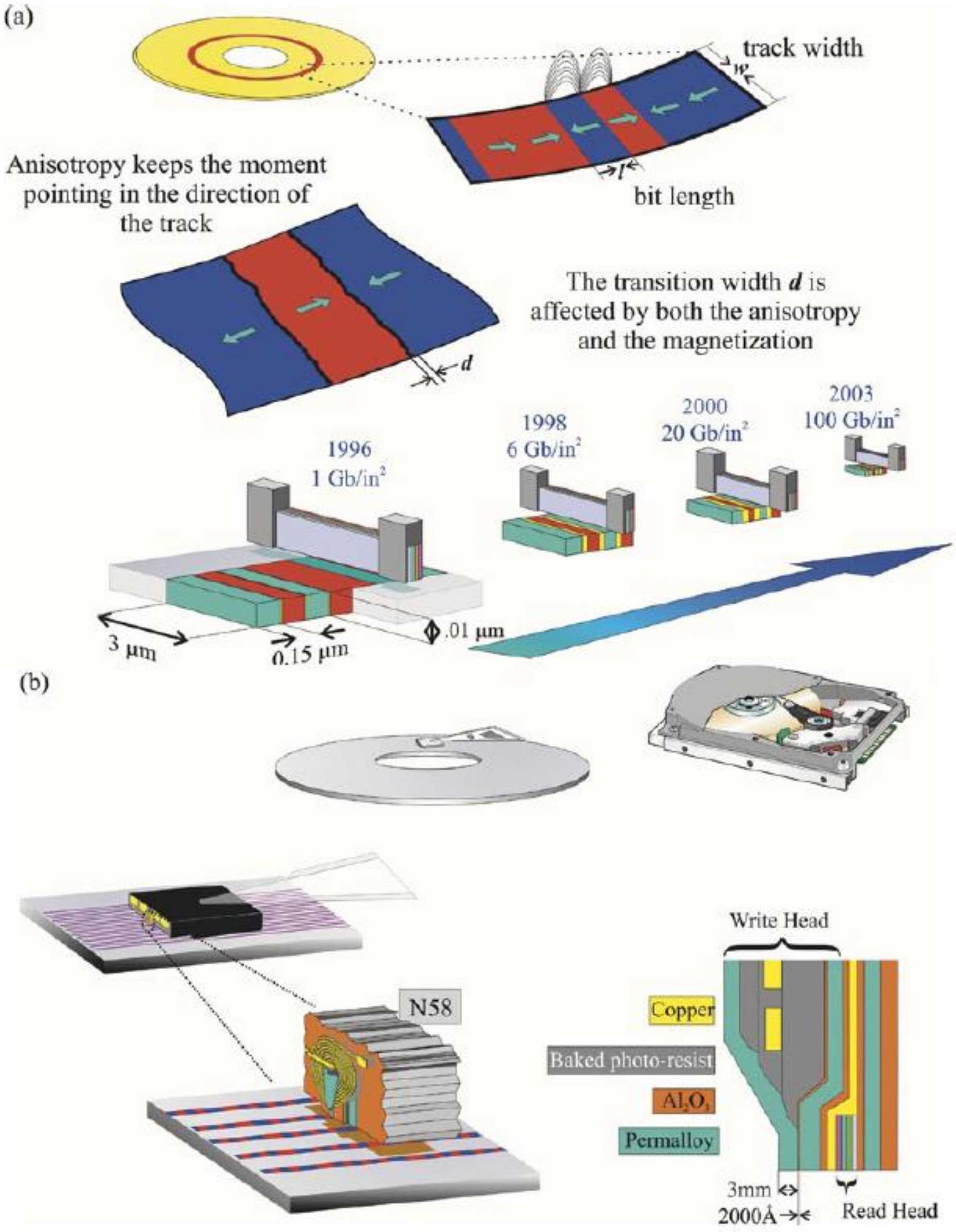
1988年，格林贝格尔的研究小组研究了由铁、铬、铁三层材料（ Fe/Cr/Fe ）组成的结构物质，实验结果显示电阻下降了1.5%。而费尔的研究小组则研究了由铁和铬组成的多层材料（Fe/Cr），使得电阻下降了50%。这么大的磁电阻MR称为巨磁阻（GMR）。

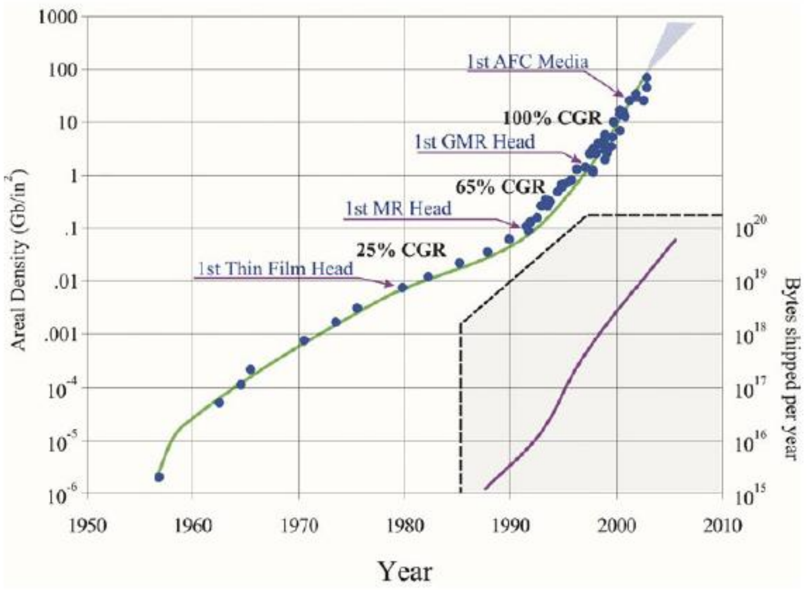
自旋平行，
磁电阻大



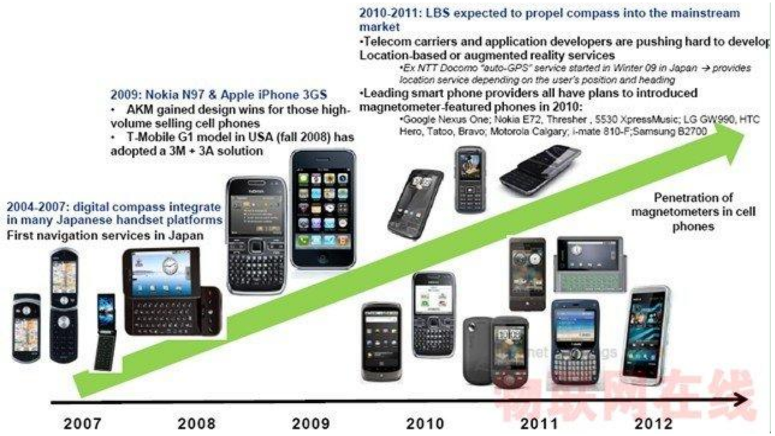
自旋反平行，
磁电阻小

Application of GMR：read head in computer





Magnetic Sensor



2010-2011: LBS expected to propel compass into the mainstream market

- Telecom carriers and application developers are pushing hard to develop Location-based or augmented reality services
  - *Ex NTT Docomo "auto-GPS" service started in Winter 09 in Japan → provides location service depending on the user's position and heading*
- Leading smart phone providers all have plans to introduced magnetometer-featured phones in 2010:
  - Google Nexus One; Nokia E72, Thresher , 5530 XpressMusic; LG GW990, HTC Hero, Tatoo, Bravo; Motorola Calgary; i-mate 810-F;Samsung B2700

2009: Nokia N97 & Apple iPhone 3GS

- AKM gained design wins for those high-volume selling cell phones
- T-Mobile G1 model in USA (fall 2008) has adopted a 3M + 3A solution

2004-2007: digital compass integrate in many Japanese handset platforms

First navigation services in Japan

2006–2012 年全球面向手机的惯性与磁性传感器市场预测

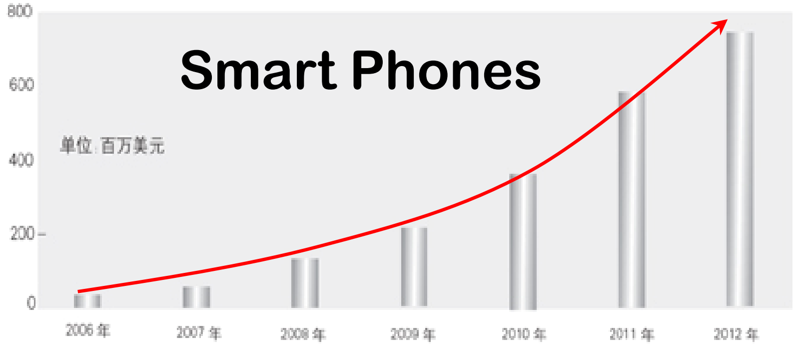
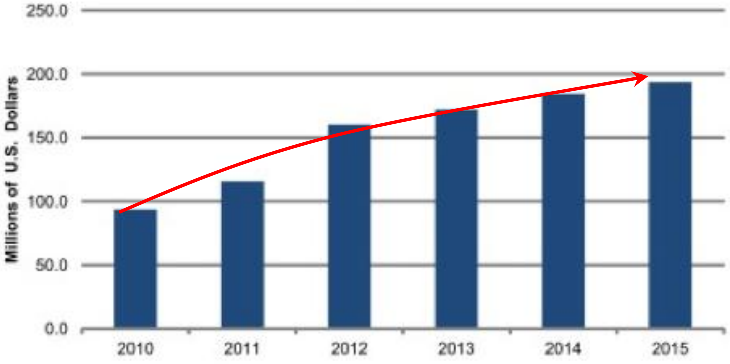


Figure 1: **Worldwide Revenue Forecast for Magnetic Sensors in Automotive Motors (Millions of U.S. Dollars)**



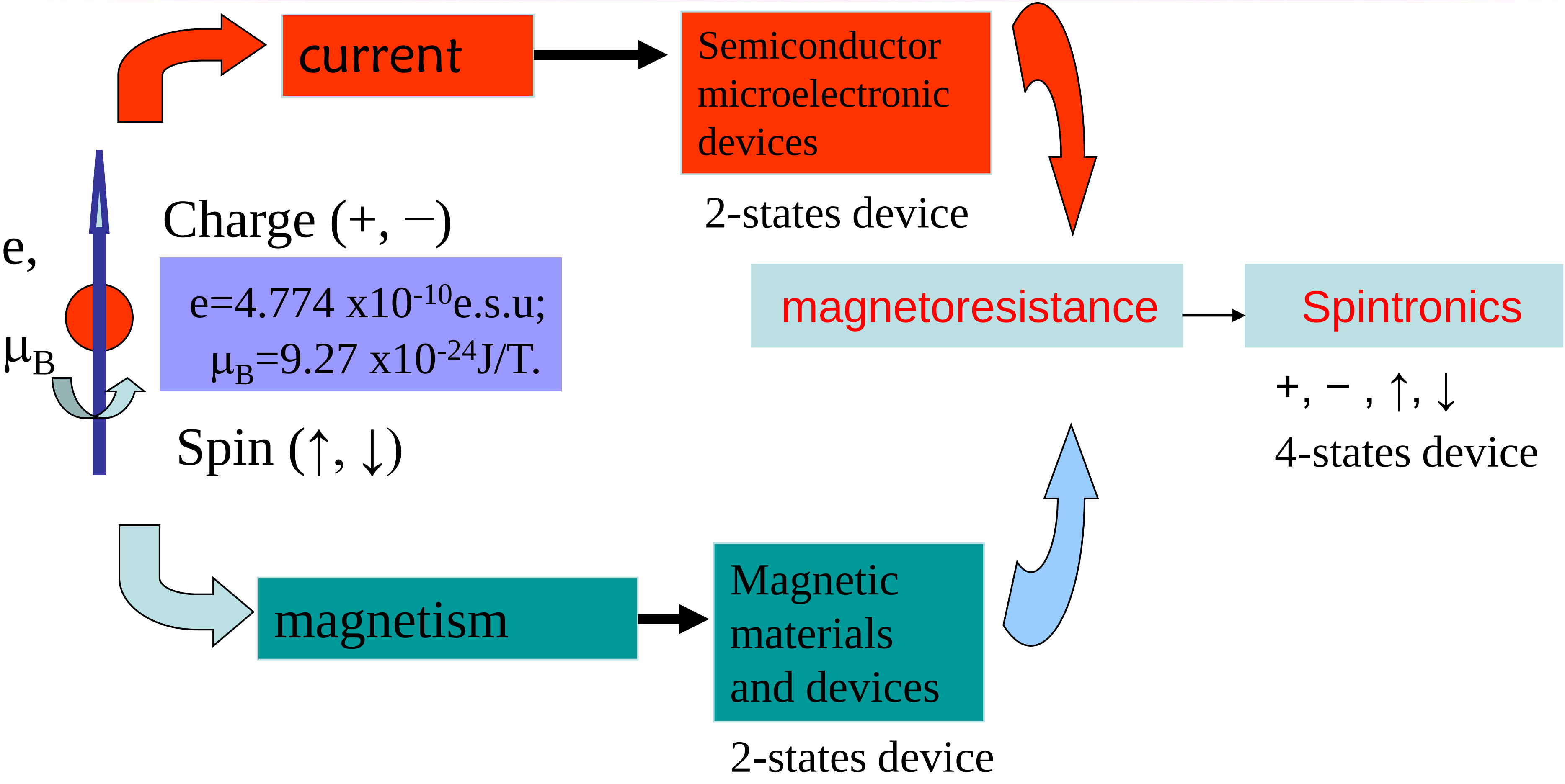
Source: IHS iSuppli Research, November 2011

Electronic compass、speed monitor、magnetic location

巨磁阻传感器的应用

电流探测、位置探测、转速测量、磁卡读头、磁罗盘、GPS应用、验钞机、接近开关、无人地面传感器、探雷、导弹导航、海洋矿物探测、陆上车辆和水下不明物如潜艇等的监控和探测等。

Spintronics



current

Semiconductor microelectronic devices

2-states device

e,

μ_B

Charge (+, −)

$e=4.774\ x10^{-10}$ e.s.u;
$\mu_B=9.27\ x10^{-24}$ J/T.

Spin (↑, ↓)

magnetoresistance

Spintronics

+, − , ↑, ↓

4-states device

magnetism

Magnetic materials and devices

2-states device

magnetoresistance (MR)

MR=[R(H)-R(0)]/R(0) %

Spintronics (spin electronics)

- Spintronics is the next generation technology utilizing electron spins to perform operations previously associated with electron charges.
- The advantages of spin manipulation compared with charge manipulation are
  - lower power consumption
  - faster processing speed
  - non-volatility
  - longer spin coherence time or length.

Spintronic Materials

- **Metal based spintronic materials （spin）**
  - **GMR & TMR， have been widely used**
  - **Applications: magnetic sensor, magnetic readhead, magnetic tunnel junction (MTJ) devices and magnetic random access memory (MRAM)**
  - **GMR&TMR 器件要用稀土材料，而稀土材料很难获得，找一种不需要稀土材料的MR 材料就非常迫切！**
- **Semiconductor based spintronic materials （charge + spin）**
  - **based on dilute ferromagnetism in transitional metal doped semiconductor, such as GaMnAs and ZnCoO, succeeded in low temperature**
  - **Applications: spin-FET, spin-LED**
- **Molecular spintronic materials**

mainly use organic materials

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     - 对称电极结构的磁电阻
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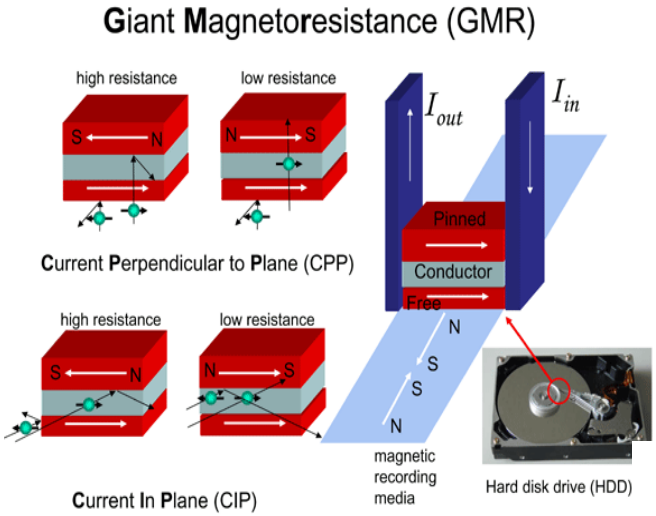
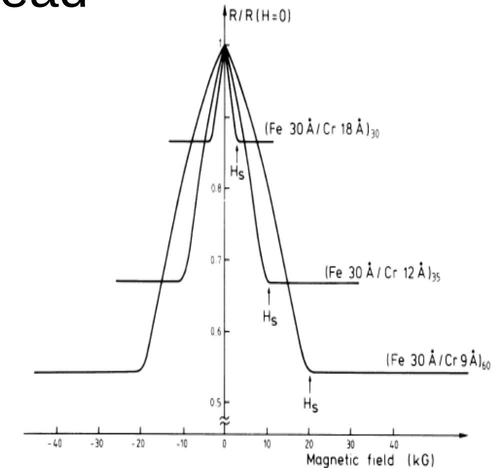
MR in magnetic materials

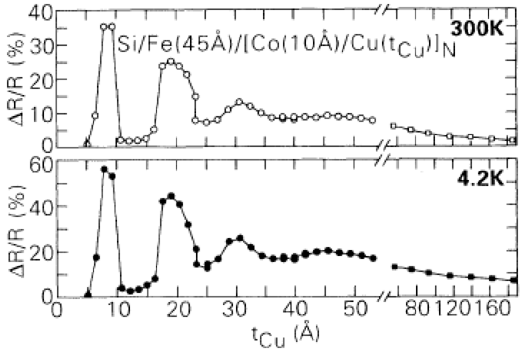
- Giant magnetoresistance (GMR)
- Tunneling magnetoresistance (TMR)
- Colossal Magnetoresistance (CMR)

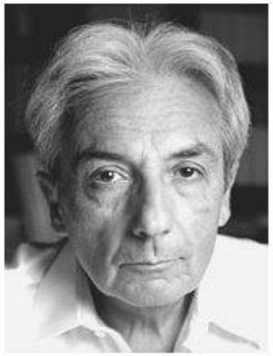
GMR: spin dependent scattering

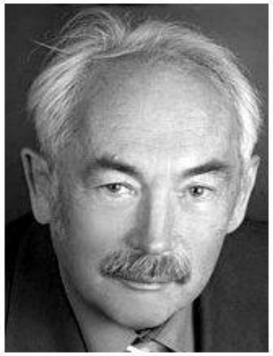
GMR was found in 1988, MR<0, MR~a few tens %, used for making magnetic head











Discovery of GMR won 2007 Nobel Prize in Physics

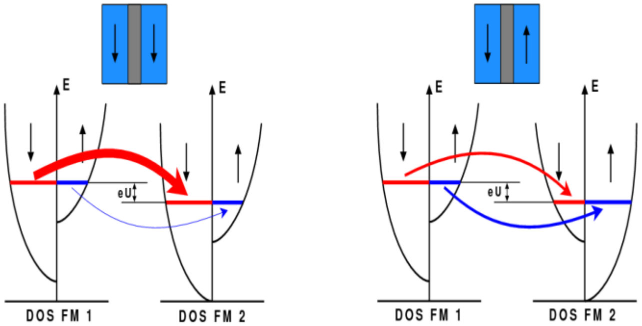
Baibich, Phys. Rev. Lett, 1988

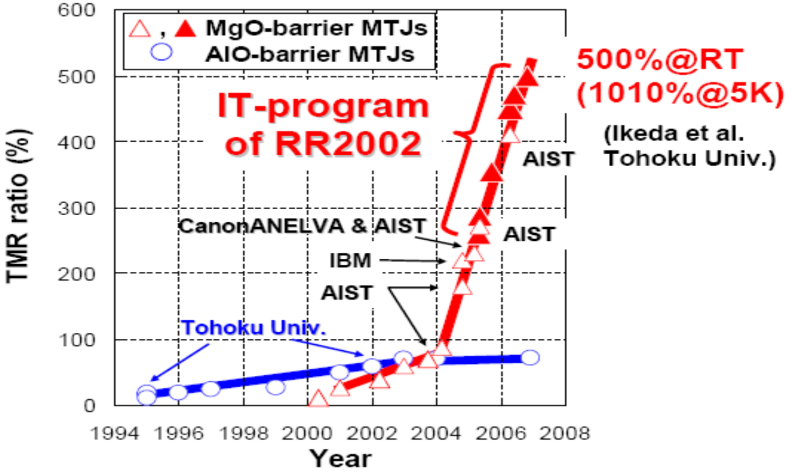
http://www.nims.go.jp/apfim/GMR.html

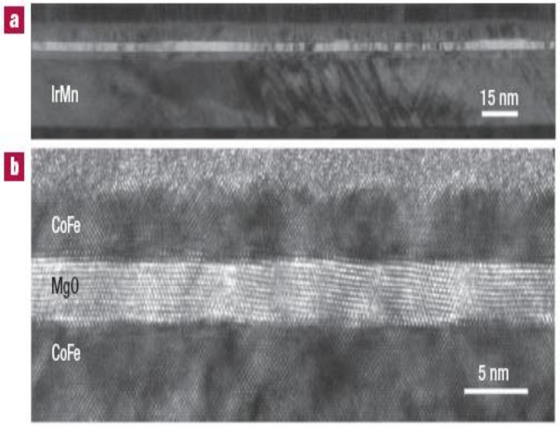
Parkin, Phys. Rev. Lett, 1991.

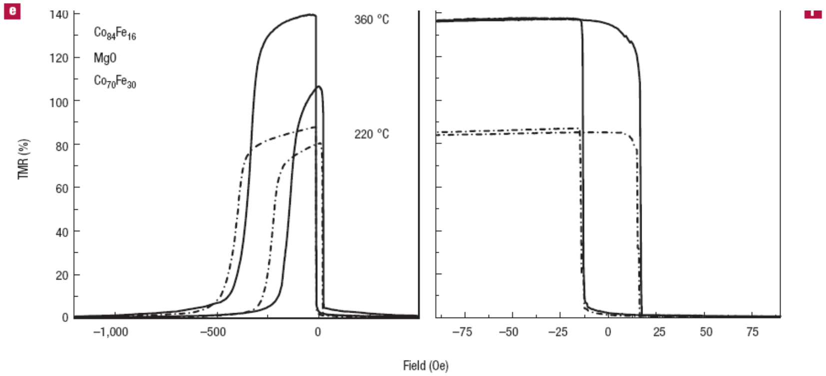
TMR: spin dependent tunneling

TMR: MR<0, MR~ a few hundred %, since 2005 it replaced GMR for making magnetic head







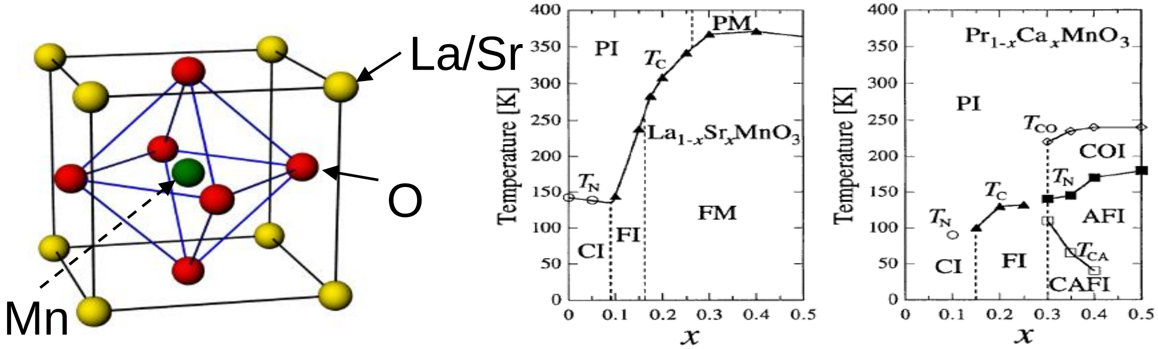


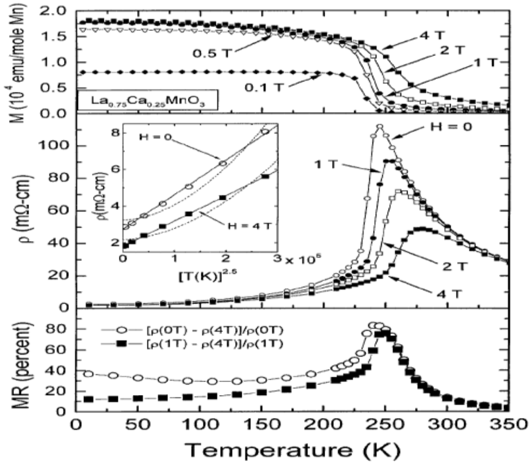
Ikeda et al has achieved 600% TMR at room temperature with MgO barrier.

