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达 （ 2012-09-27

2007 : ˆ GMR˜

Peter Grünbergˆ Germany˜ Albert Fertˆ France˜

1988 ≠ Ţ · (Peter Grünberg) ع \/\| ŵ R . (Albert Fert)№≠ ΰ ˘ ỉ ׀׀ ‶ 2007 Â

Outlines

1.

1.1 点 荷 点

1.2 点

2.

2.1 a-C/Si 点

2.2 点

2.3 点

点 点

点 点

3. 点 荷

ˆ ˜ **magnetoresistance (MR)**

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

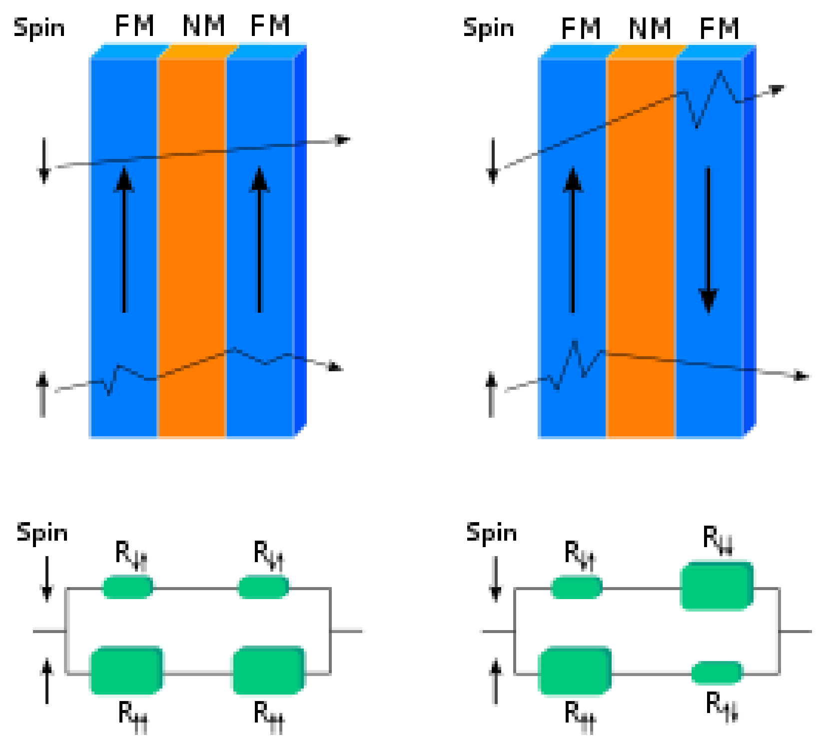
ordinary magnetoresistance (OMR),

OMR 1 2

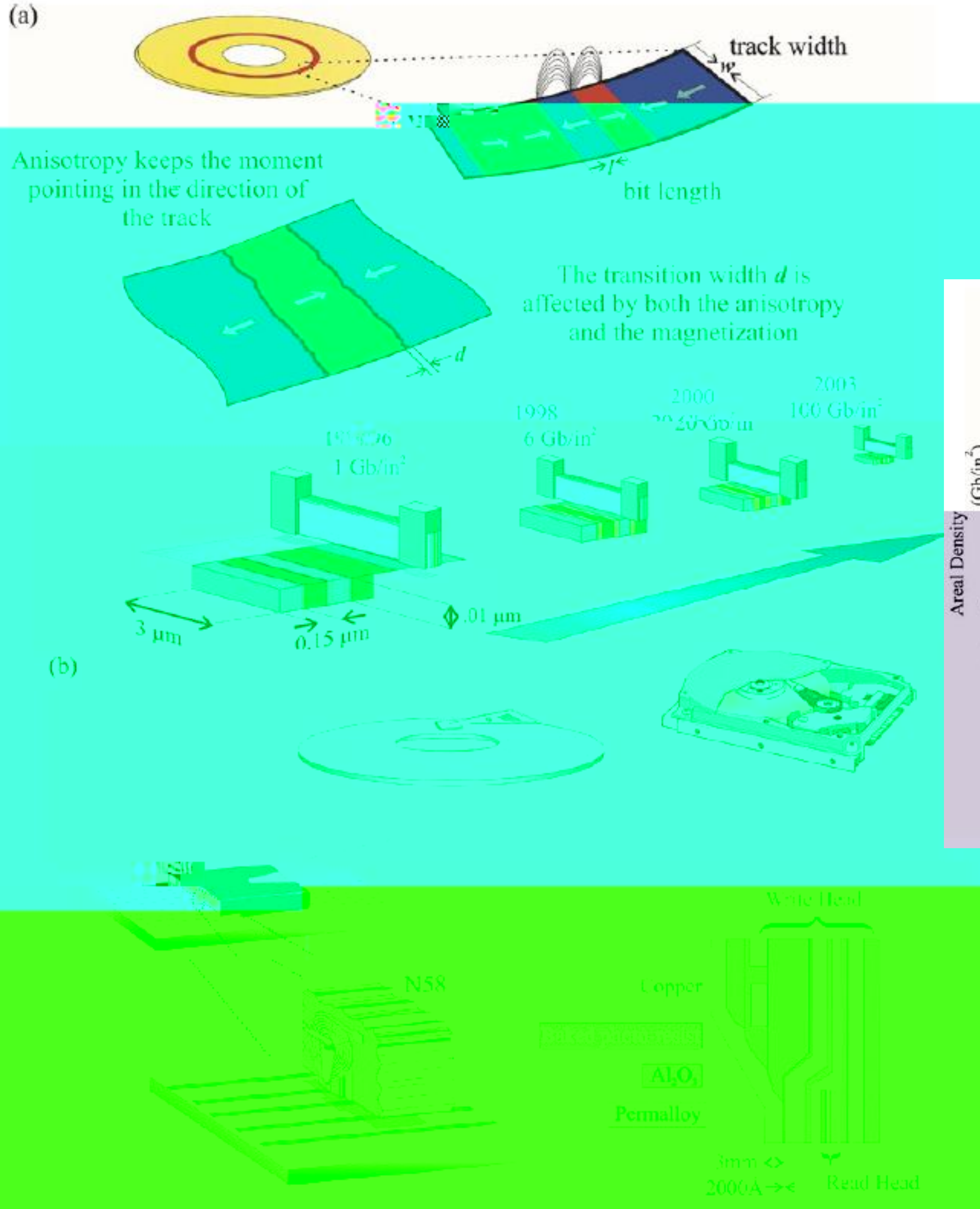
ˆ GMR˜

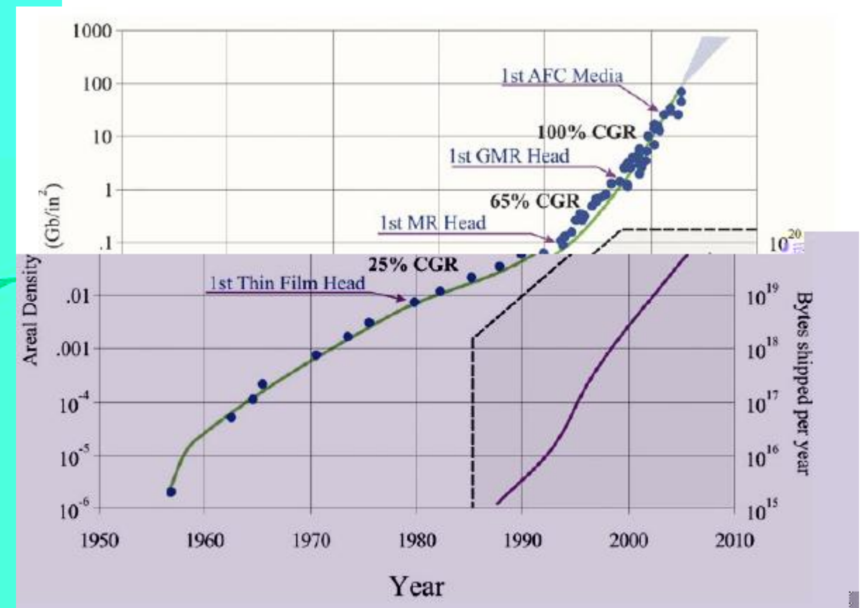
1988 ˘ ঽ __ ǟ __ ǟ
ؕ ˆ Fe/Cr/Fe ˜ ˘
Ӊ ঽ1.5% Â ↕
ঽ ǵ ˆ Fe/Cr˜ ˘ ą Ӊ
ঽ50% Â Ʉ MR ч ˆ GMR˜
Â

˘ ї ˘

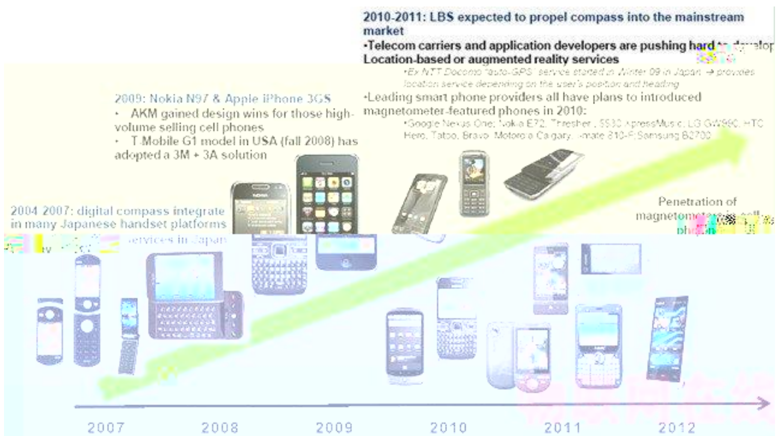


Application of GMR' read head in computer





Magnetic Sensor



2006–2012 年全球面向手机的惯性与磁性传感器市场预测

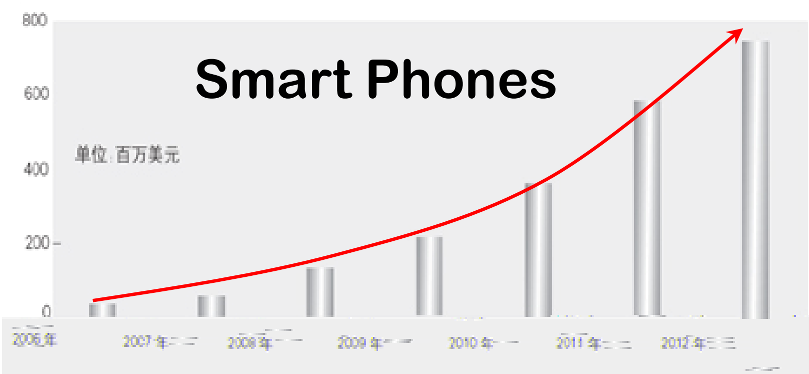
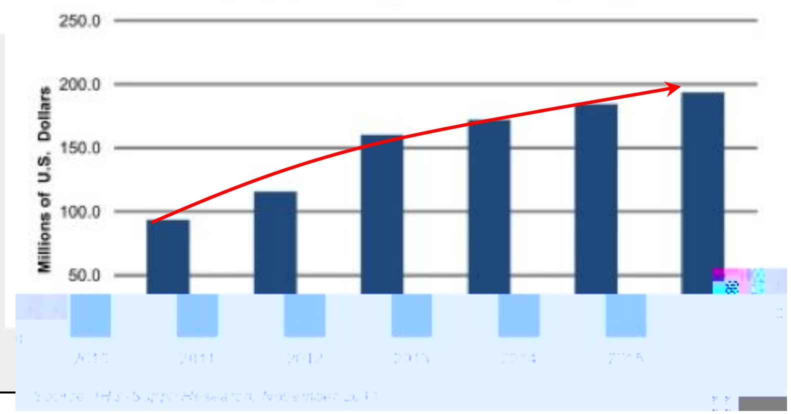


Figure 1: Worldwide Revenue Forecast for Magnetic Sensors in Automotive Motors (Millions of U.S. Dollars)



Electronic compass speed monitor magnetic location

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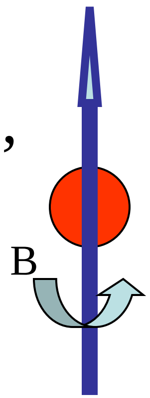
Spintronics

current

Semiconductor microelectronic devices

2-states device

e,



Charge (+,)

e=4.774 x10^{-10}e.s.u;
$_B$=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 materialsˆ 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 Ð ˘ ˘ w̃ Ѣ
MR ℗ ˛

Semiconductor based spintronic materialsˆ 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

Outlines

1.

   1.1 点 荷 点

   1.2 点

2.

   2.1 a-C/Si 点

   2.2 点

   2.3 点

   点 点

   点 点

3. 点 荷

MR in magnetic materials

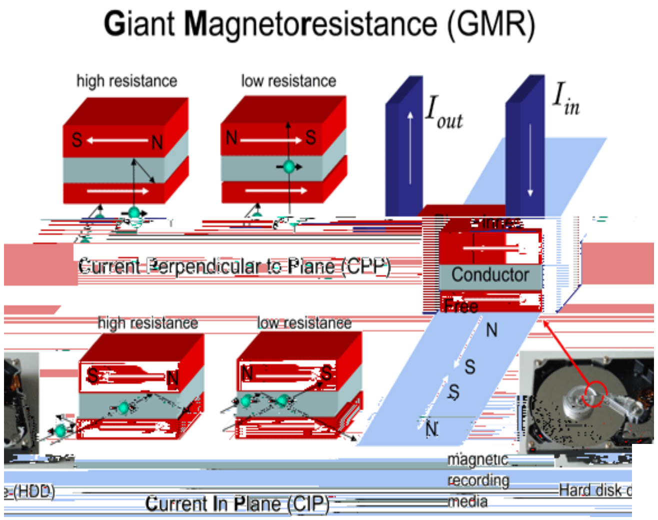
Giant magnetoresistance (GMR)

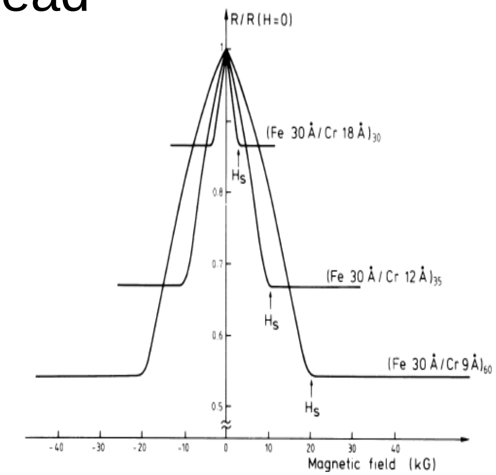
Tunneling magnetoresistance (TMR)

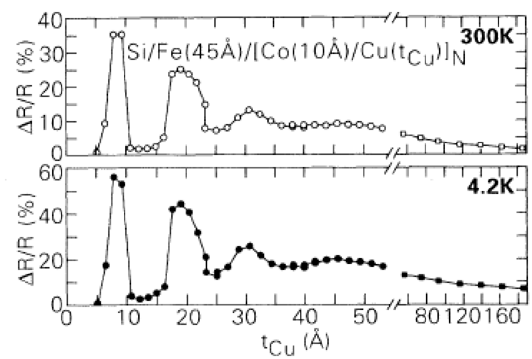
Colossal Magnetoresistance (CMR)

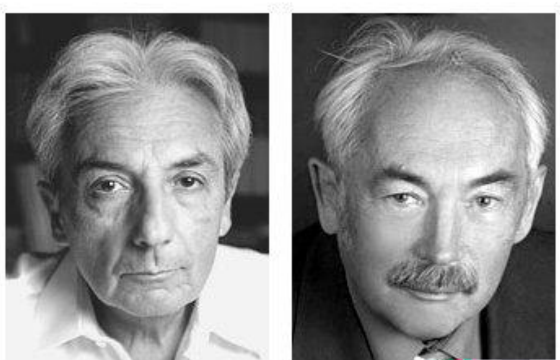
GMR: spin dependent scattering

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

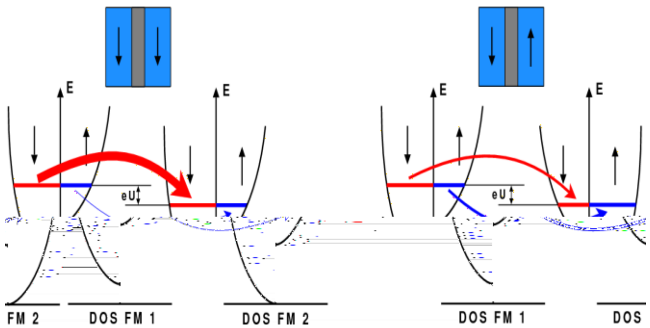
Baibich, Phys. Rev. Lett, 1988

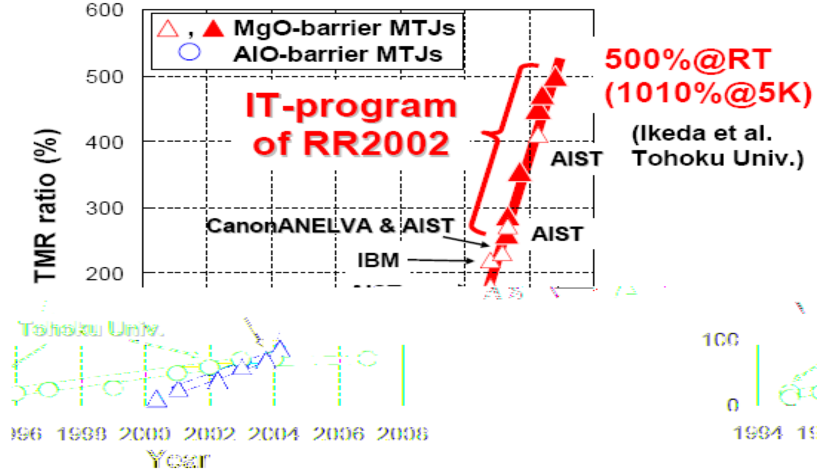
http://www.nims.go.jp/apfim/GMR.html

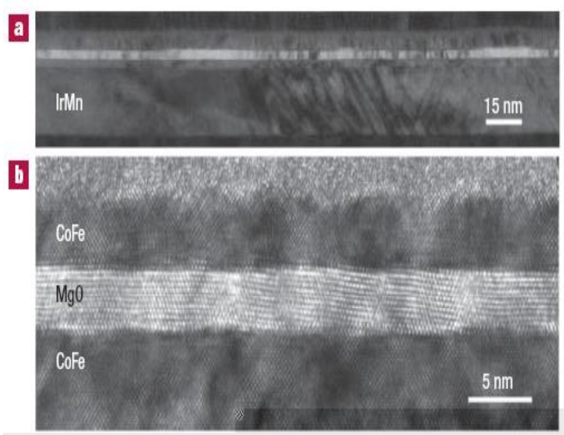
Parkin, Phys. Rev. Lett, 1991.

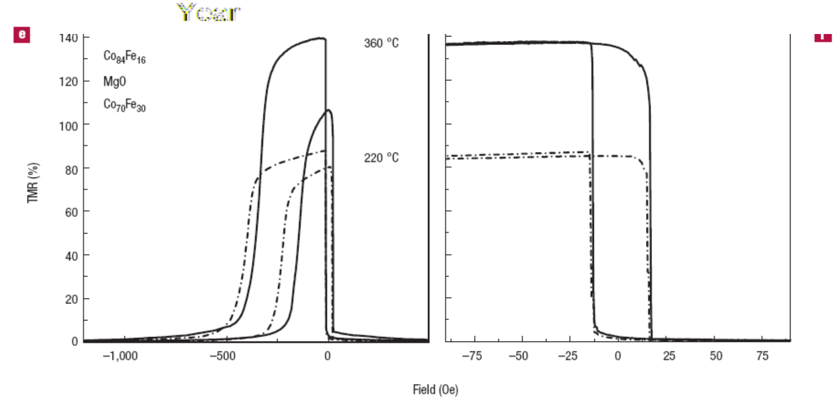
TMR: spin dependent tunneling

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







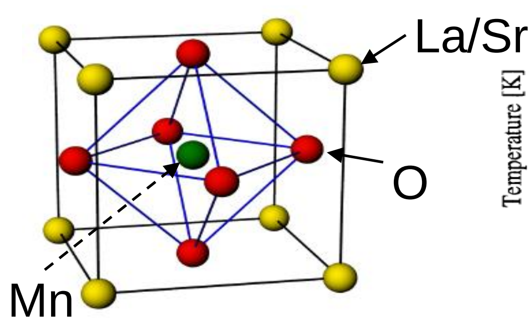


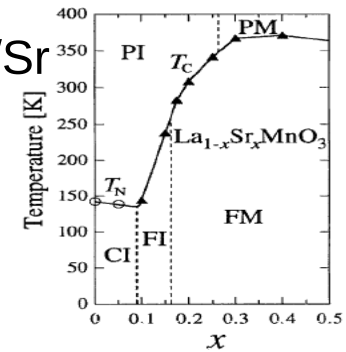
Ikeda et al has achieved 600% TMR at room temperature with MgO barrier.

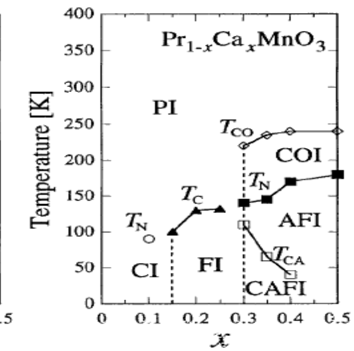
T. Miyazak, JST-DFG Workshop, 2008. Parkin, Nat. Mat. 2004.

