Giant Magnetoresistance in Quantum Point Contacts

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in cooperation with:

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and

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based on the works:

Diffusive to ballistic crossover: Phys. Rev. B, 63, 104428-4 (2001).
Quantized conductance & MR: Phys. Rev. B, 65, 214419-7 (2002).
Quantum spin valve: JMMM (submitted).

Plan of the talk

1. Motivation – García *et al* experiments.
2. Model of Nanosize Point Contact (NPC) and its solution (quasiclassical approach).
3. Analysis of the solution in the *ballistic* and *diffusive* regimes of conduction in the vicinity of NPC.
4. Analysis of the regime of quantized conduction through NPC.
5. Discussion of the conduction-band spin polarization in ferromagnetic metals

Introduction.

Magnetoresistance Definitions

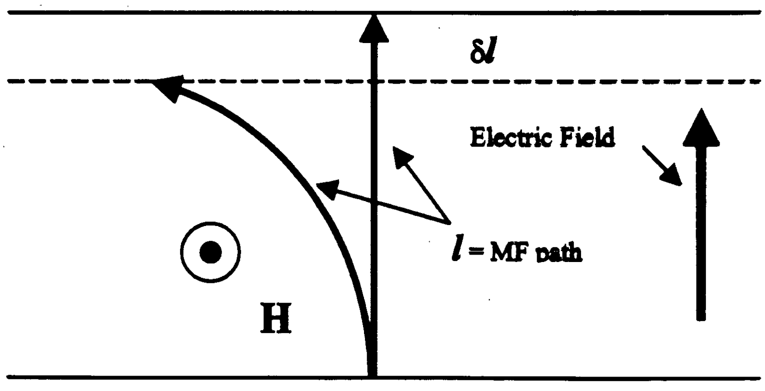
„optimistic“

$$MR = \frac{|R(H) - R(0)|}{\underline{\min}\,[R(H), R(0)]} ,$$

„pessimistic“

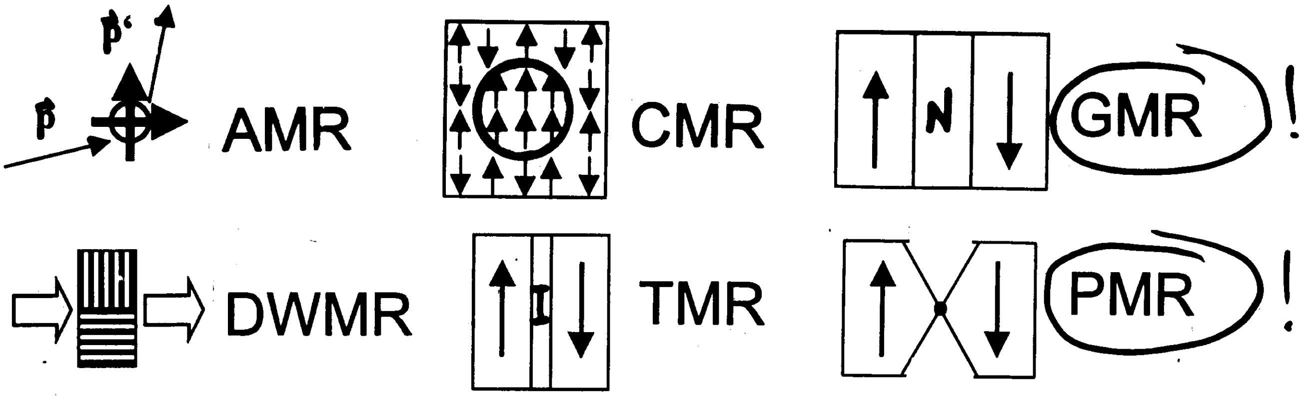
$$MR = \frac{|R(H) - R(0)|}{\underline{\max}\,[R(H), R(0)]} \leq 1 .$$

Lorentz Magnetoresistance



$\delta R_L = R(H) - R(0)$ - positive

MR in Magnetic Materials

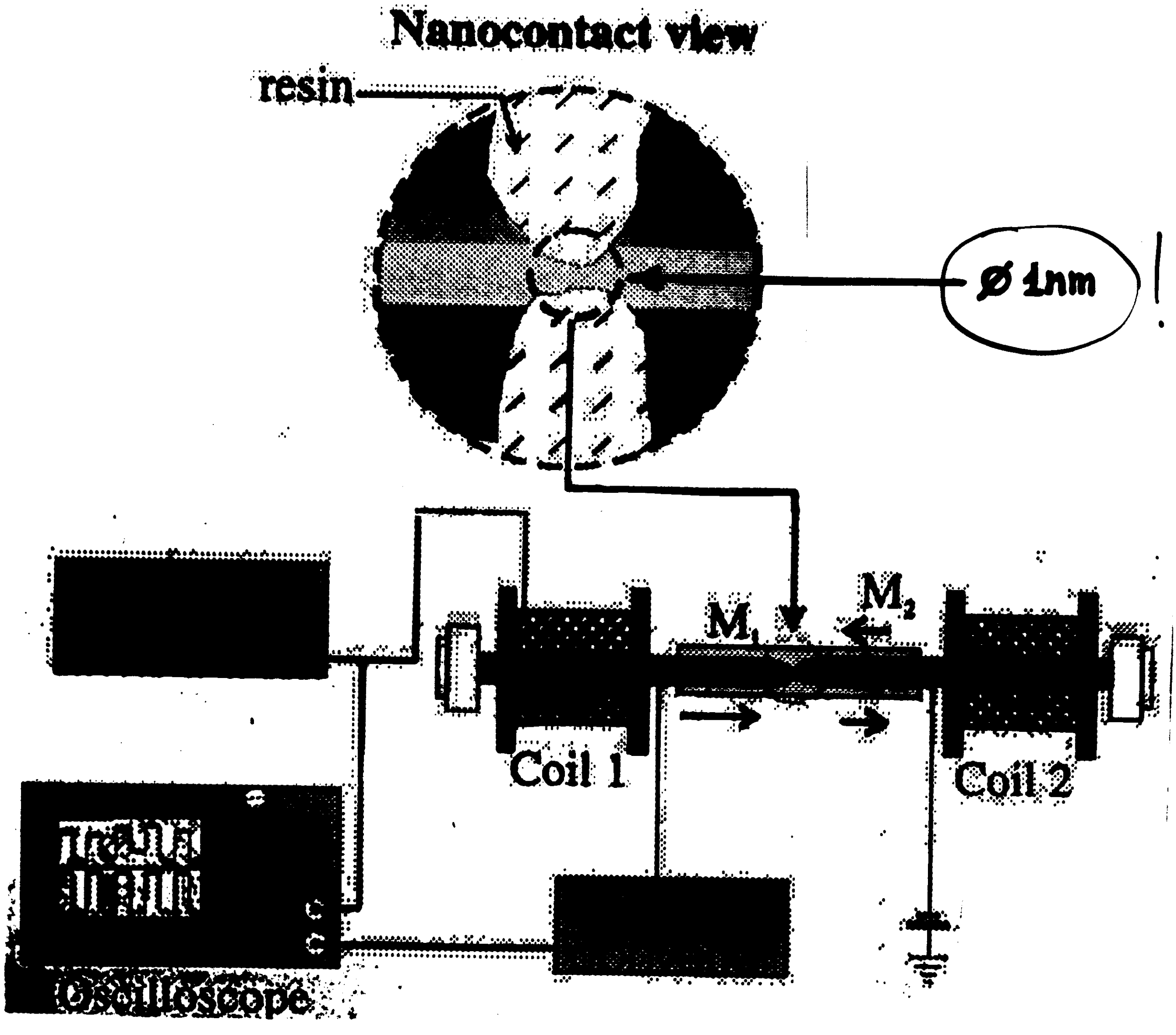


Motivation

Experiments by Garcia *el al* on nanosize point contacts (NPC):

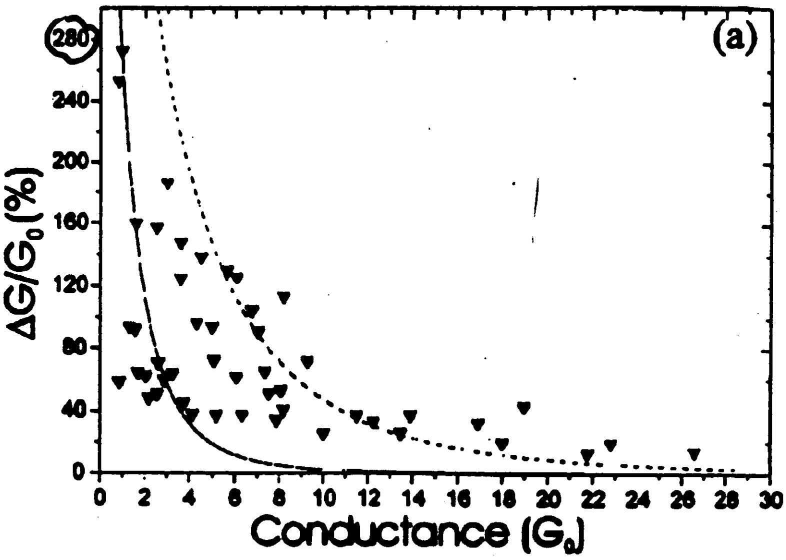
Ni-Ni: Phys. Rev. Lett. **82**, 2923 (1999),

Co-Co: Phys. Rev. Lett. **83**, 2030 (1999)

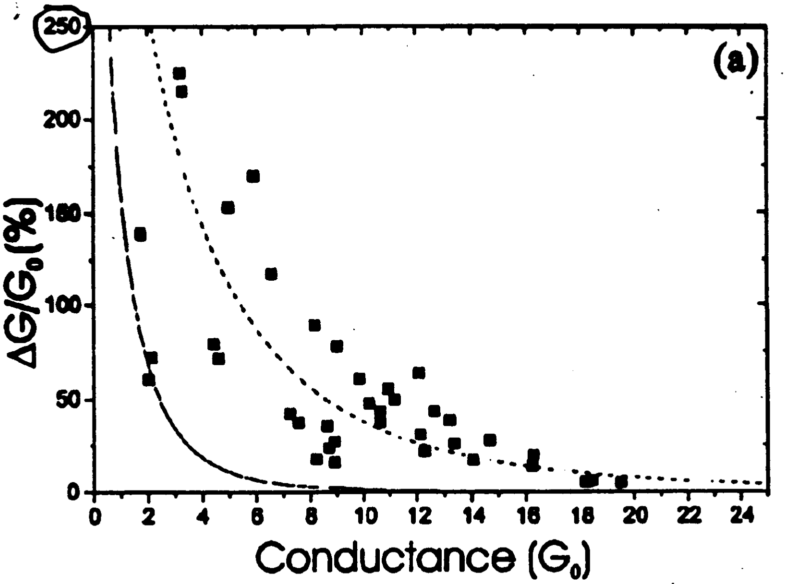


Experimental Results

For Ni-Ni NPC



For Co-Co NPC



$$MR = \frac{G_P - G_{AP}}{G_{AP}} \;; \quad \frac{h}{e^2} = 26000 \text{ ohm}$$

$$= \frac{R^{AP} - R^{P}}{R^{P}} \;;$$

MR of **iron** NPC

N.García, M.Munos, Y.-W.Zhao,
Applied Physics Letters **76,** 2586 (2000)

