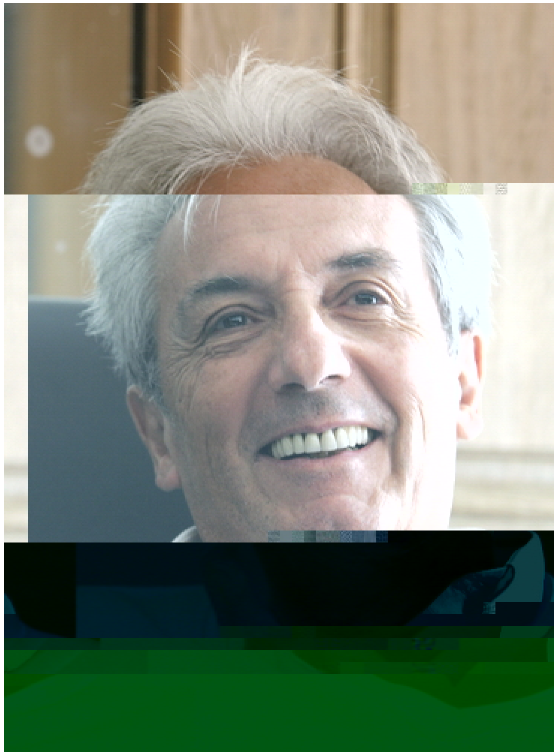
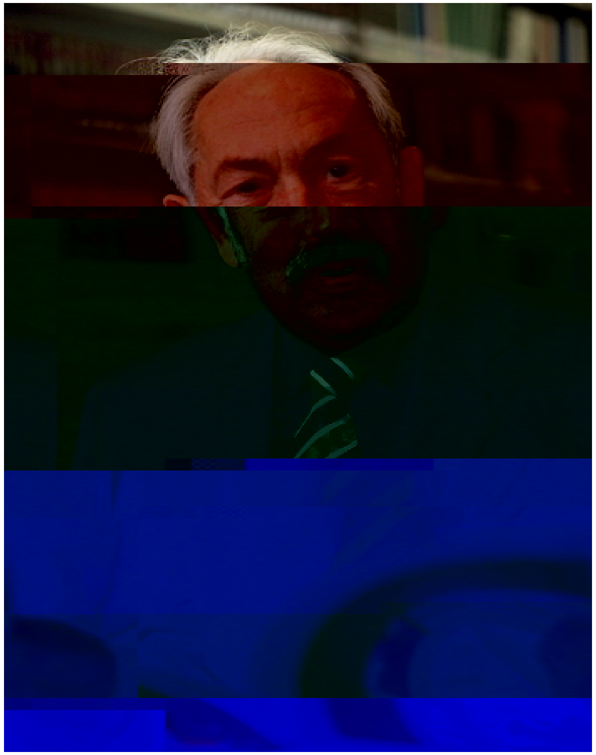
# 2007

# Albert Fert & Peter Grünberg

( X. F. Han )

2007 10 11



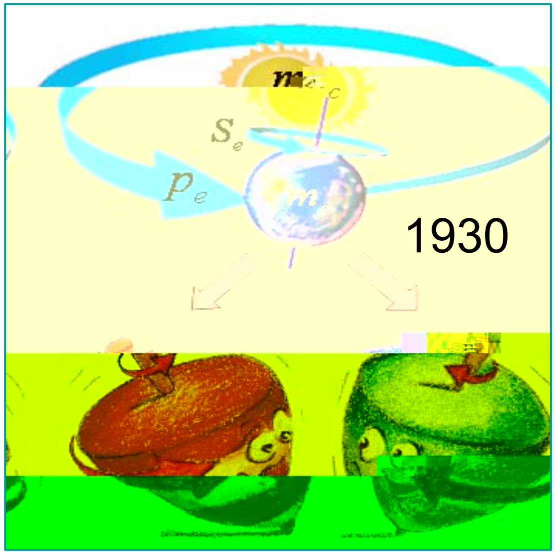


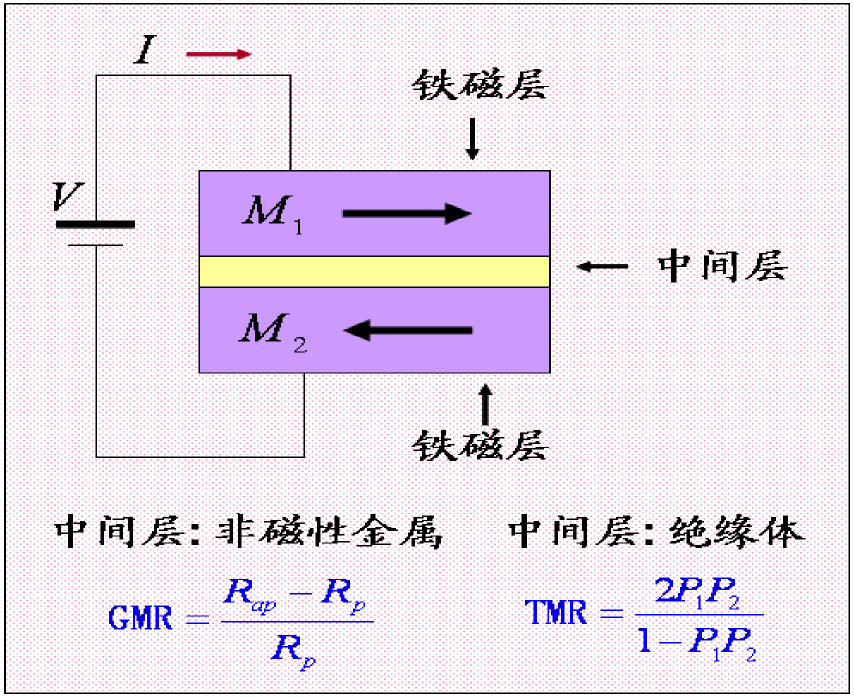
## Albert Fert

1938年3月7日出。1962年在巴黎高等师范学院获数学和物理硕士学位。1970年从巴黎第十一大学获物理学博士学位，前在该校任物理学教授。他从1970年到1995年一直在巴黎第十一大学固体物理实验室工作。后任研究小组组长。1988年，他发现巨磁电阻效应，随后对自旋电子学作出过许多杰出贡献。1994年获美国物理学会颁发的新材料国际奖， 1995年至今则担任国家科学研究中心-Thales集团联合物理小组科学主管，1997年获欧洲物理协会颁发的欧洲物理学大奖，以及2003年获法国国家科学研究中心金奖。

## Peter Grünberg

1939年5月18日出生。从1959年到1963年，克鲁伯格在法兰克福约翰-沃尔夫冈-歌德大学学习物理，1962年获得中级文凭， 1969年在德国达姆施塔特技术大学获得博士学位。1988年，他在尤利西研究中心研究并发现巨磁电阻效应；1992年被任命为科隆大学兼任教授；2004年在研究中心工作32年后退休，但仍在继续工作。他1994年获美国物理学会颁发的新材料国际奖(Fert、Parkin共同获得)；1998年获由德国总统颁发的德国未来奖；2007年获沃尔夫基金奖物理奖(与Fert共同获得)。




- **1988 GMR**
- **1994 CMR**
- **1995 TMR**

# (1) 1986 Fe/Cr/Fe

VOLUME 57, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1986

Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling

ss Cr Interlayers of Fe Layers acro

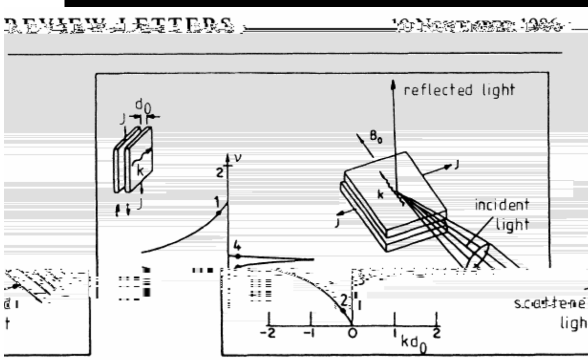
P. Grünberg, R. Schr

Kernforschungsanlage Jülich

M. B. Brodsky

Argonne National Laborato

(Received 10




across Au and Cr interlayers by means of light
ind a continuous decrease of this coupling to zero as
or Cr interlayers of proper thickness we find antifer-
nal fields such double layers order antiparallel with
ield, in analogy to the spin-flop phase of antiferro-

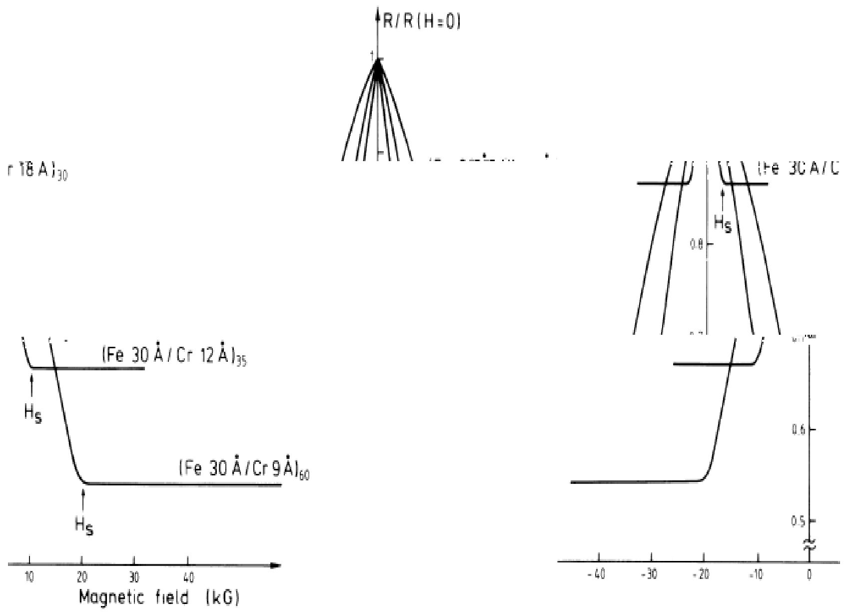
We investigated exchange coupling of Fe layers
scattering from spin waves. For Au interlayers we f
the Au thickness is increased from 0 to ≈ 20 Å. Fo
romagnetic coupling of the Fe layers. In small exte
their magnetization perpendicular to the external f
magnets.

PACS numbers: 75.30.Ds, 75.70.Dp

# (2) 1988 (GMR)

**[ Fe/Cr]n**
**nano-magnetic multilayers**

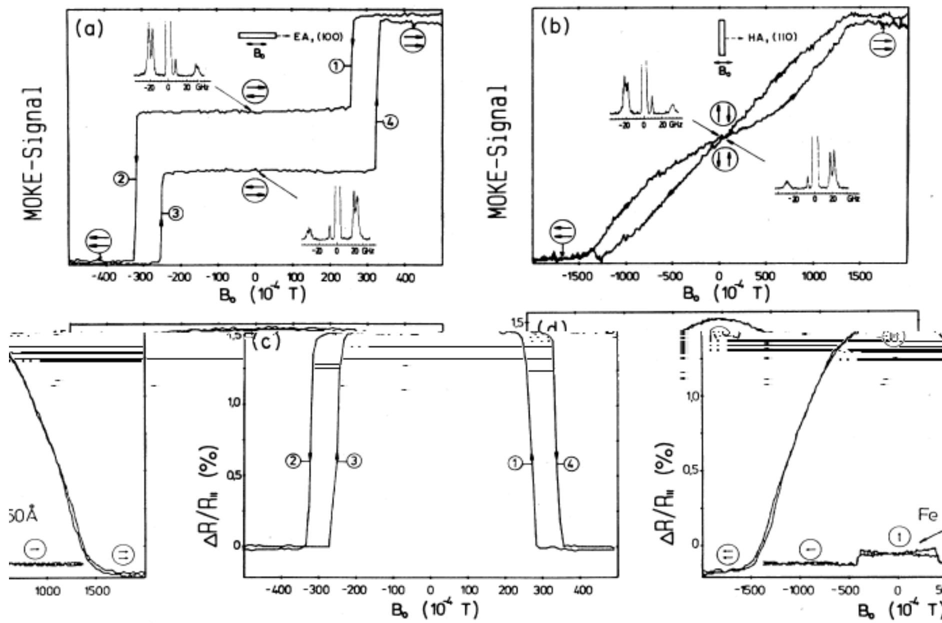
**Fe/Cr/Fe**
**Sandwich structure**




2 K. The current and the applied field are along the same [110] axis

FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.
in the plane of the layers.