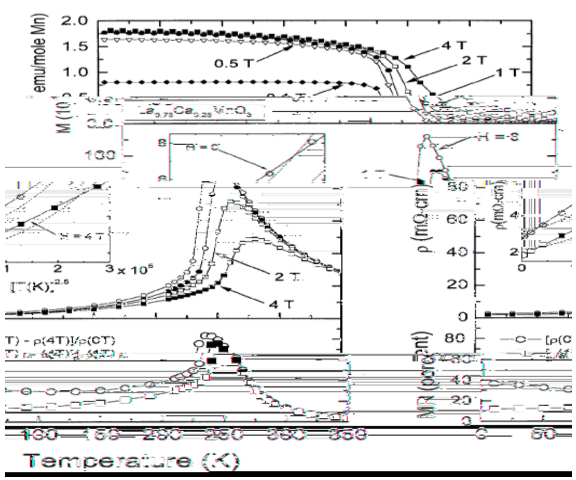
CMR: spin-orbit-charge interplay

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

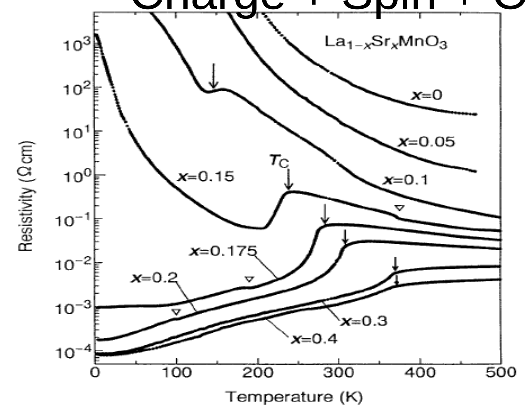








Charge + Spin + Orbit



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

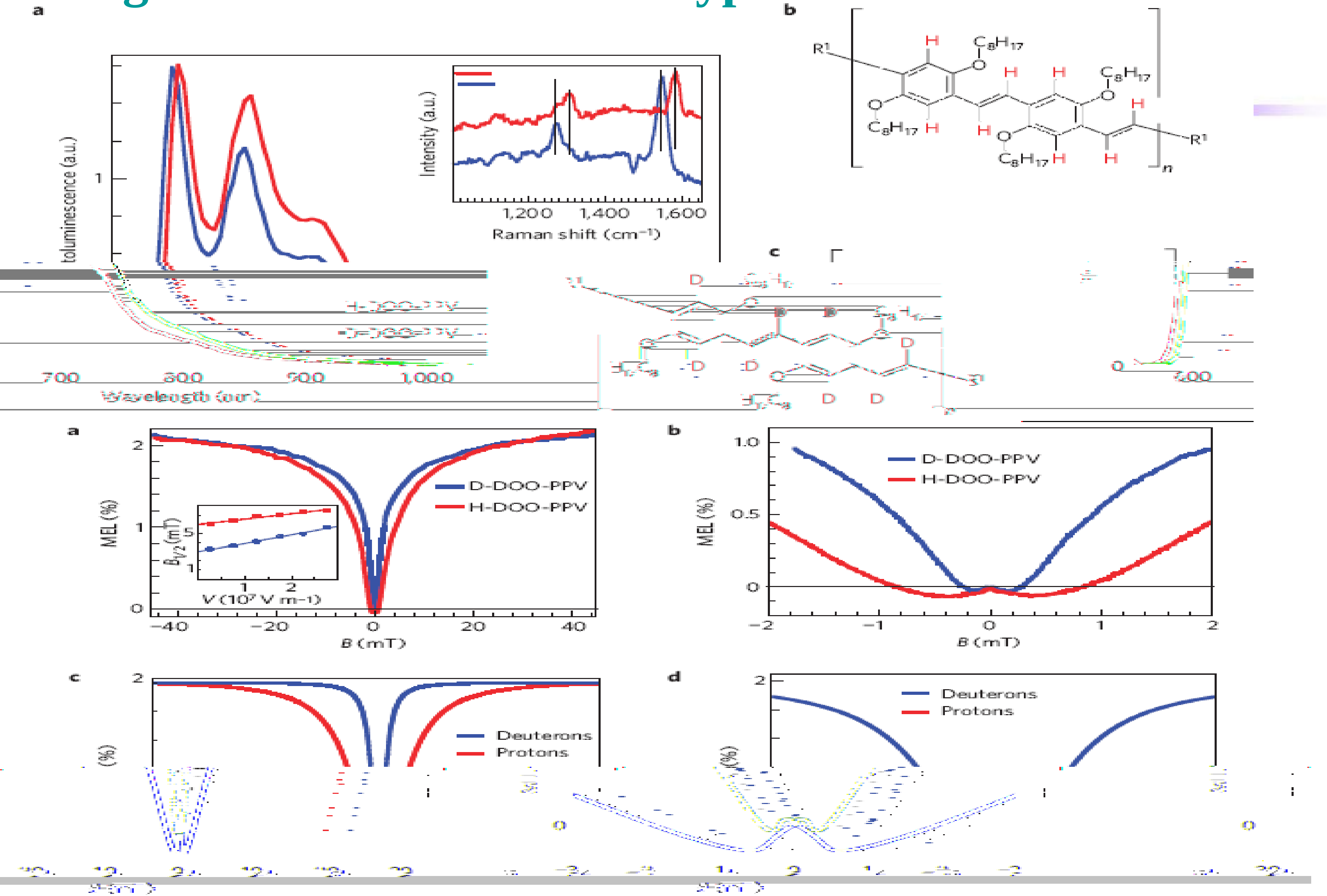
MR in non-magnetic materials

MR in Organic materials

MR in Graphene/carbon nanotubes

Inhomogeneous MR (IMR)

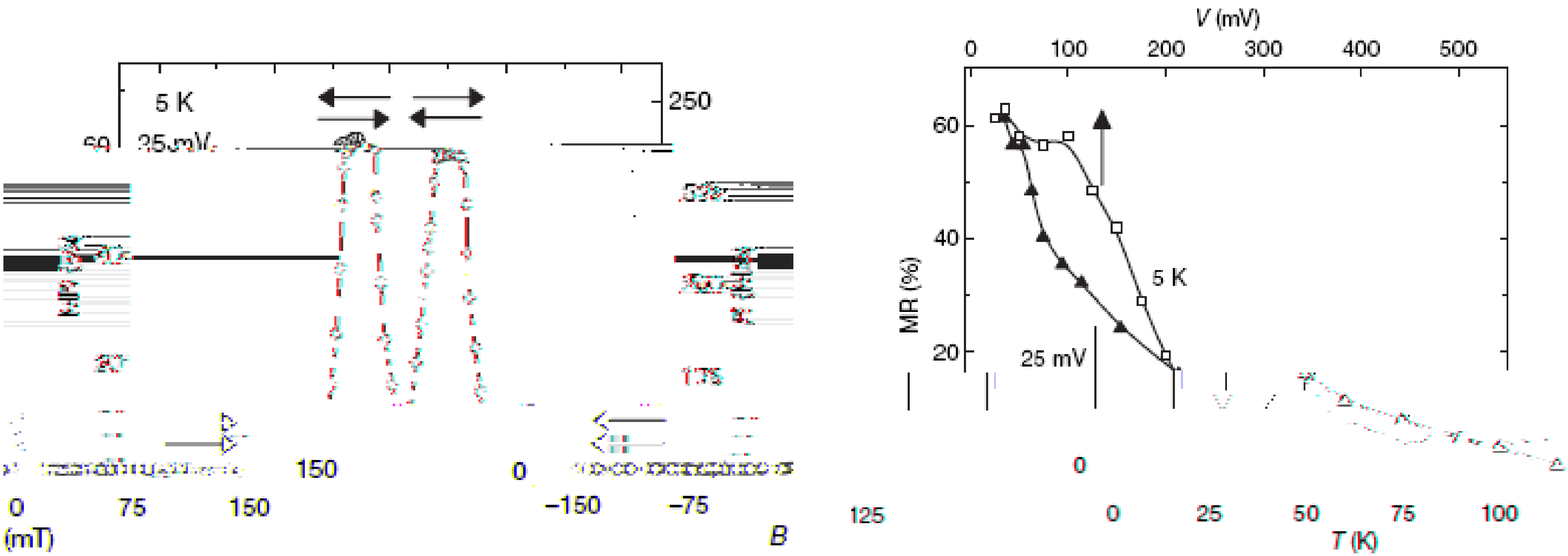
Organic MR: related with Hyperfine interaction?



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

MR of carbon nanotubes

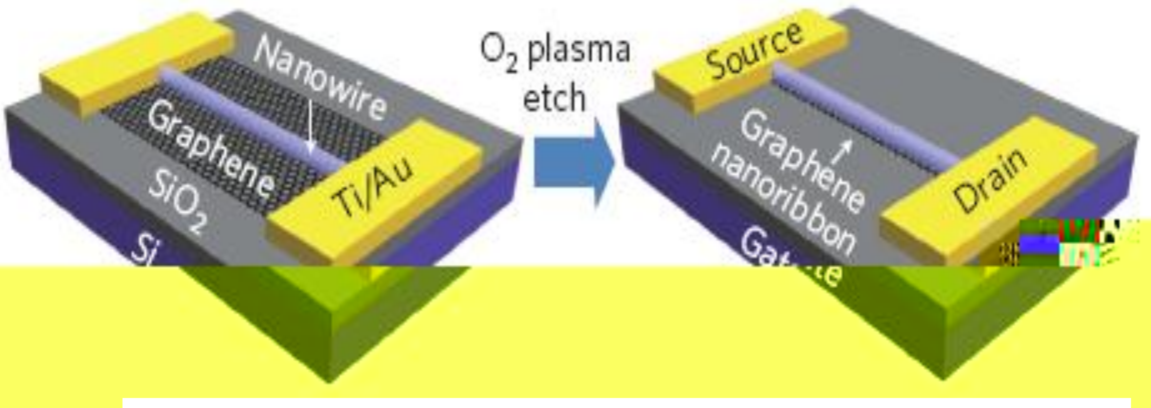
The MR of Carbon nanotube have been only observed in the low temperature. MR=61% at 5K, and it disappeared at 120K.

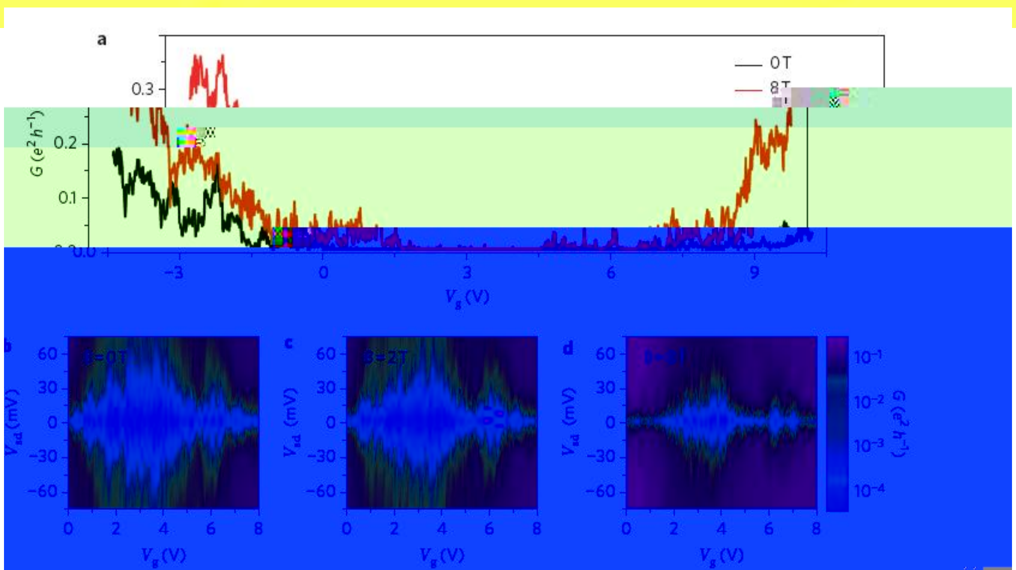


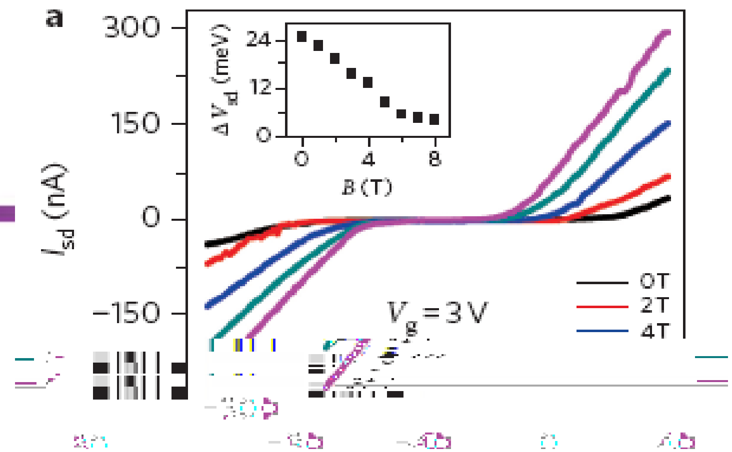
L.E. Hueso et al NATURE 445, 410 (2007)

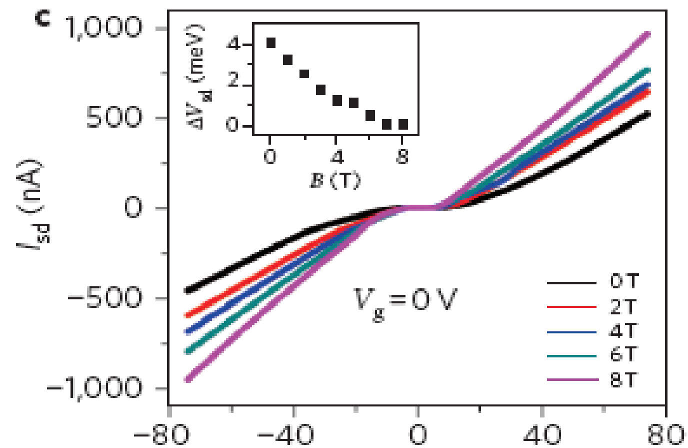
MR in Graphene Nanoribbon: quantum confinement

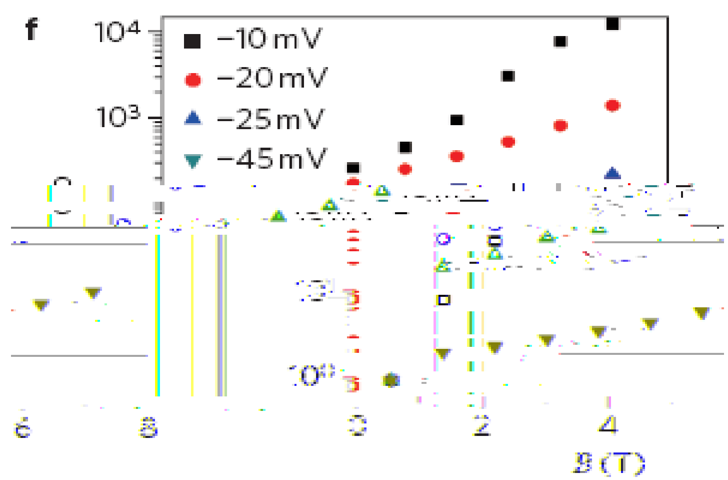
MR ~-100% at 1.6K and MR, -50% at 285K





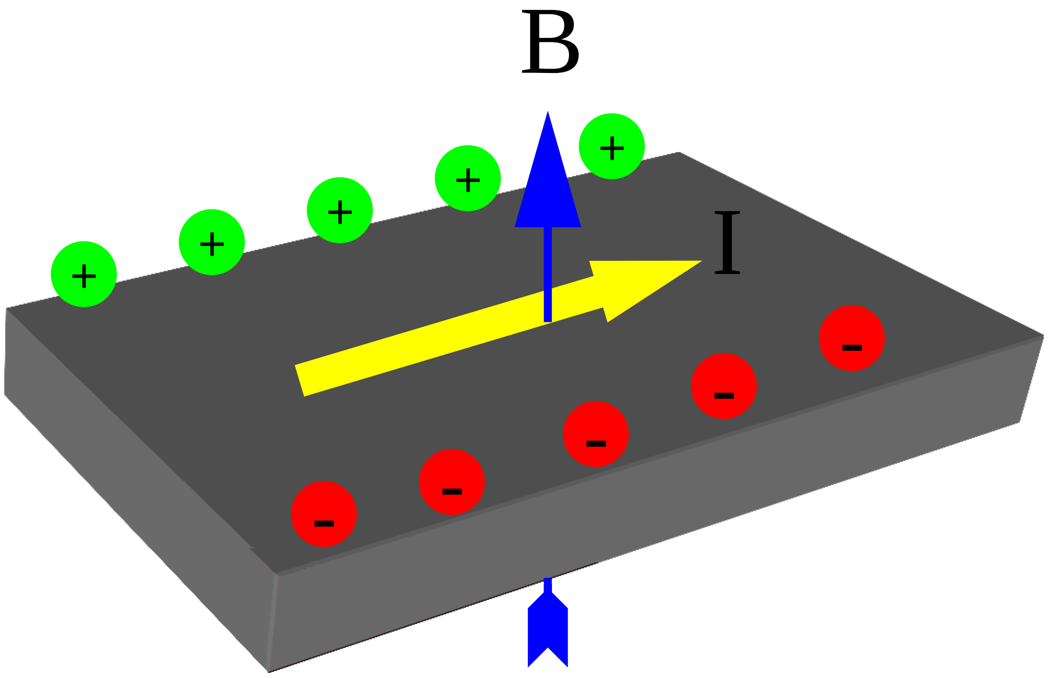






JW Bai et al, Nat. Nanotech. 5 (2010) 655.

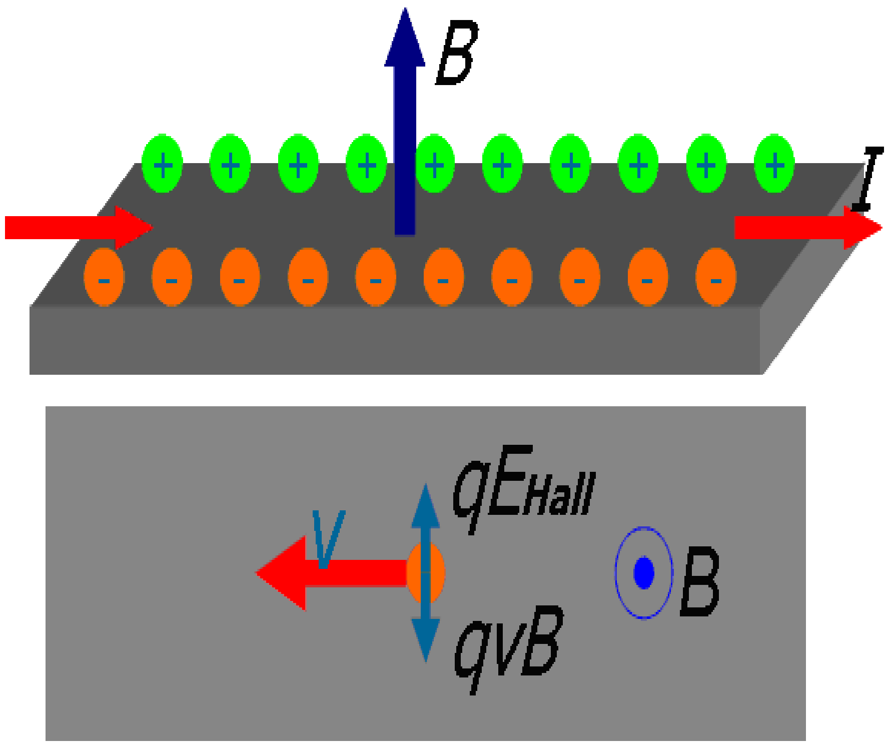
Inhomogeneous MR (IMR)



Origin: Lorentz Force

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

Ordinary MR: orbit related



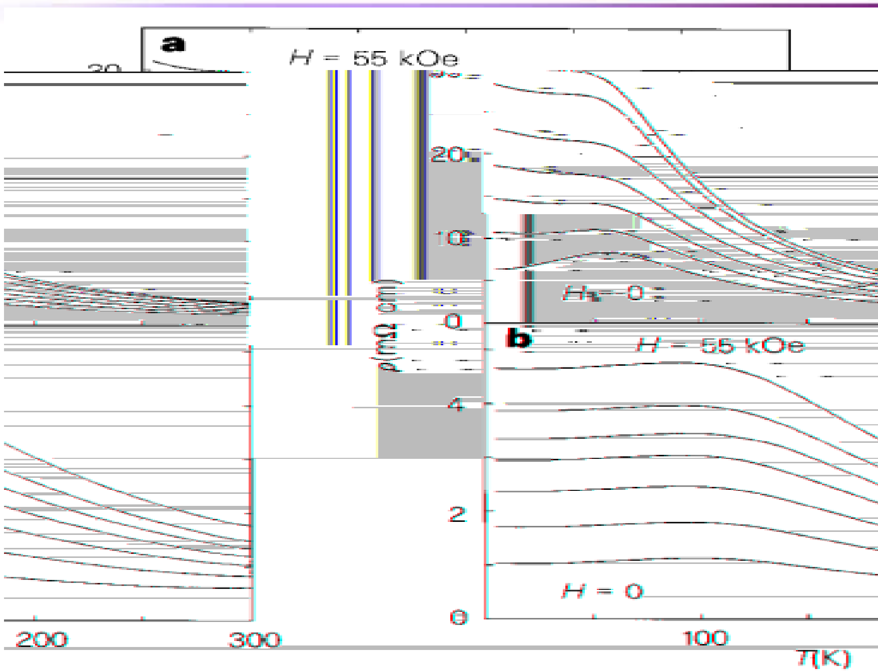
No MR would be detected in a ideal crystal in that measurement setup!!!