T. Miyazak, JST-DFG Workshop, 2008. Parkin, Nat. Mat. 2004.

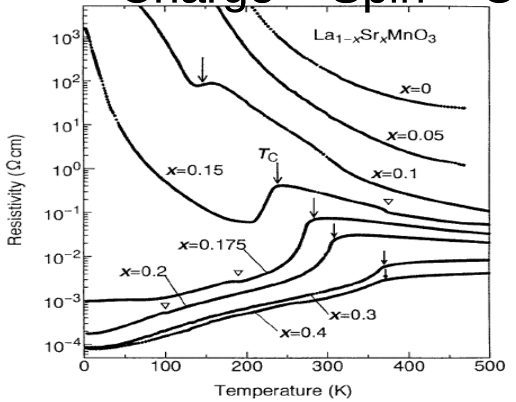
CMR: spin-orbit-charge interplay

CMR: found in 1989, MR<0**,** MR~100%,
has not found application because it need large H and its MR appeared in low temperature





Charge + Spin + Orbit

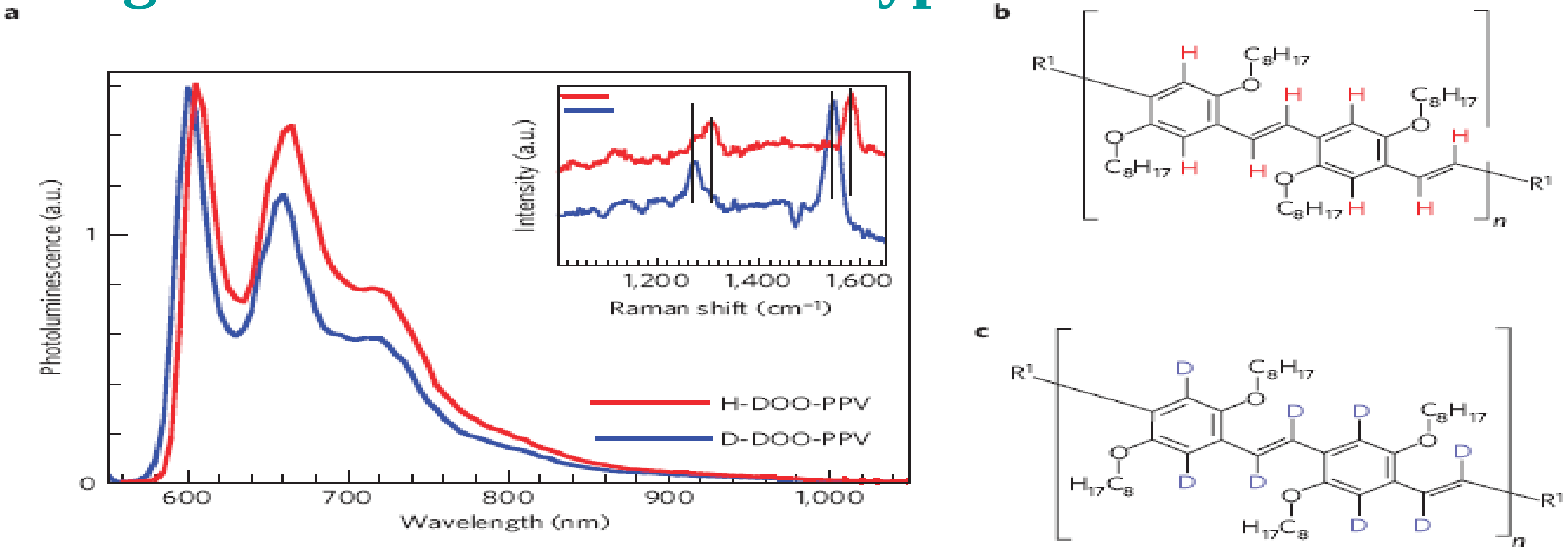


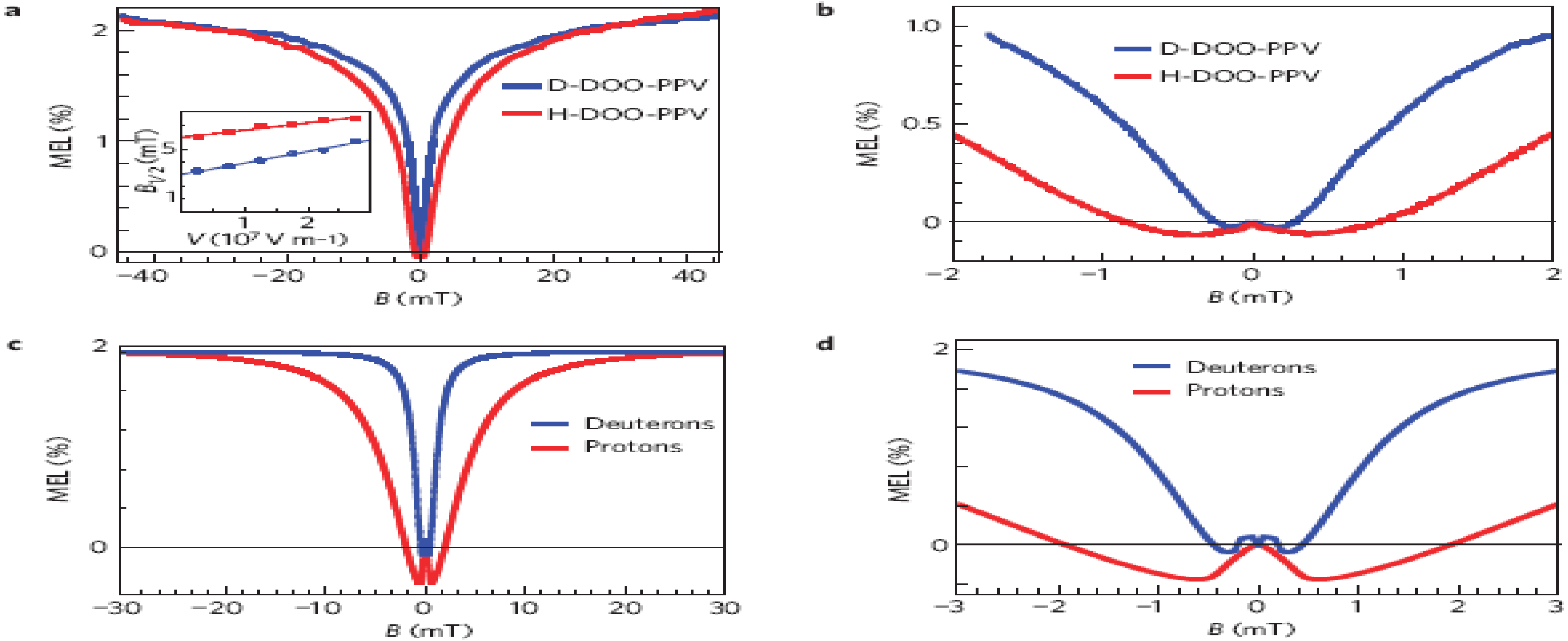
Ramirez, J. Phys.: Condens. Matter. 1997.

MR in non-magnetic materials

- MR in Organic materials
- MR in Graphene/carbon nanotubes
- Inhomogeneous MR (IMR)

Organic MR: related with Hyperfine interaction?

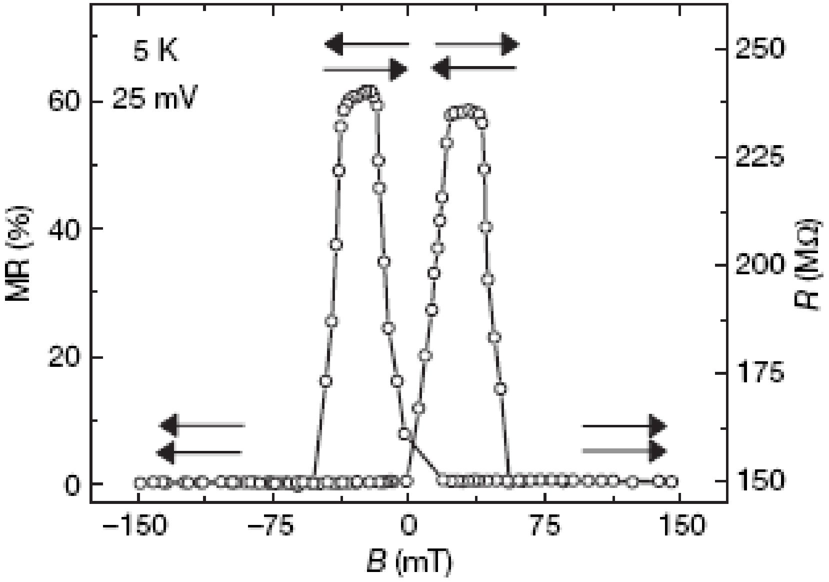


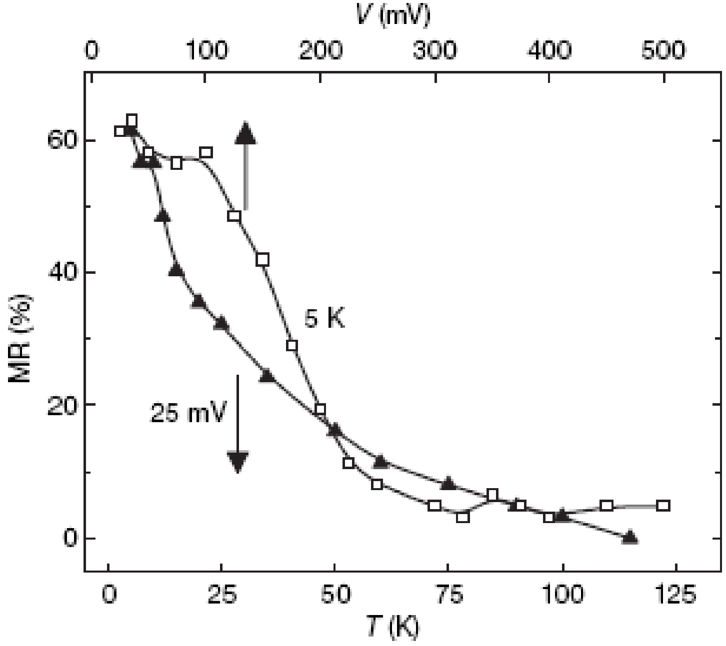


Xiong & Steitz, Nature 2004; Nguyen, Nat. Mat, 2010.

MR of carbon nanotubes

The MR of Carbon nanotube have been only observed in the low temperature. MR=61% at 5K， and it disappeared at 120K.

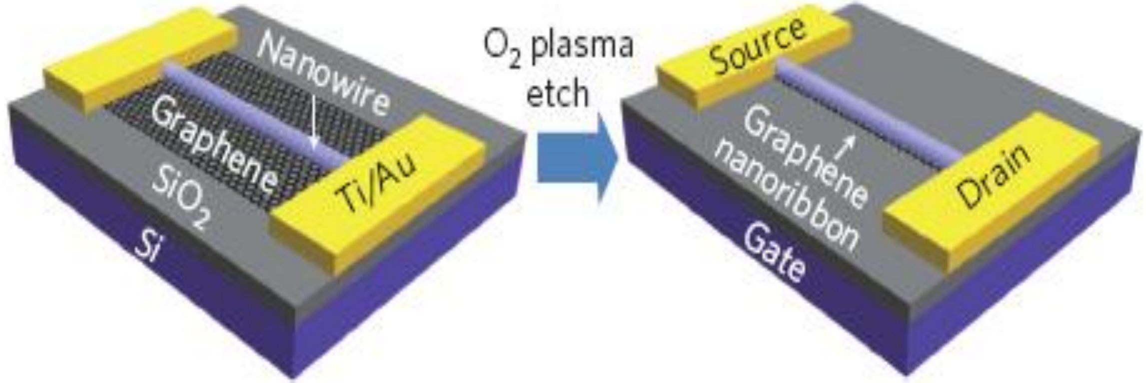


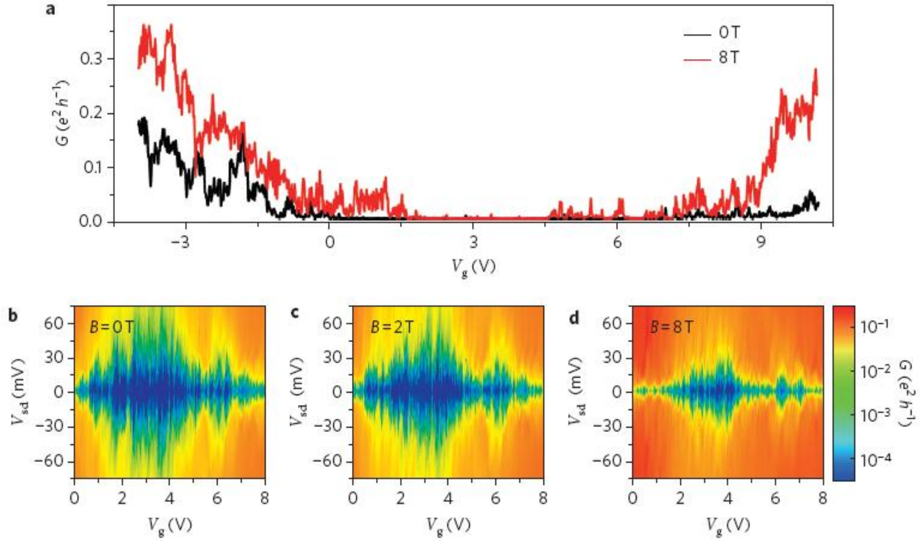


L.E. Hueso et al NATURE 445, 410 （2007)

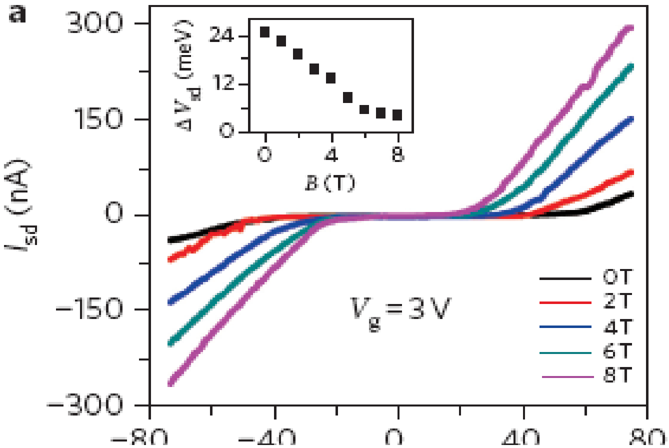
MR in Graphene Nanoribbon: quantum confinement

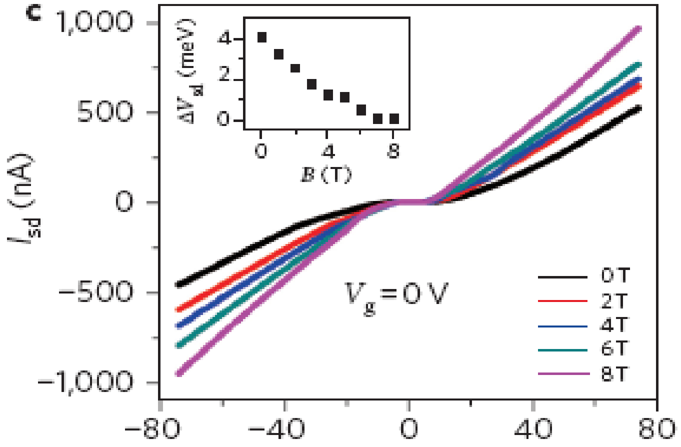
MR ~-100% at 1.6K and MR＝-50% at 285K

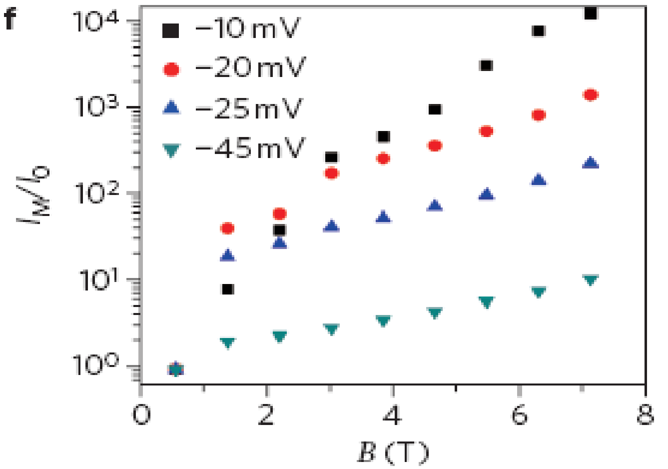




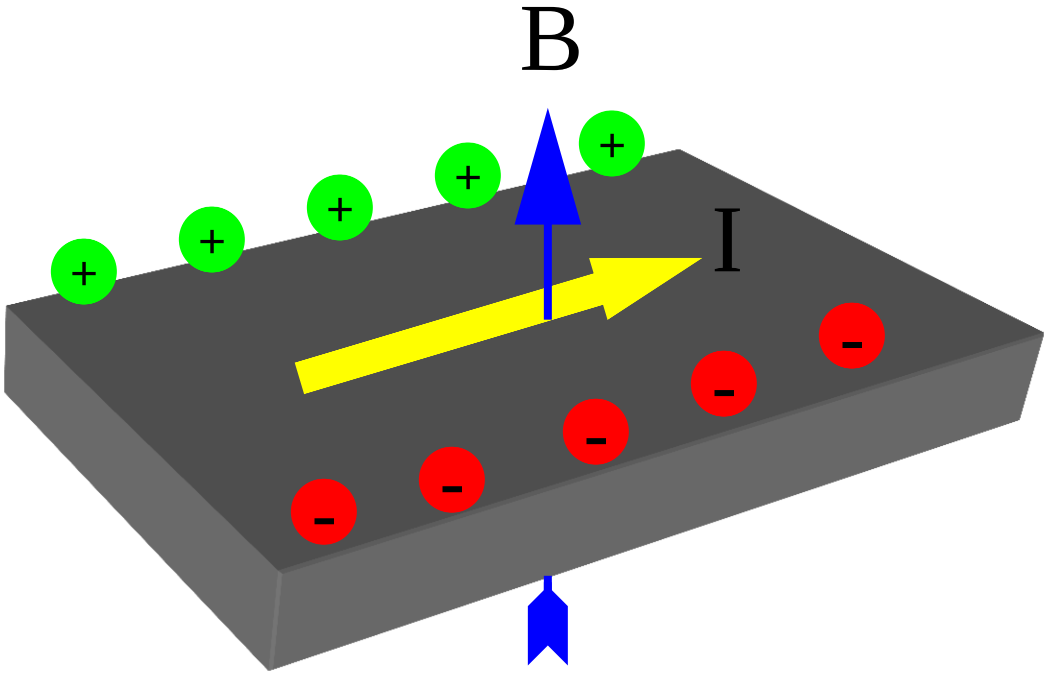
JW Bai et al, Nat. Nanotech. 5 (2010) 655.







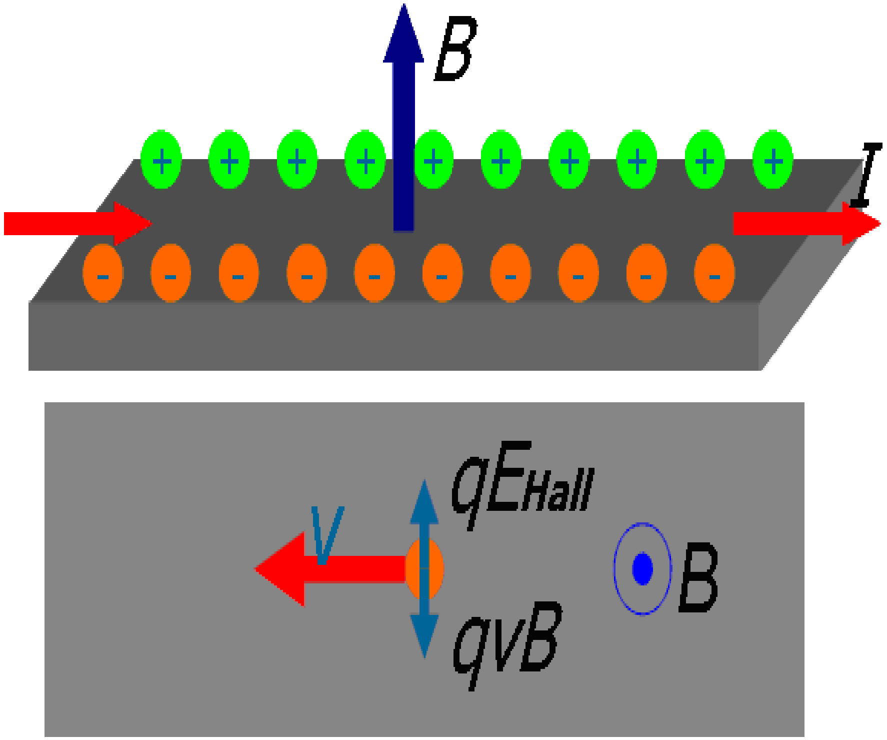
Inhomogeneous MR (IMR)



Origin: Lorentz Force

For a ideal crystal (not exist) with all carriers having the same effective mass m* and **carrier scattering time** τ, would resistance measured in four-electrode method be changed under magnetic field B?

Ordinary MR: orbit related



No MR would be detected in a ideal crystal in that measurement setup!!!