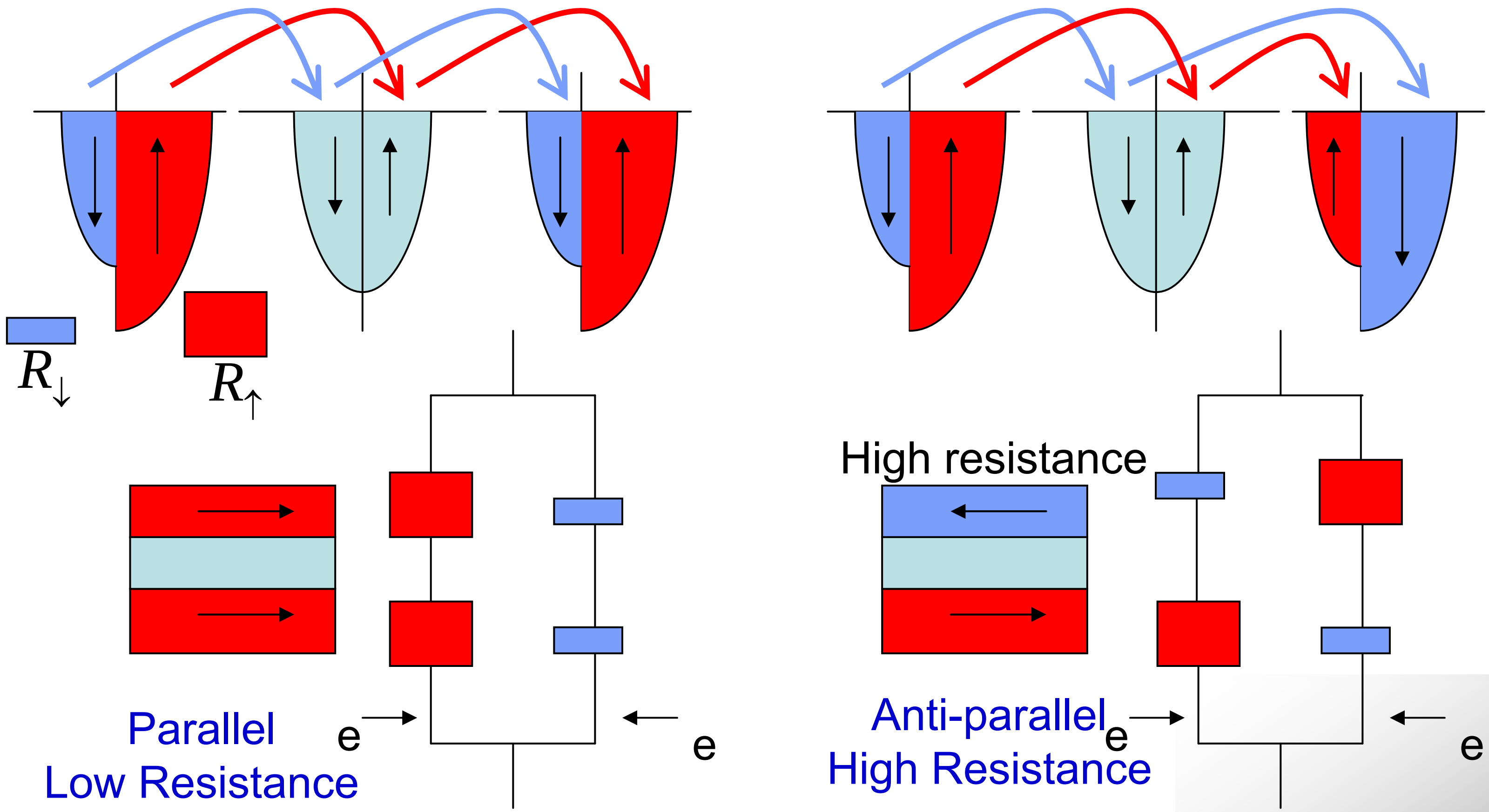
2473




M.N. Baibich and A. Fert *et al.*, PRL 61 (1988)2472.

G. Binasch, P. Grünberg, et al., PRB 39 (1989) 4828.

# Two-current series resistor model




$$\text{GMR=}\ \frac{\Delta R}{R}=\frac{R_{AP}-R_P}{R_P}=\frac{(R_\downarrow-R_\uparrow)^2}{4R_\downarrow R_\uparrow}.$$

# (3) Oscillations in Exchange Coupling in Metallic Superlattice Structure

Si(111)/Ru(10nm)/[Co(2)/Ru(d)]$_N$/Ru(5)

Si(111)/Cr(10nm)/[Fe(2)/Cr(d)]$_N$/Cr(5)

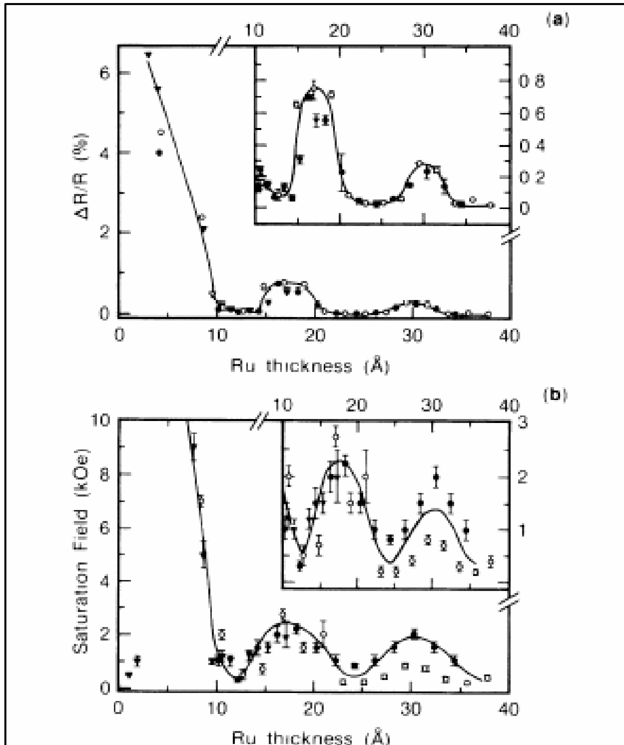



FIG. 3. (a) Transverse saturation magnetoresistance (4.5 K) and (b) saturation field (300 K) vs Ru layer thickness for structures of the form Si(111)/(100 Å) Ru/[20 Å) Co/$t_{Ru}$ Ru]$_{20}$/(50 Å)Ru deposited at temperatures of ●, 40 °C; ○, 125 °C; ×, 200 °C.

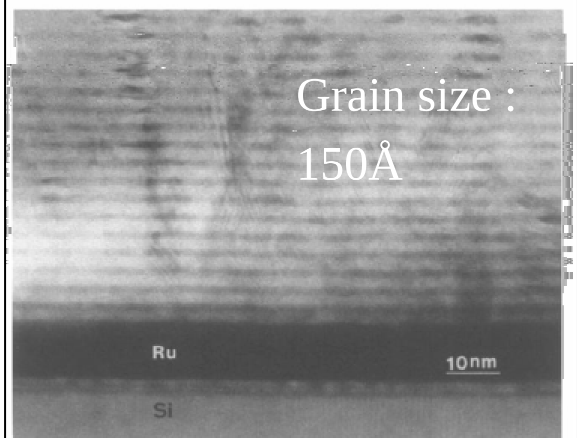
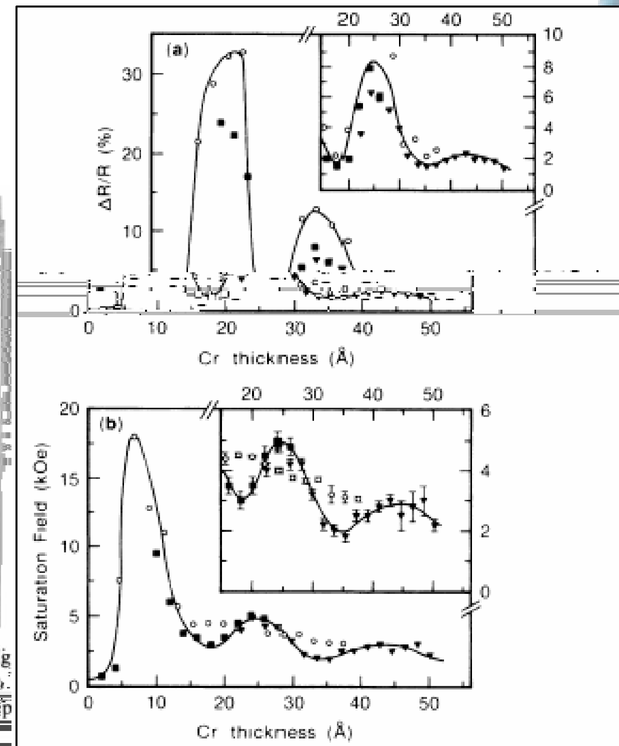



FIG. ... high-resolution micrograph taken along ... direction from the structure Si(111)/(100 Å) Ru/[(8 Å) Co/(8 Å) Ru]$_{20}$/(50 Å) Ru. The sample was dep... 40 °C.

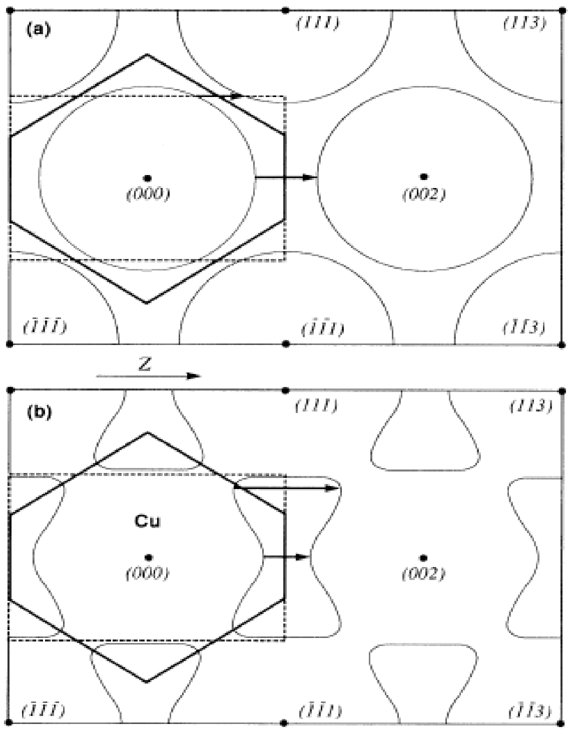


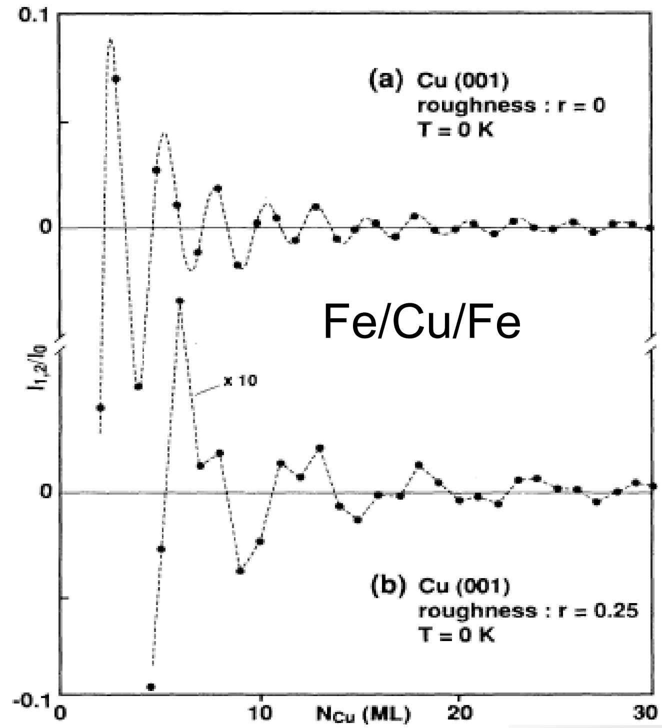

G. 4. (a) Transverse saturation magnetoresistance (4.5 K) and (b) saturation field (4.5 K) vs Cr layer thickness for series of structures of the form Si(111)/(100 Å) Cr/[(20 Å) Fe/$t_{Cr}$ Cr]$_N$/(50 Å) Cr, deposited at temperatures of △,■, ($N$=30); ○,125 °C ($N$=20).

**S. S. P. Parkin et. al., PRL 64 (1990) 2304**

# (4) Adopt RKKY-like theory to explain GMR oscillation effect

$$I_{1,2}(z) = -I_0 \sum_{\alpha} \frac{d^2}{z^2} \frac{m_\alpha^*}{m} \sin(q_\perp^\alpha z + \phi_\alpha) \frac{z/L_\alpha(T)}{\sinh[z/L_\alpha(T)]}$$




**Fe/Cu/Fe, Bruno et.al, PRL 67 (1991) 1602**

# (5) Bruno set up electron-optics model to explain GMR oscillations

- **Theoretical simulation:**
- **electron-optics model given by Bruno for the interlayer AF coupling density of *J* in the stacks of FM/NM/FM**

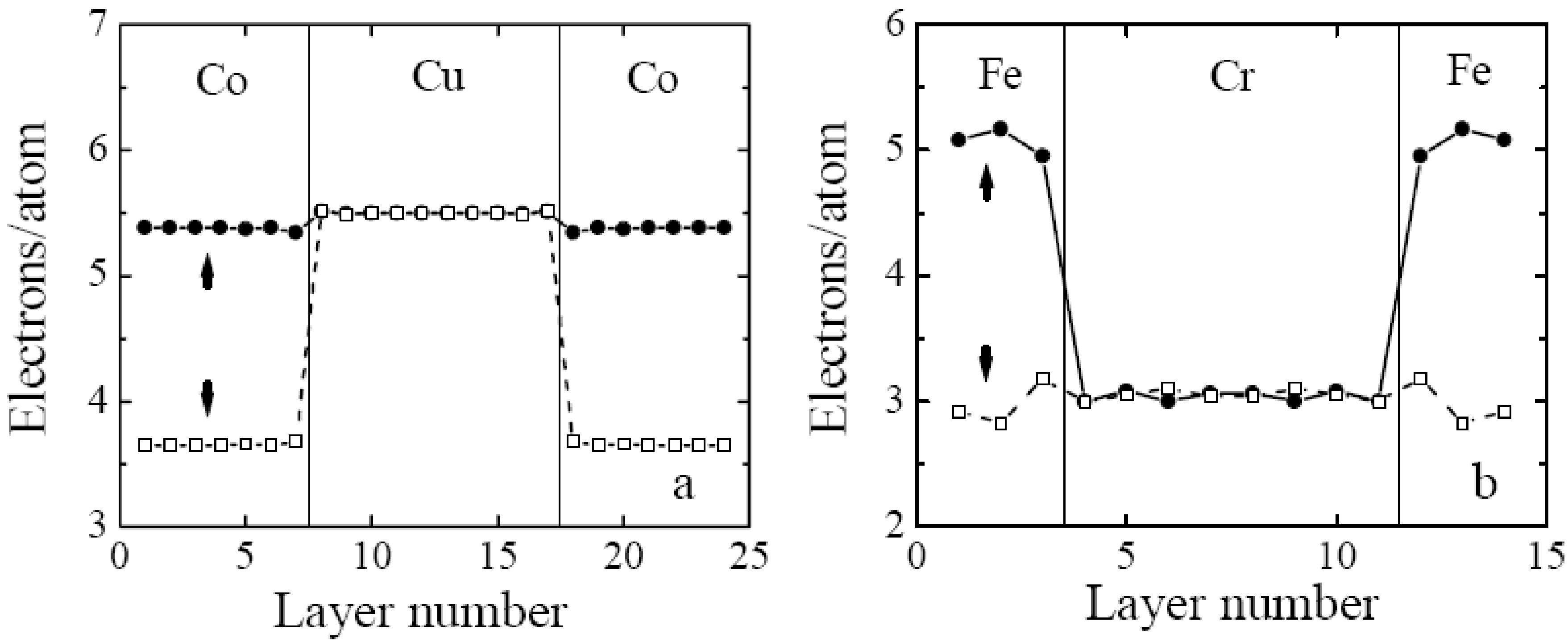
$$J \simeq \left(\frac{\hbar^2}{8\pi^2 m}\right) \mathrm{Im}\left\{ \frac{r_\infty^{\downarrow\,2}}{2} e^{2ik_F d} \left[ \frac{k_F^2}{d^2} - 2(1 - r_\infty^{\downarrow\,2}) \left( \frac{d}{k_F} + \frac{h}{k_F^{\downarrow}} \right)^{-2} e^{2ik_F^{\downarrow} h} \right] \right\}$$