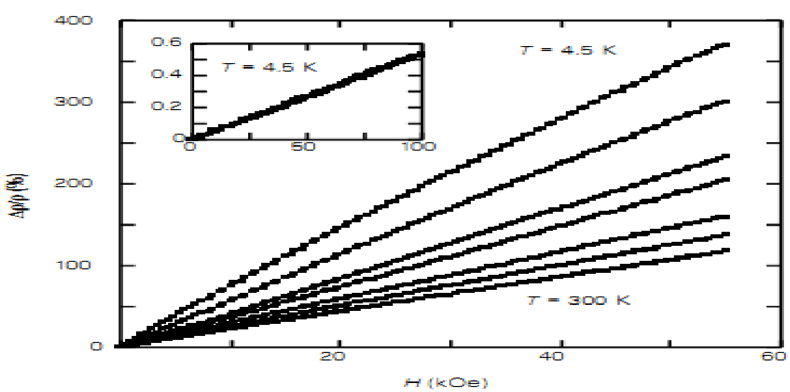
Homogenous [redacted]

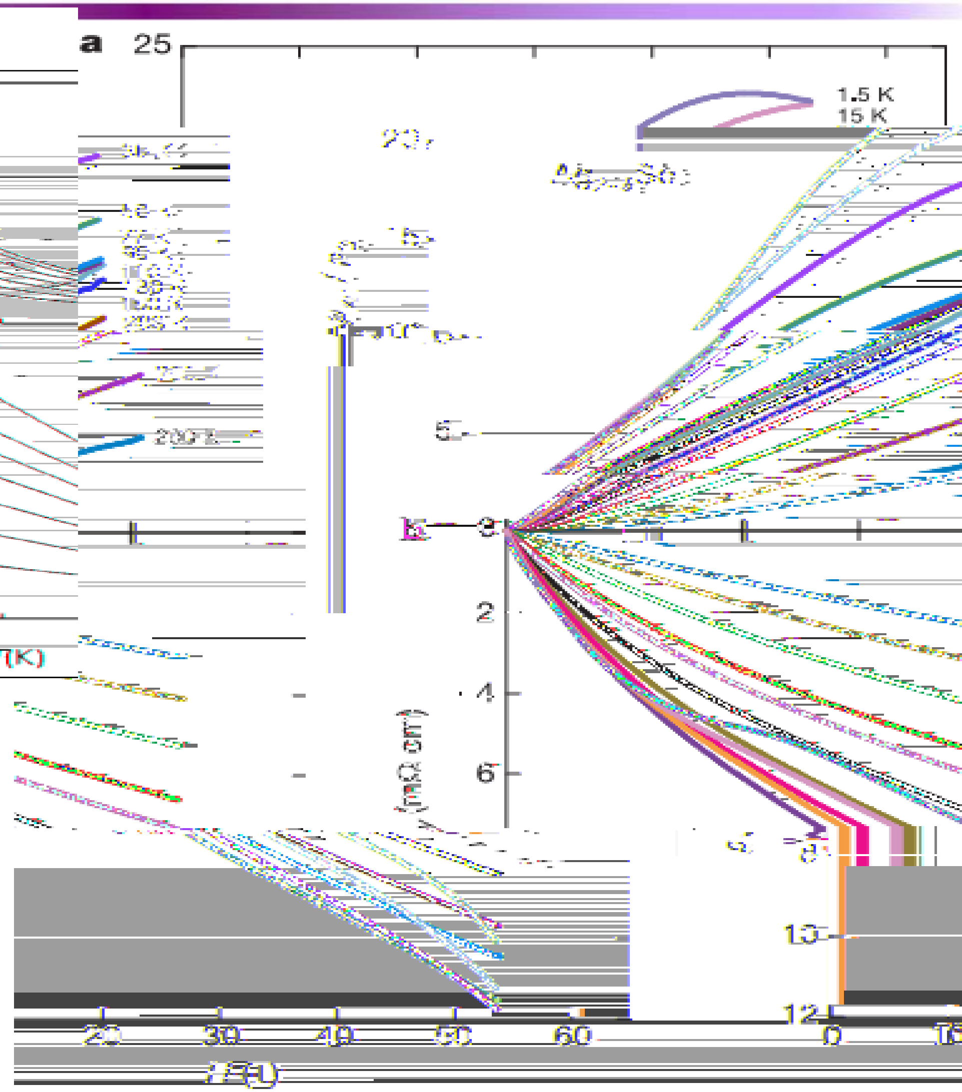
[redacted] Force

MR = 0 %

Doped silver chalcogenides

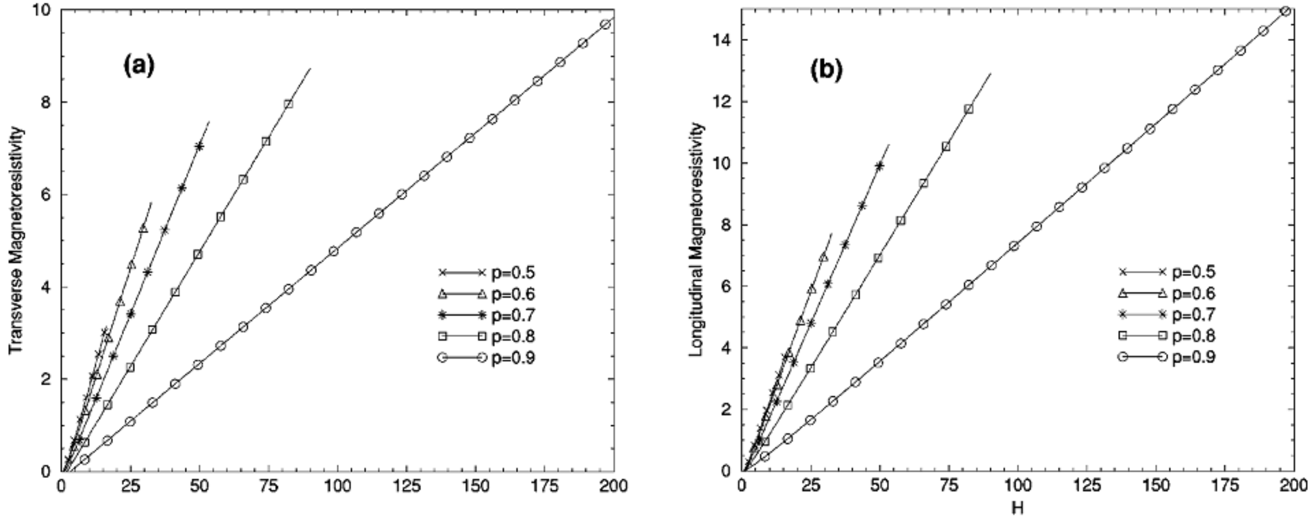


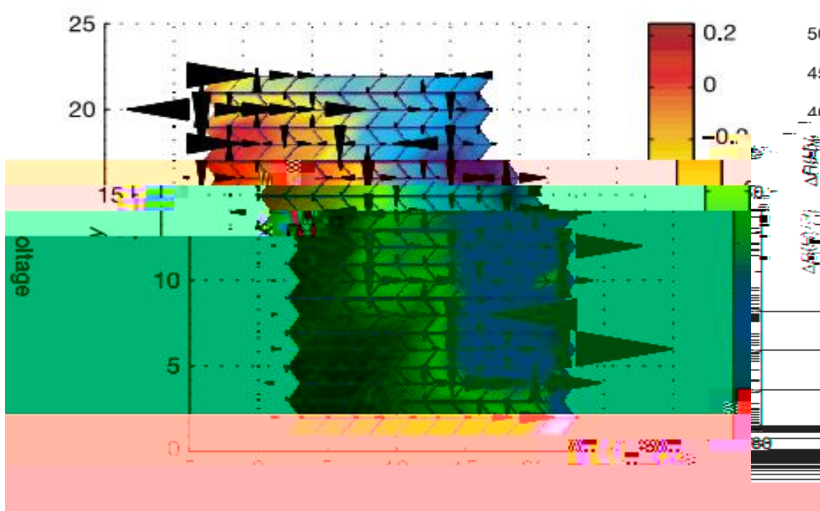


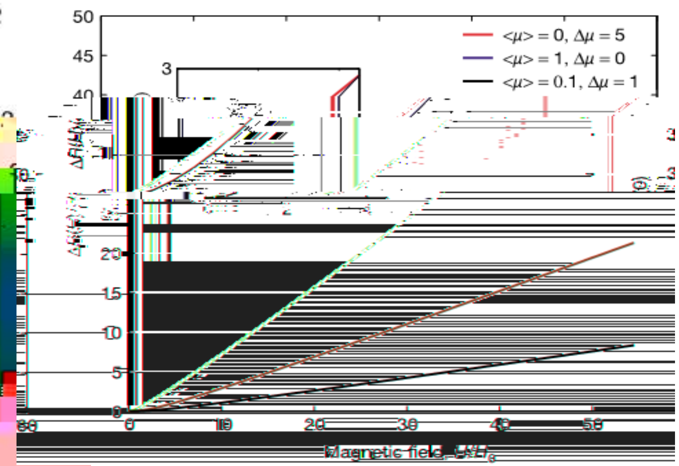


Xu, Nature, 1997; Rosenbaum, Nature, 2002.

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

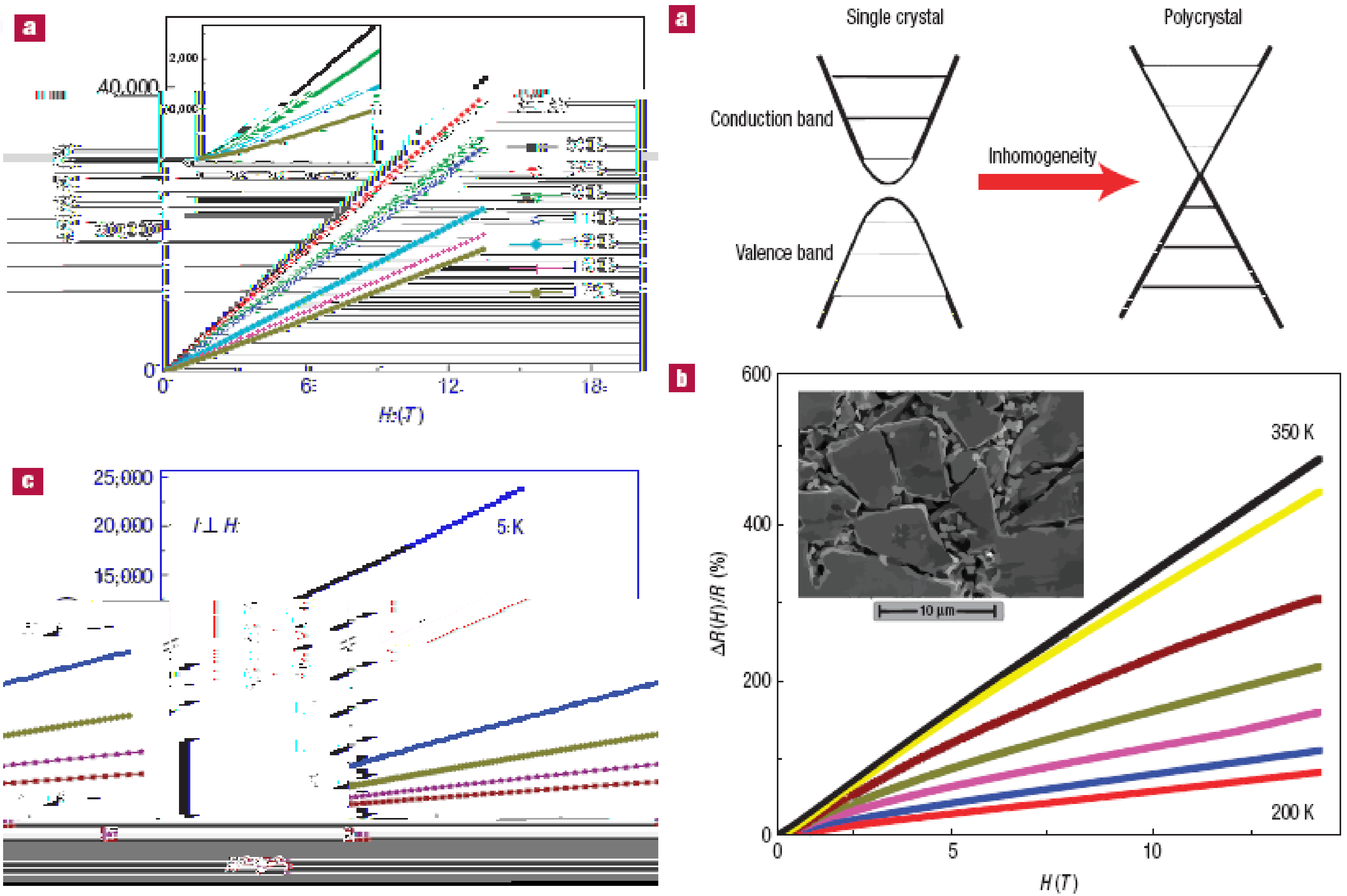






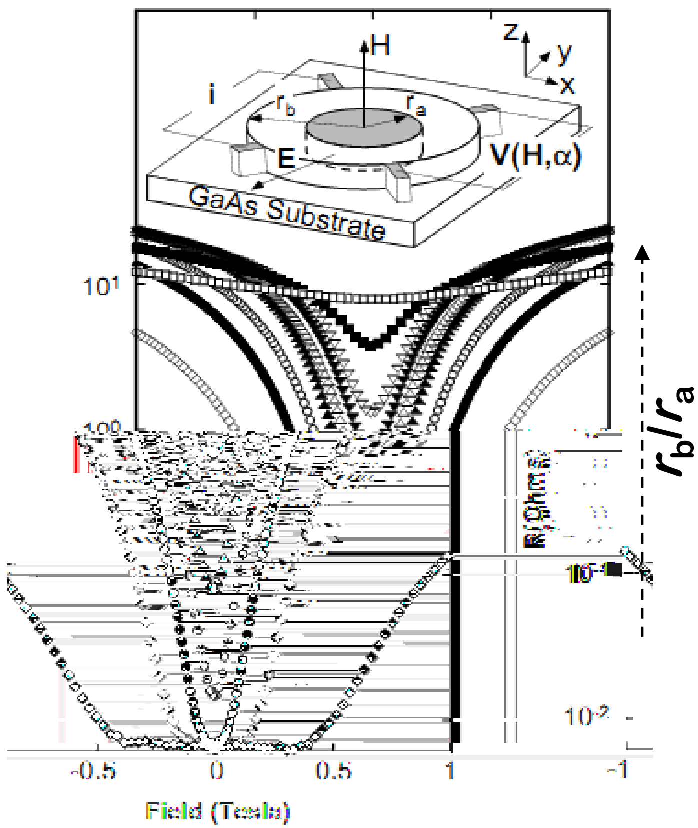
Parish & Littlewood, Nature, 2003

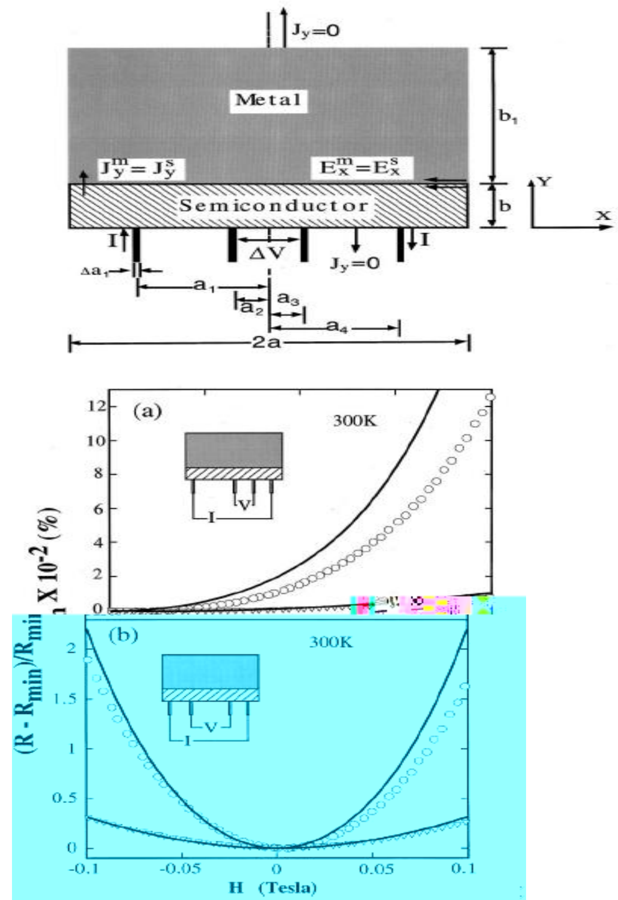
InSb linear MR



Hu, Nat. Mat. 2008.

Geometrical Enhancement





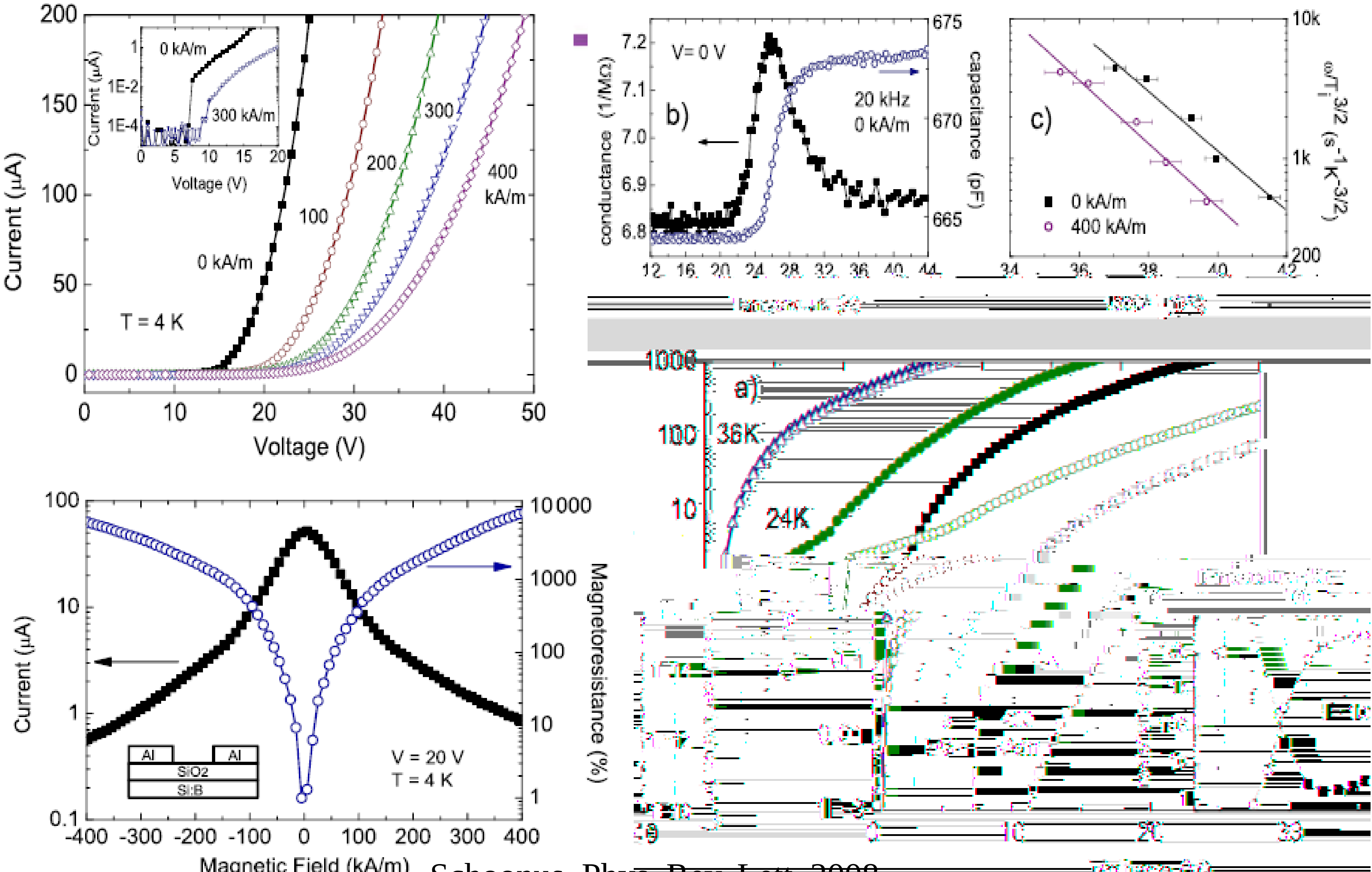
Corbino Disk: R_b/R_a ratio

Solin, Science, 2000.

Spacing between electrodes

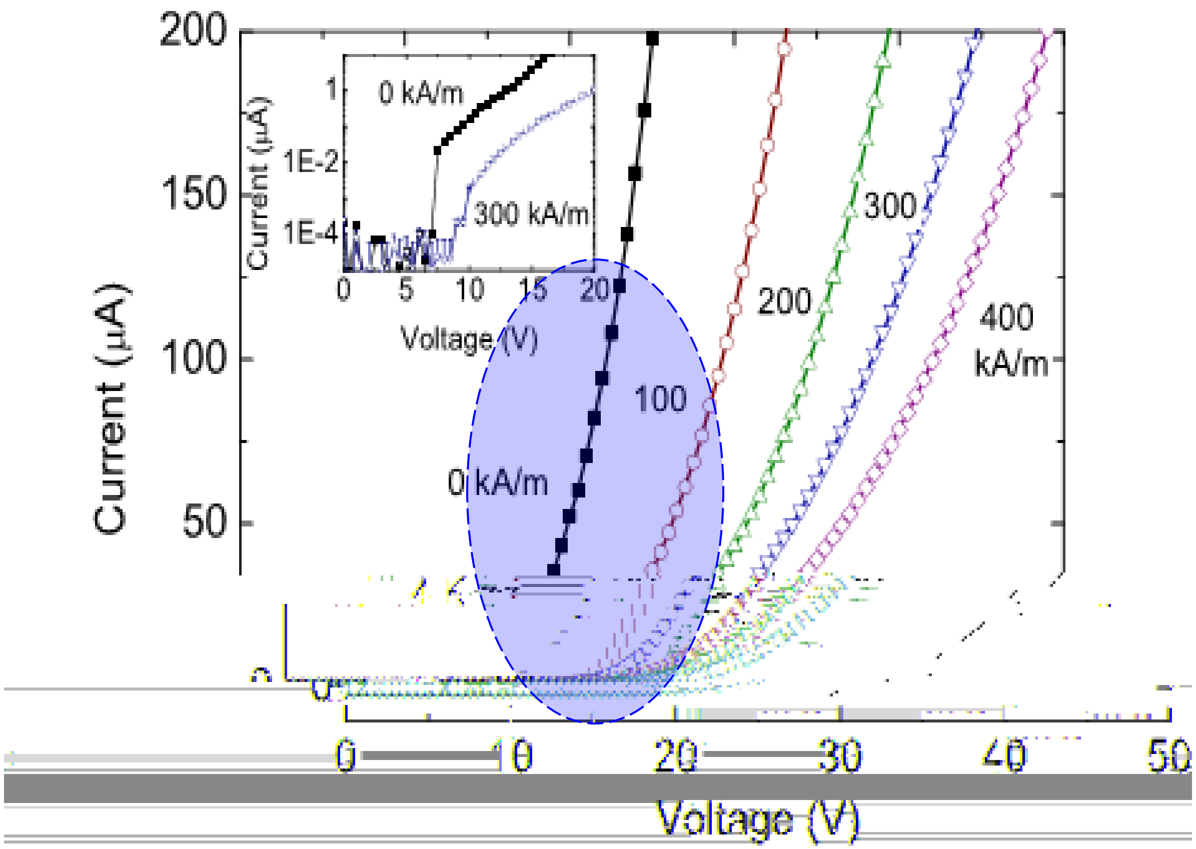
Solin, Appl. Phys. [redacted]

Silicon MR at low temperature: related with wave shrinkage?