Homogenous
Large L/W

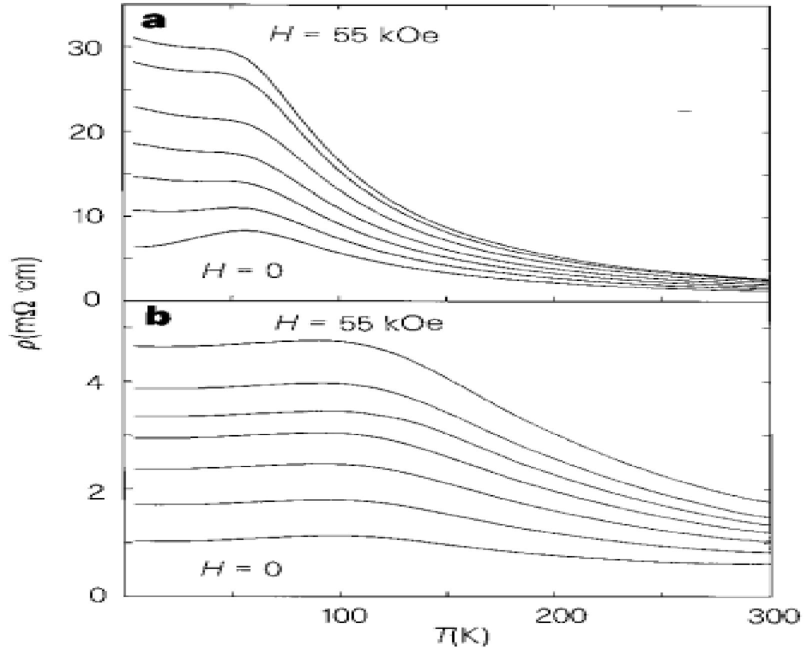
→

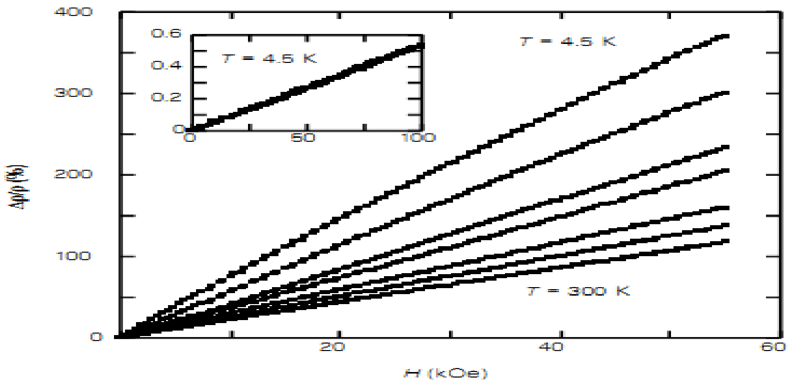
Lorentz Force
=Hall Force

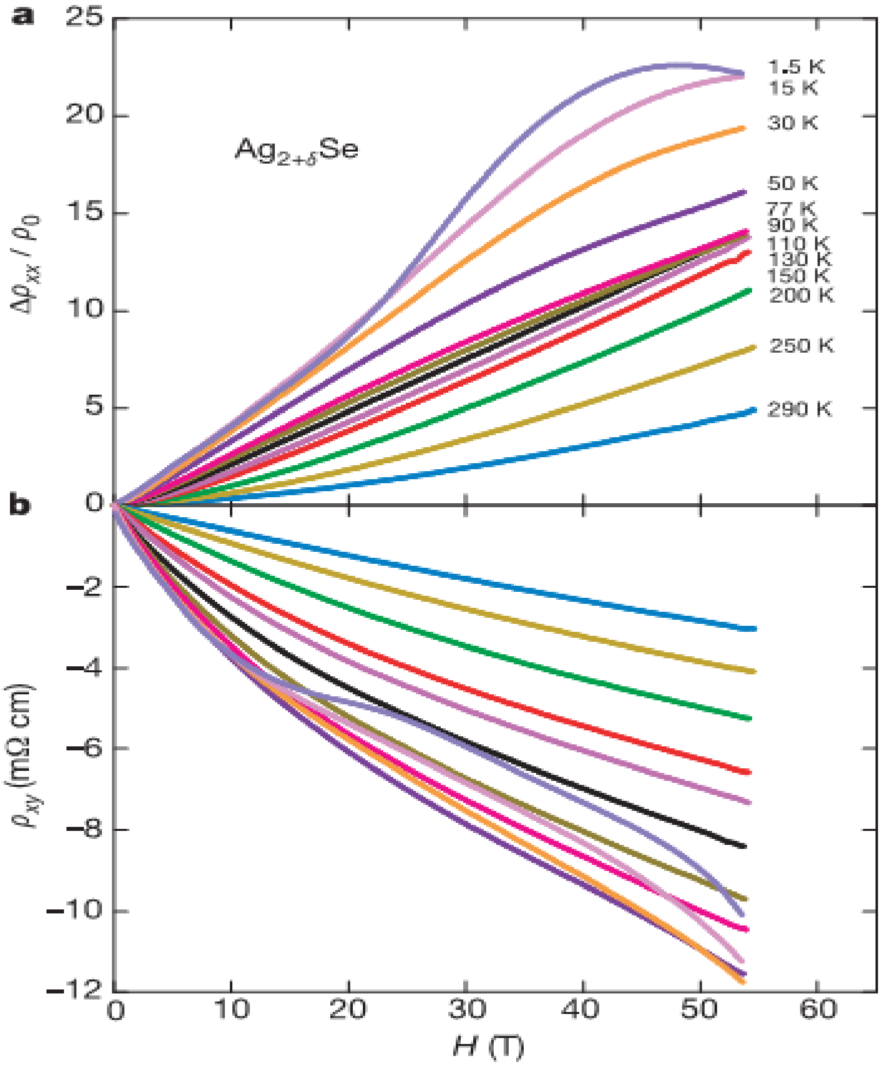
→

MR = 0 %

Doped silver chalcogenides



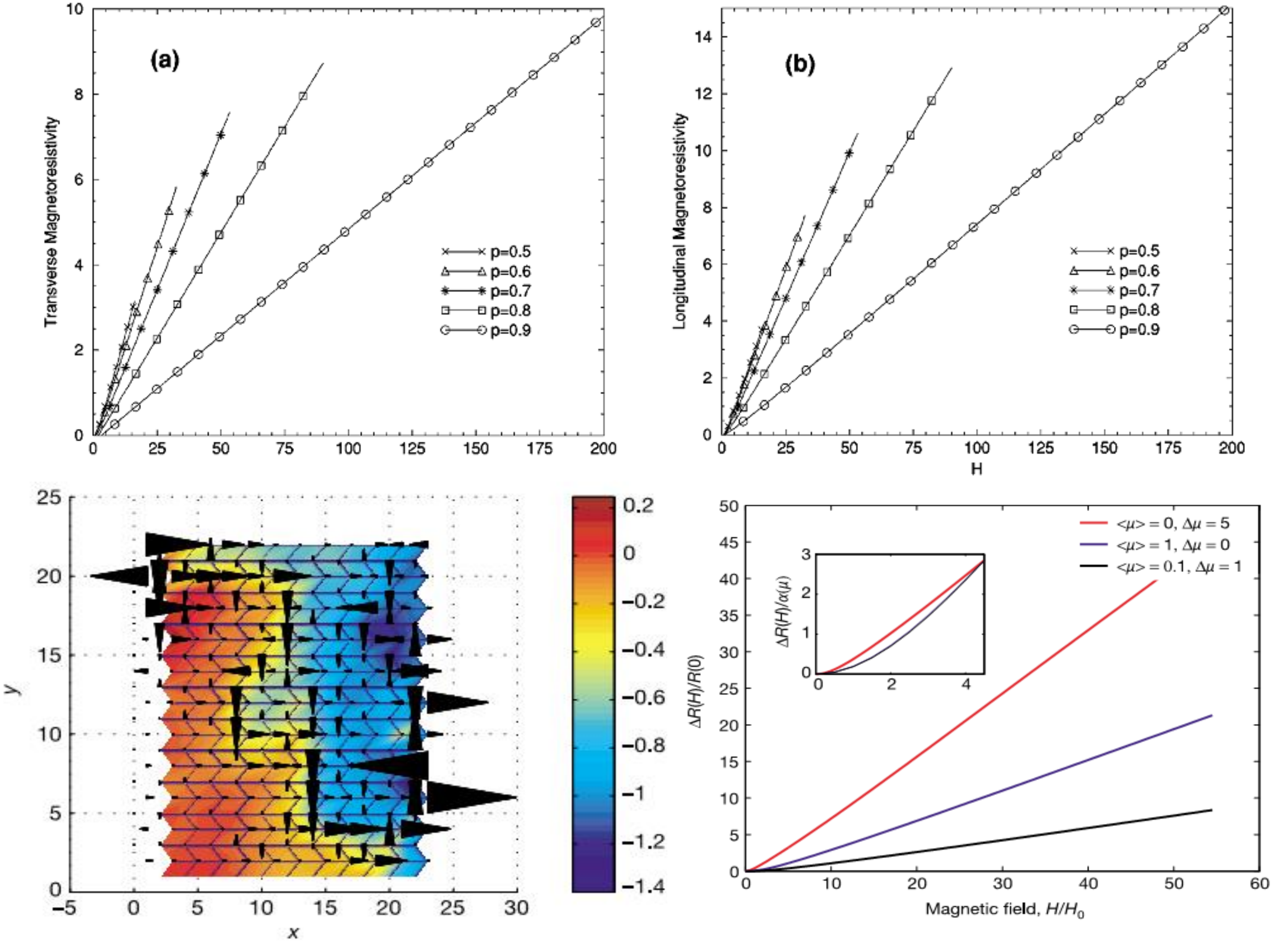




Xu, Nature, 1997;

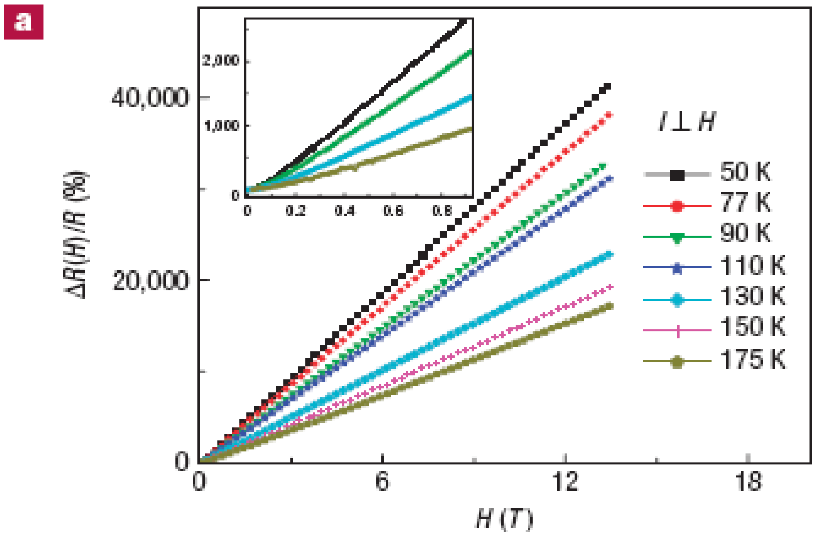
Rosenbaum, Nature, 2002.

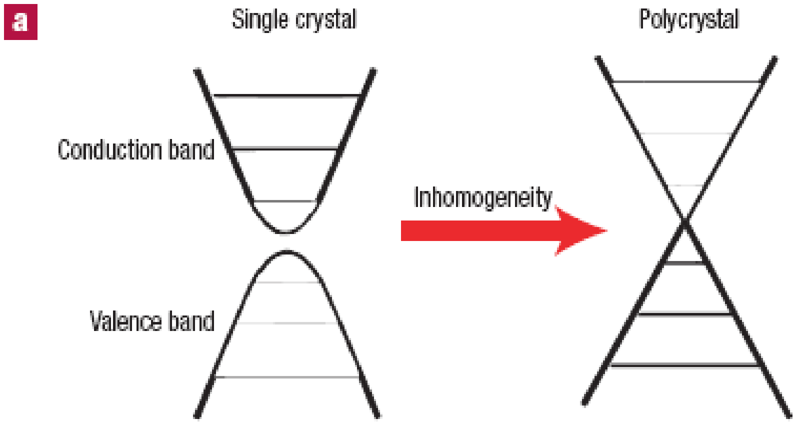
Littlewood proposed a theories: $\mathrm{MR}\propto[\mu , \Delta\mu]_{max}$ when n=p or $\Delta \mu$ maximum, IMR enhanced

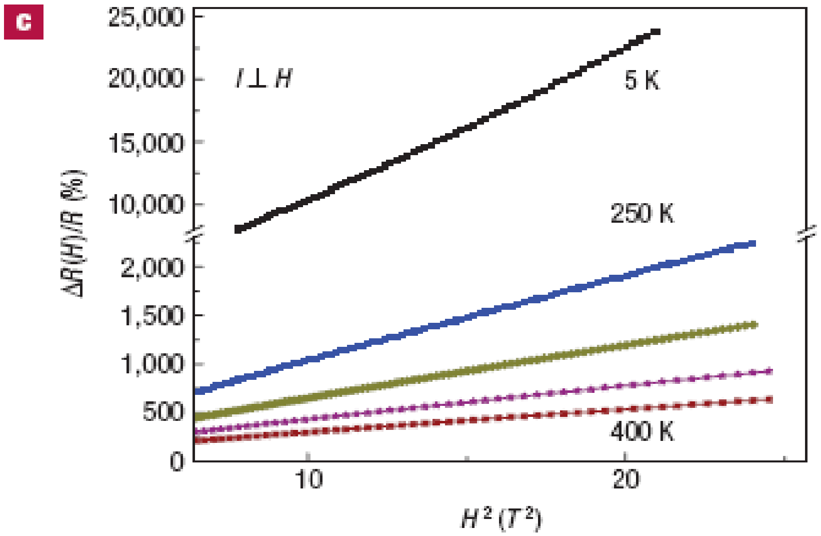


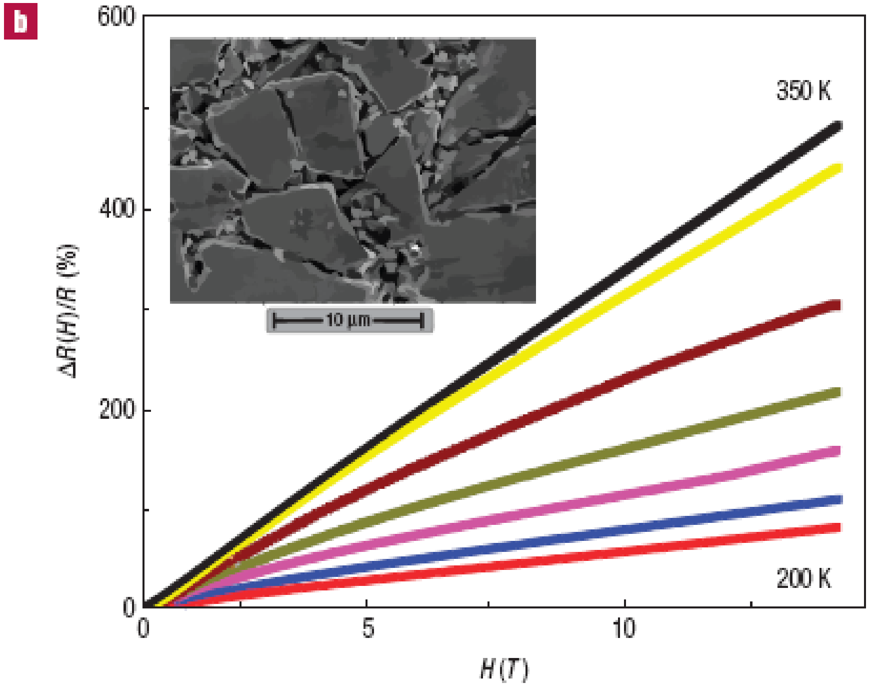
Parish & Littlewood, Nature, 2003

InSb linear MR



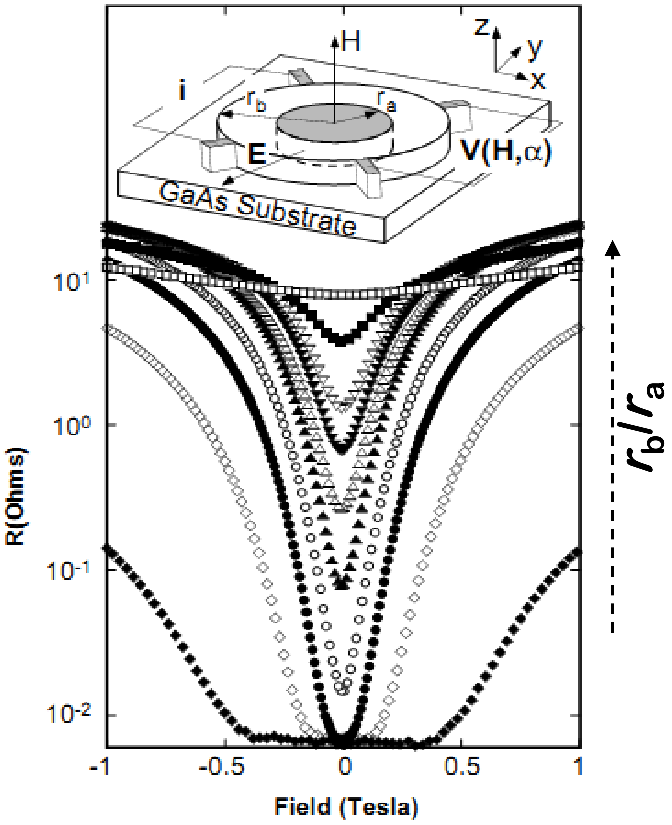


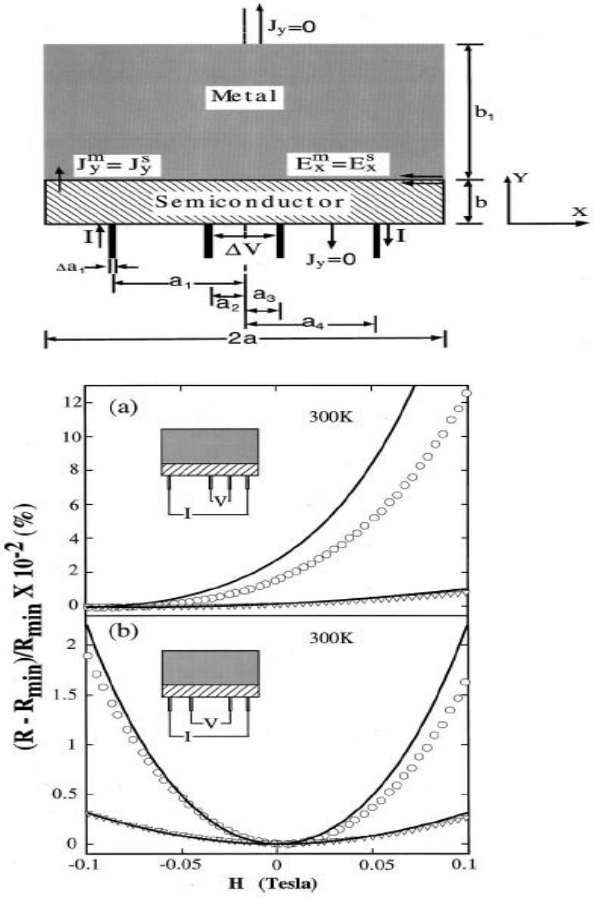




Hu, Nat. Mat. 2008.

Geometrical Enhancement





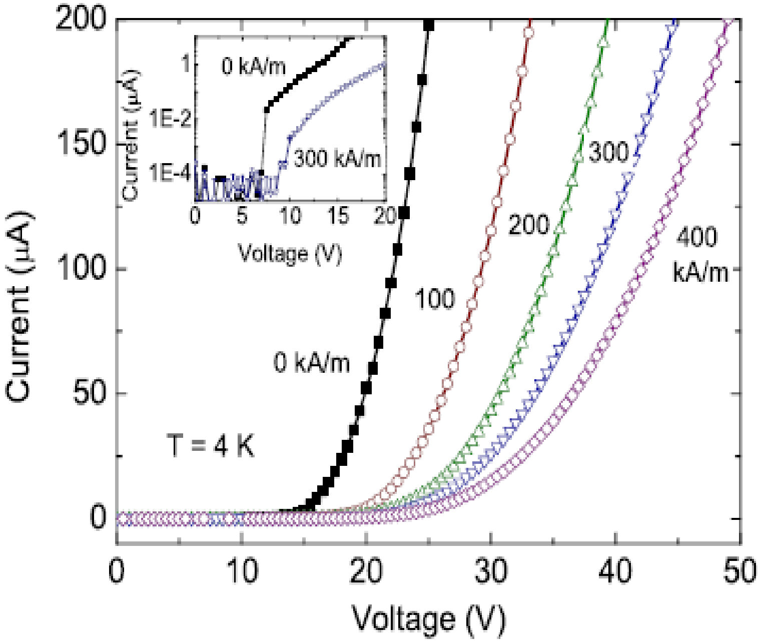
Corbino Disk: R_b/R_a ratio

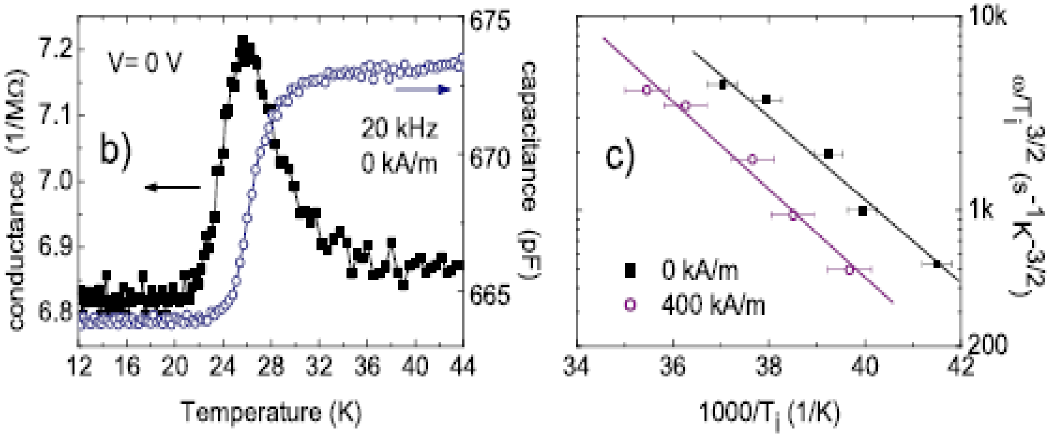
Solin, Science, 2000.

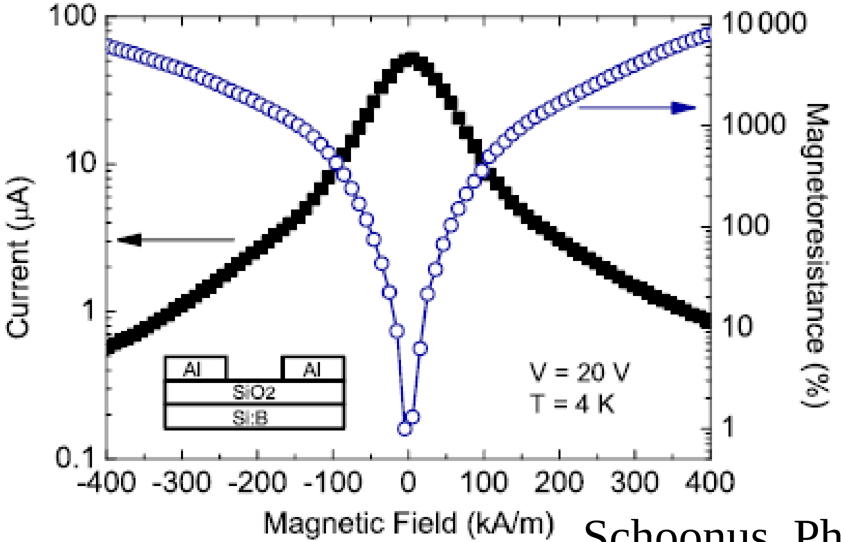
Spacing between electrodes

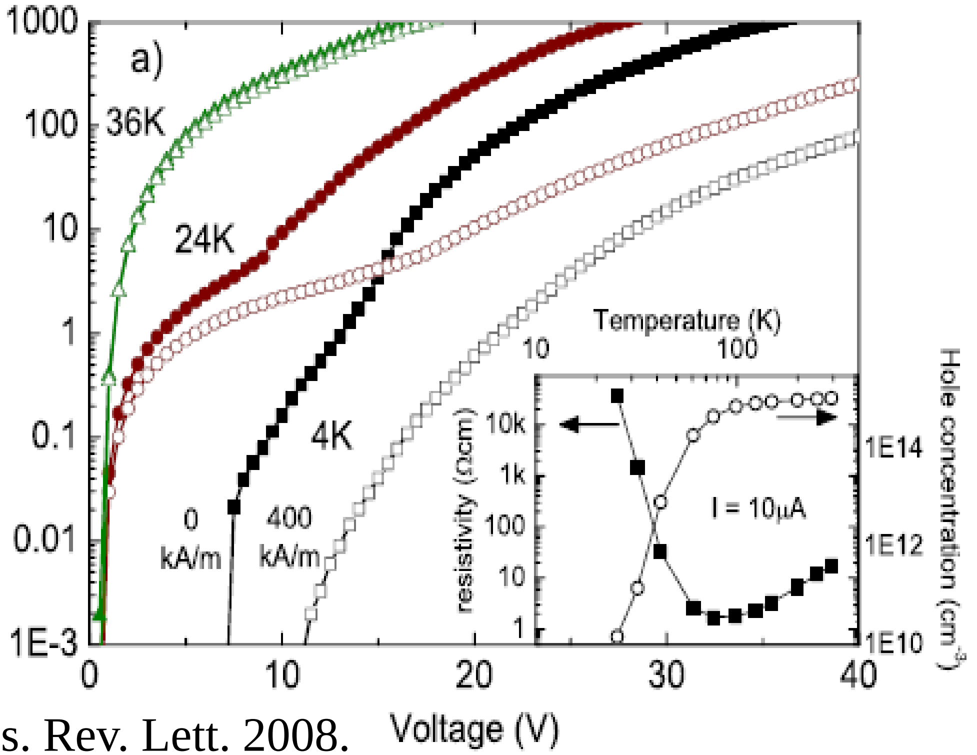
Solin, Appl. Phys. Lett. 2001.

Silicon MR at low temperature: related with wave shrinkage?



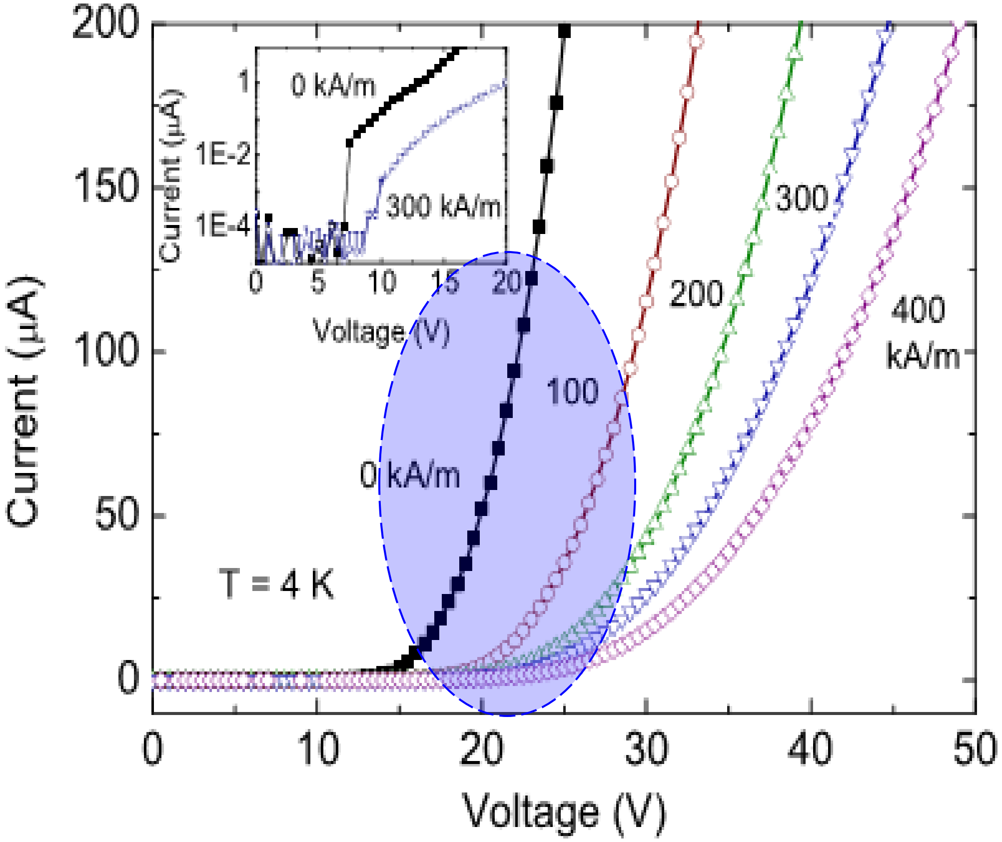






Schoonus, Phys. Rev. Lett. 2008.