- **from Fabry-Perot-like interferences of the electron Bloch waves in the** Pt($t$)/Co($h$)/Ru($d$)/Co($h$)/Pt($t$) **stacks**

$$\begin{aligned} J \simeq \left(\frac{\hbar^2}{8\pi^2 m}\right) \mathrm{Im}\Big\{ & \frac{r_\infty^2}{2}\left(\frac{d}{k_F}\right)^{-2} e^{2ik_F d} - r_\infty^2 (1 - r_\infty^2)\left(\frac{d}{k_F} + \frac{h}{k_F^{\downarrow}}\right)^{-2} e^{2ik_F d + 2ik_F^{\downarrow} h} \\ & + r_\infty^2 (1 - 2r_\infty^2)\left(\frac{d}{k_F} + \frac{h}{k_F^{\downarrow}} + \frac{t}{k_F}\right)^{-2} e^{2ik_F d + 2ik_F^{\downarrow} h + 2ik_F t} \\ & - r_\infty^2 \left(\frac{d}{k_F} + \frac{h}{k_F} + \frac{t}{k_F}\right)^{-2} e^{2ik_F d + 2ik_F h + 2ik_F t} \Big\}, \end{aligned}$$

- **P. Bruno, Europhys. Lett. 23,615 (1993); JMMM 121 (1993) 248 ;**
- **J. J. de Vries, et.al., PRL 75 (1995) 4306.**

## (6) Electronic structure for Co/Cu/Co and Fe/Cr/Fe systems from Layer KKR first principles calculation




Co/Cu/Co系统:
majority-spin 通道匹配，电子散射弱；
minority-spin通道不匹配，电子散射强

Fe/Cr/Fe系统:
majority-spin 通道不匹配，电子散射强；
minority-spin通道匹配，电子散射弱

W. H. Butler, X.-G. Zhang, *et al.* PRB 52, 18 (1995)

# (7) 1991

PHYSICAL REVIEW B VOLUME 43, NUMBER 1 1 JANUARY 1991

## Giant magnetoresistance in soft ferromagnetic multilayers

B. Dieny,* V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri†
IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120-6099
(Received 25 July 1990; revised manuscript received 21 September 1990)

We show that the in-plane magnetoresistance of sandwiches of *uncoupled* ferromagnetic ($Ni_{81}Fe_{19}$, $Ni_{80}Co_{20}$, Ni) layers separated by ultrathin nonmagnetic metallic (Cu, Ag, Au) layers is strongly increased when the magnetizations of the two ferromagnetic layers are aligned antiparallel. Using NiFe layers, we report a relative change of resistance of 5.0% in 10 Oe at room temperature. The comparison between different ferromagnetic materials (alloys or pure elements) leads us to emphasize the role of bulk rather than interfacial spin-dependent scattering in these structures, in contrast to Fe/Cr multilayers.

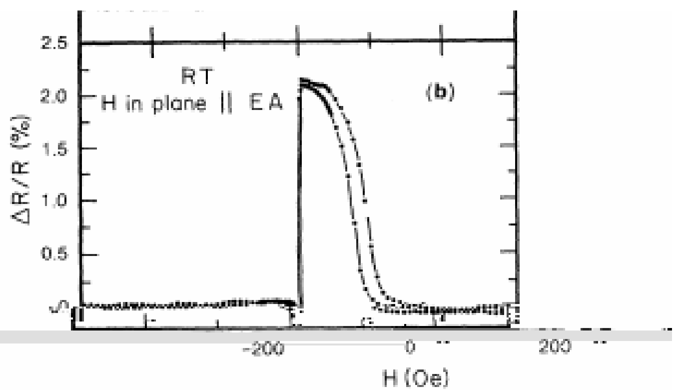



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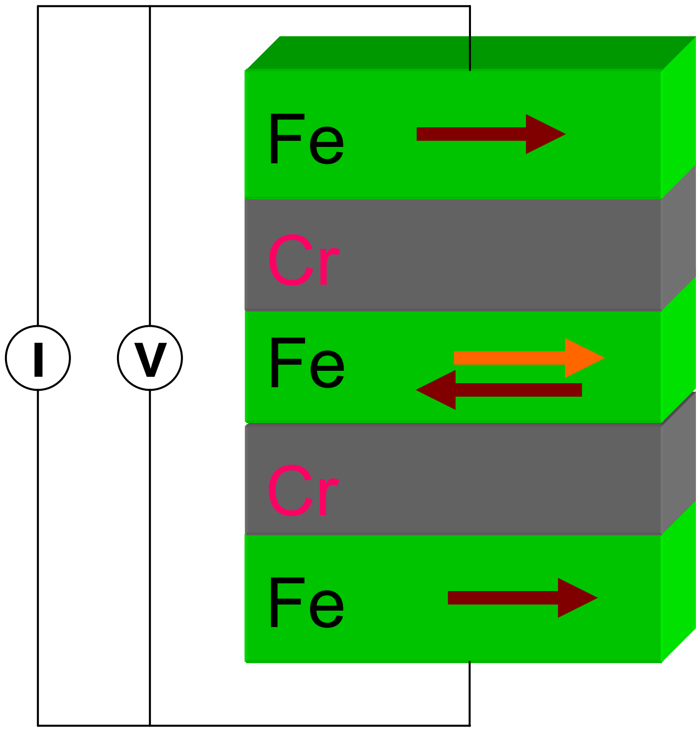
FIG. 1. Magnetization curve (a) and relative change in resistance (b) for Si/(150-Å NiFe)/(26-Å Cu)/(150-Å N (100-Å FeMn)/(20-Å Ag). The field is applied parallel to the exchange anisotropy field created by FeMn (EA). The current is flowing perpendicular to this direction.

**AMF**
**Spin-valve**

B. Dieny et al., PRB 43 (1991)1297

# (8) CPP-GMR in magnetic multi-layers



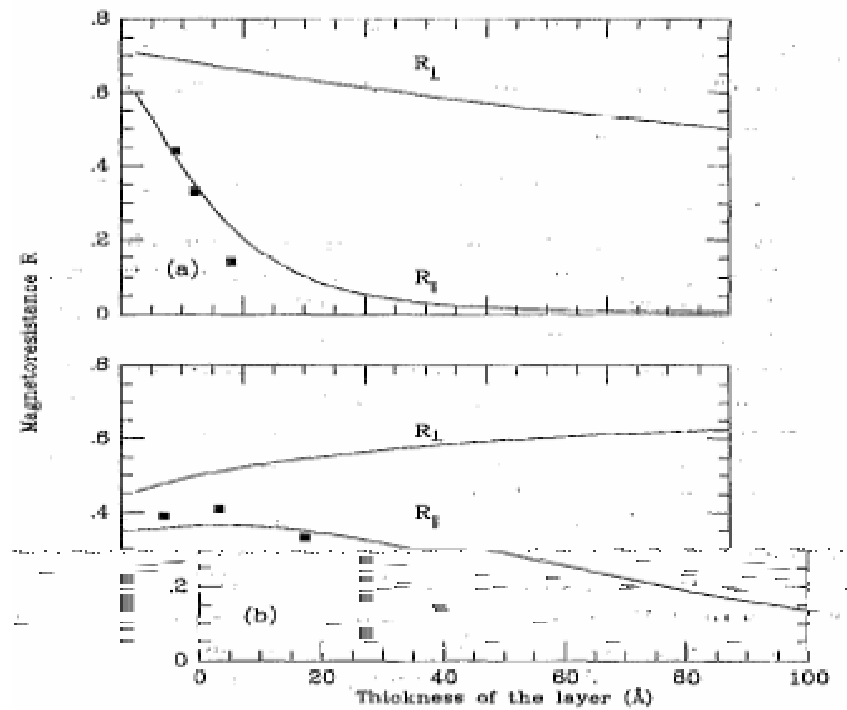




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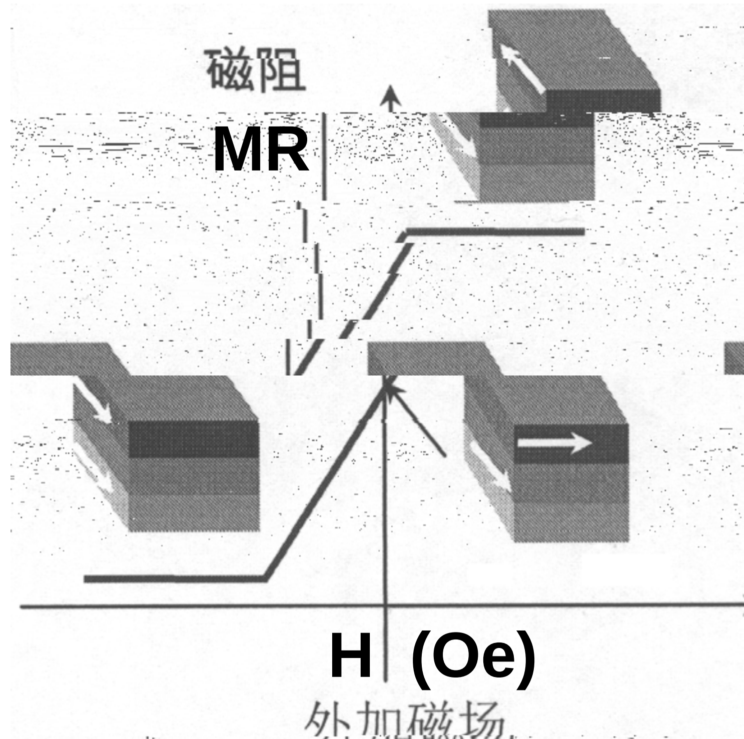
FIG. 2. The magnetoresistance ratios $R_\parallel$ and $R_\perp$ ... $R = [\rho(H=0) - \rho(H=H_s)]/\rho(H=0)$ with the parameter produce the best fit to the experimental data at $T = 4.2$ K given in 1 and 2, and recent results by Fert and co-workers (to be published $\lambda_b = 19$ Å, $\lambda_s = 0.55$ $(t_{Fe} + t_{Cr})$, and $\rho_\uparrow/\rho_\downarrow = 12$: (a) as a functi thickness of the chromium layers for for fixed $t_{Fe} = 30$ Å; (b) as a fu of thickness of the iron layers for fixed $t_{Cr} = 12$ Å.

**Zhang et al., JAP 69 (1991)4786**

# (8) GMR read head in Hard Disk Drive (HDD)

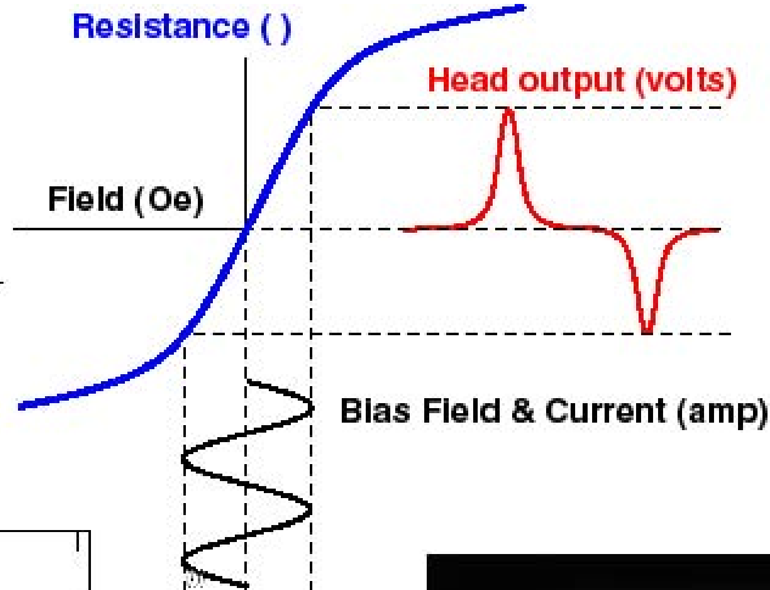

GMR 计　机磁读头

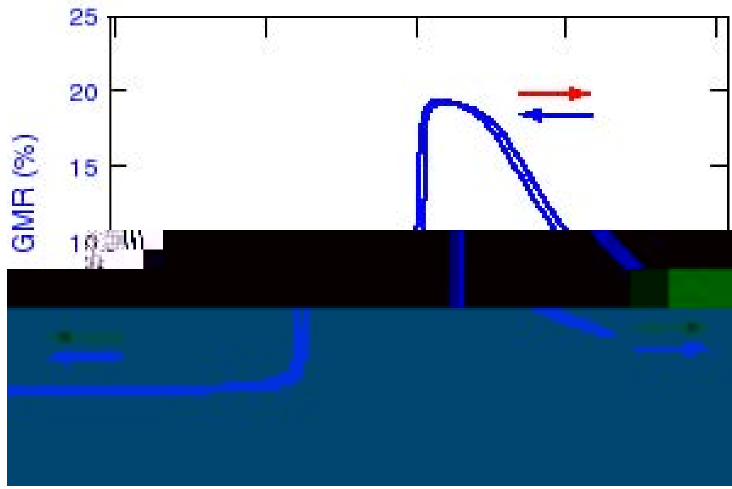
## Linear output MR signal

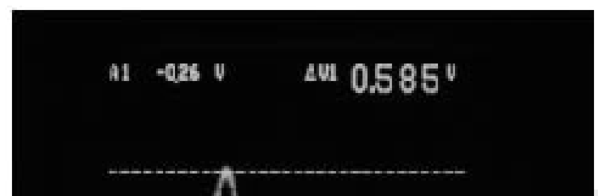



**Ref：Prof. Z.C. Jiang's report of SAE**

$$V_{max} = GMR \cdot \frac{C_w}{h} \cdot I_s R_p$$



# Scaling

4.4 Mbyte

80 Gbyte HDD

340 Mbyte

**70 kbit/s**
**IBM RAMAC 1955**
**2 kbits/in$^2$**
**50x24” dia disks**

**436 Mbit/s**
**Seagate U series 2001**
**32.6 Gbits/in$^2$**
**2 x 3.5”glass disks**

**180 Mbit/s**
**IBM Microdrive**
**1999**
**6 Gbits/in$^2$**
**1 x 1” dia disk**

(Supplied by Dr. Bin Lu of Seagate)