Schoonus, Phys. Rev. Lett. 2008.

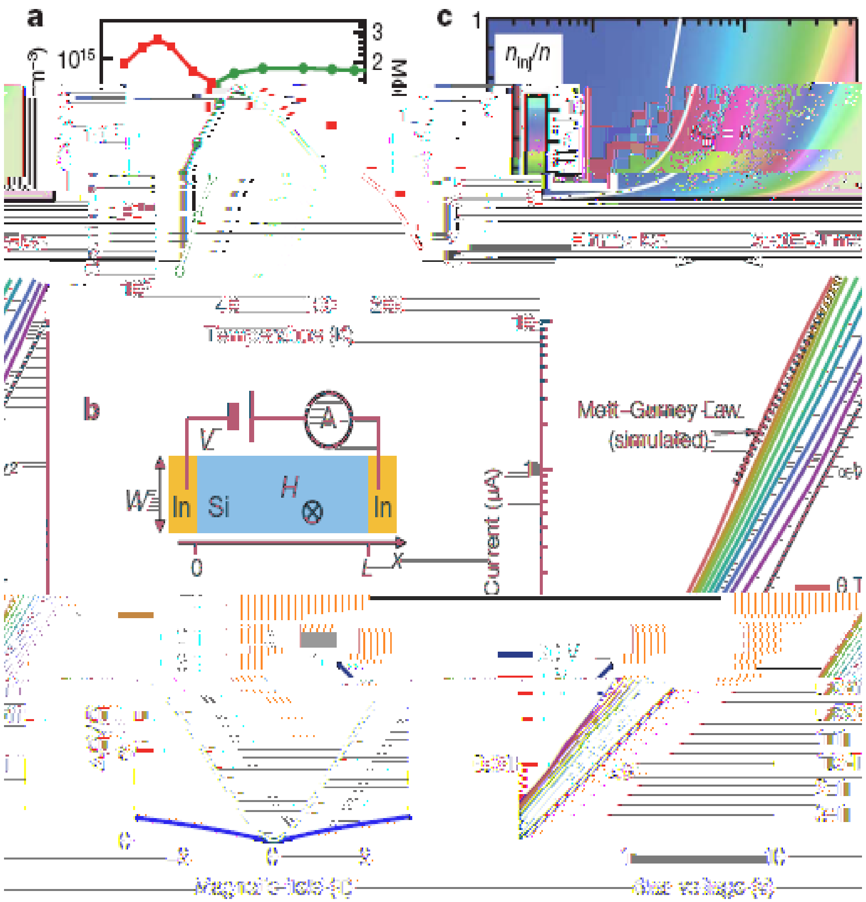
Schoonus's Case

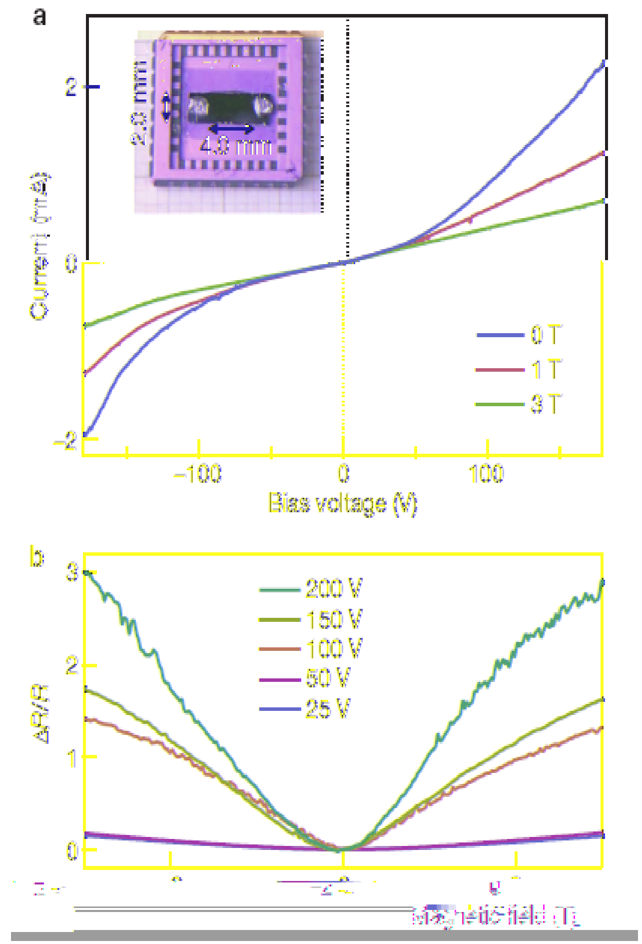


MRmax ← Avalanche Breakdown ← Breakdown voltage ← *V/B*

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



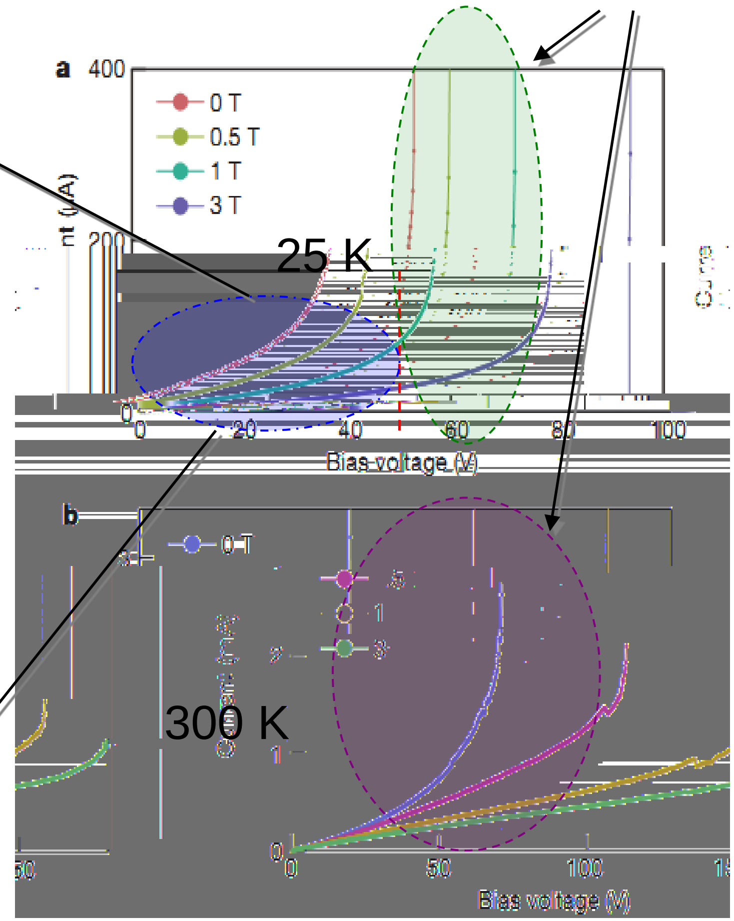


MP Delmo et al, Nature **457**, (2009) 1112

Delmo's Case

MR max

[redacted]



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Outlines

1\.

1.1 点 荷 点

1.2 点

2\.

2.1 a-C/Si 点

2.2 点

2.3 点

点 点

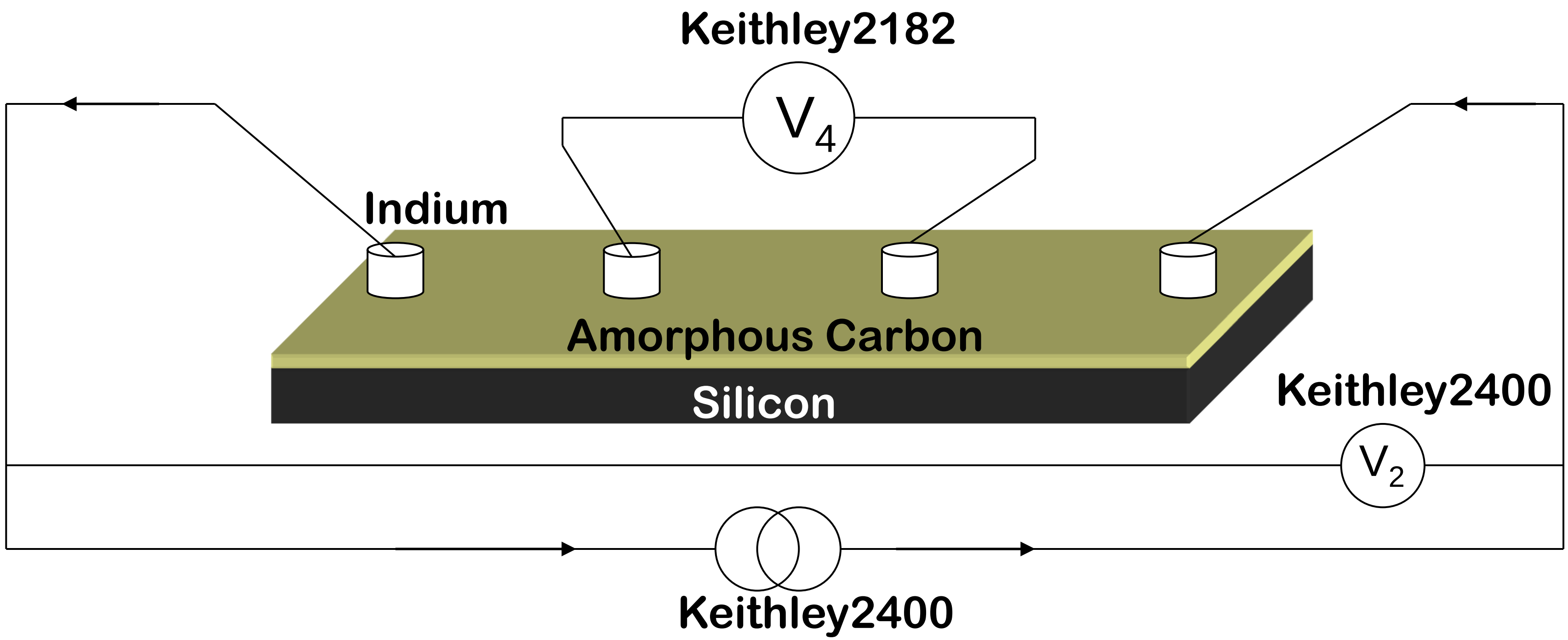
点 点

3\. 点 荷

MR in a-C/Si heterojunctions

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

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



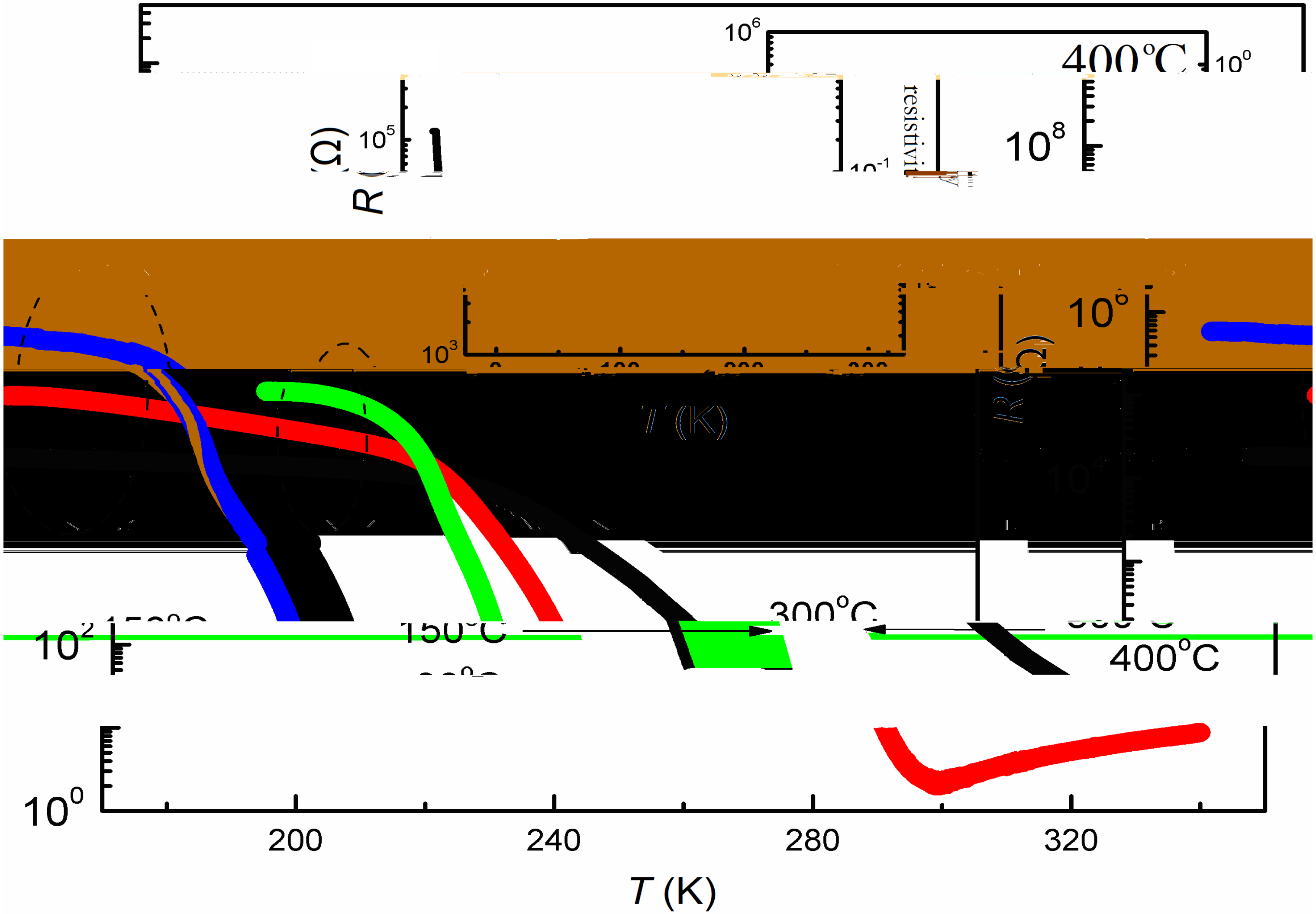
Research Methods

Film grown by Pulse [redacted]

TEM HRTEM EE [redacted]racterize structure of a-C

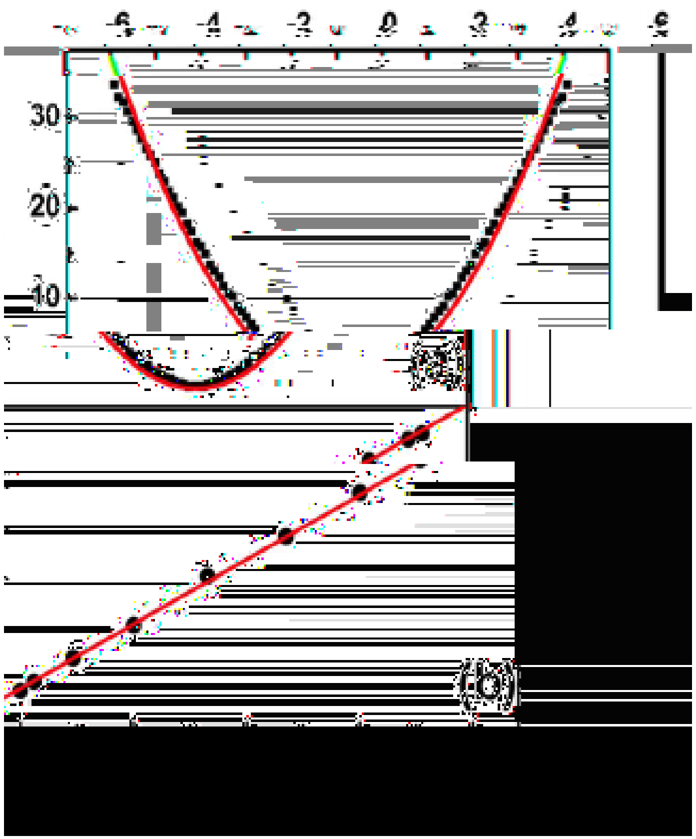
2-electrode and 4-electrode measurements with Keithley2400 2182 in MPMS or PPMS

Transport Properties of a-C/Si

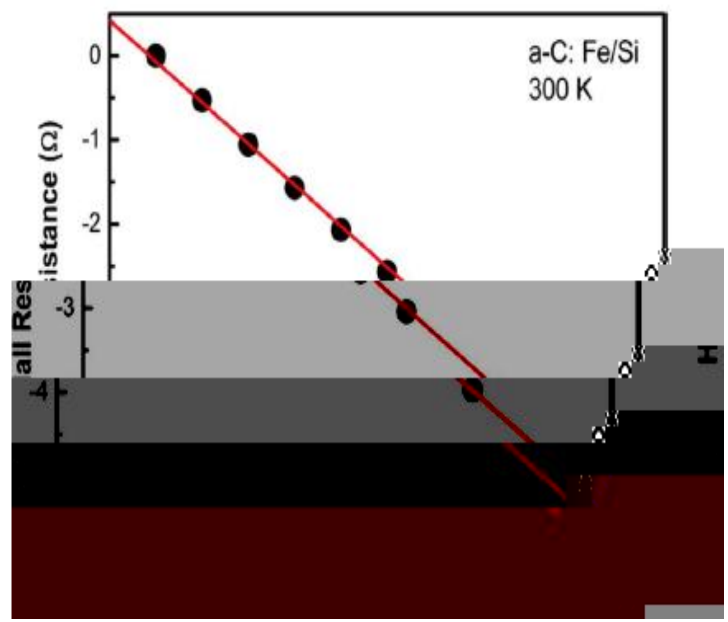


Channel Switching　low T current in a-C（ High T current in Si

MR in a-C/Si



$MR \quad \cos^{2}$



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

Outlines

1.

1.1 点 荷 点

1.2 点

2.