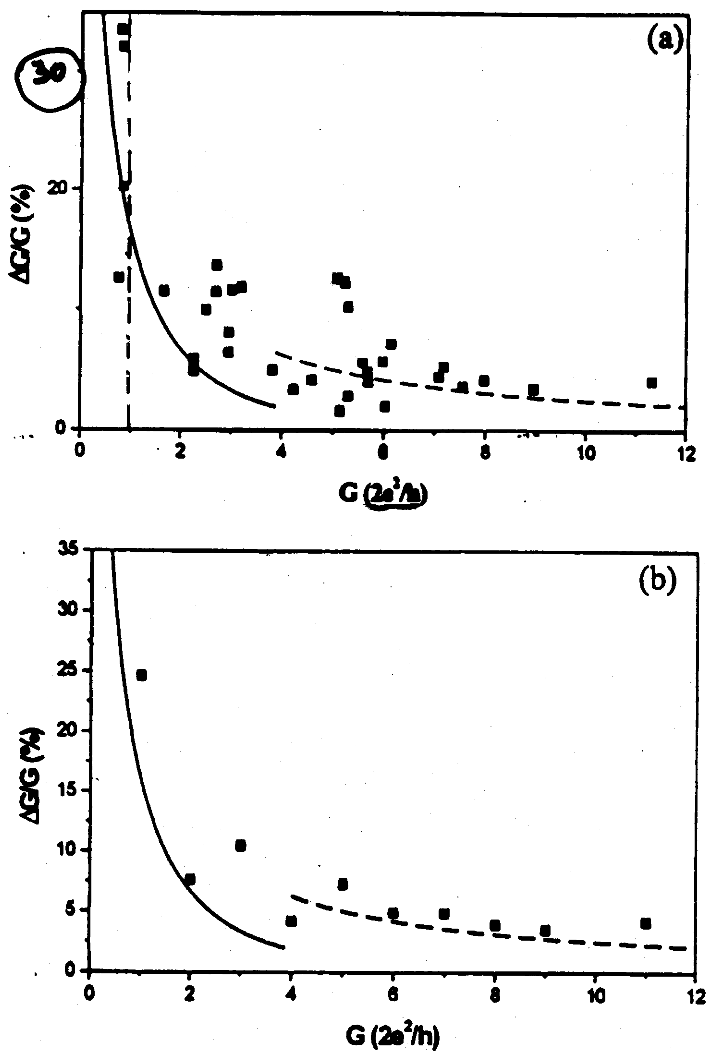


FIG. 1. (a) Experimental values of BMR for iron. The solid line is the calculation for theory developed in Ref. 2 for $\zeta=0.5$ and $r=3$ (from Ref. 7). The dashed line shows the α/N behavior ($\alpha=25$) for $N\gg1$. (b) The same as (a) but for the average experimental data. Notice that the BMR values are approximately ten times smaller for Fe than for Ni and Co (in Fig. 2).

Collection of MR data for **Ni and Co** NPC

(from N.García, M.Munos, Y.-W.Zhao, Applied Physics Letters **76,** 2586 (2000))

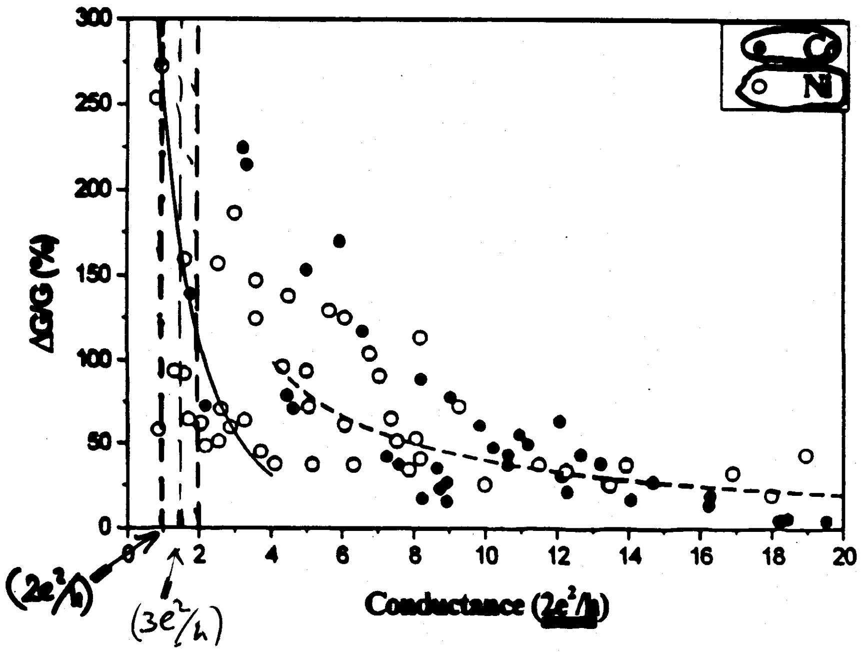
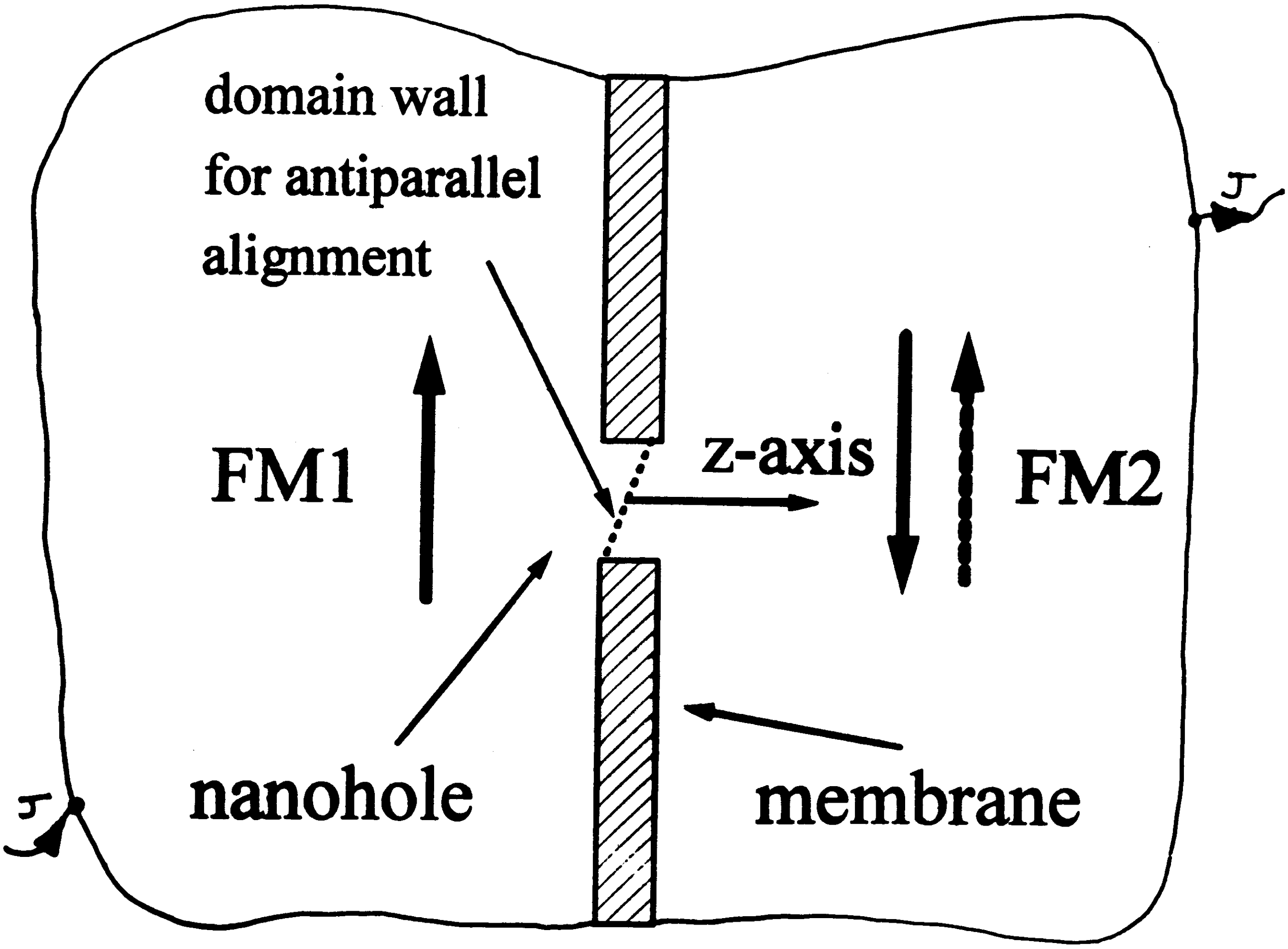


FIG. 2. Ballistic magnetoresistance for Ni and Co: the solid line is the calculation for $\zeta = 0.87$ and $r = 12$; the dashed line shows α/N behavior ($\alpha = 400$). Data for comparison are from Refs. 1 and 2.

L.R. Tagirov, B.P. Vodopyanov, K.B. Efetov, Phys. Rev. B 63, N10, p.104428 (2001).

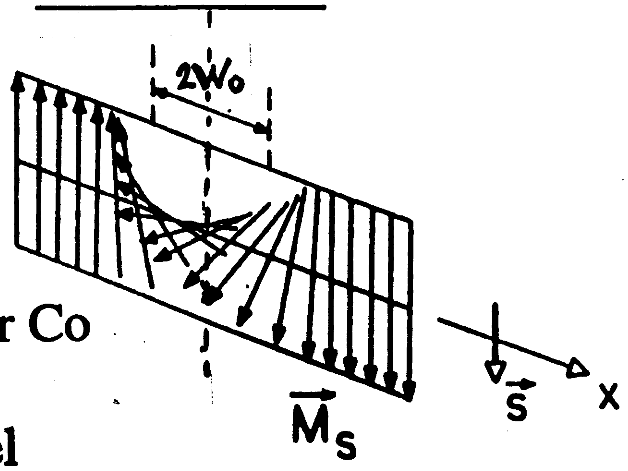
Model of NPC



Two independent spin-channels
(spin-mixing disregarded)
(bulk)