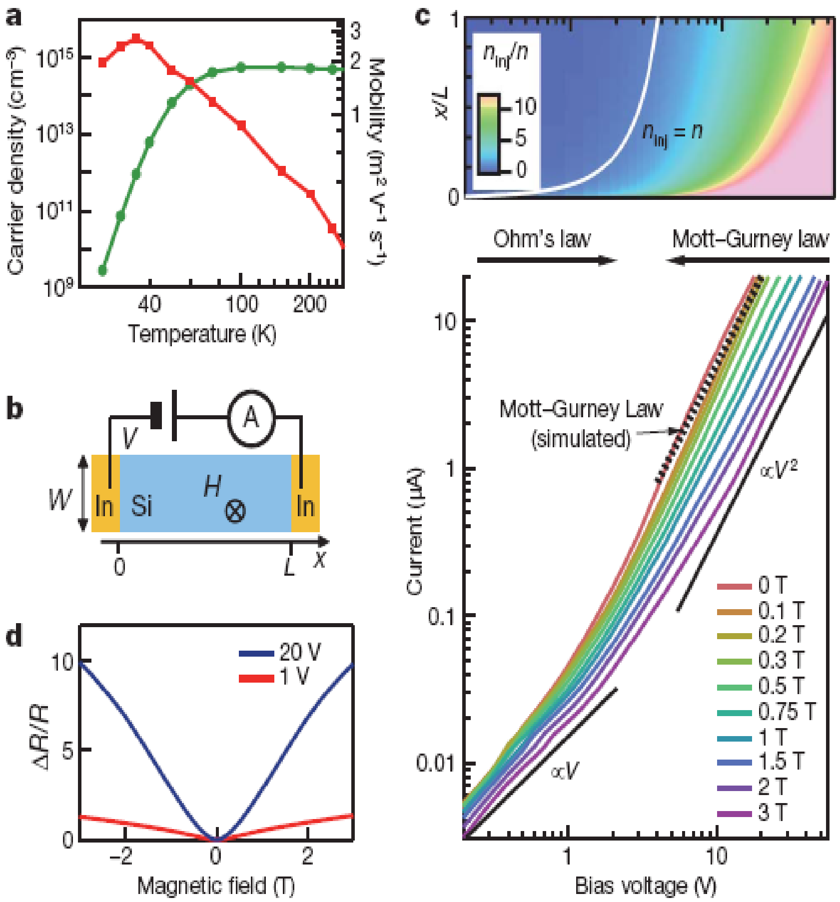
Schoonus’ s Case

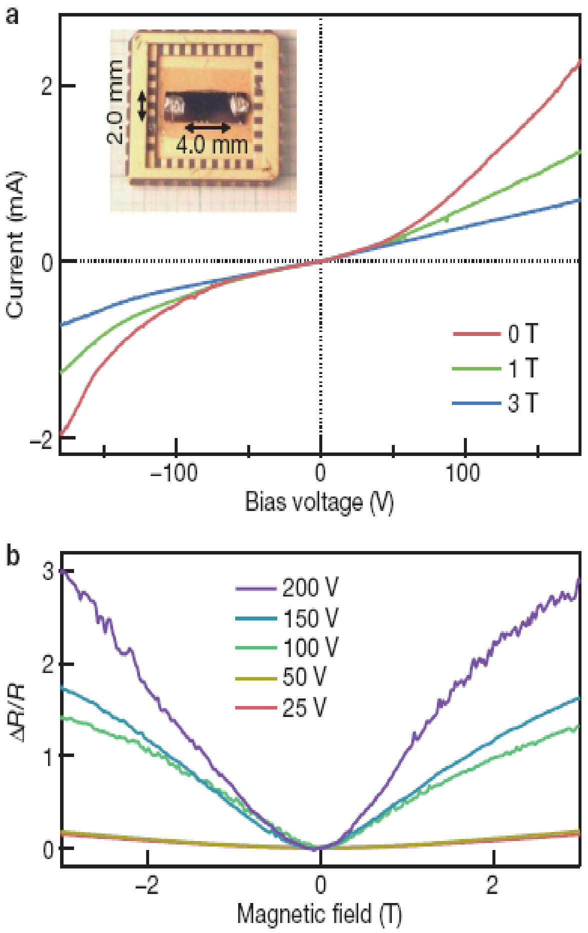


MRmax ← Avalanche Breakdown ← Breakdown voltage ← *V*/*B*

Silicon MR, related with SCLC

- A simple device based on a n-type Si between two In contacts shows a large positive MR of more than 1000% at 300K and 10000% at 25 K at H=3T and V=20V

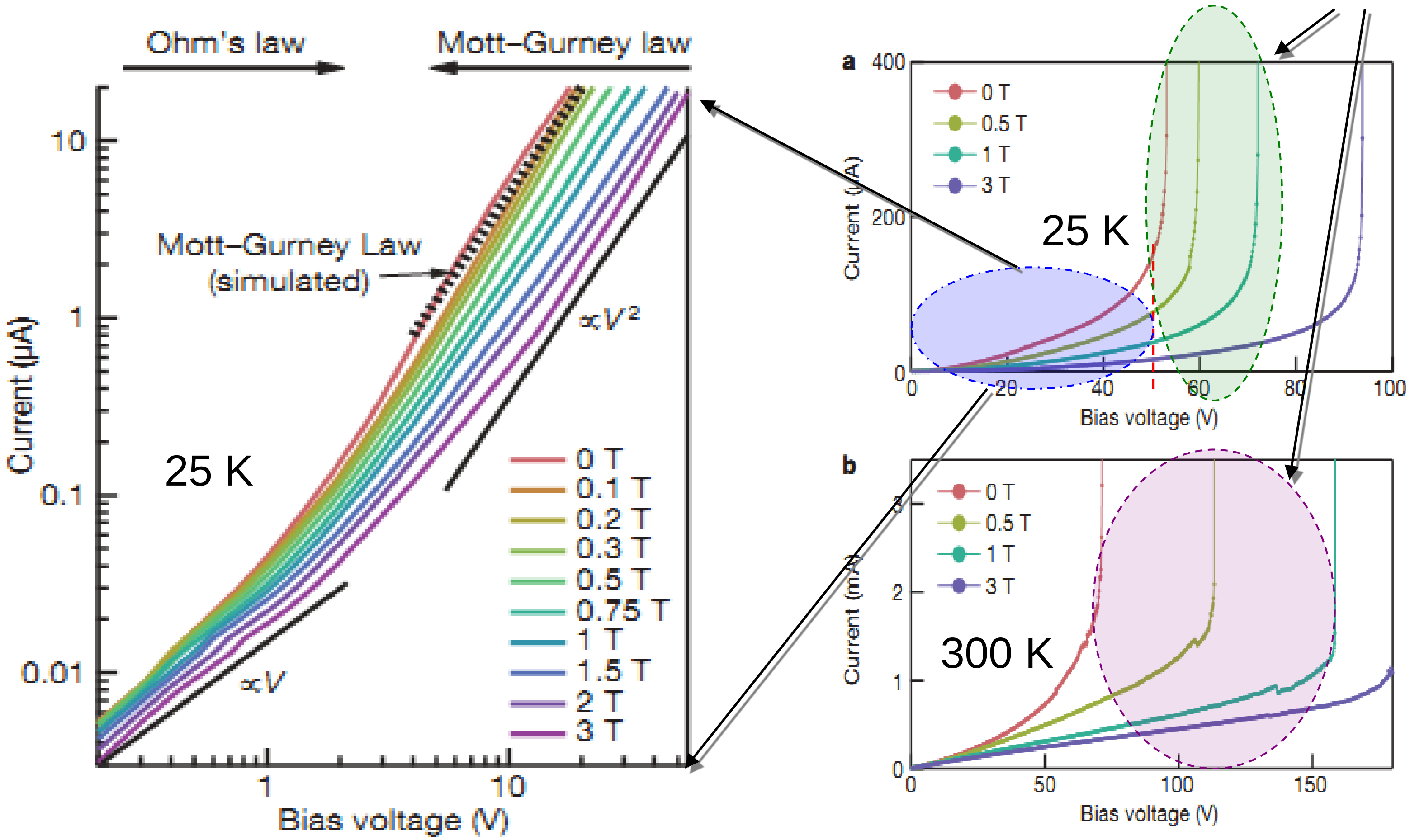




MP Delmo et al, Nature **457**, (2009) 1112

Delmo’s Case

MR max



研究动机

- 经济：做巨磁阻/隧穿磁阻材料需要使用稀土材料，而现在稀土材料是越来越“稀有”和贵重了，是国际竞争的战略性物资，

  人们需要寻找不用稀土材料的新型巨磁阻材料。

- 科学：自旋(磁性金属)→ 巨磁阻/隧穿磁阻（磁传感器的工作部分）

  电荷（半导体）=> 大磁阻?

  （普通磁阻（OMR)：1-2%）

  能否用半导体材料的电荷属性来获得大的磁阻？

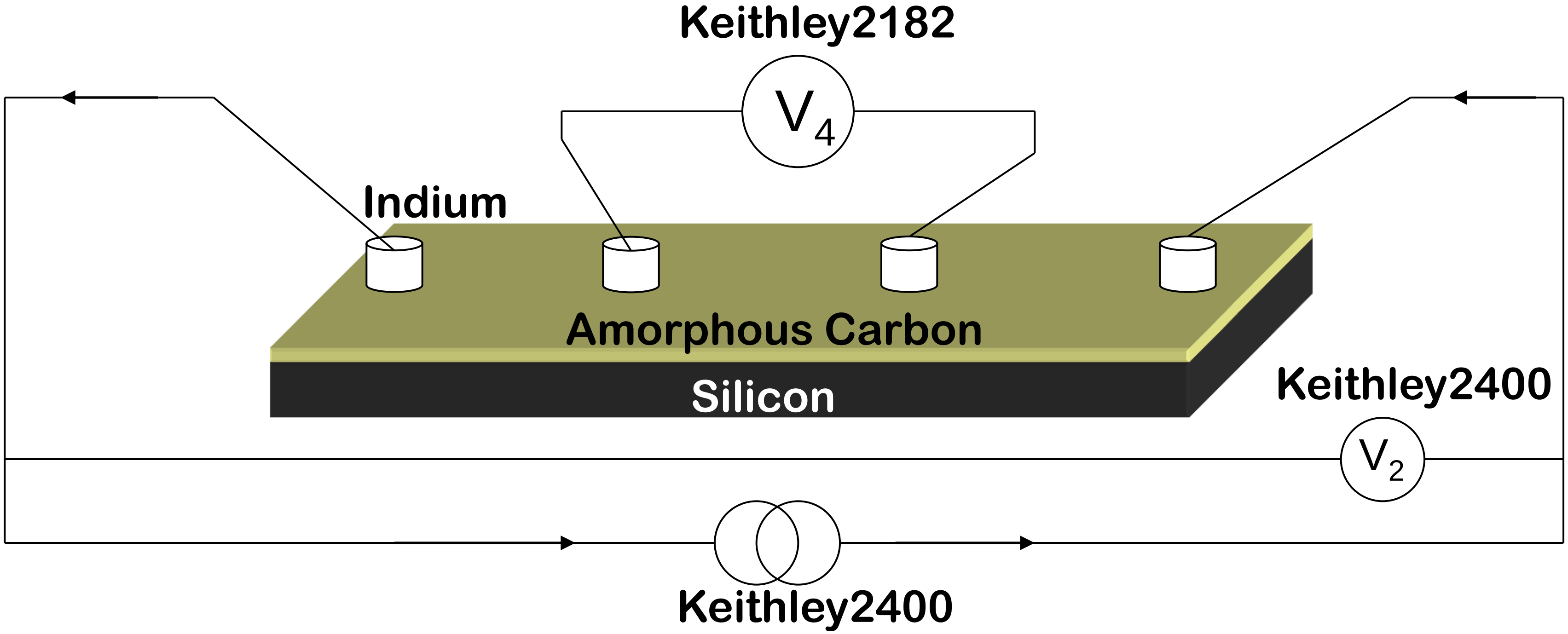
Outlines

1. 背景介绍
   1.1 磁电阻和自旋电子学
   1.2 各种磁电阻
2. 结果
   2.1 a-C/Si 异质结构的磁电阻
   2.2 硅的低温磁电阻
   2.3 硅的室温几何增强磁电阻
   对称电极结构的磁电阻
   非对称电极结构的磁电阻
3. 半导体几何增强磁电阻的优点和愿景

MR in a-C/Si heterojunctions

a-C/Si； Si orientation (100)， 0.5~1 Ωcm ， 10^{16}cm^{-3} doped with p ；

sp^2 ratio in a-C 70% ~ 80% ， graphite-like ， Eg = 0.4~0.8eV.



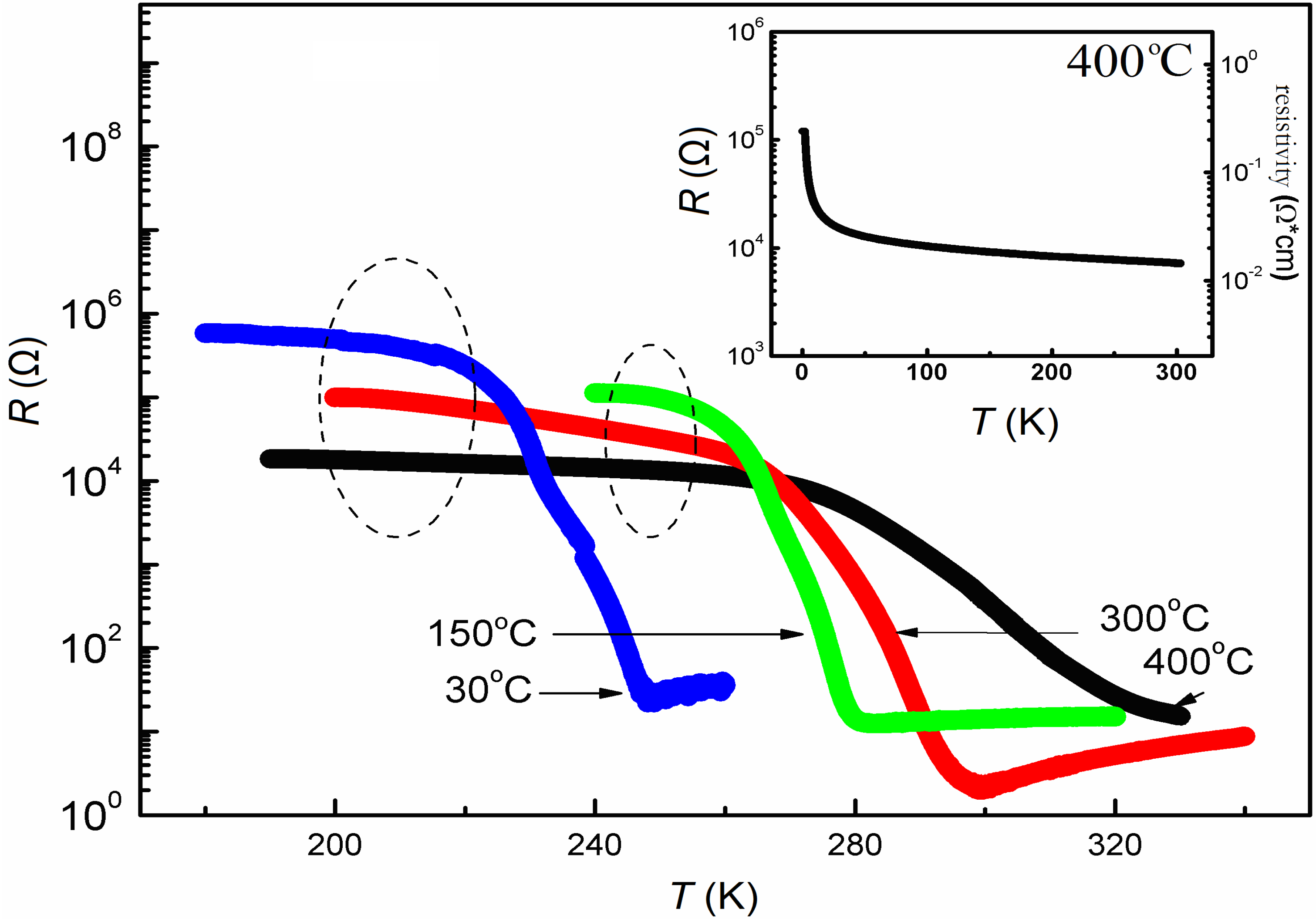
Research Methods

Film grown by Pulse Laser Deposition (PLD)

TEM、HRTEM、EELS、Raman to characterize structure of a-C

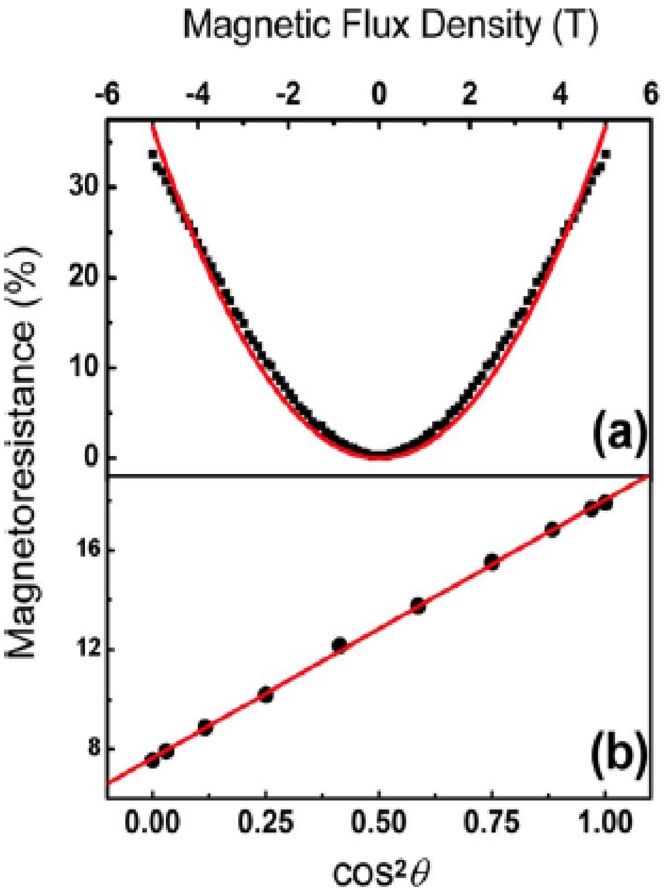
2-electrode and 4-electrode measurements with Keithley2400、2182 in MPMS or PPMS

Transport Properties of a-C/Si

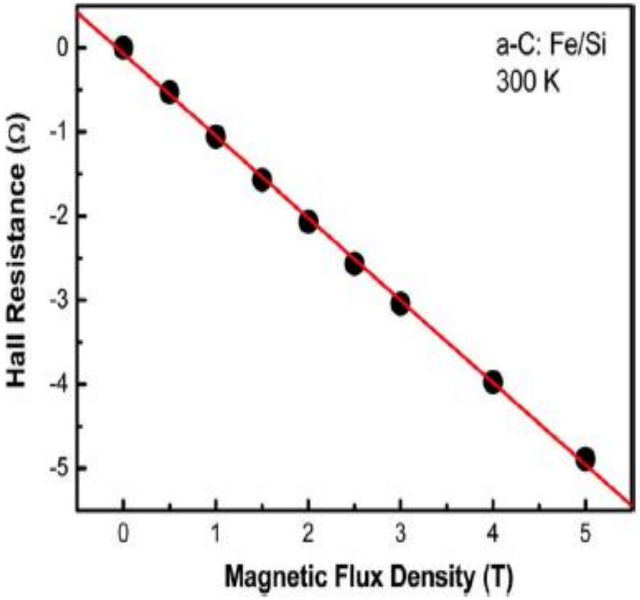


Channel Switching：low T current in a-C，High T current in Si

MR in a-C/Si



$$MR \propto \left(\mu B\cos\theta\right)^2$$



Electrons、Carrier Density 10^{16}cm^{-3} = Si Substrate → MR originated from OMR in Si

Wan C H, et al. IEEE Trans Magn, 2011, 47:2732-2734

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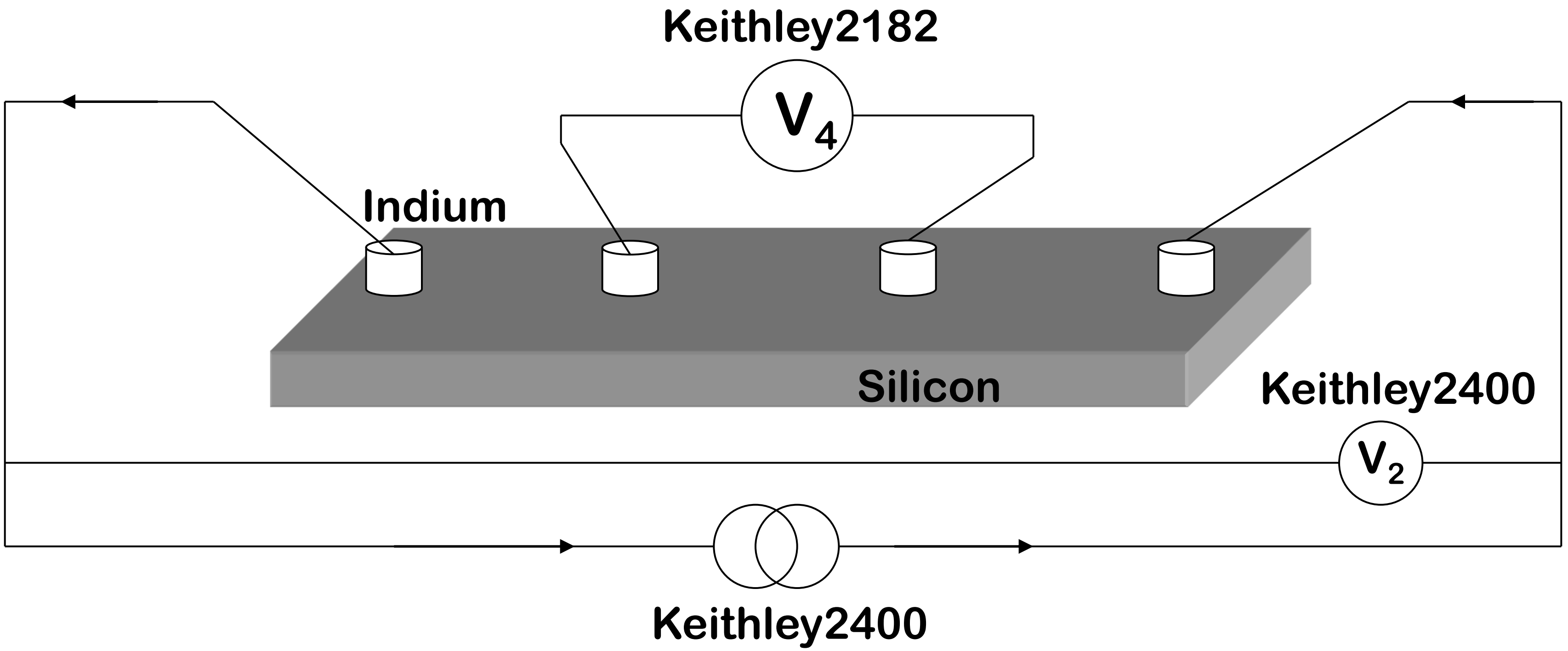
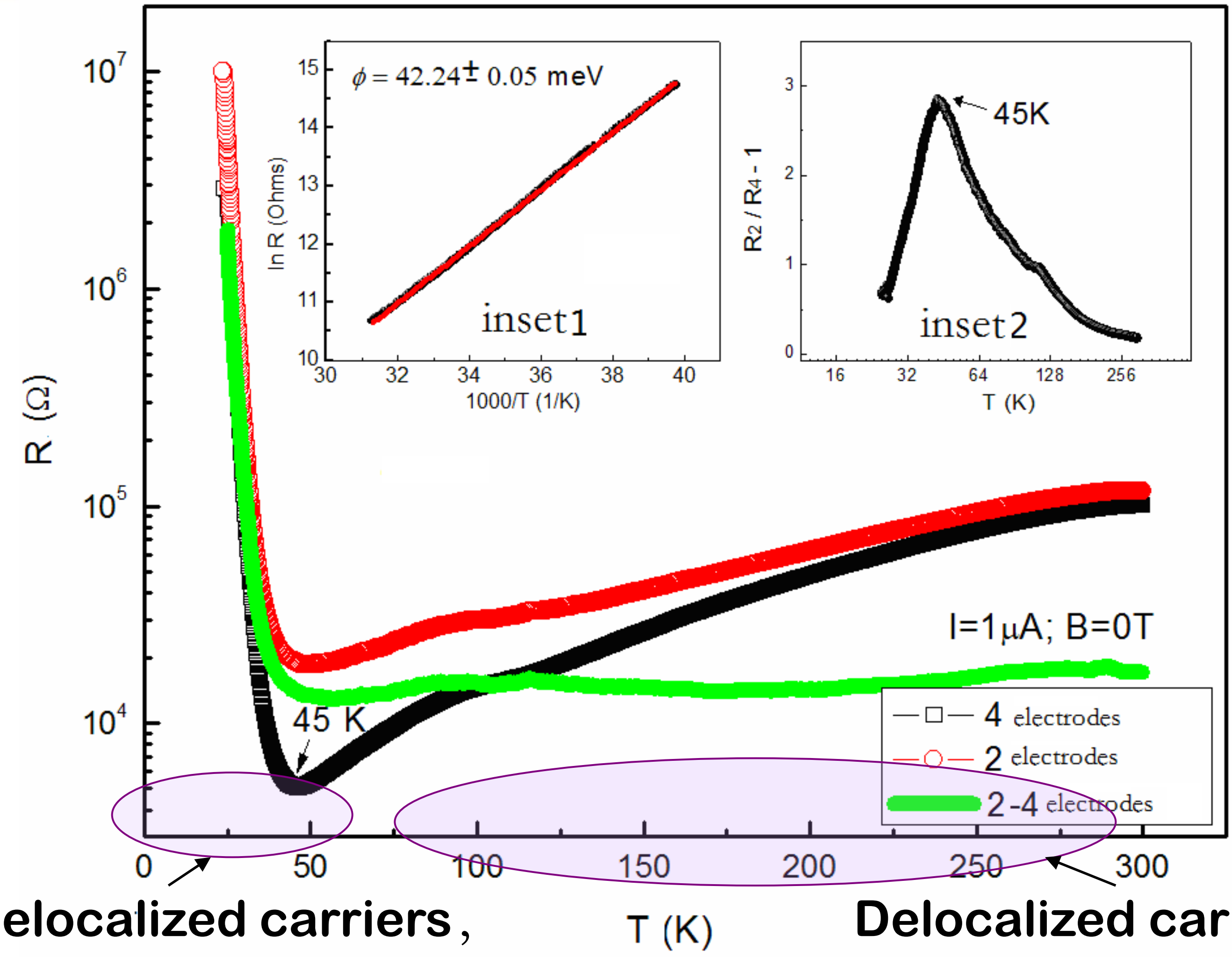
     对称电极结构的磁电阻
     非对称电极结构的磁电阻
   - 2.4 GaAs 和 Ge 的室温磁电阻
3. 半导体几何增强磁电阻的优点和愿景