2.1 a-C/Si 点

2.2 点

2.3 点

点 点

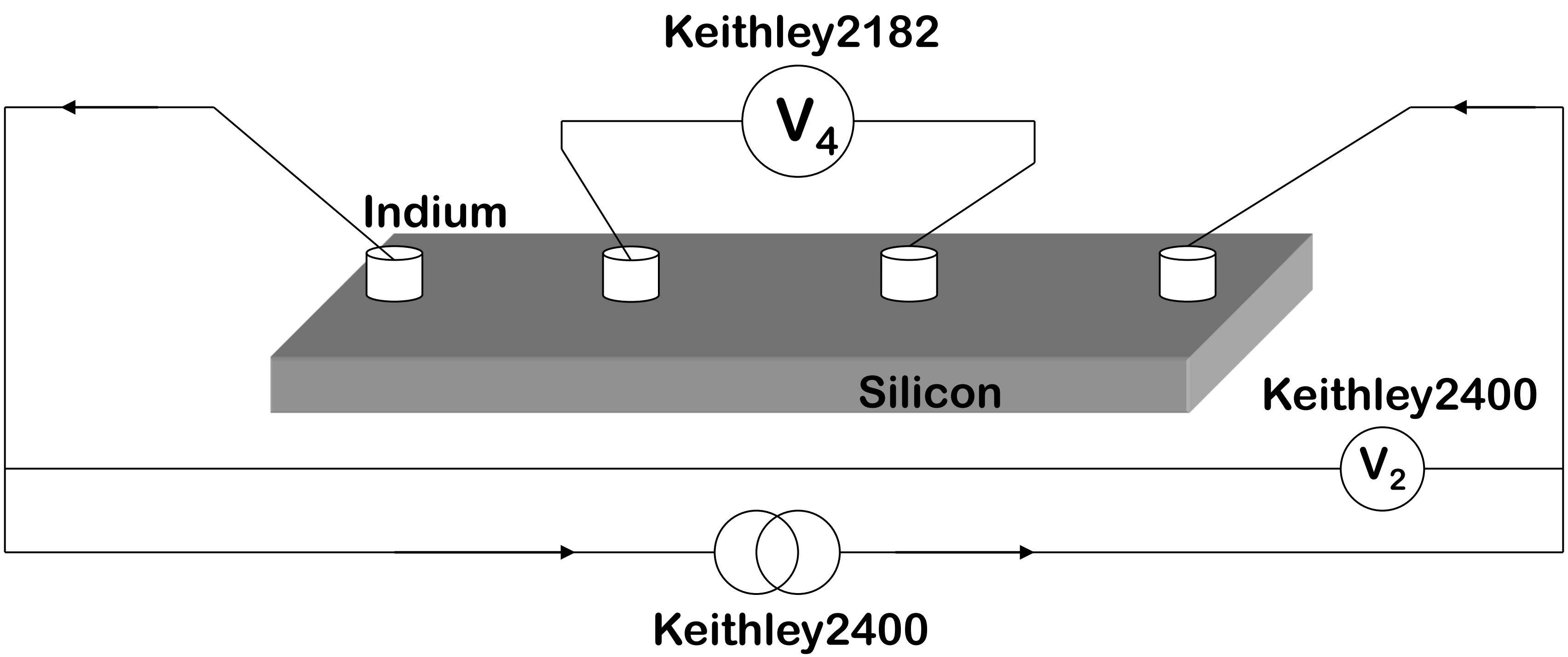
点 点

2.4 GaAs 荷 Ge 点

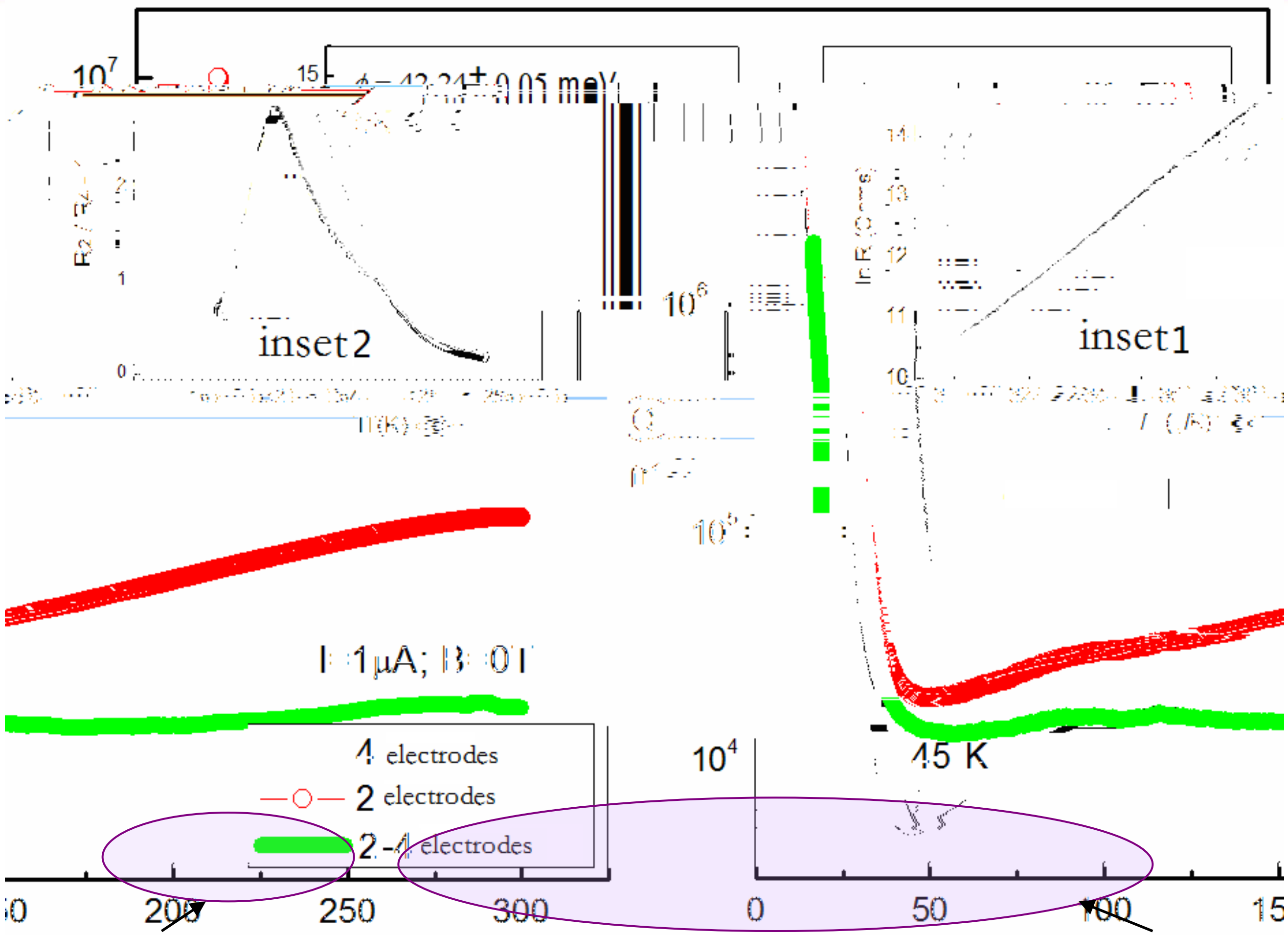
3. 点 荷

R in silicon

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



Electro-transport properties of Si



Delocalized carriers (

R-T determined by carrier density (

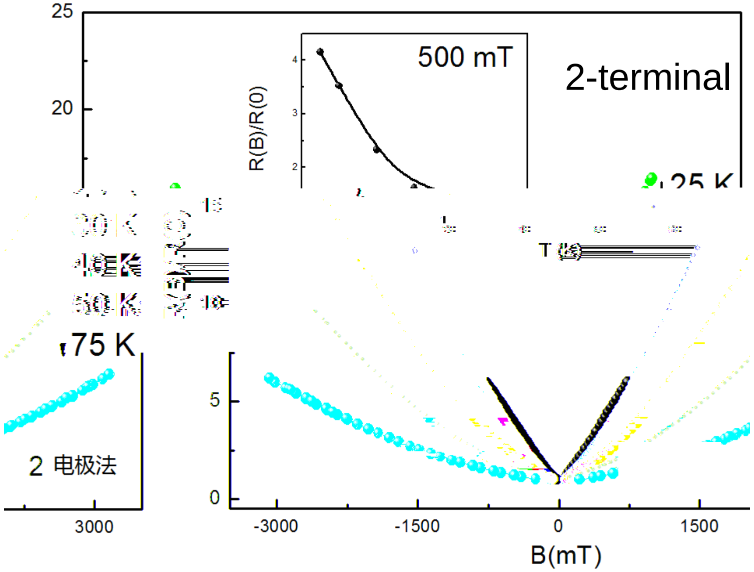
Carriers froze out from E_C

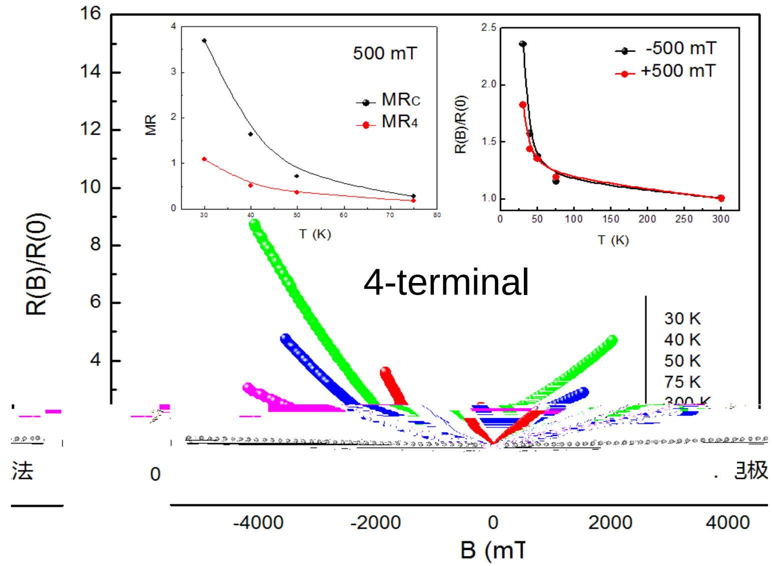
Delocalized carriers (

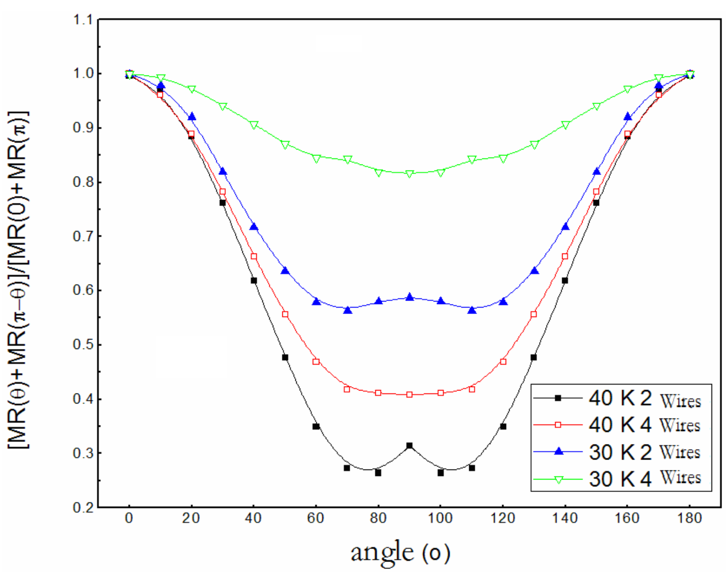
R-T determined by mobility

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 (PR [redacted]

Outlines

1.
   1.1 点 荷 点
   1.2 点
2.
   2.1 a-C/Si 点
   2.2 点
   2.3 点
   点 点
   点 点
   2.4 GaAs 荷 Ge 点
3. 点 荷

Si based MR device with symmetric electrodes

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

: 3000 *cm, 1000 *cm

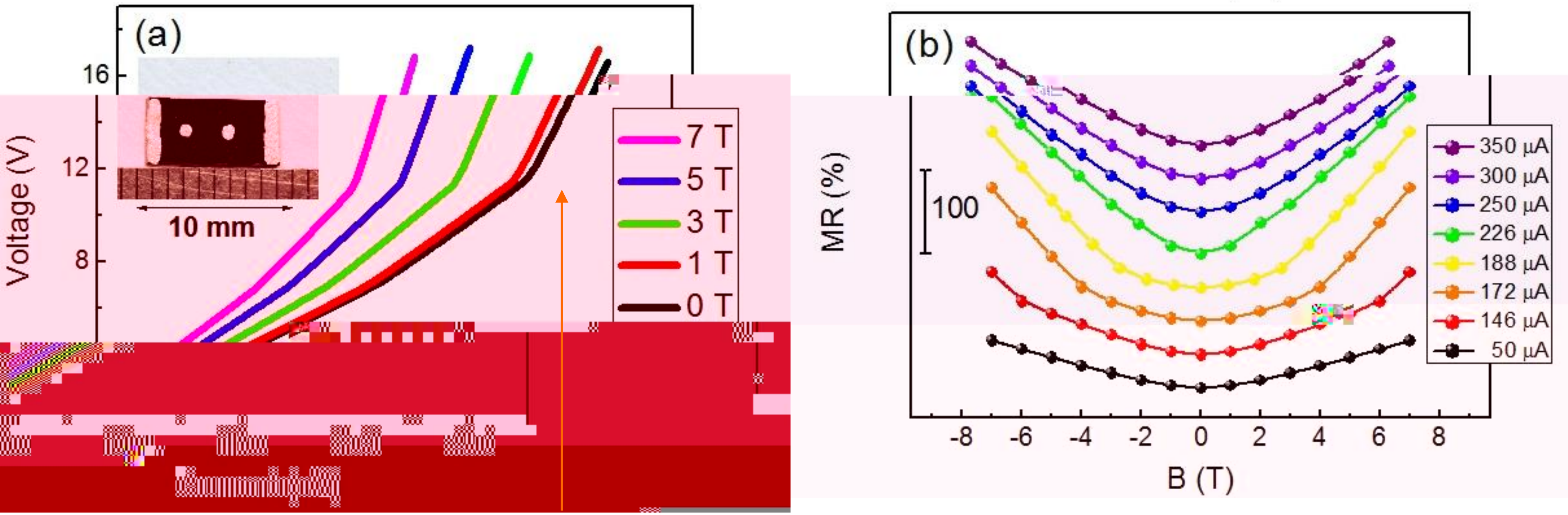
: 1200 cm^2/Vs

: 100~200 s (Bulk minority lifetime)

Electrode: Indium

CH Wan, XZ Zhang, et al, Nature **477**

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)

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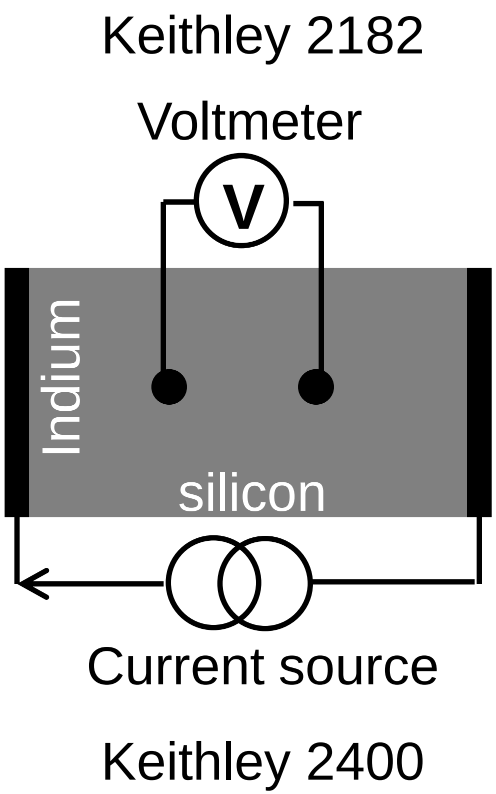
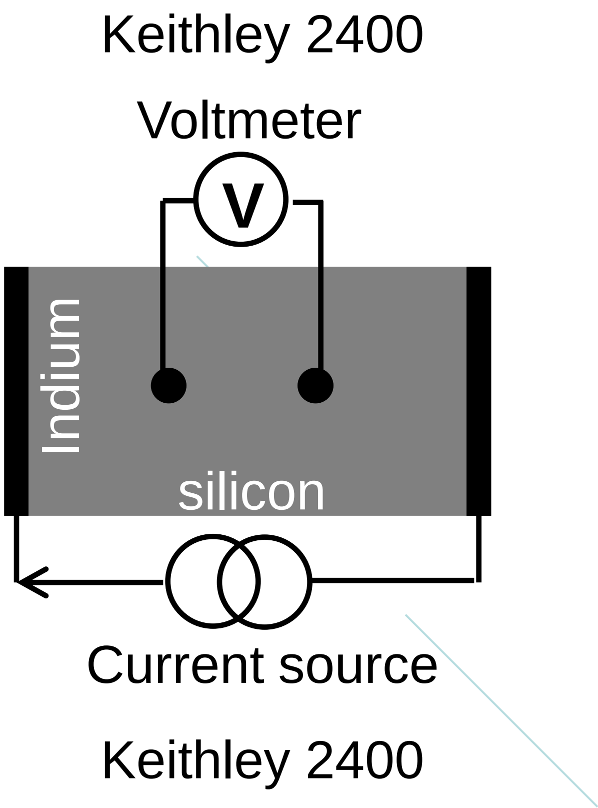
达点 （

Method 2



Method 1

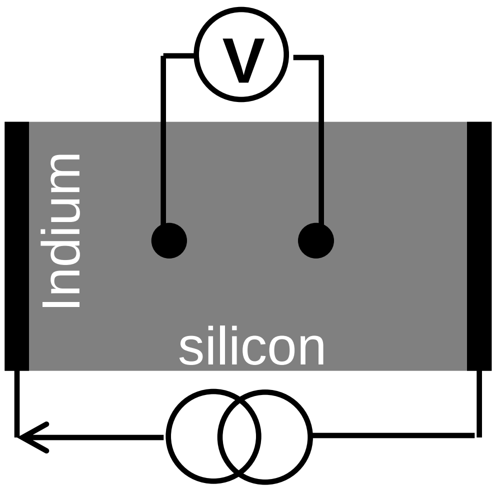


达点 （ Keithley2400 关 （

Method 2

Keithley 2182

Voltmeter



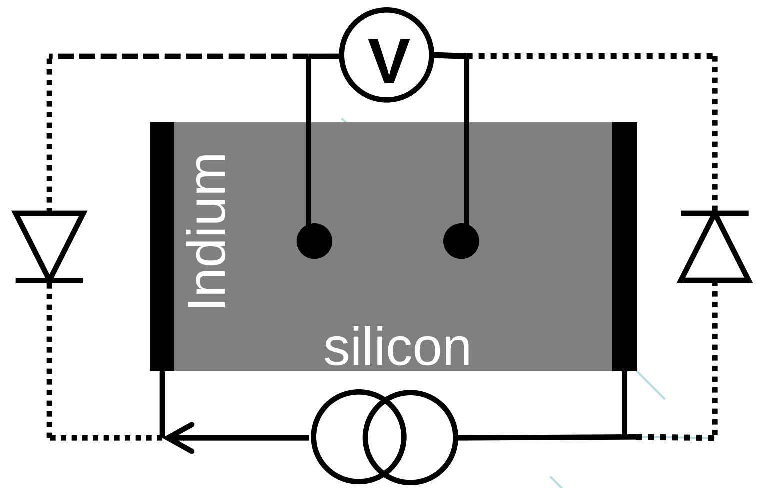
Current source

Keithley 2400

Method 1

Keithley 2400

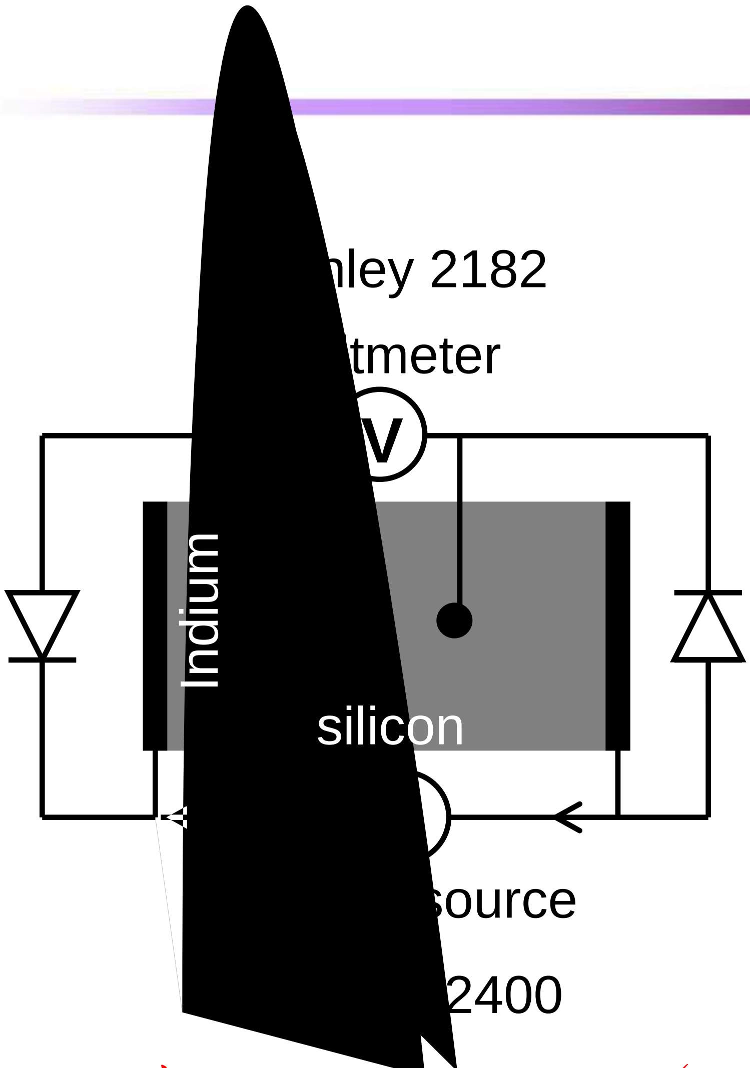
Voltmeter

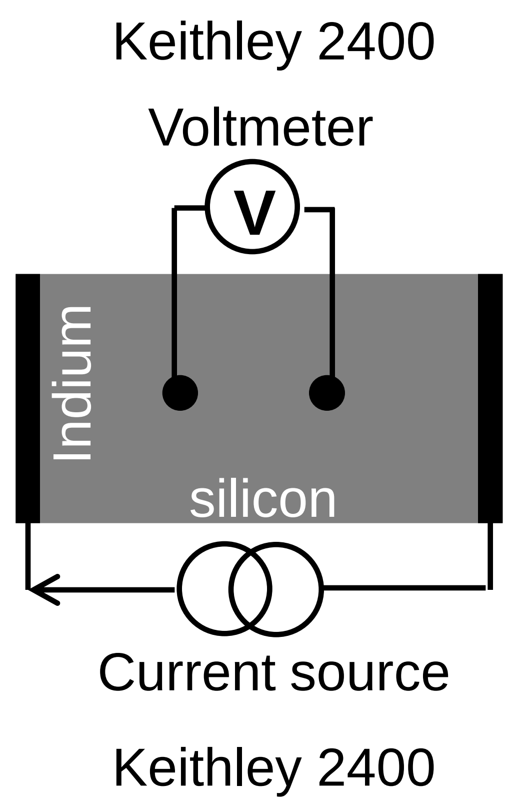


Current source

Keithley 2400

method 2 关 的





关 （
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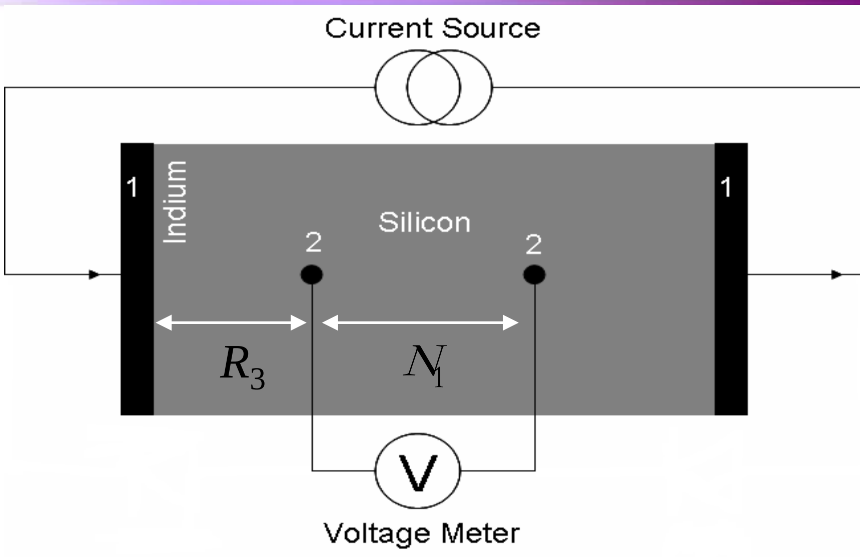
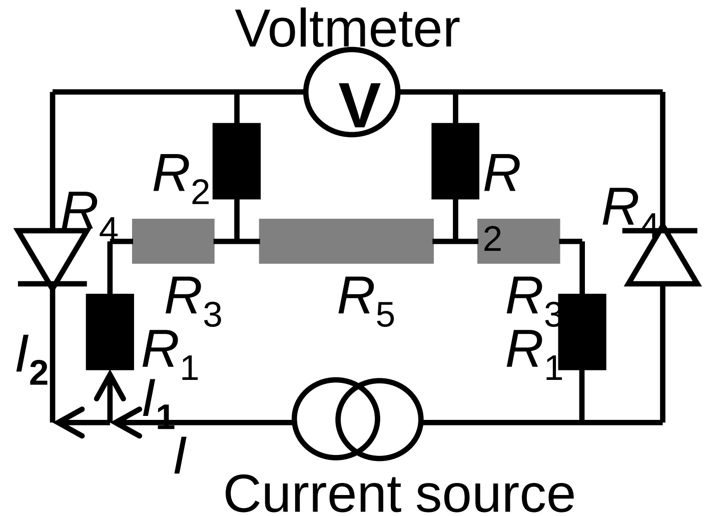
MR （