# 1995 发现室温 (TMR)

**Fe/Al-Ox/Fe MTJ** | **CoFe/Al-Ox/Co MTJ**

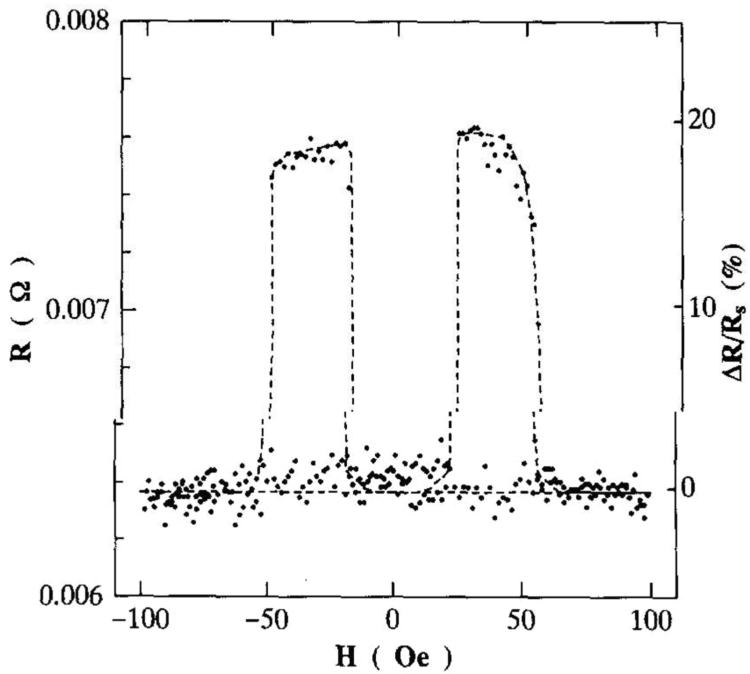



Fig. 1. Resistance as a function of the magnetic field for 1000 Å $Fe/Al_2O_3/1000$ Å Fe junction.

T. Miyazaki *et al.*, JMMM 139(1995)L231

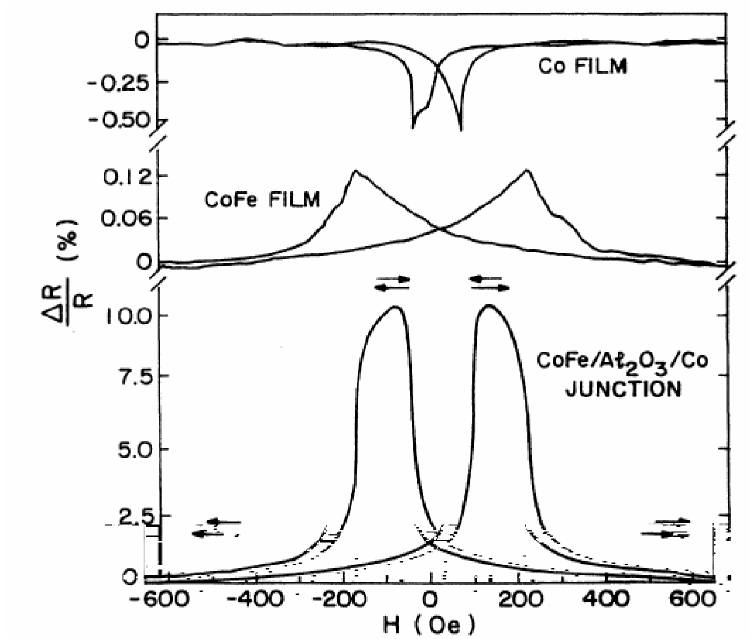



FIG. 2. Resistance of $CoFe/Al_2O_3/Co$ junction plotted as a function of $H$ in the film plane, at 295 K. Also shown is the variation in the CoFe and Co film resistance. The arrows indicate the direction of $M$ in the two films (see text).

J. S. Moodera et al., PRL 74 (1995) 3273

# (AFM)

**Table 4.1.** Characteristics of spin valves using various types of antiferromagnets

| AF films | FeMn | IrMn | NiMn | PtMn | NiO | $\alpha$-$Fe_2O_3$ |
|---|---|---|---|---|---|---|
| Critical thickness(nm) | 7~10 | 5~8 | <25 | 10~15 | <50 | <50 |
| Neel temp. | 230 | 420 | 797 | 702 | 250 | 680 |
| [redacted] | | | | | | |
| Blocking Temp. (°C) | 250 | 370 | 380 | 200 | 250 | 150 |
| Exchange bias field (Oe) | 450 | 450~860 | 500 | 200 | 40~75 | 420 |
| Corrosion Resistance | × | ○ | ○ | ○ | ○ | ○ |
| References | [3] | [4] | [5] | [6] | [7] | [8] |

# GMR/TMR

**(1)**

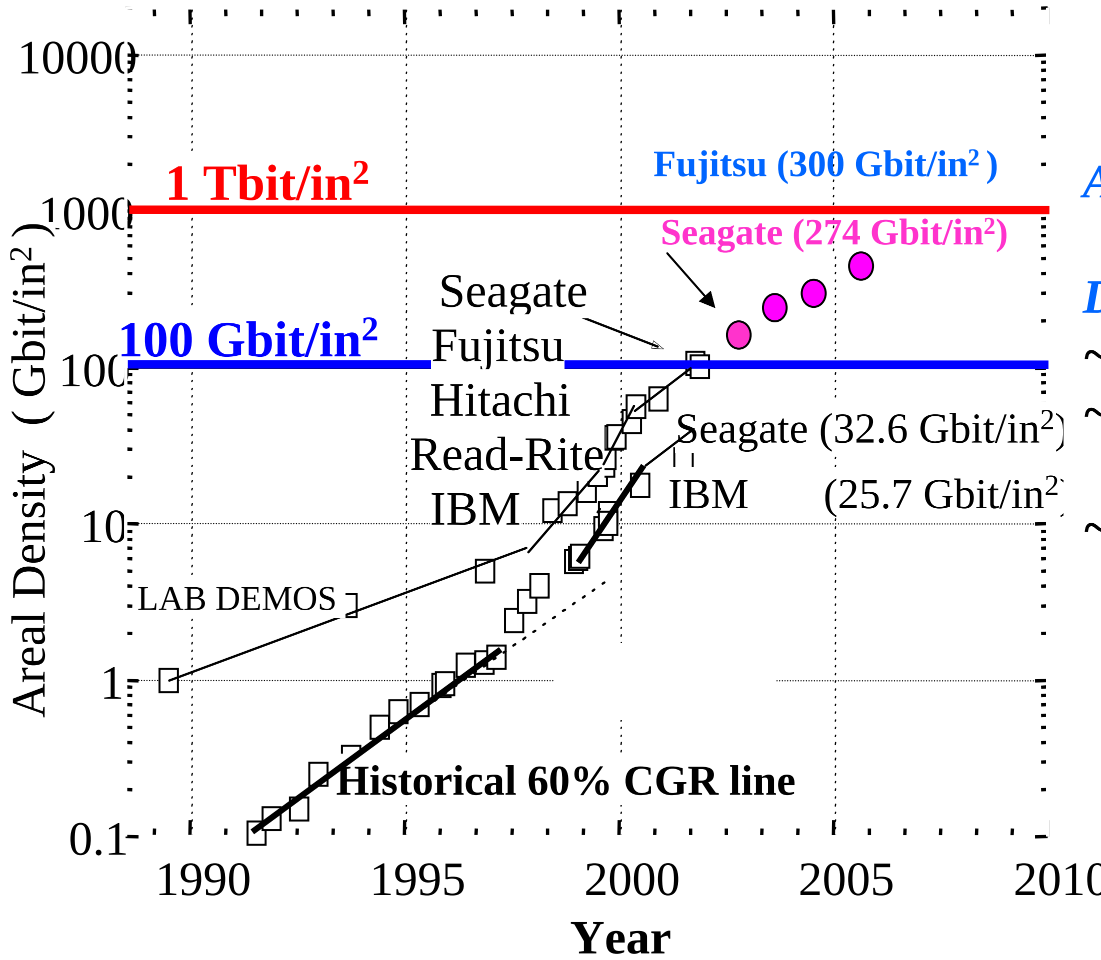
| FM | Ni | Co | Fe | $Ni_{50}Fe_{50}$ | $Co_{50}Fe_{50}$ | $Co_{20}Fe_{60}B_{20}$ | $CrO_2$ | NiMnSb | LSMO |
|---|---|---|---|---|---|---|---|---|---|
| P(%) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**(2)**

| Barrier Materials | $AlO_x$ | $MgO_x$ | $TaO_x$ | $ZrO_x$ | AlN | $CrO_x$ |
|---|---|---|---|---|---|---|
| TMR(%) | 81% | 361% | 2.5% | 20% | 15.5% | 8% |
| Journals | Wei et al., JAP 101, 09B501 (2007) | Lee et al., APL 89, 042506 (2006) | Rottlander et al., APL 78, 3274 (2001) | Wang et al., APL79, 4387 (2002) | Shim et al., APL 77, 2219 (2000) | Gupta et al., APL 78, 1894 (2001) |

# A real density roadmap

**$5 \times 10^7 \times$ a real density increase**




***As of Nov '01:***

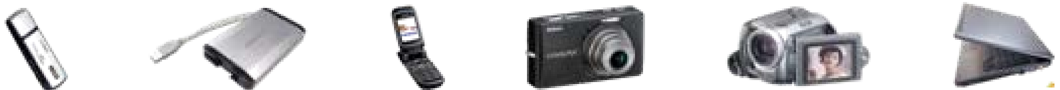
***Demos:***

~*100 Gbpsi long*

~***63 Gbpsi perp***

~*33 Gbpsi long*

(Supplied by Dr. Bin Lu of Seagate)



2007

(1)

(2) (GMR)

(3)

GMR

TMR

(4) MP3 iPod

Prof. Albert Fert Prof. Peter Grünberg

# MRAM development and related spintronics Projects

| 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|

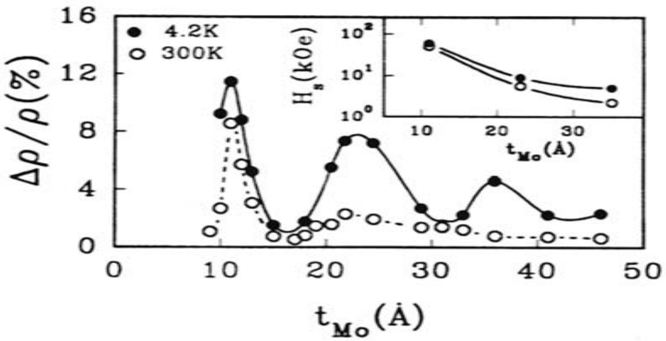
Finding GMR

| Authors (200 ~ 300 GMR related papers) | Journals | Key words |
|---|---|---|
| Q.Y. Jin, Y.B. Xu, H.R. Zhai, C. Hu, M. Lu, Q. Bi, Y. Zhai, G.L. Dunifer, R. Naik, M. Ahmad | PRL 72(1994)768 | **NMR Fe/Cu Cu** |
| M. Li, X. D. Ma, C. B. Peng, J. G. Zhao, L. M. Mei, Y. S. Gu, W. P. Chai, Z. H. Mai, B. G. Shen, Y. H. Liu, D. S. Dai | PRB 50(1994)10323 | **Fe/Pb Pb** |
| S. S. Yan, Y. H Liu and L.M. Mei | PRB 52(1995) 1107 | **Co-Nb/Pb** |
| L. M. Li, F. C. Pu, G. L. Yang and B. Z. Li | PRB 51(1995)12833 | |
| J. H. Wu, B. Z. Li, G. L. Yang and F. C. Pu | PRB 53(1996) 9471 | **GMR** |
| M. L. Yan, Z.S. Shan, D.J. Sellmyer, W.Y. Lai | JAP 81(1997) 4785 | **NiFe/Mo Fe** |
| H. W. Zhao, Y. Chen, G. S. Dong, M. Lu, X. F. Jin, Y. J. Wang, H. R. Zhai, D. Yang, R. Naik, G. L. Dunifer and G. W. Auner | JAP 81(1997) 5203 | **Co/Mo/Co** |
| L. Sheng, D. Y. Xing, Z. D. Wang J. M. Dong, Y. Li, B. Z. Li, W. S. Zhang, D. S. Dai | PRB 55(1997)5908<br>PRB 57(1998) 1079 | **TMR** |