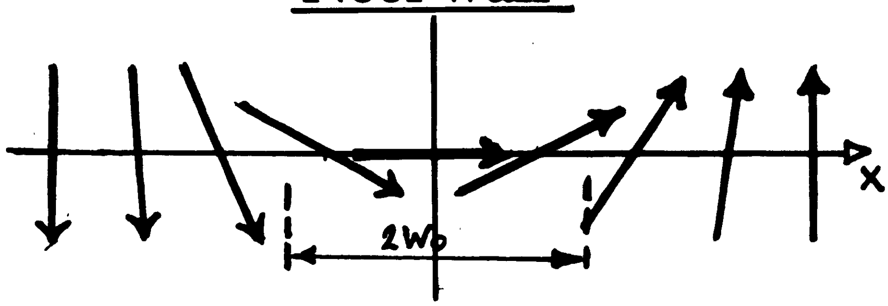
Domain Wall Structure

Bloch wall



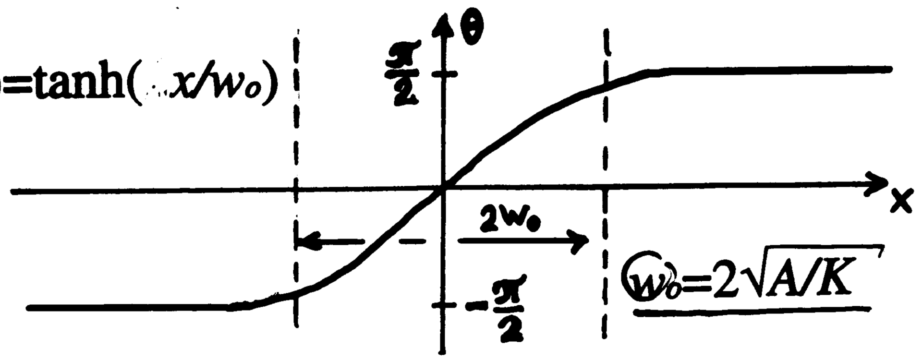
w_o=~150-200Å for Co
~400Å for Iron
~1000Å for Nickel

Neél wall



Rotation angle against coordinate

$\cos(\theta)=\tanh(x/w_o)$

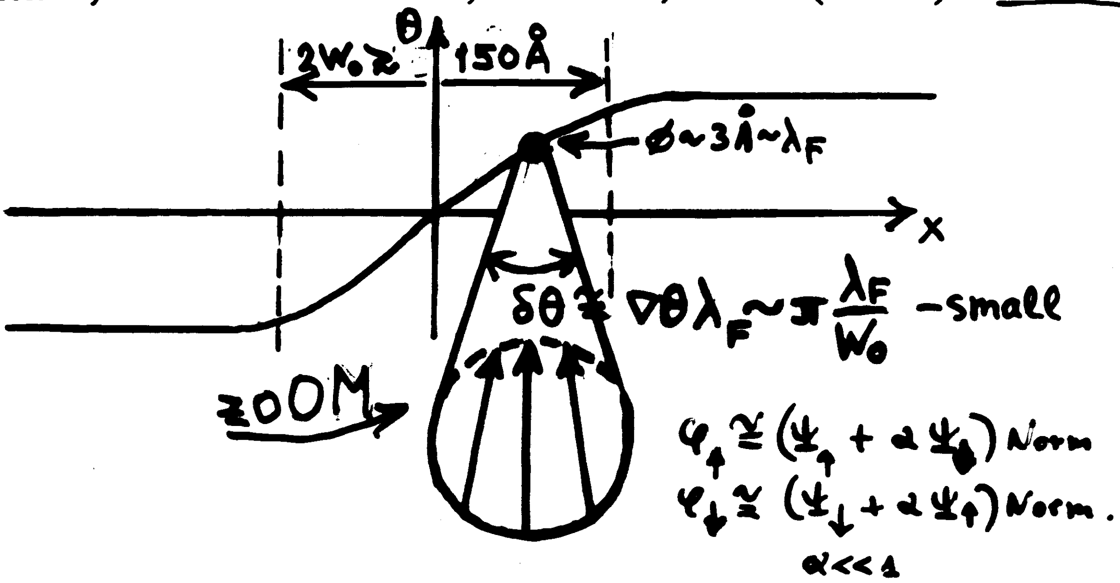


$w_o=2\sqrt{A/K}$

A – exchange stiffness const.
K – magnetic anisotropy const.

Scattering on an Unconstrained Domain Wall

G.Tatara, H.Fukuyama, PRL **78**, 3773 (1997)
P.M.Levy, S.Zhang, PRL **79**, 5110 (1997)
G.Tatara, Y.-W.Zhao et al, PRL **83**, 2030 (1999) - constrained



λ_F – electron Fermi length
mistracking $\delta\theta \sim \nabla\theta\lambda_F$ leads to spin-mixing → scattering
→ excess resistance → magnetoresistance ~ 10% (max)

Constrained Domain Wall

P.Bruno, PRL **83**, 2425 (1999)

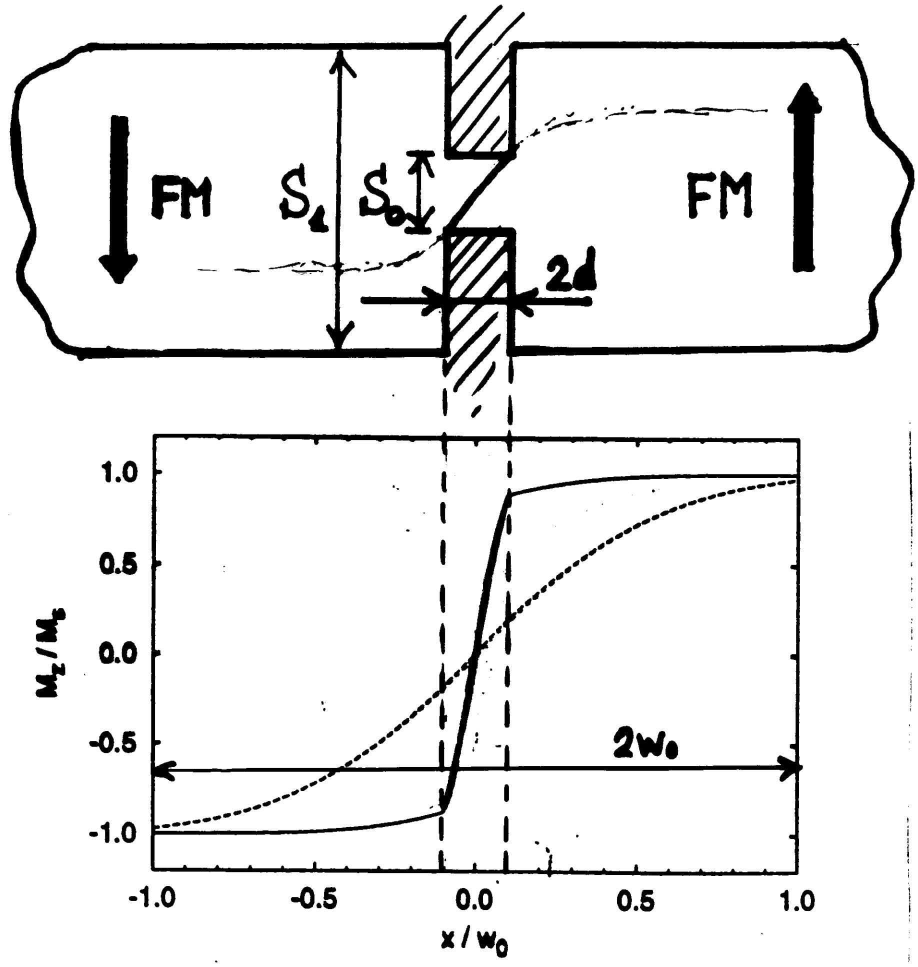
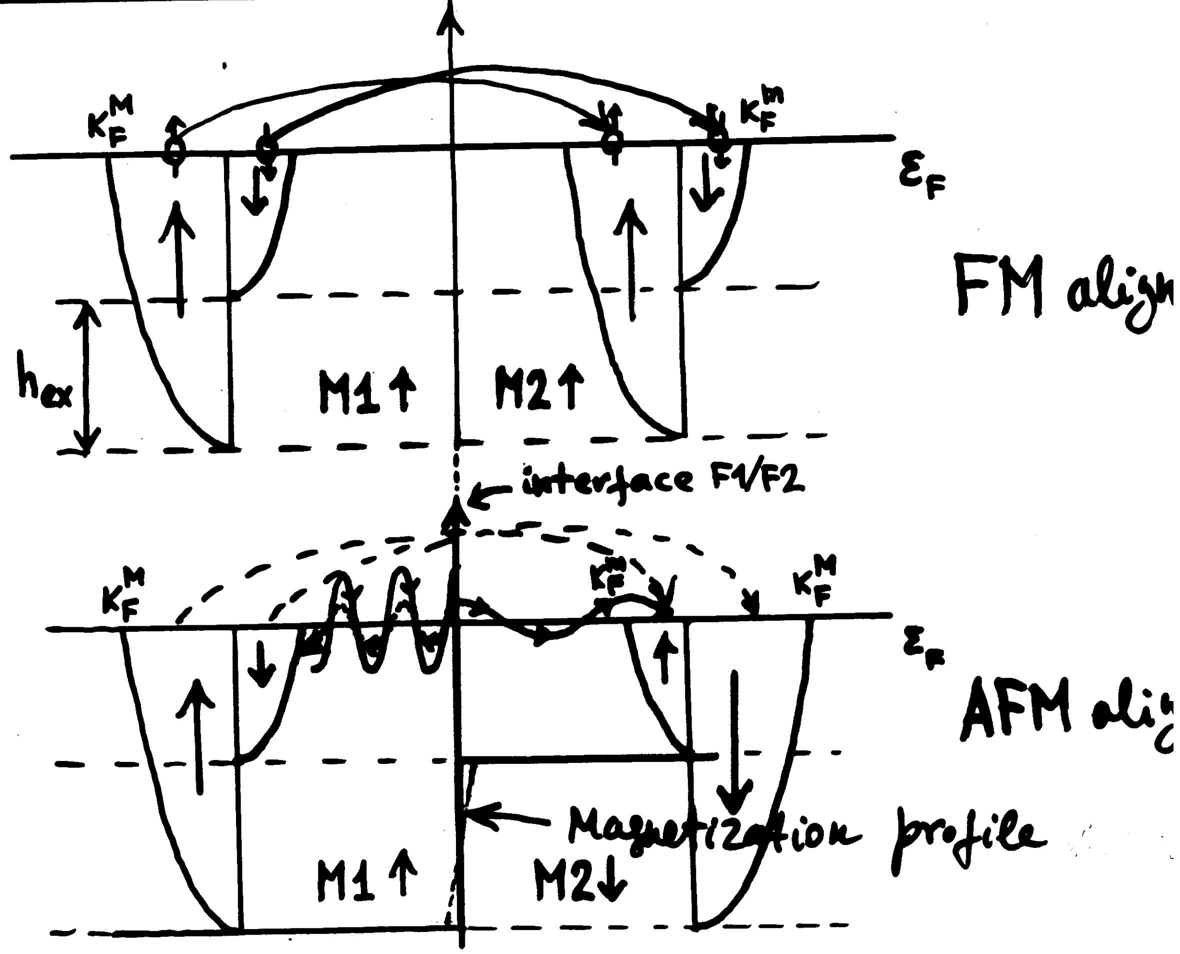


FIG. 2. Magnetization profile of a geometrically constrained magnetic wall calculated for model I with $d/w_0 = 0.1$ and $S_1/S_0 = 10$ (solid line), as compared with to the unconstrained Bloch wall (dashed line).