Keithley 2400
关

Geometrical MR Devices with Symmetrical Electrodes





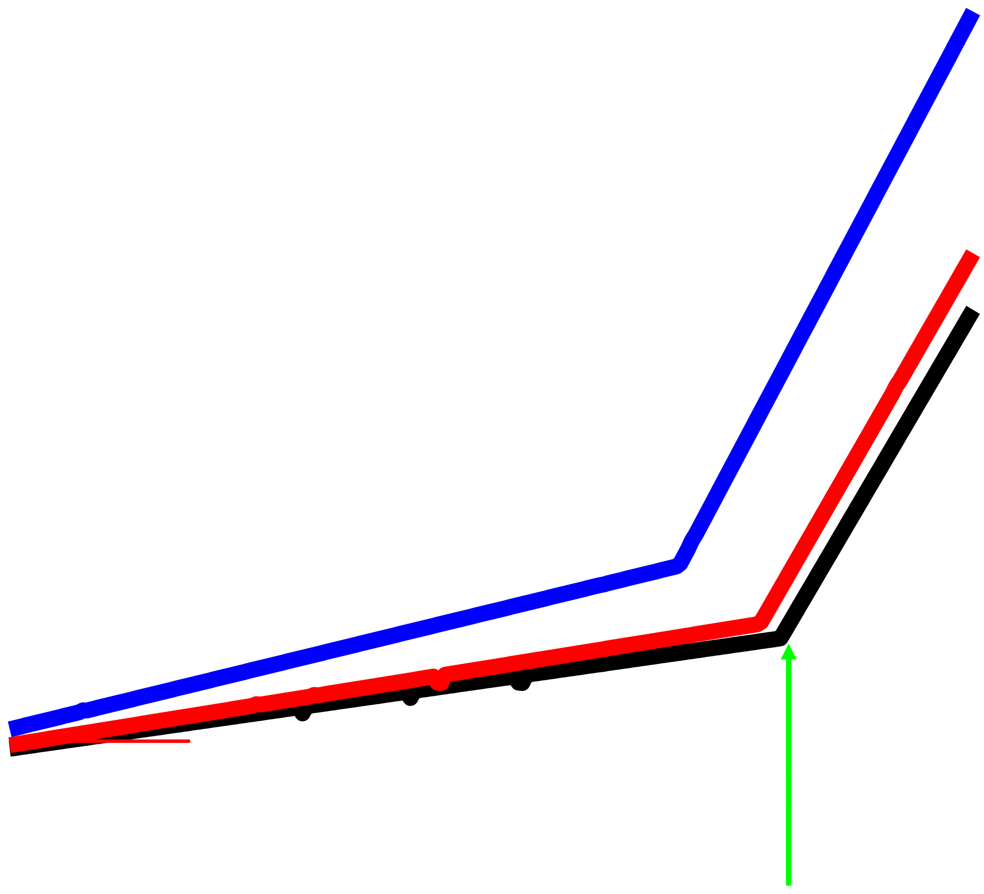
R_1 **Contact resistance of current electrodes**
R_2 **Contact resistance of voltage electrodes**
R_3 **Silicon resistance between current and voltage electrodes**
R_5 **Silicon resistance between the two voltage electrodes**

Geometry Factor

$$MR_{max} \quad 1 \quad \frac{2R_2}{R_1 \quad R_2 \quad R_3 \quad 0} \quad \frac{R_3 \quad 0}{R_5 \quad 0} \quad MR_{Si}^{sym}$$

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

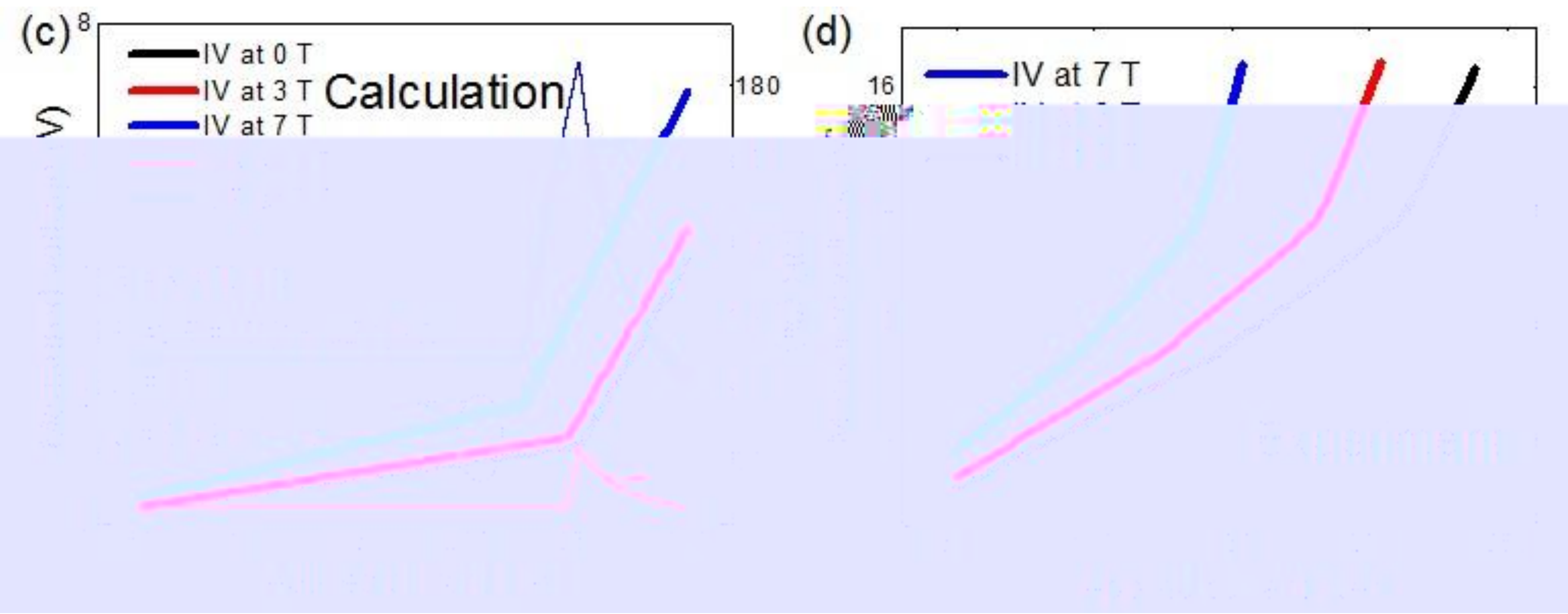
Zhang & Wan et al, (unpublished)



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

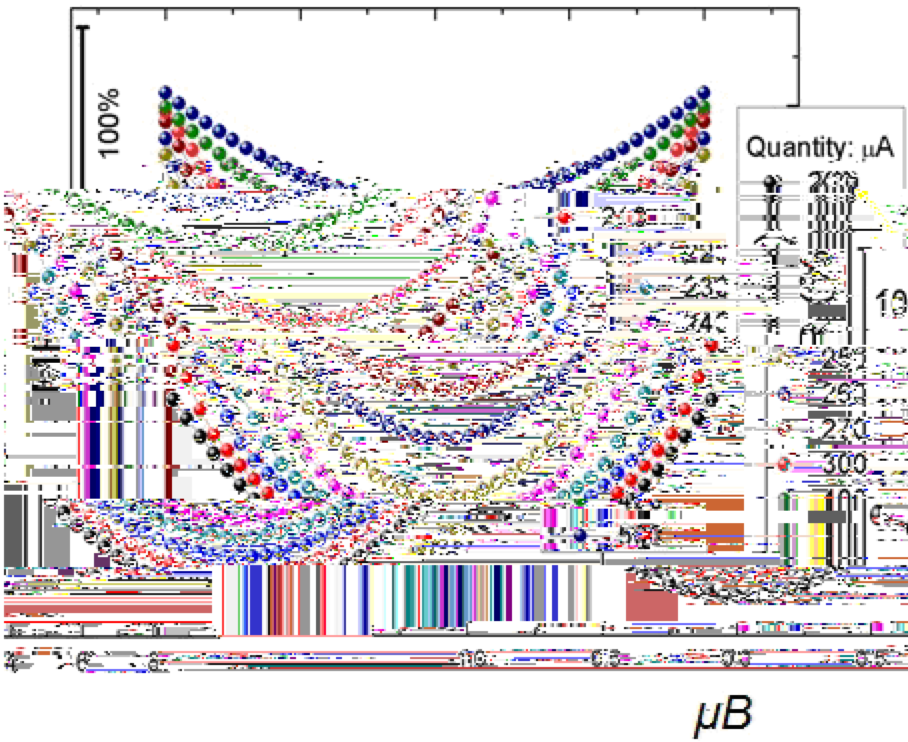
Zhang & Wan et al, (unpublished)

Comparison of simulation and experimental results

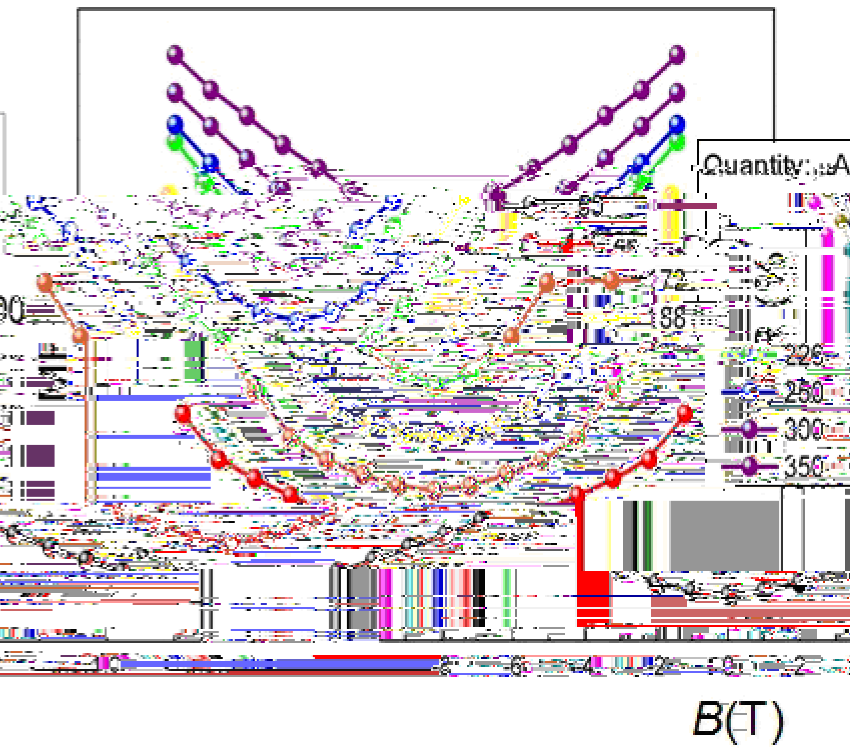


Comparison of simulation and experimental results

calculation



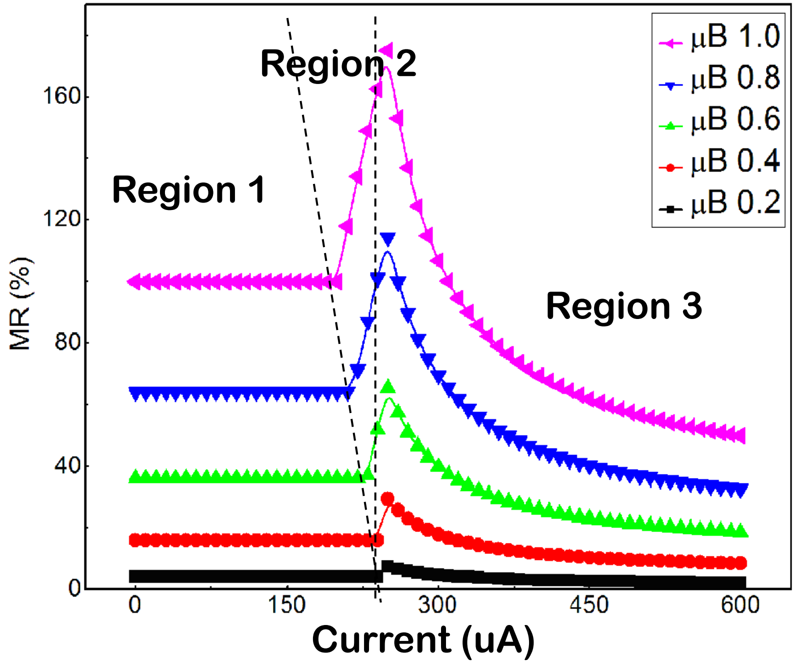
experimental

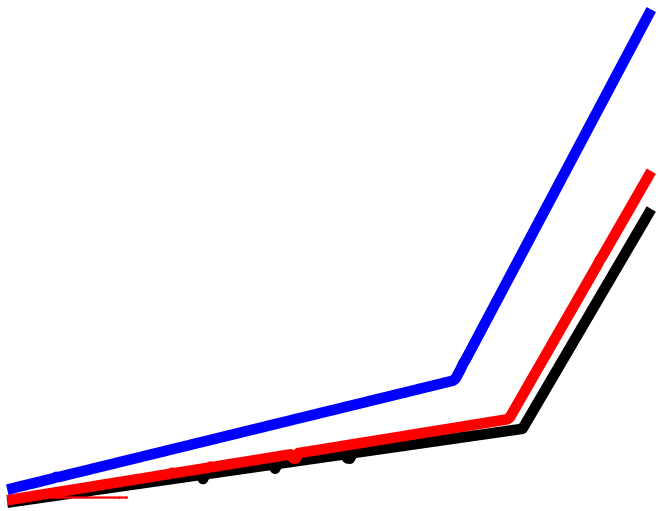


Zhang & Wan et al, (unpublished)

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

Outlines

1.

1.1 点 荷 点

1.2 点

2.

2.1 a-C/Si 点

2.2 点

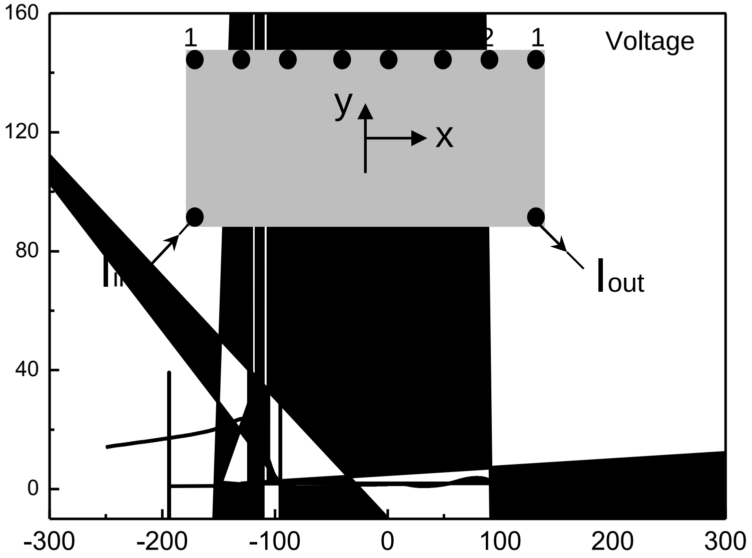
2.3 点

点 点

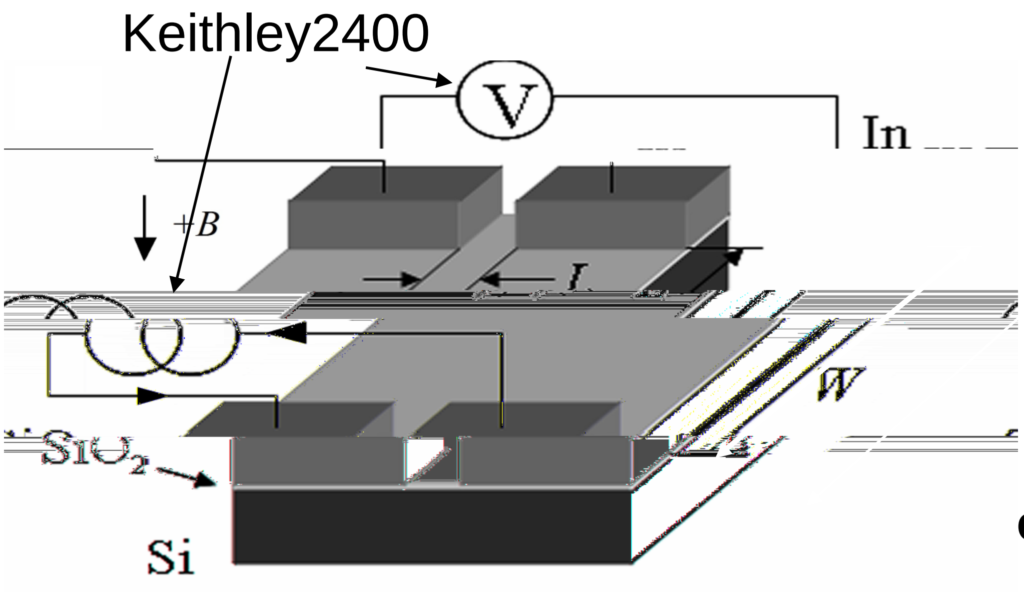
点 点

3. 点 荷

Effect of electrode position on MR



Si based MR device with asymmetric electrodes



MR Devices with Asymmetrically distributed electrodes at corners

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

: 3000 *cm, 1000 *cm

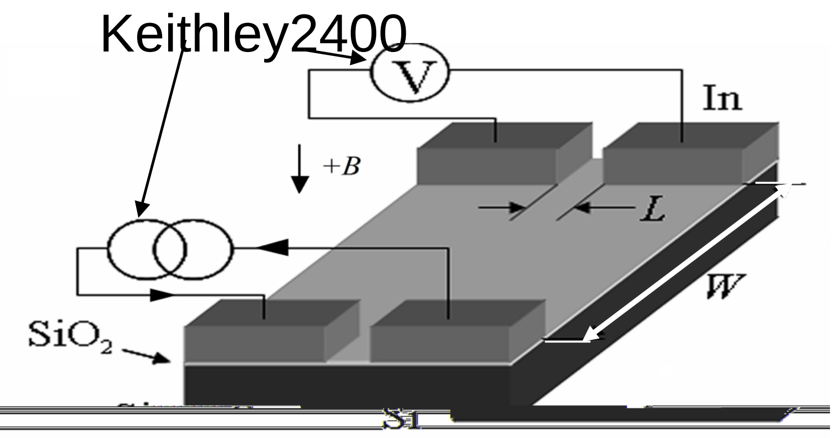
: 1200 cm^2/Vs

: 100~200 s (Bulk minority lifetime)