**JMMM在1999年出版了专集“Magnetism beyond 2000”。其中JMMM 200(1999)571一文介绍了当时国际上发现的20多种“具有GMR效应两个特点”的多层膜材料。我们有3种金属多层膜被收录。**

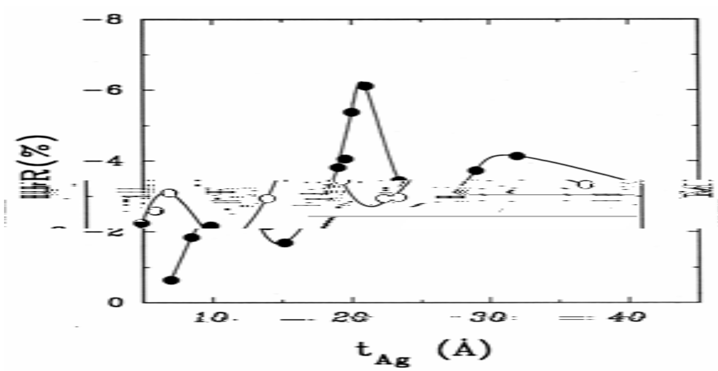
## 1 Fe / Mo GMR

**JAP 77 (1995) 1816**，阎明朗、麦正洪、赖武彦等




## （2）Fe/Ag GMR

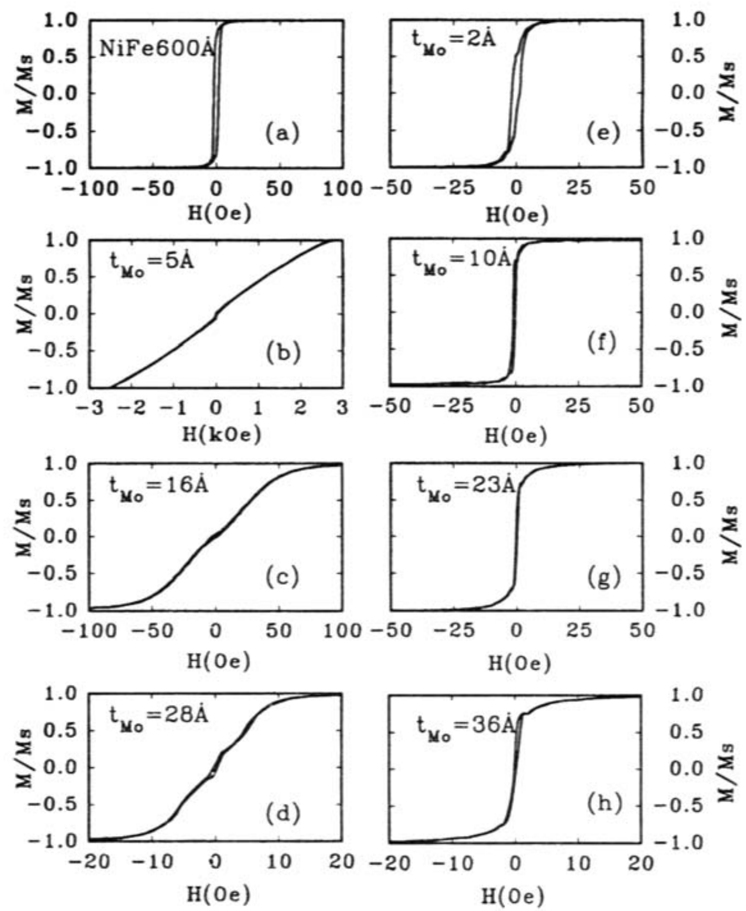
PRB 52(1995)1123，于成涛，赖武彦等




## (3) NiFe/Mo GMR

（斜的线对应磁矩的反平行；垂直线对应磁矩的平行）

**JPCM 8(1996) L711,**阎明朗、麦正洪、王文魁、赖武彦等



RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 59, NUMBER 18 1 MAY 1999-II

# Oscillatory interlayer coupling in Fe/Mn/Fe trilayers

Shi-shen Yan
*Institut für Festkörperforschung, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*
*and Department of Physics, Shandong University, Jinan, Shandong 250100, People's Republic of China*

R. Schreiber, F. Voges, C. Osthöver, and P. Grünberg
*Institut für Festkörperforschung, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany*

(Received 13 November 1998)

Fe/Mn/Fe wedged-shape sandwiches were prepared by molecular beam epitaxy under optimal conditions. The interlayer coupling measured by magneto-optic Kerr effect is very strong for thin Mn layers. The canted

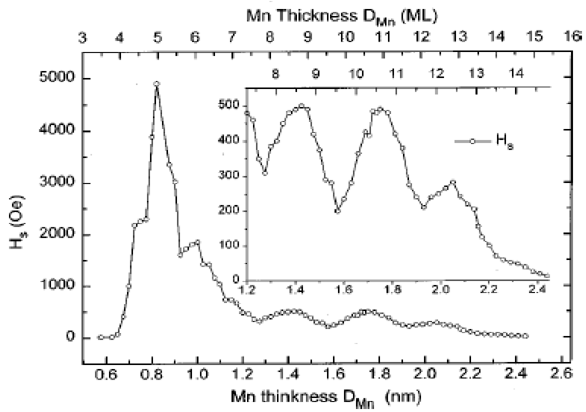



FIG. 2. The Mn layer thickness $D_{Mn}$ dependence of the saturation field $H_S$. The inset shows the details of the saturation field oscillations.

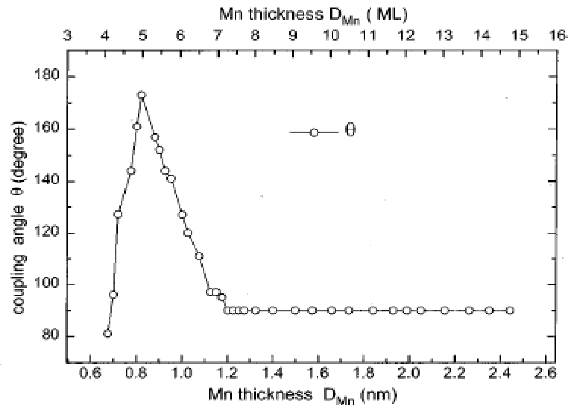



FIG. 3. The Mn layer thickness $D_{Mn}$ dependence of coupling angle $\theta$ in remanence.

VOLUME 72, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 1994

# Direct Evidence of Spin Polarization Oscillations in the Cu Layers of Fe/Cu Multilayers Observed by NMR

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*National Laboratory of Solid State Microstructure, Department of Physics, and the Center of Materials Analysis, Nanjing University, Nanjing, 210008, China*

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*Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48202*
(Received 20 May 1993)

Evidence of the existence and distribution of an induced spin polarization of the conduction electrons in the Cu layers of Fe/Cu multilayers has been obtained by nuclear magnetic resonance (NMR). Fine structure associated with the spin-echo signal of $^{63}$Cu and $^{65}$Cu nuclei shows that the spin polarization
late in sign, similar to the characteristics of the RKKY interaction.
of the period of the oscillations cannot be determined solely from

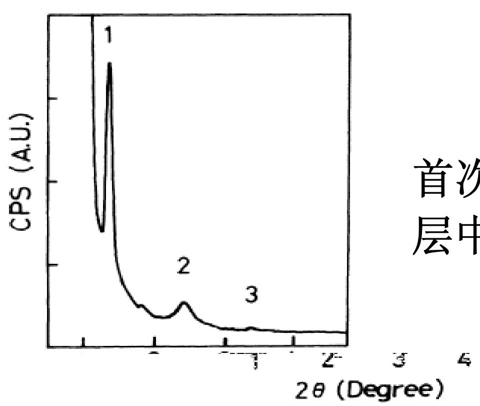
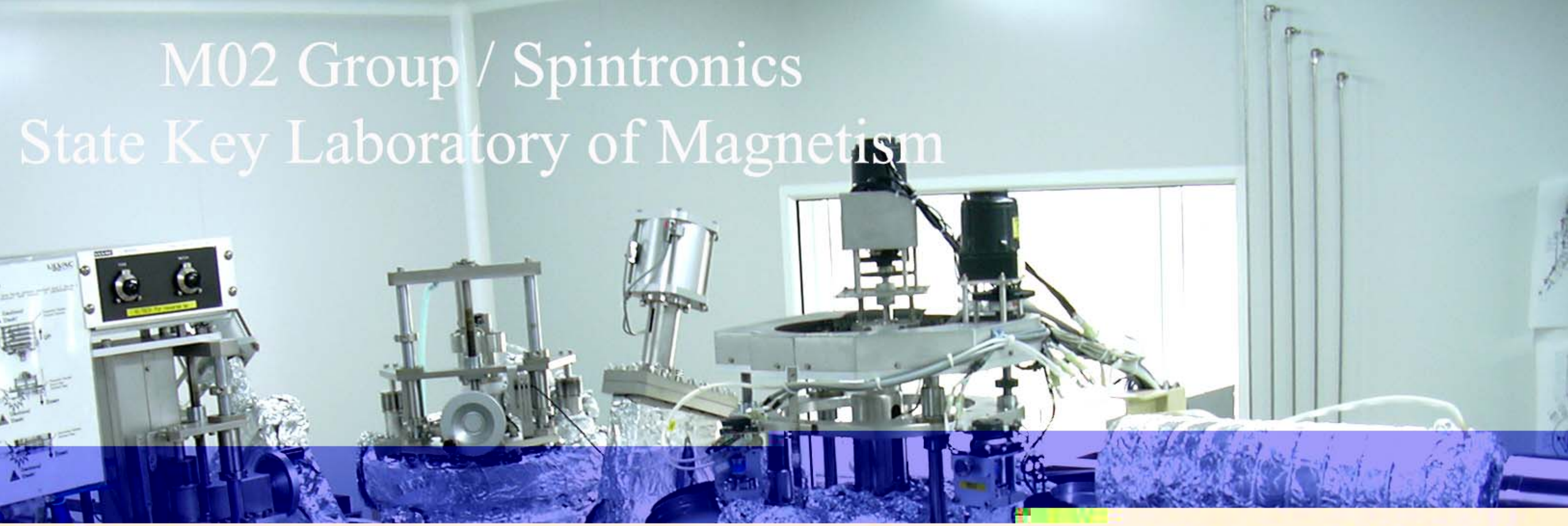



FIG. 1. Low-angle x-ray diffraction pattern of a Fe/Cu multilayer on a glass substrate.

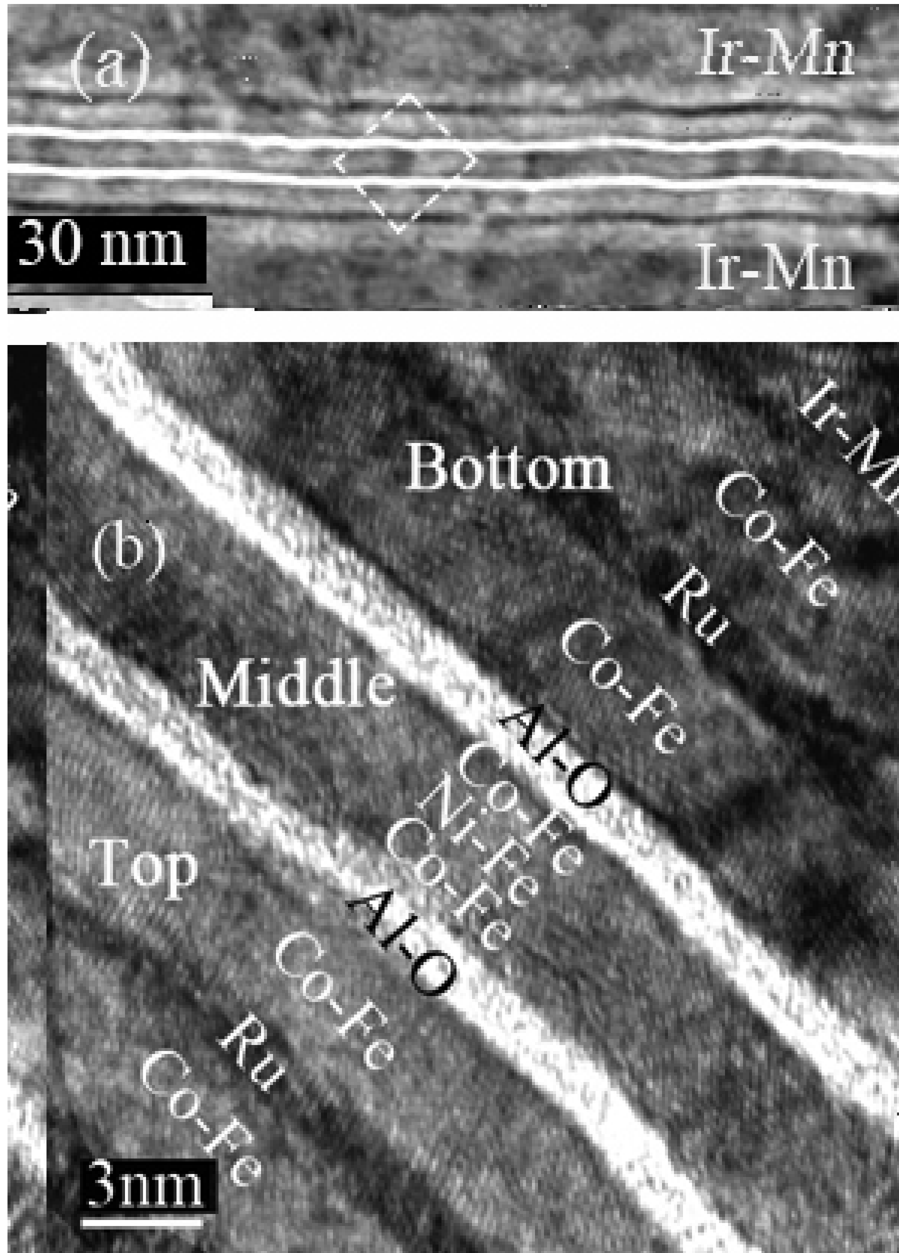
首次利用核磁共振(NMR)在Fe/Cu多层膜的Cu层中发现自旋极化传导电子的存在和分布。