Low temperature MR in silicon

Silicon orientation (100), 10^{12} cm^{-3} doped with P, resistivity 3000 Ωcm



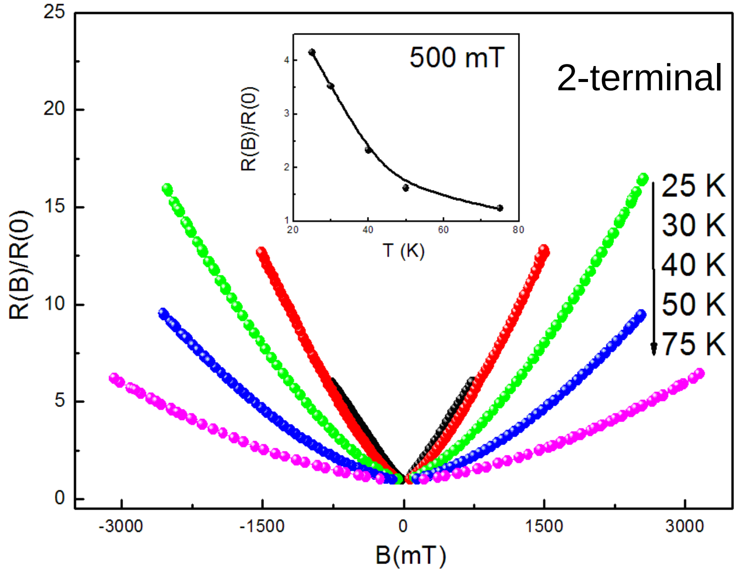
Electro-transport properties of Si

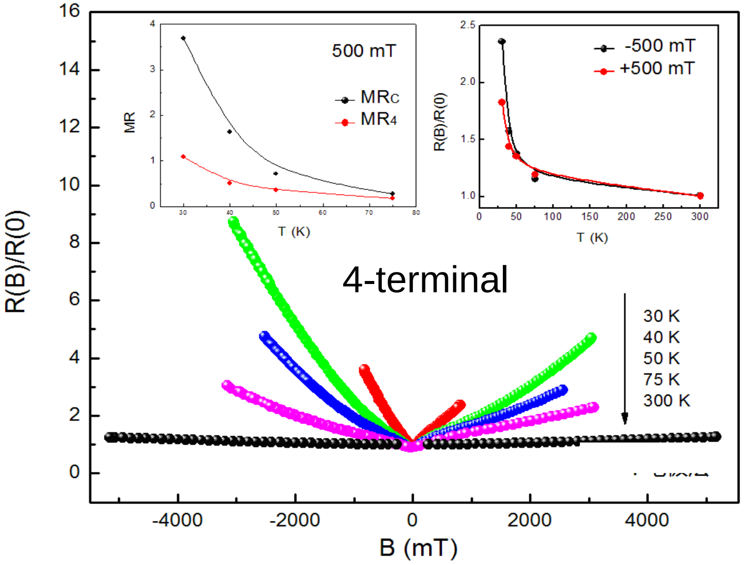


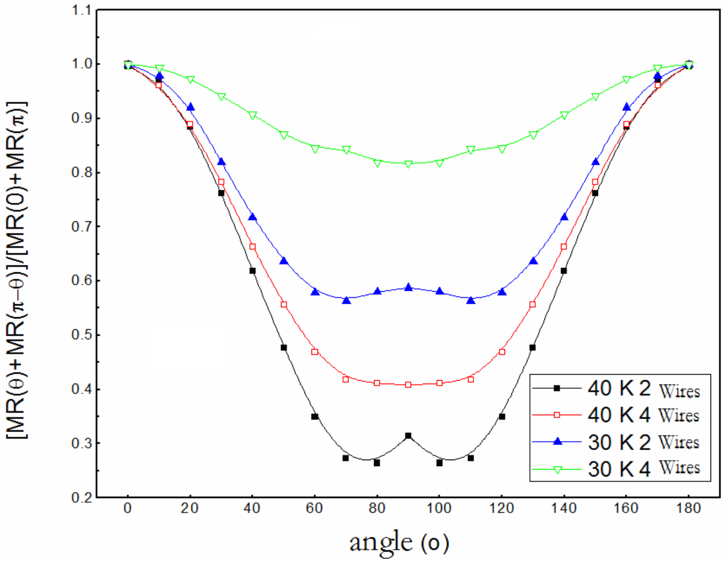
Delocalized carriers ,
R-T determined by carrier density ,
Carriers froze out from E_C

Delocalized carriers ,
R-T determined by mobility
Carriers thermo-activated

MR of silicon







1. **MR increased below 70K.**
2. **MR_2 is much larger than MR_4. (Different from Schoonus' s work (PRL))**

Outlines

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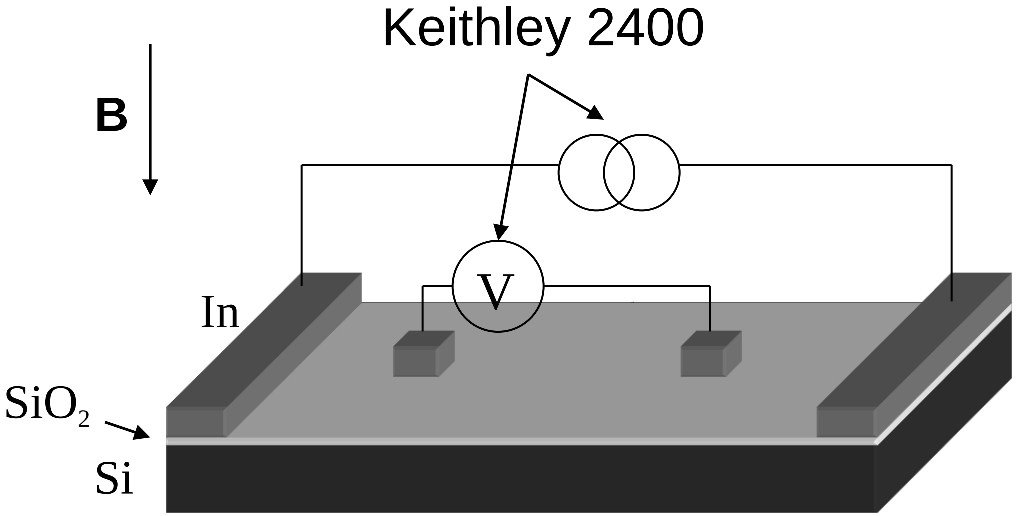
Si based MR device with symmetric electrodes

Structure: In/SiO_2/n-Si

Four electrodes methods



n-Si: Doping: ~10^{12} cm^{-3} phosphorous

ρ : 3000 Ω*cm, 1000 Ω*cm

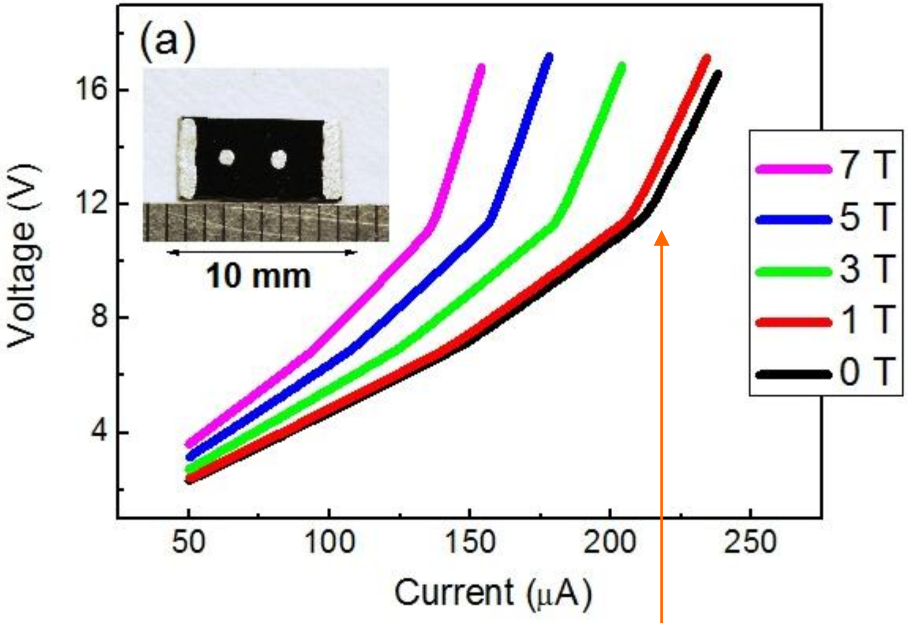
μ: 1200 cm^2/Vs

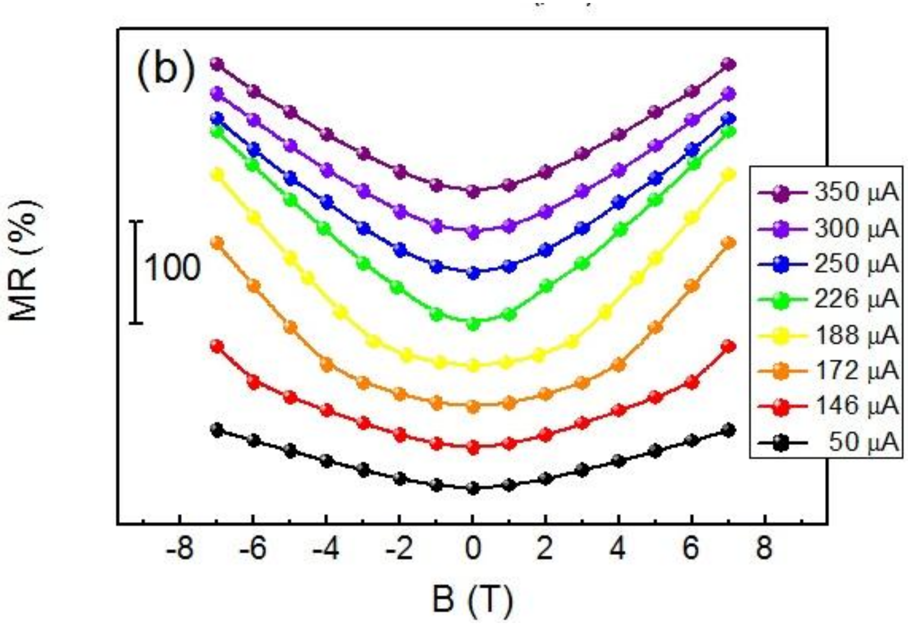
τ: 100~200 μs (Bulk minority lifetime)

Electrode: Indium

CH Wan, XZ Zhang, et al, Nature **477**, 304-307 (2011)

Current dependent MR





At this point, MR has a maximum

MR~B relation can be modulated by current from OMR to abnormal MR.

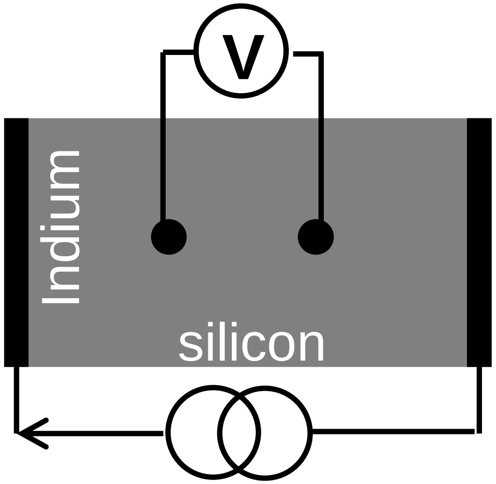
CH Wan, XZ Zhang, et al, Nature **477**, 304-307 (2011)

小电流下，两个方法测量结果一样，
大电流下，两个方法测量结果不同

Method 2

Keithley 2182

Voltmeter



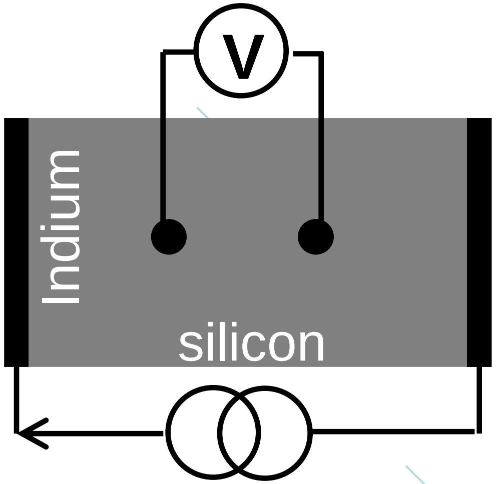
Current source

Keithley 2400

Method 1

Keithley 2400

Voltmeter



Current source

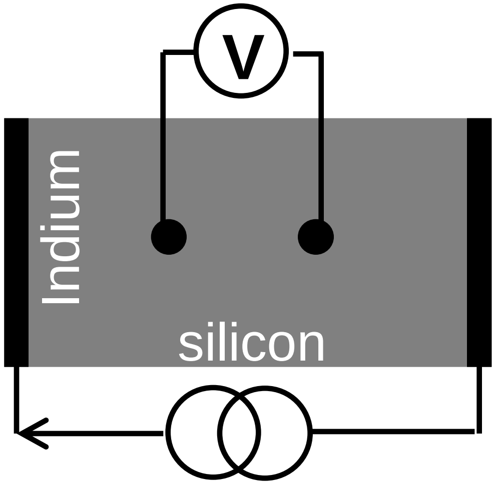
Keithley 2400

原因：大电流下，Keithley2400中的两个稳压二极管导通了，使得测量结果不同

Method 2

Keithley 2182

Voltmeter



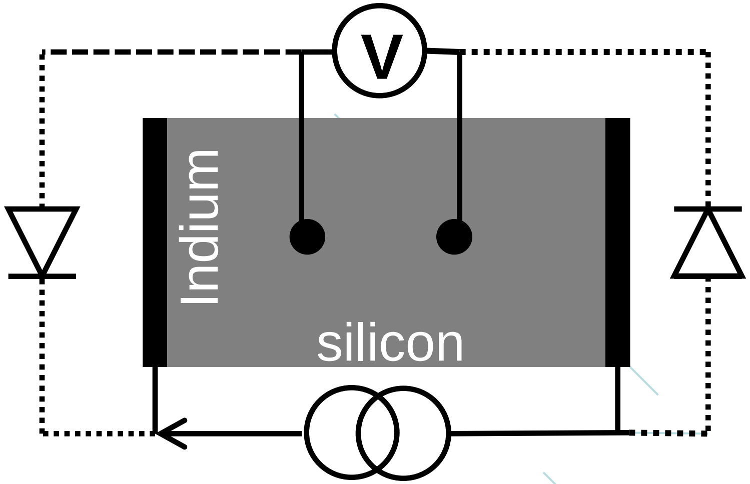
Current source

Keithley 2400

Method 1

Keithley 2400

Voltmeter



Current source

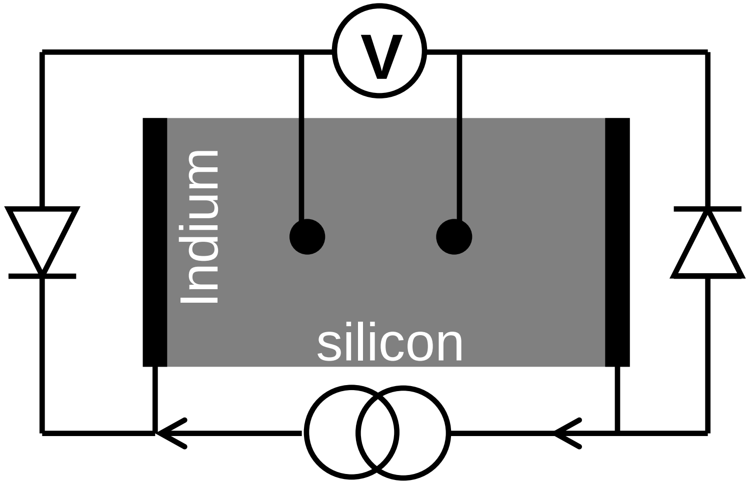
Keithley 2400

给method 2连上两个二极管就两个方法等效了

一般情况

Keithley 2182

Voltmeter



Current source

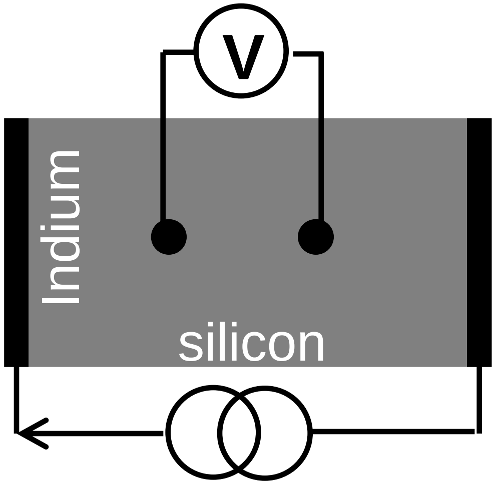
Keithley 2400

二极管可以被集成到硅片里，硅片、电极和二极管一起构成一个MR器件，该器件不依赖于测量方法

特殊情况

Keithley 2400

Voltmeter

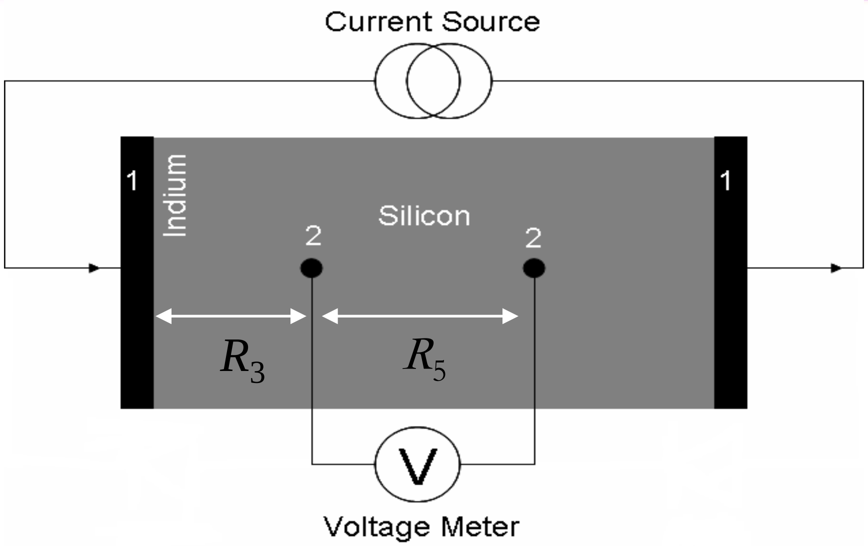


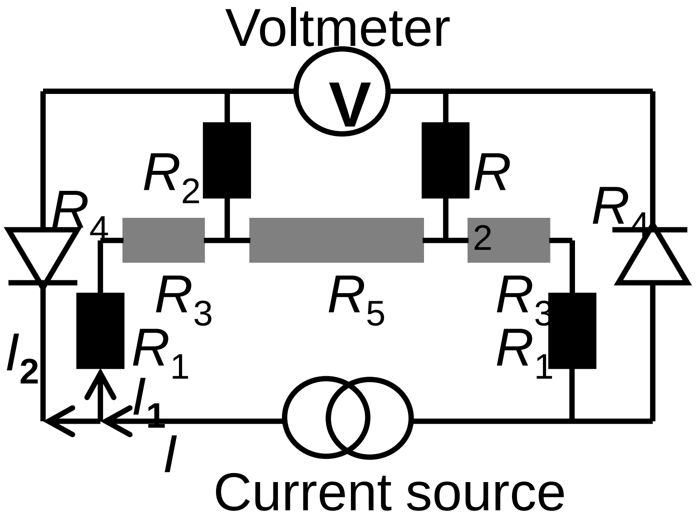
Current source

Keithley 2400

在Keithley 2400里已经连接了二极管

Geometrical MR Devices with Symmetrical Electrodes





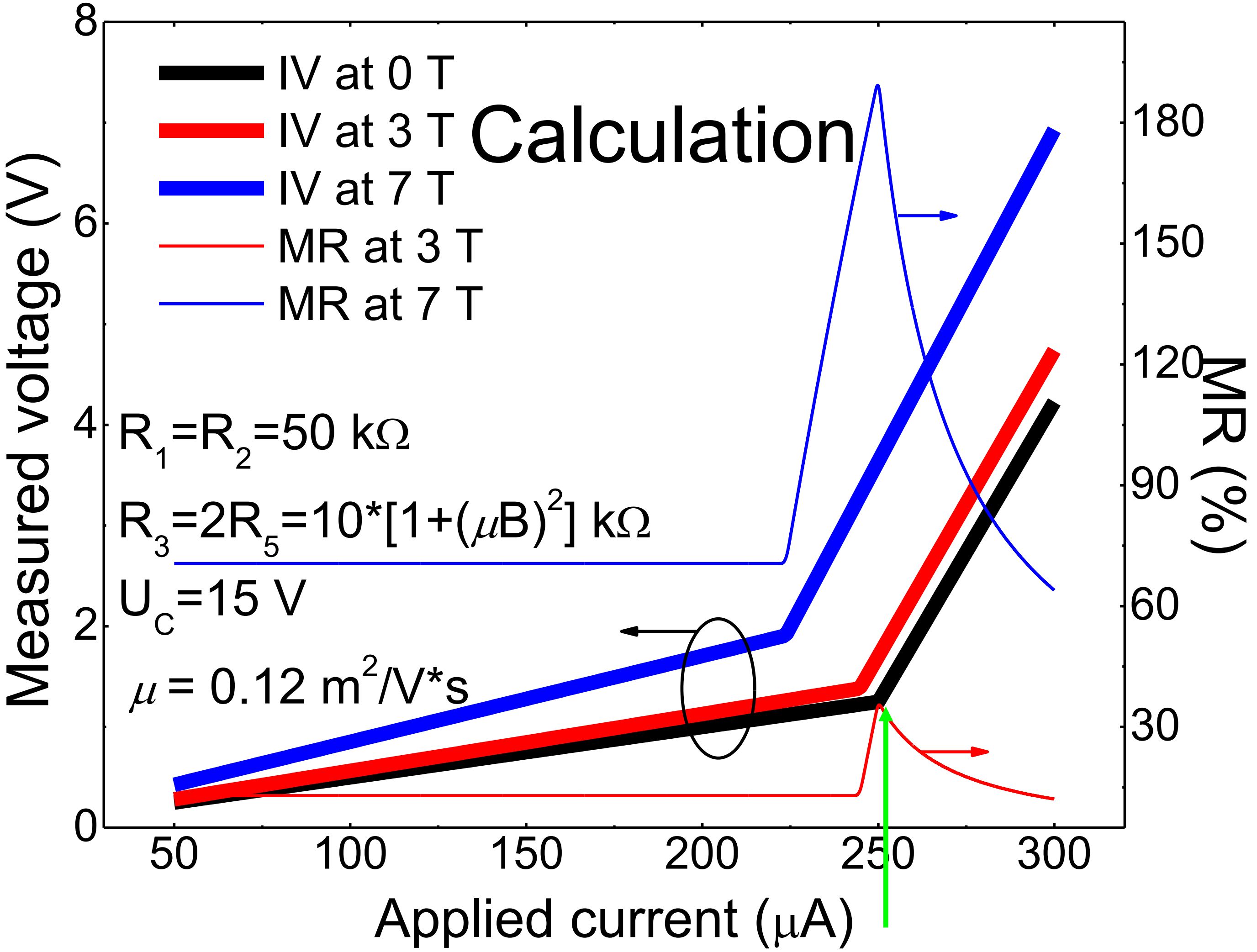
R_1: **Contact resistance of current electrodes**
R_2: **Contact resistance of voltage electrodes**
R_3: **Silicon resistance between current and voltage electrodes**
R_5: **Silicon resistance between the two voltage electrodes**

Geometry Factor

$$MR_{\max} \approx \left\{ 1 + \frac{2R_2}{\left[R_1 + R_2 + R_3(0) \right]} \frac{R_3(0)}{R_5(0)} \right\} MR_{\text{Si}}^{\text{sym}}$$