Reflection of Quasiparticles from the Constrained Domain Wall



Landau-Lifshitz, QM, §25 used by
G.Cabrera, L.M.Falicov, Physica Status Solidi (b) **61**, 539 (1974)

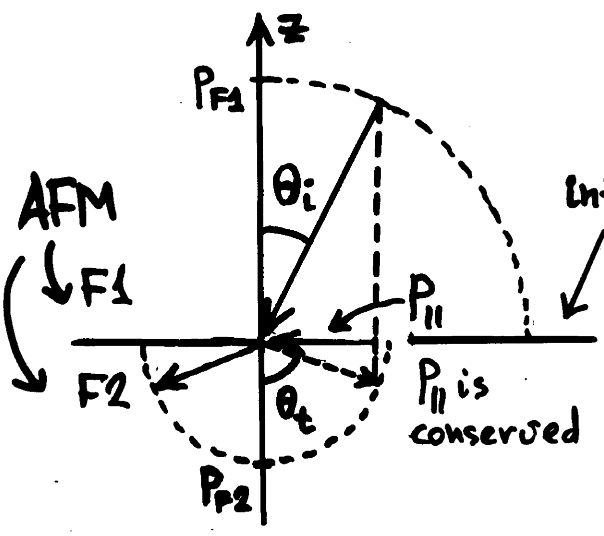
Basic Equations and Boundary Conditions

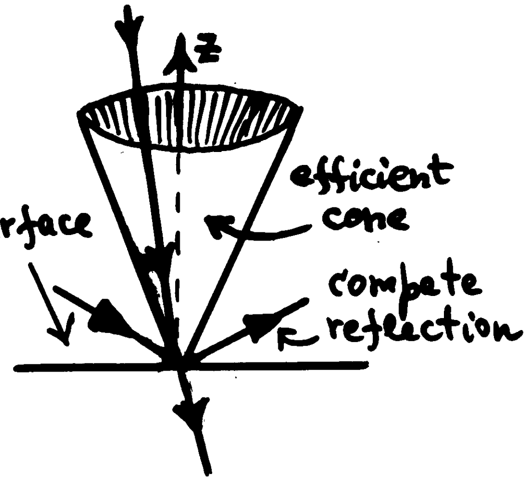
A.V.Zaitsev, Sov.Phys.-JETP **59**, 1015 (1984).

$$\begin{cases} l_z \dfrac{\partial g_a}{\partial z} + g_c = \overline{g}_c - \mathbf{l}_\parallel \dfrac{\partial g_c}{\partial \vec{\rho}}, \\ l_z \dfrac{\partial g_c}{\partial z} + g_a = -\mathbf{l}_\parallel \dfrac{\partial g_a}{\partial \vec{\rho}}, \end{cases}$$

$$\vec{l} = \vec{v}_F \tau \,, \qquad l_z = l \cos\theta,\ l_\parallel^2 = l^2 - l_z^2$$

$$\begin{cases} g_{a1}(0) = g_{a2}(0) = \begin{cases} g_a(0), & p_\parallel < p_{F1}, p_{F2} \\ 0, & \underline{\min(p_{F1}, p_{F2}) < p_\parallel} \end{cases}, \\ 2R g_a(0) = -D\,(g_{c2} - g_{c1}), \end{cases}$$





Current Density and Total Current through the NPC area

$$j^z(\mathbf{R},t) = -\frac{ep^2_{F\,\min}}{2\pi}\int_0^{\pi/2} d\Omega_\theta \cos\theta g_a\left(z,\overrightarrow{\rho},t\right).$$

$$I^z(z\to 0,t) = \int_{NPC\,area} j^z(0,\overrightarrow{\rho},t)d\overrightarrow{\rho}$$

$$= \int_{NPC\,area} d\overrightarrow{\rho}\int\frac{d\mathbf{k}}{(2\pi)^2}j^z(0,\mathbf{k},t)e^{-i\mathbf{k}\overrightarrow{\rho}}$$

$$= \int_0^\infty dk\; kj^z(0,k,t)\int_0^a d\rho\;\rho J_0(k\rho)$$

$$= a\int_0^\infty dk J_1(ka)j^z(0,k,t).$$

$p_{F\,\min}$ is the minimal Fermi momentum of two,

$J_0(x)$ and $J_1(x)$ are the Bessel functions

Solution of Basic Equations for Distribution Function

$$g_c(\varepsilon) = \tanh\frac{\varepsilon}{2T} + f_c(\varepsilon).$$

$$f_c(z>0) = g_a(z>0) + \frac{1}{l_z}\int_z^{\infty} d\xi e^{-\varkappa(\xi-z)}\overline{f}_c(k,\xi),$$

(15)

$$f_c(z<0) = -g_a(z<0) + \frac{1}{l_z}\int_{-\infty}^{z} d\xi e^{\varkappa(\xi-z)}\overline{f}_c(k,\xi).$$

$$\varkappa = \frac{1 - i k l_\parallel}{l_z}.$$

Then we integrate the equations (15) over the solid angle

$$\overline{f}_c = \overline{g}_a + \int_z^{\infty} d\xi K(\xi - z)\overline{f}_c(k,\xi),$$

$$K(\eta) = \frac{1}{l}\int_0^1 dx \frac{e^{-\frac{\eta}{l x}}}{x} J_0\left(k\eta\frac{\sqrt{1-x^2}}{x}\right) \qquad (x = \cos\theta)$$

$$\simeq \frac{1}{l}e^{-\frac{\eta}{l}}\Psi\left(1,1;\eta(\sqrt{k^2+l^{-2}}+l^{-1})\right),$$

Final Solution for $g_a(z=0,k,\varepsilon)$:

$$g_a(0,k) = -\frac{1}{2}D\gamma_k\left(\tanh\frac{\varepsilon}{2T} - \tanh\frac{\varepsilon - V}{2T}\right)$$
$$\times\left\{1 - \left[\frac{1}{2\left(1-\lambda_1\right)\varkappa_1 l_{z1}} + \frac{1}{2\left(1-\lambda_2\right)\varkappa_2 l_{z2}}\right]\right.$$
$$\left.\times\frac{\overline{D}}{1 + \frac{\tilde{\lambda}_1}{2(1-\lambda_1)} + \frac{\tilde{\lambda}_2}{2(1-\lambda_2)}}\right\}.$$

$$\gamma_k = \int_0^a \rho d\rho \int_0^{2\pi} e^{i\vec{k}\vec{\rho}} = \frac{2\pi a}{k}J_1(ka), \qquad V = -e\Delta\varphi,$$

$$\lambda_i(k) = \int_0^\infty d\xi K_i(\xi - z) = \frac{1}{kl_i}\arctan kl_i,$$

$$\tilde{\lambda}_i = \left\langle\frac{D}{\varkappa_i l_{zi}}\right\rangle = \int_0^1 dx \frac{D_{ii}(x)}{\sqrt{1 + k^2 l_i^2 (1 - x^2)}}.$$

General Expression for the Current Through NPC

$$I^z = -\frac{eVp_{F\,\min}^2 a^2}{2\pi} \int_0^\infty \frac{dk}{k} J_1^2(ka) \left\langle D \cos\theta F(k;\theta) \right\rangle_{\Omega},$$

$$F(k,\theta) = 1 - \left[\frac{1}{2(1-\lambda_1)\varkappa_1 l_{z1}} + \frac{1}{2(1-\lambda_2)\varkappa_2 l_{z2}}\right] \times \frac{\tilde{D}}{1 + \frac{\tilde{\lambda}_1}{2(1-\lambda_1)} + \frac{\tilde{\lambda}_2}{2(1-\lambda_2)}}.$$

→ Ballistic cond-ce.

D(cosθ) is the interface transmission coefficient

Magnetoresistance of NPC

(formulas) continued

Parallel magnetization (current)

$$I^{(P)}_{\uparrow\uparrow} = \frac{e^2\left(p_{F\uparrow}^2 + p_{F\downarrow}^2\right)(\pi a^2)}{4\pi^2}\int_0^\infty \frac{dk}{k} J_1^2(ka)$$

$$\times\left\{\frac{p_{F\uparrow}^2}{p_{F\uparrow}^2 + p_{F\downarrow}^2}\frac{k^2 l_\uparrow^2}{\left(1+\sqrt{1+k^2 l_\uparrow^2}\right)^2} + \frac{p_{F\downarrow}^2}{p_{F\uparrow}^2 + p_{F\downarrow}^2}\frac{k^2 l_\downarrow^2}{\left(1+\sqrt{1+k^2 l_\downarrow^2}\right)^2}\right\},$$

Antiparallel magnetizations (current)

$$I^{(AP)}_{\uparrow\downarrow} = \frac{e^2 p_{F\downarrow}^2 (\pi a^2)}{\pi^2}\int_0^\infty \frac{dk}{k} J_1^2(ka)$$

$$\times\int_0^1 dx\, x\left(D^\uparrow(x)\right)_{\uparrow\downarrow}\left\{1 - \left[\frac{1-\lambda^\uparrow}{\sqrt{1+k^2 l_\uparrow^2 - k^2 l_\uparrow^2 x^2}} + \frac{1-\lambda^\downarrow}{\sqrt{1+k^2 l_\downarrow^2 - k^2 l_\downarrow^2 x^2}}\right]\right.$$

$$\left.\times\frac{\left(\overline{D^\uparrow}\right)_{\uparrow\downarrow}}{2\left(1-\lambda^\uparrow\right)\left(1-\lambda^\downarrow\right) + \widetilde{\lambda}^\uparrow_{\uparrow\downarrow}(1-\lambda^\downarrow) + \widetilde{\lambda}^\downarrow_{\uparrow\downarrow}(1-\lambda^\uparrow)}\right\}.$$

Magnetoresistance of NPC

(formulas)

$$MR = \frac{R^{AP} - R^{P}}{R^{P}} = \frac{I^{P} - I^{AP}}{I^{AP}}.$$ – "optimistic" definition.

Interface transmission coefficients

$$\left(D^{\uparrow}(x)\right)_{\uparrow\downarrow} = \frac{4(v_{z1}^{\uparrow})_{\uparrow}(v_{z2}^{\uparrow})_{\downarrow}}{\left((v_{z1}^{\uparrow})_{\uparrow} + (v_{z2}^{\uparrow})_{\downarrow}\right)^2} = \left(D^{\downarrow}(x)\right)_{\uparrow\downarrow}.$$

with $v_{z2}^{\uparrow} = v_{z1}^{\downarrow}$ for the *antiparallel* alignment.

$$\left(D^{\uparrow}(x)\right)_{\uparrow\uparrow} = \left(D^{\downarrow}(x)\right)_{\downarrow\downarrow} = 1,$$

$$\left(D^{\uparrow}(x)\right)_{\uparrow\downarrow} = \left(D^{\downarrow}(x)\right)_{\uparrow\downarrow} \simeq \frac{4x\sqrt{b^2 + x^2}}{\left(x + \sqrt{b^2 + x^2}\right)^2},$$

where

$$x \equiv \cos\theta, \quad b^2 = \frac{1 - \delta^2}{\delta^2}, \quad \delta = \frac{p_{F\downarrow}}{p_{F\uparrow}} = \frac{v_{F\downarrow}}{v_{F\uparrow}} < 1.$$!