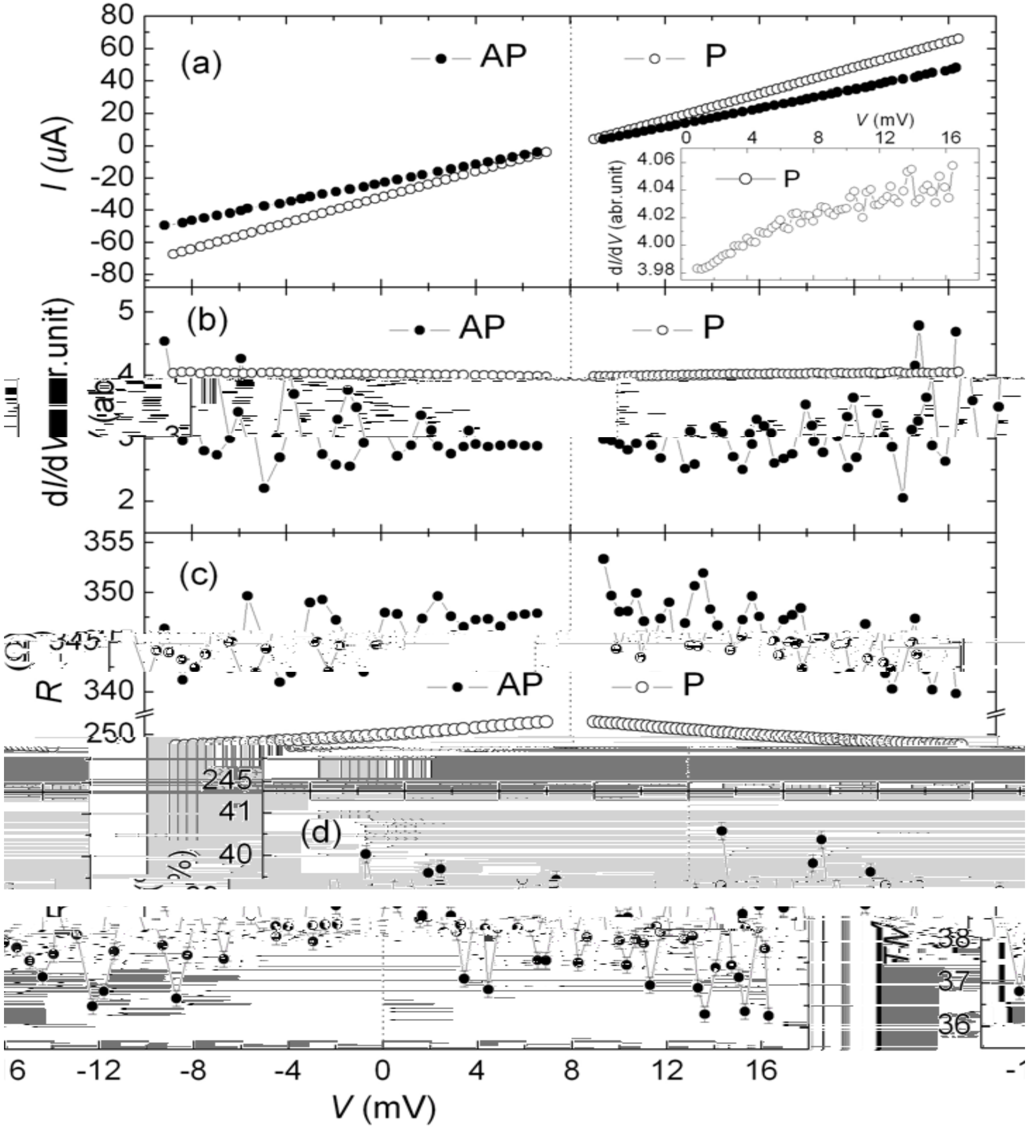
# M02 Group / Spintronics
# State Key Laboratory of Magnetism



# TEM image

1 Cover layers
2 $Ir_{22}Mn_{78}$ (10)
3 $Co_{75}Fe_{25}$ (3)
4 Ru (0.9)
5 $Co_{75}Fe_{25}$ (3)
6 Al-O (1)
7 CoFe(1)/Py(1)/CoFe(1)
8 Al-O (1)
9 $Co_{75}Fe_{25}$ (3)
10 Ru (0.9)
11 $Co_{75}Fe_{25}$ (3)
12 $Ir_{22}Mn_{78}$ (10)
13 Seed layers





TMR Oscillation Effect

at 300 K observed

in the DBMTJ

using PPMS

Z.M. Zeng, X.F. Han et al.,

PRB 72 (2005) 054419-1-5

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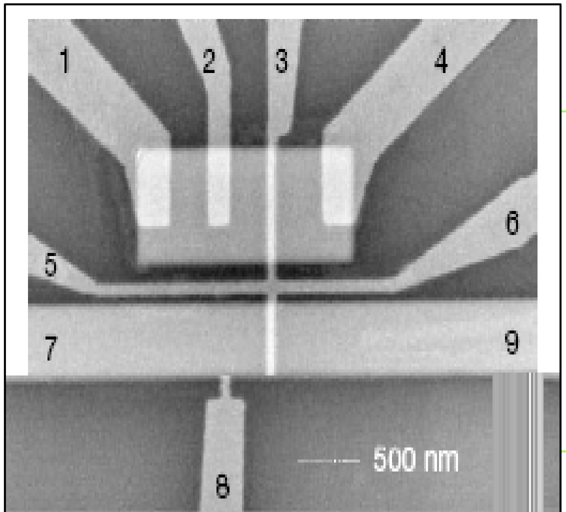
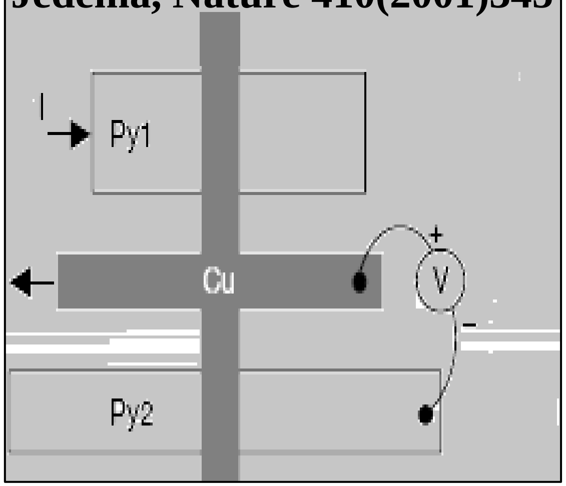



Jedema, Nature 410(2001)345




1
2
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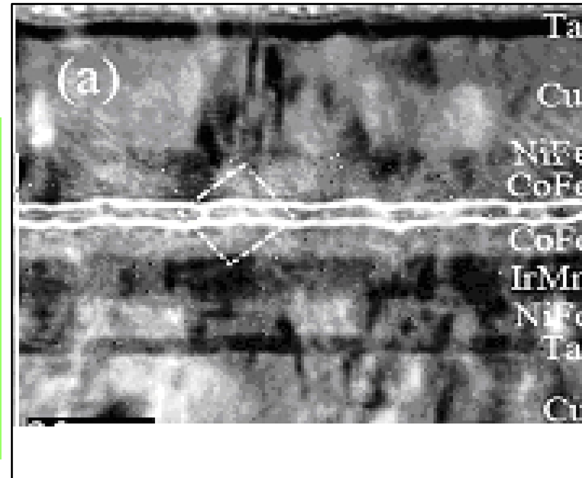


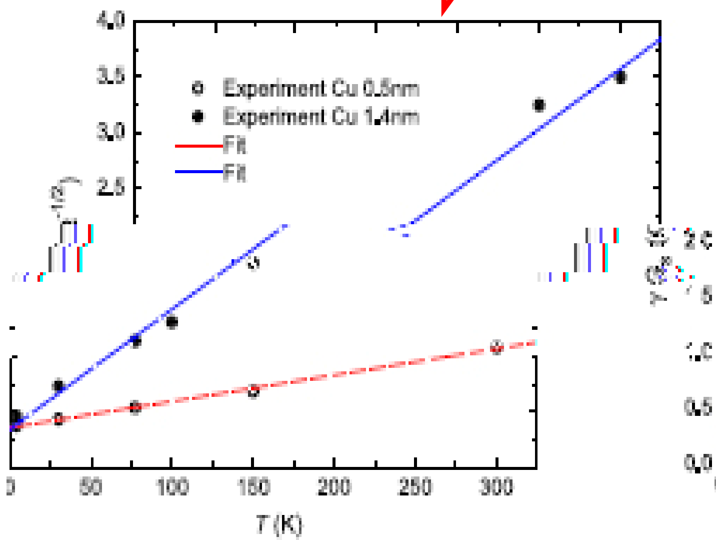


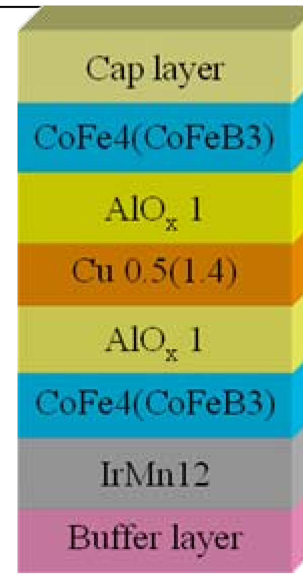


Z.M. Zeng et al., *Phys. Rev. Lett.* 97, 106605 (2006)

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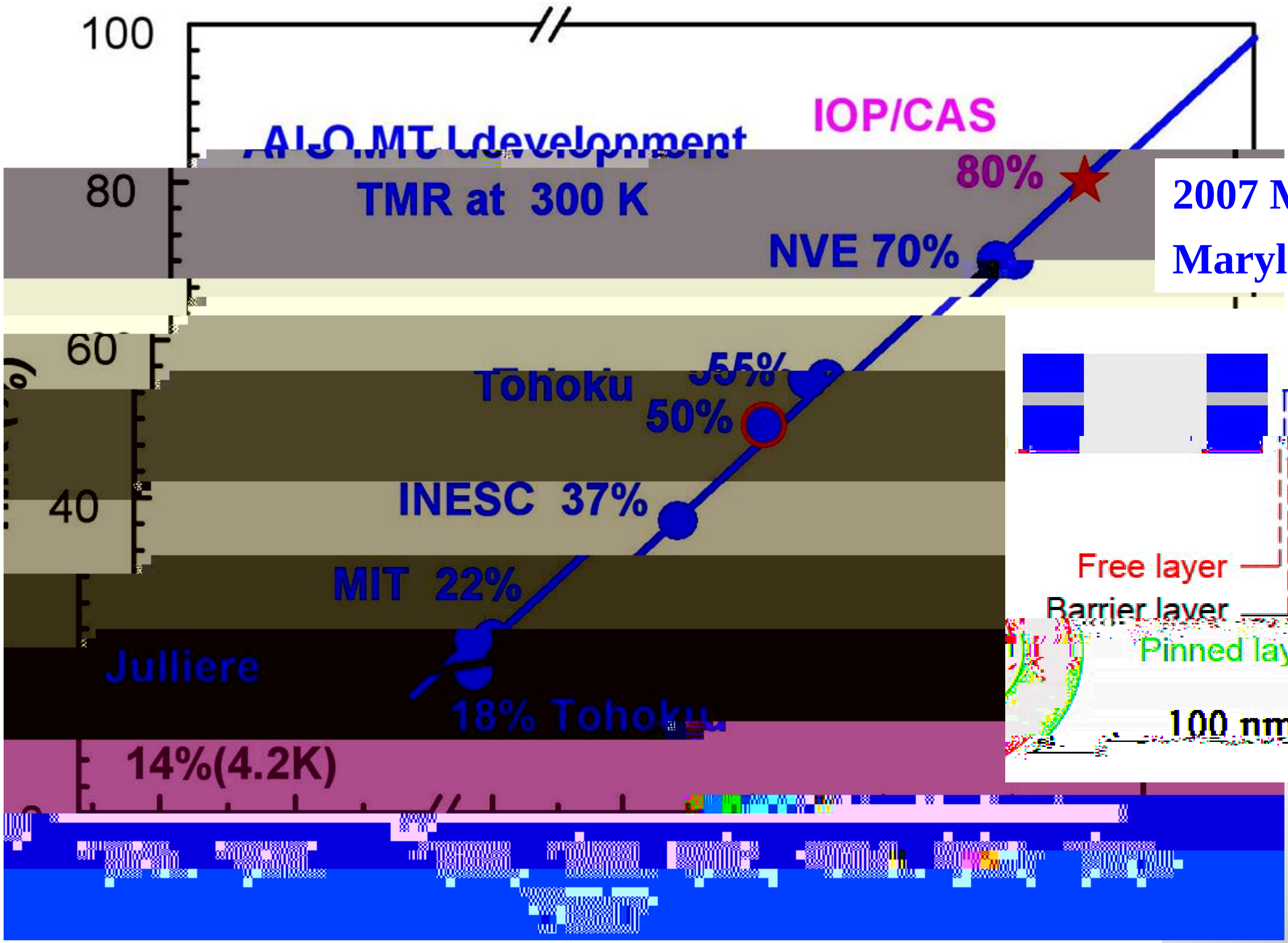
# TMR