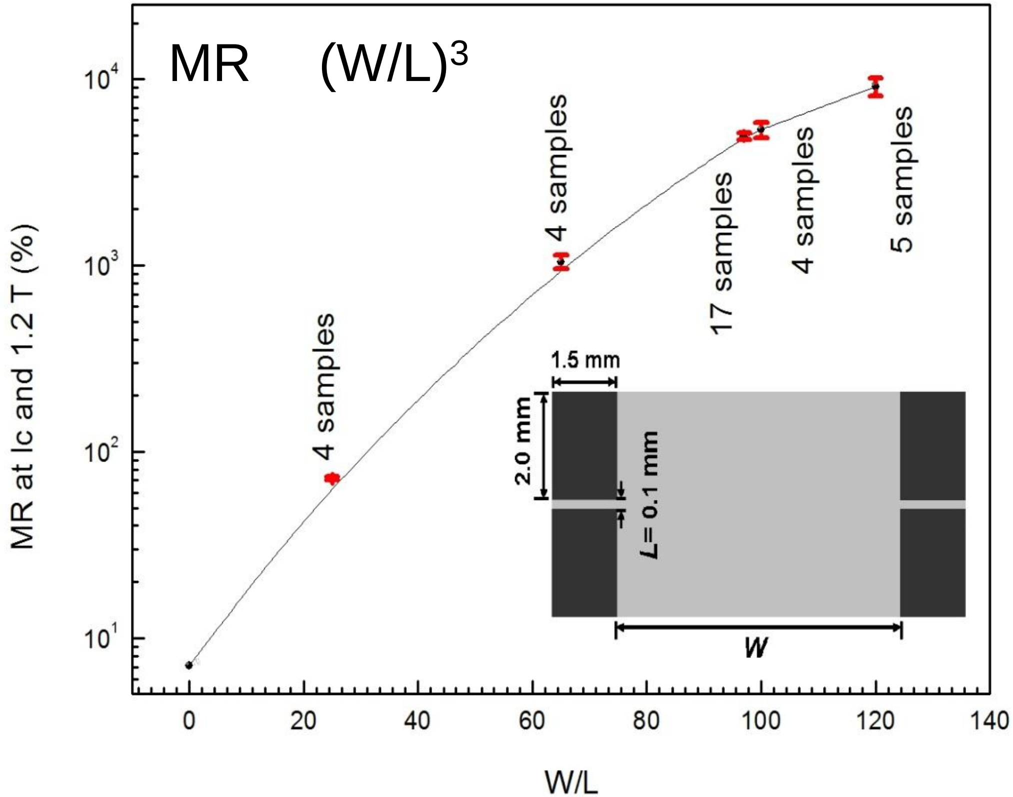
Electrode: Indium

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

Si based MR device with asymmetric electrodes



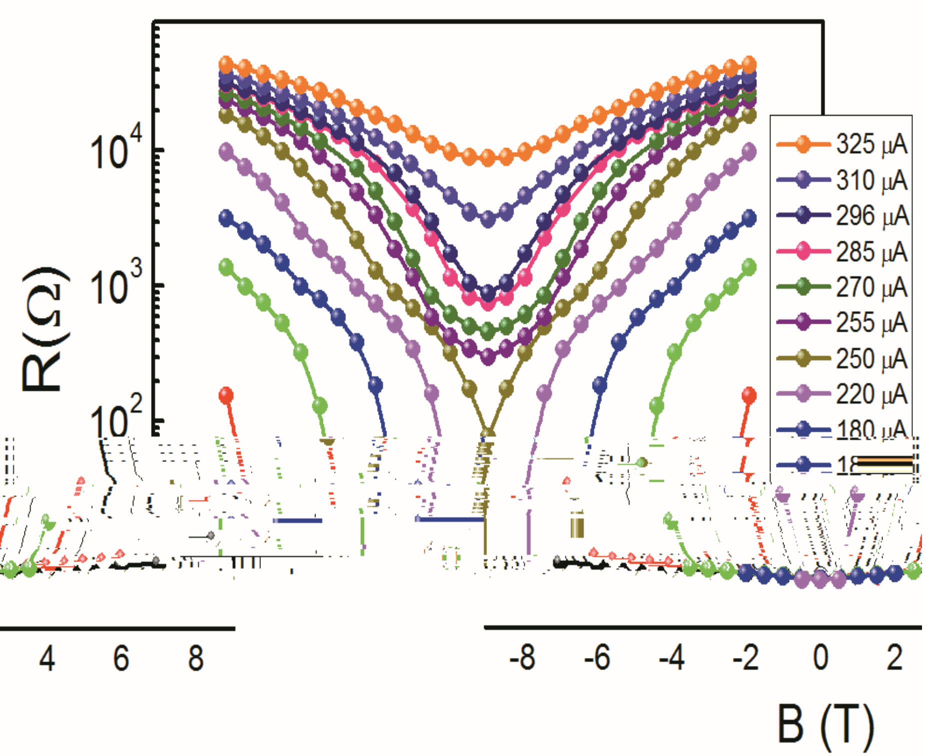
MR Devices with Asymmetric Electrodes

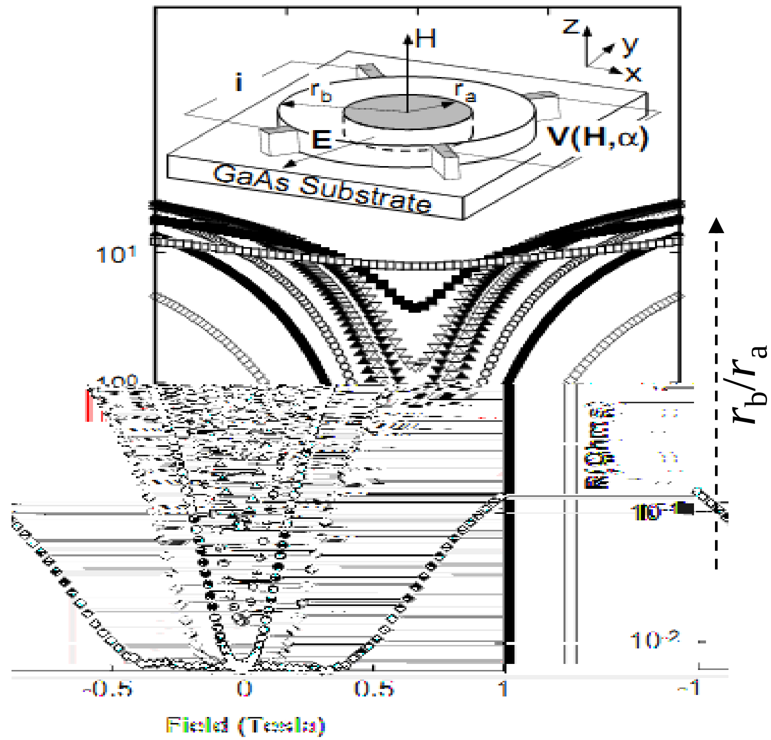


MR increases with increase of $(W/L)^3$

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

Comparison between Si and InSb based Geometrical enhanced MR Devices



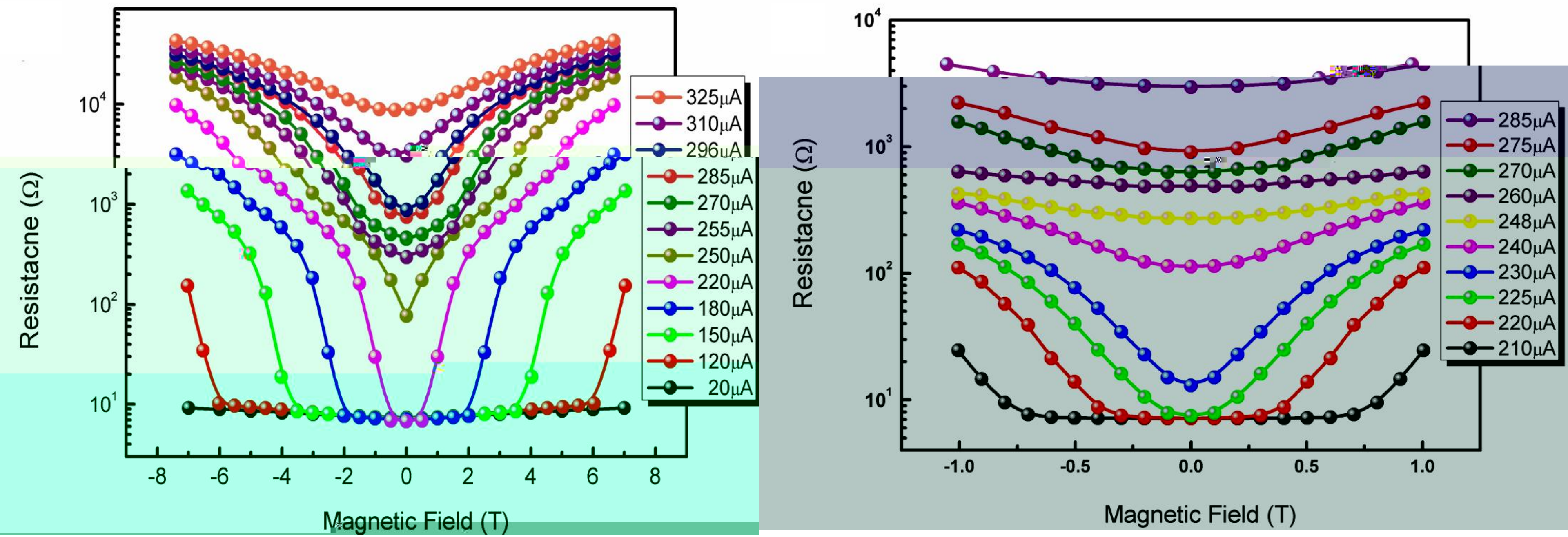


1. MR *B* evolves in a similar manner
2. The Control parameter in Si was current
3. The Control parameter in InSb was shape

Wan & Zhang et al, Nature, 2011

Solin, et al, Science, 2000.

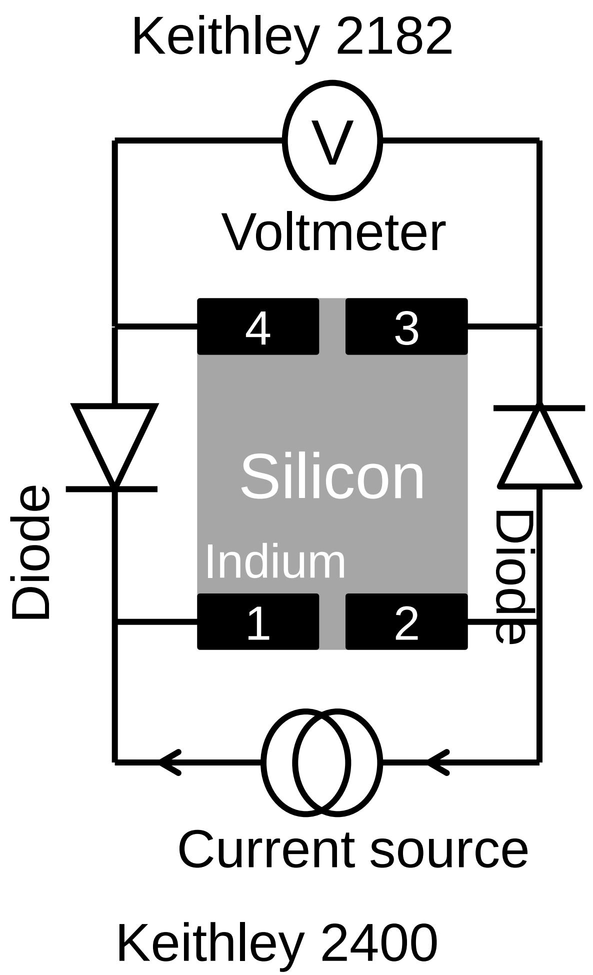
Current dependent MR

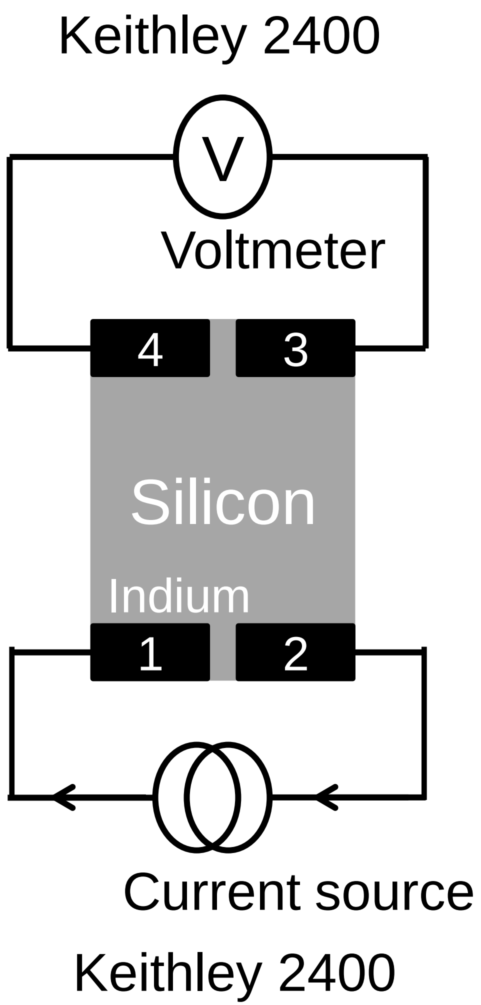


RT MR reaches 30% at 0.065T and 100% at 0.2 T

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

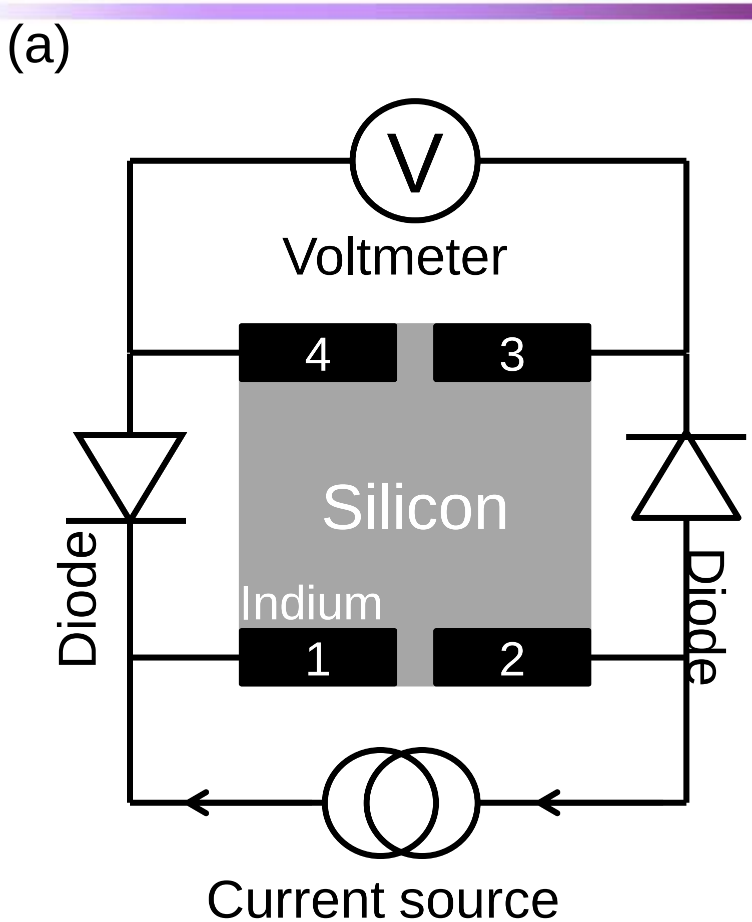
Measurement setup of asymmetrical electrode sample

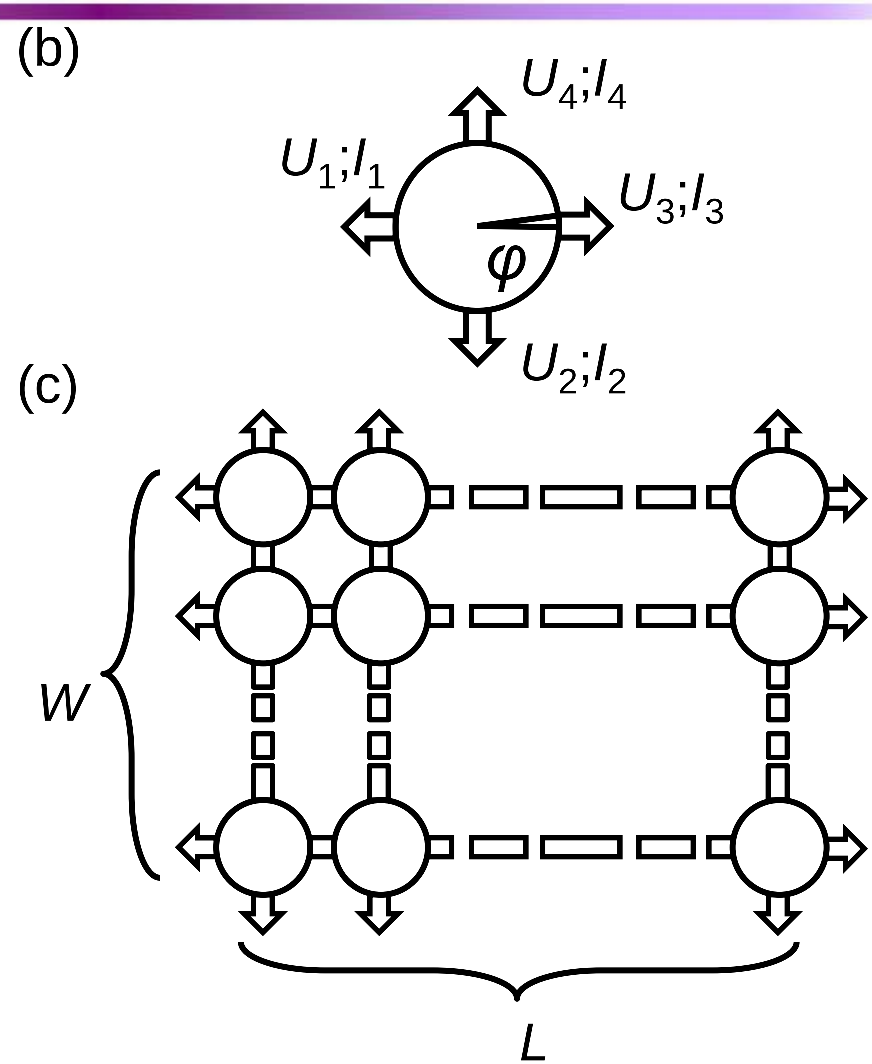




The diodes had already inherently incorporated into the Keithley 2400

MR model for asymmetrical electrode sample

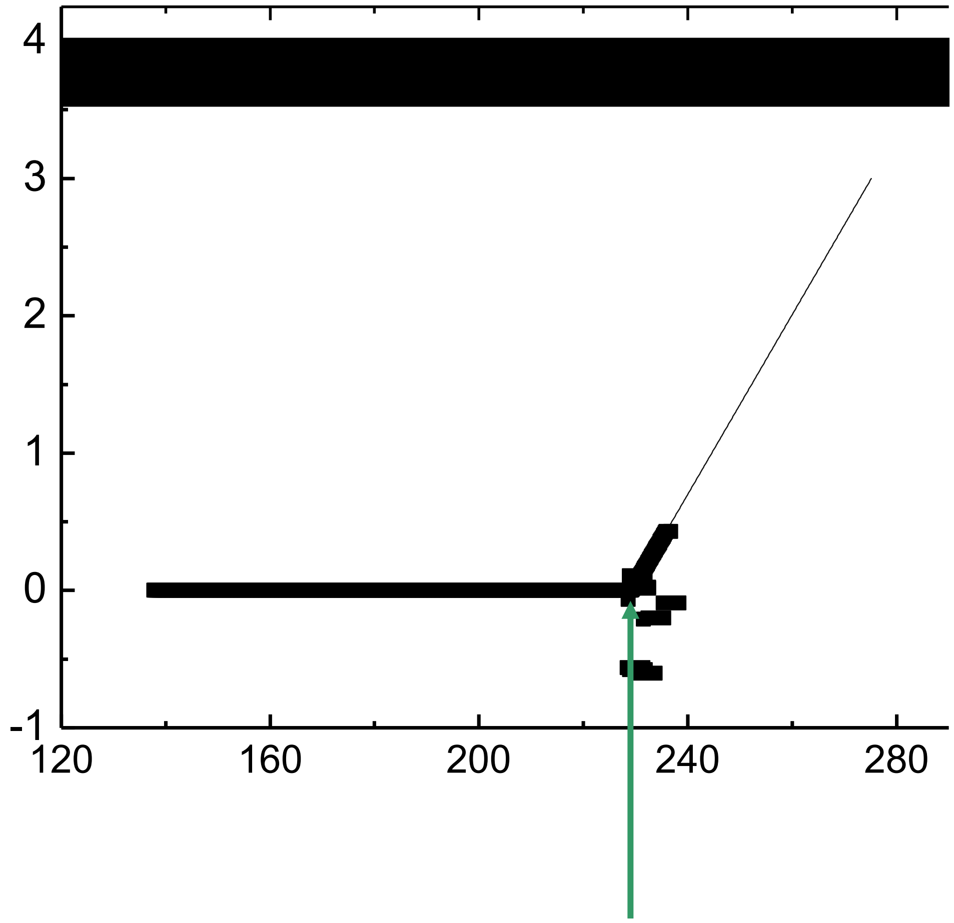




Our model was similar to the model proposed by Parish and Littlewood except the differences in the geometry of electrodes and the two diodes

Parish & Littlewood, Nature, 2003

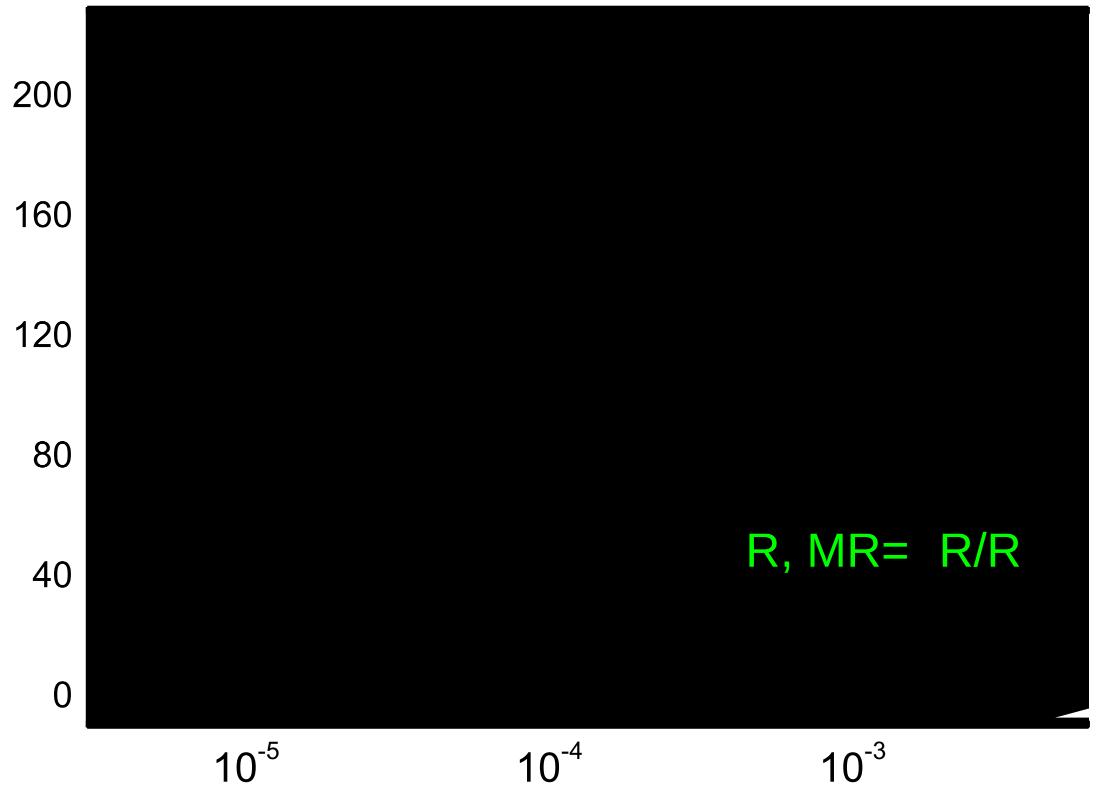
The maximum MR occur at turning point of I-V curves



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)