Intrinsic MR_{si} is "amplified" by a geometry factor R_3/R_5

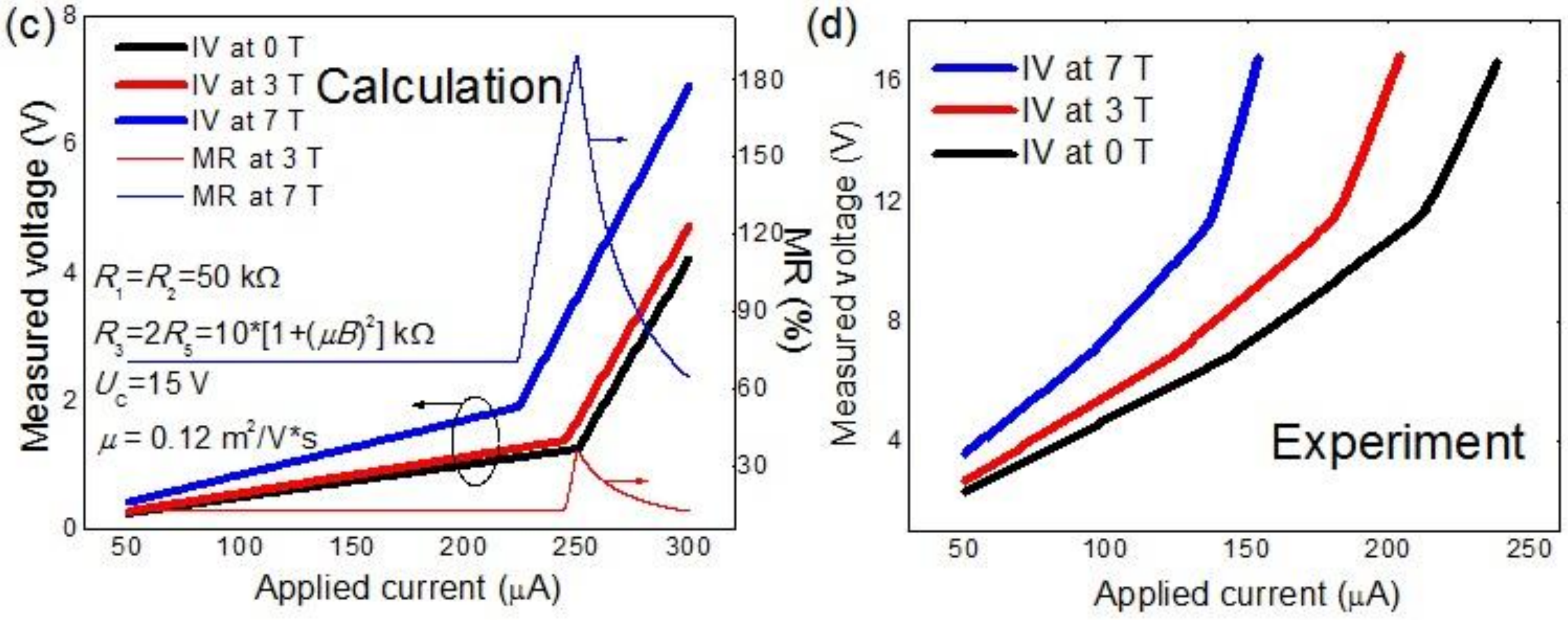
Zhang & Wan et al, (unpublished)



Turing point $I_c = U_C/[R_1+R_3(0)]$

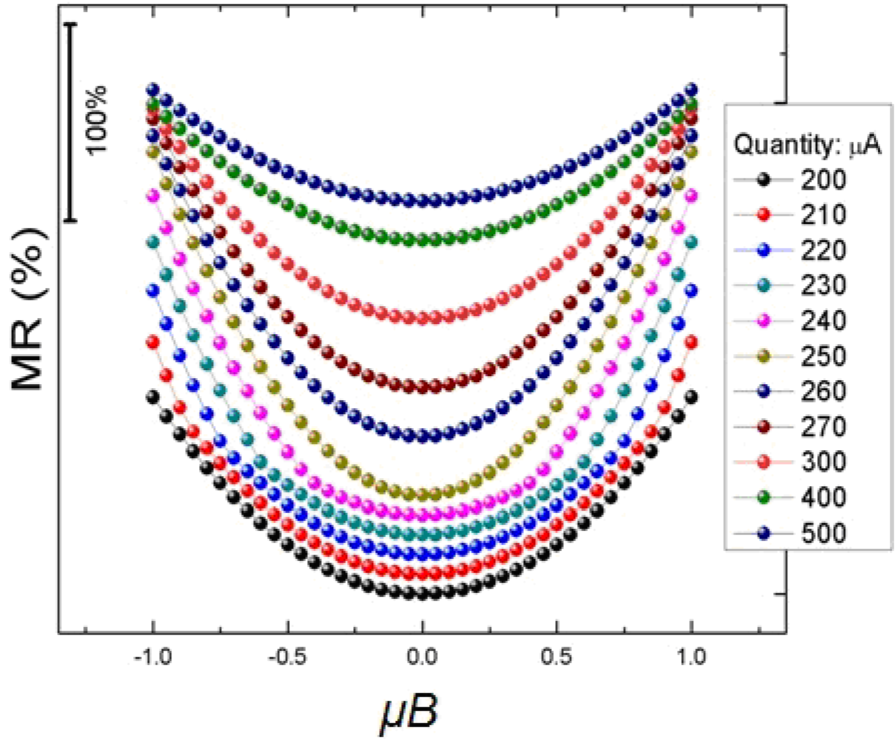
Zhang & Wan et al, (unpublished)

Comparison of simulation and experimental results

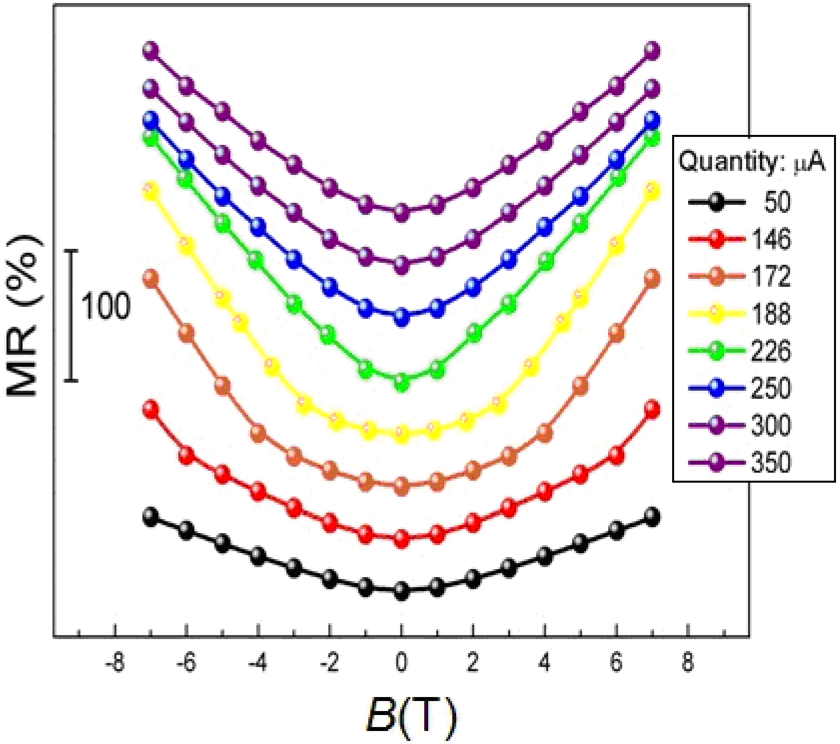


Comparison of simulation and experimental results

calculation



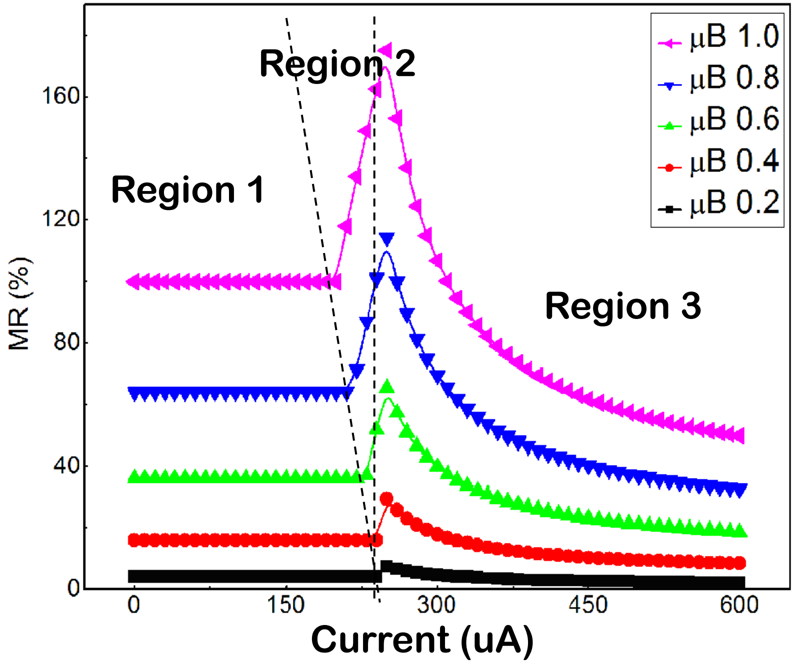
experimental

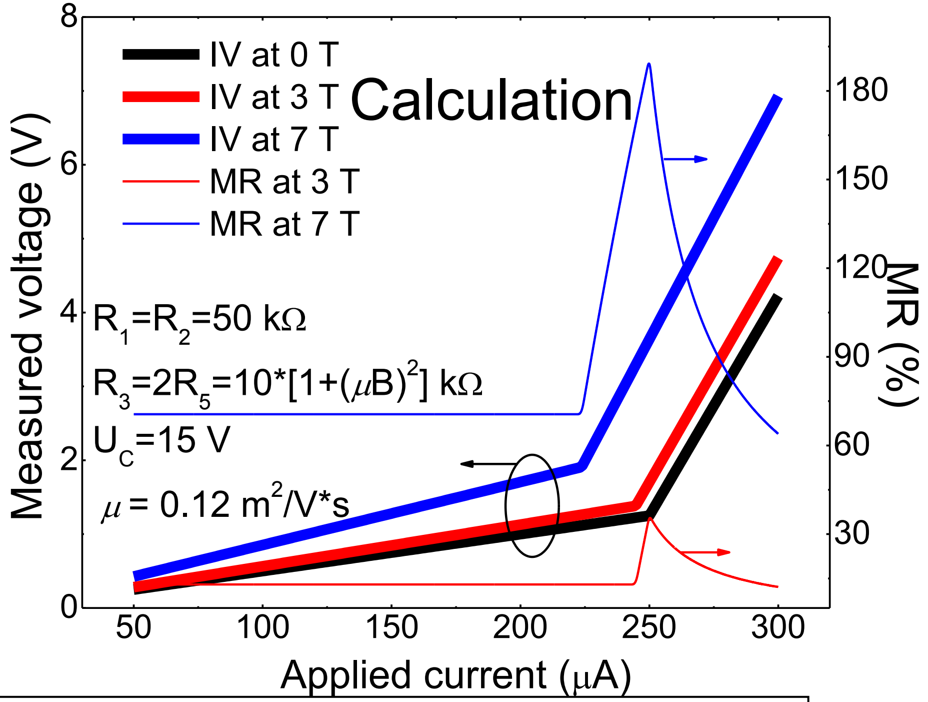


Zhang & Wan et al, (unpublished)

CH Wan, XZ Zhang, et al,
Nature **477**, 304-307 (2011)

MR ~ Current dependence





1. A MR peak existed in MR-I curves.
2. The peak occurred at the turning point of I-V curve

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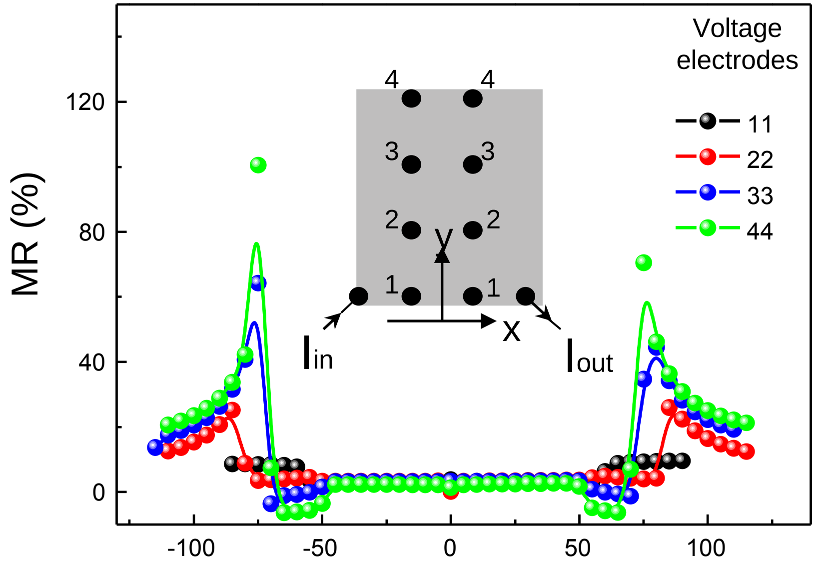
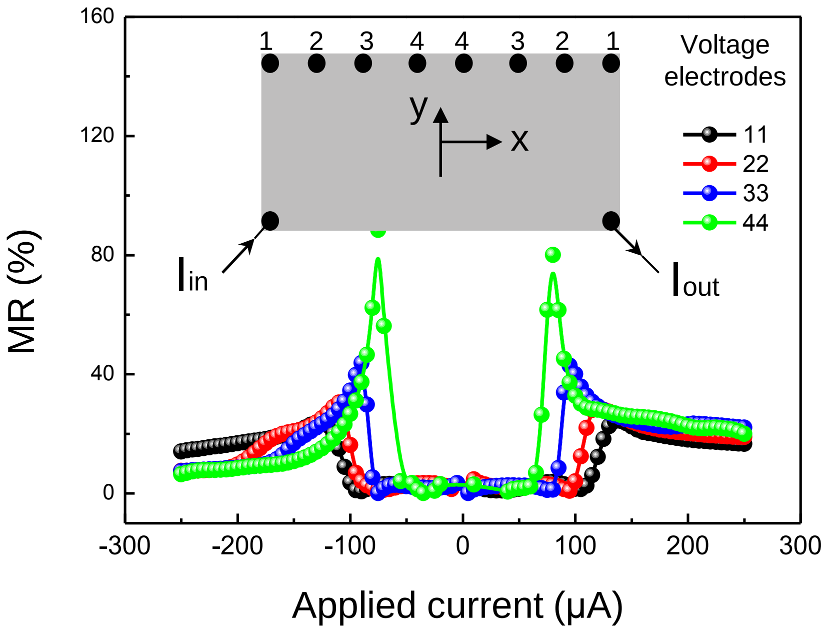
Effect of electrode position on MR

(c)

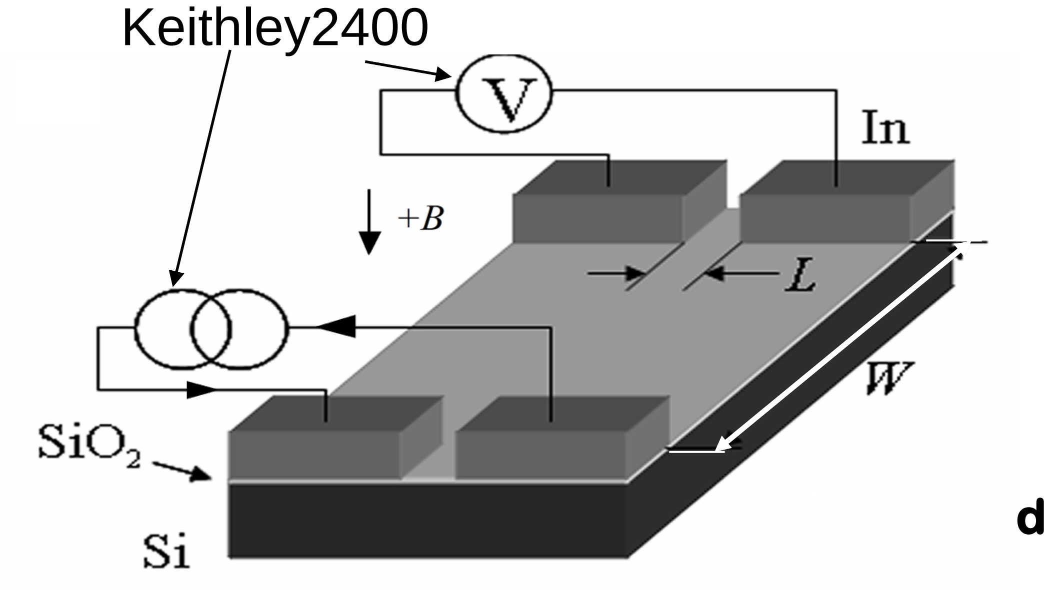


(d)



CH Wan, XZ Zhang, et al, Nature **477**, 304-307 (2011)

Si based MR device with asymmetric electrodes

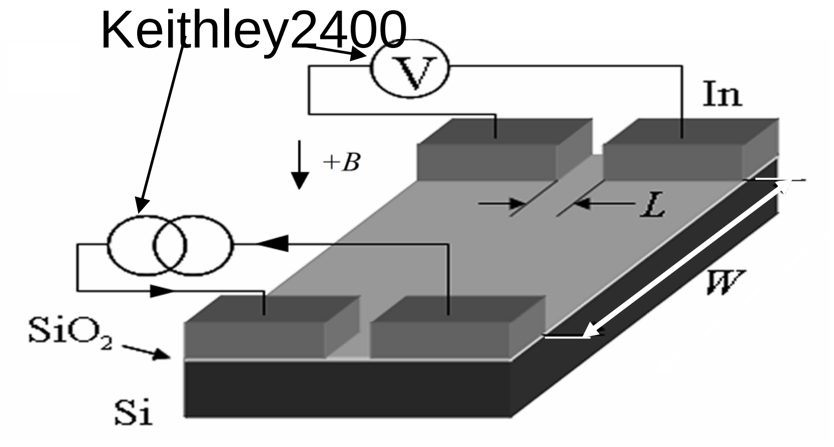


MR Devices with Asymmetrically distributed electrodes at corners

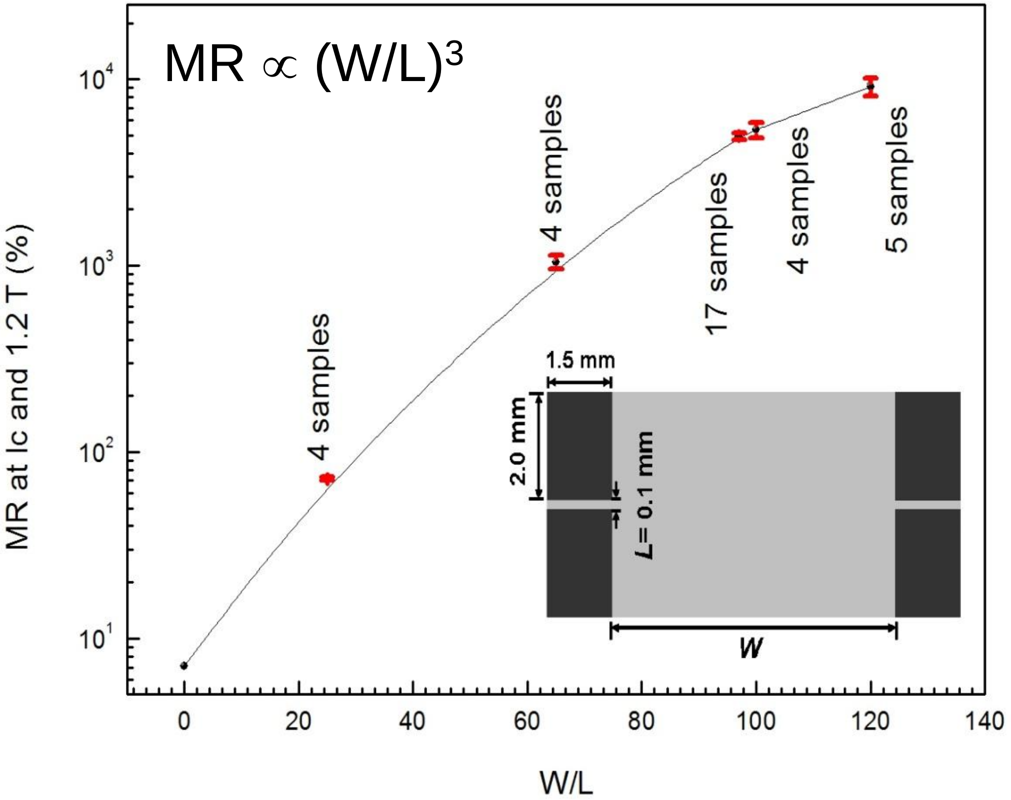
n-Si: Doping: ~10^{12} cm^{-3} phosphorous
ρ : 3000 Ω*cm, 1000 Ω*cm
μ: 1200 cm^2/Vs
τ: 100~200 μs (Bulk minority lifetime)
Electrode: Indium

CH Wan, XZ Zhang, et al, Nature **477**, 304-307 (2011)

Si based MR device with asymmetric electrodes



MR Devices with Asymmetric Electrodes

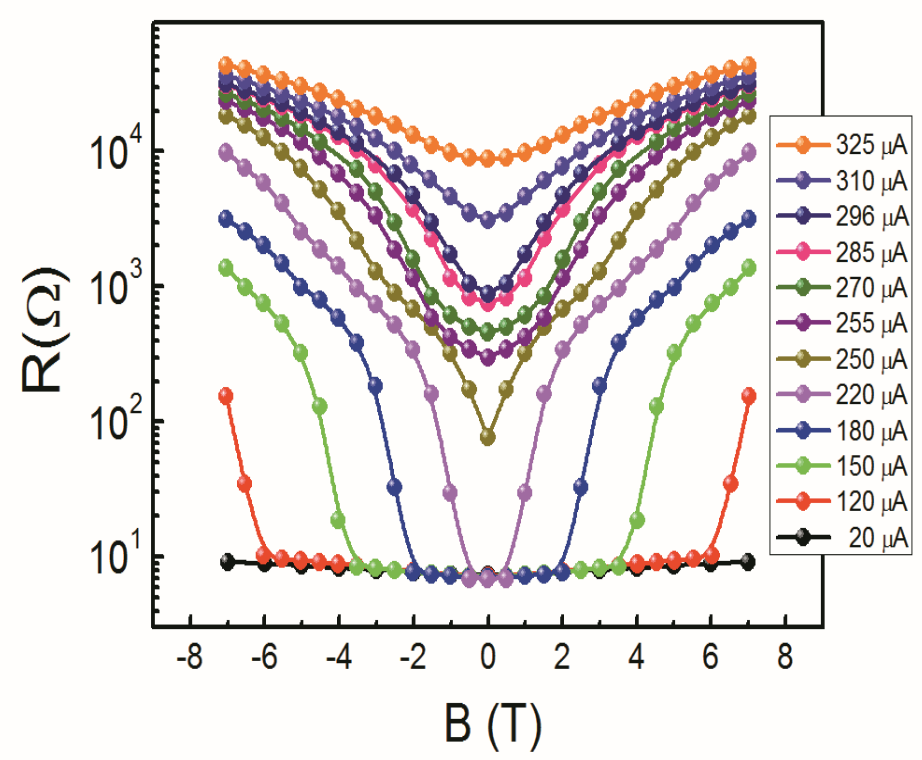


MR increases with increase of $(W/L)^3$

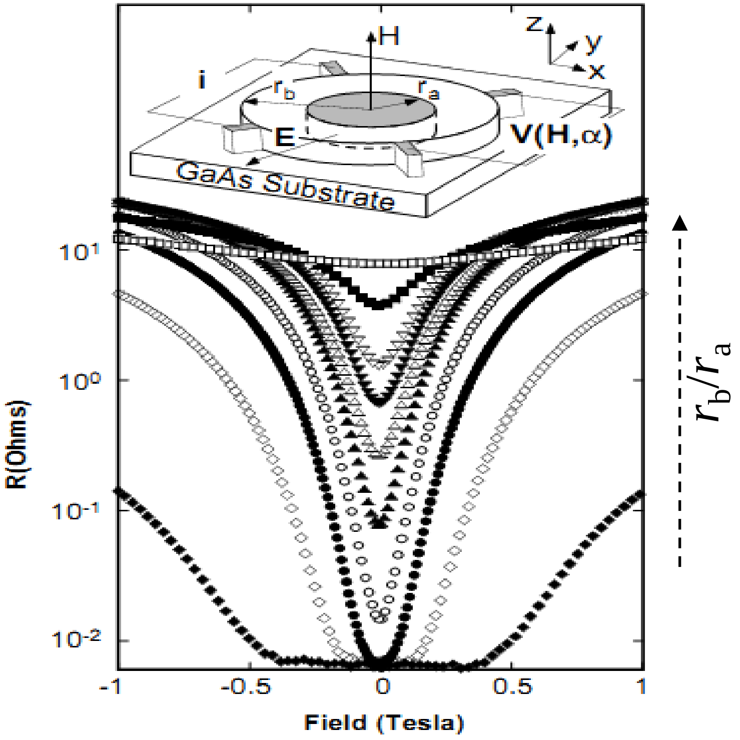
CH Wan, XZ Zhang, et al, Nature **477**, 304-307 (2011)

Comparison between Si and InSb based Geometrical enhanced MR Devices

Si



InSb/Au

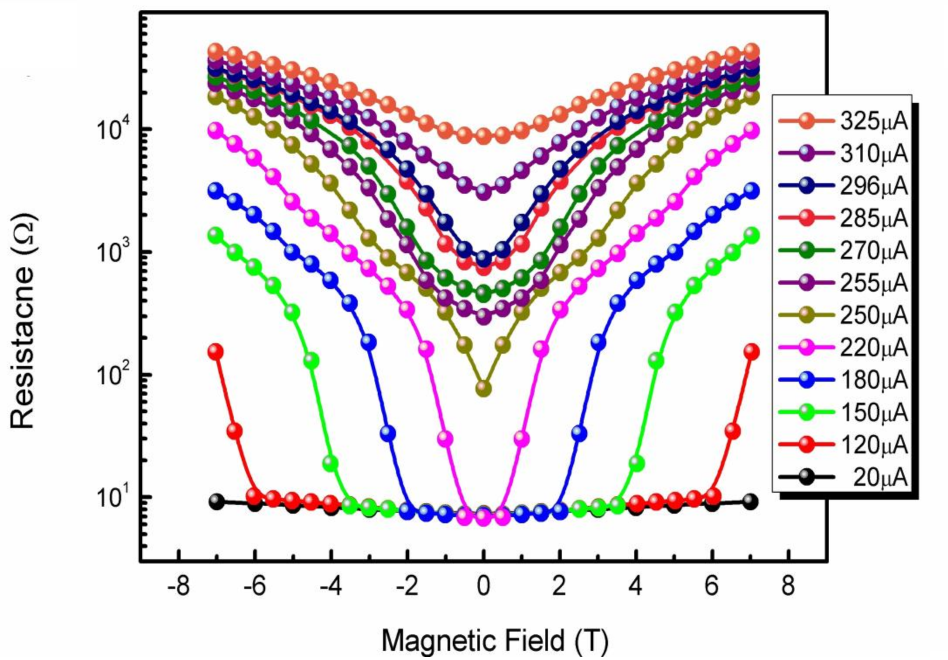


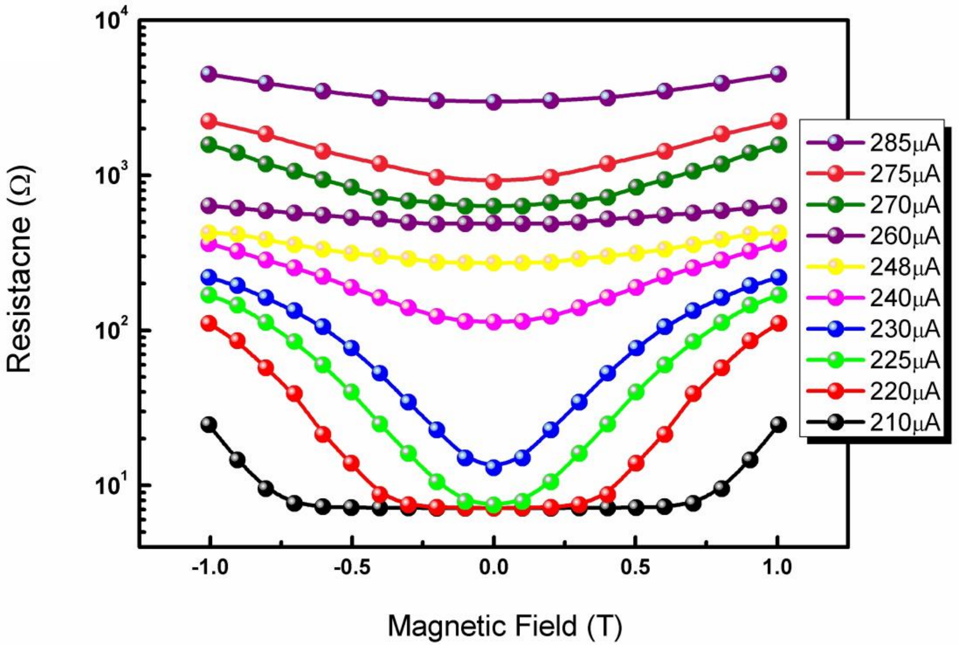
1. MR ~ B evolves in a similar manner
2. The Control parameter in Si was current
3. The Control parameter in InSb was shape

Wan & Zhang et al, Nature, 2011

Solin, et al, Science, 2000.