Ballistic Limit MR (BMR)

For pure ballistic transport ($a/l_\uparrow \to 0$) all integrals can be evaluated analytically, and magnetoresistance reads

$$BMR = \frac{(1-\delta)\{5\delta^3 + 15\delta^2 + 9\delta + 3\}}{8\delta^3(\delta+2)}.$$

If $\delta = 1$ then $MR = 0$,

$\delta = 0.5, MR = 238\%$,

$\delta = 0.4, MR = 455\%$, $\delta = \frac{p_{F\downarrow}}{p_{F\uparrow}} = \frac{p_F^m}{p_F^M} < 1$!

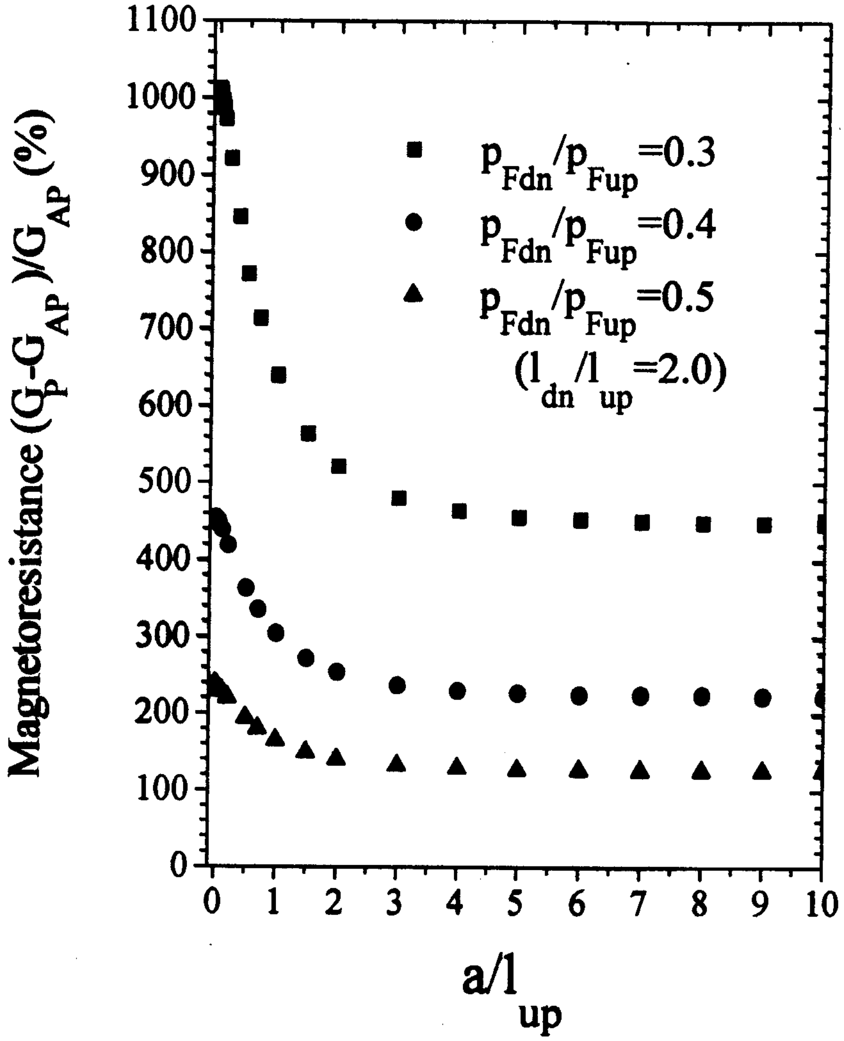
$\delta = 0.33, MR = 780\%$, $\left\{ P = \frac{1-\delta}{1+\delta} \right\}$

$\delta = 0.3, MR = 1012\%$.

280% (Ni) получаются при $\delta(Ni) \simeq 0{,}47$

230% (Co) получаются при $\delta(Co) \simeq 0{,}5$

Ballistic *versus* Diffusive Magnetoresistance



L.R.Tagirov, B.P.Vodopyanov, K.B.Efetov :
Physical Review B 65, 214419-7 (2002).
(MR in quantum point contacts)

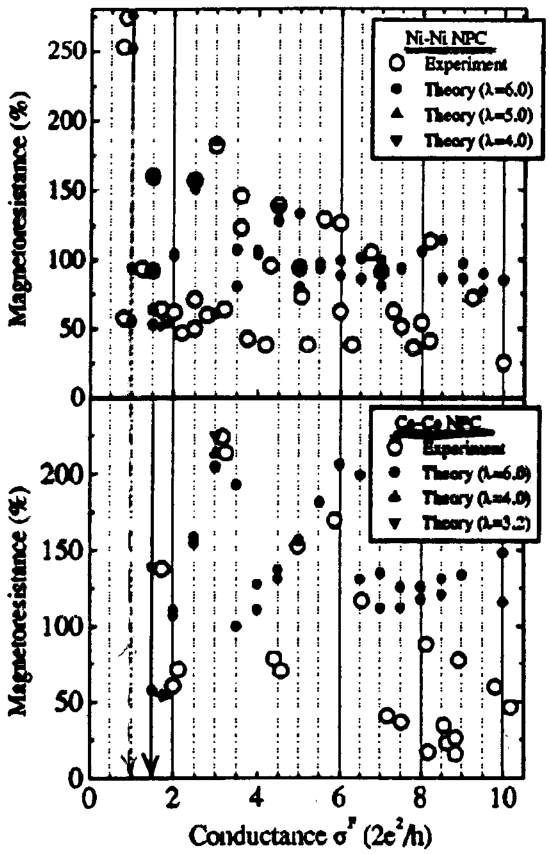


FIG. 3. Comparison between the theoretical and experimental values of the magnetoresistance for Ni ($\delta=0.64$) and Co ($\delta=0.57$) nanosize point contacts. The experimental data are taken from Ref. 3. For a discussion of the calculated MR values see the text.

PHYSICAL REVIEW B 66, 020403(R) (2002)

Ballistic magnetoresistance over 3000% in Ni nanocontacts at room temperature

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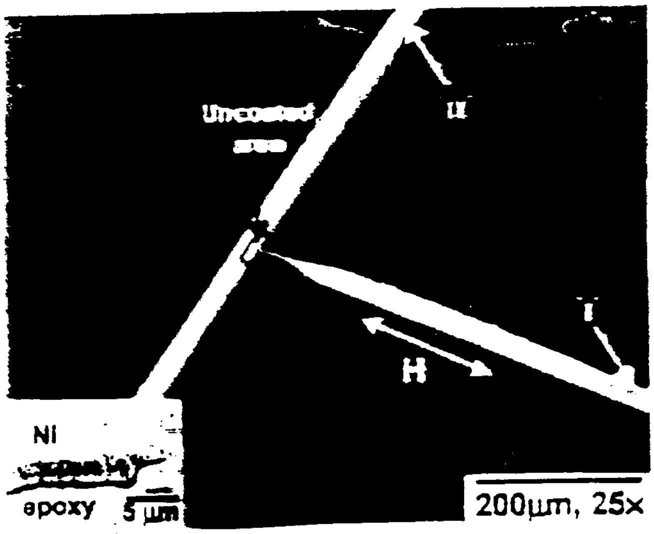
(Received 30 April 2002; published 26 June 2002)

This paper reports ballistic magnetoresistance (BMR) measurements in Ni nanocontacts made by electrodeposition. BMR in excess of 3000% is observed at room temperature and the observed large values of BMR are obtained in switching fields of only a few hundred oersteds. The results are attributed to spin-dependent electron transport across nanometer sharp domain walls within the nanocontacts.



PHYSICAL REVIEW B 66, 020403(R) (2002)

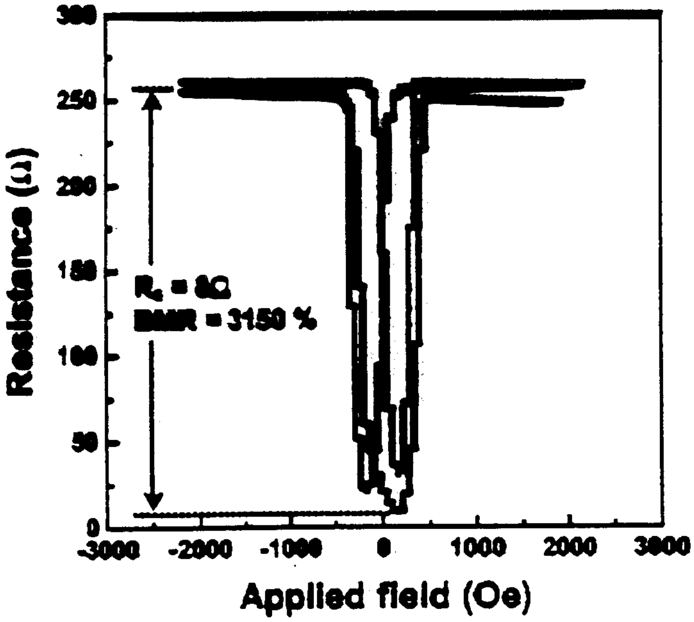


FIG. 3. Successive BMR loops from a Ni nanocontact showing 3150% BMR.

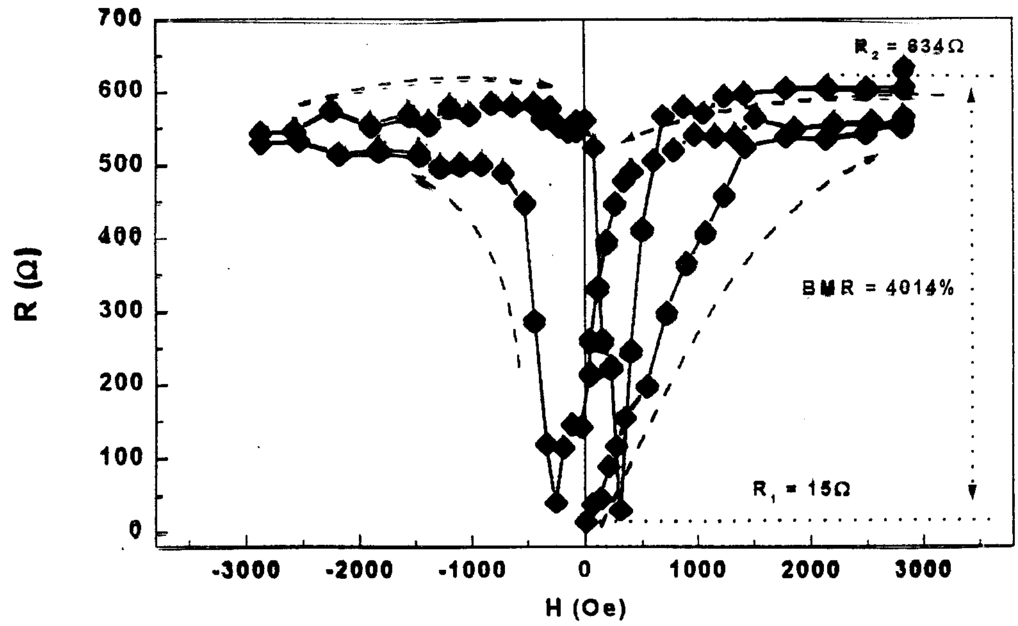
(cond-mat/0207516 - July 2002)

Ballistic Magnetoresitance over 4000% in Ni-Ni Electrodeposited Nanocontacts

Hai Wang, H. Cheng and N. Garcia*

Laboratorio de Fisica de Sistemas Pequenos y Nanotecnologia

This paper reports ballistic magnetoresistance values over 4000% measured in electrodeposited Ni-Ni nanocontacts with T geometry previously developed . Over the time, after several magnetic field cycles, the ballistic magnetoresistance relaxed to a 400%. While that the magnetoreistance of a contact could rise indefinitely; relaxtion and reproducibility are, however, the main issue. We find that the tip ending radius conforming the contacts appears not to play the main role.