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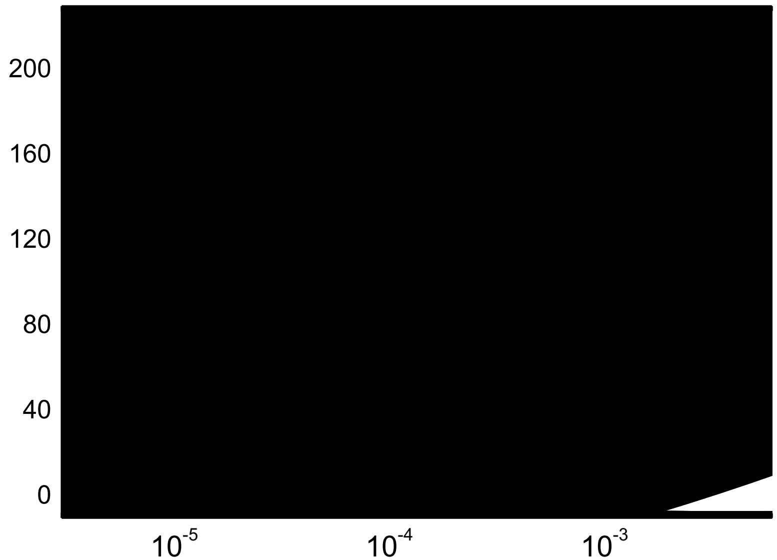
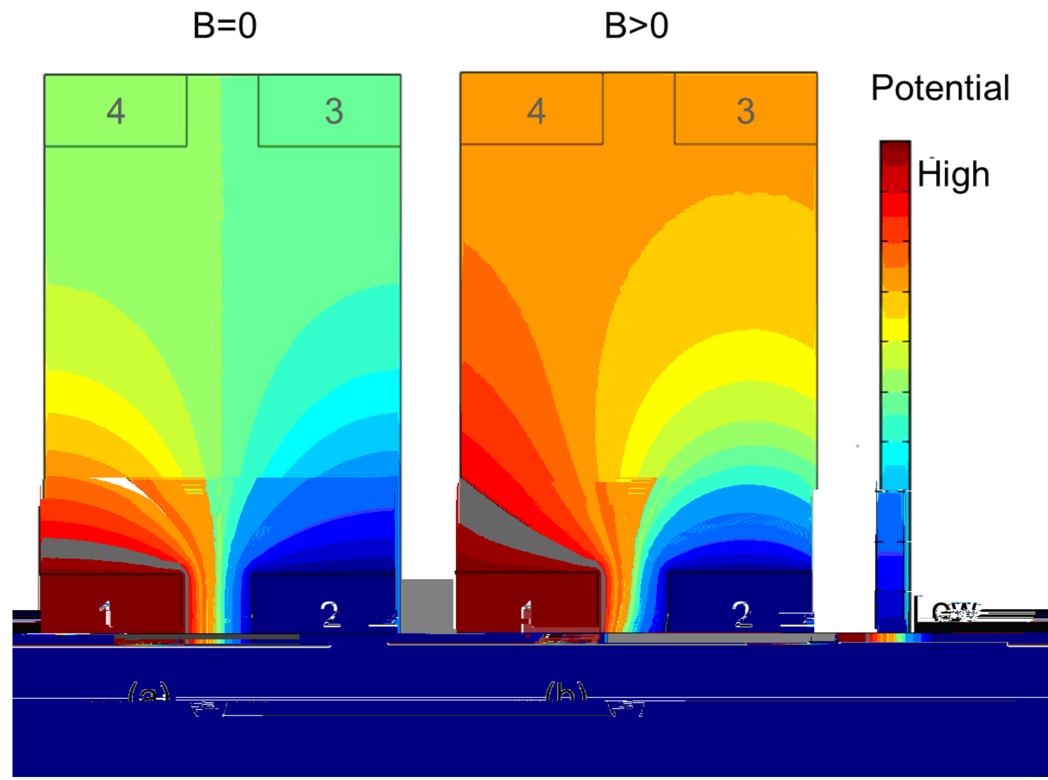
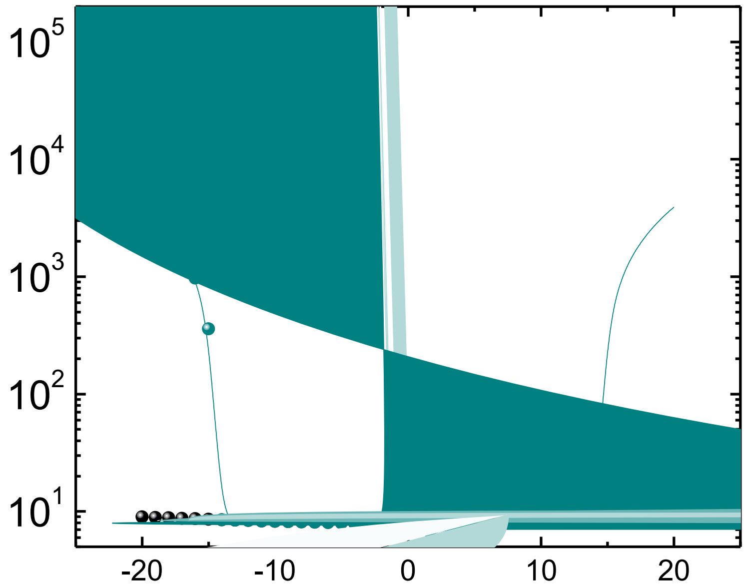


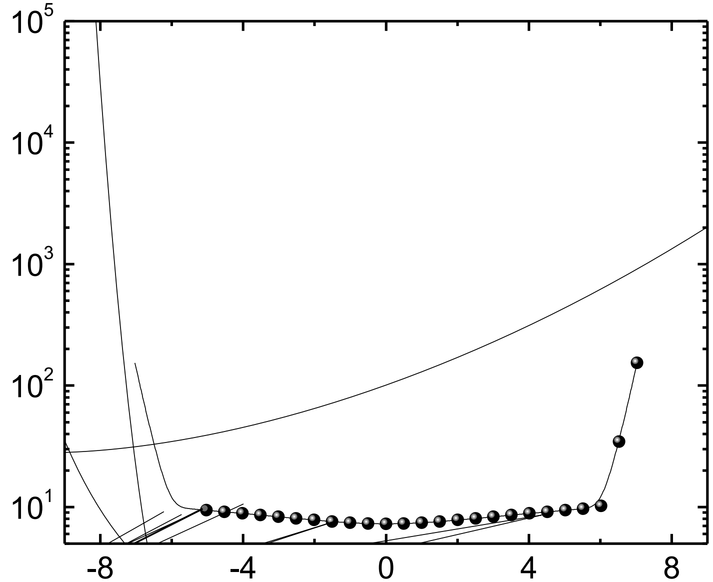


关半 点 **LRS%** 点 **HRS%** (
(点 达达

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.

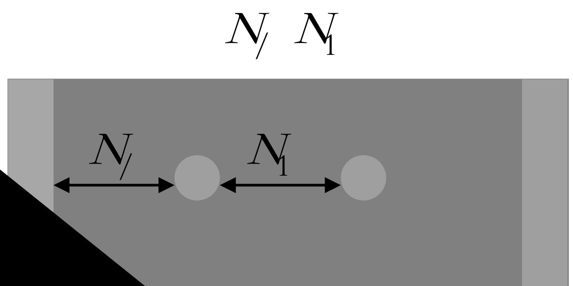
Zhang & Wan et al, (unpublished)

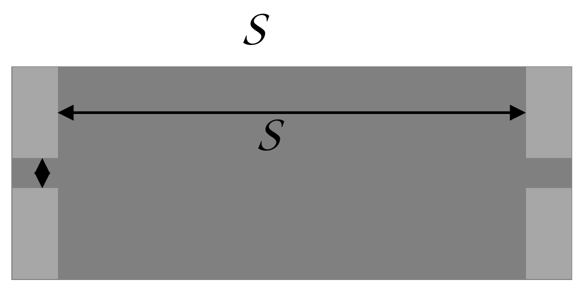
Wan & Zhang, Nature (2011)

Comparison between the two geometry

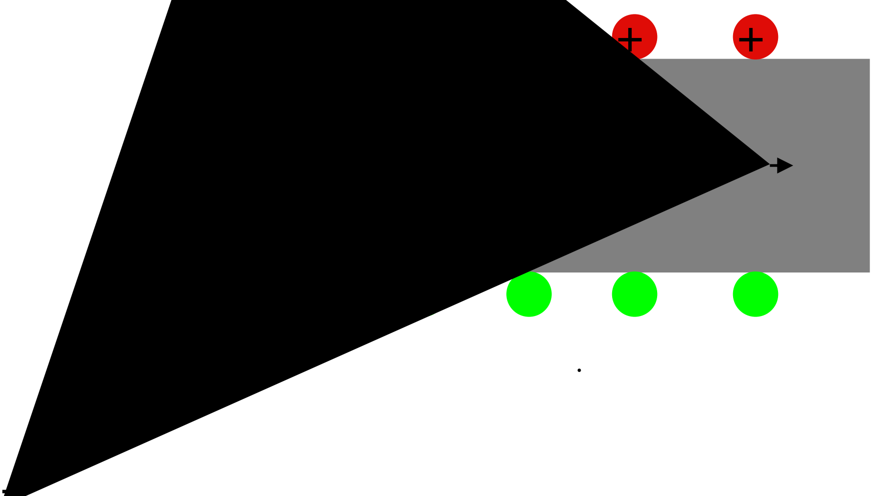
Symmetrical

Asymmetrical





[redacted]l Factor



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$\mathrm{d}V/\mathrm{d}B$ B

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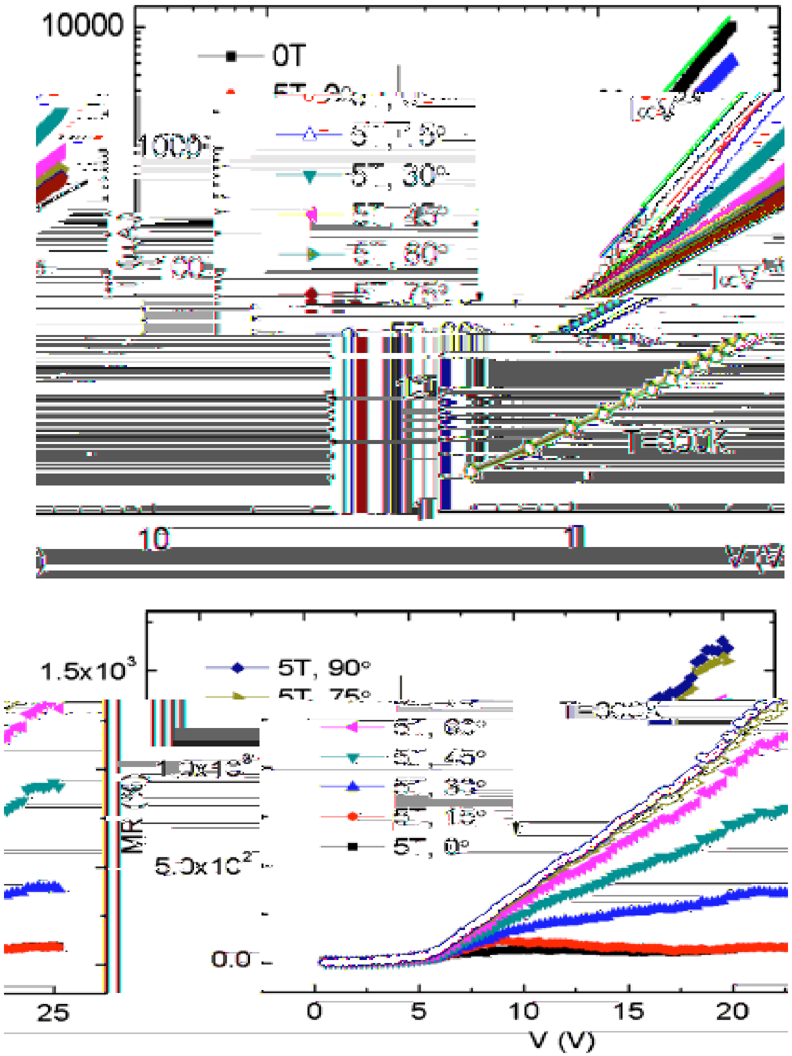
Comparison among different MR devices

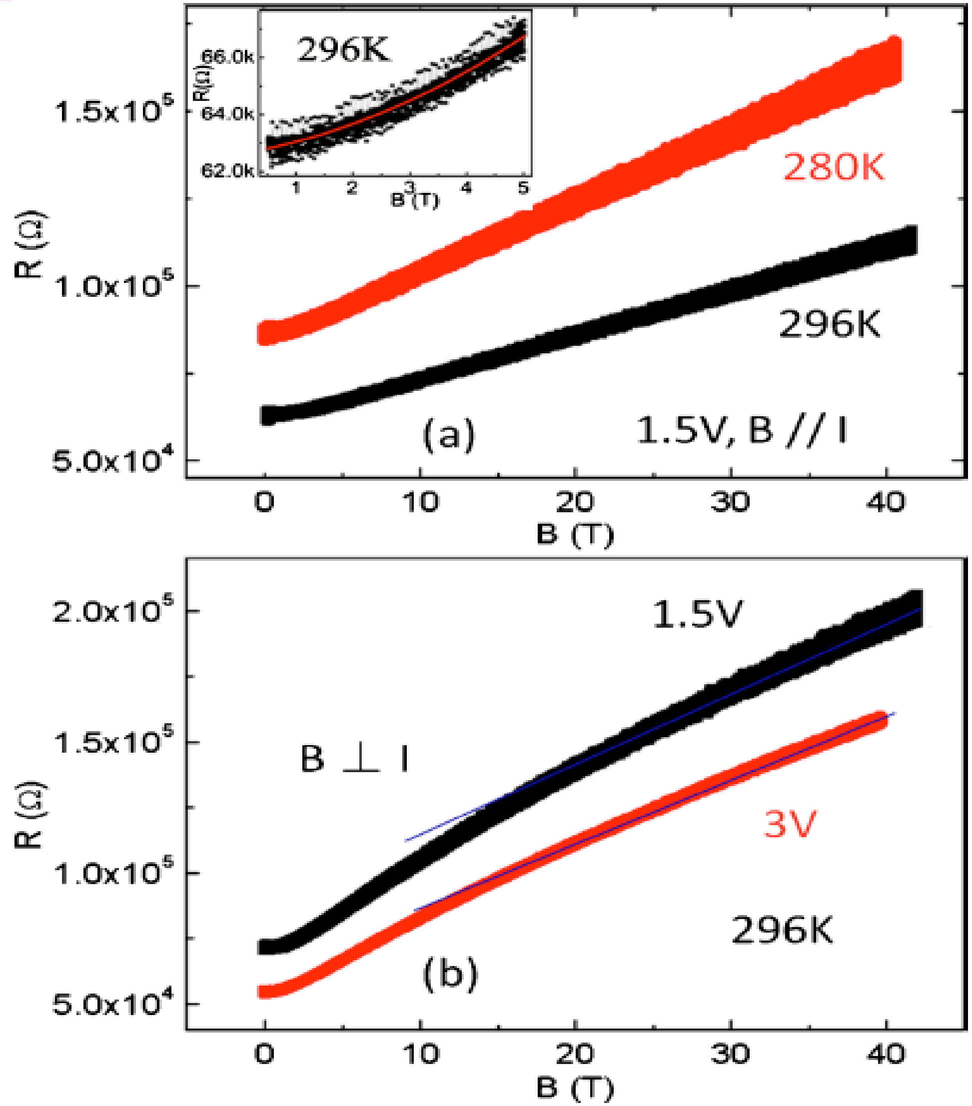
Type	S T^{-1}% $S=MR/B$	Field needed	others	Ref
Delmo s Si	1.0	0.5 T	V=100 V	1
Schoonus s Si	8.0	1.25 T	V=80 V	2
InSb	3.0	0.19 T	[redacted]	3
Si geometrical enhanced MR	5	0.06 T	I=0.2 mA, V=10 V	Ours

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.

1.1 点 荷 点

1.2 点

2.

2.1 a-C/Si 点

2.2 点

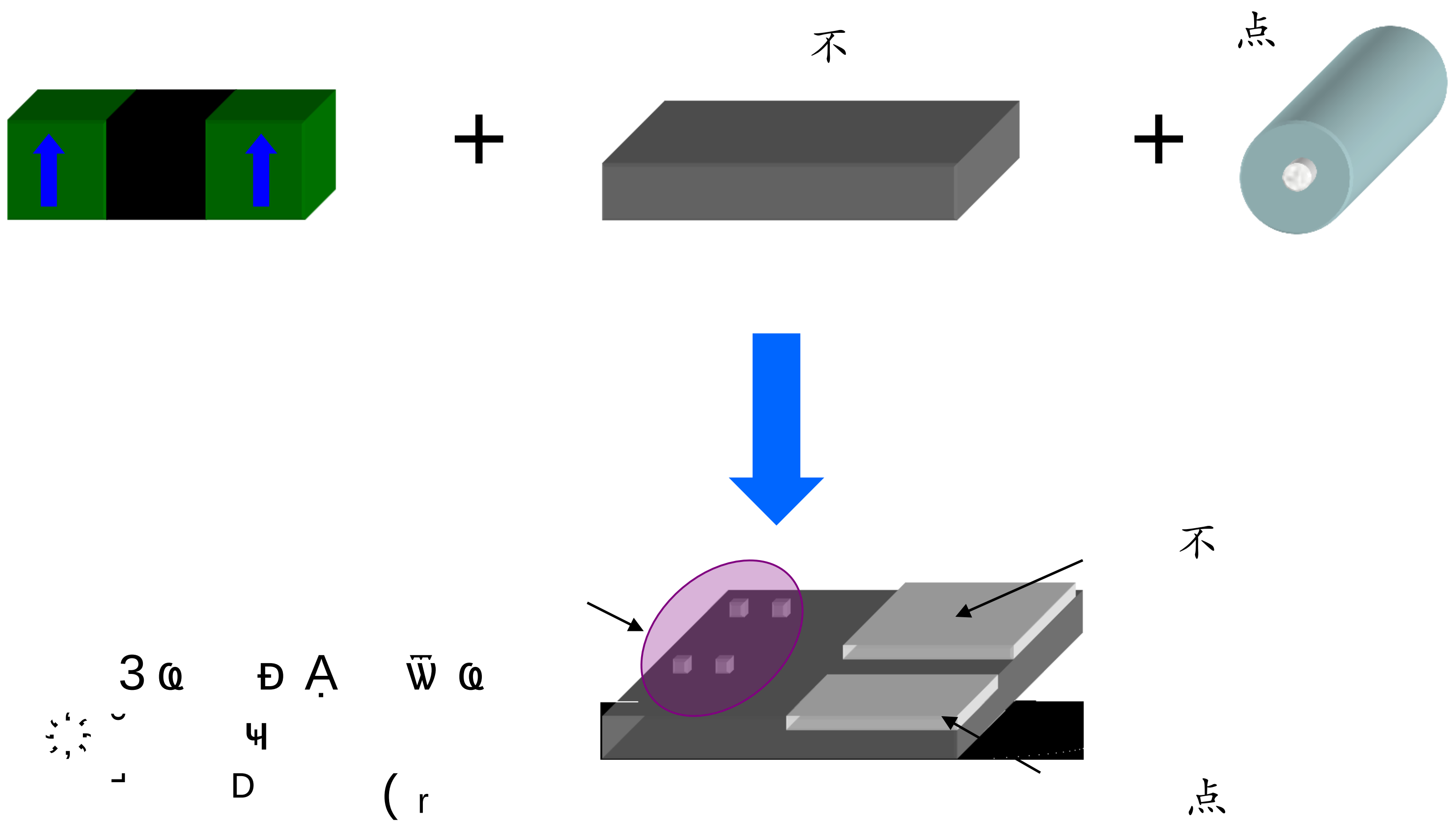
2.3 点

点 点

点 点

3. 点 荷

2
G 0 40T
3 V
GaAs Ge
MR



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Impact

Tsinghua University

1. Silicon electronics Silicon magnetoelectronics

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

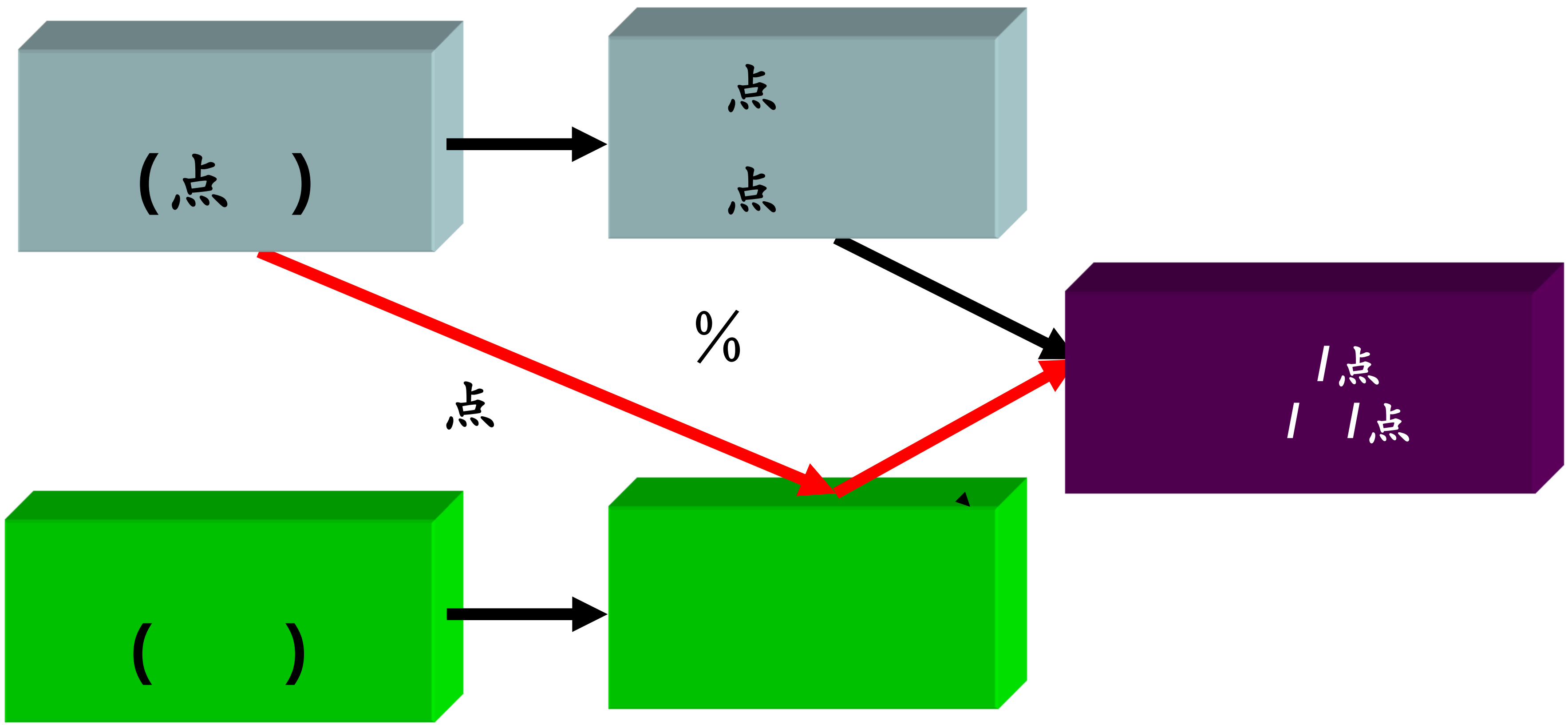
2. Silicon based MR sensors

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

B n i no Magnetic MR sensors: Magnetic Hysteresis(Failure at high fields(inactive to current.

Impact

Si à GaAs à Ge



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NPG Asia-materials ɣ Magnetoresistance: Silicon joins the party ӌ highlightঌ ꞁ ƀ .

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2011

2011

2011 3 2

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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 ?

1. 关 点 (GEMR).
关半 点 [redacted]
HRS% ((点
达
2. 点 点 OMR% (
达 点 (点
MR MR 0.06T 30 (
W/L)^3 达(MR 达 (
荷
3. Si, GaAs 荷 Ge GEMR
点
4. 点
(MR),
荷

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The Ministry of Science and Technology of China

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Prof. Y. Wang, Institute of Microelectronics,
Tsinghua University

Students & Postdocs

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Thank you for
your attentions!
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