Current dependent MR

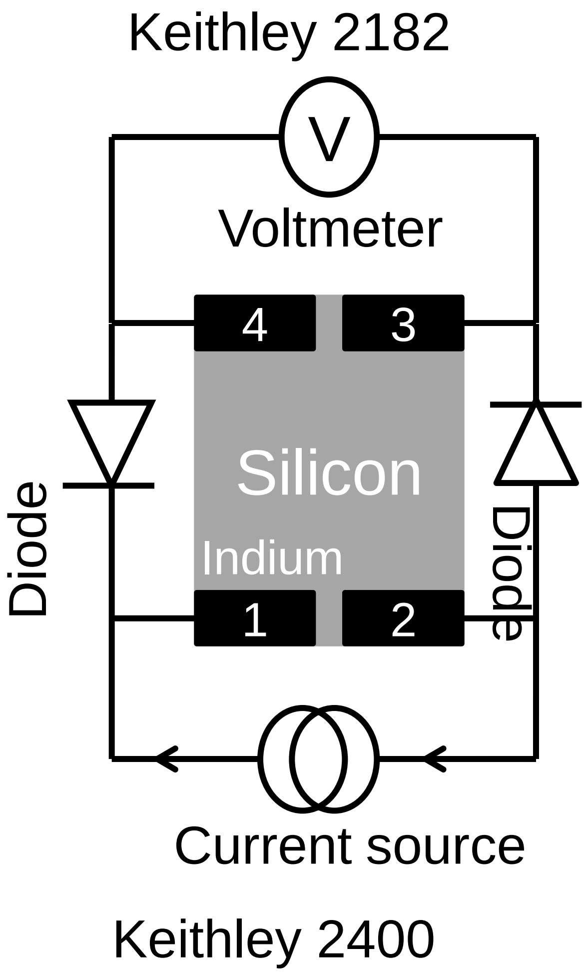


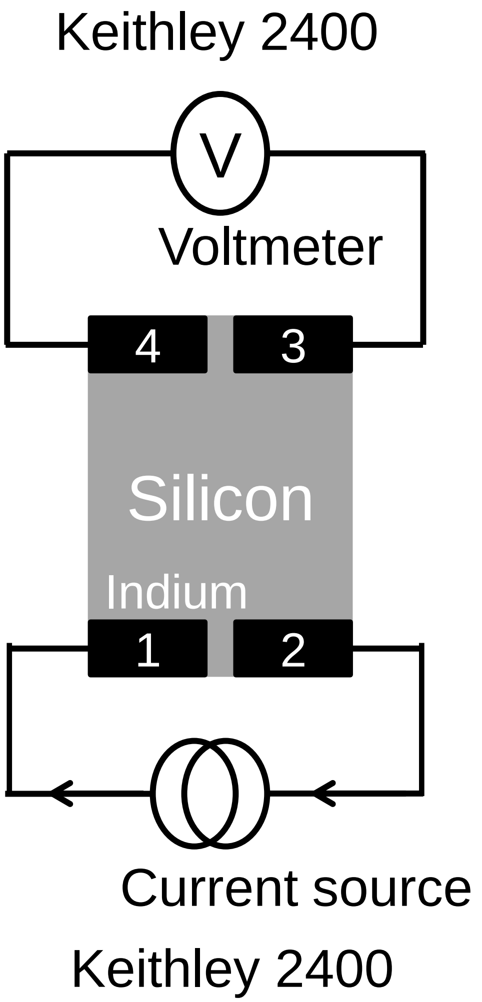


RT MR reaches 30% at 0.065T and 100% at 0.2 T

Wan & Zhang, et al, Nature **477**, 304-307 (2011)

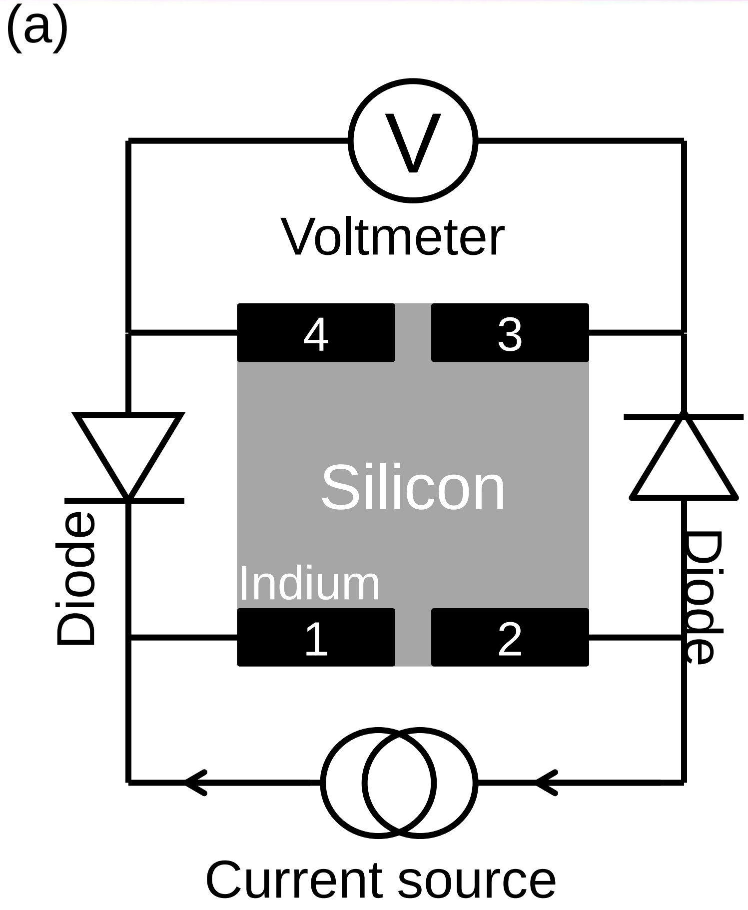
Measurement setup of asymmetrical electrode sample

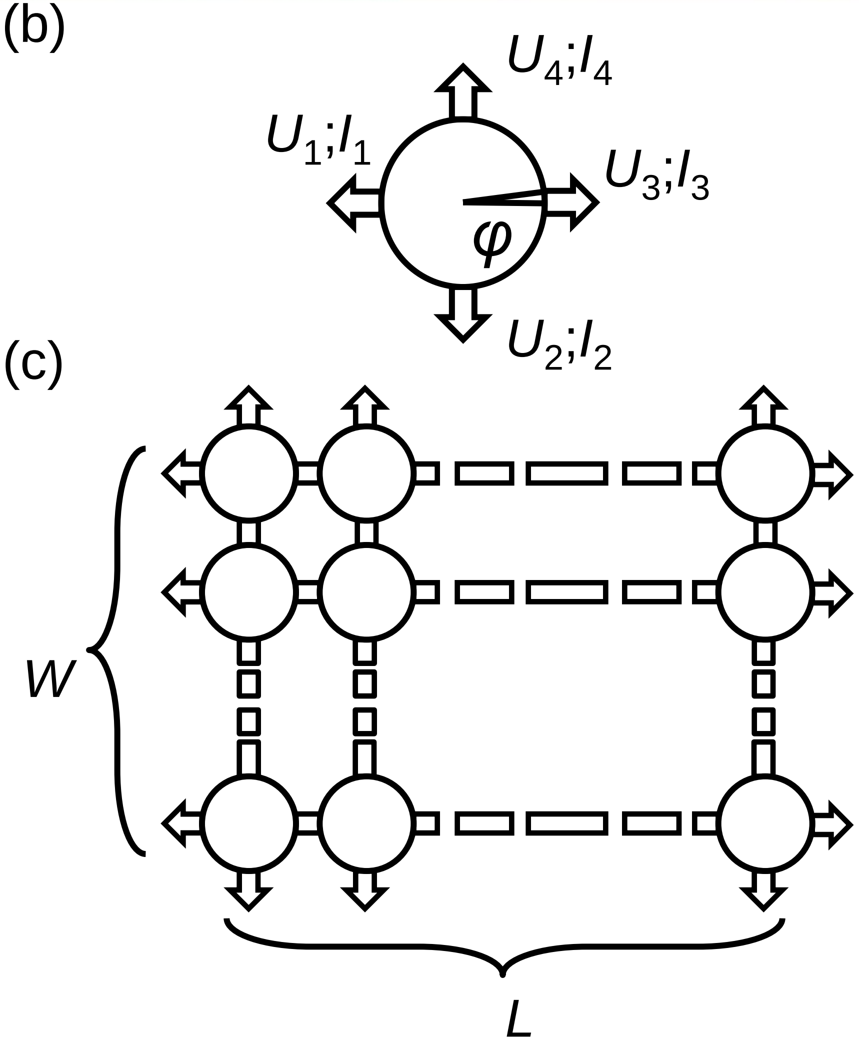




The diodes had already inherently incorporated into the Keithley 2400

MR model for asymmetrical electrode sample

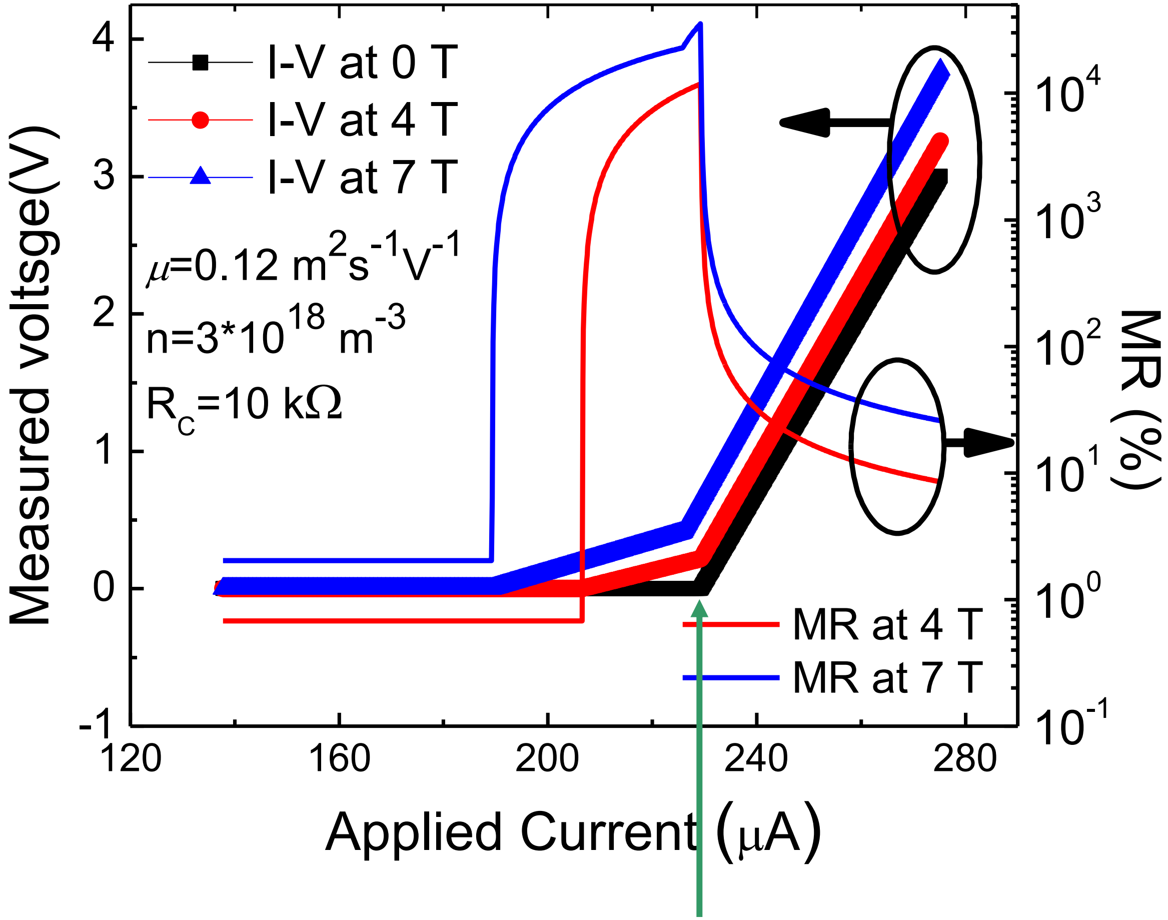




Our model was similar to the model proposed by Parish and Littlewood except the differences in the geometry of electrodes and the two diodes

Parish & Littlewood, Nature, 2003

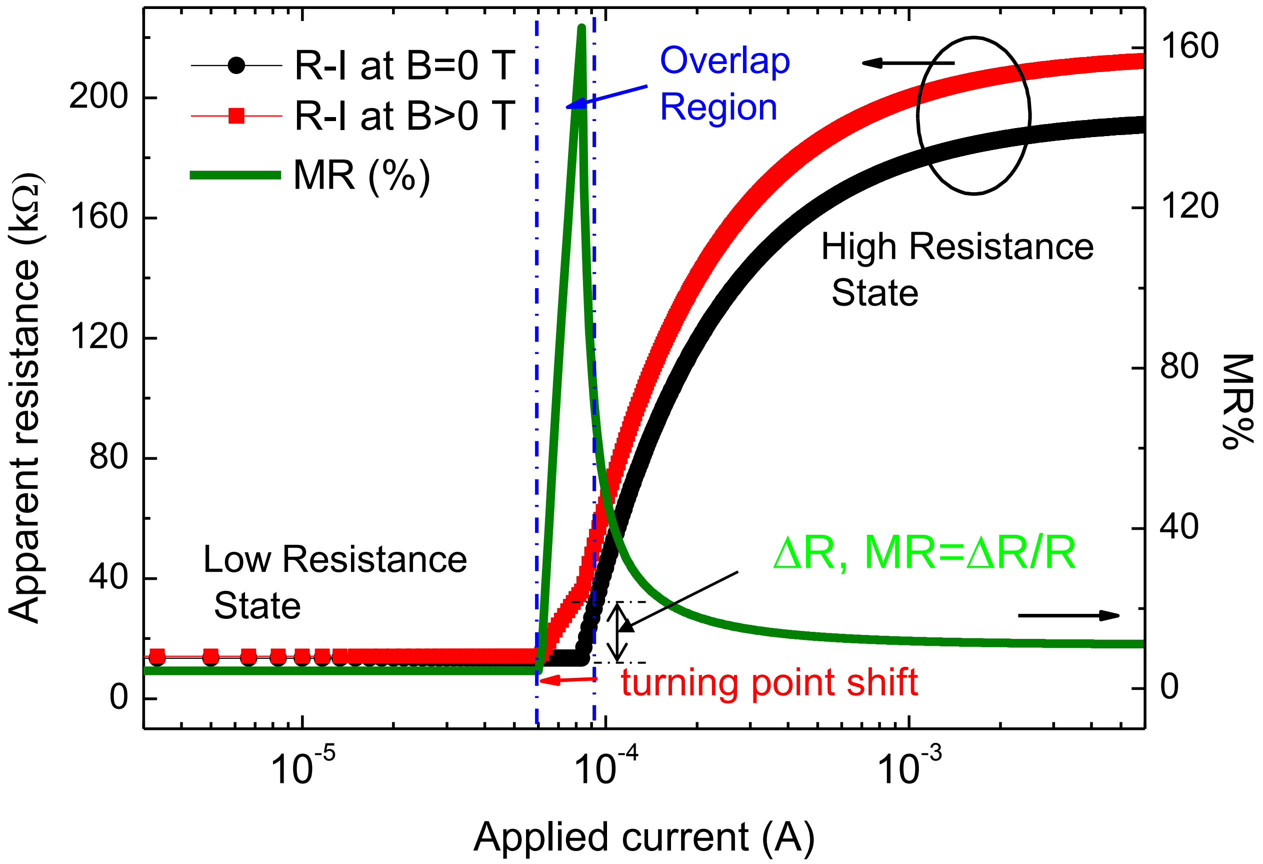
The maximum MR occur at turning point of I-V curves



Turning point

Zhang & Wan et al, (unpublished)

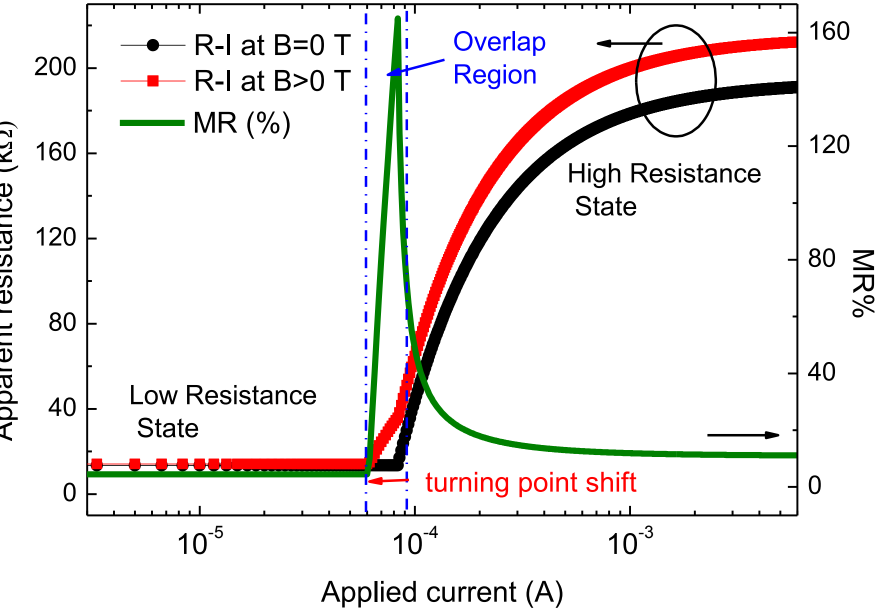
Mechanism of geometric enhanced MR

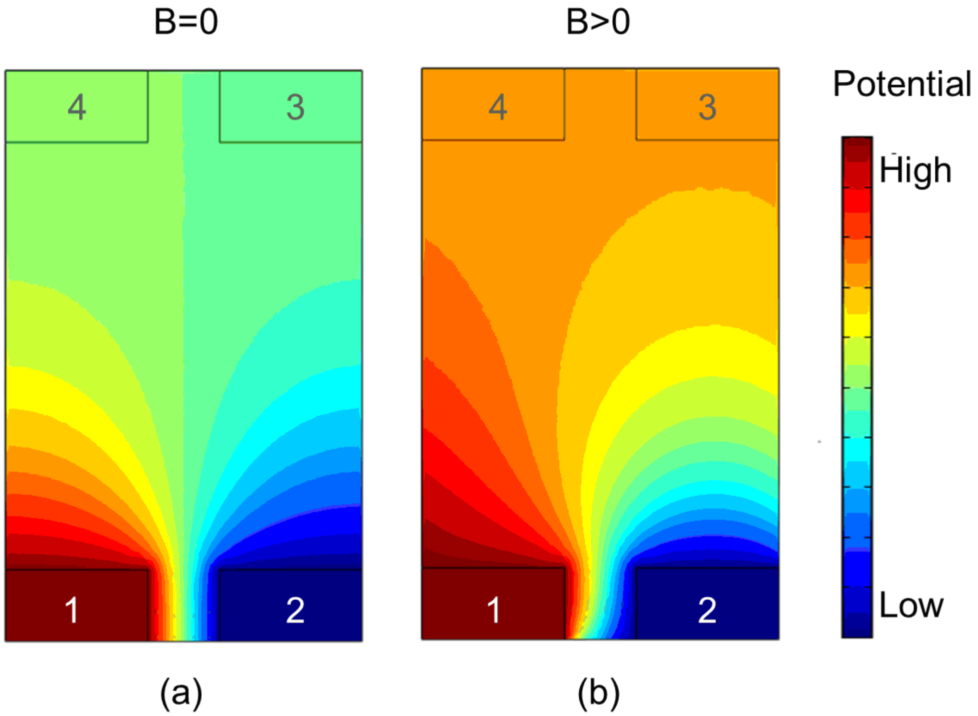


The diodes help to create a low resistance state (LRS) and a high resistance state (HRS). At the boundary between LRS and HRS, MR has its maximum.

Zhang & Wan et al, (unpublished)

在转变点，磁场极大地改变了MR器件电势的分布



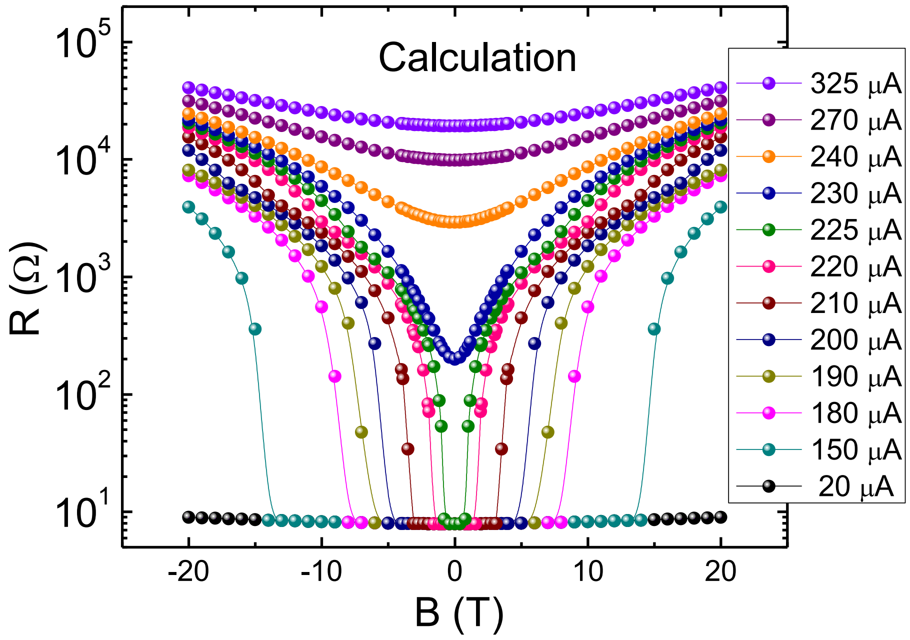


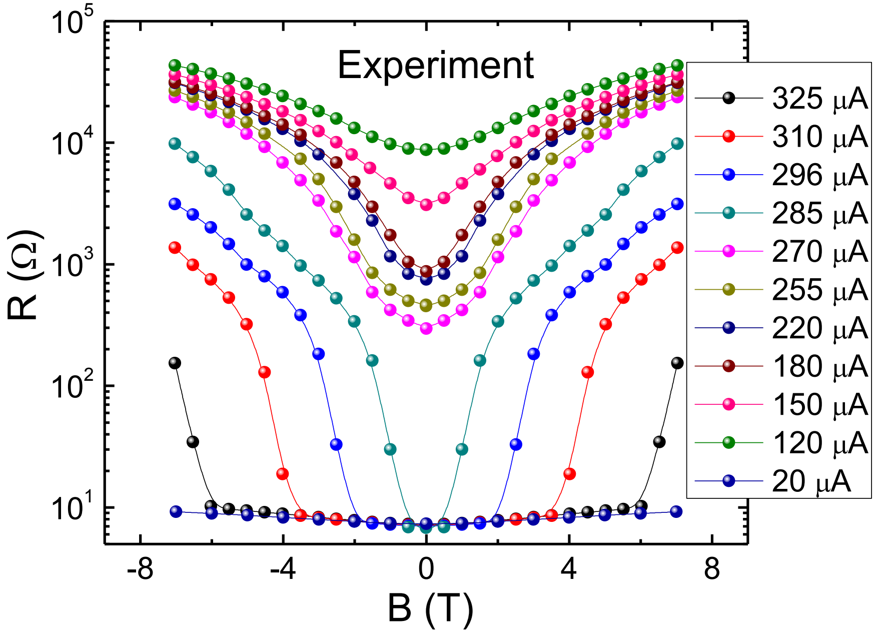
(a) (b)

二极管帮助建立了一个从低电阻态（LRS）到高电阻态（HRS）的转变，在该转变点，磁电阻被大大增强。

Zhang & Wan et al, (in submission)

Comparison of simulation and experimental results





1. MR(B) dependence modulated by applied current.
2. There existed a transition from OMR to abnormal MR with elevating current.