[9] Regarding the indefinitely grow of BMR N.García reports that in the year 2000 his students Y.W. Zhao and M. Muñoz wrote a report to him were BMR values up 100000% were observed in three cases as well as other over 1000% in 10-30nm section nanocontacts. These data were discarded because we did not understand them and could not be justified for Ni using ref [2,3]. In the view of the dead magnetic layer and presence of other chemical agents that Ni in the dead layer interpretation, these row data as well as many other, the most representative out of over 10000 samples, will be presented in a Review-Report shortly

Conductance Quantization in Magnetic Point Contacts

PHYSICAL REVIEW B VOLUME 55, NUMBER 8 15 FEBRUARY 1997-II

Conductance quantization at room temperature in magnetic and nonmagnetic metallic nanowires

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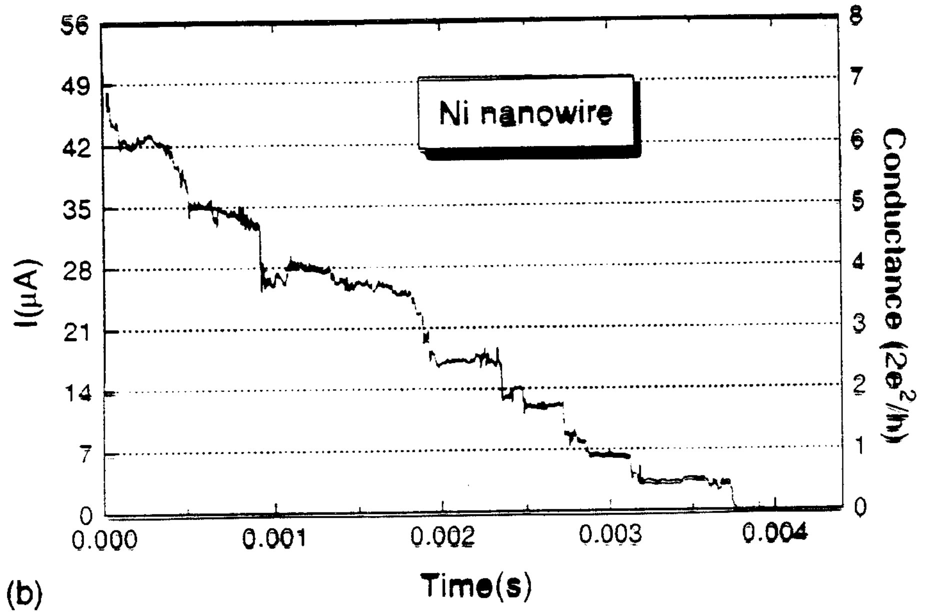
(Received 14 November 1996)



(b)

FIG. 1. Typical conductance curves for (a) gold and (b) nickel nanowires at RT in air. The applied potential difference between the separating electrodes is 90.4 mV.

Quantized conductance in a contact between metallic oxide crystals

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Laboratoire de Chimie des Solides, Universite Paris-Sud, 91405 Orsay, France

(Received 26 January 1998)

The conductance of a point contact between two crystals of metallic $(La_{0.75}Sr_{0.25})MnO_3$ shows steps as the contact is broken. A histogram of the conductance values observed in 60 breaks exhibits a series of sharp peaks at integer multiples of $G_0 = 2e^2/h$. Quantum conductance in these ceramics is qualitatively different from that normally seen in metals and suggests that no neck formation occurs during fracture of a contact between these brittle materials. [S0163-1829(98)02731-3]

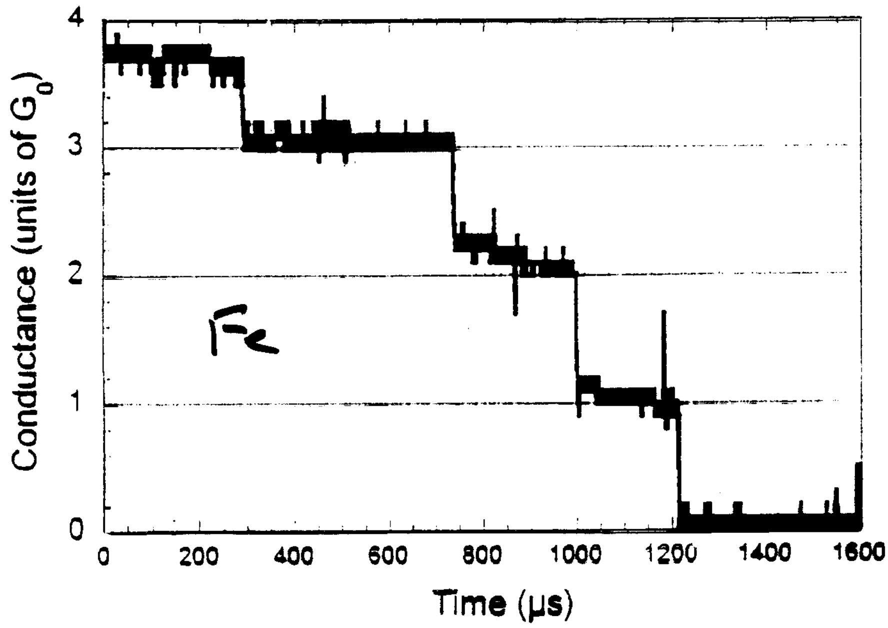

FIG. 1. Quantized conduction during the breaking of a contact between two iron wires.

APPLIED PHYSICS LETTERS VOLUME 75, NUMBER 11 13 SEPTEMBER 1999

$2e^2/h$ to e^2/h switching of quantum conductance associated with a change in nanoscale ferromagnetic domain structure

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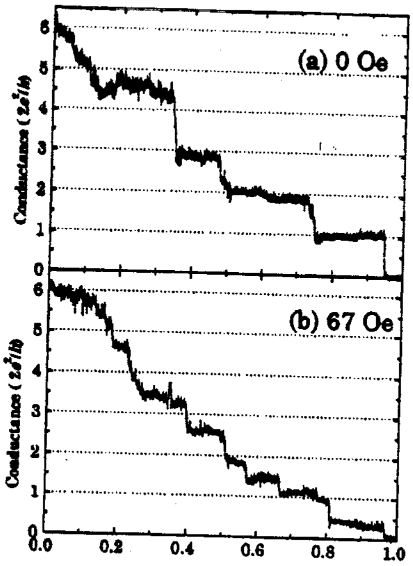
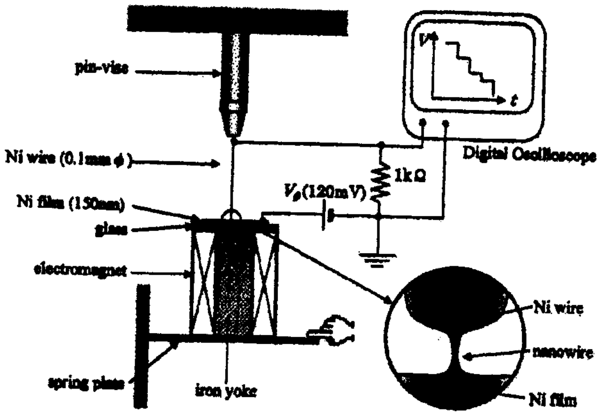




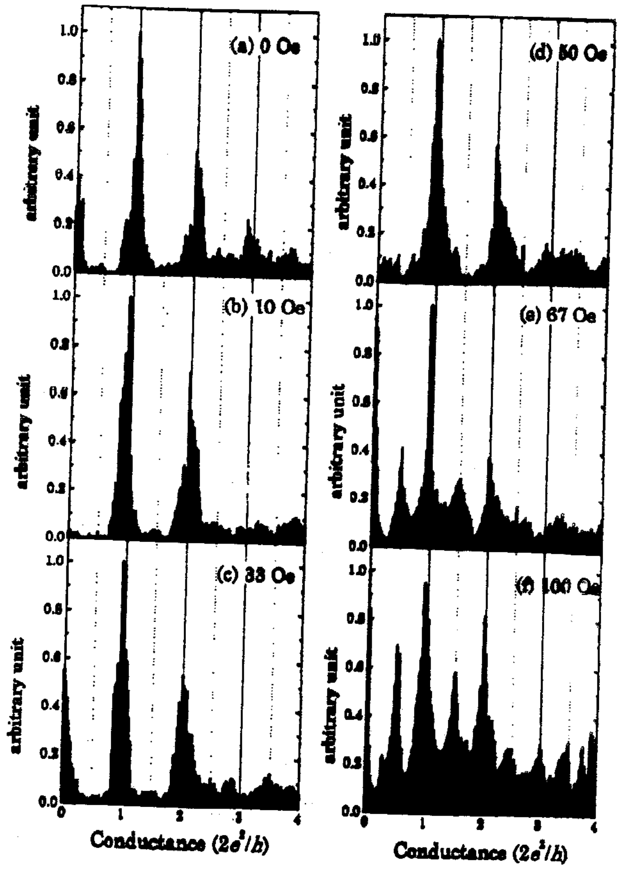


FIG. 3. Conductance histograms for Ni without magnetic field (a) and with the magnetic field of 10 (b), 33 (c), 50 (d), 67 (e), and 100 Oe (f). Each histogram is constructed from 20 conductance curves.

Magnetoresistance at quantized conductance regime

L.R. Tagirov, B.P. Vodopyanov, K.B. Efetov

published ~~submitted to~~ Phys. Rev. B (2002).

(Ballistic channel)

$$MR = \frac{R^{AF} - R^{F}}{R^{F}} = \frac{\sigma^{F} - \sigma^{AF}}{\sigma^{AF}},$$

$\sigma^{AF} \to 0$, $MR \to \infty$.