2007 MMM / InterMag
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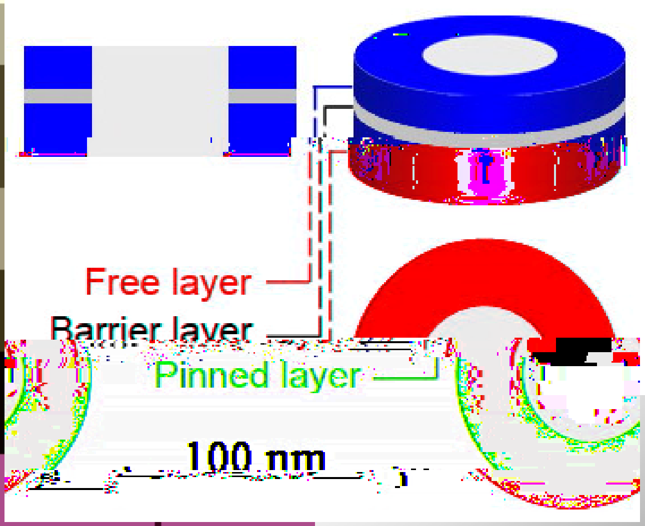
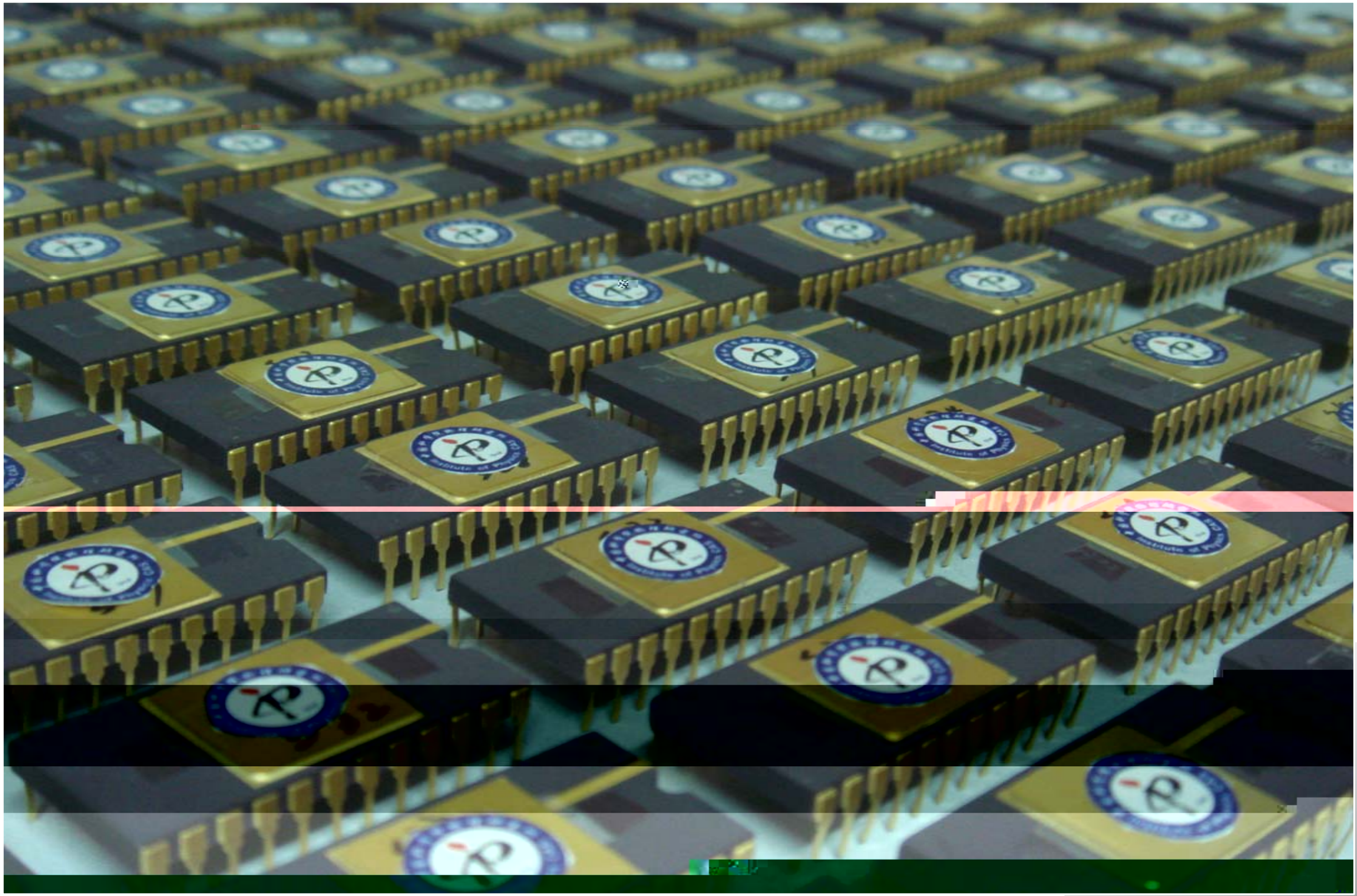
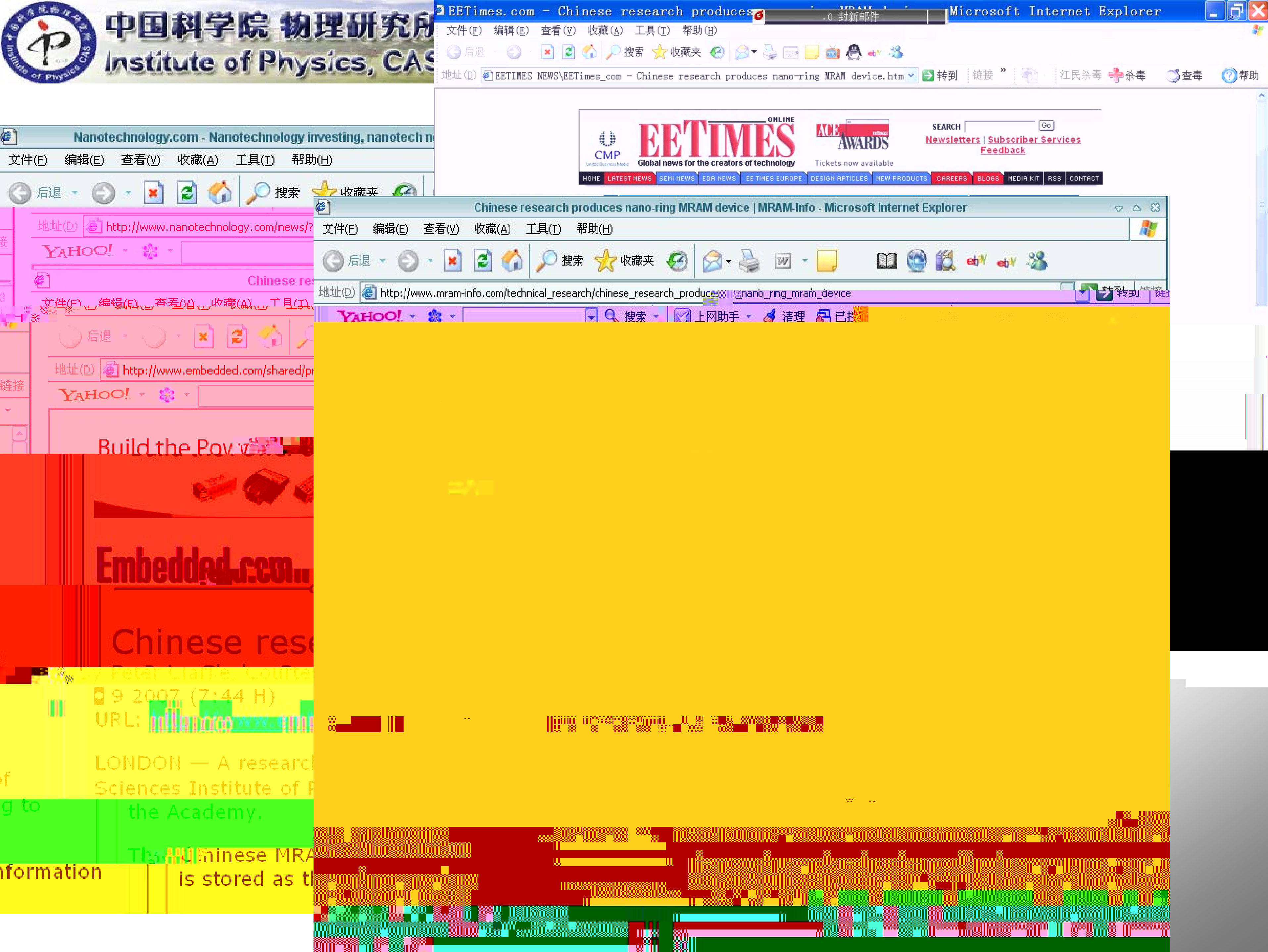


# Nano-Ring MRAM using Spin Polarized Current Switching

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Institute of Physics, CAS
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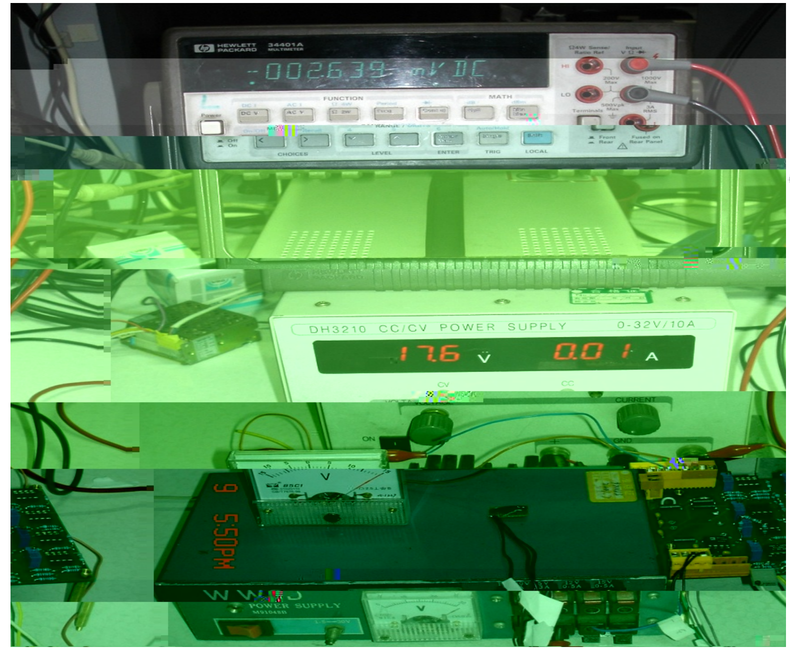
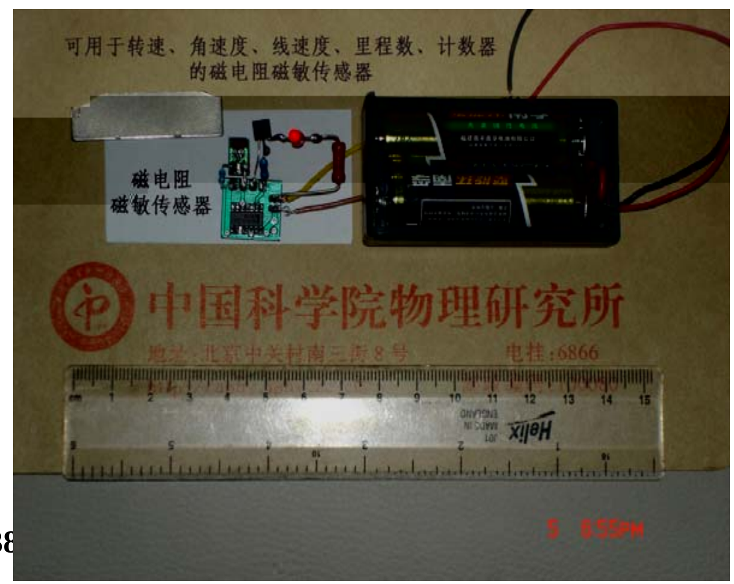
中国科学院物理研究所