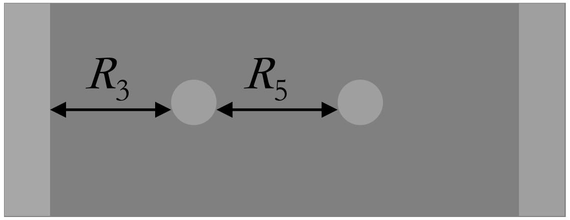
Zhang & Wan et al, (unpublished)

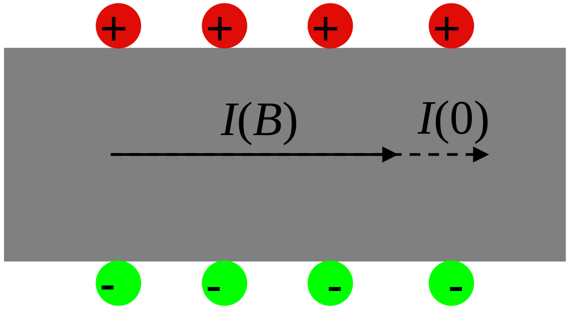
Wan & Zhang, Nature (2011)

Comparison between the two geometry

Symmetrical

R_3/R_5

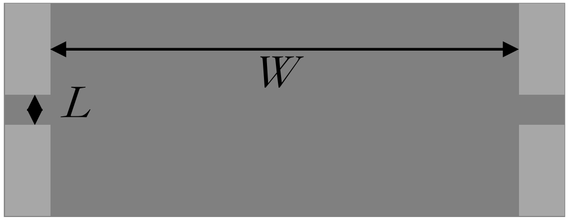




$(\mu B)^2$

Asymmetrical

W/L



Larger Geometrical Factor

No charge accumulation

(μB)

2.4.5 各因素对磁电性能的影响程度对比

本征因素	增强因素	增强效果
洛伦兹力偏转载流子 $(\mu B)^2$	非均匀性	1~2倍
	几何效应	几何因子$(W/L)^3$ $\mathrm{d}V/\mathrm{d}B \sim B$
	PN结效应	PN结因子 $[\ln f(U)]'\ U_\mathrm{C}$

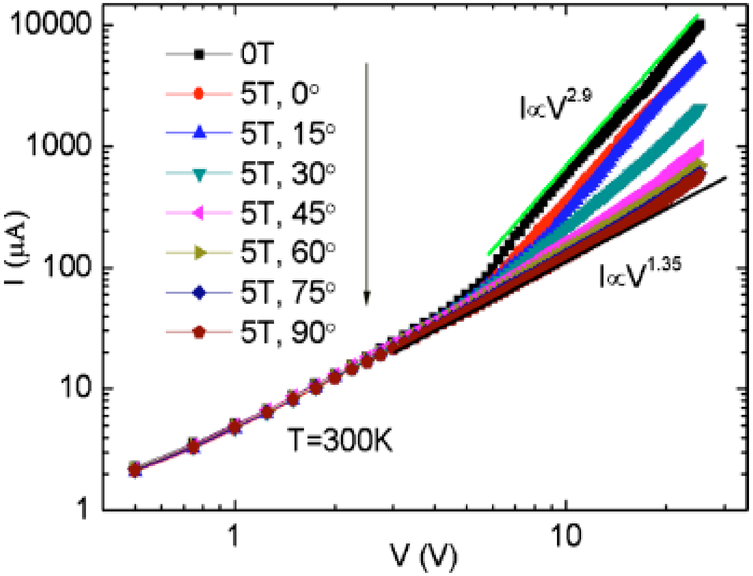
Comparison among different MR devices

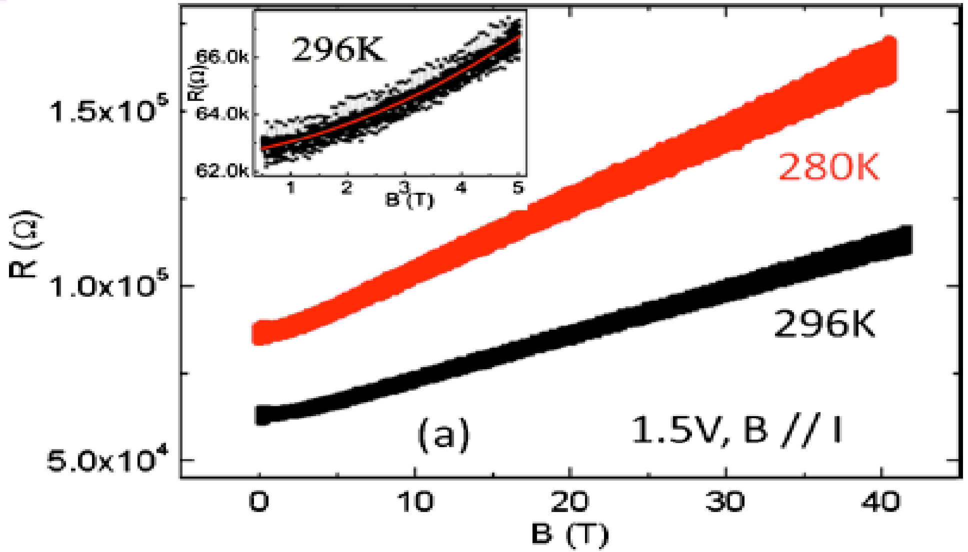
Type	S（T^{-1}） $S=MR/B$	Field needed	others	Ref
Delmo's Si	1.0	0.5 T	V=100 V	1
Schoonus's Si	8.0	1.25 T	V=80 V	2
InSb	3.0	0.19 T	Low resistivity	3
Si geometrical enhanced MR	**5**	**0.06 T**	**I=0.2 mA, V=10 V**	**Ours**

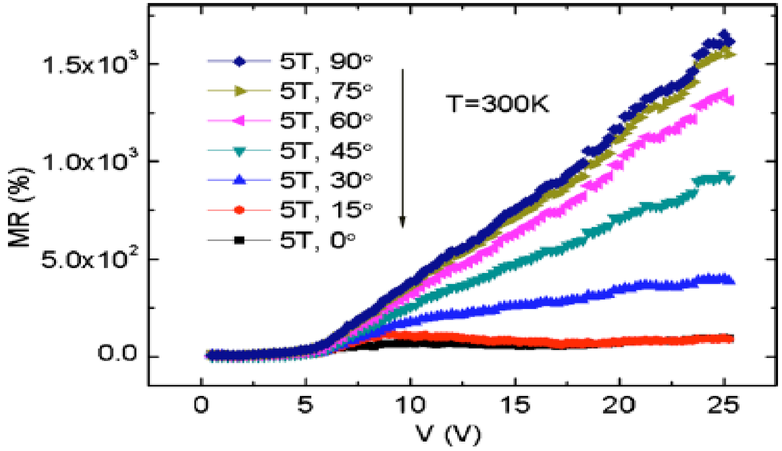
Speed monitor：0.1 T, reader：0.01T, Compass：0.5×10^{-4}T

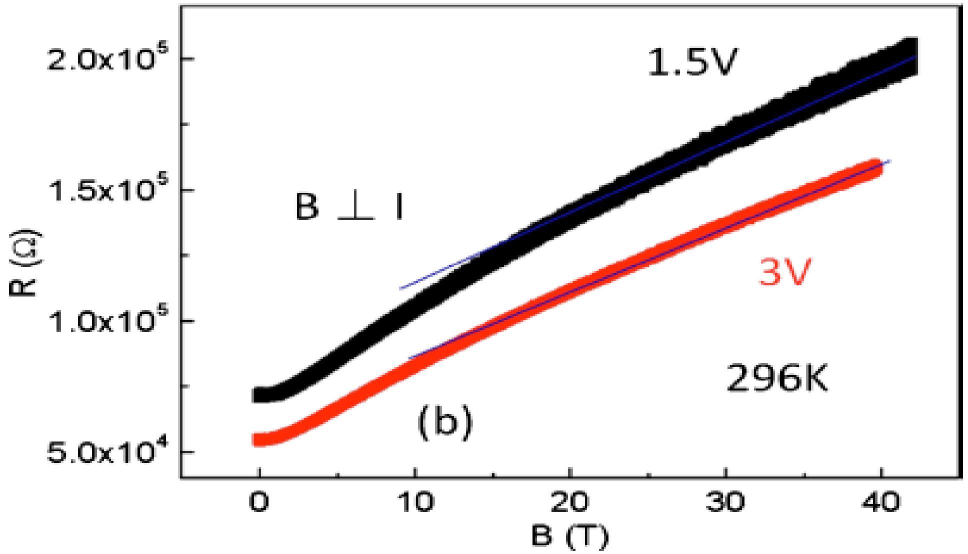
1. Delmo M P, et al. Nature, 2009.
2. Schoonus J J H M, et al. J Phys D: Appl Phys， 2009.
3. Heremans J. J Phys D: Appl Phys, 1993.

Magnetic sensor made by Si can be used in both weak field and high field (up to 40T)









Wu, Zhang et al Appl. Phys. Lett. 98 (2011) 112113 .

Outlines

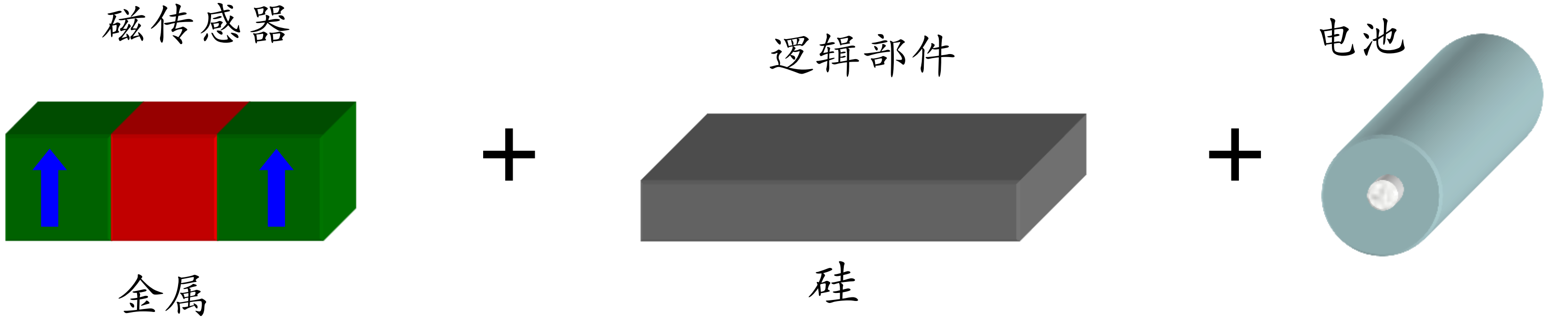
1. 背景介绍
   - 1.1 磁电阻和自旋电子学
   - 1.2 各种磁电阻
2. 结果
   - 2.1 a-C/Si 异质结构的磁电阻
   - 2.2 硅的低温磁电阻
   - 2.3 硅的室温几何增强磁电阻
     - 对称电极结构的磁电阻
     - 非对称电极结构的磁电阻
3. 半导体几何增强磁电阻的优点和愿景

硅基磁电阻的优点（相比巨磁阻/隧穿磁阻）

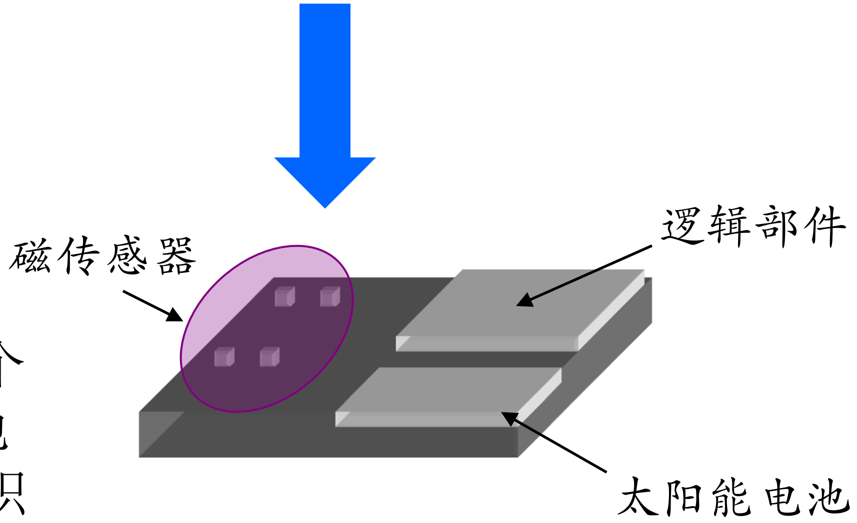
- 无磁噪声
- 原材料来源丰富（硅地球丰度第2）
- 可以用于从弱场到强场很宽的范围（0－40T）
- 可以用成熟的硅基微电子技术，从研究转化为生产快
- 这种几何增强磁阻可以用于其他半导体（如GaAs， Ge等）
- 这种半导体MR器件可和其他半导体器件集成，可能产生新颖的磁电或者磁光电器件

未来的磁传感器

现有的磁阻器件



未来的硅基磁阻器件



原来的3个器件做在一个硅片上， 成为自带电池的自驱动磁传感器 (体积小，功耗低，速度快）

Impact

1. Silicon electronics → Silicon magnetoelectronics

More flexible controllability (Electro-， magneto-， non-connected modulations)

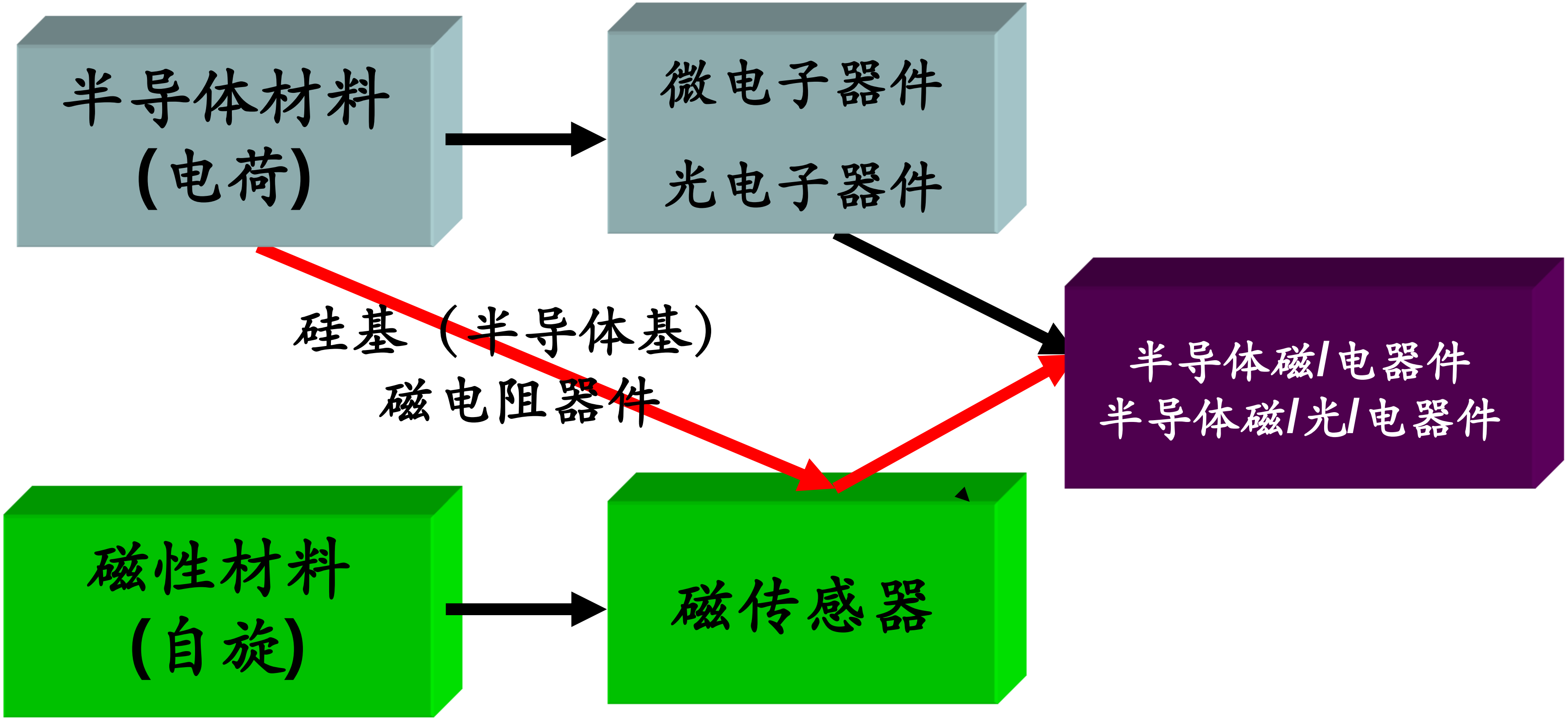
2. Silicon based MR sensors

covering high/medium/low field range、applied current dependent、self-powered， ample raw materials

For comparison: Magnetic MR sensors: Magnetic Hysteresis， Failure at high fields， inactive to current.

影响力（Impact）

以硅为主的半导体工业和以磁性材料为主的磁传感器和磁存储工业是信息工业的两大独立支柱。硅基磁电阻器件的发明让用半导体材料（我们已经在Si、GaAs、Ge上实现磁电阻）来制备过去不存在的磁－光－电复合器件成为可能，实现半导体工业和磁传感器工业的联姻。



国际评价

- **NPG Asia-materials** 以 **Magnetoresistance: Silicon joins the party** 为题**highlight了我们的工作**.
- **创刊于1899年的MIT著名杂志《Technology Review》的中文版采访了章晓中**，并且写了特别报道“磁电阻革命——硅基磁传感器的工业化实现”介绍我们的工作。
- **受邀在InterMag 2012 会议上做邀请报告**（国内唯一的邀请报告）
- **受邀**于**2012**年**7**月召开的磁学界最高级别的国际会议**第19届国际磁学和强关联电子系统大会做半大会报告**（国内唯一的一篇大会和半大会报告）。

home » featured highlight » Magnetoresistance: Silicon joins the party

NPG Asia Materials featured highlight | doi:10.1038/asiamat.2011.182
Published online 05 December 2011

Magnetoresistance: Silicon joins the party

Magnetoresistance in silicon can be enhanced to match that of commercial devices by designing appropriate device geometries.

Giant magnetoresistance, which allows electrical resistance to be varied by relatively small magnetic fields, has had a huge impact on everyday technology, with widespread use in information storage and magnetic field sensing. Xiaozhong Zhang and colleagues from Tsinghua University in China have now demonstrated that it is possible to enhance inhomogeneous magnetoresistance (IMR) in silicon devices to levels comparable to that of conventional rare-earth-based technologies[1].

Most magnetoresistance-based devices are made

Photograph of a silicon-based magnetoresistive element

NPG Asia Materials is now open for submissions. The journal will publish its first Original Articles in January 2012.

current reviews
- DNA-based switchable devices and materials
- Metamaterials and metaoptics
- Laser-based imaging of individual carbon nanostructures

site resources

特别报道 REPORT

磁电阻革命
——硅基磁传感器的工业化实现

做为磁传感器材料中的新星，硅已被广泛关注。章晓中教授让硅基磁传感器的工业化实现成为了可能。科技创新加上技术实现，使得这项技术的市场潜力不容小觑。

撰文／陈兆瀚

每天早上，我们按时打开手机，更新每日的新闻内容，来到办公室，打开电脑开始一天的忙碌。做会议演示的时候，可能还会用 U 盘把幻灯片拷到公用电脑上。所有的这一切活动都离不开一项技术——数据存储。在数据存储这一领域的发展上，巨磁阻效应（GMR）的应用功不可没。自从 1988 年被发现以来，GMR 就被用于制备电脑硬盘驱动器磁头和固态硬盘，微弱的磁场强度变化即可导致 GMR 材料的电阻发生巨大变化，从而将磁场信号转化为电信号，使得磁头可以在磁盘上读出数据。

虽然基于 GMR 的磁存储技术已经非常成熟，但这并不意味着磁电阻技术已经发展到了尽头，通过其他方式实现磁电阻功能，依然有其意义。其中，清华大学材料科学系章晓中教授所研究的非均匀性导致的磁阻效应（IMR），就有着重要的应用价值。正是基于 IMR，章教授成功地使得半导体硅成为磁传感器，并使其工业化成为可能。

在章晓中之前，有科学家已经开始着手进行非磁性半导体的磁阻效应的研究，并且得出了非均匀性导致的磁电阻效应与磁场的线性依赖关系。从事磁电阻方面的研究的剑桥大学卡文迪许实验室的彼得·利特尔伍德（Peter. B. Littlewood）教

国内评价

硅基磁电阻工作入选

- **2011年度“中国科学十大进展”**
- **2011年度“中国高等学校十大科技进展”**

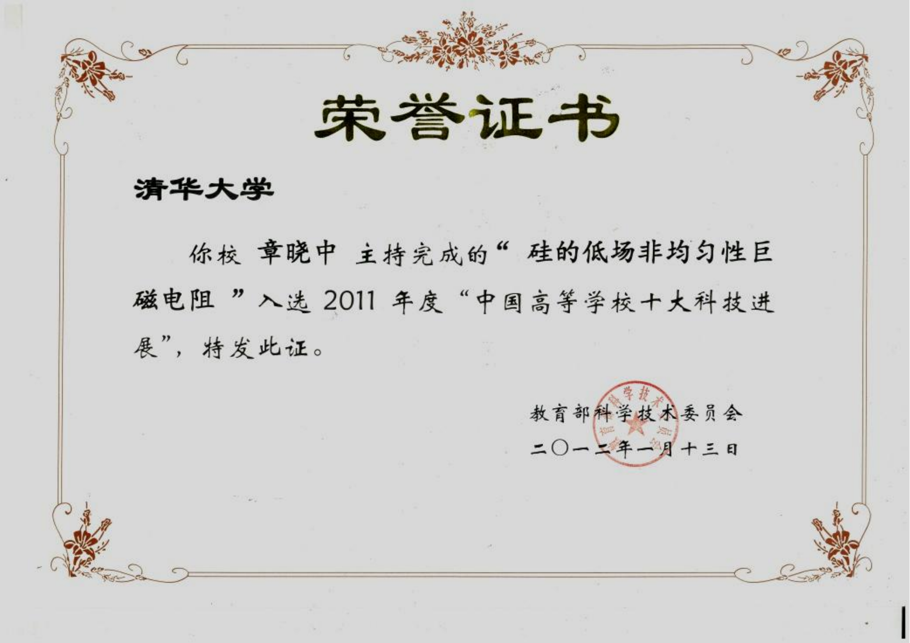
中国2011年度共有3个“十大进展”评选，同时入选2个十大进展的只有3个项目 （天宫/神八上天， 蛟龙号深海潜水器， 硅基磁电阻）

2011 年度中国科学十大进展

设计出兼具低场高灵敏和高场大磁电阻的硅基磁电阻器件

主办单位：科技部基础研究管理中心

协办单位：《科技导报》杂志社
《中国科学院院刊》编辑部
《中国科学基金》编辑部
《中国基础科学》编辑部



荣誉证书

清华大学

你校 章晓中 主持完成的“ 硅的低场非均匀性巨磁电阻 ”入选 2011 年度“中国高等学校十大科技进展”，特发此证。

教育部科学技术委员会
二〇一二年一月十三日

Some recent works in silicon

- Spin injection into silicon
  - – Nature 462, 491 (2009)
- Oribitronics in silicon
  - – Nature 465, 1057 (2010)
- Gometrical enhanced magnetoresistance (GEMR) in silicon
  - – Nature 477, 304 (2011)
- What else in silicon ?

结论

1. 我们利用连接二极管发明了几何增强磁电阻(GEMR). 二极管帮助建立了一个从低电阻态（LRS）到高电阻态（HRS）的转变，在转变点附近，本征磁电阻被几何因子放大。
2. 硅中的本征磁电阻是普通磁电阻（OMR）效应，可以通过几何效应来放大本征磁电阻，对非对称电极结构MR器件的MR可以在0.06T下达到30%，几何因子（W/L)^{3}越大，MR越大。进一步优化器件，可以进一步提高性能。争取做到微型化和高灵敏度。
3. 我们已经在 Si，GaAs 和 Ge上实现了GEMR。这提供了在单一材料上实现磁光电复合功能的可能性。
4. 我们的工作表明半导体的电荷属性也可以做个别传统上由磁性金属的自旋属性完成的工作(如MR), 这可能造成半导体工业和磁传感器工业的联姻。

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  - Prof. F.H Yang, Institute of Semiconductors, CAS
  - Prof. Y. Wang, Institute of Microelectronics, Tsinghua University
- Students & Postdocs

Dr. C.H. Wan, Dr. X.L. Gao, J.M. Wang, J.J Chen, S.C. Luo, Dr. X.Y. Tan, Dr. L.H. Wu, Dr. H. G. Piao

吾将上下而求索

路漫漫其修远兮

Thank you for

your attentions!