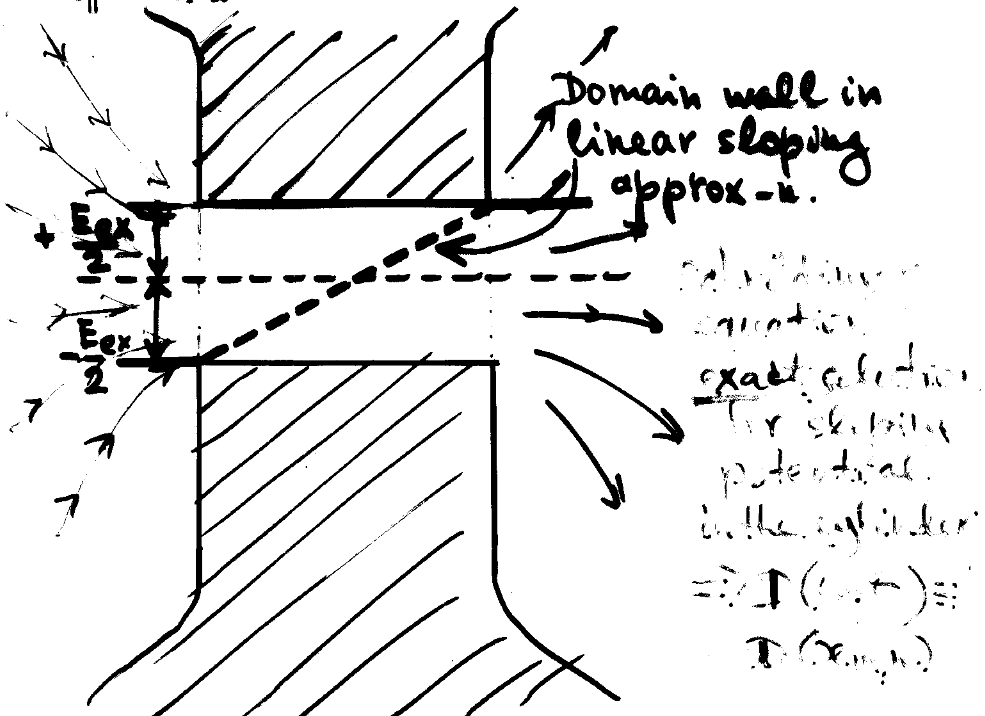
$$\sigma^{F} = \frac{e^2}{h} \widetilde{\sum_{m,n}} \{D_{\uparrow\uparrow}(x_{mn}) + D_{\downarrow\downarrow}(x_{mn})\},$$

$$\sigma^{AF} = \frac{2e^2}{h} \widetilde{\sum_{m,n}} D_{\uparrow\downarrow}(x_{mn}).$$

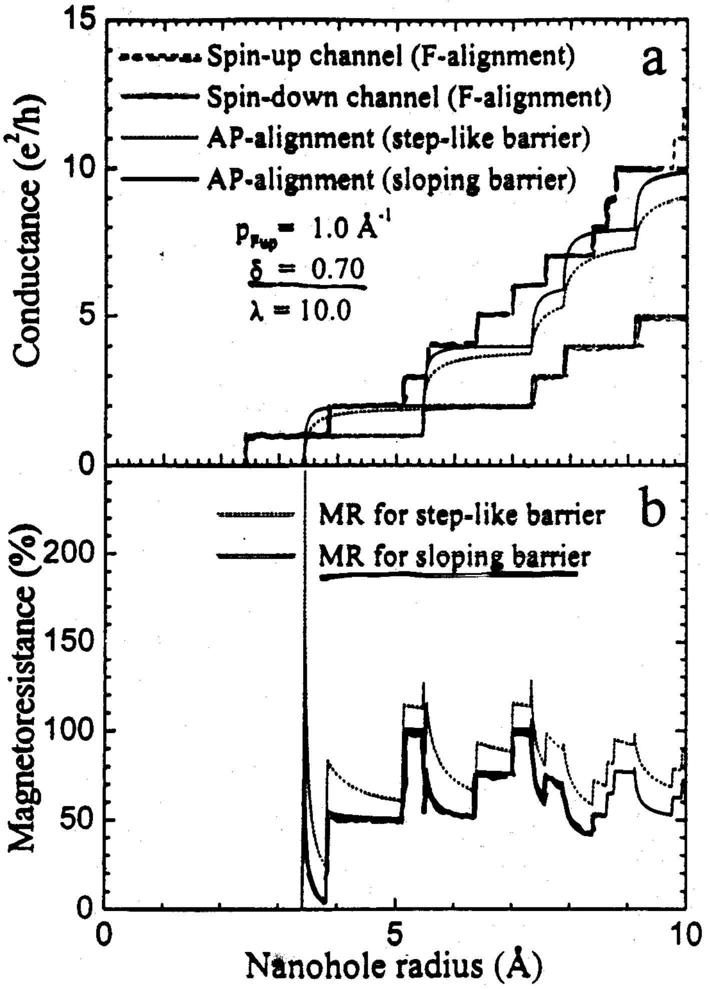
$J_m(Z_{mn}) = 0$;
↑ Bessel function

$$x_{mn} = \sqrt{1 - (Z_{mn}/k_{F\alpha}a)^2} \le 1.$$

$$k_{\parallel} \equiv k_{F\alpha}\sin\theta = k_{mn} \equiv a^{-1} Z_{mn},$$

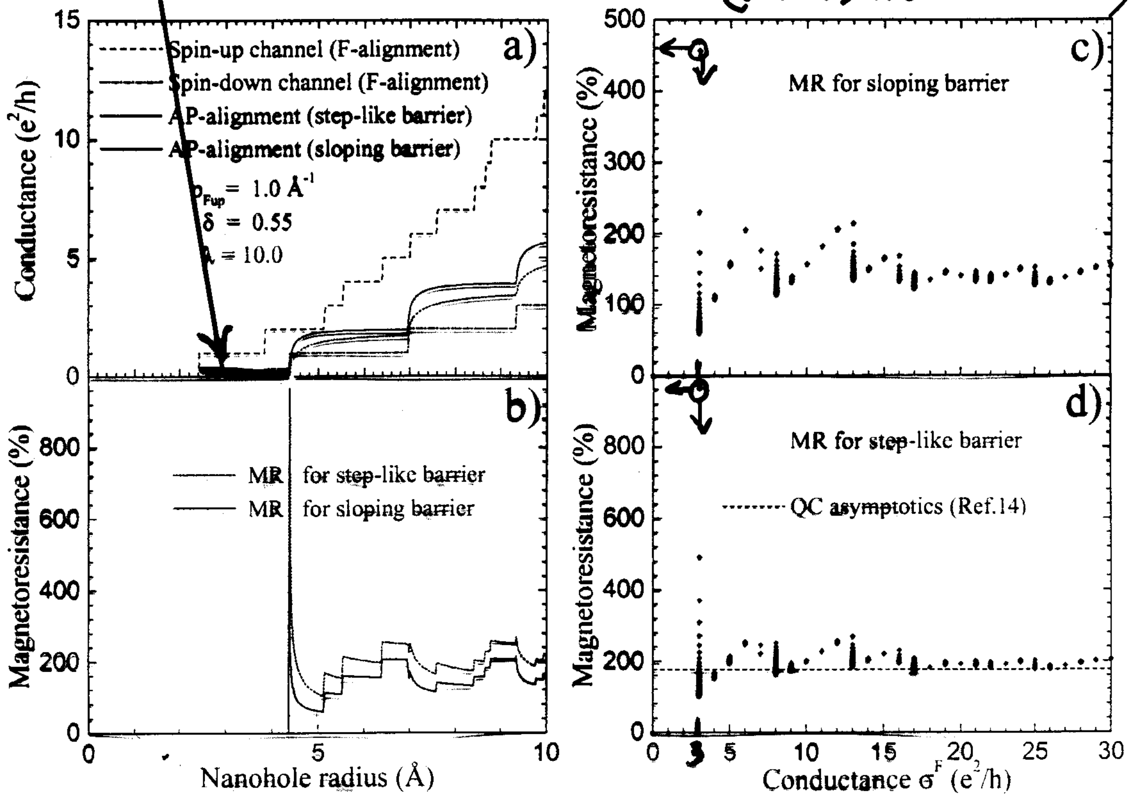


Quantized conductance, and MR of NPC

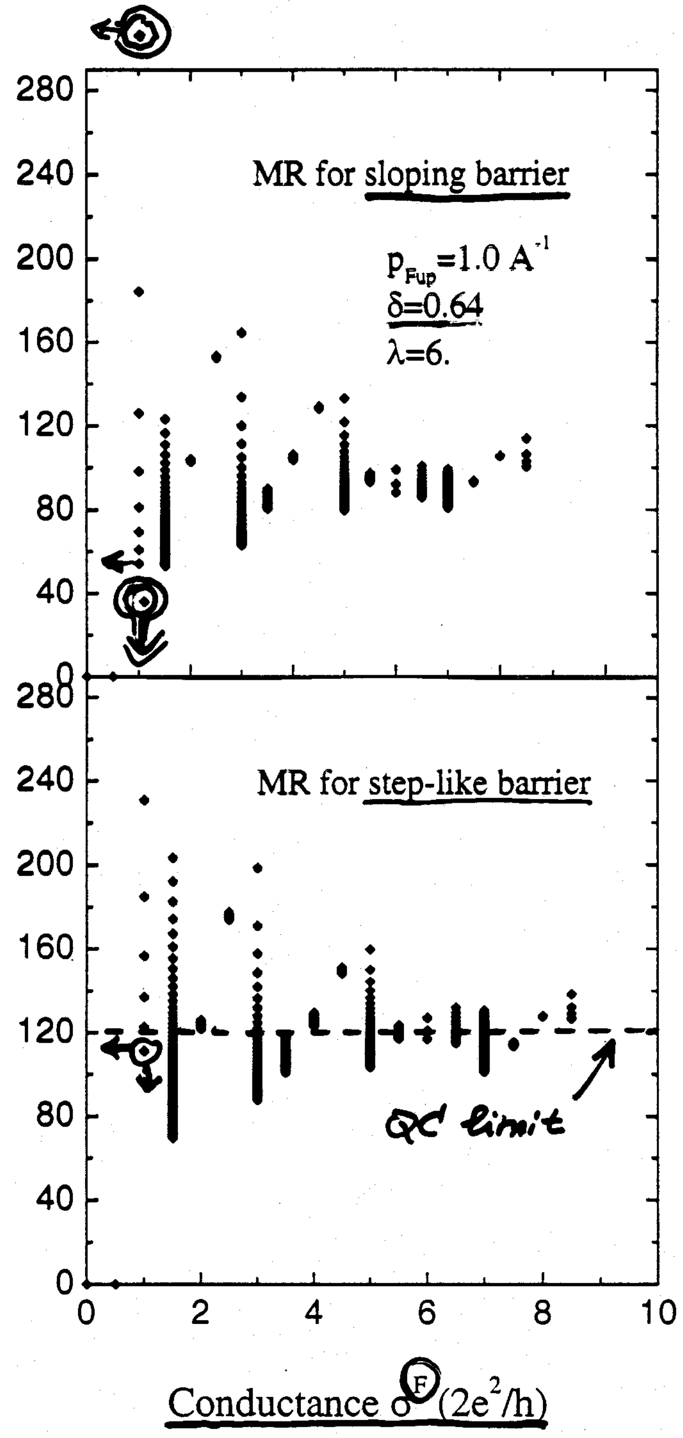


MR for δ = 0.55 ($P_{F\downarrow}/P_{F\uparrow}$)

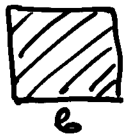
Quantum spin-valve regime region. (MR is NOT shown)