DH3210 CC/CV POWER SUPPLY 0-32V/10A
17.6 V
0.01 A


可用于转速、角速度、线速度、里程数、计数器
的磁电阻磁敏传感器
磁电阻
磁敏传感器
中国科学院物理研究所

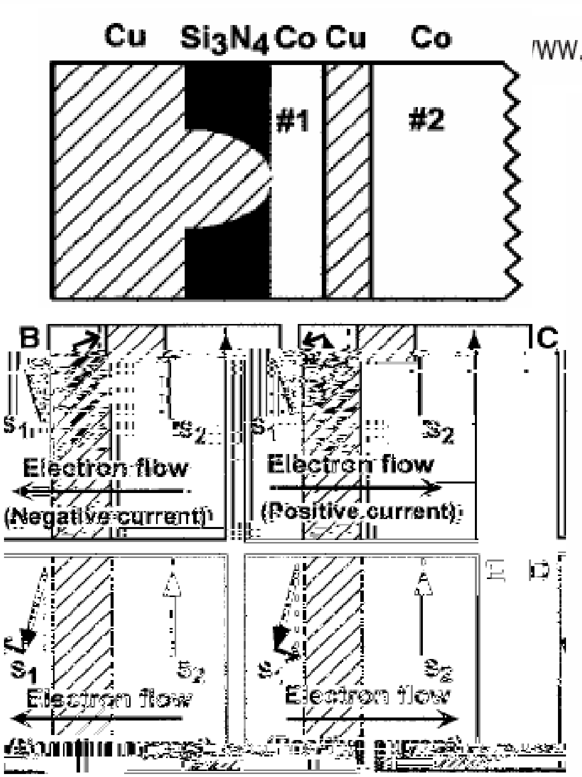

MINI MONEY DETECTOR
100
£50
10000

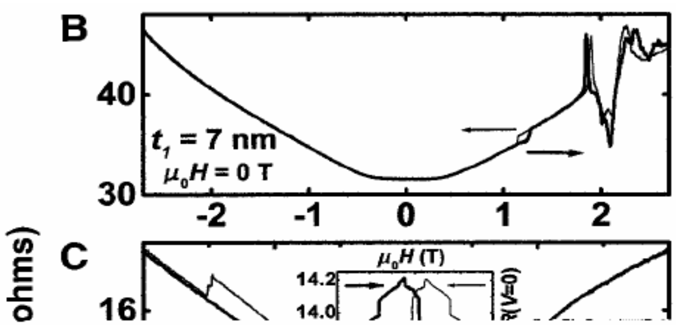
# GMR TMR

## Current-Induced Switching of Domains in Magnetic Multilayer Devices

E. B. Myers,[1] D. C. Ralph,[1*] J. A. Katine,[2] R. N. Louie,[2] R. A. Buhrman[2]

www.sciencemag.org SCIENCE VOL 285 6 AUGUST 1999 **P.867**



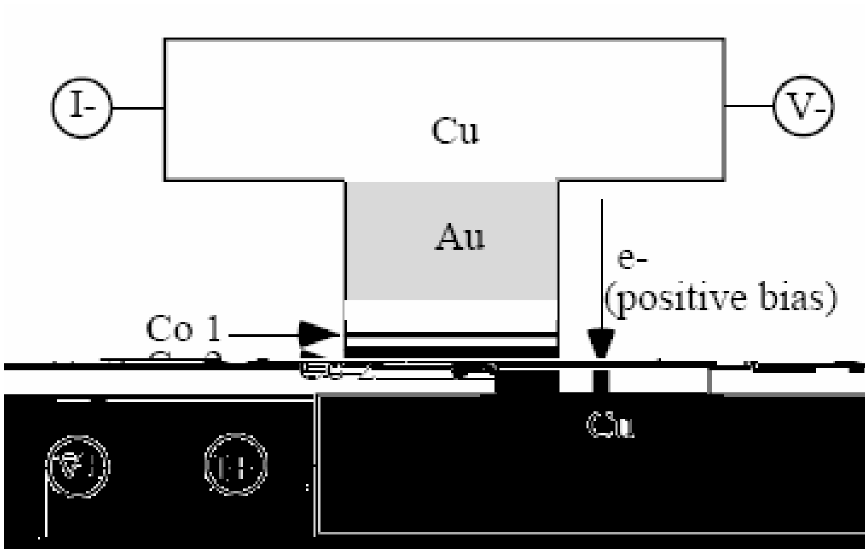
VOLUME 84, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 2000

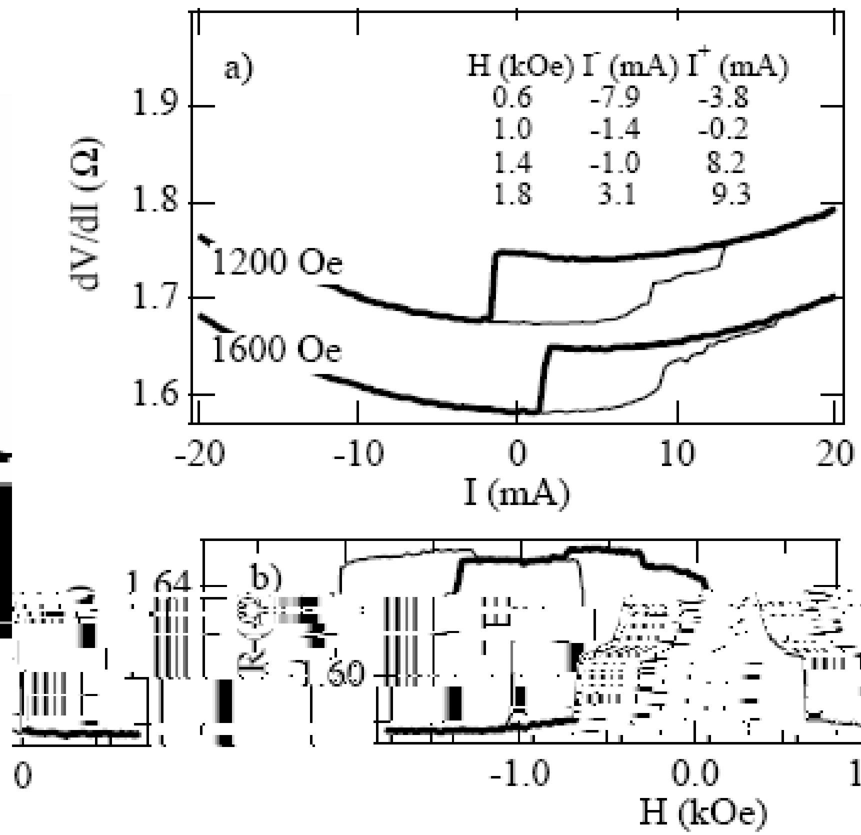
# Current-Driven Magnetization Reversal and Spin-Wave Excitations in Co/Cu/Co Pillars

J. A. Katine, F. J. Albert, and R. A. Buhrman
*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853*

E. B. Myers and D. C. Ralph
*Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853*

(Received 12 July 1999)



VOLUME 93, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2004

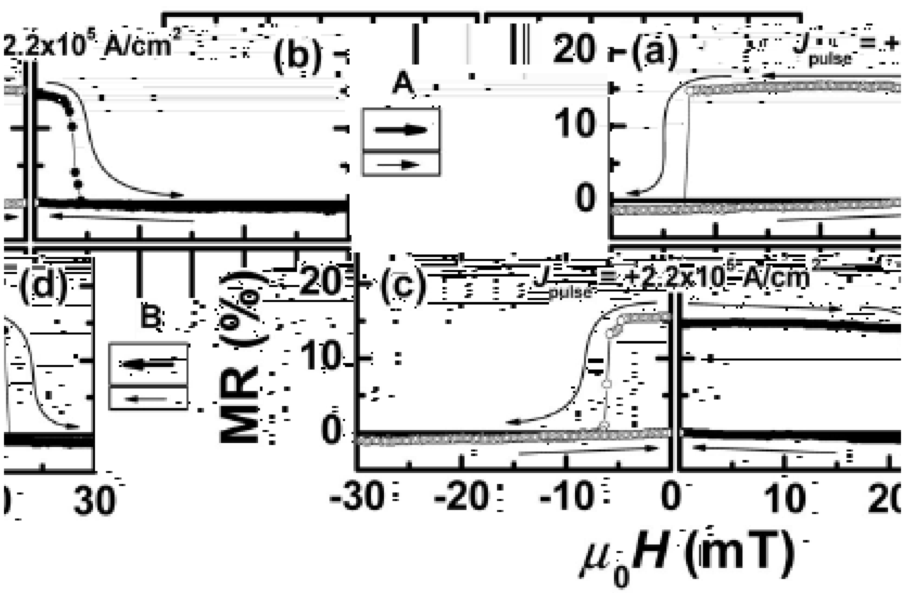
# Current-Driven Magnetization Reversal in a Ferromagnetic Semiconductor (Ga, Mn)As/GaAs/(Ga, Mn)As Tunnel Junction

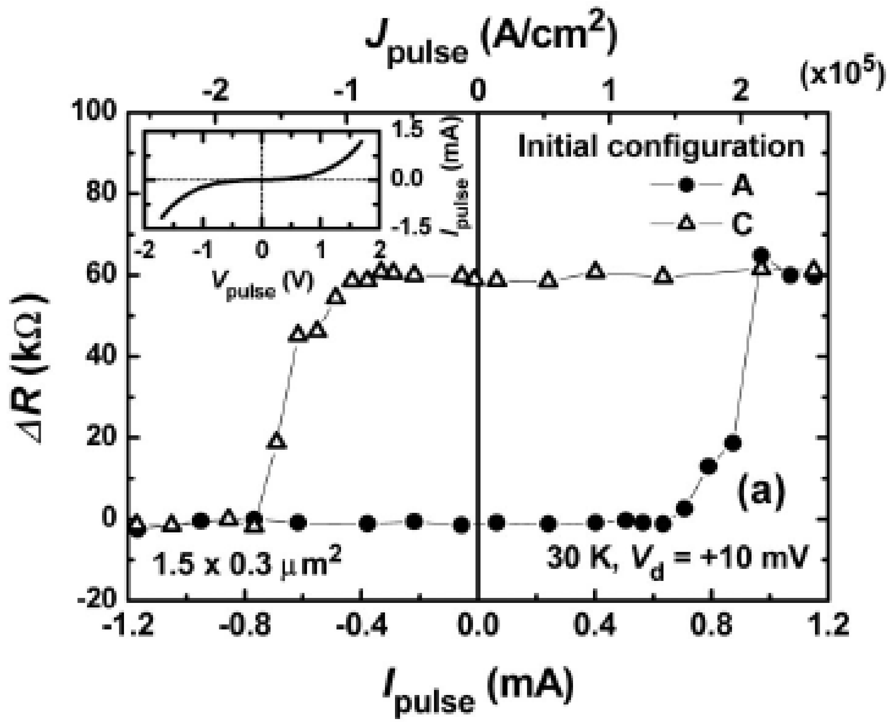
D. Chiba,[1,2,†] Y. Sato,[1] T. Kita,[1,2] F. Matsukura,[1,2] and H. Ohno[1,2,*]

[1]*Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan*

[2]*Semiconductor Spintronics Project, Exploratory Research for Advanced Technology, Japan Science and Technology Agency, Japan*

(Received 15 March 2004; published 18 November 2004)

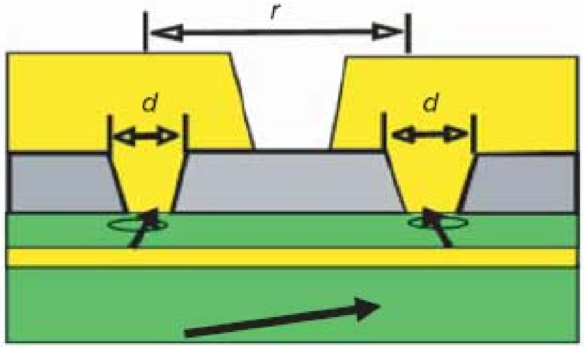


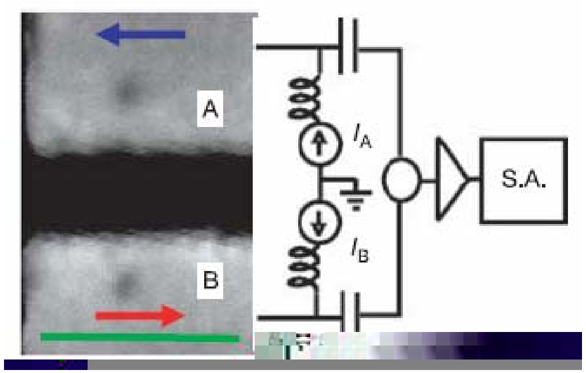



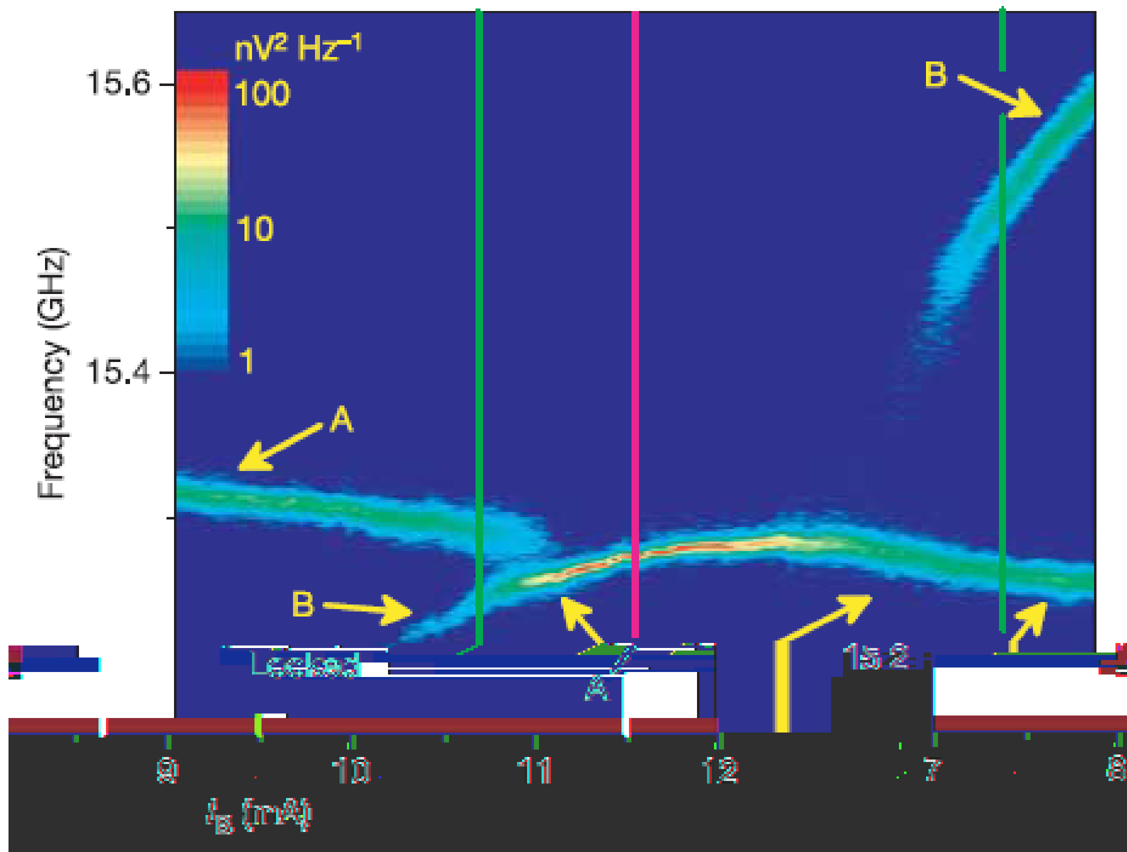
Vol 437|15 September 2005|doi:10.1038/nature04035

# Mutual phase-locking of microwave spin torque nano-osci ators

Shehzaad Kaka[1], Matthew R. Pufall[1], Wil
liam H. Rippard[1], Thomas J. Silva[1], Stephen E. Russek[1]
& Jordan A. Katine[2]



# Thanks for your attendance!