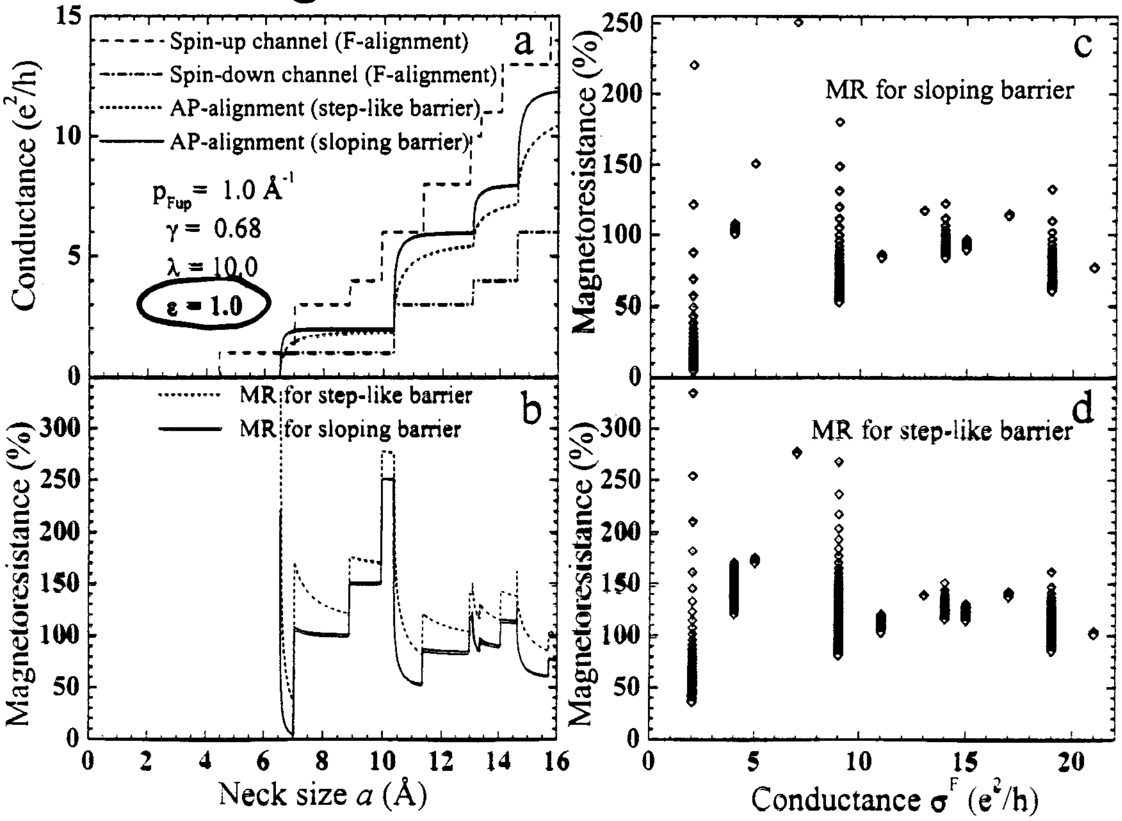
Calculated MR for the sloping and abrupt barrier



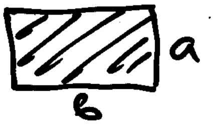
Neck of a rectangular cross-section



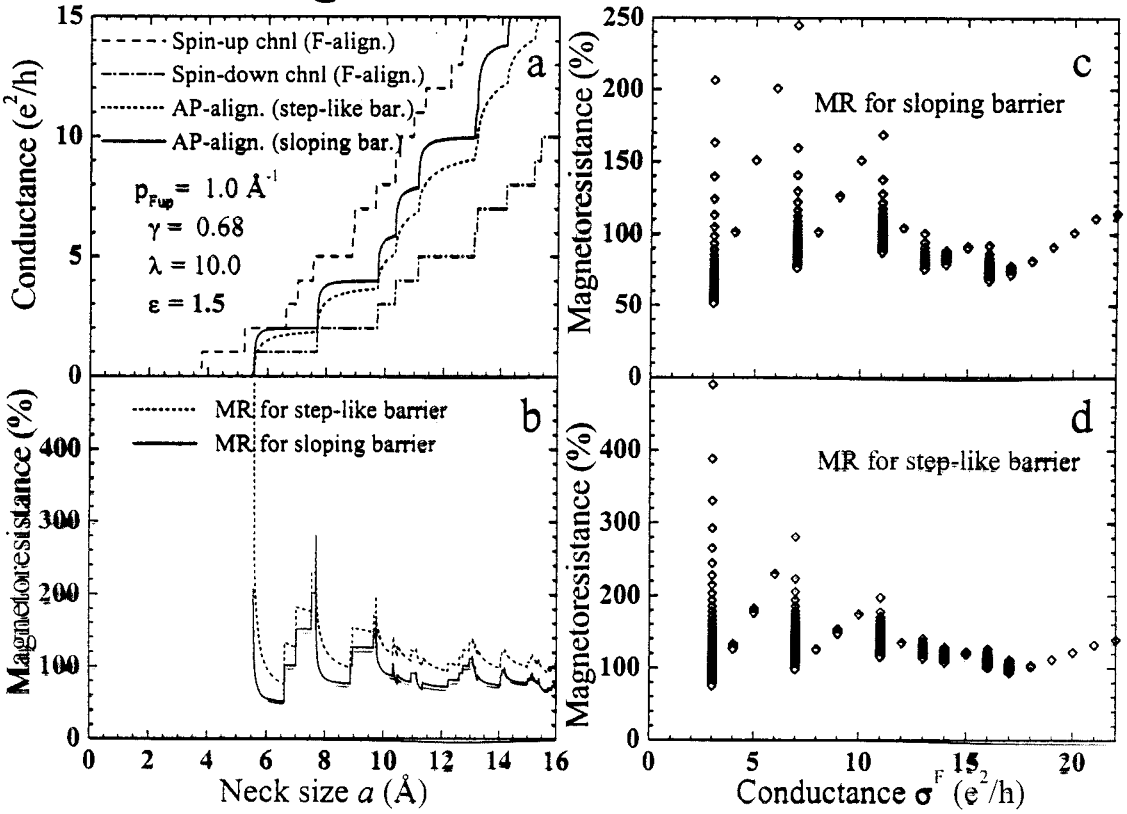
b/a = ε – aspect ratio.



Neck of a rectangular cross-section



$\varepsilon = b/a$ – aspect ratio



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100,000 % ballistic magnetoresistance in stable Ni nanocontacts at room temperature

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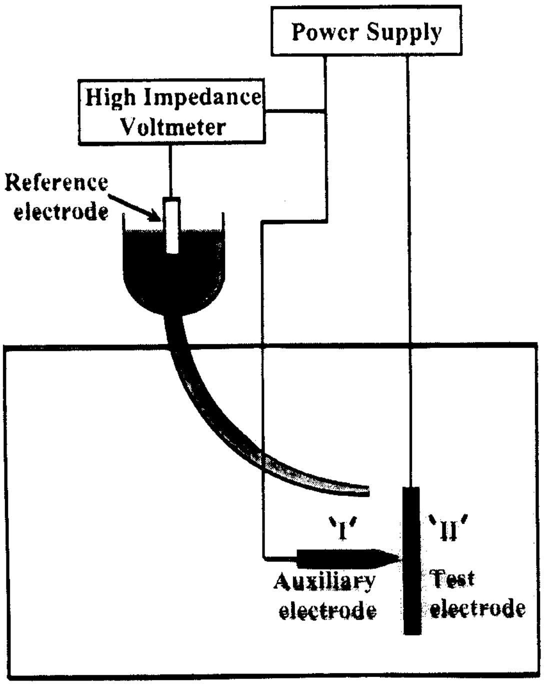


FIG. 1. Experimental layout of the electrodeposition method using the three-electrode system.

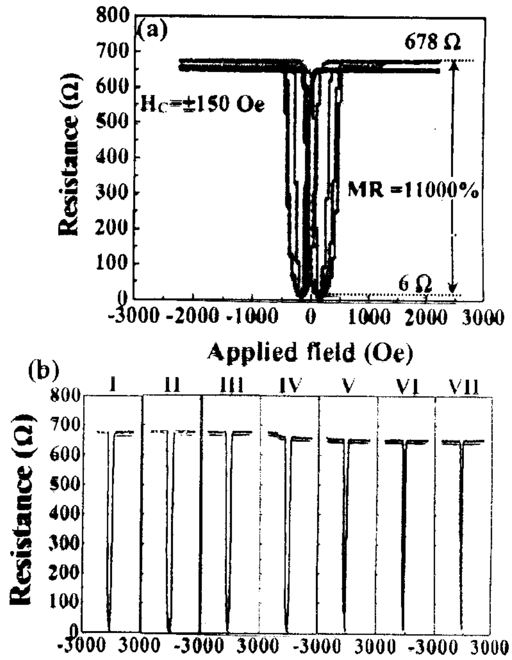
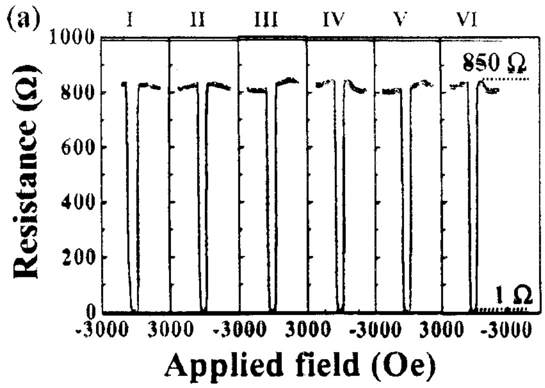


FIG. 2. (a) Seven successive positive BMR loops measured from a sample, which shows a 11 000% effect. Each of the seven loops shown in (a) are shown separately in panels I through VII in (b) to emphasize the stable nature of the nanocontact.



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Ballistic versus diffusive magnetoresistance of a magnetic point contact

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PHYSICAL REVIEW B, VOLUME 65, 214419

Multivalued dependence of the magnetoresistance on the quantized conductance in nanosize magnetic contacts

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Giant magnetoresistance in quantum magnetic contacts

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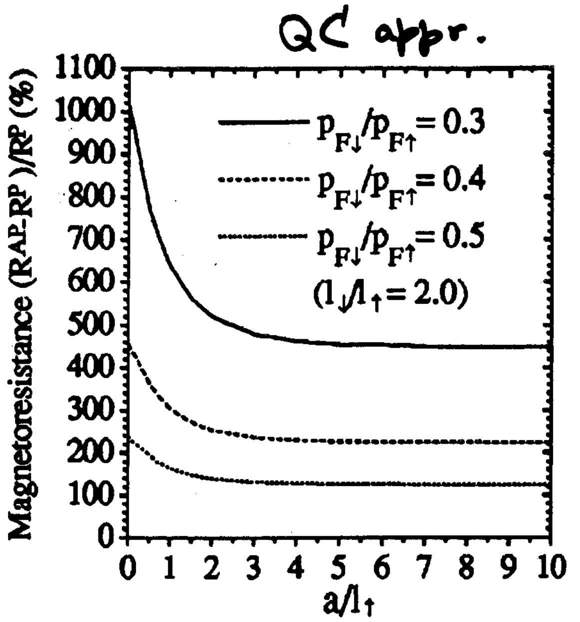

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